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MEETING AT NEW YORK, N. Y., NOVEMBER 17, 1921

Presented at the 366th meeting of the American Institute of Electrical Engineers, Akron-Cleveland, Ohio, January 14, 1921.

THE APPLICATION OF ELECTRIC POWER TO THE RUBBER INDUSTRY

BY THE SUB-COMMITTEE OF THE INDUSTRIAL AND DOMESTIC POWER COMMITTEE ON THE RUBBER INDUSTRY*

INTRODUCTION

HISTORY shows that something was known of rubber to civilization as early as 1525. In 1736 a French expedition of scientists, who were sent to South America for geographical research, sent back samples of rubber, and reported that it was obtained from a certain tree which the natives called *hevea.* Even at this early date they further reported that the natives were using this material to waterproof various articles of wearing apparel. This material was soon used in England for removing pencil marks, and hence has been termed *rubber.*

About the beginning of the nineteenth century Samuel Peal and Charles Macintosh, both of England, in turn, proposed the use of rubber in solution for impregnating fabric. The former attempted to make air-cushioned beds, and the latter made waterproofed rain coats. The attempt of Macintosh in 1820 marks the first important step toward the application of rubber to the needs of civilization.

It was not however until Charles Goodyear in 1839 made his almost accidental discovery of vulcanization, that rubber promised to become a material of a very important and far-reaching industry. The facts that the addition of sulphur to crude rubber, and as

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later learned, adding sulphur with other compounding ingredients to rubber, and subjecting the mixture to heat, so that the mass became *cured*, making further changes of its physical properties practically unchangeable within reasonable ranges of temperature; and further that the compounding materials could be adapted, both in kind, and in amount, to produce a rubber of widely varying physical characteristics; all laid the foundation for an industry which today is manufacturing articles of universal use and application, and, according to Government statistics, stands at the head of the list of "Individual Large Users of Electric Power."

Crude Rubber is obtained from certain species of tropical and sub-tropical trees, shrubs, vines, and the roots of certain plants. In the case of trees and some vines it is coagulated from the milk-like fluid known as latex which exudes from cuts or sores in the bark, while rubber exists in some vines and most shrubs in a solid form incorporated with the woody fiber. In the case of the latter the rubber is obtained by complete maceration of the entire shrub by the means of suitable pulp grinding machinery assisted by the use of water, which carries off the pulp and bark while the rubber is reduced to an agglomerate mass, and passes out of a suitable opening provided in the machine.

The various grades and brands of rubber are usually known by the name of the geographical locations in which they are obtained. This nomenclature is especially common among practical rubber men. It is now true that there is a tendency, especially among engineers and chemists, to speak of rubber according to a botanical or other scientific classification. The finest quality of rubber is obtained from South America, while grades of less value are obtained from Central America, and Mexico, and some of the shrub variety from Texas. Large quantities of rubber with some very good grades are secured from the tropical, and sub-tropical regions of Africa, Asia and Australia.

Milling and Washing of a thorough character of all grades of rubber are essential. At the plantations it is either run through a sheeting mill, or through a creping mill, while in the case of those kinds shipped without receiving either of the above operations, it is thoroughly mechanically disintegrated in a washing mill at the various rubber factories.

Summary of Committee Activity

United States Government statistics show the rubber industry to be the largest individual user of electric power.

How this large amount of electric power is applied, is the duty of this committee to show. We hope that our work may assist the engineer in electric power application problems, to render this large power more efficient, and thus help assist humanity in its efforts toward conservation.

This committee has planned its work to include a number of divisions, each division being sub-divided, making it more easy to digest.

Power Consumption

1. *Basic Machinery Applications.* The power demands in this division are for electrical units of relatively large horse power and constant speed. These general milling operations embrace the following machines:

   a. Washers.
   b. Crackers.
   c. Mixers.
   d. Batch mixers.
   e. Safety stops.

2. *Intermediate Process Applications.* The power demand in this division is met as a rule by special applications of moderate-size electrical units, adjustable speed.

   Semi-Finishing Machines
   Calenders and Calender Drives.
   a. Individual drives.
   b. Conveyers.
   c. Synchronous control of calenders, and of calenders and conveyers.

3. *Finishing Process Applications.* The power demand in this division is for electrical units of relatively

small capacity. Constant speed as a rule. Some machines require adjustable speed, continuous running. Others are intermittent, frequent "start" and "stop," and some types must be equipped for frequent "reversals."

Finishing Machinery.

a. Fabric bias cutter.
b. Tire building machinery.
c. Tubing machines.
d. Insulating machines.
e. Hose loom.
f. Hose braiding machines.
g. Hose wrapping machines.
h. Hose stripping machines.
i. Hose building machines.
j. Rubber shoe machinery.
k. Rubber glove machinery.
l. Hard rubber machinery.
m. Mechanical rubber goods machinery.

4. *Electric Heating Applications.* Only a limited amount of electric heating has been applied to the rubber industry. Possible applications are being investigated.

5. *Contributory Problems and Applications.*

. Power Supply. Transmission.

a. Power and lighting switchboards.
b. Transformation of alternating current to direct current for adjustable motor speed requirements.
c. Air compressors.
d. Hydraulic pumps.
e. Elevators and hoists.
f. Floor and street trucks.

POWER ECONOMY

A study of the subject in the abstract, should show the engineer where, by making a power application of a certain type in one division, he may lessen the losses in another division.

A study should be made of each concrete problem, selecting units of relatively low initial torque but high all day efficiency where high initial torque is not required; and selecting units of relatively high initial torque, and of a continuous load capacity suitable for the work, so that power efficiency can be increased. This conclusion is reached without overlooking the facts, that much of the rubber mill machinery is subject to high peak loads, and that continuity of operation is of importance to production.

It is not the intent of this paper to reflect in any manner against the progress that has been made, but to suggest that possibly greater care should be taken in selecting electrical equipment of the most suitable type and size for each application so that increased efficiency will obtain.

PROTECTION TO OPERATIVES

Owing to the tenacious characteristic of rubber in its plastic state, a hazard to the mill operators is at all times present. Hence the need of safety protection is imperative.

CONCLUSIONS

a. Possibilities of electric power.
b. Application of 40-degree and 50-degree motors.
c. Steam *vs.* electrically heated drying ovens, (250 deg. fahr.)
d. Steam *vs.* electric heat treatment of vegetable compounds. (250 deg. fahr.).

BASIC OPERATIONS

General Considerations

PROCESSES

The general milling or basic operations obtain in every class of manufacture of rubber articles.

It is in this general division that the crude rubber is treated, compounded and probably colored, to produce the mixture required for the specific need. The per cent of pure rubber in different articles is a large variable, being high in one class, and low in another. In general milling operations, there are many variables that affect the power requirement. Examples: Source of supply of crude rubber. Working temperature of rolls. Pressure on rolls. Grade of compound or mixture.

General milling operations include the "washing," "cracking," "mixing," and finally "batch warming" ready for the calenders.

MOTOR SELECTION

Gearless Drive. The earlier type of motor drive involved a moderate-speed motor, geared to the mill shaft through spur gear reduction gears, the gear ratio employed, as a rule, being approximately 1 to 6, to provide a mill-line shaft speed of approximately 90 rev. per min. Of recent years, the herringbone gear became popular for rubber mill machinery, with the result that a large proportion of installations made during the past few years have been equipped with herringbone gears.

The prevalent tendency is an endeavor to eliminate the gear reduction, and connect the motor shaft directly to the mill-line shaft. This requires a very low-speed motor, and is impracticable with large size induction motors, either of the squirrel-cage-rotor, or of the wound-rotor type. The synchronous motor however is readily adaptable to this low speed and provides the advantages of high power factor, which is of large significance in view of the widely varying loads encountered in milling, in addition to the elimination of costly, noisy gearing. The elimination of gear maintenance is a large factor.

The first gearless installations made, of which this committee has record, are at the plant of the Republic Tire and Rubber Company, Youngstown, O. These were installed many years ago, and the reports obtained by this committee indicate that the company feels after years of operation that its judgment was sound in their selection.

The point we wish to bring out, however, is the possibilities of the gearless drive. This question settled it simply becomes a question then, of selecting the suitable modern type of low-speed motor.

Voltage. The majority of milling operations require motors of large capacity and of constant-speed characteristics. That these motors may advantageously be of high voltage, direct from service lines, eliminating step-down transformers with their additional losses, is a factor worthy of consideration in power application.

Motor Size. In motor size selection two important factors for first consideration are: Torque capacity to pull through the peak loads, and mean thermal capacity. High mean efficiency and high mean power factor are important, but are secondary to the ability of the motor to do the required work within reasonable temperature limits.

Horse power rating is not important. This term means simply that a motor will, when developing a defined rated torque (known as full-load rated torque), at a defined rate of speed (known as full-load rated speed), have a temperature rise not in excess of a defined value.

This may be amplified by time limitation, such as 30-minute rating; one-hour rating; two-hour rating; but it assumes a constant load.

In milling operations does this condition exist?

The load, that obtains in milling operations, has a possible variation from a minimum of friction load, with all mills empty, up to a possible maximum of simultaneous loading of all mills on the line.

With an individual drive (one mill only for each motor), both the minimum, and maximum condition will obtain. With two mills the same result is probable. With three mills to a drive, it is probable at infrequent intervals. With increasing number of mills to a drive the probability of obtaining the possible maximum peak load decreases. With five mills the probability is that the maximum load at any one time will be 75 per cent of the possible maximum. With eight mills to a drive the probable maximum load will be 50 per cent of the possible maximum. The greater the number of mills to the line, the more closely is a constant-load condition approached.

This is not intended as a justification of placing all mills in a plant on one mill line. The number of mills, and sizes of mills to a mill line are governed by local conditions over which the electrical engineer has no control.

The purpose is to emphasize the conditions which confront us in motor size selection.

We want to bring out clearly:

1. That greater number of mills to the mill-line drive does not increase maximum torque requirement proportionately.

2. That greater number of mills to the mill-line drive does eliminate to some extent the depth of the valleys in the load curve, and that the peak loads do not increase proportionately to the number of mills.

The two important factors are: Torque and thermal capacity.

a. Select a motor having a pull-out torque capacity in excess of the maximum torque requirements; this motor to have a thermal capacity sufficient to carry the mean load continuously without heating beyond prescribed temperature rise limit.

b. This motor should have a high mean power factor carrying the mean load determined for the thermal capacity selection.

c. This motor should have a high mean efficiency, carrying the mean load determined for the thermal capacity selection.

d. This motor should have good speed regulation characteristics when carrying the loads that obtain when developing any torque, between 20 per cent of the maximum torque pull-out value, and maximum torque pull-out value.

e. This motor should be mechanically constructed so as to withstand the load shocks imposed by the frequent peak loads that obtain. (Caution should be exercised to obtain ample size of shaft, bearings, and rotor structure).

A motor selected on this basis would not be over-size. Over-size motors increase investment, have a lower combined mean power factor efficiency, and are not justified for economical production.

If motors have poor speed regulation characteristics, under the varying loads that obtain, production is lessened. One example of motor selection on this basis can be cited, and there are probably many others.

In 1915 an installation of 40 mixers was contemplated for low-grade compound for one plant. The plan was to operate in groups of two, with a total of 20 drives. One machinery manufacturer offered 100-h. p. motors. Another 75-h. p. The engineer, considering the nature of the compound, was satisfied with neither. The order was placed for the mills, and the motor size selection withheld 30 days, during which time a continuous test was made with a graphic meter (24 hours per day, three shifts of workmen), on the same size of mills and the same mixture of compound.

The result, was the selection of motors nominally rated at 50 h. p. but which had ample pull-out torque capacity for the peak loads, and ample thermal capacity rating for the mean load. These motors have now been in successful operation for over three years, and over a considerable period of time were operated 24 hours per day.

In 1919 eight similar drives were added.

In another plant is a four-mill drive fitted with a 400-h. p. nominal rating motor. A test with all mills operating showed a maximum load of 300 h. p. After several hours of test showing a load fluctuating between 50 h. p. and 300 h. p., an appeal was made to the superintendent to provide conditions that would give a maximum load condition.

The superintendent had a special grade of stock trucked in for the test. He instructed all workmen to handle the work in a manner to provide the maximum load possible, and the highest load peak obtained was 405 h. p.

These examples are not offered as a plea for small or under-size motors, but simply to emphasize against the waste of using over-size motors.

Motor Controller. The motor controller recommended by this committee for general milling work would comply with the following specifications:

a. Controller to be of a totally enclosed type.

b. Controller to be manually operated, from a lever or external mechanism.

c. Controller to be fitted with inverse-time-limit overload protection.

d. Controller to be fitted with low-voltage protection.

e. Controller primary switching mechanism to be of a type suitable to the voltage of the system. For 550 volts or less, air-break, fully enclosed, primary switching mechanism to be preferred. For 2200 volts or higher, the switching mechanism of the primary switch to be oil-immersed.

f. The resistor, if required, to be of cast metal grids, 30-second duty rating, open structure, for mounting separate from the controller.

g. The controller to be interlocked with the safety stop mechanism so that the motor cannot be started with any of the safety stop devices in the "safe" position.

Washers

CRUDE RUBBER TO PURE RUBBER

Crude rubber, whether *wild,* or *plantation,* is a dirty brown mass. It may be in the form of large balls, small balls, or rectangular chunks. In any event it is a conglomeration of dirty gum, sand, stones, and sticks. It may be "smoky," or it may not be.

It must not only be "washed," but it must be disintegrated, and the rubber particles separated from all foreign substance. When thoroughly washed, disintegrated and separated, the color of the resultant granule is that of rich cream. Thus, the change from *crude* rubber to *pure* rubber. The quality of the pure rubber is dependent largely on the geographical source of supply of the crude rubber.

Continuation of the washing produces coagulation, and results in rough uneven crepe-like sheets, of about the size of a page of your daily newspaper.

If the *sheeting* term is disregarded and the mind is placed on a granular substance, such as granulated sugar, the next phase of procedure will be more readily understood. We must now change the "granulated sugar" into "taffy."

The next operation causes coalescence. The granules are broken down, and fused, resulting in heavy sheets of pure gum approximately 3/8 inch in thickness. Although water is not used in this phase of the process, we class it with washing, in that the accounting systems of many plants use the same classification.

The crude rubber is "accounted out" to the washer room as crude rubber, and is "accounted back" to the store room from the breaking-down mills, as the resultant product of these various procedures.

MOTOR SELECTION

Disintegration. This process involves machines, known as "washers" in some plants, and as "crackers" in others.

The rolls on these machines are fluted spirally. Both rolls are fluted in the same direction, but are rotated in opposite directions. The speed of one roll is higher than the other. The ratio of friction is unusually high, as a rule. This ratio is as high on many machines as 1 to 1⅜. The distance between the rolls may be ⅜ inch or greater.

Analysis of this type of machine and the material it must handle shows the following load characteristics; all of which obtain simultaneously, and all of which are in the nature of suddenly applied loads:

a. A relatively short heavy chunk of cold crude rubber forced into the V between the rolls, until the rolls grip and wedge it through, causes a heavy suddenly applied load, with resultant shock.

b. The spirally fluted rolls, one of higher peripheral speed than the other, cause a combination of dragging in, wedging, crushing, cutting and tearing apart action producing a heavy, suddenly applied load, with resultant shock.

c. The high ratio of friction, the peripheral speed of one roll so much greater than the other, is a large factor in itself toward producing a heavy, suddenly applied load with the resultant shock.

d. The wide separation between rolls is another large factor toward producing a heavy, suddenly applied load with resultant shock.

All of the foregoing indicate that every characteristic produces heavy suddenly applied loads with resultant shock. Aside from the mechanical ability of the motor to meet high shock demands there must be that ability in the motor to pull through the peak. There must be the required turning ability in the motor to absorb the resultant shocks. Turning capacity is the essential feature for peak loads.

There is one redeeming feature to washer work. The peak loads are of short duration. The peak load obtains only when the heavy, cold chunks are passed through. The actual time of passing a chunk through the washer, assuming good speed regulation, would be from $^2/_3$ of a second, to 1½ seconds. It is possible to have this condition repeated in rapid succession. This could result from feeding chunks to the washer in rapid succession.

Nevertheless, the peaks are of short time duration and kinetic energy of rotation should be included in calculations determining motor size selection.

The turning ability then can be the result of two factors. *Inertia* and *torque.* If the inertia is relatively high, the torque may be proportionately decreased, so that the sum of the two is of ample capacity to carry any reasonable peak load.

It is fallacy to permit mill operators to force the mills to do unreasonable work, and it is not good practise to equip a mill or mill line with motors of a capacity largely in excess of that of the mechanical equipment. The mechanical equipment is designed to absorb all reasonable shocks. The motor capacity should be proportionate and the motor should have suitable protective devices to protect it in event of attempted abuse by operators. When this protective device stops the mill line, there should be no attempt made to force the motor and mill line to do the unreasonable, that which it is not designed to do. The jammed material should be backed out of the mills or the pressure on the rolls released, thereby relieving the equipment of unreasonable abuse.

If this cooperation obtains between the production department and the engineer there will be no temptation to equip with motors largely in excess of reasonable requirements or in excess of the capacity of the mechanical equipment.

A suggestion that is not irrevelant at this stage, would be the installation of a visible signal on each washer mill. This signal would indicate to the operator at any time that the reasonable load point had been attained. The operator on any one mill would know that the mill line was up to capacity. Each would know at once whether his individual mill were overworked; if not, he would feed with reason; if so, he would delay further feeding. Non-attention to the signal and further forcing and abuse would cause a shut-down on the mill line.

With a signal system of this nature the motor size selection may be on a basis of reasonable peak load, with assurance that not only the motor but the entire mechanical equipment as well, will suffer little abuse.

Then,—(1) With a true knowledge of the nature of the material to be washed, (2) With a true analysis of the characteristics of the machine, (3) With a thorough understanding of what is a reasonable peak load, the problem as far as turning capacity is concerned, simply becomes one of selecting that type of motor which is best suited to the plant conditions and to the mechanical structure of the drives, that is, whether geared or gearless.

Due consideration must be given to a washer line where a number of washers are involved. Also to a mill line that may incorporate sheeting and breaking-down rolls.

The law of average will obtain on a mill line driving a number of washers, or a mill line driving a number of mills of different types.

On washer mill lines the engineer may make a formula along the following lines, such to be based on tests in his own plant under the class of material conditions and the working conditions that obtain there. The formula here presented represents average plant conditions, as owing to the many variables it is impossible to offer a formula that is applicable to all.

Assume one washer on a given stock, reasonable peak load to equal 100 per cent.

Let N = number of washers
K = a constant

TABLE OF CONSTANTS

No. of Washers	K equals
1	1.00
2	1.00
3	0.85
4	0.82
5	0.80
6	0.72
7	0.67
8	0.62

The formula then would become 100 per cent $X\ N\ X\ K$ = peak load capacity required for a given number of washers in per cent of the peak load capacity required by one mill.

Assume a given size of washer requires a peak load capacity equal to 132 actual h.p., then four such mills would on this basis indicate a peak load requirement of 432.96 h. p.

The constants given here are average, and are conservative considering the test data available. They should not be considered, however, as recommended working constants. Each problem should be studied from its own or similar plant conditions.

It is important however to bear in mind, that calculations should be based on peak load capacity of the motor, and not on the nominal h. p. rating.. This is of especial importance if applied to synchronous motors, as there is a wide difference between the maximum torque capacity of the synchronous motor and the induction motor. It is also important as there is frequently an appreciable difference between the maximum torque capacity of different induction motors of the same nominal h. p. rating.

The important point is the selection of a motor of sufficient turning capacity, when operating at its rated speed, to carry through those peak loads that have been determined as reasonable. Second, to signal the operators when they have attained that peak load, that has been determined as reasonable. Third, to shut the line down, should the peak assume an injurious proportion.

The following abridged list is given of some existing installations which were selected at random, and not purposely to show the wide divergency in motor selection that it is possible to show. They are included to emphasize the fact that a definite basis of selection cannot be given. At least not until all available data, and all data that it may be possible to secure, have been brought together under one head, thoroughly analyzed and tabulated.

SOME TYPICAL WASHER INSTALLATIONS

Face of Mill	Nominal H. P. Rating of Motor	Nominal H. P. Per Inch of Face
30 inch	50	1.66
36 "	40	1.1
4—48 "	250	1.3
4—40 "	150	0.94
3—60 and 1—36 inch	250	1.15

Any engineer would be justified in remarking the apparent inconsistency, although all the mills may be consistently equipped. The table does not indicate diameter of rolls, nor grade of material. The data do not indicate the friction ratio, nor the distance between rolls.

Can we have a rule, applying correctly, based on the length in inches of the face of the roll? Can we have a rule, applying correctly, based on the nominal h. p. rating of a motor?

This committee believes that neither question can be answered in the affirmative. Such rules must be general or be so liberal that to equip with motors safely those mills that do the hardest work, all other drives will be inefficiently over-supplied with power.

The committee believes that such rules have not been followed in general, as data it has indicate some mills equipped with as low as 0.695 nominal rated h. p. per inch of roll face, and other similar mills with as high as 1.39 nominal rated h. p. per inch of roll face.

The committee is confident that many engineers directly associated with the rubber industry have studied the basic problem and that they personally were responsible for the correct motor equipment of their mill lines.

All of the foregoing concentrate on that one phase of motor selection, that phase which determines the peak load capacity which must obtain in the motor. If this were the only issue then the problem would be solved by simply selecting a motor able to meet this demand. But following the process of disintegrating further shows clearly the other factors that must be considered.

That portion of the initial operations which produces high peak loads, is a part of the initial operation load cycle. For that brief period while the "chunk" is passing through, the peak load obtains. During the remainder of the cycle the machine is empty. The load valley is low. In the initial operation the load varies from a minimum of friction load only to the maximum peak load. The thermal capacity requirement of the motor is correspondingly reduced.

Following the disintegrating process further, we find that after the initial operation, of passing through the crude dirty chunks, the now partially disintegrated material is passed through the mill a number of times, this being continued until complete disintegration has been accomplished. This portion of the process must be considered in conjunction with the initial portion of the process in order to determine the mean load value.

The maximum peak load that obtains during the process following the initial process, is approximately 50 per cent of the maximum peak load of the initial process, so if the motor has peak load capacity to handle the initial process peak load we need have no further concern on peak load capacity. But this lower peak load that obtains after the initial process, is a factor in determining the mean load; in determining the thermal capacity requirement of the motor; in determining the basis for efficiency and power factor selection.

An analysis of the actual conditions will show:

1. Abnormally high peak loads, few in number and each of short-time period.

2. Abnormally light-load short-time periods.
3. A mean load that does not exceed 30 per cent of the probable maximum peak load.

(Note) Please bear in mind that this suggested analysis is to be on a basis of one washer room line and do not confuse it with the load factor of an entire plant.

The committee considers this a problem. Is it possible to equip this disintegrating mill line with motors without sacrificing efficiency and power factor and at the same time maintain that large important factor of electric application, namely, flexibility of power application?

It is reported that in tire mills, one horse power is required per tire per day. If this is correct, is it a high tax to place upon the output? If so, can it be decreased?

The extreme flexibility of electric power application has been probably the largest factor in popularizing its use in the rubber industry. Has the flexibility been extended beyond a reasonable and efficient point? Have mill lines been split up into such a large number of units for production efficiency at a sacrifice of electrical efficiency, that in some instances may not be warranted? This committee does not imply in any manner that such is true. It simply asks the question.

The power requirement as indicated by reported connected load statistics is stupendous. It is so prodigious, that we feel that only by close cooperation between the electrical engineer and the plant production department, weighing together the advantages and disadvantages of segregating here or grouping there, can electrical efficiencies obtain. This must be evident to all.

Where a production efficiency is to be gained at a sacrifice of power efficiency and where this anticipated gain in production efficiency would be less than the resultant losses in power, so that the net result would be a loss, the fact should be recognized and a compromise made that will permit of production on a reasonably efficient basis, with the power application on a similarly efficient basis with a net result of gain.

Where a production efficiency is to be gained at a sacrifice of power efficiency, and where the anticipated gain in production efficiency would be in excess of the power losses, there will as a rule be no question of compromise involved. The net result would be gain, and it is obvious that the engineer would cooperate fully with the production department.

In motor selection the foregoing should be determined definitely so that the engineer may know the operating requirements of that specific department of that specific plant. That point being determined he then has at least two possible factors that will help him to select motor equipment efficiently; these factors are as follows:

1. The adaptability of a signal system to guard against abnormal peak loads. The adaptability of a protective device to stop the mills should the operator disregard the signal.

2. The practicability of placing a number of washers (disintegrating process mills) all on one line, and obtaining the benefit of the law of average, and also the practicability of driving those mills which are contributory to the washing process on the same mill line.

The first type of contributory mill to consider would be the *sheeting mill.* The purpose of this mill is explained in the early part of this paper. This mill, as a rule, is fitted with one fluted roll and one smooth roll. Disintegrated rubber is fed into the mill and the material worked to form the crepe-like sheets.

That high peak loads comparable to the disintegrating mill do not obtain, is readily appreciated. In fact the peak load requirements of the two classes of work, contrast strongly. The highest probable peak load on a sheeting mill is approximately one quarter of the probable peak load, on a washer mill used for disintegrating. The mean load on a sheeting mill approaches the probable peak requirement of this type of mill more closely than the mean load of a disintegrating mill approaches its probable peak requirement. On some installations the probable mean load of a sheeting mill may be as high as 60 per cent of the probable peak load requirement.

A combination then, of the washers used for disntegrating and the washers used for sheeting would promote efficient motor equipment, due to the fact, that the probable combined peak load would be proportionately lessened, and the probable mean load would be proportionately increased.

The next mill that could be considered as contributory to the washing process, is the breaking-down mill. The propriety of advocating the possibility of grouping this type of mill with the washer division may be questioned by many. It may be impracticable in some plants. This suggestion is made here in the hope that it may be helpful to some. Also in many plants the accounting schedule includes the breaking-down process as a function of the washing department.

The breaking-down mill is practically identical to a "warmer" mill, which will be described in a later section of this paper. The rolls on this mill are smooth, and heated. The crepe-like sheets are fed into this mill for the purpose of breaking down the granules, or the coagulated structure, and producing in its place a plastic, tenacious coalescent mass.

A study of the work to be done indicates that:

1. Peak loads are probable.
2. That the manner in which the operator feeds the material into the mill will have a direct bearing on the degree of peak load that will occur.
3. That the peak loads will be of appreciable time duration though gradually decreasing due to the fact, that as coalesence takes place, the mixture adheres to the rolls and some pressure is therefore always evident with this material between them; and also due to the frequent cutting off, and re-feeding by the operator.
4. Although peak loads will and do obtain on any rubber mill, the operator by using a small amount of judgment in feeding and in re-feeding, and by starting the charge at one side of the mill, and permitting it to feed across the face of the roll, can, without sacrificing efficiency in production, control the value of the peak loads within reasonable limits on breaking-down mills.

The probable maximum peak load of the breaking-down mill is approximately 60 per cent of the probable peak load of the initial process of the disintegrating mill, and the probable mean load on a breaking-down mill is approximately 44 per cent of the probable peak value. We now should be in position to condense our analysis as follows:

a. *Initial disintegrating.* Severe and sudden shocks. High peak loads of short duration. Intervals of friction load only, light load. Low, mean load factor. Short-time operation.

b. *Continued disintegrating.* Sudden shocks. Peak loads of greatly reduced value. Fewer within a given time. Fewer intervals of friction load only. Higher mean load factor. Protracted time operation.

c. *Coagulating.* Peak loads of relatively low value. Fairly high mean load factor. Protracted time operation.

d. *Coalescing.* Sudden shocks. Peak loads of appreciably lower value than those obtaining during initial disintegrating and controllable by the operator. Few intervals of friction load only. Fairly high mean load factor.

(a) and (b) cannot as a rule be separated. (b) is usually a continuation of (a) on the same mill. But, with a number of mills performing disintegrating operations at one time on one mill line the maximum peak of the mill line will not be equal to the product of the peak load of one, times the number of mills in operation. Further, as it is not probable that all mills will be empty at the one time, the mean load will be higher.

If (a) and (b) operations can be combined with (c) all on one line the probable peak load will be appreciably less than the combined maximum peak loads of separate units. If to this can be added the (d) operation a further saving can be effected.

This committee believes that it is not advocating any departure that differs from practise followed by many, but that probably the subject has not been heretofore presented for discussion to a body of men outside of an industrial organization.

The committee submits for consideration the following basis of motor selection for washer mill application:

a. Group as many portions as production efficiency will permit, of any one general process into one mill drive. Preferably group, where practicable, portions whose load characteristics contrast.

b. Determine the probable reasonable peak load demand that will obtain in this group arrangement, with a defined understanding with the production department, what peak load will be considered as reasonable, based on a defined kind of stock, methods to be followed by operators to prevent abuse, the defined peak load value that will give a signal to the operators, and the peak load value which if exceeded will cause the protective device to stop the mill line.

c. Determine the probable mean load that will obtain in this group arrangement.

Then, select a suitable motor of:

1. Ample ability to carry through the peak load.
2. Sufficient thermal capacity to carry the mean load, with as high efficiency, and high power factor characteristics at this mean load as practicable.

A plan of this, or of comparable nature, should provide ample size of motor and eliminate any necessity for oversize of motor. It should also give to the rubber industry that honor of not only being the largest individual user of electric power, but also the most conserving user of electric power.

The grouping as suggested in paragraph (a) should provide a relatively high mean load factor per motor. This should result in a definite known efficiency for each drive. This feature is in contrast to data that show us the load factor of an entire plant, in per cent of nominal h. p. connected load. The power factor of an entire plant can be determined, but the electrical efficiency can not be determined from such data. The load factor of the entire plant in percentage of nominal h. p. connected is the combined mean load on all motors. Some motors may be underloaded and working at low efficiencies. Other motors may be overloaded and working at low efficiencies.

Others may be operating under an average load condition that represents satisfactory efficiency.

The efficiency of the electrical equipment cannot be determined by the ratio of electrical input of an entire plant, and the nominal h. p. connected load, but if each application is analyzed in its entirety and motor selection is based on this analysis, each mill drive then will not only be supplied with ample motor equipment to carry on production, but it also will perform that work with high electrical efficiency, and will be a credit to the engineer of selection.

Mixers

PURE RUBBER TO RUBBER COMPOUND

The process up to this point has not changed the physical properties of the rubber. If these properties could not be changed, rubber would be of small value to humanity. Chemical changes can be made within the mass, with the result, that the otherwise useless mass becomes a product that is applicable to many uses. This process of chemical change is a function of mixing, compounding and vulcanizing.

Mixing sulphur with pure rubber, together with the application of heat and pressure, is an essential of vulcanizing. Mixing of other ingredients in addition to sulphur is essential to produce diversified product. The specific use to which the rubber will be put, determines the nature of the ingredient or ingredients used. Every ingredient added produces a chemical change in the rubber to enhance the value of the resultant compound, for that specific commodity of which it will be an important adjunct. In fact the importance of the rubber, and even the importance of rubber of that specific compound, may be such that without it, the article could not be produced.

Process. The cold plastic mass of pure rubber is thrown into the mixing rolls which are heated to a temperature consistent with the kind of rubber and its ultimate use. It is worked and warmed on the rolls of the mixers until the required plastic consistency essential for compounding is reached. The compounds are added a small amount at a time, the working process being continued, until there is absolute uniformity of the mass.

The physical properties are now radically changed and the rubber is then sent to the store-room, as green-stock.

MOTOR SELECTION

In determining motor size, the operating *temperature* of the rolls should be taken into consideration, as the load on the motor is affected by the temperature of the rolls.

In determining motor size, the *kind* of rubber should be taken into consideration (kind of rubber, in this article refers to geographical source of supply). All other conditions being equal, one specific kind of rubber will produce peak loads 100 per cent greater than another specific kind.

In determining motor size, the fact that cold rubber is *thrown* into the mills, and that it is worked and warmed must all be considered. The cold rubber thrown into the mixing mill, produces high peak loads. This cannot be prevented; but if it is thrown into the mixing mill too rapidly, it produces excessive peak loads. This to a large degree can be corrected, by intelligent feeding, and a signal system.

In determining motor size, it should be noted that during the entire mixing operation the mass is worked. This working produces peak loads of prolonged time duration. The working is that operation where the rubber is cut diagonally from the roll, and re-fed into the rolls. The manner of this re-feeding has a direct bearing on the resultant peak load. This can be controlled by the operator to some extent, by starting the re-feeding at one end of the roll, and permitting the material to work across the face of the roll, and by a signal system which will warn the operator if he or others are feeding carelessly.

In determining motor size, the fact that after the initial feeding of cold rubber, subsequent feedings will be warmed, and in consequence the peak loads of re-feeding will be of lower value than the initial feedings of cold rubber, should be taken into consideration.

In addition to the variables involved in the process, the characteristics of each mill must be considered. Large diameter rolls result in a smaller angle of approaching stock, hence a larger wedging force in proportion. This results in higher peak loads, large bearing pressures, increased friction losses. The ratio of friction between the rolls has a direct bearing on the load demand, and must be included in any analysis of conditions, determining suitable motor size.

The number of mills to the mill line should be considered, taking advantage of the law of average. Where a number of mills are involved on one line, the peak load will not equal the peak load of any one, times the number of mills. The fact that a number of mills may be on one line, some working on one kind of rubber and other mills on another kind of rubber should be considered, as the resultant load will not be the product of the heaviest kind of load, times the number of mills, but will be the resultant or mean peaks of the combined heavy kind of load, and the lighter kind of load.

This committee has reports which indicate maximum peak loads on mixing mills as high as 3.5 h. p. per linear inch of roll face. It has been reported that the following rule has been applied; whether it is in actual use, the committee cannot determine.

Take maximum h. p. per inch of roll face 3.5.

Divide this by the value of the ratio between the normal full load torque rating of the motor, and its pull-out torque value.

Multiply by number of inches of linear roll face.

Answer equals nominal h. p. rating of motor to select.

Assume, pull-out torque of motor 2½ times full load rated torque.

Assume, 360 linear inches of roll face.

Then $\frac{3.5 \times 360}{2.5} = 504$ h. p., nominal rating, would be the answer, or a nominal rating of 1.4 h. p. per linear inch of roll face.

But, will this apply to every mixing mill line, irrespective of kind of rubber, all diameters of rolls, all ratios of friction between rolls, all temperatures and all pressures that may be involved?

If this is the absolute maximum under the most severe conditions, then the problem becomes one simply of selecting a motor that will surely be large enough and in many installations will be oversize. This committee believes that the problem of the engineer is to equip each mill line with a suitable size of motor as determined from an analysis of the load conditions that obtain on that line.

Another report of record, which this committee received, is as follows:

MIXING MILL LINE LOADS

Highest 30-minute average peak load	100 per cent
Highest 5-minute average peak load	120 per cent
Highest 1-minute average peak load	155 per cent
Highest instantaneous peak load	215 per cent

This condition could readily obtain on a specific drive on a specific stock under specific working conditions; but, can it be applied as a general rule for the equipping of all mixing lines with motors?

The following list of installations is submitted, not as a basis of selection nor as a basis of approved practise, in that this committee does not have the detail of each installation, but it does indicate that the formula quoted is not followed generally, and it also appears to indicate in some instances at least, that the work to be done by a specific mill line had been taken into consideration.

We are not including the addresses of these installations in that this has no bearing on the situation from the engineering standpoint. They however include installations in the U. S. from coast to coast, and also Canada, France and Japan.

MIXER LINE INSTALLATIONS

Number and Size of mills	Nominal H. P. Rating of Motor	Nominal H. P. Per Linear Inch of Roll Face
3—40 in., 3—36 in.	150	0.66
3—60 in.	375	1.04
3—60 in., 1—36 in.	250	1.16
3—20 x 60 in.	200	1.11
9—40 in.	375	1.04
5—42 in., 5—60 in.	500	0.98
8—48 in.	200	0.595
6—36 in.	150	0.696
8—60 in.	700	1.46
7—60 in.	450	1.07
6—84 in.	500	0.9925
9—84 in.	800	1.055
4—38 in., 1—44 in., 1—46 in., 1—54 in.,	200	0.675
3—18 x 60 in.	200	1.11
6—60 in., 1—38 in., 1—40 in.	250	0.57
3—32 in., 1—40 in.	150	0.84
2—18 x 48 in.	100	1.04
4—60 in.	300	1.25
4—20 x 54 in.	250	1.155
1—60 in.	100	1.67
2—60 in.	250	2.08
3—60 in.	250	1.39
3—16 x 45 in.	150	1.11
6—84 in	600	1.19
2—18 x 46 in., 1—18 x 20 in	150	1.29
2—16 x 48 in., 1—18 x 30	150	1.19
5—14 x 36 in.	100 (reclaiming)	0.555

This list could be continued into hundreds of installations without affecting the conclusion as a whole.

The committee concludes that satisfactory motor size selection cannot be made for each specific mill line by generalizing on limited data. Each mill line should be equipped with motors on an engineering basis; the engineer to have complete data of requirements and to select the size and type of motor which analysis of the conditions that will obtain on that specific drive calls for. No general rule based on nominal h. p. per lineal inch of roll face is applicable. Motors cannot be satisfactorily selected on an arbitrary nominal h. p. rating, which rating means nothing more nor less than that a given motor will carry a certain load continuously with a temperature rise of a certain value.

In general milling operations a uniform even load does not exist on any one mill line. It is not only a varying load, but it is a widely fluctuating load. (This is not intended to apply to the total load of the plant, or to the plant load factor. The plant load factor is the mean load of the entire plant. It is the result of the law of average of the entire plant. We are interested in the equipment of one mill line in that plant and the one mill line is therefore the point of discussion. There is a wide difference). This widely fluctuating load is the problem; how to equip it with motors effectively to maintain production, and also economically.

In a paper presented by Mr. H. C. Stevens of Akron, Ohio, before the Ohio Section of the The National Electric Light Association, meeting of January 21, 1920, is shown an estimated average power factor for four rubber manufacturing plants of 67 per cent. This may include lighting and other unity power factor loads. In any event, can it be improved? A 67 per cent power factor simply means, that all equipment used in producing, transforming and transmitting the power must be of 50 per cent greater capacity than the actual power supplied.

In another table submitted by Mr. Stevens, covering seven rubber manufacturing plants, the maximum demand in percentage of connected load, varies from 39.5 per cent on the lowest, up to 78 per cent on the highest, and on the largest installation shown by the table, the maximum demand is only 89 per cent of the total connected load. This was in August of 1919 at which time the production of rubber was large.

In the same table by Mr. Stevens, we find in six rubber manufacturing plants, an annual load factor based on 8760 hours, for the year 1918, of 30.9 per cent and for the year 1919 on seven plants of 32.7 per cent. Based on a working day of eight hours and a working year of 300 days, this factor would be high, but when compared with other data in the same table it would appear that the working time was in excess of eight hours per day. It would be interesting to know the load factors of the same plants for the year 1920.

A partial analysis or generalizing would indicate the possibility of more efficient motor equipment. Every dollar tied up in oversize or unsuitable motors, and in contributory equipment represents just that much waste. Every unnecessary loss in operation of oversize or unsuitable motors, and in contributory equipment represents just that much waste.

If such waste does obtain we believe that the remedy lies in engineering. Let the electrical engineer look upon each size and type selection as a specific problem. If he has done so in the past, may he continue and with determination analyse even more carefully in the future.

To select a motor large enough, from a given maximum rule, with a constant that is conservative even for the most severe condition, can be the function of anyone, but the selection of a suitable motor for a specific drive, can only result from the careful analysis of complete facts by the engineer. In his analysis, he has, and will continue to consider the following:

a. The mechanical characteristics of each mixing mill. Length of roll face. Diameter of rolls. Ratio of friction between rolls. Width of opening between rolls.

b. *Kind* or preferably *kinds* of rubber on one mill line. Pressures on rolls. Temperatures.

c. That operators can be taught efficient feeding. That this be an understanding with the production department. That a signal system can be used to warn the operator against injudicious feeding. That if the operator ignores the warning and attempts to force, and abuse the mill, a protective device can be used to shut down the mill line. The load on which the signal is to give warning, and the load at which the protective device is to operate would be determined in cooperation with the production department.

d. Grouping of mixer mills to the greatest number permissible on one line, without sacrificing production, and grouping, as far as is consistent, mills on various *kinds* of stock, and obtain that benefit which will result from the law of average, using a constant that the engineer will develop from his own plant operation similar to the typical table of constants given in this paper under the subject of washers.

e. After determining all of the foregoing factors, the engineer will be in position to determine the peak load requirement, and also the mean load for a given period of time. From characteristic performance curves he will select that motor which has sufficient maximum torque capacity to handle the maximum torque requirement of that specific mixer mill line, and will select that type of motor which will not only do this, but which also will have sufficient thermal capacity to carry the mean load, and will do this efficiently and with a minimum of reactive current.

Atmospheric Conditions of Mixing Rooms. Mixing is usually attended by dust of the compounding ingredients. Some is highly abrasive, some is only slightly so, in any event it is preferable to so plan the installation that this dust cannot prove detrimental to the motor bearings.

The situation has been somewhat accentuated since the advent of organic accelerators, ingredients that are added to hasten vulcanization, as this dust is frequently injurious to health. Probably the best solution is an installation of a dust collecting, and ventilating system with a motor-operated blower to remove fumes and dust, thereby protecting the operators and machinery alike.

In the foregoing the subject has been one of mixing rolls and does not refer to batch mixers or mixing machines.

This committee has no test data applying to the mixing machine and can make no comments with reference to peak load demands.

The manufacturers list two sizes in their literature as follows:

Size	Batch Capacity Crude Rubber	H. P. of Motor Individual Drive	Average H. P.
3	70 lb.	75	50
9	210 lb.	200	125

This committee would be glad to receive from any engineer any data he can give us with reference to the power requirements of the mixing machine.

Warmers

The green-stock is accounted back to the storeroom from the mixer room and after a "seasoning" is accounted out to other departments, such as calender room, tube room, etc. Warming is the initial program in the various departments where it is used. The warmer mill discussion is closely allied in this paper to that of the mixing mill, in that the machine itself is practically identical to a mixing mill and the motor problem is similar.

PROCESS

The cold green-stock is thrown into the warmer to warm the stock to render it soft and pliable so that it can be calendered readily.

In the mixing operation the stock was changed from a plastic condition to a tough, resilient product.

In addition to warming, the stock is worked on the warmer rolls to affect its consistency throughout uniformly.

MOTOR SELECTION

The fact that the warmer mill is practically identical to the mixer mill makes all suggestions that apply to one, apply to the other, with two possible exceptions.

1. The cold green-stock thrown into the warmer does, as a rule, owing to its less plastic nature, cause higher peak loads than the cold pure rubber thrown into the mixer.

2. There is less probability of its being practicable to combine on one mill line a number of warmers, or of having warmers on one mill line handling various kinds of stock at the one time. It can be done in many

instances, and it is advisable to take advantage of the opportunity wherever practicable.

In evidence that in some plants at least, a general rule is not applied in motor size selection, we add the following table:

Size of Warmer	Nominal H. P. Motor Rating	Nominal H. P. Per Linear Inch of Roll Face
1—18 x 36 in.	40 h. p.	1.11
1—16 x 36 in.	25 h. p.	0.695
1—18 x 36 in.	50 h. p.	1.39

Conclusions

The basic idea of this committee is to equip rubber mill machinery with motors on an engineering basis. The committee believes that with the large amount of power involved more efficient motor equipment can obtain in many plants if we have a plan to provide the proper cooperation.

The committee concludes that many engineers have their own plans that they execute faithfully and with success.

The committee does not advocate a plan, simply on account of the plan, but if one can be developed that will be helpful to the engineers in the rubber industry as a whole, the committee then would favor it and gladly cooperate, not for the success of the plan as a plan, but for the benefit that would result to the engineers of the rubber industry.

Safety Stop

HAZARD

The *danger* which is prevalent in the various operations of *general milling* or *basic operations* is due to the tenacious character of rubber in its plastic state.

The operator is very likely at any time to become caught in the folds of the rubber and drawn into the rolls. He may be caught on either hand, or both hands may become entangled. The safety mechanism should be, therefore, of such a nature that if both hands are entangled he can trip the mechanism with his head. The safety mechanism of all machines on any one mill line should be so interconnected that any operator on that mill line may stop the entire mill line from his own mill should another operator become caught.

Although this is a dangerous condition under which these men must work it has one redeeming feature. The operator does not become caught directly in the rolls. If so then he would be damaged to some extent no matter what device were used for the stopping of the mills. He is caught in the folds of the rubber some several inches from the point of contact of the two rolls.

If a suitable type of safety stop is used and if prompt action is taken either by the operator who is caught, or by one of his companions at an adjacent or nearby mill, or in fact at any mill along that line, it is entirely within reason to obtain a stop sufficiently quick to prevent damage to the individual.

SAFE STOPPING DISTANCE

The diameter of the average roll is 22 in. A diagram would indicate clearly why the maximum stopping time of the roll must not exceed approximiately 40 angular degrees of periphery travel between the time that the man is actually caught and the time in which the mill is brought to rest.

This brings the actual stopping time available from the moment that the safety mechanism is tripped until the mill is actually at rest to about 20 angular degrees of periphery travel. Put this in terms of inches of periphery travel and it gets to that short distance of 4 in. This should be measured by a chronograph in that the eye cannot detect this with a sufficient degree of accuracy.

If a device will stop the mills within 4 in. of travel of the roll periphery it can be depended upon as a rule to prevent damage to the operator.

SUITABLE STOPPING DEVICE

This committee has knowledge of only one basic way in which this stopping can be obtained.

The means for this service consists of a device which will disconnect the prime mover, which is a high inertia load, from the driven mill line, which is a low inertia load, and which device will simultaneously apply a brake to the driven load.

With devices of this nature sufficiently quick stops can be obtained without any probability of damage to the equipment through the shock of this quick stopping. Second and most important the stopping can be done quickly and with sufficient speed to consider such a device as a safety stop—not simply a stop.

Clutch brakes are made in both the magnetic, and the air type. The magnetic clutch brake has been most generally used. It is an easy matter to "tie in" the magnetic clutch brake type with the electrical system. It also undoubtedly has that advantage of being most simple in structure.

Many schemes have been tried which do not contemplate disconnecting the motor mechanically from the mill line.

Plugging the motor to reverse it to bring it to a stop has been tried, but this has never met with any degree of success. Even were it successful in stopping quickly it would still have the disadvantage that it depends on an outside source of supply for its ability to stop the mills at a critical moment. This alone would militate against it.

The one other method that has been tried to some extent and which is the only one so far that we can find that begins to approach a safety stop, is that one which contemplates the opening of the motor circuit and the applying of a magnet-operated mechanical brake.

However, when it is considered that at least 85 to 90 per cent of the stored energy of angular rotation of the combined motor and mills is in the motor, it can readily be appreciated what a large size this brake must be in order to absorb the large amount of stored energy that is in the motor, in order to bring the motor and the mills to a stop, that begins to approach that stop which would be considered a safety stop in every sense of the word.

We have found for example, on a 50-h. p. motor where the normal motor torque is 510 lb-ft., that the torque required to bring mills to a stop within a travel of 6 in. of the periphery of the rolls means an energy absorption equal to 2380 lb-ft. This means a ratio of required torque on stopping to normal torque of 4.65.

On a 200-h. p. motor where the normal motor torque is 2050 lb-ft. the torque required for 6-in. stop is 10,700 lb-ft. or a ratio of 5.2 to 1.

On a 500-h. p. motor, the normal motor torque lb-ft. is rated at 5,100, whereas the torque required for a 6-in. stop of roll periphery travel is 15,500 lb-ft. A ratio of 3 to 1.

The above refers to motors operating at a speed of 514 rev. per min.

With a roll diameter of 22 in. and a roll speed of 18 rev. per min. a 6-in. stop on that roll would require that the motor be stopped in 2½ revolutions, or in about 0.58 second.

Complete consideration of these figures will indicate to the engineer the size of brake that would be required to bring the motor and the mills to rest within a time lapse that would be safe. It will also show the heavy strain that must be imposed on the rotor structure, in that the mechanical brake must be attached to the rotor shaft, whereas practically all of the energy of rotation is in the rotor proper.

Stopping Test Results

The following tests were made on a mill drive including two Farrel 22 x 60, back roll 23.07 rev. per min. Front roll 18.03 rev. per min. Friction ratio 1.27.

The motor was a Westinghouse type C. W. 1002, 250-h. p. 580 rev. per min.

Tests were made both with a device which was arranged for disconnecting the motor mechanically from the mill line and applying a brake, and with the other device arranged for opening of the motor circuit and applying a brake to stop both motor and the mills.

Stopping with no safety device the roll travel was 240 in.

Stopping by disconnecting the motor mechanically from the mill line and permitting the mill line to come to rest against its own friction, the travel of the front roll was 103 in.

Disconnecting the motor from the source of supply electrically and applying the brake to stop the motor and the mills, the travel of the front roll was 40 in.

By using the combination which disconnected the motor mechanically from the mill line and applying the brake to the mill line only, the travel of the front roll was 8 5/8 in.

The above test was conducted with all of the mills empty. This would be the worst condition that could obtain for the reason that the friction on the mill line would be low. This condition could not obtain at a time when safety stop would be required for the reason that no one is likely to be caught under this condition.

The worst condition under which an operator can be caught is that one which obtains with only one mill operating and all of the other mills idle. This presents an opportunity for an operator to be caught and at the same time with a minimum of load on the mill that could be depended upon to assist in quick stopping.

The following test data were obtained with one mill loaded, the load on the motor being 130 h. p.

Stopping naturally by simply disconnecting the motor from the line electrically and applying no outside force the front roll travel was 75 in.

By disconnecting the motor from the mill line mechanically and applying no brake to the mill line, the mill lines come to rest with a travel of the front roll of 16 in.

By disconnecting the motor from the source of supply electrically and applying the brake to stop the motor and the mill line simultaneously the front roll travel was 16⅜ in.

By stopping with the device which disconnected the motor from the mill line mechanically and applied a brake to the mill line only, the front roll travel was 4⅛ in.

COMPENSATION

This is a very important question. It is one where even human life is involved. Some years ago before safety stops were used as generally as today every mill had its quota of cripples, and even today you will find an unusual number who were injured through being caught in this plastic material and drawn into rolls.

The Industrial Commission as a rule favors the worker, and the employer must pay heavy indemnities varying in many States from approximately $120.00 minimum for loss of the ring finger at the second joint up to a maximum of approximately $5,000.00 for the loss of an arm at or near the shoulder. In addition to this the employer must pay all doctor and hospital bills.

Further, there is a loss to the community of the man's idle time.

On the other hand,there is no question but that it would be much more fitting had the accident never occurred. We question if there is any other one feature on which the engineer can be more careful than in the selection of suitable accident preventive devices in connection with this class of work.

RECOMMENDATIONS

It is the recommendation of this committee that the most suitable manner in which safety stops can be electrically connected is in such manner that when the safety mechanism is operated the entire mill line drive including the motor will come to rest; whether or not the motor comes to rest as quickly as the mill line is not important, but that it also be so interlocked with the motor control system that even the motor cannot again be restarted until all safety devices have been placed in the "run" position, so as to have assurance that all workmen are clear of the mills, is important.

We favor also an arrangement, or combination of arrangements, of such nature that the operator who has charge of restarting of the mills cannot restart the mills at least, even though he may be able to start the motor, excepting from such location that the entire front of the mill line is visible to him, so that he can be assured that all is "clear" before he actually puts the mills in operation. We believe this to be important as it would eliminate entirely possible accidental restarting of mills.

DISCUSSION ON "THE APPLICATION OF ELECTRIC POWER TO THE RUBBER INDUSTRY," (SUBCOMMITTEE ON RUBBER INDUSTRY OF INDUSTRIAL AND DOMESTIC POWER COMMITTEE), AKRON-CLEVELAND, OHIO, JANUARY 14, 1921.

A. P. Lewis (Read by B. T. Mottinger): I wish to present certain conclusions I have come to differing from those of the Committee:

I. *Gearless Drives*. I do not believe the direct-connected low-speed slip-ring mill motor is a factor to be seriously considered, due to

a. To its inherent bulk, restricting aisle space particularly.

b. To its inherently poorer electrical characteristics, 25 per cent in power factor, and 6 per cent in efficiency.

c. To its probably greater $M V^2$ effect as compared to the smaller high-speed machine, and its resultant slower deceleration at times of emergency stop. This feature will be mentioned in more detail later.

d. To the physical difficulty of replacement with a reserve motor in case of failure.

e. To the fact that the installation will not, as a rule finance itself as compared with a high-speed drive.

My experience, contrary to the Committee's findings, is that gear maintenance on this work is substantially negligible. In fact, I have knowledge of only one replacement out of approximately 500 gear case years, and this one after a life of six and one-half years. This result was obtained, I believe, only by the use of very superior units of careful design, but I believe it justifies their increased cost.

II. *Controllers*: In mentioning controllers, inverse time-limit overload protection is recommended. This application is undoubtedly correct in many instances. The exceptions, however, ar worthy of mention. In those plants using high-vol tag motors, and connected to systems of high capacity, I feel that definite time relay protection has its advantages:

(a) It permits the use of oil switches of lower rupturing capacity with safety as intense failures can then be handled, or remote switches of large capacity, set to trip by means of instantaneous or inverse relays. This means lower cost of motor panels.

(b) It permits, I believe, a result more in line with the nature of the load as far as protection is concerned. A combination of time and current may be determined from test curves which will permit the motor to carry through the sustained peaks well within the thermal capacity of its design, and yet provide full protection against abnormal sustained overloads. It seems for example that on a 350-h. p. motor, a minute and three-quarters time setting at one and one-third times full-load current results in very infrequent, tripping and then only when it should.

I would like to see improvements in definite time relays, at least as we use them. Their resetting value is too low, and they are very susceptible to dust and grit. There is, however, one relay developed, which although as yet untried by me, has, I believe, the earmarks of meeting the requirements of this service.

In reference to the resistors as recommended of the cast grid type: After some careful investigation I have adopted a carbon pile secondary controller with, after a year's use, excellent results. The reason for this trial was that: (a) An infinite number of accelerating points are available, productive of smooth speed increase. (b) A large number of copper contacts are eliminated. This reduces maintenance and the chance of trouble due to high resistance heating, and still preserving full protection to itself.

The latter point is, I consider, of prime importance in the average mill room. The controllers I have had purposely neglected, and thus far, after years of service, no troubles have come to the surface.

III. *Signal System.* The use of a signal system to guard against abnormal peak loads is worthy of serious consideration. I suggest a step further, however, and propose a "batch dispatcher" for the mixing work, who has control of the four elements of time required in this work, the mill operator performing his functions as per a determined schedule of signals. This has resulted, in one instance, to my knowledge, of very efficient handling of motor loads as well as improvements in production capacity per mill hour.

IV. *Atmospheric conditions of mill room:* I feel that too little stress is laid on the extremely bad conditions under which all apparatus labors, in the excessive dirt and dust of the mill room. Sulphur is prevalent and soap stone is an extreme abrasive. Motor bearings should receive careful attention to prevent dust entering. Over a period of nearly two years records show 42 per cent of motor troubles directly due and traceable to bearings. This figure considers approximately 1500 motors of various sizes and makes. Only through thorough familiarity with the conditions can manufacturers meet this severe operating situation. Relay equipment is especially susceptible to fine dust and requires special precautions as to slip ring brush holders, low-voltage coils, armatures, and in fact all reciprocating or revolving parts.

V. *Mixing machines.* The requirements as furnished in reference to the No. 9 machine, are somewhat liberal. From graphic tests in hand, I feel that a standard 100-h. p. motor with 250 per cent pull-out torque will be very satisfactory as regards electrical characteristics. The graph shows that the load of these machines is irregular. It increases abruptly at the start, and falls when the batch is finished in the same manner. The average condition seems to show a maximum peak of 215-h.p., a peak of 160 h.p. for five minutes, and an average of 90 h. p. for the batch period of 20 minutes. These are input figures.

VI. *Safety stop and hazards.* I feel strongly, however, that one of the most important functions in connection with proper safety protection has been rather slighted. I refer to the element of time—not the time of actuall stopping the advance of the roll, but the time in which the unfortunate limb is removed from contact with the hot roll and rubber. This temperature is, without exception, above that at which living tissues can exist, as such for more than a matter of minutes. Experienced doctors advise me that very rarely is amputation necessary in mill or calender accidents, provided the flesh, usually stripped from the bone, is not killed by heat. If this period is correct, removal from contact becomes equally, or more, important with stopping further washing or stripping action of the rolls and rubber.

A large number of motor and gear installations have been made which have resulted in completely satisfactory results. The scheme is briefly as follows: A motor direct connected by flexible coupling to gear unit, the pinion shaft of the latter extended and having mounted thereon a mechanical brake, which may be tripped by the operator, and which brings the motor and mills to a quick stop. The motor is, of course, first disconnected from the source of energy supply. This design, as a whole, was most carefully checked in all details. The total energy to be absorbed for a 6-mill drive with 400-h. p. motor was found to be 508,000 ft. lb. With a 505 rev. per min. machine, 4 rev. per min. of the motor was the limit for stopping. Of the total energy, a certain per cent is in the rotor. With these facts in mind the engineers of the manufacturers advised that the stresses developed in this quick stop were approximately half those of plugging for an equally quick retardation. The brake drum actually used was 35 in. diameter by 12 in. face. The motors used were of the so-called steel mill type, pedestal bearings, extended shaft rotor, sliding stator, rated 400 h. p., 40 deg. cent., 250 per cent pull-out torque.

The results in practise with this installation have been more than expected. Shop tests showed quicker stops than figures, about 3½ rev. per min. of the motor, with no jar, vibration or noise to indicate undue mechanical strains. After installation, periodical checks were made with the same findings.

The advantages, I believe, lie in the ease with which an operator can be extracted at a time when excitement and false moves are most likely to be made. To explain, the stop having been made either by the victim or his co-workers, it leaves the motor at a standstill with the controller and switches open and the brake set. It only requires then that the person starting the motor in reverse, raise the brake by means of a 90 deg. throw, of a small brake handle, which actuates the air piston, raises and resets the brake, and then closes the reversing primary switch. Two simple movements effect the desired end. This procedure is, I believe, reduced considerably in time below that required for other combinations to meet the same results.

All of the preceding argument is based on reversing to extricate the victim. Some companies do not permit this, and the method is not superior, from a safety standpoint, in that case, though I believe equally good.

Stop tests with the equipment are as follows: 150 h. p. motor, 2-60-in. mills empty, 4⅜ in. average; no recorded tests operating.

400 h. p. motor, 6-60 in. mills empty, one mill loaded lightly; no recorded tests operating.

The checks are made under the worst conditions in mills idling, and must meet a maximum of 5 in.

J. F. Lincoln: The maximum production in the Goodrich plant I am told, runs about $800,000 per day. The power cost is $4000 per day under these maximum conditions. This means that the total power cost amounts to one-half of 1 per cent of the value of the product. It is therefore, evident that the amount of saving possible in percentage must be slight. If in attempting to save power, production is reduced, it is only necessary to reduce it a very small fraction of 1 per cent to more than eliminate any possible saving in power. It is self evident that the devices named in the paper have for their purpose the saving of power by eliminating peaks. This means the reduction of the speed of operation, at least at times. I cannot believe that the advantages to be gained can possibly equal the loss of production which would be encountered.

Byron T. Mottinger: This element prevails in practise—the motor mill line is liable to kick off, any how, and if by the use of these devices certain pre-knowledge can be given to the operator, so it will not kick off, it will not only prove to be a saving in power, but a saving of time lost. When the mills are kicked off the line, the compound in many cases has to be gotten out, and the mills started up again.

Heber McFarland: Would it be practicable to put a flywheel set on the motor to take the big loads and flatten out the load curve?

J. H. Vance: Answering Mr. McFarland's question, the inertia that would be stored up in a flywheel, placed on a mill motor, would be lost in a very short space of time, and it has been found absolutely impracticable to use flywheels to take away from the peak load demand.

W. H. Horton, Jr.: In that connection I will say that flywheel motors—I may be betraying my own ignorance about the flywheel motor sets of the sort that Mr. McFarland asks about—have been applied successfully to rock crushers, which I imagine have about the same fluctuating characteristics that a washer would have. I know of an installation of some twenty-odd units, where 50 and 60 h. p. motors on each unit have been replaced with 25 and 30 h. p. units, reducing the instantaneous peaks, from approximately 75 h. p. to 30 h. p. Are the fluctuations in a washer more extreme than that?

J. H. Vance: The load has longer standing on the washer.

C. W. Drake: The fourth paragraph on page 14 states that there is a wide difference in the maximum torque of synchronous and induction motors, and that this should be taken into consideration when making motor applications. Although this may apply to certain types of machines it is entirely possible and practicable to make the same guarantees of maximum torque for synchronous as for induction motors. However, assuming that both types do have the same maximum torque, I believe that a mill line driven by a synchronous motor may be stalled more frequently than one driven by an induction motor of the same capacity. This is due to the fact that the synchronous motor pulls out at synchronous speed or in other words, maintains constant speed to the point of maximum torque, so that the operators have no idea of the load it may be carrying. On the other hand, an induction motor slows down as the load increases and the maximum torque is usually obtained at approximately 75 per cent of synchronous speed. This gradual drop in speed indicates to the operators that the motor is being over-loaded and it is entirely possible in most cases to prevent it from pulling out by proper feeding or manipulation of the stock.

A "Rule of Thumb" with which some of us are familiar is given in the third paragraph on page 17. It reads as follows: "It is reported that in tire mills 1 h. p. is required per tire per day." As rules of this kind are often of great assistance in making estimates I believe a more complete definition would be desirable. For instance, does horse power mean electric horse power demand, or nominal motor horse power installed and also does the plant work twenty-four hours a day or only eight or ten hours? I believe it means that to produce 1000 tires per day on the 24-hour basis would require a motor installation of approximately 1000 h. p., but I am not sure whether this is the interpretation intended by the authors.

Factors to be considered in determining the horse power required to drive mixing mills are classified in the middle of page 28 beginning with paragraph "a". All of the characteristics indicated are of vital importance, but we also believe there is another item of equal importance and that is "speed." In other words, with all of the mechanical characteristics in paragraph "a" remaining constant, the power will vary approximately with the speed of the rolls or the rate at which the stock is being handled or delivered.

Mr. Mottinger and I believe Mr. Lincoln brought up a point which is well worth discussion and, that is, that after all of these mechanical factors and conditions of operation have been determined, what assurance is there that they will be the same in one year or perhaps five years afterwards? Is it not possible that chemists may devise new compounds or methods of mixing or that different speeds may be used? Commercial conditions may change and the equipment may be required for a different product so that after all of the calculations have been made, it is a question whether it is not advisable to install a motor of sufficient capacity to carry any reasonable load that may be imposed upon the mills. This is the present policy of many companies, especially the smaller ones, having only one or two mill lines, while the larger companies having many mill lines may use motors of various sizes and thus utilize the motor capacities to the best advantage.

Wirt S. Scott: In the rubber mill industry, power is required for heating purposes in the curing of the rubber, or of vulcanizing. I would hazard a guess, that converting the B. T. U's in the kw. hours, that the demand for heating would be equivalent to the motor load on the plant. How we will obtain that load I cannot say at the present time, but I believe that the load is available, and that it is something to which we should give consideration.

The sub-committee on Industrial Heating would like to work with the various sub-committees in connection with these power applications and investigations for the purpose of determining what applications can be made of electrical heating. You might say offhand, that you cannot compete with steam. We have found that it can be done in many cases. I believe in the course of time we will find that it will be economical to do the vulcanizing and curing of rubber in plants, electrically, just as it is being done now by steam.

Earnest W. Pilgrim: It has been found that the actual maximum torque is about 2.5 times the full-load torque of the motor, and therefore as far as the motor is concerned, we thought it would be advisable to use 2.75 per cent as the maximum pull-out torque of the synchronous motor, applied to a mill line, and I think this figure would be better to use than 2.5 per cent as it would give you a little more safety.

Regarding the horse power per tire per day, it would seem to me that it would be better expressed if it were kw-hr. per tire which would give power cost per tire.

Regarding the gearless type of mill line drives we recently had an investigation where a man of considerable experience in the rubber mill industry has said it is costing him $500 a year to keep his herringbone gears in operation, and therefore it would seem that the additional first cost of large gearless motors would be amply justified.

G. A. Maier: Most of the discussion has referred to the direct-connected induction motor.

I have in mind a case where the direct-connected synchronous motor was chosen, and it worked out that the direct-connected motor was cheaper than a moderate speed motor with a gear reduction, and this being a 25-cycle installation, the space requirement was not greater than the moderate speed motor with the gear reduction.

When you consider the cost of the direct-connected unit, you should consider the cost of the gear reduction, the location of the motor with respect to the mill, and the cost of maintenance of the gear. Some say gear maintenance does not amount to anything, and others say it is about $500 a year.

Byron H. Clingerman: One of the interesting phases of this problem is the low power factor of a motor for a mill line which is used for both mixing and breaking down.

The mixing operation takes perhaps 60 per cent of the rating of the motor, if the motor is rated to take care of the breaking down operation, and if the motor is an induction motor, that means poor power factor. In the rubber companies where induction motors are used both for the large drives and small drives, you will find relatively poor power factor.

A synchronous motor lends itself very well to the situation, for the reason that the synchronous motor, designed we will say, with 80 per cent leading power factor, will at its rating carry the mixing load. It will also correct for the poor power-factor of these smaller motors usually found in rubber plants and necessarily induction motors. · Now, coming to the breaking down operation, which may be off-peak, the motor, rated on the mixing load and working up to the rating on the mixing load with an 80 per cent leading power factor, can then be adjusted by the rheostat (by a simple device of arrows on the field ammeter indicating the limits of breaking down) to operate on a breaking down load on unity power factor, automatically increasing the motor rating to the required load. .

Take a typical installation. A 600-h. p. 80 per cent leading power factor motor is driving a mill line. Its load on the mixing operations is, we will say, 540 or 550 h. p. There we have the compensation for the poor power factor of the smaller motors by operating at 80 per cent leading power factor. When we get to the breaking down operation, we change the excitation and that same motor, with approximately the same temperature rise, will carry continuously about 725 or 750 h. p. Obviously the synchronous motor lends itself directly to the requirements of the case, and the induction motor with its poor power factor under light loads is passing out.

Some reference has been made to signals and motor protection. Signal devices must necessarily be practicable, and we feel that the motor should be designed to carry the normal operation in the mill room, without tripping out. If the motor carries more than 275 per cent of its rated load, and therefore approaches the pull out torque, it is advisable to have the automatic devices open the circuit. A signal is provided to show that this particular condition existed. If the motor operates for a while at slightly beyond its rating and its temperature rises, the protection is obviously a temperature relay, a relay set at perhaps 90 deg. cent., and if abnormal conditions exist for a long period of time, the motor should be thrown out of service. The temperature relay does this through operation on the under-voltage release.

There should be still another development in the matter of protection of motors, since it is undesirable that motors should go off the line on a surge. We therefore feel that an under-voltage relay with a time element should be developed and applied to the installation. That gives, then, continuous operation during a surge, but causes disconnection of the motor under no voltage.

B. A. Waltz: I believe there is a well-defined move in the smaller plants to take a growing interest in the different methods of operation. We have followed this matter with reference to the greater proportion of the larger and medium sized plants, 24-hour operation. We can figure our saving in efficiency, we can figure the investment and capitalize the difference in investment on different sizes of motors, and different kinds of drives, but in the case of some of the smaller plants, with one shift or two shift operation, the question of demand, it seems to me, would be particularly worthy of consideration.

The mill calendering process takes a large amount, proportionate to the total amount of power absorbed by a rubber plant. If we attempt to apply a complete mill equipment during one ten-hour operation, we are thereby creating a large demand for a very large part of the power consumed.

Would it not be well for some of us minor operators in spite of the adoption of one 10-hour or two 8 hour operating periods, to consider 24-hour operation of the mill in calender work, in order to reduce the demand. The saving which can be brought about in this way capitalized in a large number of these small plants, will so far overshadow the returns from savings brought about by various other means, that you will almost forget the slight saving made by a reduction in the horse power of the motor of 50 or 25 per cent. I have in mind a particular case where such a scheme reduced the power demand charges by nearly 50 per cent. We can overlook a lot of the savings to be obtained by very careful technical consideration of other points, when we figure the demand charge.

Martin Berthold: The committee is wondering whether it is appreciated, that in the motor application to gearless drives the low-speed squirrel cage induction motor must be excluded from this consideration on account of its low power factor and efficiency in operation at any load imposed, and therefore, we consider essential the application of the synchronous motor. The synchronous motor can be designed from the point of efficiency high enough to deserve consideration, the synchronous motor being operated at unity power factor.

The pull-out torque has to be determined by the engineers of the rubber plants, and so also the starting torque; the lower the speed, the higher the starting torque. There should be no difficulty in designing a machine to meet the requirements for gearless mill drives.

A. M. MacCutcheon: On the question of electric heating, is it possible that the quality of the rubber can be affected by a close heat regulation which can be secured with electric heat, just as in the heat treating of steel they have found that the electric furnace, although it is more expensive, more than pays for itself in the quality of the material that is produced. Whether or not such a question is germane to the rubber industry, I do not know.

I am much interested in the matter of signals. I gather that the limiting factor in working the rubber through the apparatus is the motor with regard to the load demand. Now, if that is the case, why surely some signal as to how fast the material can be fed in or worked in, is invaluable. If it is valuable to show when the machine is approaching the limit of production, is it not also valuable to show when it is approaching the limit of inefficient production; or in other words, to call for a signal when they are not feeding fast enough, as indicated by the power demand on the motor.

B. C. Dennison: Why is it necessary for the men to feed these crude rubber chunks into the rolls by hand, there to be distintegrated or reduced to small particles. In paper mills, for instance, we do not expect that the pulp log is to be forced in between two rolls and reduced in one process to the fine pulp. We, on the other hand, expect that the logs will be thrown into the hopper of an automatic machine which chops them up, or, if grinding is desired, that the log will be held in some automatic clamp, which will hold it against a rough wheel which will reduce it to fine particles. Of course, rubber is a tenacious material, but could it not first be reduced in some automatic machine to fine shavings, and then fed into the rolls entirely automatically, without danger and without these sudden applications of excessive load to the driving machines?

Byron T. Mottinger: In answer to that question it is only fair to state that innumerable attempts have been made to design rubber mills in the past 40 or 50 years that would automatically feed the rubber into the mills. There was much effort made in this direction in England and European countries, more, I dare say, than was made here, but all of these attempts were failures, and the fundamental reason why it is impracticable, as I see it, is particularly this one reason which I think you will all agree in—the process, for instance, of mixing a batch of rubber is of short duration. The time will vary with the contents and various practises of the various rubber manufacturers, and I dare say that there are mixes which are made in as short as four minutes, and mixes which require as long as 20 minutes, and even 40 minutes, and during that period of mixing you begin with one condition of materials and end up with materials of all together different properties. You start in with a chunk of previously broken down rubber, cold and tough, and end up with a thoroughly disintegrated mass of warm, plastic, compounded material, which has to be cut off the roll. The pieces must be rolled up, or sheeted out, and after this operation is finished, the whole operation is started over again, in from, say four to twenty minutes.

There are automatic attachments which are applied to mills if the mills are to be used continuously for mixing. A conveyor like belt passes underneath the mill rolls, and up around the back roll, far enough so as to deliver the rubber and compounding materials to the top side of the rolls as rapidly as it passes down between the rolls. Similar attachments have been applied to mills for breaking down, warming and washing, but have found no general application. If my sizing up of the situation is not correct, I should like to be enlightened.

L. B. Timmerman: Being interested in the safety device game, the point I wish to refer to is in regard to the elimination of the safety device, and drawing a man out of the rolls by reversing them. I believe that the factories at Akron have tried that out, and have found tha tthere is more damage done to a man's arm and limb when he is caught in a machine by picking him out than is done by leaving him in long enough to back the rolls off. That is, the rolls being of different diameter, the flesh is pulled in one way, and when the rolls are reversed, it is pulled out the other way, and actually takes the flesh from the man's arm or limb and makes it useless, and I believe it has been found practicable, after consultation with the medical authorities, that the average operator in the mill can relieve the pressure on the rolls and take the man out in a time short enough to prevent any permanent injury to his limb from overheating.

J. H. Vance: The statement about the backing up of the mill in the case of an operator with lacerated hand in four minutes is correct. There is a rule in our plant that in no case when a person is caught in a mill shall the mill be backed up, as we have found in so doing the injury is made greater than was made by the initial action.

H. W. Eastwood: My engineering experience has been almost entirely in the steel industry, and it was impossible for me to go through the Goodrich plant without noticing the exact similarity of layout, between rubber mill lines and sheet mill lines. With that in mind it is very hard to understand why improved efficiency cannot be secured by the application of flywheels on rubber mill drives.

Sheet mill lines are usually laid out with a number of mills in one line up to as many as eight, and the general arrangement is exactly the same with the exception, of course that the horse power required is greater; where you have a 500 or 600-h. p. motor, in a rubber mill, you have a 1600 or 2000-h. p. motor in a steel mill, but I have not seen any sheet mill without a flywheel in connection with the drive.

Another point in connection with the sheet mill drive is that they are all equipped with induction motors, slip-ring motors, with automatic slip regulation of some type, either with liquid rheostats or notched back relays.

Mr. Vance has brought up the point that the duration of the load in the rubber mill is so great that it would be impossible for the flywheel to be of any advantage. The duration of the load in the rubber mill I am sure is no greater than in the sheet mill, and yet it has been found advantageous there, and I believe that the matter deserves further investigation.

Byron T. Mottinger: Flywheels are not new things to rubber mill engineers. They were used fundamentally and our evolution has been from that standpoint. Since the introduction of electric power into rubber mills, flywheels have been used and have been found to be more expensive than beneficial. The data which we present to you show there are peak loads of 155 per cent, comparatively, for one minute, and approximate 200 per cent for one-half minute. How big a flywheel do you propose?

J. H. Vance: Answering that question, we have put flywheels on which weigh approximately one and one-half times the weight of the motor, and the results were the same as if there were no flywheels.

Paul M. Lincoln: There has been a good deal of discussion here tonight on the use of the synchronous motor in order to improve the power factor. I would like to ask the gentleman whether in the purchase of power from power companies, it is usual that power is purchased under a power factor specification; that is, is there a penalty applied for bad power factor, and if so, how is the penalty applied, and how much does it amount to?

W. H. Horton, Jr.: I recently had occasion to examine some fifteen tariffs of various large power companies operating east of the Mississipp River. The majority of the power rates in these tariffs were based on demands which were affected to some extent at least either by the kv-a. or the power factor of the load. Answering Mr. Lincoln's query directly it would seem that power companies are tending towards basing their charges on a power factor basis.

J. H. Vance: I was wondering if the conclusions reached by the committee are as they are for the reason that pretty nearly every rubber mill engineer has different ideas how to do it. It depends largely on the size of the rubber mill, how you do it. If you have a small plant with one washer, or maybe two, to motor that washer on the ratio of 1¾ to 2 h. p. per linear inch of roll face, is perfectly good engineering. If you have a string of five or seven, as in the Goodrich plant to motor them on the basis of one and one-half horse power per inch face, is good engineering. When you come to the mixing mill operation, to motor that on a basis of a horse power per inch face, with certain kinds of compounds is good engineering. With other types of compounds, to motorize on the basis of 0.8 horse power per inch of face, assuming the motor capable of giving 200 per cent torque, is good engineering.

When it comes to calendering operations, I can remember the day when we put 40 h.p. on a 60-in. calender. We had calenders in those days with rolls 18 in. diameter and 60 in. face. We ran seven to ten yards a minute, and thought it was good business, and it was good business. Today, when we run them at forty yards a minute, you have got to motor accordingly. The speed of production has an influence on the power demand.

When you come to the warming mill, which in rubber mill operation is one of the lesser power demand types of apparatus, 0.8 of an inch of roll face per horse power will take you through very nicely, provided you have a group of four or more mills. I have seen the 40 in. face mills take power in excess of two horse power per inch of face in warming for tube machine operations, so that in all of this discussion as to the power demand, the speed of production is a very large factor. The type of materials, which are mixed in a rubber mill, has a very decided influence on the power applied.

F. H. Oberschmidt (by letter): Under the subject of safety stops, your committee recommends that the motor be stopped each time a mill line safety switch is operated. I believe that this procedure is unnecessary and entails a loss of production, which is unwarranted, since no additional safety is secured by following this procedure. With the accepted standard type of magnetic clutch brake, opening the clutch and brake circuits, by operating a safety switch, instantly disconnects the mill line from the motor and the brake is applied, resulting in a very quick and safe stop.

In many plants the safety rods on the mills are operated not only in an emergency but also for service stopping. This practise I believe should be encouraged since the more frequent operation of the safety rod by the operator will better acquaint him with its functions and in an emergency he will instinctively trip the safety mechanism.

A safety device is only effective when it is in satisfactory operating condition hence periodic tests should be made to insure that such is the case. Also there are many times when a safety rod is tripped accidentally.

If we grant the advisability of using the clutch brake for service stopping and that it should be tested regularly each day, then it is evidence that stopping the driving motor each time the clutch is disconnected would result in considerable production loss, owing to the time required to re-start the motor after each stop. This is especially true in the case of large synchronous motors and in plants where the operating electrician is the only person authorized to start the motors. The larger the mill line the more serious this delay becomes and it is only necessary to refer you to Mr. Lincoln's statement with reference to the value of a day's production to appreciate the time lost in restarting the motor 18 or 20 times a day (these are average actual times a safety switch on one mill line is operated in one large plant in a 24-hour day) results in considerable loss of production without any safety gain.

Probably a better plan would be to have some push button or other arrangement for disconnecting the clutch only and not applying the brake for service stopping. However, I believe that you will find that it is standard practise in the larger rubber companies in the Akron territory to use the safety switch for service stopping in addition to its use as a safety device.

As a suggestion, it might also be advisable in a case of an overload on the mill line motor, to have the overload contacts so connected as to simply open the clutch circuit instead of stopping the motor on overload. This arrangement would immediately take the overload from the motor by disconnecting the mill line and would eliminate the necessity for restarting the motor.

William E. Date: First, with regard to Mr. Lewis's discussion, which was read by Mr. Mottinger, I believe there must be some misunderstanding regarding large size low-speed slip ring motors, as on page 6, the paper states:

"The prevalent tendency is an endeavor to eliminate the gear reduction, and connect the motor shaft directly to the mill-line shaft. This requires a very low-speed motor, and is impracticable with large size induction motors, either of the squirrel-cage-rotor, or of the wound-rotor type. The synchronous motor however is readily adaptable to this low speed and provides the advantages of high power factor, which is of large significance in view of the widely varying load encountered in milling, in addition to the elimination of costly, noisy gearing. The elimination of gear maintenance is a large factor."

A synchronous motor, I am given to understand, say, for example, 500 h. p., approximate 100 rev. per min., can be designed with the necessary torque to meet the requirement, with an efficiency of 73 per cent for 60 cycles, and of unity power factor. The same size of motor, for 25 cycles, can be designed for an efficiency of 80 per cent, and unity power factor.

Passing now to the safety stop question; irrespective of whether it is preferable to back the man out of the rolls, or whether it is preferable to loosen the pressure on the rolls, the important point is this,—provide a safety stop that will stop the mill in case of an emergency before the man is drawn into the rolls.

On the question of washer peak loads, we should not consider washing as a process in its entirety, but should segregate as we have done in the paper. The initial disintegrating peaks are high peaks and are relatively short time peaks. The following disintegrating peaks are lower.

Another point, in considering the difference in load, we should not confuse the "kind" of rubber with "compounds" of rubber. It is true that rubber of a specific kind will require 100 per cent more power than rubber of another kind, and the paper shows that what is meant by the kind of rubber is the geographical source of that rubber. It is true that different "compounds" of rubber do cause different load conditions, but they are not so marked as the different load conditions that are brought about due to the "kind" of rubber.

Again, on efficiency, we say that a motor should be efficient, but that is not all that is to be considered. In any plant necessary contributory equipment must be provided in proportion to the connected motor load. The power lines, the transformers, the switching mechanism, in fact all of the equipment is on the basis of the motor size selection. It is necessary to consider the installation as a whole, and if investment costs can be reduced, the saving should be effected. This applies both to the initial investment and to operating costs.

On the question of electric heating, it is the intention of this committee to cooperate fully with the Main Committee on Industrial heating.

Mr. MacCutcheon brought up the question of what effect electric heat would have on the quality of the output. That would be covered, we had hoped, under "Conclusions," items "C" and "D", page 5. We had in mind two factors; one, economy of operation, and the second, the effect on the product.

Finally, this Committee does not hope to attain 100 per cent efficiency in every plant, nor in every application, but we do hope that by studying each application improvements may be effected.

G. A. Maier: I object to Mr. Date's statement that the synchronous motor can be designed to apply to this service. I would like to have that changed to has been designed. At the present time I know of approximately 50 gearless drives going in in four different plants.

William E. Date: I accept the statement. The quotation referred to by Mr. Drake, and also by Mr. Pilgrim, namely; "It is reported that in tire mills one horse power is required per tire per day," was offered to emphasize a condition, and if the report is correct, to ask, can the condition be improved?

Our understanding of the report is that it referred to connected horse power, and on a basis of one shift per day. It was not the intention of the Committee to offer the reported condition as a rule, nor as a basis of computing operation costs. The consensus of the committee as reflected in the paper, is that it is not convinced that general rules can be applied, second, that though cost statistics are useful and in fact necessary to any line of manufacture, that the purpose of this committee should be toward a larger and broader basis, namely; to assist in any way it can toward the efficient application of electric power, to every operation in the rubber industry, and efficiency here is intended to cover production efficiency (continuity of service) as well as doing the work on an economical power cost basis.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 16, 1921.

PRESENT DAY PRACTISE LIMITATIONS OF OIL CIRCUIT BREAKERS

BY THE SUB-COMMITTEE ON OIL CIRCUIT BREAKERS AND SWITCHES OF THE PROTECTIVE DEVICES COMMITTEE*

H. R. WOODROW, CHAIRMAN
Stone and Webster Inc., Boston

IN ORDER to summarize the present-day indefinite operating requirements and limitations of oil circuit breakers, the A. I. E. E. (Protective Devices Committee), N. E. L. A. (Apparatus Committee) and Electric Power Club (Power Switchboard and Oil Circuit Breaker Section) cooperated in sending out a joint questionnaire for oil circuit breaker data to the larger operating companies. The response to this questionnaire was prompt and rather complete, which is an indication of the interest taken by the operating companies.

This subject has been given careful consideration in the past and several papers have been presented, and still there remains much research work to adequately determine the proper limitations of design and application. To this end it is suggested that operating companies add to their systems, equipment which will register essential transients that can not be registered on the usual quota of indicating and recording meters. On account of lack of generator capacity and operating complications, it has been impossible to test oil circuit breakers to any great extent to determine their

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limiting interrupting capacity and consequently the circuit breaker of today is based largely on deductions from the results of system trouble, the conditions of which are usually of rather indefinite nature. At the present time, however, the operating companies are showing an increasing willingness to cooperate with the manufacturer in the development of oil circuit breakers by allowing constructive tests to be made on the generating equipment of their systems.

We feel that the results of this cooperation will lead to a marked improvement in that it will make possible the elimination or correction of a number of minor defects, which in the few tests that have been made have been shown to be a factor in causing previous failures.

In the paper on "Rating and Selection of Oil Circuit Breakers", by Messrs. Hewlett, Mahoney and Burnham, presented before the A. I. E. E. in February 1918, the basis for the present day manufacturers' standards was outlined, and we propose to summarize in this report the operating companies' viewpoints of these standards, as brought out in the replies to the questionnaire, together with recommended revisions.

The general requirements for oil circuit breaker specifications have been classified as follows: first, rated voltage; second, rated continuous current-carrying capacity; third, rated momentary current carrying capacity; and fourth, rated interrupting capacity.

Rated Voltages

The present standards of the A. I. E. E. specify that oil circuit breakers shall be given a dielectric dry test consisting of the application of 2¼ times the rated voltage plus 2000 volts between the live parts and ground for 60 seconds. Although the questionnaire did not indicate in any way that such a test would not give adequate insulation it was brought out in the discussion that some operating companies are purchasing apparatus of a voltage rating higher than the system voltage on which the apparatus is to be used.

It is recognized that the dielectric test recommended by the Standards of the A. I. E. E. must meet the requirements of average systems. It must also be recognized that systems not protected by adequate lightning arresters and systems of very large capacity may be subjected to voltage rises due to surges or lightning that will exceed the insulation values required by the Standards of the A. I. E. E. Taking those points into consideration, it is not recommended that these Standards for dielectric tests be changed. However, for systems that have characteristics, or inadequate lightning arrester protection, such that higher insulation is required, the present practise of selecting apparatus of the next higher voltage rating is endorsed.

RATED CONTINUOUS CURRENT-CARRYING CAPACITY

There has been little trouble reported of oil circuit breakers overheating under normal operation, although the reports indicate that some operating companies order oil circuit breakers with current rating above their requirements. This has probably been a wise policy as it allows a greater margin of temperature rise in the breaker under short-circuit conditions and a greater margin of safety. Some trouble of overheating has been reported which has been caused by poor workmanship, such as poor alignments of contacts. It would be a great help if the contacts were made for greater ease and permanency of adjustment.

In order to reduce the maximum temperature and to prevent accumulation of explosive mixtures in cell compartments which has given some trouble, we would recommend that careful consideration be given to ventilation of compartments cautioning at the same time against ventilation which would allow gas from one compartment entering an adjacent cell. One company has found it desirable to carry the ventilation from each tank to the outside of the building.

RATED MOMENTARY CURRENT-CARRYING CAPACITY

Trouble has been experienced by some of the larger operating companies through the failure of oil circuit breakers to carry heavy short-circuit currents for the period of time required to open the circuit and in some cases of the inability of the current-carrying parts to withstand the strain produced by the electromagnetic forces. We are very fortunate in having the accompanying paper by Mr. Torchio which outlines the results of a very extensive series of tests along these lines, showing very conclusively certain weaknesses in oil circuit breakers from this standpoint. The principal weaknesses brought out in these tests have now been corrected.

It is recommended that all oil circuit breakers be given a short-circuit current rating for a period of say both one and five seconds.

RATED INTERRUPTING CAPACITY

The limiting factors entering into the operation of an oil circuit breaker when interrupting a current have never been conclusively determined. The present-day practise of rating oil circuit breakers to interrupt a given r. m. s. current at normal voltage two times at a two-minute interval and then be in a condition to be closed and carry its rated current until it is practicable to inspect and make necessary adjustments, is not in accord with operating requirements as reported in the replies to the questionnaire. There is considerable difference in the operating requirements depending upon the character of the system. On such parts of a system as will not cause interruptions to service by the opening of an oil circuit breaker, it is general practise not to throw in the breaker again until the circuit is tested and in some cases until the breaker is carefully inspected as well. In other cases where the opening of an oil circuit breaker interrupts service such as distribution feeders, single transmission lines, etc., there is a general tendency to throw in the breaker as soon as possible without testing the circuit. In many cases, the latter method restores service, as the opening of the oil circuit breaker may have been caused by a flash-over or other intermittent trouble. In some of these cases the operators find that even after the breaker has opened automatically, two, three, four and some as high as five times, a reclosing of the breaker will restore service, and, therefore, they feel it desirable to have the breaker rated to withstand this service.

Considerable time is required in testing a feeder, and in many cases the only available means is by closing the circuit through the oil circuit breaker. In some cases, however, this heavy requirement on the oil circuit breaker could be relieved by the installation of proper testing facilities, particularly where there are many feeders or points of high power supply.

It is felt that the interrupting capacity tests that are being made at the present time in the factories and on some of the larger companies' systems will give a better idea of the limitations of the oil circuit breaker to withstand the stresses produced by the reclosing feature. Also the installation of recording devices on systems which will give some record of the service imposed on a breaker under short-circuit conditions should lead to progress in the design of oil circuit breakers.

Some companies consider it desirable to compare the constants of the circuit breaker, such as tank dimensions, length of break, speed of operation, expansion chamber etc., before selecting one for their conditions, and it is hoped that the results of the above tests will tell us more regarding the relative importance of these features.

It appears, therefore, that the operating companies may require ratings on duty cycles, other than the present recognized standard as given in the paper by Messrs. Hewlett, Mahoney and Burnham. There is considerable difference of opinion regarding the point of ending the duty cycle, the allowable condition of the breaker at that time, and what is considered satisfactory operation of the breaker. The opinions vary so much that we hesitate to recommend a definition and therefore suggest that the satisfactory operation would mean the interrupting of current within a definite time after the energizing of the trip coil, which time allowance could be relied upon for selective operation of relays on the system, without throwing burning oil outside of the tank or causing permanent deformation of tanks or any of the current-carrying parts.

It is suggested that the rating be made with only the manufacturer's factor of safety to cover any inequalities of materials and manufacturing processes so the purchaser of an oil circuit breaker could then rely on a given rating at all times and should not count on more.

Very few data were given which would show the relation of the constants (reactance and resistance) of the circuit as affecting the interrupting capacity of the breaker, although some tests made by one of the operating companies showed that reactance imposed a heavier duty on the oil circuit breaker than resistance for the same value of current.

In several cases reported, the increase in the speed of operation of some of the older type breakers has made an improvement in the interrupting capacity.

Ninety per cent of the cases reported have found venting the tanks desirable.

There is no universal standard for oil to be used in circuit breakers, although some companies have interchangeably used oil of one manufacture in breakers of another. It would be desirable if some standards could be adopted by the oil circuit breaker manufacturers so as to reduce the number of types of oil required for stock with companies having several makes of breakers.

It has been impossible to answer satisfactorily these questions at this time, and it is, therefore, suggested that this matter be given careful consideration by next year's sub-committee.

GENERAL COMMENTS

The subject of oil circuit breakers as reported by this committee was intended to cover the field of station breakers which would have to rupture large amounts of power rather infrequently, and is not intended to cover the subject of circuit breakers such as used in control equipment where they should be capable of interrupting full-load current a large number of times per hour for long continued periods and not be required to interrupt heavy short-circuit currents.

The activities of this sub-committee have been confined this year entirely to the subject of oil circuit breakers and it is suggested that next year's sub-committee consider the question of rating and rupturing capacity of fuses, both of the power class and potential transformer class, in addition to following up the study on limitations of oil circuit breakers.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 16, 1921.

HIGH-CURRENT TESTS ON HIGH-TENSION SWITCHGEAR

BY PHILIP TORCHIO

Chief Electrical Engineer, New York Edison Co.

Abstract of Paper

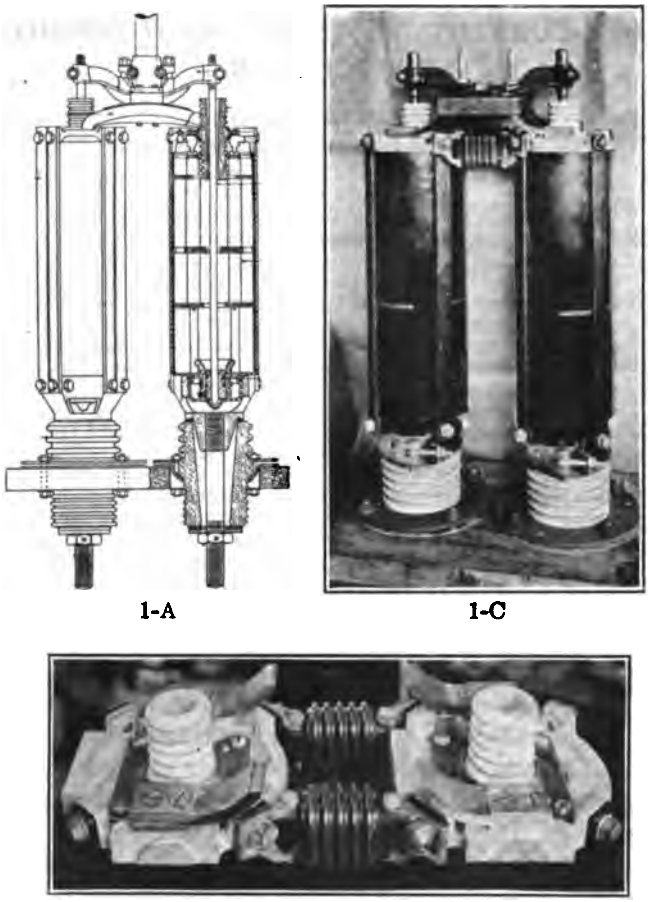
The article describes a series of tests on oil circuit breakers and disconnecting switches to determine their strength at brush contacts and supports in withstanding the mechanical stresses engendered by the magnetic flux due to the flow of large currents of the order of 100,000 amperes, as may exist at times of short circuits on large systems. Other tests were made on current transformers and potential transformer fuses.

For the first time, a synchronized motion picture machine and an oscillograph, were coupled to reproduce the coincident actions of the apparatus tested, and the variations of voltage and current in the circuit. The tests proved that practically all the circuit breakers then on the market had the brush contact placed in the wrong position, creating arcing before the operating mechanism had sufficient time to perform its function. The tests emphasized the importance of strong locks for disconnecting switches. Only single-turn primary-type current transformers and potential transformer fuses with resistance in series, were found adequate to give the service requirements.

THE high-current tests on oil circuit breakers, disconnecting switches, current transformers, and potential transformer fuses were carried out in 1918 and 1919 by the engineers and the Photographic Bureau of The New York Edison Company. The manufacturing companies lent effective cooperation in arranging the apparatus for the test, and in analyzing the results. For the first time, a synchronized motion picture machine and an oscillograph were coupled to reproduce the coincident actions of the apparatus tested and the variations of voltage and current in the circuit.

Oil Circuit Breakers

In connection with the study of very high-current electric welding apparatus, certain phenomena took place on the ordinary type of brush contacts, which prompted an investigation and subsequent tests to determine what would happen on the circuit breakers used in our central stations when subjected to currents



1-A

1-C

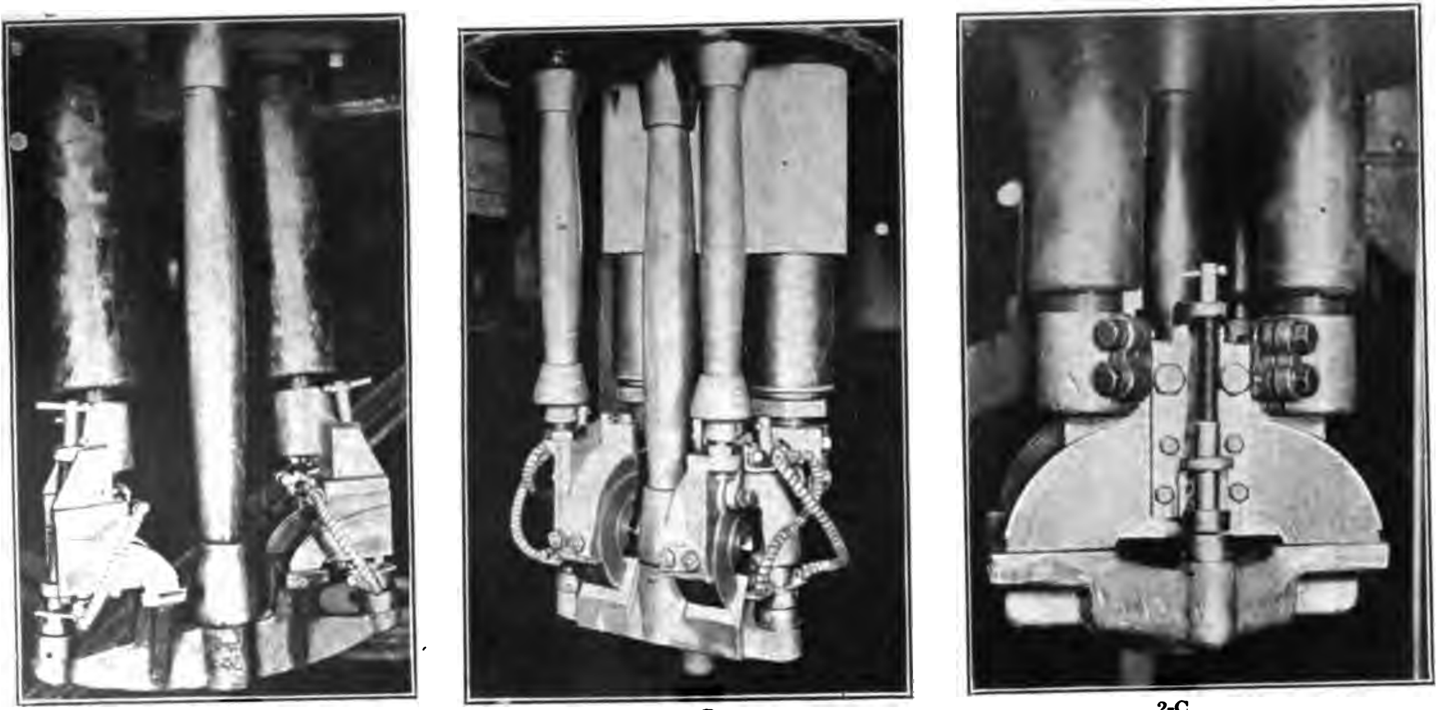
1-B

Fig. 1—G. E. Co. Type F H-3 Oil Circuit Breaker Showing Improvements

1-A. Original standard construction of contacts.
1-B. Detail of new inverted contact brushes and tie insulators.
1-C. Assembly of new inverted contacts and tie insulators.

of the order of 100,000 amperes, as may exist at times of short circuits on large systems.

The phenomenon which was noted was the well-known fact that when current is flowing in a closed

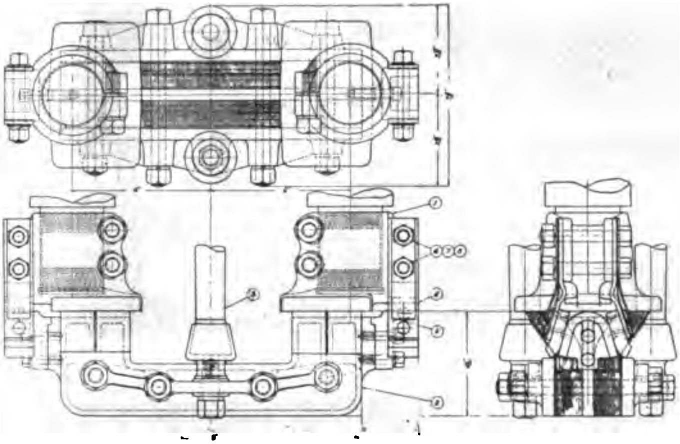


2-A 2-B 2-C

FIG. 2—WESTINGHOUSE ELEC. & MFG. CO. OIL CIRCUIT BREAKER PARTS SHOWING IMPROVEMENTS. (FORMER DESIGN SHOWN IN FIGS. 9, 10, 14 AND 15.)

2A. Quarter elliptic form of inverted brush contact used in the CO-2 1200-ampere 60-cycle circuit breaker.

A circular form of inverted brush contact used in the CO-1 1200-ampere. 60-cycle circuit breakers. Considerable circuit, the magnetic field set up by the current will tend to expand the loop outward. Therefore, if a circuit breaker is designed with a loop circuit so arranged that the mechanical pull due to the magnetic flux is to open the contact, the switch will present a weakness at that point; while if the movable contact parts are inverted so that the mechanical pull due to the magnetic flux is to force them more solidly against the fixed parts, the contact will be improved.



2-D

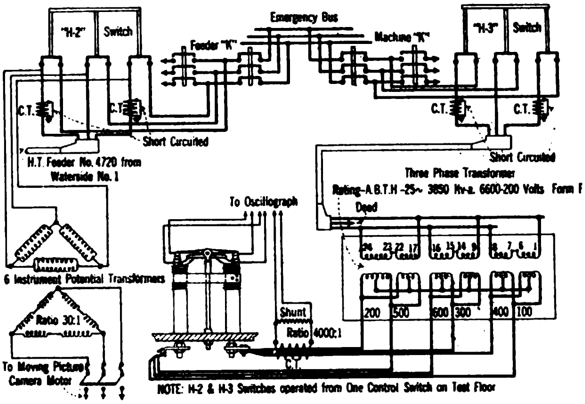


Fig. 3—Diagram of Connections for Tests

The circuit breakers tested were the *K*-52, *H*-3 and *H*-6 of the General Electric Company; and the *E*-9 and *O*-1 of the Westinghouse Electric & Manufacturing Company.

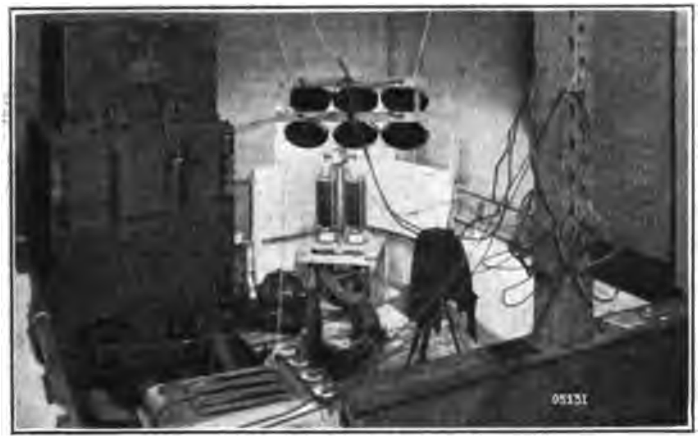


FIG. 4—SET-UP OF APPARATUS FOR TESTS

The tests proved that practically all the circuit breakers then on the market had the brush contact placed in the wrong position, so that when the current flowed the resultant mechanical force acted in a direc-

FIG. 5—CONTROL APPARATUS FOR TESTS; MOUNTED ON GALLERY ABOVE THE TEST FLOOR

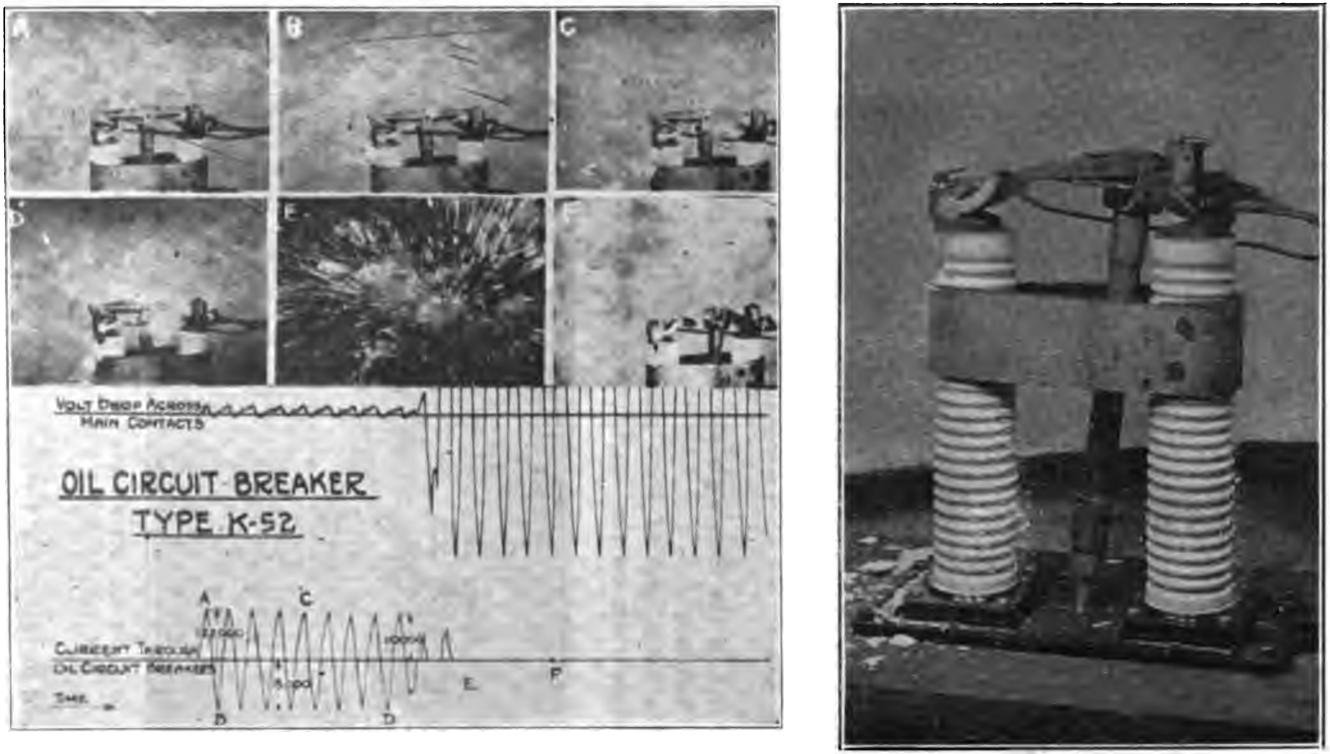


FIG. 6—G. E. CO. K-52 CIRCUIT BREAKER REINFORCED WITH FIBER BAND

Rating, 125,000 kv-a., 31,500 amperes at 2300 volts.

This circuit breaker was first tested at 27,000 and at 31,000 amperes mean effective which it withstood satisfactorily. It was then given 85,000 amperes mean effective which spread the porcelain pillars, breaking one at the special support, and twisted the movable contact around and entirely off the stationary contacts. Open-circuited at the 9th cycle.

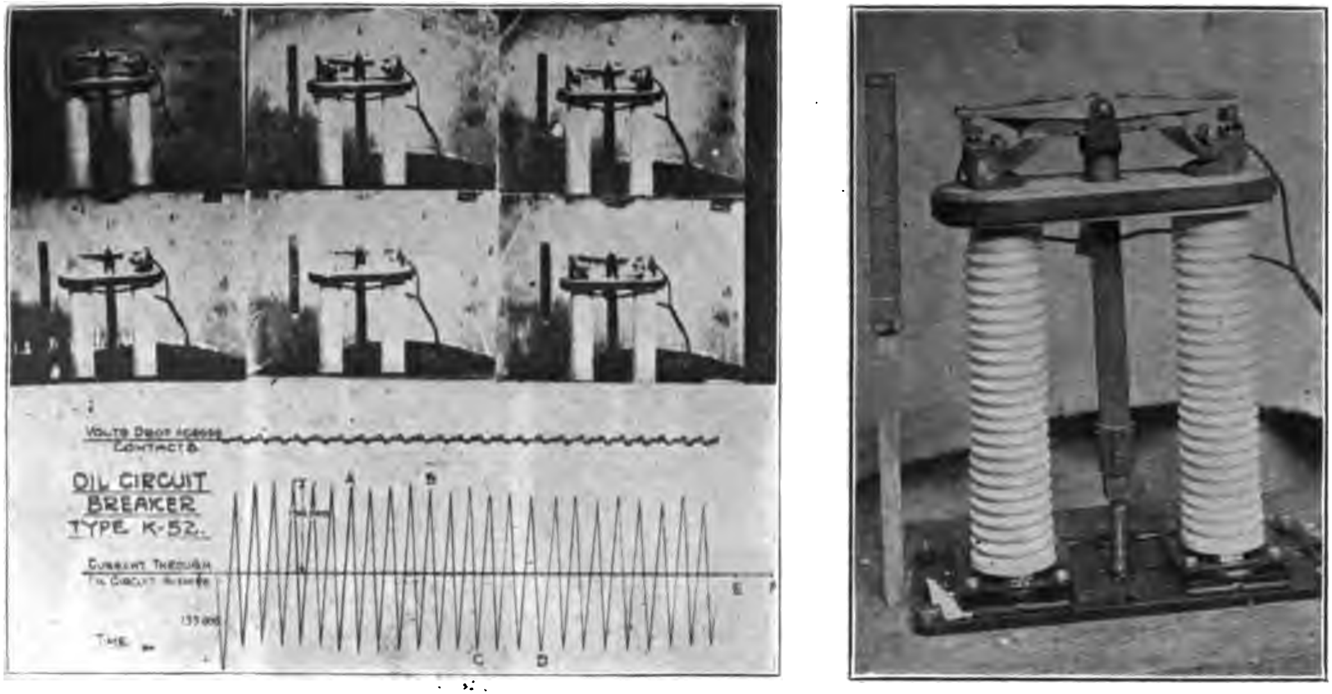


FIG. 7—G. E. CO. K-52 CIRCUIT BREAKER REINFORCED WITH WOOD AND STEEL

Rating 125,000 kv-a., 31,500 amperes at 2300 volts.

First withstood a test of 67,000 amperes mean effective. On 98,000 amperes mean effective the porcelain broke at 12th cycle. Slight arcing. Toatl spread of contacts approximately 3/16 in.

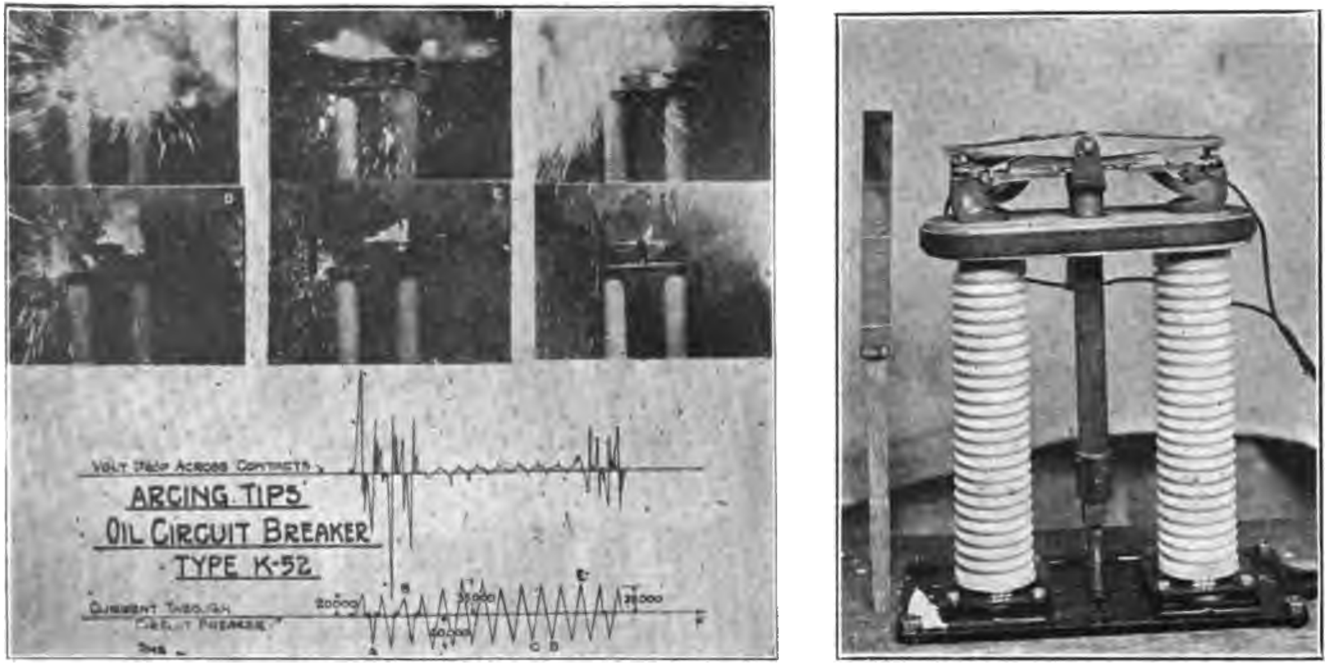


FIG. 8—G. E. Co. K-52 CIRCUIT BREAKER

Test on arcing tips only. Tested at 21,000 amperes mean effective. Contacts lifted on first ½ cycle, and for three consecutive cycles. Remained closed for seven cycles, and again opened for three cycles. Severe burning.

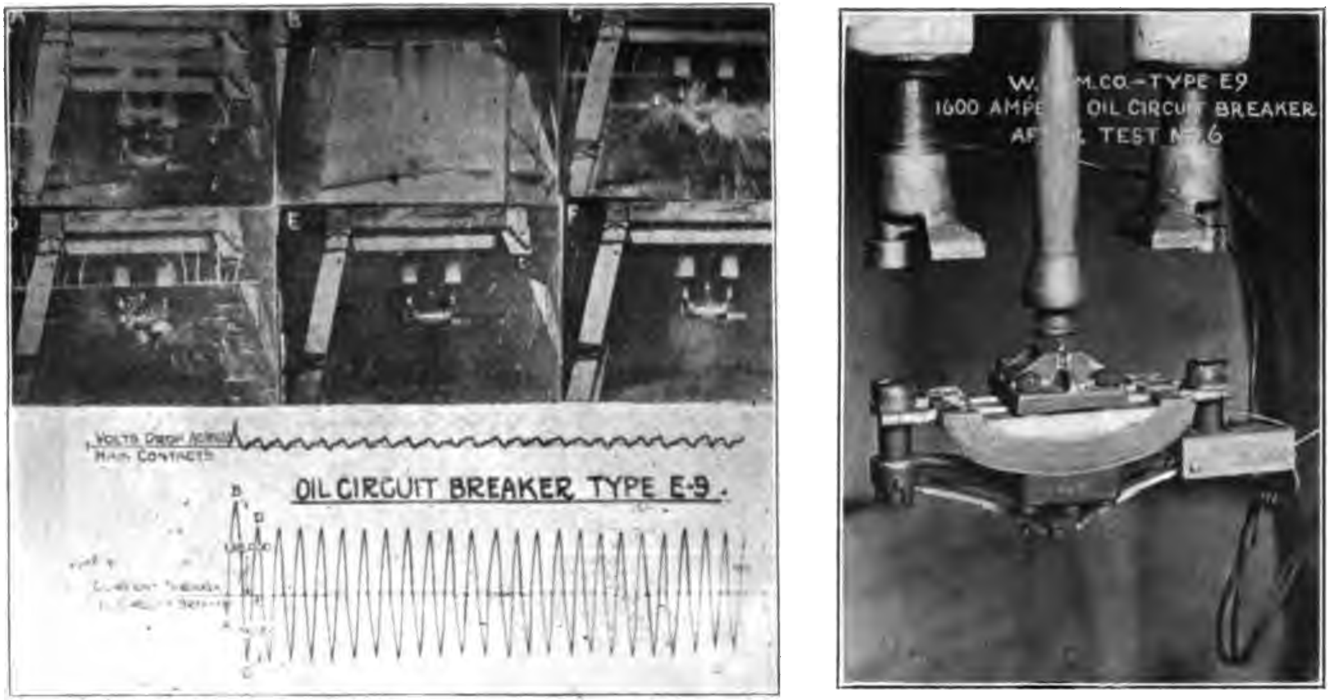


FIG. 9—WESTINGHOUSE E-9 CIRCUIT BREAKER

Rating 160,000 kv-a., 40,000 amperes at 2300 volts.
Tested at 79,000 amperes mean effective. Brushes lifted on first ½ cycle, arced and froze. Total spreading of contacts approximately 5/32 in.

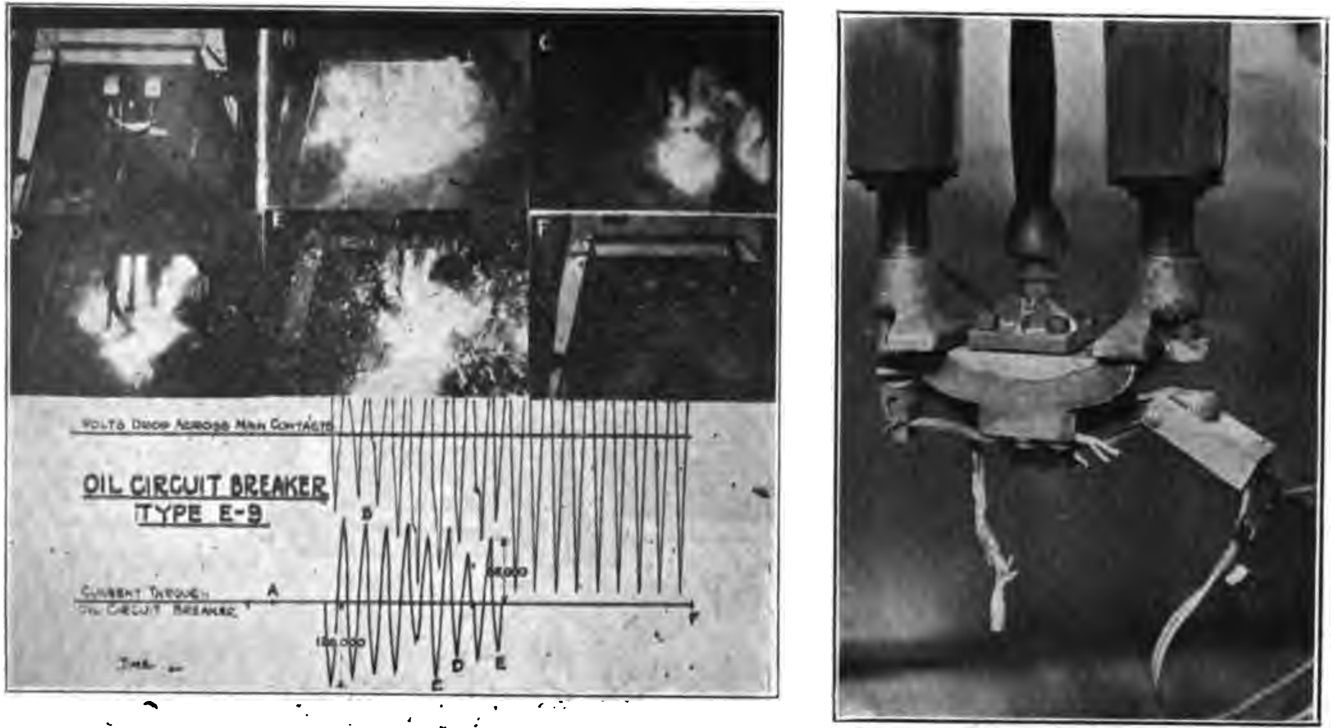


FIG. 10—WESTINGHOUSE E-9-CIRCUIT BREAKER

Rating 160,000 kv-a., 40,000 amperes at 2300 volts.

Tested at 89,000 amperes mean effective. Brushes lifted on first ½ cycle and burned clear at 8½ cycles.

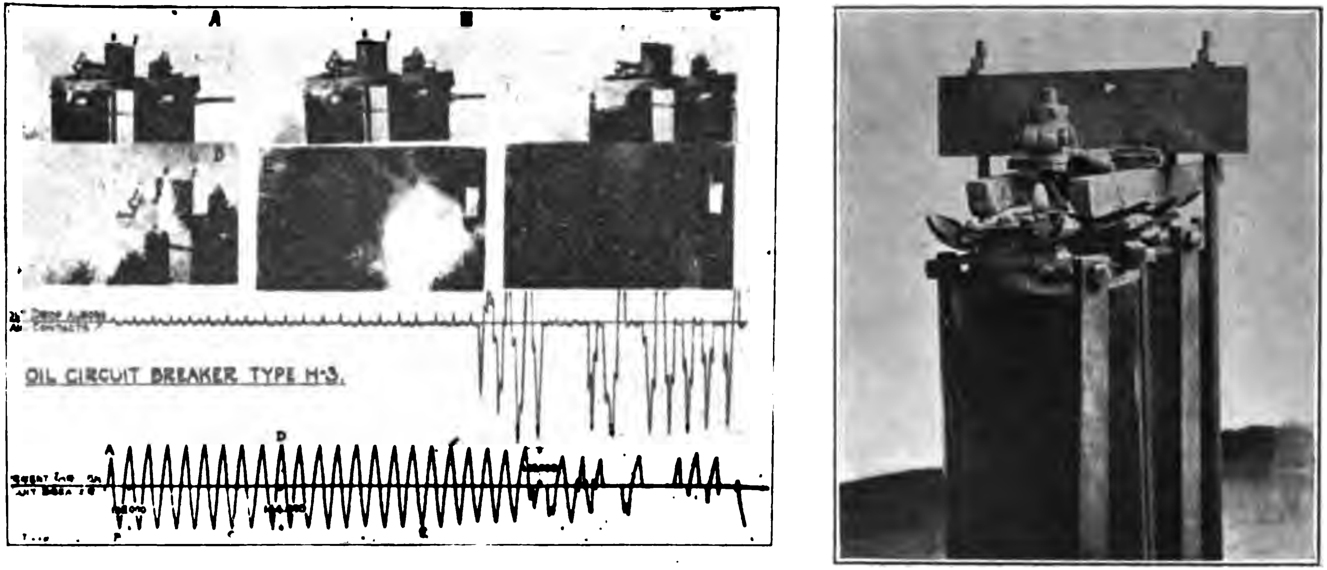


FIG. 11—G. E. CO. H-3 WITH INVERTED BRUSHES

Rating 225,000 kv-a., 63,000 amperes at 2300 volts.

Tested at 103,000 amperes mean effective. Slight arcing at contacts due to vibration and spreading of pots, contact plates collapsed, one of the brass rods burned off, and switch open-circuited.

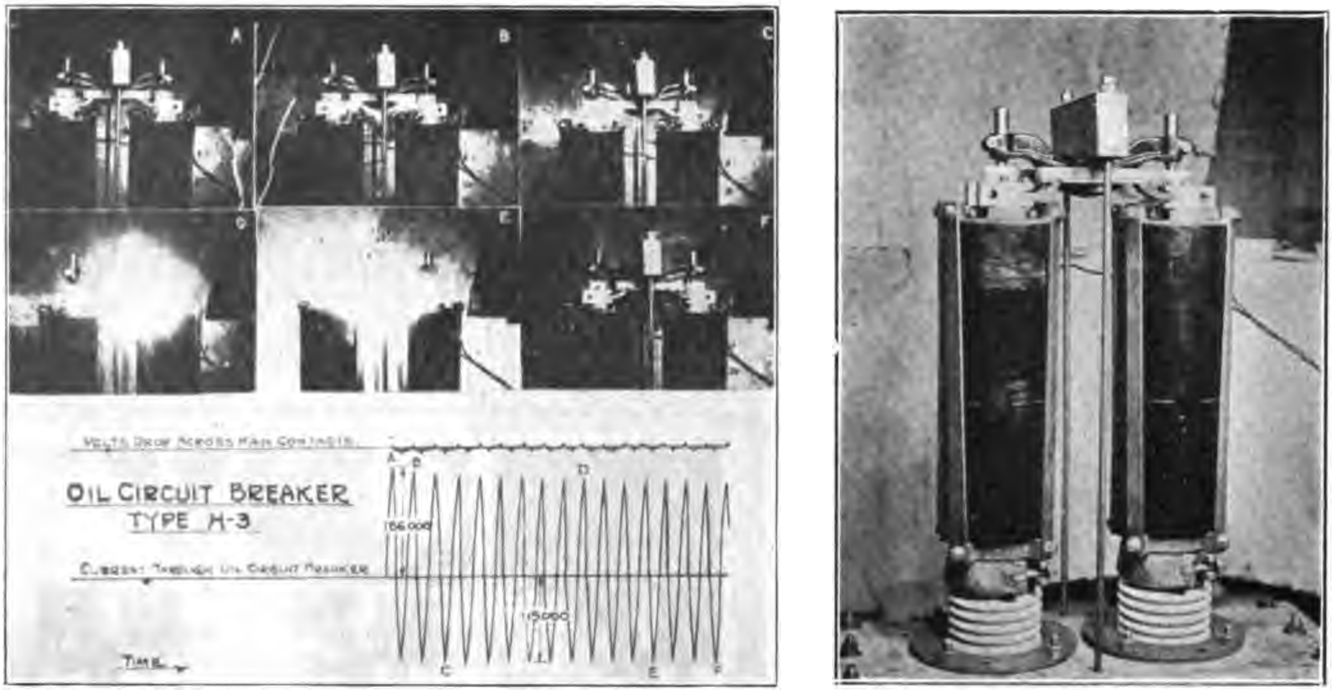


FIG. 12—G. E. CO. H-3 WITH TRIAL BRUSHES

Rating 225,000 kv-a., 63,000 amperes at 2300 volts.

Tested at 112,000 amperes mean effective. Slight arcing at contacts due to vibration. One brass rod was bent. Total spreading of pots 1 1/8 in. The bright irregular lines at the left edge of Section B of the film are caused by static discharge due to the high speed at which the films were taken This appears in a number of the motion pictures, notably Section E of the film in Fig. 17.

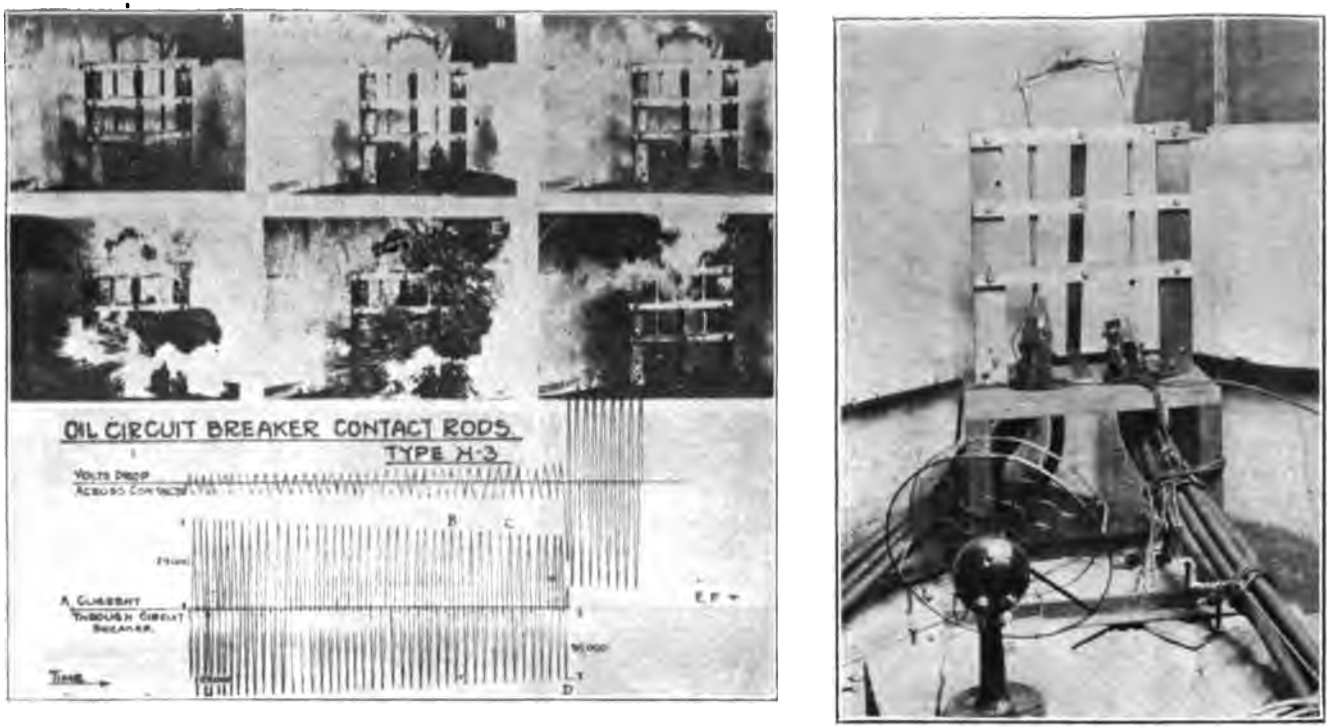


Fig. 13—G. E. Co. H-3 Contact Rods

Standard brass rods tested at 41,000 amperes mean effective, burned off at contact with crossarm in 0.57 sec. Copper rods tested at 91,000 amperes mean effective, burned off in body of rod in 1.8 sec. Copper rod test shown above. Note bending between supports.

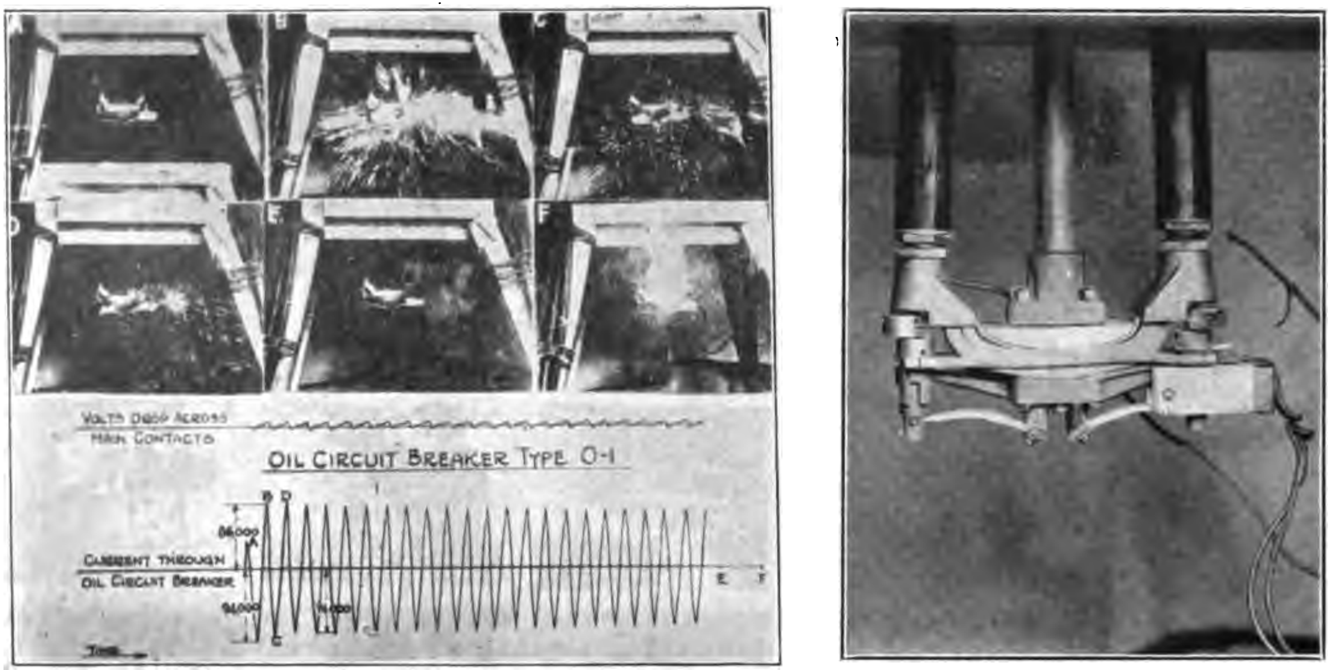


FIG. 14—WESTINGHOUSE 0-1 CIRCUIT BREAKER

Rating 350,000 kv-a., 88,000 amperes at 2300 volts.

Tested at 63,000 amperes mean effective. Brushes lifted on first ½ cycle, froze and remained closed. Total spreading of supports approximately 3/16 in.

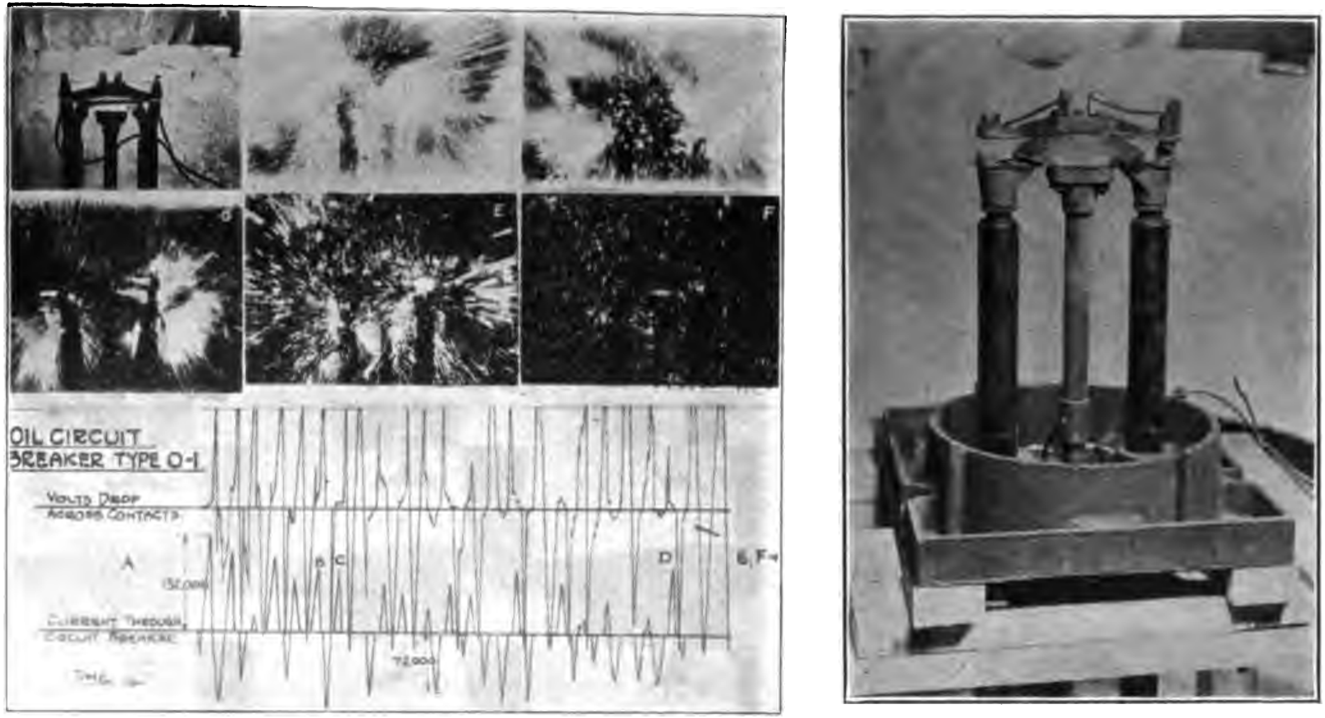


FIG. 15—WESTINGHOUSE O-1 CIRCUIT BREAKER

Rated at 350,000 kv-a., 88,000 amperes at 2300 volts.

Tested at 84,000 amperes mean effective. Brushes lifted on first ½ cycle and continued intermittently throughout test. Arcing tip destroyed. Considerable spreading of supports during test but no permanent spreading noticed.

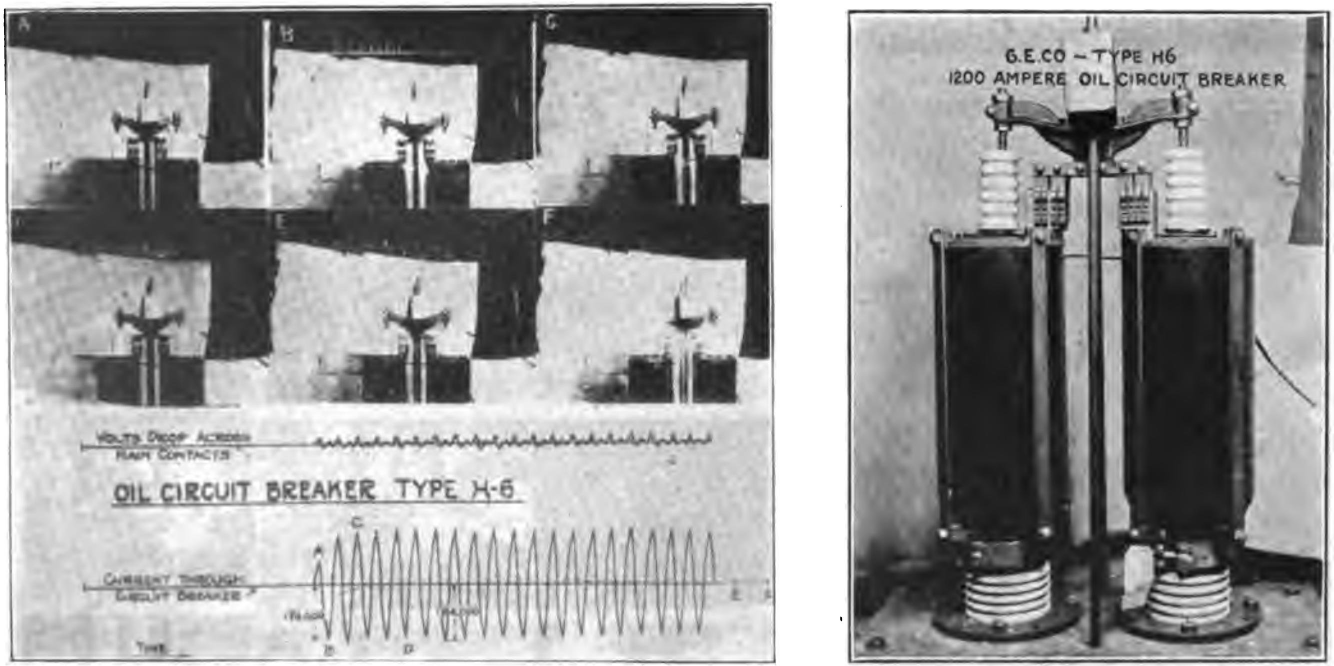


FIG. 16—G. E. CO. H-6 CIRCUIT BREAKER

Rated at 350,000 kv-a., 88,000 amperes at 2300 volts.

Tested at 130,000 amperes mean effective. Pots spread at first ½ cycle, no arcing. Parallel paths through moving contact causes attraction of contact fingers and, therefore, tightening instead of opening of contacts. Total spreading of pots approximately one inch

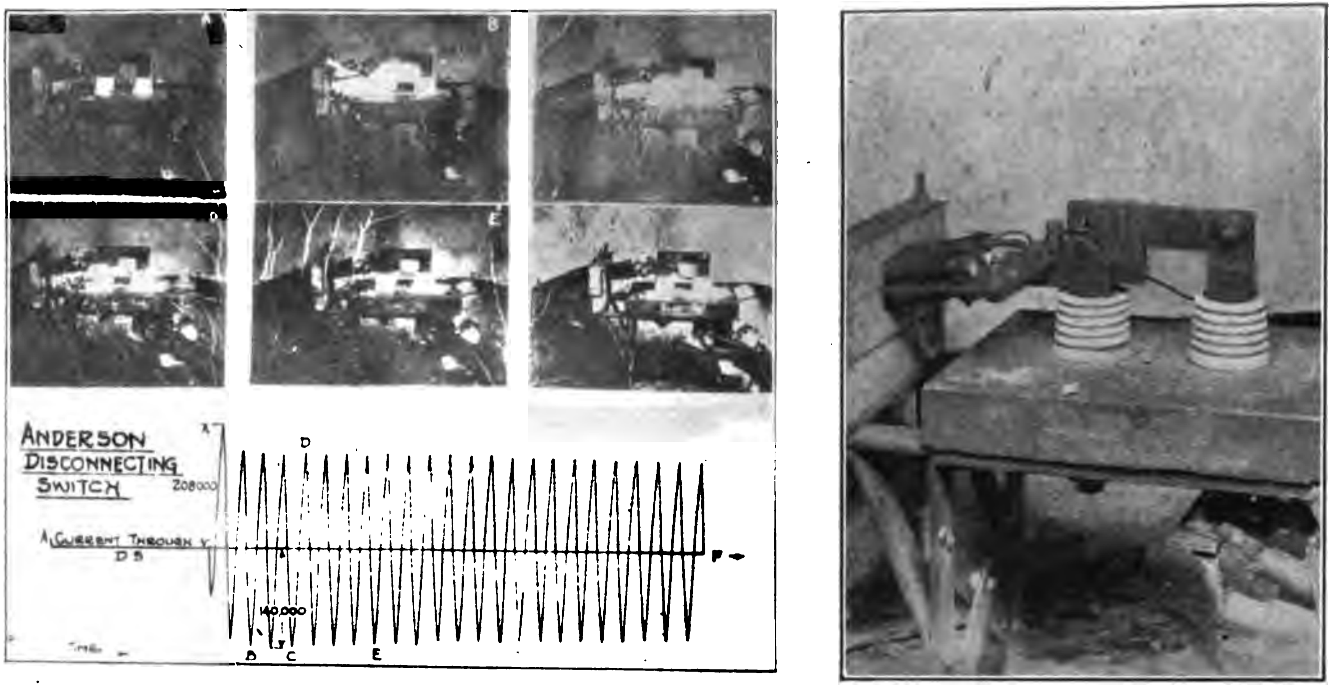
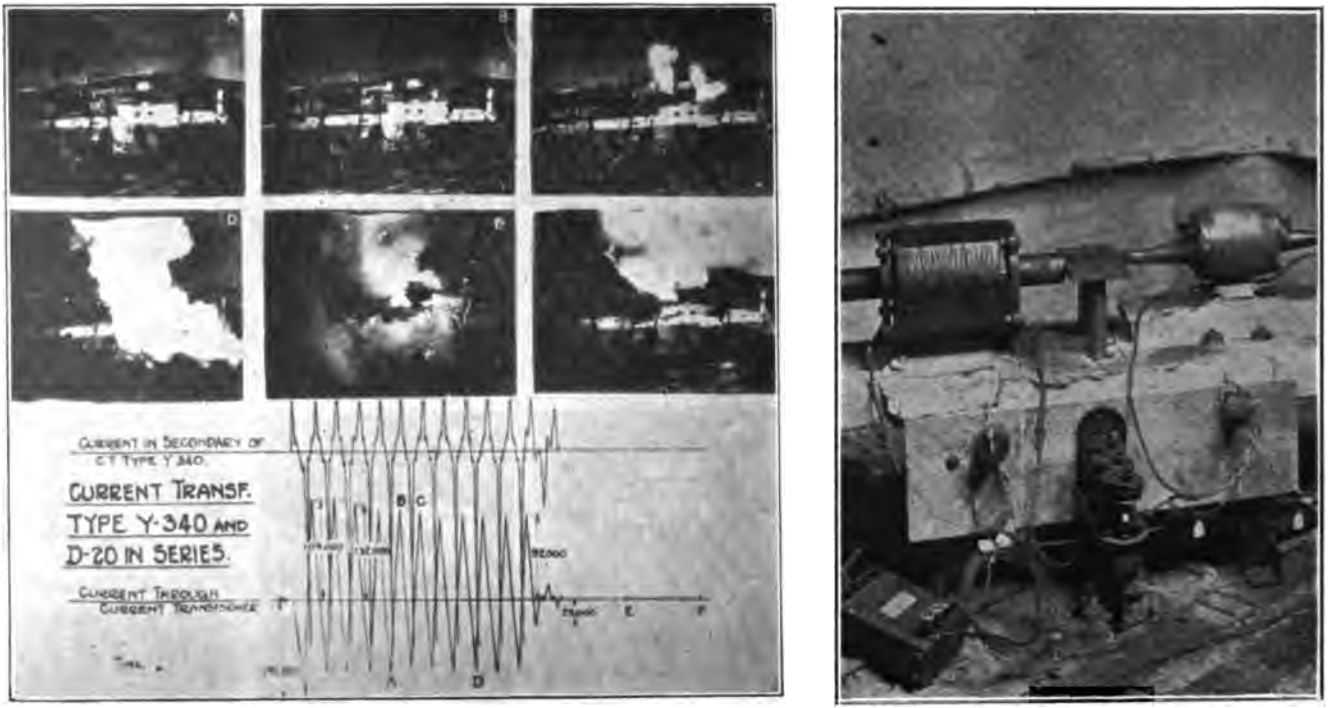


FIG. 17—ANDERSON DISCONNECTING SWITCH WITH SPECIAL LOCK

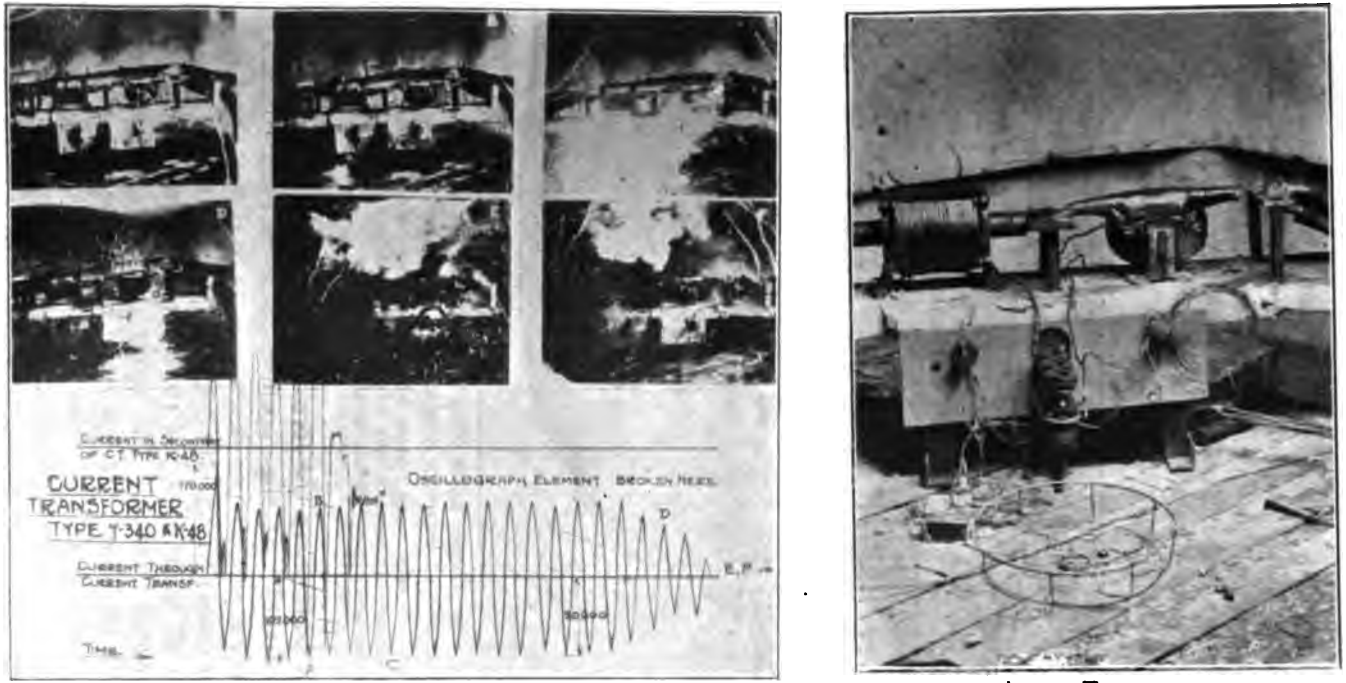
Tested at 130,000 amperes mean effective. Slight chipping of porcelain. No damage to switch. Arcing shown was due to poor contact at terminal.



AFTER TEST

FIG. 18—G. E. CO. CURRENT TRANSFORMER Y-340 AND D-20, SINGLE-TURN.

Tested at 92,000 amperes mean effective. Primary of D-20 blew open after 12¼ cycles. Secondary destroyed. Y-340 not injured. (D-20 is a superseded type).



AFTER TEST

. FIG. 19—G. E. CO. CURRENT TRANSFORMERS. Y-340 AND K-48 SINGLE-TURN.

Tested at 101,000 amperes mean effective. Primary of K-48 opened after 23½ cycles, due to failure at terminal. Y-340 not injured.

tion opposed to the brush pressure, thus tending to open the contact at this point; whereas, if the position of the contact brushes had been reversed, the mechanical force due to this current would have been exerted in the same direction as the brush pressure, thereby tending to improve the contact.

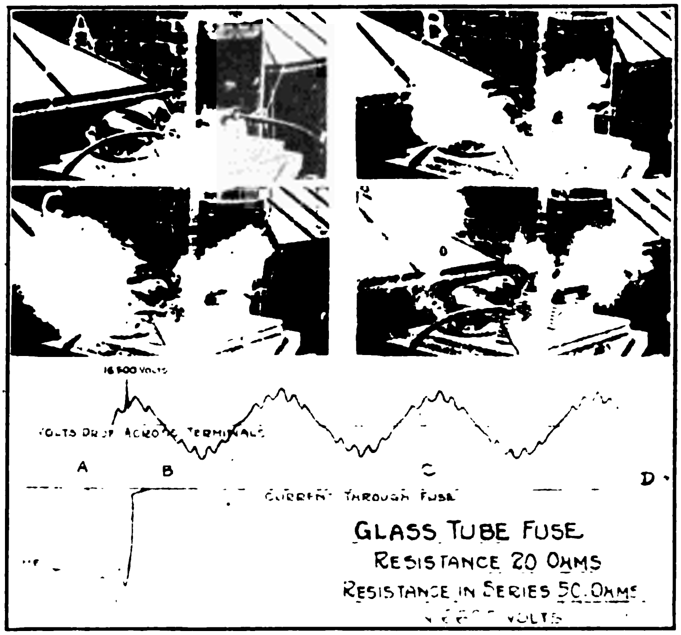


FIG. 20—GLASS TUBE FUSE OF 20 OHMS RESISTANCE WITH 50 ADDITIONAL OHMS IN SERIES.

Tested at 6600 volts. Mean effective 156 *amperes maximum*. Tube was unbroken but asbestos filler was expelled from both ends. Duration of current 0.27 cycle. Circuit opened successfully.

In addition to the force exerted at the contacts, it was found that the repelling force between contact supports was of such magnitude as to distort, and in some cases permanently displace, these parts.

In all these tests, the *circuit breakers were locked in the closed position. The arcing, therefore, was caused by the opening of the main and arcing contacts due to the mechanical force resulting from the high current.* This phenomenon occurs in practise before the operating mechanism has had sufficient time to perform its function in opening under short circuit.

On the basis of the results obtained, the manufacturers have revised the design of their circuit breakers so as to eliminate the trouble due to contact separation and displacements, as shown in Fig. 1 for General Electric Company apparatus, and in Fig. 2 for Westinghouse Company apparatus. Other detail improvements are referred to in the illustrations hereinafter given.

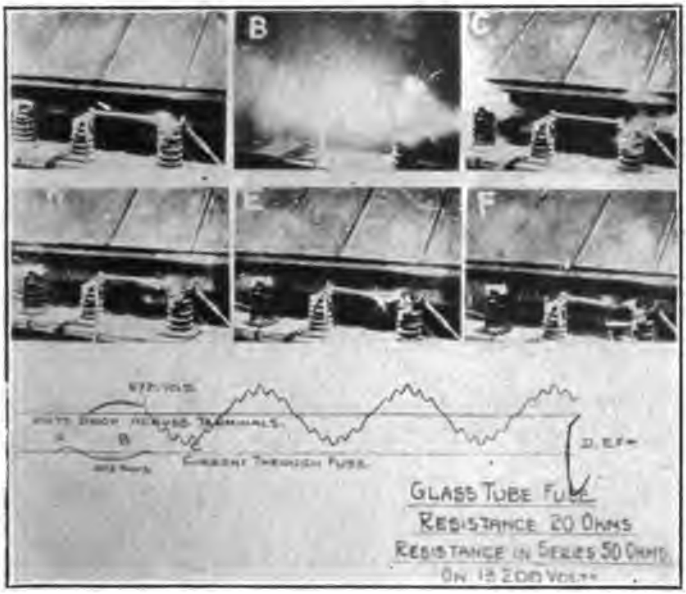


Fig. 21—Glass Tube Fuse of 20 Ohms Resistance With 50 Additional Ohms in Series

Tested at 13,000 volts mean effective, 202 *amperes maximum*. Fuse exploded. Caps remained in clips. Duration of current 0.58 cycle. Fuse opened circuit.

TESTING EQUIPMENT

Current for the tests was supplied by two 10,000-kw. generators in Waterside station, operated in parallel and connected through their reactors to an emergency bus. This bus was connected, through the tie bus reactors, to a second emergency bus to which a 350,000-cir. mil feeder was connected for supplying power for the tests at the West 41st Street substation. (See Fig. 3.)

At the substation, the feeder *H*-2 and the *H*-3 switch of a 3500-kw. synchronous converter were connected in series through their *K* switch and the emergency bus to the high-tension side of a 3850-kv-a., three-phase synchronous converter air-blast transformer. The control circuit of the two *H* switches was connected to operate from the control switch as a four-break unit. The three high-tension transformer windings were connected in multiple as a single-phase transformer. The six low-tension windings were similarly connected, giving 170 to 200 volts at full voltage.

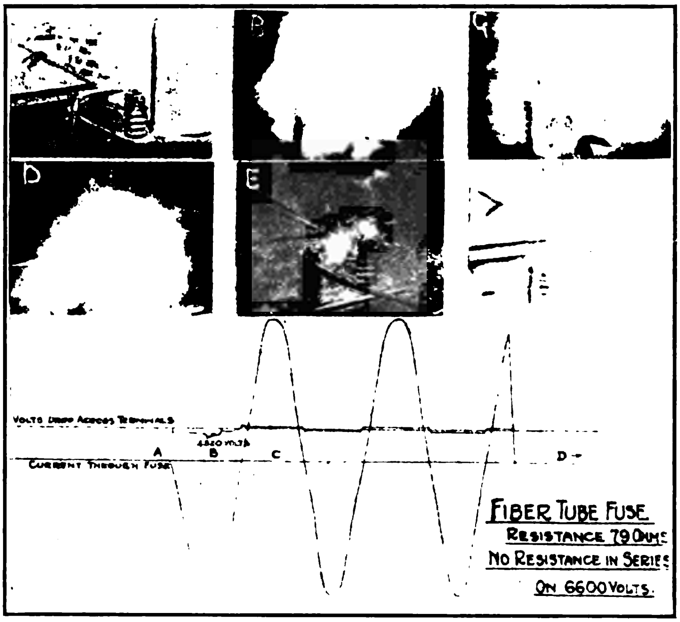


FIG. 22—FIBER TUBE FUSE OF 79 OHMS RESISTANCE WITH NO ADDITIONAL RESISTANCE IN SERIES

Tested at 6600 volts mean effective 1970 *amperes maximum*. Fuse completely blown to pieces. Circuit opened manually. Duration of current 3.1 cycles.

The records of the test were made by oscillograph, and a motion picture camera was driven synchronously from the feeder supplying energy for the tests; also a Lichtenberg high-speed camera was used. In addition, close-up pictures were made of each subject with the ordinary camera after each test.

The oscillograph had three vibrators, one of which was used to measure the secondary current in the type *E*-3 General Electric Company current transformer, 20,000-ampere, 4000 to 1 ratio. The second vibrator was used to measure the voltage drop across the brush contacts. The third vibrator was used to give a 25-cycle timing wave from the Waterside main bus, excepting in tests of circuit breakers having auxiliary arcing tips. On circuit breakers so equipped the third vibrator was connected to give an alternating wave only when the auxiliary contact was lifted 1/32 inch or more. For some of the tests, the third vibrator was connected to measure the current on the primary side of the testing transformer. The oscillograph was calibrated immediately before and after the tests.

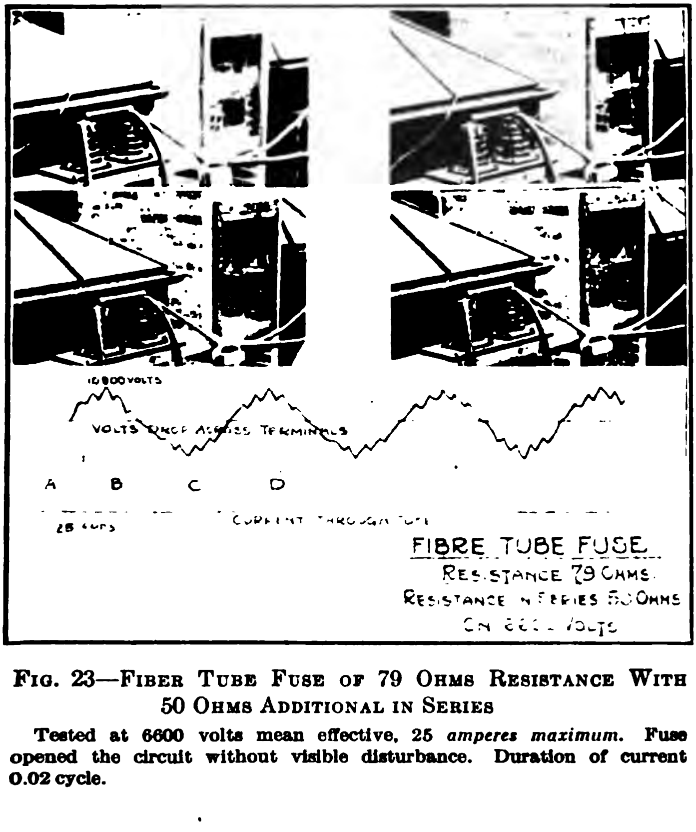


FIG. 23—FIBER TUBE FUSE OF 79 OHMS RESISTANCE WITH 50 OHMS ADDITIONAL IN SERIES

Tested at 6600 volts mean effective, 25 *amperes maximum*. Fuse opened the circuit without visible disturbance. Duration of current 0.02 cycle.

The motion pictures were made by a standard Moye camera, gear-driven, from a ½-h. p. synchronous motor. The calibration was accomplished by photographing an ordinary arc lamp operating on 25 cycles from the same source which drove the motor, and adjusting the shutter so that the full opening occurred at the point of greatest brilliancy in the arc.

The camera was started and brought to synchronous speed before the test current was applied to the subject. The camera operation was continued synchronously until after the test current was interrupted. Two pictures were taken during each cycle, adjacent pictures therefore, showing events at a time interval corresponding to 180 electrical degrees, or one-fiftieth of one second. The camera shutter design was such that the exposure for each picture lasted during about 60 electrical degrees. Figs. 4 and 5 show the apparatus.

The Lichtenberg camera was equipped with a lens board and 24 lenses arranged to give successive exposures. It was set to take its 24 pictures during the first two cycles of the test current. As the tests progressed, however, the time of exposure was increased somewhat to obtain better negatives. Although these pictures were, in general, a success, they are not shown herein, as the motion pictures, being in synchronism with the oscillograph records, more adequately illustrate the results obtained.

RESULTS OF TESTS

From all the records, in Figs. 6 to 16 inclusive, are combined characteristic results of motion pictures and oscillographs for the apparatus tested.

DISCONNECTING SWITCHES

The same mechanical stresses caused by flow of high currents, as reviewed in the paragraph on oil circuit breakers, apply, to a large extent, to the design of disconnecting switches. The ideal installation would be a straight disconnecting switch in series with the main circuit without bends. When, however, bends are necessary, the blade opening should be at right angle to the main lead. In addition, suitable strong locking devices are to be provided. See Fig. 17.

CURRENT TRANSFORMERS

In large systems, only current transformers of the single-turn, primary type are capable of withstanding short circuits as may occur on the system. The other current transformers are too weak, and will be either ruptured mechanically or destroyed thermally. See Figs. 18 and 19.

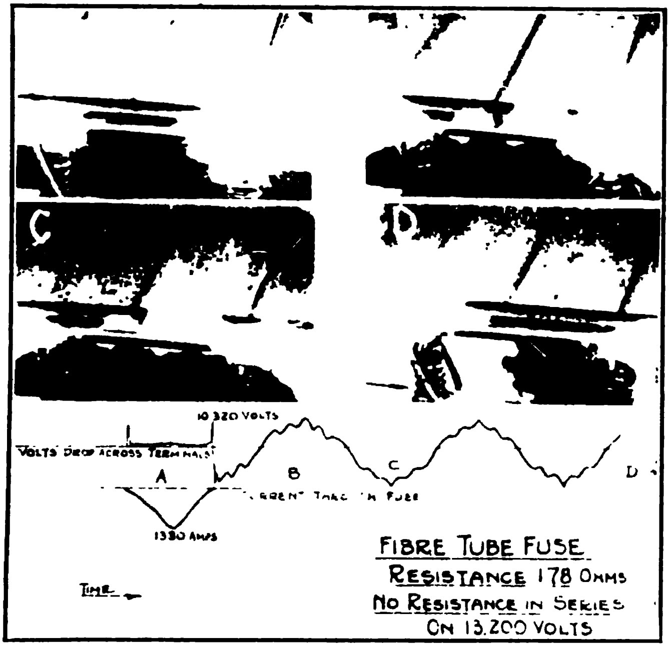


FIG. 24—FIBER TUBE FUSE OF 1.78 OHMS RESISTANCE WITH NO ADDITIONAL RESISTANCE IN SERIES

Tested at 13,000 volts mean effective, 1330 *amperes maximum*. Fuse blew out end of caps but opened the circuit. Duration of current 0.54 cycle.

POTENTIAL TRANSFORMER FUSES

Extensive tests were made with and without resistance in series. The tests have conclusively proved that no type of potential fuse on the market can satisfactorily open the circuit without a resistance in series.

The company first used a resistance wire wound spirally on a rope core and insulated suitably for the voltage on which it was applied.

Recently, the suggestion has been made to use an asbestos card with a resistance wire wound on it in series with the fuse. Where space does not permit the use of the high-resistance lead, this substitute may be of advantage. See Figs. 20 to 24, inclusive.

DISCUSSION ON "PRESENT DAY PRACTISE LIMITATIONS OF OIL CIRCUIT BREAKERS" (WOODROW) AND "HIGH-CURRENT TESTS ON HIGH-TENSION SWITCHGEAR" (TORCHIO), NEW YORK, N. Y., FEBRUARY 16, 1921.

Peter Junkersfeld: At the time oil breakers were first put into service, they were simple and inexpensive affairs as compared with what we have today, it naturally leads one to think whether the art will not have to go to some rather radical improvement, because of the expense of present oil circuit breakers. The many things that go with them are increasing in greater proportion than the expense of any other part of the electrical system.

In connection with the matter of potential transformer fuses, I noted most if not all of them were tested in the horizontal position. Many of the potential fuses operate in either position, but there are some designed to operate only in a vertical position. I do not know whether any of these were tested or not. Dr. E. J. Berg and I witnessed tests on liquid fuses operated in a vertical position a number of years ago that gave remarkable results. The fuses in that case were connected to a 2000-kw. motor generator and that in turn to a 12,000-kw. turbine, operated independently. I do not remember the values, but the fuses opened the circuit very satisfactorily on short circuit when they operated in the position for which they were designed.

E. P. Peck: The suggestion in Mr. Woodrow's paper that oil switches have ratings in addition to those ordinarily given, based on operating the switch one time, two times, three times, four times, and five times, is a very excellent one. It is not possible to lay out all transmission and distribution systems in such a manner that each customer will have duplicate service, and a good many districts must necessarily be fed from one transmission line. When there is trouble on the system which causes a circuit breaker to open, good operating practise requires that the circuit breaker be closed in a very short time. The rule in several companies is that the oil circuit breaker be closed three times as rapidly as possible after an interruption, before the line is left out of service. The reason for this is that a large number of interruptions are caused by temporary disturbances on the line, such as an insulator flash-over, a short from a tree limb which may burn off, or an accidental short caused by a workman. In most of these cases the line is ready for service as soon as the arc is interrupted, and the operating company is not justified in leaving the line out of service until they know that it is not capable of carrying the voltage.

There are a number of troubles, however, which have to be repaired before service can be restored. The operating company's rule then forces the oil circuit breaker to stand three operations on a short circuit, and these operations are often made in a period of a few seconds only.

Under the present oil switch ratings, the operating engineers have difficulty in selecting switches which may safely be closed three times on a short circuit, and it is very desirable that ratings be given which will enable the operating engineer to select a switch for the service which he knows it will be required to stand.

In connection with Mr. Torchio's paper, I would like to ask if the series resistances used with the fuses burn open when the fuses blow. I would like to ask also if the carbon tetrachloride fuses were tested, and if so, how they performed.

N. J. Conrad (read by N. L. Pollard): In the last paragraph of Mr. Torchio's paper he states that extensive tests were made on potential transformer fuses with and without resistance in series, and that these tests have conclusively proved that no type of potential fuse on the market can satisfactorily open the circuit without a resistance in series.

Mr. Torchio in his paper, does not state the conditions under which the potential transformer fuses were tested. He doesn't say what the capacity and rated voltage of the generator was; what the kv-a. capacity and reactance of the step-down or step-up transformer was; neither does he give any particulars regarding other circuit conditions. He infers in his paper that the types of fuses which he refers to would be satisfactory if used with a series resistance, and it would be reasonable to suppose that the resistance he recommends would be 50 ohms, which is the amount of the series resistance given in the reproduction of the oscillograms and photographs.

The paper contains data on five different fuse tests. In three of these tests a series resistance of 50 ohms was used. Of the three fuses tested with series resistance, one exploded and two apparently operated successfully. If this is an indication of the percentage of failures, it certainly does not speak well of the effectiveness of the series resistance with the ordinary glass tube fuse. A series resistance properly designed so that it does not become a dangerous element in itself, will undoubtedly improve the operation of potential transformer fuses under short-circuit conditions, but it also certainly is desirable if a series resistance is used that an efficient and effective fuse be used to interrupt the current.

In 1910 very extensive tests were made by the Commonwealth Edison Company, of Chicago, on all types of fuses then on the market and also on a liquid fuse at that time newly developed. These tests were very complete and were made under known conditions, and reliable photographic and oscillographic records were obtained. These tests showed that the ordinary glass tube, fibre tube and expulsion type fuses could not handle successfully the short-circuit current of a 500-kw., 9000-volt, 25-cycle, high-reactance, slow-speed generator. The liquid fuse, on the other hand, in these tests handled without any difficulty and without any series resistance the short-circuit current of a 2000-kw., 25-cycle, 9000-volt generator, and also the short-circuit current of a 12,000-volt, 1500-kv-a., 60-cycle transformer, of about 6 per cent reactance. The short-circuit currents successfully interrupted in these tests, as shown by the oscillograms, were as high as 1250 amperes. These tests were witnessed by some of the most prominent engineers in the country, among them Peter Junkersfeld and Dr. E. J. Berg.

Some time later, short-circuit tests were made on the same type of fuses at the Keokuk plant of the Mississippi Power Company. These tests were made on a 66,000-volt fuse connected between one phase and the neutral point of the 110,000-volt busses, or, in other words, with 63,500 volts across the fuse. Ordinarily, of course, two of these fuses would have been in series on 66,000 volts. These tests were made with first one, then two, and finally with three 9000-kw. generating units in parallel. The fuses operated successfully under these conditions and opened the circuit within one-half cycle.

Other severe and extensive tests have been made by large operating companies, but they will not be referred to further here.

From the above it will be evident that the rupturing capacity of the liquid fuses is very high compared with ordinary types of fuses. There are however, other requirements besides rupturing capacity which are extremely important in connection with successful potential transformer fuse service. The ordinary fuses, when they do blow, melt at some point along their length and then keep arcing for some time until the break is sufficiently long to interrupt the flow of current. Under these conditions any fault which may occur very probably will develop to actual dead short-circuit condition before the circuit is interrupted. In many cases this arcing in the fuse lasts so long that the entire fuse tube is burned up or broken up before the fault becomes a short circuit, and this arcing may in turn result in the establishing of an arc to ground or to adjacent conductors.

The liquid fuse with its combination spring and liquid break introduces a definite gap the instant the current reaches a value sufficient to melt the fuse wire. It, therefore, acts positively no matter how small or how large the fault current. On account of this feature it will interrupt the current flow before the fault in the transformer develops into a complete short circuit. This feature, combined with the high rupturing capacity of the fuse, makes it entirely reliable for potential transformer service with or without series resistance. Naturally, a reliable series resistance used with the liquid fuse will result in improved operation of the fuse, but unless the resistance is very carefully designed and constructed it might be a hazard rather than an improvement when used with the ordinary types of fuses.

Many thousand liquid fuses have been in service on potential transformers for the past 10 years. There have been many cases that we know of where potential transformers have broken down and the liquid fuses functioned safely and properly in all of these cases. We know of no case where a liquid potential transformer fuse failed in regular service.

In view of this very extensive experience and the very complete tests made more than 10 years ago, I feel that the statement made in Mr. Torchio's paper is by no means warranted, especially in view of the fact that the data submitted in the paper on potential transformer fuse tests are very vague and incomplete.

E. E. F. Creighton: From my own viewpoint, it is perfectly evident that new circuit breakers will have to be designed to open successfully, not only once or twice, but a dozen times in succession, as rapidly as the mechanism can put them into operation. Just when this period will arrive is hard to predict. It is an extremely difficult problem. The factors which limit the disruptive capacity of oil circuit breakers have not yet been fully determined. There is a possibility that the answer will, in fact, be an entirely different type of circuit breaker.

H. E. Trent: I wish to discuss the high-tension fuse. Some time ago I developed and had tested a fuse of rather novel design and based on different principles to other types of fuses.

Fig. 1 shows the fuse renewal element for 65 amperes at 2400 volts. It consists of (A) a uniform cross section wire of aluminum, size 14 B. & S. gage. (B) are cement blocks which are electrically insulating, heat conducting, arc resisting, and capable of absorbing and cushioning the explosive action of the fuse. (C) is an asbestos tube, reinforced by a thin fibre tube. (D) are the brass terminals. These fusible elements were then inserted in a fibre tube container with robust metal ends, the whole being substantially air-tight.

The conditions imposed in the construction of these fuses were (a) to reduce the amount of fusible material to a minimum. (b) to articulate the fuse in proportion to the voltage of the circuit. (c) to restrict the quantity of air in the immediate vicinity of the fuse element. (d) to prevent the expansion of the gases by rendering the fuse container substantially airtight. (e) to absorb the products of combustion in the infusible parts of the fuse element. (f) to distribute the internal stresses over the length of the container. (g) to cushion the force of the explosion.

FIG. 1

The initial action of this fuse depends upon the principle, that an insulated conductor will carry considerably more current for a total temperature rise than an uninsulated conductor. Therefore fusion takes place first at the uncovered portion of the fuse wire, and as there are several arcs in series and because of the small quantity of air in the vicinity of the fusible portion and restricted space, the arc does not persist. It has been found with comparatively low-powered short circuits that the only metal vaporized is the exposed intermediate portion between the cement blocks, but with an extreme overload the entire fuse wire may be melted and driven or absorbed into the cement block as is shown in Fig. 2 which shows a cross section of one of the cement blocks after the fuse was blown under heavy short-circuit conditions.

Temperature tests made on these fuses showed that they were within the Underwriters' limits for enclosed fuses, which indicates the ability of the cement blocks to dispose of the heat rapidly by convection and radiation.

The short-circuit test consisted of connecting each fuse across the 2400-volt side of a 200-kw. transformer and limiting reactances. No resistance was used in series with the fuses. The fuses opened the circuit easily with very little noise and an absence of outward distress. The oscillograph of Fig. 3, gives the values of current and voltage and it should be noted that the voltage graph of lower amplitude represents the sustained short-circuit voltage.

Fig. 2

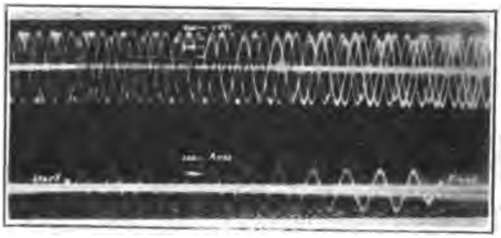


Fig. 3

Fig. 4 shows the cement blocks after the test reassembled for photographic purposes.

While it is recognized that the voltage is considerably lower than those employed in Mr. Torchio's tests, it is expected that this new fuse, when designed for higher voltages will meet the need suggested by Mr. Torchio.

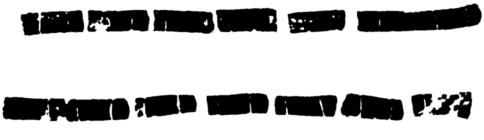


Fig. 4

William A. Moore: There is a paragraph in Mr. Woodrow's paper under the heading "Rated Momentary Current-Carrying Capacity", which reads as follows: "Trouble has been experienced by some of the larger operating companies through the failure of oil circuit breakers to carry heavy short-circuit currents for the period of time required to open the circuit and in some cases of the inability of the current-carrying parts to withstand the strain produced by the electromagnetic forces. We are very fortunate in having the accompanying paper by Mr. Torchio which outlines the results of a very extensive series of tests along these lines, showing very conclusively certain weaknesses in oil circuit breakers from this standpoint. The principal weaknesses brought out in these tests have now been corrected."

After reading that statement and seeing the pictures tonight I have the feeling that many oil circuit breaker failures (that is where the breaker was not in a condition to be closed after interrupting the circuit) were accelerated by the arcing due to electromagnetic forces which tended to open the circuit breaker contacts in question before the relays had functioned to trip the breaker. The oil circuit breaker might have interrupted the circuit satisfactorily as the relay was set to operate in one or two seconds but for the fact that the damage was started in the first tremendous peak of current and the oil circuit breaker was therefore not permitted to get underway properly to interrupt the circuit.

Mr. Woodrow goes on to say in the second paragraph under the same heading "It is recommended that all oil circuit breakers be given a short-circuit rating for a period of say, both one and five seconds." Would it not be advisable to include a short-circuit current rating not related to time but only to the maximum current which an oil circuit breaker could carry without the resulting electromagnetic forces causing failure due to distortion or arcing at the contacts.

L. B. Chubbuck (by letter): Referring to the paragraph towards the end of your paper suggesting a "single shot" basis of rating for oil circuit breakers, we feel that this would mean additional complication in a rating that is already too involved for the ordinary circuit breaker purchaser. Some years ago we started to rate the breaking capacity of oil breakers simply by the station generator capacity, this was then qualified in turn by service voltage, decrement curve, etc., etc. We feel that different ratings for single shot, two shot, etc., is unnecessary complication, and that oil circuit breakers sold on the usual "two shot" basis with a fair operating factor of safety, should be sufficient."

Philip Torchio: May I say a word on Mr. Woodrow's paper? I think the industry is to be congratulated upon the effective work that this Committee is doing. The plan they have outlined to improve the rating and understanding of circuit breakers is going to be of great value. There is, however, a tendency on the part of many users to use the cheapest, I mean the smallest circuit breakers they can buy. Now, in growing systems with an increasing number of interconnections, circuit breakers that may be entirely suitable for the service today or the next two or three years may be entirely inadequate four or five years from now.

I would strongly advocate that users, in making their layout for new installations and new additions should take a look to the future, and put in, not the circuit breaker that they think will do the work for this year or next year, but one that has breaking capacity consistent with the future developments of which there is a reasonable prospect of growth.

H. R. Woodrow: I am sorry that more discussion has not been given tonight, particularly from the operating people, as this paper was primarily intended to start us all thinking as to the basis of oil circuit breaker ratings, so a definite rating can be established and the manufacturers will know the operating requirements, and be able to make their guarantees accordingly.

In regard to the suggested tests of short duration, it was intended that the one-second rating would cover the maximum stress conditions. It is essential that the assymetrical peak condition be considered for stresses, and that point should be carefully weighed in the determination of this rating.

Referring to Mr. Torchio's paper, I would like to see emphasized, the fact that the resistance in series with the fuse may be confused with the resistance of the fuse. You will note from the test oscillograph records that a 79-ohm fuse did not limit the current in proportion to 79-ohms and there was practically a dead short-circuit across the fuse after the fuse blew, whereas the insertion of the series resistance with the fuse reduced the interrupting load on the fuse, to a relatively low value.

Philip Torchio: Mr. Haar has asked for an explanation of Figure 2-D. The ends of the contact brush, separated in Y shape and carrying current in the same direction, are attracted toward each other and against the stationary contact thereby increasing the contact pressure, and therefore the efficiency of the joint.

Selby Haar: Is that the main contact or auxiliary?

Philip Torchio: The main contact; not the arcing contact or auxiliary.

Selby Haar: It looks to me as if it is a laminated brush.

Philip Torchio: That is right. All these pictures show laminated brushes.

Selby Haar: There are laminated brushes of this type?

Philip Torchio: Yes. Col. Junkersfeld asked if some of the fuses were tested vertically. In the motion picture, some of the fuses shown in the compartments were mounted vertically.

E. S. Peck has asked two questions; one is if the resistance would not introduce a hazard. Mr. Woodrow has already given the answer. In the paper, I have only abstracted a few of the tests shown in the motion pictures; this, perhaps, led my friend Conrad to say that the statements in the paper were very vague. As a matter of fact, the motion pictures show that the tests were really extensive and covered more than the few illustrations given in the paper.

Now, the resistance limits the current to a very small amount. You will see from the illustrations, that in one case the current was 202 amperes; and in another case, 25 amperes; and in another case, 156 amperes. Without the resistance in series, the currents were 1970 and 1330, an entirely different order of values. The smaller currents can be very conveniently handled by a properly designed resistance. The resistance we use, as I stated, was made by winding around a jute core a resistance wire, and then insulating it so that it could be installed in the compartment as a cable. Where there is no space available for the installation of a long cable, probably it may be advantageous to use a card resistance, but it must be properly designed and proper care taken to enable it to handle the current that it may have to sustain.

As to the question of Mr. Peck about the carbon-tetrachloride fuses, I will answer it, in answering Mr. Conrad's contribution.

In partially answering Mr. Conrad's contribution at this time, I want to state that we did not test the Conrad fuse. As a matter of fact, I have personally a high opinion of that fuse, but while it is called a fuse, I never considered it in that light because it has the characteristic of a circuit breaker, combined with the fuse. Therefore, I regret sincerely that, under the pressure that the Chairman put upon me to write this paper in a few days, I made the generic statement that no potential fuses on the market can satisfactorily open the circuit, because I did not intend to include the Conrad fuse.

However, I am very glad to be in full agreement with the conclusions as Mr. Conrad has stated, that resistance properly designed is an improvement; and that is all I wanted to convey. It was very far from my thought to condemn any fuse of any make; my intention was to indicate that the resistance in series, properly designed, is an improvement and I think it should be used.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 17, 1921.

THE MAXIMUM SAFE OPERATING TEMPERATURE OF LOW-VOLTAGE PAPER-INSULATED CABLES

BY W. A. DEL MAR

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ABSTRACT OF PAPER

The Standards of the Institute state that for low-voltage cables the maximum safe operating temperature is 85 deg. cent. Experiments show that continuous operation of 100 deg. cent. for less than a month, seriously impairs the mechanical condition of impregnated paper. A standard of permissible mechanical condition should, therefore, be established, if such high temperatures are to be allowed. Operation at higher temperatures than allowed by the present Standards is, however, in the nature of a gamble and it is questionable whether the Standards should take cognizance of it.

STATEMENT OF THE PROBLEM

NOTHING would seem more simple than to determine the maximum safe operating temperature of an insulating material such as impregnated paper; but the problem is really very complicated as several preliminary problems of an important character must be settled before the main problem can be adequately attacked. These preliminary problems are as follows:

1. What is the criterion of quality of paper insulation by which we may say whether it is satisfactory for service?

2. What is the effect of the continued application of various degrees of heat, expressed in terms of the criterion selected?

3. Will intermittent heat have the same effect as continuous heat provided the aggregate time of exposure and the temperature are the same in both cases?

4. If the above questions should be satisfactorily answered, what form of rule should be adopted so as to make the best economic use of the information thus obtained?

5. If a rational rule for the maximum permissible temperature of paper insulation should be developed, how can the hottest-spot temperature of a cable in a duct be measured in order to ensure that the cable is working within the rule?

These questions cannot all be answered at the present time, and the object of this group of papers is to gather together such data as are available in order that the Standards Committee of the Institute may be able to revise its present rule for the temperature limits of paper insulation in the light of the best information which the members of the Institute can furnish.

CRITERION OF QUALITY

In the case of low-voltage cables, which are the only ones under present consideration, the criterion of quality by which we may judge whether the cable is usable, should be the mechanical strength, because it is that quality which determines whether the cable can withstand handling, expansion and contraction, and possible reinstallation. New cables of the best quality have but little margin of strength to take care of the stresses imposed on the insulation during installation. Large cables are often installed in splicing chambers originally designed for small cables, and are consequently bent on curves of dangerously small radius, and are subjected to very rough handling. Even where splicing chambers are adequately designed, the cables are often handled with entire disregard of their mechanical limitations. However, once the cables are installed, they are free from mechanical stresses except such as may result from expansion and contraction due to variations of temperature. A different criterion of quality may therefore conceivably be adopted for cables after they are installed from that for new cables, but the use of such a standard would preclude the possibility of reinstalling cables which have deteriorated to that standard.

Some cable specifications contain clauses requiring the paper to have a certain minimum tensile strength, but tensile strength tests are unsatisfactory because the paper may become brittle, and may tear easily, while the tensile strength remains quite high.

Bursting strength tests, as made on a Mullen tester, are unsatisfactory for the same reason. A test, which proved to be really satisfactory, is the tearing test. A piece of paper about three centimeters wide is carefully cut with a razor along its center line from one end to about its center, and a pencil mark made one centimeter beyond, as shown in Fig. 1. It is then suspended from one of the small ends as shown in Fig. 2, and a balance pan attached to the small free end, the large end being allowed to swing free. Sand is then poured continuously into the pan until the paper begins to tear. The stream of sand is then continued slowly, stopping if the paper continues to tear, but proceeding if the tearing stops. It is continued until the tear reaches the centimeter mark. The total weight of pan and sand expressed in grams is taken as the tearing strength of the paper. The reason for letting the paper tear a definite amount, rather than to observe the

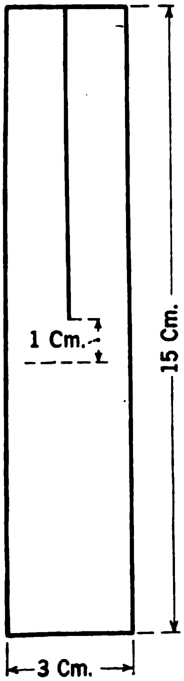

Fig. 1—Sample for Tearing Test

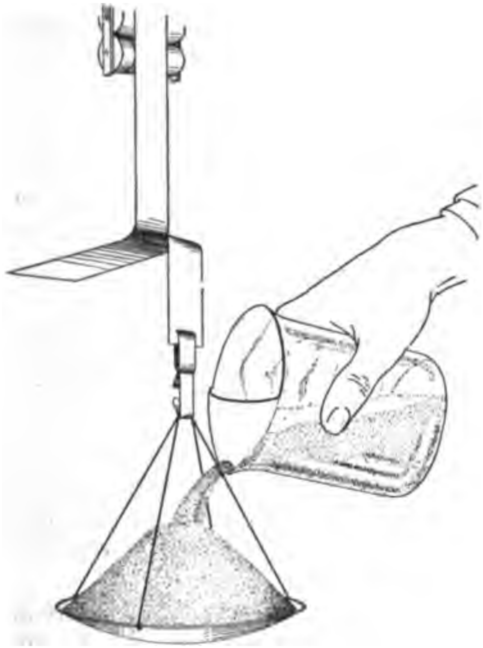

Fig. 2—Tearing Test

weight at which the paper begins to tear, is that paper varies in thickness and condition from place to place, and the initial tear would only represent the strength at a spot and would not be a measure of the average quality. The tearing strength of unimpregnated Manila rope paper 0.02 mm. (8 mils) thick, under ordinary conditions is from 170 to 285 grams (6 to 10 oz.) When impregnated, the tearing strength is usually less than this, depending upon the nature of the impregnating compound, the temperature and duration of the process of impregnation and the amount of the compound retained upon cooling. Manila rope paper usually contains from 5 to 10 per cent of moisture. Tests were made to ascertain whether the percentage of moisture had any effect upon the tearing strength. The results are shown in Fig. 3, which shows that an increase of moisture increases the tearing strength up to a certain point and decreases it above that point. Statements of tearing strength are, therefore, not complete unless the moisture content is specified.

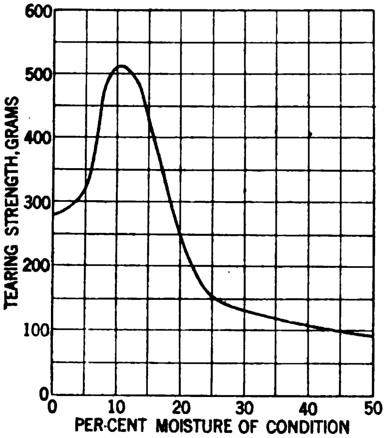

Fig. 3—Effect of Moisture on Tearing Strength of Unimpregnated Paper

Effect of Continuous Heating

Tests, to ascertain the effect of the continued application of various degrees of heat, were made upon rolls of paper immersed in open beakers of petrolatum-resin compound maintained between 85 and 90 deg. cent. for a year. These tests were made before the development of the tearing test and the results are therefore expressed in terms of tensile strength. The gradual loss of strength is shown in Fig. 4, which shows that at the end of a year, the paper had lost about half the tensile strength it possessed just after impregnation. It is probable, that the tearing strength would have been even more reduced. The paper, however, was in quite good enough condition at the end of a year for new low-voltage cables.

Tests were made upon unimpregnated paper with the object of determining the behavior of Manila rope paper exposed to high temperatures. Samples of paper were heated in vacuo successively at 70 deg., 80 deg., 90 deg., 100 deg., 110 deg., 120 deg., 130 deg., 140 deg., 150 deg., and 160 deg. cent., the temperature of all samples being maintained at each of these points for as many periods of one hour as were required to ensure that constant weight was obtained. The average results are shown in Fig. 5 which indicates that the loss in weight increases slowly up to about 120 deg. cent., but then rises rapidly. At 130 deg. cent. oily globules distil off; at 140 deg. cent. the paper darkens, indicating charring. The loss of weight which occurs above 120 deg. cent. is not necessarily due to loss of moisture. However, some of the material which distills off is undoubtedly moisture, but this may be due to the decomposition of the cellulose, which is a carbohydrate having a composition of $(C_6H_{10}O_5)_x$, which may, therefore, be reasonably expected to yield water among its products of decomposition.

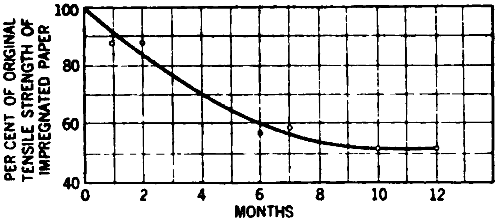

FIG. 4—LOSS OF TENSILE STRENGTH OF IMPREGNATED PAPER IN PETROLATUM-RESIN COMPOUND AT 85-90 DEG. CENT.

Another series of tests was made by putting a roll of dried paper in a beaker of petrolatum-resin compound for three hours and noting the loss in tearing strength. This test was made on a separate roll for each of six temperatures from 70 to 140 deg. cent. The results are shown in Fig. 6 and indicate the degree that impregnated paper may be injured by three hours exposure to the temperatures covered by these tests. As in the year test at 85-90 deg. cent. the paper in any of these rolls was in good enough condition for new low-voltage cables.

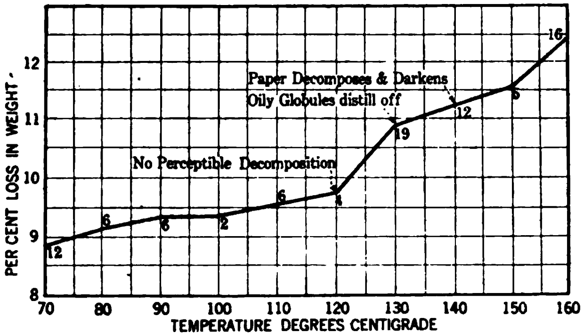

FIG. 5—UNIMPREGNATED PAPER

The figures at each point of the curve represent the number of hours of heating at each temperature before proceeding to the next. A steady weight was reached in about one hour less than these periods.

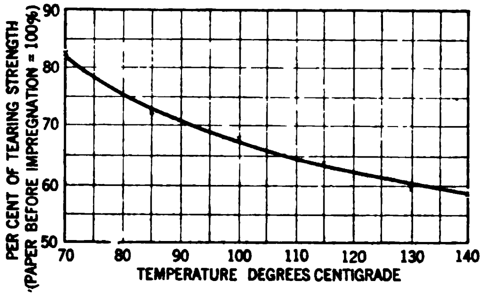

FIG. 6—EFFECT OF HEATING PAPER IN A BEAKER OF PETROLATUM-RESIN COMPOUND FOR THREE HOURS

A special sample was used for each point.

The most decisive series of tests was made on sealed lead-sheathed cables placed in an electric oven maintained carefully at a temperature of 100 deg. cent. The temperature was measured by three thermometers, one above, one below the samples, and one fastened to a cable sheath under a felt pad. The reading of the upper thermometer was about 99 deg. cent. and the under thermometer about 101 deg. cent. The thermometer on the cable sheath read a fraction of a degree below the mean air temperature in the oven. The mean temperature was kept constant by a calibrated thermostat, the maximum variation being 1½ degrees above or below the mean. At the end of a week, one sample of cable was removed and its paper tested for tearing strength and tensile strength. About 6 pieces of paper were taken for each test, and the results being substantially uniform, mean values were taken for the tearing strength and the tensile strength. This test was repeated at the end of 2, 3 and 4 weeks. After the fourth week, the paper had become so brittle that it cracked apart when folded. The results of the test are shown in Fig. 7, and they indicate that the mechanical strength of paper insulated cables is seriously impaired by *continuous* exposure to a temperature of 100 deg. cent. for three or four weeks.

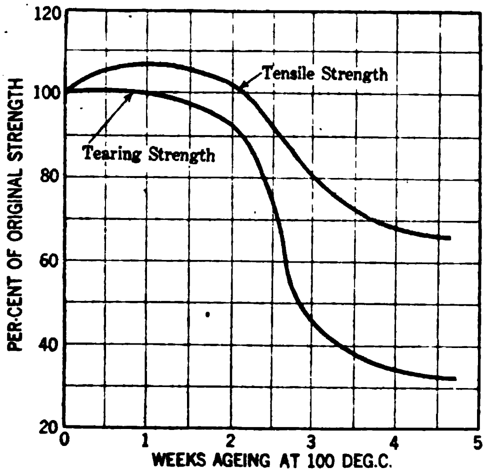

FIG. 7

As the insulation was intact before the samples were opened at the end of a month, and as they were thoroughly dry, the electrical properties of the cable were undoubtedly quite good enough for low-voltage operation, provided it was not disturbed.

Distribution systems may therefore be in satisfactory operation with cables in the condition of these samples, but the risk of operating them in this condition is obviously greater than with the insulation in good mechanical condition.

INTERMITTENT OPERATION

A test to give the same aggregate exposure to heat as in the test described above would last 8 months if the cable were heated for 3 hours every day. Possibly intermittent heat has less effect than continuous heat of the same aggregate duration, but experimental data to settle this point are lacking.

FORM OF RULE FOR MAXIMUM TEMPERATURE

The present Standards of the American Institute of Electrical Engineers give 85 deg. cent. as the maximum permissible temperature of impregnated paper insulation for low-voltage cables. The following table shows the increase in carrying capacity that would result from operation at higher temperatures, assuming 40 deg. cent. duct temperature.

Ultimate temperature deg. cent.	Increase of carrying capacity over that for 85 deg. cent. ultimate temperature, per cent.
85	0
90	5
95	9
100	13
105	17

This increase of carrying capacity may sometimes warrant the use of cables at destructive temperatures, and the operating engineers may rightly consider such a procedure to be entirely justified. It is questionable, however, whether the Institute should make a rule to cover such cases, as an Institute rule necessarily represents an agreement between manufacturer and user and it is unreasonable to expect the manufacturer to share the risks resulting from operation at or beyond the limit of endurance of his product.

USE OF A RULE FOR MAXIMUM TEMPERATURE

Assuming all of the above problems to be satisfactorily answered, we would still be confronted by the difficulty of applying our knowledge to practical operating conditions, because it is almost impossible to ascertain accurately the hottest-spot temperature of a cable in a duct. This problem is complicated by the presence of other cables in neighboring ducts and by the variable thermal resistivity of the soil. The Cable Research Committee of the National Electric Light Association is giving serious attention to this problem.

The present interest in this subject arises from the increased loads which war conditions suddenly imposed on the central stations and the consequent enforced operation of cables at higher temperatures than were previously thought safe. The experience of the central station men indicates that low-voltage cables may be operated at higher temperatures than were considered safe a few years ago. Whether this experience should be the basis of a modification of the existing rule, is a matter for debate.

It is to be hoped that the operating experience of the central station men will be satisfactorily correlated with the laboratory work of the manufacturers before a new standard is established.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 17, 1921.

PERMISSIBLE OPERATING TEMPERATURES OF IMPREGNATED PAPER INSULATION IN WHICH DIELECTRIC STRESS IS LOW

BY PHILIP TORCHIO

Chief Electrical Engineer, New York Edison Co.

Abstract of Paper

The writer reviews the effect of temperature on insulating materials, abstracting from the 1913 Steinmetz and Lamme report, and the 1905 British Engineering Standards Committee tests. Then he gives surveys of low-tension cables in large distributing systems, and special tests on cables including sheath cracking, high temperature tests, effect of bending on cables heated at high temperatures, distillation of cable compounds, ambient temperatures in subway ducts as affected by thermal conductivity of concrete, amount of moisture in soil, different arrangements of ducts and load factors at which the cables are operated.

From this review, conclusions are derived that the permissible operating temperatures are to be a function of the load factors at which the cables operate. The writer recommends 105 deg. cent., 95 deg. cent. and 90 deg. cent. for load factors of 33 per cent, 50 per cent, and over 66 per cent, respectively.

A LARGE amount of study has been given in the last seven years to the limiting temperatures of high-tension cables and the attendant dielectric losses. (For details, refer to A. I. E. E. Trans., Vol. XXXVI—1917, p. 417-527). As these losses begin to increase sharply for voltages higher than 5000 volts around 70 deg. cent., for paper impregnated with vegetable compounds, and 80 deg. cent. for paper impregnated with mineral compounds, an arbitrary limit of "85 deg. cent. minus E in thousand volts" was adopted in the Standardization Rules. With the preponderant feature of dielectric losses in mind, very little consideration was given to low-tension cables per se, so that the arbitrary constant in "85 deg. cent. minus E" became 85 deg. cent. for low-tension cables. It is the object of this paper to deal more intimately with low-tension cables and to present results of extensive investigations and special tests, together with a review of the results of long years of practise.

1. EFFECT OF TEMPERATURE ON INSULATING MATERIALS

In approaching the subject, it may be opportune to quote from the paper of Steinmetz and Lamme of 1913:

> Paper insulation will have a comparatively long life even at ultimate temperatures as high as 100 deg. cent. * * *. At materially higher temperatures than 100 deg. cent. the life is greatly shortened, and temperatures of 125 deg. cent. will apparently ruin the insulation, from the mechanical standpoint, in possibly a few weeks, *if such temperature is maintained steadily.* However, for low voltages, insulating qualities may still be very satisfactory even at this temperature (125 deg. cent.) * * *.

The 1913 paper of Steinmetz and Lamme had been written to present general information on behavior of different insulating materials used in construction of electrical apparatus and to furnish a basis for work of the A. I. E. E. Standards Committee, which culminated in the promulgation of the Standardization Rules in 1916. It is of assistance to us in discussing the problem to refer to these rules for the class of materials under which impregnated paper is classed, *i. e.,* Class A insulation. The limiting temperature allowed by the Rules for Class A insulation is 105 deg. cent. *continuous.*

2. BRITISH STANDARDS ENGINEERING COMMITTEE

It may be of interest here to reproduce results of careful tests made in 1905 by the Engineering Standards Committee of Great Britain. These tests, at the time the A. I. E. E. Rules were worked out, were probably the most comprehensive study then published. I am selecting from numerous tests on a great number of materials some that more closely approximate the condition of impregnated paper.

The tests were made by subjecting the samples either to continuous temperatures or temperature over periods of twelve hours daily for several months up to nine months or one year. The samples were tested for dielectric strength, shearing and bending. The shearing test was determined by the use of a punch of one-half inch in circumference, and determining the pounds pressure at which the samples broke. The bending tests consisted in taking a strip of the insulation sample and bending it over a series of cylinders of gradually decreasing diameters, note being taken of the cylinder diameter over which the fracture would first occur.

A number of curves showing the results of the shearing and bending tests of various samples of insulation are presented. In either case, the *total number of hours, with the heat on,* was computed, omitting the hours when the heat was off, so that the abscissas represent the *equivalent weeks of continuous heating.*

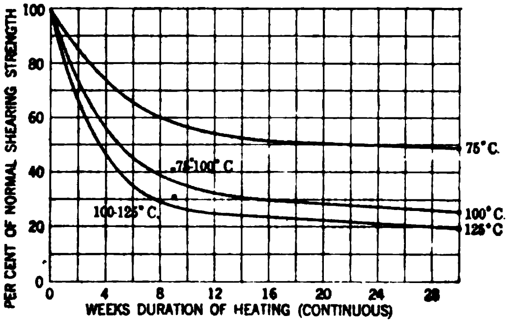

FIG. 1—MANILA PAPER—0.012 IN. (0.3 MM.)

For the object of comparison, instead of giving the pounds test pressures for each sample, the shearing tests are plotted in per cent of the shearing strength of the unheated sample, taken as 100 per cent. The shearing curves in Figs. 1 and 2 have been interpolated from results of two separate investigations on similar samples of Manila paper, extending approximately 9 and 30 weeks, while the shearing curves in Figs. 3 to 6 were obtained from tests taken at 12 periods throughout an interval equivalent to 26 weeks' continuous heating.

The bending curves in Figs. 7 to 14 are interpolated from the results of three separate investigations on similar samples extending 4, 9, and 30 weeks, respectively. The ordinates of these curves represent the minimum diameter of cylinders over which the samples can be bent without fracture, and they are interpolated for 75, 100, and 125 degrees heating.

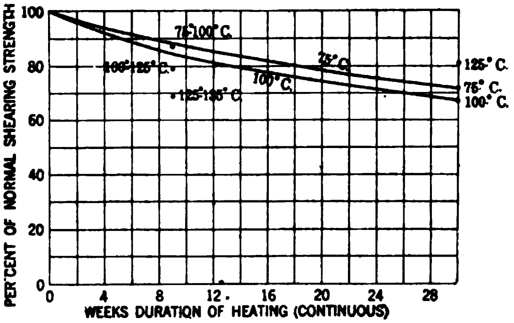

Fig. 2—Manila Paper Varnished—0.014 in. (0.355 mm.)

The *bending curves* for various materials *cannot be compared directly* as the bending test is a function of the insulation thickness which varies in each case. However, they are of interest to show the bending qualities of each sample as compared to its original unheated condition. In many cases, a $\frac{1}{16}$-inch cylinder is shown as a minimum and most samples could be bent in the unheated state ten or more times over this cylinder without injury. For the large diameters, however, the curves represent a single bending.

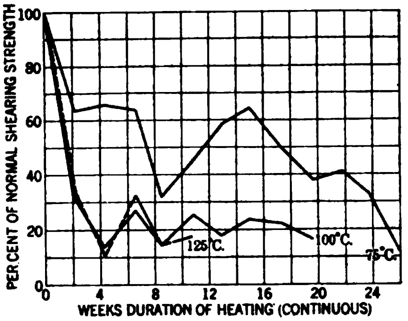

Fig. 3—Empire Cloth—0.040 in. (1.016 mm.)

Fig. 1 gives the shearing tests on a sample of untreated Manila paper of 12-mil thickness. The shearing strength of the heated samples has been greatly reduced at the end of the 30th week over the unheated sample; the percentages being 49, 25, and 19 for the

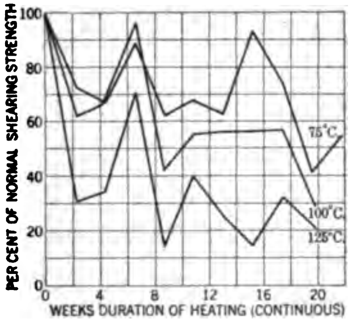

Fig. 4—Calico Impregnated with Elastic Insulating Varnish—0.016 in. (0.406 mm.)

75, 100, and 125-deg. cent. heating, respectively. Corresponding to the shearing curves in Fig. 1 are shown the bending curves of Manila paper in Fig. 7. The unheated sample could be bent over a $\frac{1}{16}$-inch cylinder ten or more times without injury. After being heated for 30 weeks, the sample could only be bent around

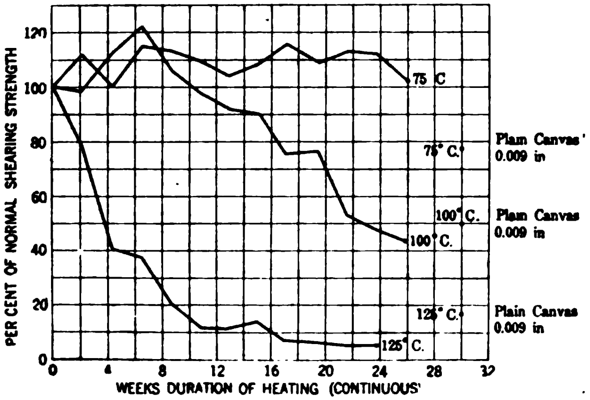

Fig. 5—I. R. Prepared Duck—0.027 in. (0.686 mm.)

cylinders of ¼-, 1½- and 2-inch diameters for the 75, 100, and 125-deg. heating, respectively.

Fig. 2 gives the shearing tests of a sample of varnished Manila paper of 14-mil thickness. (Only the 75 and

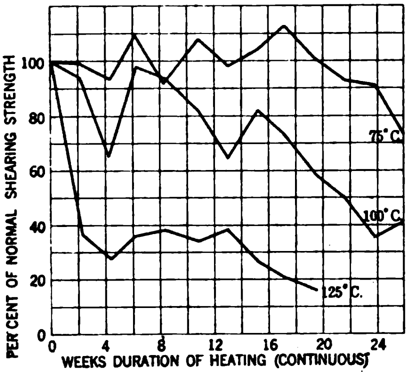

FIG. 6—PRESS-SPAHN—0.040 IN. (1.016 MM.)

100-deg. cent. curves have been drawn as the 125-deg. points seemed somewhat irregular. The values are, however, the average of several tests taken on different

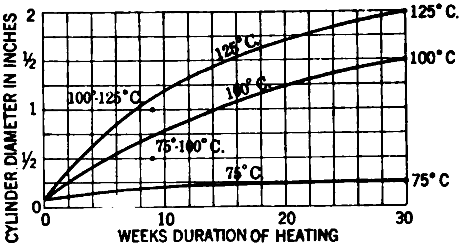

FIG. 7—PLAIN MANILA PAPER—0.011 IN. (0.23 MM.)

part of each specimen.) After being heated for 30 weeks at 75, 100, and 125 deg. cent., these varnished Manila paper samples had values of shearing strength equal to 71, 68, and 81 per cent respectively, of the

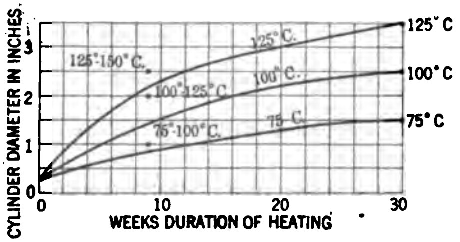

FIG. 8—MANILA PAPER VARNISHED—0.014 IN. (0.355 MM.)

unheated sample. Their shearing strength is, therefore, retained to a much greater extent than in the untreated Manila paper samples.

Corresponding to the shearing curves for varnished Manila paper shown in Fig. 2 are the bending curves

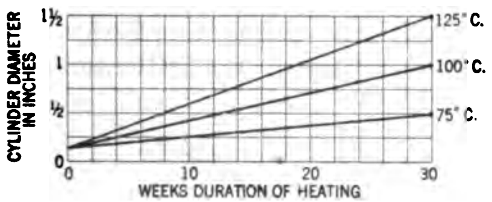

Fig. 9—Canvas Varnished—0.0157 in. (0.40 mm.)

shown in Fig. 8. The unheated sample could be bent around a ¼-inch cylinder without injury, while the samples heated at 75, 100, and 125 deg. cent for 30 weeks could only be bent around cylinders of 1½-, 2½- and 3½-inch diameters, respectively.

Only rough bending tests were taken on samples whose shearing curves are shown in Figs. 3 to 6.

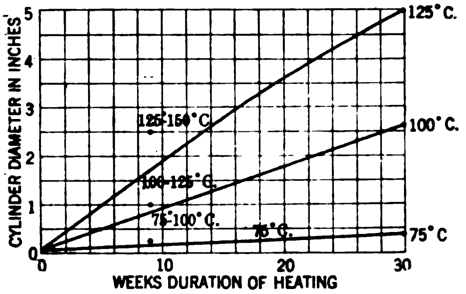

Fig. 10—Berrite Fabric—0.013 in. (0.33 mm.)

They were bent to and fro, and note taken as to whether they cracked or broke.

Fig. 3 gives the shearing tests for empire cloth. The sample was destroyed at the end of the 20th week at 100 deg. cent., while the sample heated at 125 deg. cent. was destroyed at the end of the 11th week.

Fig. 4 gives the shearing tests for a sample of calico impregnated with elastic insulating varnish. The

75-degree sample broke on bending at the 20th week; the 100-degree sample at the 4th week; and the 125-degree sample at the 2nd week.

Fig. 5 gives the shearing tests for a sample of I. R. prepared duck (reinforced rubber). The 75-degree sample was practically unaltered at the end of the 26th week. The 100-degree sample showed only 43 per cent of its shearing strength for the same time, while the 125-degree sample broke on bending at the end of the 24th week. (On the same figure are shown the shearing values of untreated canvas of 9-mil thickness, heated at 75, 100, and 125 deg. cent. for 30 weeks).

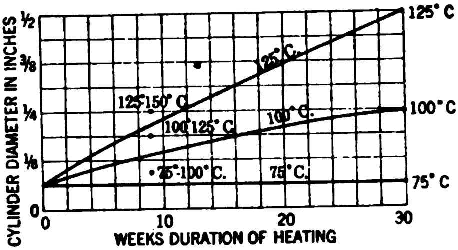

Fig. 11—Excelsior Linen—0.0063 in. (0.16 mm.)

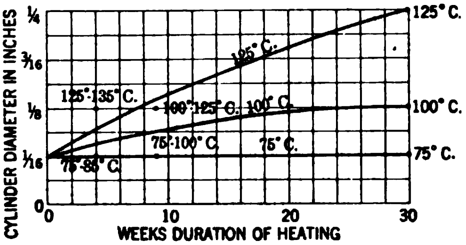

Fig. 12—Excelsior Paper—0.0047 in. (0.12 mm.)

Fig. 6 gives the shearing tests for a sample of press-spahn. The 75-degree sample cracked on bending at the 26th week, but was practically unaltered up to the 22nd week. The 100-degree sample cracked on bending at the 20th week, while the 125-degree sample broke on bending at the end of the 2nd week.

Bending tests of other samples of insulation, such as varnished canvas, Berrite fabric, press-spahn, and oiled cloth, are shown in Figs. 9 to 14 inclusive.

In general, treated Manila paper compares very favorably in shearing strength with other types of vegetable fibrous insulation, and it also has the same general bending characteristics. Varnished Manila paper of 14-mil thickness, at the end of 30 weeks' heating at 100 deg. cent., still had a shearing strength of 68 per cent of the unheated sample, and could be bent around a cylinder of 2½-inch diameter, while the same temperature destroyed a sample of empire cloth at the 14th week, of I. R. prepared calico and press-spahn at the end of the 16th week, and of varnished calico at the end of the 18th week.

In practically all samples, *the dielectric strength showed but small deterioration until mechanically destroyed.*

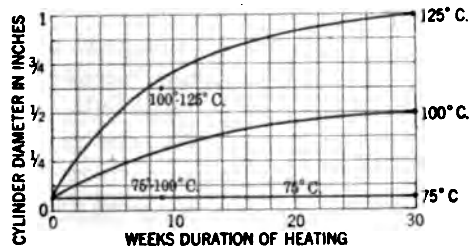

FIG. 13—PRESS-SPAHN—0.010 IN. (0.25 MM.)

3. APPLICATION TO CABLES

Having before us these results of different insulating materials, we may review their limitation to specific uses by applying our engineering judgment. It is, of course, difficult to make an exact comparison of the conditions under which insulating materials are to operate in the great variety of apparatus to which they are applied.

However, we may start from the point that impregnated paper, under the A. I. E. E. Standardization Rules as Class A insulation, is good for 105 deg. cent. continuous. It is not here the case of discussing whether this limit is too high or not. Personally, after studying similar data as given in the British Committee tests, from which I have abstracted the few illustrations in the foregoing paragraphs, I feel that 105 deg. cent. is too high if applied continuously; but to this I shall make reference later. For the present, we may assume that impregnated paper as Class A insulation should withstand safely 105 deg. cent. If such is the case, what consideration would prevail to modify this limit on account of the possible different conditions that might exist in cables versus other electrical apparatus like armature coils, et cetera?

3A. REASONS ADVANCED FOR LOW TEMPERATURE LIMITS

The principal reasons advanced for adopting lower temperature limits than 105 degrees cent. for cables have been two:

1. That the compound in the cable, when warm, may leave the paper, especially when the cable is installed in inclined ducts, with a tendency to flood the lower portion of the cable and to leave the upper part of the cable dry.

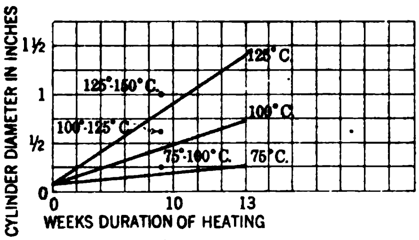

FIG. 14—OILED CLOTH—0.0087 IN. (0.22 MM.)

2. That cables are oftentimes removed from subways for reinstallation in other locations and, therefore, if the paper becomes brittle, it would crack inside the lead sheath.

Another reason for advocating the lower temperatures is that the expansion and contraction of long lengths of *large size lead-covered cables* may cause cracking of the lead sheath at sharp bends in manholes.

3B. THE RELATION OF TEMPERATURE LIMIT TO LOAD FACTOR

It is now my purpose to present data to prove that these reasons are insufficient to make an exception to the Standards Rules for Class A insulation for 105 deg. cent for low-tension cables; but before presenting these facts, I want to emphasize the point that while in machinery the 105-degree allowable limit is reached for long periods of time of operation of the apparatus, on the other hand, *low-tension cables, as usually used in large distributing systems, are not subjected to the maximum temperature except for short periods of time each day,* so that in such cases the 105 *deg. cent. for the low-tension cables is immeasurably safer* than the 105 *deg. cent. for machinery,* which may operate at that temperature continuously or at least for periods of eight or ten hours each day. Anticipating my conclusion, I will broadly state that the *limiting temperature* should be a *function of the load factor* (*average load to yearly maximum*) under which the apparatus is to operate, so that *if the apparatus, either cable or machinery, is to operate for long hours at full load, the limiting temperature should not exceed say* 90 *deg. cent.,* while on the other hand, *if the cable or machinery is to operate for a short number of hours* at heavy load and then be subjected to a long period of cooling, as occurs on cables in large systems of distribution, the limiting temperature for the peak loads should be raised, and the 105 deg. cent. limit should be standardized.

4. SURVEYS AND TESTS

I herewith submit conclusive evidence of the fact that 100 deg. cent. to 110 deg. cent. are safe and standard in practise in large subway and distributing systems. The evidence consists of (1) results from observations obtained by wide and close scrutiny of the physical and electrical conditions of all the low-tension cables of a large electric power company, The New York Edison Company; and (2) results of special tests carried out by engineers and laboratory men.

4A. FIELD SURVEYS

Investigations of a very thorough and exhaustive character were prompted by three occurrences, unprecedented in the history of the company, of serious short circuits of low-tension cable feeders. These occurrences were at first unexplainable and therefore were highly perplexing to the managers and engineers. The coincidence of these disturbances at the period of the winter of 1919 when the company was called upon to furnish an unprecedentedly and unexpectedly heavy increase in power demand, causing the low-tension cables to carry heavier loads than customary in any previous year, naturally led one to suspect that the cable insulation might have been damaged.

The results of the physical inspection of all cables showed that a number of 1,000,000-cir. mil concentric feeder cables, not necessarily carrying heaviest loads, but in congested banks of ducts, had their sheaths cracked near the edge of the ducts and at sharp bends in manholes where the movement of the cables, due to expansion and contraction, was impeded. These cracks extended to the insulation, leaving an open path for moisture and water to reach the copper and to cause a local short circuit, which would endanger the neighboring cables and cause manhole explosions. It is not here the place to enter into a description of ways and means developed to securely protect the system from these dangers of low-tension cable short circuits, but what is of vital interest is the fact that

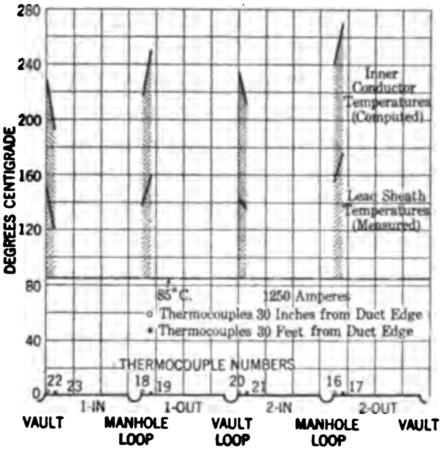

FIG. 15—MAXIMUM TEMPERATURES—CABLE SHEATH CRACKING TEST

not a foot of cable was found with impaired insulation outside the point of the crack or burn-out at the short circuit. That is, that cable a few feet from the burn-out, and all the rest of its length, was thoroughly sound and undamaged.

4B. SHEATH CRACKING AND HIGH-TEMPERATURE TESTS

One of the numerous special tests carried out in the comprehensive study of the subject throws additional light on the findings of the physical inspection of all the cables on the system. We made a series of tests on four 278-ft. lengths of cables installed in ducts between manholes connected in series, with bends and splices to simulate actual conditions. The object was to determine loads, temperatures, and expansion of cables at which the sheaths would crack if the cables were submitted to specified cycles of eight-hour load and sixteen-hour no-load for periods of weeks, extending over two months. Temperatures of sheaths were taken by thermocouples and the inner copper temperatures calculated, using the Atkinson constant of thermal resistivity of 354, which we have independently checked and which seems to be approximately correct. Fig. 15 gives the maximum temperatures for lead sheath and inner copper for the different thermocouple locations at a 1250-ampere run. Figs. 16, 17 and 18 give characteristic runs at 800, 1000, and 1250 amperes continuous load for eight hours. Inner copper tempera-

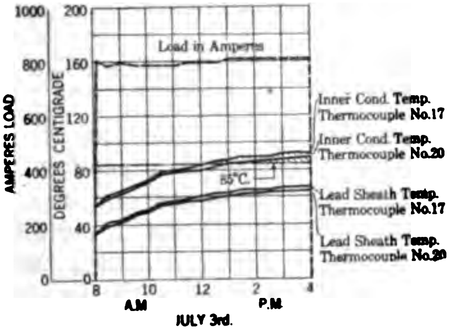

FIG. 16—CABLE SHEATH CRACKING TEST
800-Ampere d-c. run

tures at location of thermocouple No. 20 for the full period of test are graphically represented in Fig. 19. From the diagram, it appears that the insulation at the point "thermocouple No. 20" withstood the following temperatures:

Inner Conductor Temperature (Degrees C.)	Hours	Remarks
Less than 85	73	Hours of tests with current on —exclusive of hours of cooling with current off.
85—90	13	
90—100	26	
100—110	37	
110—125	88	
125—150	36	
Over 150	169	
Total duration of test periods	442	

The sample of cable at location "thermocouple No. 20" showed its insulation in good condition, the inner insulation being darkened and of considerably reduced tensile strength, but yet in perfect condition for indefinite service, notwithstanding the fact that the insulation operated at over 110 deg. cent. for 293 hours; temperature of over 125 deg. for 205 hours; and temperature of over 150 deg. for 169 hours.

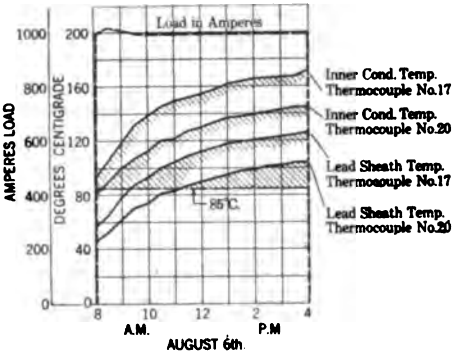

FIG. 17—CABLE SHEATH CRACKING TEST
1000-Ampere d-c. run

At other locations, the maximum temperature exceeded the temperature noted for location "thermocouple No. 20." (See Figs. 15 and 18). At thermocouple No. 17, the copper temperature reached a maximum of 269 deg. cent., and temperature in excess of 240 deg. cent. existed for 4½ hours.

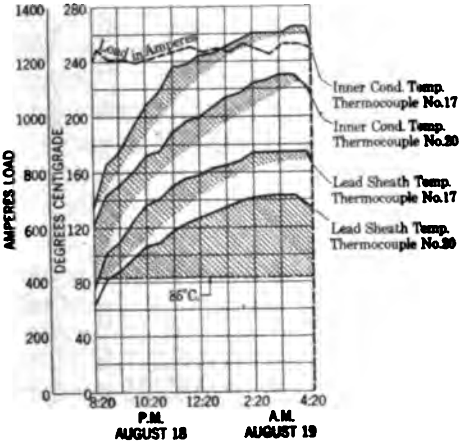

FIG. 18—CABLE SHEATH CRACKING TEST
1250-Ampere d-c. run

4c. EFFECT OF BENDING

With these enormously high temperatures, only 20 feet of one length, out of the 1112 feet of cable, had their insulation destroyed. The four lengths were removed from the ducts and reeled, and re-reeled in some instances twice, and after this handling the cable lengths were subjected to regular factory voltage and insulation tests, with the following results:

		Voltage Tests 5-minute application		Insulation Test megohms per mile	
Section	No. of times re-reeled	Inner to outer and lead	Outer to inner and lead	Inner to outer and lead	Outer to inner and lead
1 in	1	5400	5900	460	184
1 out	2	5400	*	770	. . .
		5500	5700	703	289
2 in	1	5500	6600	100	56
2 out	2	5400	5800	520	105

*Broke down 12 feet from the end near hub of reel after two minutes at 6000 volts. Balance portion retested with results in second line "1 out."

Apparently even after the withdrawing and rehandling of this cable, which had been subjected to

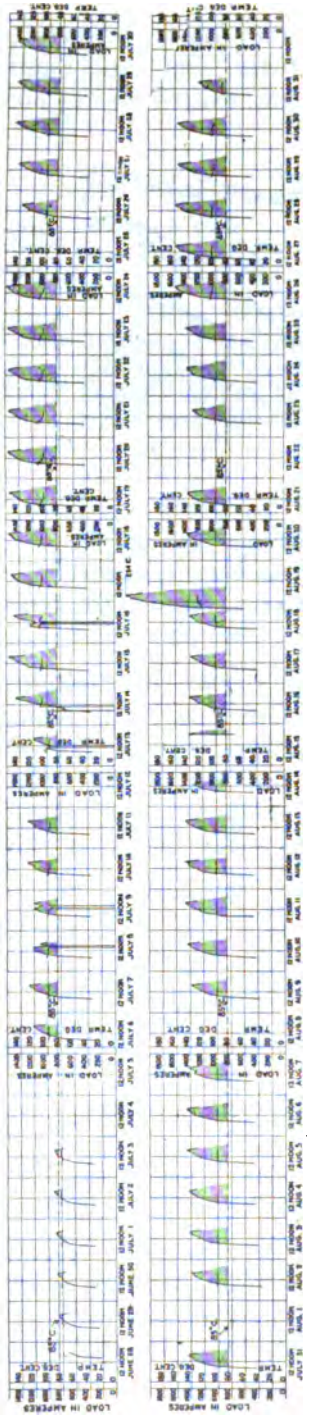

Fig. 19—Inner Copper Temperatures at Location of Thermocouple No. 20 for Period of Test

such high temperatures, in excess of 200 deg. cent., over 98 per cent of the cable was still in such fair condition that it would have been reinstalled, if the lot had come from ordinary withdrawals. The insulation of this cable that, at thermocouple No. 20, withstood for 169 hours temperatures of over 150 deg. cent., must have been immeasurably more affected than if the temperature had been limited to 105 deg. cent. for a great number of years of service during the winter peaks as prevailing on large systems of distribution. (Time does not permit of figuring out the total hours of high, average, and minimum temperatures engendered by the characteristic load curves for different seasons of the year; but for any one interested in the subject, I attach diagrams of average daily output throughout the year, and characteristic load diagrams for each season of the year, as per Figs. 20 and 21). The point that may be made here is that the operation of a cable at 105 deg. cent., in ordinary systems of distribution, will not prevent the cable from being removed and reinstalled without injury.

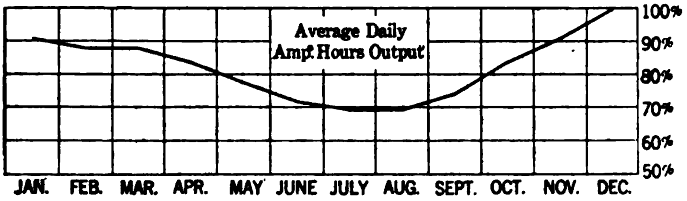

Fig. 20

4D. Other Companies' Experience

The experience of several large companies, like The New York Edison and Commonwealth Edison Company of Chicago, who have operated for the last twenty years a substantial number of their cables at loads producing temperatures of 100 to 110 deg. cent. during the winter peaks, proves without question that these seasonal temperatures for periods of peak loads have not impaired the cable or its insulation for occasional withdrawal and reinstallation any more than on cables of the same age which have never sustained but lower temperature. The hardening of the oil in the insulation which, as we have seen, takes place if temperatures of 100 deg. cent. and over are sustained continuously for periods of several months, will either not take place at temperatures of 105 deg. cent. applied only for short periods for certain seasons of the year; or if any hardening takes place, the process will extend over long periods, exceeding 15 or 20 years. At the ends of these periods, it is improbable that any substantial amount of such cable will still be required for reinstallation, if removed, but if the lead sheath is intact, the tests on the sample cables submitted to almost destructive temperatures have shown that the cable can still be reeled and re-reeled without destroying its efficiency for service both as to dielectric strength or insulation resistance; in practise, the aging and deterioration of the lead sheath, due to chemical action electrolysis, et cetera, will be the *paramount factor in the life of low-tension cables.*

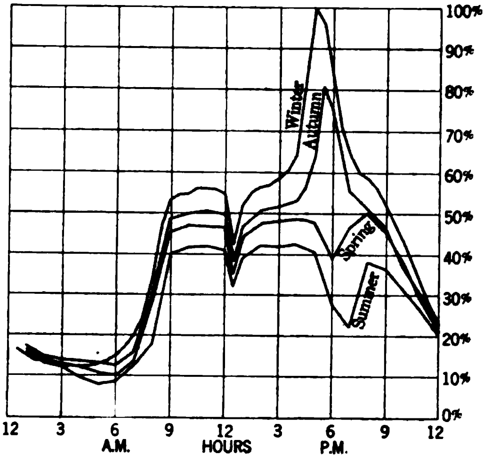

FIG. 21

Regarding the question of the compound leaving the insulation, I think it can be dismissed by considering the fact that this migration of compound will only be partial, and whatever remains of the compound with the paper still offers a factor of safety in dielectric strength from ten to twenty-five times the low-tension operating voltage.

The difficulties of lead sheaths cracking in large sized cables are essentially problems of careful installation and handling of the cable. In the sheath cracking test, we have been unable to produce cracking under the extraordinarily severe conditions of temperatures which gave expansions as large as 8 inches in 278 feet. In practise, with 105 deg. cent. temperatures, the expansion would only be 3¼ inches.

5. DISTILLATION TEMPERATURES OF CABLE COMPOUNDS

The question has also been raised that the compound might distil or vaporize at temperatures of above 100 deg. cent. An exhaustive investigation was made by The New York Edison Company to determine the effect of temperature on cable impregnating materials. The results of laboratory tests carried out by the Electrical Testing Laboratories indicated that the mineral compound gave the first drop of distillate at 205 deg. cent. A supplementary investigation was made to determine if the compounds would distil any appreciable amount at temperatures below 200 deg. cent. when exposed to these temperatures for long periods of time. No distillate, however, was obtained for either mineral or resin compounds after being maintained successively at temperatures of 115, 130, 145 and 160 deg. cent. for three days. Similar results were obtained when the temperature was maintained at 180 and 200 deg. cent. for 24 and 36 hours.

To further determine if the increasing temperature produced any gas within the cable, an investigation was made with a test tube and the temperature raised from 100 to 200 deg. cent., an attempt being made to ignite the vapor above the surface of the compound at the different temperatures. In the case of the mineral compound there was absolutely no tendency to ignite throughout these temperatures. With the resin compound, however, it was found that the passage of a spark at a temperature of 145 deg. cent. caused the vapor to explode, this action continuing up to

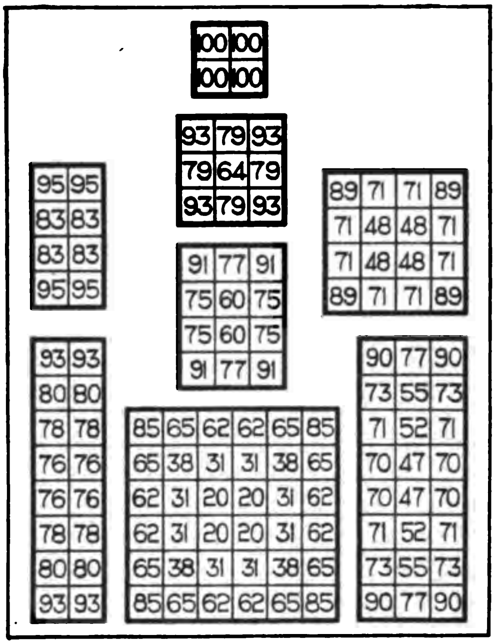

FIG. 22—RELATIVE WATT LOSSES FOR INDIVIDUAL DUCTS AND BANK OF DUCTS PER FOOT OF CABLE FOR SAME TEMPERATURE RISE (PER CENT OF 2 BY 2 BANK)

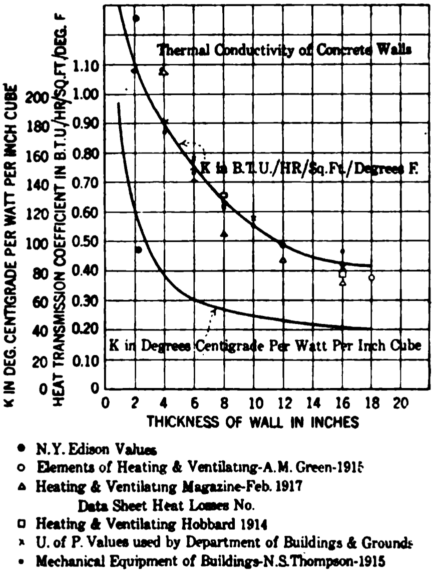

FIG. 23

160 deg. cent. beyond which no further explosions took place as the temperature was raised to 200 deg. cent.

These tests conclusively dispose of the possibility of danger from all compounds operated at temperatures below 125 deg. cent.

6. VITAL IMPORTANCE OF AMBIENT TEMPERATURES IN SUBWAY DUCTS

Before making the final recommendations, I wish to bring out a point of importance, that the operator must carefully study the temperatures under which the cables will operate when placed in subway ducts, especially when the trunk lines contain many ducts and cables in one bank.

The paramount importance of carefully surveying the ambient temperature conditions in ducts is shown in Fig. 22 giving the relative allowable losses for a given temperature on each cable with different duct arrangements. In the figure, the losses in a bank of two by two ducts are assumed as 100 per cent.

The actual values of losses allowable per duct-foot will vary greatly according to the load factor, the thickness of the concrete wall surrounding the bank of ducts, and the amount of moisture in the soil. The thermal conductivity of concrete, as obtained by special tests by The New York Edison Company, is shown in Fig. 23, which also represents a compilation of results obtained by other authorities for different thicknesses of concrete. The variation in conductivity with thickness is probably due to the fact that surface drops were also involved.

The thermal conductivity of the soil under various conditions of moisture was determined with the following results:

Dry sand	90	deg. cent. per watt, per inch cube
Natural soil (approximately 6 per cent moisture)	39	
Natural soil with 9 per cent moisture added	19	

7. THE RECOMMENDATIONS FOR TEMPERATURE LIMITS

After having reviewed all of the foregoing data, including the Steinmetz and Lamme report, the British Engineering Standards Committee tests, the surveys of large operating companies, and all special tests and findings herein presented, I submit that the permissible operating temperatures of impregnated paper insulation, in which dielectric stress is low, are to be a function of the load factor at which the cable operates. The load factor for cables used in systems of distribution is intended to be the ratio between the yearly average load and the maximum load on the cable. It is certain that a load factor of say 33 per cent with seasonal winter peaks and correspondingly smaller maximum loads for the rest of the year will produce an average temperature on the cable considerably below 85 deg. cent., so that a limit of say 105 deg. cent. at peaks for 33 per cent load factors is unquestionably safer than 85 deg. cent. continuously, as allowed by the present Institute Rules. The proposed plan corresponds with the well established practise of rating electrical apparatus at a temperature rise of say 40 deg. cent. for continuous loads and from 55 to 65 deg. cent. for two or three hours overload. Machinery so designed has given excellent service for the last 25 years.

I should suggest for consideration for impregnated-paper, low-tension cables the temperature limits in function of the load factor of the cable, as follows:

105	deg.	cent.	for	load	factors	around	33 per cent
95	"	"	"	"	"	"	50 per cent
90	"	"	"	"	"	over	66 per cent

The suggested temperature limits may perhaps be presented in a more general form by working back from the load factors to corresponding values of rise of temperature allowable for normal loads and overloads for specified hours. I *prefer to use the load factors* as they are fundamental in the determination of the most economical current density in cables as per *the Kelvin law which prescribes lower current density, and consequently lower losses and smaller temperature rise, the greater the load factor.* This gives a balance between economy and heat stress upon insulation. However, the important principle to be established is that the limiting temperature must be lower the greater the number of hours the insulation works at that temperature.

The shortcomings of the present Rules are that for cables they do not allow any rise of temperature for brief overloads above the 85 deg. cent. which is the limit for continuous operation, while they allow, for the same type of insulation in machinery, 105 deg. cent., continuous.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 17, 1921.

PERMISSIBLE OPERATING TEMPERATURES OF IMPREGNATED PAPER INSULATION IN WHICH THE DIELECTRIC STRESS IS LOW

BY D. W. ROPER
Superintendent of Street Department, Commonwealth Edison Co., Chicago

FOR a number of years the standard low-tension direct-current feeder cable in Chicago was 1,000,000-cir. mil two-conductor concentric paper-insulated cable with three pressure wires laid up with the outer conductor. Apparently there has been the greatest tendency to overload this particular size of cable more than any other as, with both single and concentric cables in service, it was difficult to make a proper distinction between the carrying capacity of the two kinds of cables. About ten years ago we had two cases in which the cables of this kind were called upon to carry loads somewhat larger than had been customary, and steadily throughout the day instead of a short peak in the evening. The two customers in these cases, in different portions of the city, were both manufacturing customers with an eight-hour load, and on account of some increase in business they increased their load on short notice when no cable was available for another feeder to their premises. In each case, the cable has to be ordered from the factory so that this unusual load was carried by these cables for some three or four months. In the first case of this kind we were so disturbed about the temperature that we made a rather extended series of temperature measurements, using one of the pressure wires imbedded in the outer conductor as a resistance, and determining the temperature by the rise in resistance. This, of course, would give us the temperature of the outer conductor which would be probably 8 or 10 deg. lower than the inner conductor. The temperature measured in this manner was slightly above 100 deg. cent., and as there was some doubt regarding the accuracy of the determination made in this manner, it was checked by cutting a small hole in the lead sheath of the cable and in the outer insulation, and measuring the temperature of the outer copper with a thermometer. The temperature taken in this way checked very closely with the temperature as determined by the rise in resistance of one of the pressure wires. The insulation removed in this manner was carefully preserved and compared with the insulation in a piece of new cable, and it was impossible, by careful examination, to discover any appreciable difference.

In the second case which occurred some months later, we were not so disturbed about the damage to the insulation, although the load carried per cable was approximately 10 per cent heavier than in the first case. The temperature measurements were on this account omitted. The line was carefully patrolled several times per week, however, in order to detect any symptoms of impending trouble and a number of minor mechanical defects in the lead sheath were discovered during the time that this cable was overloaded.

In each of the above mentioned cases the service over these cables was discontinued, a few years after the period of overload, due to the customers moving to another location. The cables were, therefore, removed, carefully examined, the insulation found to be in good condition and the cables reinstalled at another location.

Messrs. Clark & Shanklin in their paper on "High-Tension Single-Conductor Cable," presented before the Institute on June 24th, 1919[1], give some data for the radiation constants of conduits under average heating and hot-spot conditions. The authors of the paper advise that the figures for average heating were determined as the result of a large number of observations, and the carrying capacity obtained from these data appears to check fairly well with our experience

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[1] Vol. XXXVIII, p. 944.

with the sizes of cables under discussion. In later years 1,000,000 and the 1,500,000-cir. mil single-conductor cables have been our standard sizes for low-tension direct-current feeders. The carrying capacities of these several sizes of cable as determined from the Clark and Shanklin data for average conduit conditions and for a maximum copper temperature of 100 deg. cent. are as follows:

Size	Load per conductor Amperes
1,000,000-cir. mil single conductor	1110
1,500,000-cir. mil single conductor	1360
1,000,000-cir. mil concentric	790*

*Note: this figure is one-half the current for a 2,000,000-cir. mil single-conductor cable.

Our records indicate that a considerable percentage of all of our low-tension feeder cables will exceed these figures for a few hours each night during a month or two of the maximum load period in the winter.

The paper by R. W. Atkinson in the September, 1920 JOURNAL of the Institute gives the data for calculating temperatures of copper conductors in cables by an entirely different method. For the purpose of calculating the maximum temperature by the Atkinson method, the air temperature in an idle duct in the conduit in which the cables are installed and the load carried by the cable are necessary. During the past few months we have made a number of temperature surveys and have calculated maximum copper temperatures by the Atkinson method, and have made curves of temperature over a number of consecutive days in some of our heavily loaded conduits. These curves show that the minimum temperature occurs Monday morning after the light loads on Saturday afternoon and Sunday, and further that there is a gradual increase in the maximum daily temperature from Monday until Friday. It is, therefore, a rather tedious job to discover frôm such tests and from our load records the total length of time during any given period that the copper temperature has exceeded any specified figure on any particular cable. The results obtained to date by this method indicate the maximum copper temperature of our low-tension feeder cables in the large and crowded conduits immediately adjacent to the substations is generally higher than 105 deg. cent., and in a number of locations considerably exceeds this figure for several hours per day for each of five days in the week during the winter months.

In one or two cases where, in the case of our older substations, we have 20 or 24-duct conduits leaving the substations with nearly all ducts occupied with loaded feeder cables, vacant duct temperatures of approximately 100 deg. cent., are found for a short time on Friday afternoon during two or three weeks in December. Such idle duct temperatures, together with the load readings, indicate by the Atkinson method a maximum temperature approaching 200 deg. cent. on the inner conductor of a concentric cable. One of the concentric cables in this conduit was removed and examined for the purpose of this investigation, and incidentally an opportunity was afforded to report on one item not scheduled. Upon removing this section of cable, a hole about one inch in diameter was found in the lead sheath about eight inches from the mouth of the duct. It had apparently been caused by the sheath catching on the edge of the duct when the cable was installed without being noticed by the workmen. In the immediate vicinity of this hole, the paper insulation is not only quite black but also quite brittle, so that it breaks very readily when handled. At another point thirty feet away, the paper insulation, while slightly darkened, is still well filled with compound, and pliable, although it has lost some of its strength. From the information secured from this sample of cable and from other samples secured from similar crowded conduits in the vicinity of large substations, I think that we may reasonably conclude that when the copper of one of the low-tension cables on our distribution system reaches a maximum temperature of 180 deg. it is being heated beyond a safe limit, and deterioration of the insulation will result; and further, that the deterioration will be greater if there are holes in the lead sheath at the point where such temperatures are reached.

During the past year in connection with changes on our distribution system, we have removed concentric cables from locations where records and subsequent examination into the conditions indicate that the maximum copper temperature must have materially exceeded 100 deg. cent., but the exact amount cannot be definitely stated. We do know, however, that in such cases the insulation has been found in good condition, so that the cables have been reinstalled and placed in service at a different location.

The time during which the maximum temperature is maintained has undoubtedly a considerable bearing on the subject. We know, for example, that the insulation next to the lead sheath of a new cable shows no sign whatever of damage by heating, although the lead is applied at a temperature which probably exceeds 300 deg. cent. We know, also, that when our cables are suddenly overheated because of a burn-out at a more remote point from the source of supply, that the insulation shows no indication whatever of damage, although the temperature of the copper must have considerably exceeded 100 deg. cent. for a short period. It is apparent, therefore, that not only due consideration should be given to the time during which the maximum temperature of the copper persists, but also that in an operating system it is not possible to determine the maximum safe limit exactly, as the temperatures are continually changing and it is not possible under working conditions to maintain any particular maximum temperature for any considerable time. Apparently the best that can be done is to determine the maximum temperature and also average curves showing the number of hours per year that temperatures near the maximum are maintained. From an examination of the insulation of cables corresponding to a number of such curves we should be able to establish, first: A lower limit at which the insulation will not be injured, even when the temperature is maintained for long periods of time; and second: An upper limit above which we know that the insulation will be injured if such temperature is maintained for any considerable time. From the information so far obtained in Chicago, the best that can be done is to place the lower limit at about 110 deg. cent. and the upper limit at about 180 deg. cent. It is recognized that these limits may be too widely separated to be of material value in the settlement of the question at issue, but it is hoped that as further investigations are made, additional information will be forthcoming which will serve to bring these limits within a narrower range.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 17, 1921.

NOTES ON THE EFFECT OF HEAT ON IMPREGNATED PAPER FROM CABLE INSULATION

BY WALLACE S. CLARK
General Electric Co., Schenectady, N. Y.

THE tests outlined below were made to determine at what temperature marked deterioration in the paper of impregnated paper cable took place. There are many shots well off the target in these results, although the average was determined from something over six hundred readings. Anyone who is familiar with the manufacture of paper and with the handling of it, knows the wide variation which occurs in different parts of the same sheet. The maximum tensile strength in a series of tests is frequently twice the minimum.

The first series of tests was started in December, 1917, and completed nine months later.

The sample was three-conductor cable, lead-jacketed, 4 ft. long, with 00 cylindrical conductors, saturated with a compound composed of resin and petrolatum. The paper wall on the individual conductors was 9/32 in. of 0.005 Manila paper and the overall jacket was 7/32 in. of 0.008 Manila paper; lead jacket 1/8 in. The sample was cut from a cable coming through in the regular course of production and was representative of ordinary manufacturing practise.

A narrow section was cut off and six strips of paper from the outer jacket were unwound and tested for tensile strength. The distance between jaws was approximately 7 in., rate of separation 20 in. per minute, average tensile strength 7343 lb. per sq. inch. Each end of the cable was then sealed and it was placed vertically in an oven. This oven had the following temperature cycle:

From 7 a. m., Monday, to 12 noon, Saturday, average temperature ran from 68 to 74 deg. cent. Steam was shut off at 12 oclock, Saturday, and by 6 a. m., Monday, the temperature had dropped to 30 deg. cent., when the steam was again turned on.

At different times short sections were sawed off from the sample, and the sample resealed and put back into the oven. The results showed average tensile strength given in Table I.

TABLE I

Average Tensile Strength per Sq. Inch

Not heated	1 mo. bake	2 mos. bake	4 mos. bake	6 mos. bake
7343 lb.	7816 lb.	7338 lb.	7088 lb.	8290 lb.

The above samples were from the outer jacket. Samples of paper from the individual conductors showed similar results. Samples were also bent and twisted in the fingers to detect brittleness.

The same sample that had the six months' bake, with each end sealed, was then placed in an oven at a temperature of 100 deg. cent. At the end of the first month the average tensile strength was 7240 lb. per sq. inch; at the end of the second month, 7173 lb. per sq. inch.

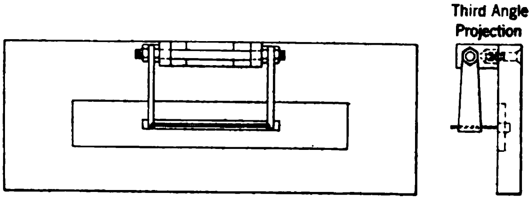

Fig. 1—Apparatus for Making Break-Down Voltage Tests on Narrow Strips of Insulation—Plan and Elevation

In the spring of 1920 another test on the same size and insulation was undertaken. In this case, seven samples were cut from one length of cable coming through in regular production. Each end of each sample was sealed. Sample *A* was held as a check; sample B was heated for 30 days at 100 deg. cent.‘ sample C was heated 60 days at 100 deg. cent., sample

D—90 days at 100 deg. cent., sample E—30 days at 110 deg., sample F—60 days at 110 deg., and sample G—90 days at 110 deg. On each of the paper samples a break-down test was made, using the so-called knife-blade apparatus shown in Fig. 1.

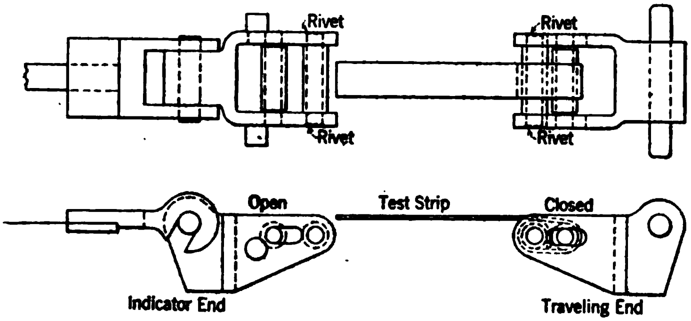

Fig. 2—Grips for Machine for Testing Tensile Strength of Cable Paper

Straight tensile strength tests were made, and in addition tensile strength tests were made where the stress applied to one edge of the paper was greater than the other. Paper was folded over the rollers of the grip shown in Fig. 2, the roller at one end being

TABLE II

	Break-down volts per mil	Breaking strain lb. per sq. inch	Tearing strain lb. per sq. inch
A —Jacket	420	9000	6833
Singles	380	9600	6666
B —Jacket	375	9000	6833
Singles	340	10333	7600
C —Jacket	320	6666	4500
Singles	410	7600	5466
D —Jacket	360	7000	3667
Singles	360	6933	4266
E —Jacket	333	6833	3500
Singles	360	7200	4666
F —Jacket	300	5016	2166
Singles	310	5333	3466
G —Jacket	300	5000	2500
Singles	320	5333	4133

slightly tapered, thus applying greater tension to one edge than to the other when the jaws were separated. The average results of these tests are shown in Table II

We note from this table that the ratio of tearing strength to the average breaking strength in sample A, cable not heated after manufacture, is 0.72; in sample D, heated 90 days at 100 deg., 0.57, and in sample G, heated 90 days at 110 deg., 0.64. This shows definitely that the tensile strength of the paper deteriorates less rapidly than its resistance to tearing. The higher rate of deterioration at 110 deg. cent. is clear and is well marked by comparing the results from sample D, 90-day bake at 100 deg., with sample E, 30-day bake at 110 deg., the deterioration in 30 days at 110 deg. being practically equal to deterioration in 90 days at 100 deg. From these results, we can say in a preliminary way, that deterioration at 70 deg. cent. is negligible; at 100 deg. is marked in 90 days; at 110 deg. is marked in 30 days, applying to the particular quality of paper and impregnating compound which were under test.

A load with a two-hour peak, allowing such peak to occur for 30 days in each year, would give 60 hours yearly operation at maximum temperature, which we will assume at 100 deg. cent. It is evident that the cable on this basis could be used for many years, operating at 100 deg. cent. as its peak temperature, before reaching the stage of deterioration obtained in the 90-day test at 100 deg. cent. It is, of course, impossible to state the exact time because we do not know the rate of deterioration at temperatures below 100 deg. cent.

From an examination of the cable and paper taken from sample G, there is no question in the writer's mind but that cable with paper in this condition would be perfectly safe for operation at low voltages. Further the writer believes that cable so treated could have been withdrawn from conduit and reinstalled. Briefly, the temperature limit fixed for the operation of a low-tension cable, to avoid undue deterioration, must take into consideration the length of time during which temperature is maintained.

APPENDIX

TENSILE STRENGTH

The samples for testing are taken from the finished cable after it is leaded. In case of a multiple-conductor cable, part of the samples are taken from the overall jacket and part from each of the individual conductors. If the strips are over ¾ in. wide, they are cut to ¾-in. width with a steel straight edge and a sharp pointed knife. The jaws of our testing machine will not take strips over ¾ in. wide. The test strips should be about 12 in. long so that the distance between jaws will be about 7 in. When the strips are placed in the jaws, it is important that they are put in straight, so as to get a straight pull. The jaw travels at the rate of 20 in. per minute, the machine used being our standard rubber testing machine which registers the pounds pull when the sample breaks.

TEARING TEST

This test is made the same as tensile strength except that the back roller in the traveling jaw has a taper of 0.025 in. per inch. When the tearing test is made, the straight roller is taken out of the movable jaw and the taper roller inserted in its place.

CREASING TEST

Samples of paper as described for tensile strength test are looped back on themselves and flattened down with a 10-lb. weight placed over the loop for a period of one minute, thus making a crease in the paper. This method is used in order to make a uniform crease in all samples. The strips are then straightened out and put into the machine using straight rollers in the jaws, and the tensile strength measured.

The jaws used for making the tests are shown in Fig. 2.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 17, 1921.

THE EFFECT OF HEAT ON PAPER INSULATION

BY H. W. FISHER AND R. W. ATKINSON
Both of Standard Underground Cable Company

Abstract of Paper

A discussion is given in detail of the mechanical properties of paper especially as influenced by drying, heating, and impregnating. Tests for measuring the changes due to these causes are discussed and it is shown that tensile tests are unsatisfactory for this purpose. A measurement of tearing resistance is found to be satisfactory and two machines for this purpose are described. Measurements are given of rate of deterioration of paper at different temperatures. The relation of these data to allowable operating temperature is considered.

No discussion is given of the various causes including heating due to dielectric losses which affect the limiting temperature of high-voltage cables.

The rapid increase of deterioration with temperature is shown. Emphasis is placed on the importance of not exceeding intended temperatures through lack of knowledge of conditions.

IN a discussion of the limiting temperature for paper insulation of low-voltage cables, the matter for first consideration is the effect of high temperature upon the properties of the material. The principal importance of this effect lies in the reduction of the mechanical strength of the paper. In the case of low-voltage cable, the only changes in electrical properties of importance are incidental to the mechanical changes and therefore a discussion of these mechanical changes forms a complete basis for consideration of temperature limitation.

The deterioration of paper due to continued high temperature is not measured by change of tensile strength of the paper. The change is apparent in reduced ability to withstand tearing forces, or bending or folding. Satisfactory study of aging of paper can be made only with the use of suitable apparatus for measuring one or more of these properties. This article includes description of instruments for this purpose as well as data of a considerable number of tests made on paper, after various kinds of heat treatment, as described.

Following the report of experimental data is a discussion of the question of temperature rating of this class of insulating material. The effect of high temperature upon the impregnating medium is not considered in detail except in-so-far as the rate of deterioration of the paper may be influenced by the medium.

If a quantity of paper of uniform quality is subjected to a high temperature and successive samples are taken from it, from time to time, it will be found that the successive samples differ progressively in ability to withstand tearing between the fingers, or to withstand without breaking, creasing or bending. The first effect noticeable is the greater ease with which the paper is torn. Later samples may not be creased without cracking. With a further degree of deterioration, it is actually not possible to bend the paper an appreciable amount without breaking. A still further amount of aging produces a material which crumbles to a powder. If the successive samples of paper are subjected to a tensile test made very carefully so as to avoid injury of the nature of incipient tears, or unequal tension on the specimen, it will be found that even those samples which show an evidently reduced ability to withstand tearing, will have as high a tensile strength as originally. In a number of samples which have been subjected to high temperature for sufficient time to produce a very marked decrease in tearing resistance, it will be found that, even though the tensile tests are made very carefully, there will be a wide variation in the strength measured for the individual samples. The maximum readings may be practically as high as the original strength of the paper, though tests on other individual samples fall as low as 40 or 50 per cent of the original value. The fairly apparent cause of this condition is the great difficulty of obtaining an actually fair tensile test on the very brittle material so that only an occasional specimen will show the real tensile strength of actually something near the original value. Of course, as deterioration is increased still farther there is an actual reduction in tensile strength as well as in loss of tearing resistance.

We may now consider the essentials of a suitable method of measuring aging. The requirements are not peculiar to this particular measurement, but they are very frequently overlooked and it is well to make a specific mention of them so as to make a clearer examination of testing methods with these requirements in mind.

The first requirement is that the property measured is actually a measure or at least an indication of the usefulness of the material to meet the required service conditions.

The second essential of the method of test is that it shall permit definite distinction between samples which are different only in a slight degree. That is, the difference in the measurements of two such samples must be large in comparison with the variations in the measurements on samples which are identical. This constitutes effective sensitivity.

The third requirement is that the measurements be such as to be capable of permanent record and preferably of a definite quantitative form. It is in this particular that the tearing test by hand is unsatisfactory though it meets the first requirement and, to a fair extent, meets the second one.

We believe it is fairly generally recognized that a tearing test by hand meets the first requirement, that is, it measures or indicates the usefulness of paper to meet the service conditions of cable practise. It is well-known in the art that paper containing only the amount of moisture normally present when exposed to the dry air prevalent indoors in winter time, is much more difficult to run in cable wrapping machines than is paper exposed to the high humidity prevalent in summer weather. Also, it is recognized that if paper insulation is damaged by overheating after application to a cable, it is less able to withstand handling and bending such as is incident to installation.

Therefore, a method which shows progressive difference with moisture content and with aging at high temperature, meets, at least as far as concerns these variables, the first requirement of a suitable paper testing device. In any event it fulfills this requirement as far as concerns measurement of aging. It follows from what has been said that a measurement of tensile strength by the ordinary method is quite unsuitable from the standpoint of this first requirement.

From the standpoint of the second requirement, tests of tearing resistance even by hand are fairly satisfactory. Until very recent years, there has been no machine as suitable from this standpoint as the hand test. We will later describe two machines which are very satisfactory from this standpoint. The tensile test is unsatisfactory also from the standpoint of the second requirement.

The difficulty in the way of securing consistent results with a tensile test, on account of accidental damage, etc., suggested the use of a method of testing by damaging the specimen in a certain definite way and then making a tensile test. Such a method of test was standardized by making a transverse cut in the paper for a distance equal to one-quarter of the width of the paper. Tensile tests were then made upon the modified samples. Somewhat more satisfactory results were obtained by noting the elongation of the specimen before rupture, than by noting the tensile strength obtained. This method was in use for some time but was never more than partly successful and has now been abandoned for methods described later.

A machine for testing the tearing resistance of airplane fabric was given in a discussion by F. J. Hoxie at the annual meeting of the American Society of Mechanical Engineers in December 1919. We quote his very brief description: "Tear tests were made on a horizontal testing machine by cutting the specimens three in. wide and placing them in three in. jaws with one in. of cloth between the jaws at the front of the machine and three in. between them at the back." We have seen this method applied on cloth with very satisfactory results. As the test was further developed a transverse cut was made in the cloth on the stretched side before applying the tension test.

A similar problem to that of paper is encountered in the insulated cable industry in the case of varnished cambric. It was found that frequently a high tensile strength was found on samples which were obviously inferior from the standpoint of use and also from the standpoint of tearing resistance as measured by hand.

In the attempt to find a suitable machine for testing this material, a type of machine much used in paper testing, a so-called "pop tester," was tried. We were much surprised however to find that the results with this type of machine were quite in accord with the tensile tests and thus did not rank the material in the same order at all as its practical usefulness or as the ranking by tearing resistance as made by hand. The machine used for these bursting tests was one using liquid pressure against a rubber diaphragm which in turn pressed against a strip of the cloth under test. Tests of less extent made on paper showed similar results as far as they were carried. There is a published record of a similar experience of another experimenter with the use of this machine for testing paper. (H. N. Case in the *Journal of Industrial and Engineering Chemistry,* page 49, January 1, 1919.) It is interesting that this writer found the "bursting test" machine, or "pop tester," a useful addition to his testing equipment, but found that sometimes a desirable test condition is the combination of a high tearing resistance with a *low* test with the "pop tester."

FIG. 1

In the same article is described a "home-made" machine for measuring tearing resistance. Details of test results as used for determining usefulness of paper for various applications, are given. Fig. 1 shows the apparatus described and used by Case. A method developed by the writers and described below was suggested by the successful results obtained by Case with his machine. Case's machine is also of interest in its close resemblance to the apparatus used by Mr. W. A. Del Mar, described in his paper presented at this symposium.

Description is given in an appendix, of the tearing testing machine developed by the writers and on which was obtained much of the data reported herein. This machine differs in the most important degree from the machines of Case and of Del Mar in that the measure of the tearing resistance is made by the use of a spring as a dynamometer instead of by means of a weight in a pan. We refer to this instrument as machine No. 1.

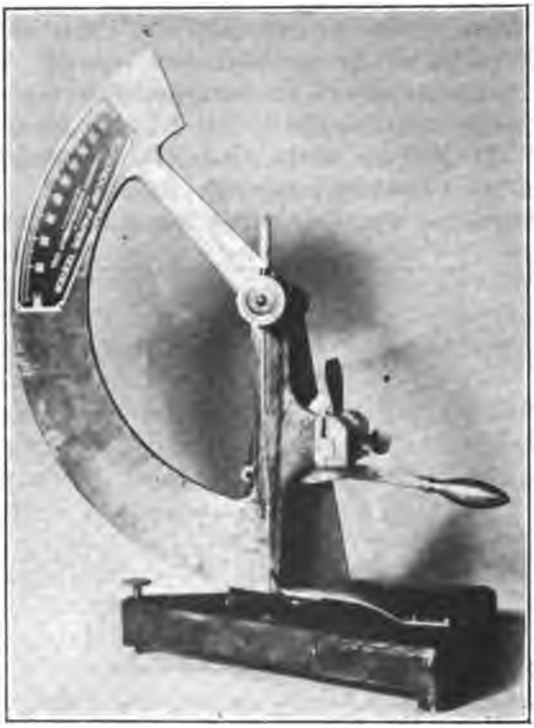

Fig. 2

Just before the actual preparation of the manuscript of this article we secured a machine which seems to be practically an ideal instrument for measuring tearing resistance. The instrument, which is illustrated in Figs. 2 and 3 and described in the appendix to this article, is made by the Thwing Instrument Company of Philadelphia. We refer to this instrument as machine No. 2. It is pertinent to remark that this machine is not a certain older type made by this concern and on the market for sometime. We have not had any experience with the older type. This machine No. 2 differs from all previously described instruments for measuring tearing resistance in that each single measurement of the machine determines the average tearing resistance over a considerable length of paper. On this account when measurements are made on a uniform paper, individual readings differ by only small amounts and thus the average of a very few measurements can be repeated with great exactness on a second lot of similar samples. A further advantage of the machine is the facility with which tests can be made and the simplicity of the testing itself.

FIG. 3

Study of the tearing resistance test as we have made it with either No. 1 or No. 2 machine indicates that it is a very satisfactory method of comparison of similar samples, or of samples which differ in only one important particular. Thus it is possible to rank accurately samples from the same original lot, but differing at the time of test in moisture content, or in length of time subjected to various aging conditions. Without further evidence, however, it does not necessarily follow that two samples differing in several particulars, but giving the same tearing resistance, are equal in usefulness. Thus we might get the same tearing resistance on a sample originally of high resistance, but subjected to an aging test, as on a sample originally of poorer quality but not subjected to the aging test. Undoubtedly, the measurements of the instruments we have used are of very great value in making comparison even under such an instance as this, but conclusions to be drawn from tests of samples from different sources and under different conditions must not be considered complete or final without a further analysis of the matter.

Before describing recent tests made with the aid of a tearing resistance machine we will describe some very old tests made by one of the authors during 1905. These tests are of very considerable importance for two reasons. They constitute an important part of the basis for the present temperature rating of paper cables. Second, though they are in agreement with some other tests reported by other observers, they point to materially different conclusions from most of the other tests reported in this paper. Suggested explanation of some of the difference is given later.

In this series of tests, sealed samples of lead-covered cable were heated for a period of respectively one week and four weeks, one lot at a temperature of 100 deg. cent., and one lot at a temperature of 93 deg. The samples were submerged in a bath of melted paraffin, heated by a gas flame. The temperature was controlled by means of a thermostat (bi-metallic spring) which controlled a solenoid operating a valve controlling the gas. The thermostat was sensitive enough to respond to less than one-fifth deg. cent. When the temperature was lower than the setting of the thermostat, it closed the circuit for the solenoid causing it to open a valve so that the gas flame was strong enough to raise the temperature to the setting of the thermostat, after which the solenoid would release and reduce the gas flame to the lower limit and allow the temperature to fall.

It will be understood that, at the time of making these tests, there was not available any testing machine as good as a test of tearing with the fingers. The results of the test are however definite to a fairly satisfactory degree. The samples subjected to a temperature of 93 deg. for one week were not deteriorated by an important amount. It was thought that some change had occurred, but no definite assurance of this was found. However the deterioration in four weeks' time was so much that it was considered that we could not think of recommending operation at that temperature. The temperatures above, and throughout the paper, are in centigrade.

The samples subjected to a temperature of 100 deg. cent. for one week were found to be badly damaged, probably about the same as those at 93 deg. in four weeks. Those subjected to 100 deg. for four weeks were found "rotten." The paper was so stiff that it could not be bent without breaking. Later in this article, some comparison is made between these tests and more recent ones.

These tests were reported in sub-committee meetings of the Standardization Committee of the Insitute and, together with supporting information from other sources, are the basis of the present temperature limit of 85 deg. cent. as given in the Standards of the Institute for low-voltage paper cables. The temperature of 85 deg. was chosen as a safe amount lower than the test temperature of 93 deg. which resulted in serious injury to the insulation in four weeks.

Before discussing the effect of heat upon the mechanical properties of paper, it is well to say a word about the effect upon its composition. If paper in its natural condition is dried at say 100 deg. cent. for a short time, or at a lower temperature and under vacuum, it will lose up to nearly 10 per cent of its weight in moisture. This easily removable moisture is sometimes called "moisture of condition." If paper is exposed freely to the atmosphere, the moisture content will vary with the humidity and temperature of the air. Thus paper exposed to air in an ordinary heated room in the winter time contains very much less moisture than similar paper exposed freely to outdoor air in the winter, or to air in the summer time. Accompanying this change in moisture content, and doubtless caused by it, there are important changes in the mechanical properties of the paper, as will be shown. If the heating of the paper is continued at high temperatures for long periods of time, longer time being required at relatively lower temperatures, there is a continued and slow loss of weight of the paper and a continued change in its mechanical properties. These changes are very similar to the changes however that are undergone when only the moisture of condition is driven off.

Tests of tearing resistance of paper were made under a wide variety of conditions. Tests on several different kinds of paper were made each under several conditions. The different conditions studied include effect of moisture content and of saturation with different kinds of compound and a study to determine the part played separately by the saturation and by the drying where a sample is subjected to both drying and saturating. Aging tests were made on samples exposed to air and on samples submerged in two different kinds of compound.

The first striking fact in connection with these tests is that impregnation itself affects only very slightly the tearing resistance of the paper. The cause of the great loss of tearing strength when the sample of paper is dried and impregnated is the change in moisture content and is not due to the impregnation with compound. Tests of the tearing resistance of paper dried for a short time in oven and of similar paper dried by immersion in compound at 125 deg. showed practically the same result. Some more careful comparisons were made as follows. Paper was dessicated under vacuum and at room temperature. One lot was tested dry, one lot after saturating with "lectroseal" transformer oil, and one lot after saturation at 80 deg. cent. in the petrolatum compound which was used in the tests. The sample in transformer oil was about

10 per cent weaker than the dry sample. Samples impregnated with petrolatum compound have shown as much as 35 per cent greater strength than dessicated samples. In other cases the difference has been slight.

Another lot of paper which had not been treated and was merely exposed to air at 80 per cent humidity was divided into three lots. A lot which was impregnated in cold transformer oil was found to have exactly the same strength as the original sample which was not treated. Another sample was impregnated in petrolatum compound at 80 deg. cent. and was found to be 24 per cent stronger than the original sample. As four papers were grouped together during the tearing test, it was thought that adhesion between the samples might have been responsible for the increase of strength. Some of the original paper and some of the impregnated paper were tests with only a single sheet. With single sheets the impregnated paper was 18 per cent stronger than the original. Thus, perhaps a portion of the increase was due to the cause suspected.

The next striking fact to be observed is the extremely large variation in tearing resistance with change in moisture content of the paper. Thus, a given sample of untreated paper was subjected to an atmosphere of approximately 100 per cent humidity. A similar sample was subjected to a vacuum, both samples being treated at ordinary room temperatures of about 20 deg. cent. The tearing resistance of the second sample was less than 40 per cent of the first sample. Samples exposed to air of different degrees of humidity show intermediate tearing resistance.

With the paper tested and with the oils used, and for the relatively short series of tests which were made, there is an astonishingly small difference between the aging effect at a given temperature of paper submerged in oil and the paper exposed to air in an enclosed vessel, either sealed or unsealed. This is contrary to the usual understanding that the deterioration in air is much greater than under oil. However, some observers have reported the contrary, namely, that deterioration is more rapid under certain classes of oil than in air. Such differences as we have found are not entirely consistent and thus there is room for further study of the matter. In general, the tendency seems toward a higher rate of deterioration under oil than in air at high temperatures and where the periods are very short. For longer periods of time, the rate of deterioration seems to tend to be a little greater under oil, (but the difference is not of very great amount). In any comparison which we so far have made, the difference has not been greater than the difference due to perhaps five degrees variation in temperature.

The above paragraph applies specifically to a simple mixture of 80 per cent commercial petrolatum and 20 per cent commercial resin. Tests were also made with a mixture of 80 per cent commercial resin oil and 20 per cent commercial resin. Commercial differences in the ingredients do not have a very important effect upon the particular property under consideration, namely the aging of the paper. Therefore it is considered that the test with these two specific mixtures will represent fairly well the result to be expected with most of the impregnating media which are in extensive commercial use. Tests were made with similar lots of paper in the respective types of compound and at 125 deg. cent. for periods of one week and two weeks. The results indicated a greater rate of deterioration in the resin oil compound. The difference was not large and we do not consider the results conclusive, except so far as they indicate that the difference in the effect of the kind of saturating medium is not very great; not as great as would be caused by a temperature difference of 5 deg. cent.

Measurements of the aging of several different kinds of paper, were made. There is a fairly definite variation obtained with different samples of standard grades of Manila cable paper. For comparison, some Kraft paper composed of wood pulp was tested, also a sample of Bond writing paper. These last named samples were much lower in original strength, but the percentage of reduction due to the aging was of the same order of magnitude as for the Manila. The decrease in tearing resistance at 125 deg. was as great on one sample of Manila paper as would be expected with the best Manila paper at a temperature of perhaps 10 degrees higher, and for the same time. From the standpoint of aging, no paper was found better than the paper which furnished the basis for the curves in Figs. 4 and 5. Even though the deterioration of a sample of low original strength is not at a higher rate in terms of the original strength, the paper would be at all times, weaker than another sample of better original quality.

In Fig. 4 are given three curves showing the loss of tearing resistance at 125, 150 and 175 degrees respectively. In the case of the 175-degree curve, the tearing resistance of the samples, tested before opportunity for reabsorption of moisture from the atmosphere, in terms of the strength of the original paper dessicated under vacuum at room temperature, is plotted as ordinates. Number of hours aged is plotted as abscissas. The tests at the other two temperatures were made on samples which had been allowed to come to equilibrium as regards moisture, in air at about 30 per cent humidity and 20 degrees temperature. The ordinate in these two cases is expressed as the tearing resistance in percentage of the original tearing resistance of the paper, with it also in equilibrium as regards moisture content with atmosphere at 30 per cent humidity. As all the samples had been exposed

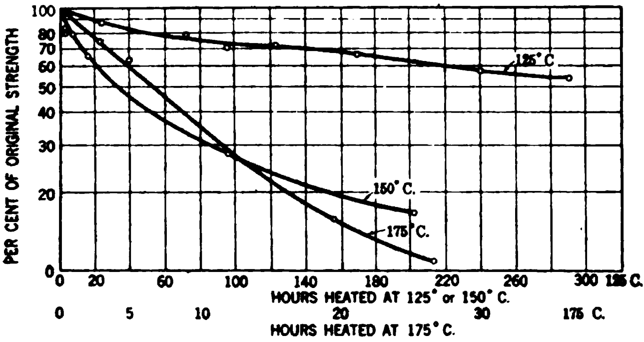

FIG. 4

together to the atmosphere for a long period of time the conditions were similar. Tests were made on some of these samples aged, after dessication and in comparison with dessicated but unaged original samples, and the percentage of strength based on these figures is not materially different from those plotted, in Fig. 4. For purposes such as now under consideration, values determined as for the 175-degree curve would be preferred.

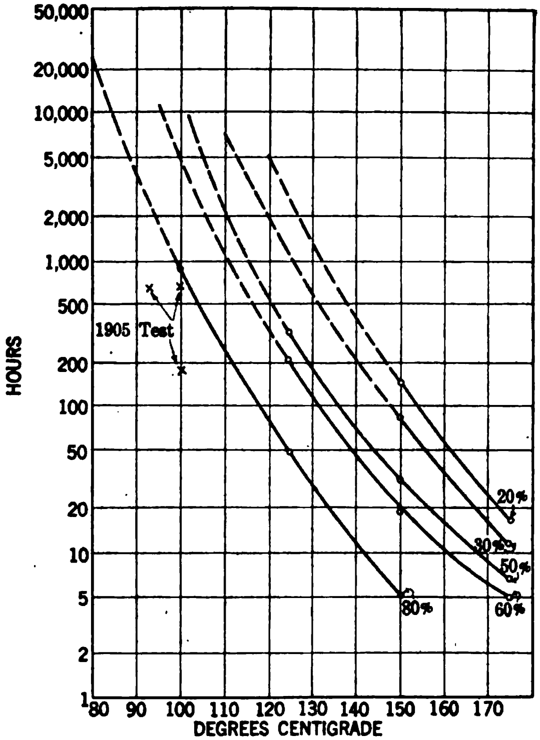

Fig. 5

From the data of the curves in Fig. 4, Fig. 5 has been constructed as showing the relation between temperature and number of hours required to produce certain definite amounts of deterioration. Each curve on Fig. 5 represents a certain definite amount of deterioration and shows the length of time required for the tearing resistance to fall to a certain percentage of the original tearing resistance. Thus, the lowest curve shows the time required to come to 80 per cent of the original tearing resistance. The three points indicated by a cross belong to another series as will be mentioned presently.

A point on one curve in Fig. 5 is given at 100 degrees. This is from a test on paper saturated in petrolatum compound and maintained at 100 deg. for 37 days.

It will be noted that the scale of time is logarithmic and covers several decades. The curves have been extrapolated at the left-hand side with the idea of estimating time required for deterioration at lower temperatures with correspondingly very long time. Of course it is recognized that extrapolation is likely to cause serious errors in conclusion and therefore these conclusions must always be interpreted with caution. If some additional points are obtained at the higher temperatures, and particularly if points are obtained at lower temperatures than those at which most of the tests were made, it will be quite reasonable to expect fair accuracy of extrapolation into the range of temperature with which we are most concerned. Even with the data as now presented, some important conclusions can be drawn.

It is interesting and important to note that the different curves approximately parallel each other. The slope of these lines is of perhaps as much importance as the actual numerical values. Thus, it will be observed that the rate of deterioration doubles for a temperature increase of about 8 deg., at temperatures near 125 deg. Within range of 100 deg. and lower, the increase of rate of deterioration with temperature is even greater. Thus, as the lower curve in the figure is drawn, the rate of deterioration is doubled in about 5 deg. increase of temperature. These rates correspond respectively to increasing the rate of deterioration tenfold in about 25 deg. and about 15 deg. respectively. That is, the rate of deterioration at 100 deg. is roughly ten times as great as at 85 deg.

As the curve is drawn, an appreciable deterioration (about 20 per cent) is shown at 85 deg. in about nine thousand hours, that is about one year. In case the extrapolation is wrong and the deterioration at 85 deg. is much lower than thereby indicated, the slope of the curve is greater and the increase in rate of deterioration with temperature is even greater than the figures named in the preceding paragraph.

On the basis of the slope of the curve as drawn, in Fig. 5, may be determined the effect of intermittent loading at high temperature. Thus the annual rate of deterioration of a cable loaded so as to produce a temperature of 100 deg. cent. for about two and one-half hours per day and a temperature much lower than 85 deg. for the rest of the day will be about the same as that of a cable loaded continuously so as to produce a temperature of 85 deg. Now it is not improbable that the rate of deterioration at 85 deg. is materially lower than as indicated in Fig. 5. If that is correct, then an intermittent load producing a temperature of 100 deg. cent. for some shorter period than two and one-half hours would be equivalent to a continuous load producing a temperature of 85 deg.

If the continuous loading produces a high temperature, followed by higher temperatures for short periods, the deterioration due to both conditions must be considered. Thus, on the basis of the specific values given in Fig. 5, the rate of deterioration of a cable having a temperature of 100 deg. for two and one-half hours per day, and of 85 deg. for the remaining time would be nearly twice as great as for a continuous temperature of 85 deg.

We may now refer again to the 1905 tests previously described. While of course, as stated, no permanent record could be kept showing the degree of deterioration of the paper in the 1905 tests, the following method of comparison was used. Samples which were aged recently and had been measured, were compared with the recollection and description of the aged paper of the old tests in an attempt to obtain some rough numerical value for the deterioration obtained in those tests. Little doubt was entertained that the sample which had been maintained at 100 deg. for four weeks, was as bad as recently tested samples, which had been reduced by aging to 30 per cent of their original tearing resistance. On this basis, the deterioration obtained at 100 deg. in the old series of tests was as great as would be expected from recent tests at 125 deg. in the same length of time. This difference in temperature is large as compared with the uncertainty of the comparison, and we may thus consider that roughly the relation just stated exists between the old and the new tests.

It is important to consider the possible causes of this large difference. It is not unlikely that part of the difference lies in the paper itself used with the two tests. There is an apparent possibility of accounting for perhaps 10 deg. of the difference in this way. The data for the curves in Fig. 5 are based largely on tests on saturated paper exposed to air; the 1905 tests were upon samples of cable saturated with resin oil and sealed in the lead cover. The apparent greater rate of deterioration obtained in recent tests on resin oil saturated samples as compared with petrolatum saturated samples, or perhaps with samples exposed to air, may account for another part of this difference. This is particularly true as there was some evidence in the recent tests of a greater rate of deterioration at temperatures lower than 125 deg. of samples saturated in compound than those exposed to air.

A further point of difference between the old tests and the new is that the old tests were made upon an actual cable sample which had undergone a certain amount of aging in the process of manufacture, whereas the recent tests were upon paper not subjected to such preliminary aging. The shape of the curves in Fig. 4 would tend to point to this fact as not helping to account for the difference, but the reverse. That is, a sample loses a greater percentage of its original strength in a period of given length after the beginning of the aging than it does in a second equal period, even with the loss of strength in the second period expressed in terms of the strength at the beginning of that period. However, in a study of the possible reasons for the different results obtained, this difference in the manner of tests should not be overlooked. We are not at all inclined to be satisfied that the three possible causes mentioned are sufficient to account for the difference between the old and the new tests.

Even after there are available sufficient experimental and laboratory data as to the degree of deterioration occurring at different temperatures and under different conditions, there still remains to be determined what is an allowable amount of deterioration from the standpoint of operation of the cable. As the deterioration is continuous and gradual and as there is no temperature at which there is a sudden change in the rate of deterioration, any definite limit to deterioration which is set will be arbitrary. We will now consider the matter of limitation, in the light of operating experience and operating demand.

It is known that cables have been in service for long periods of time and with various degrees of deterioration of the paper even up to practically complete carbonization. In most cases where such conditions existed, we believe that not a very large amount of cable has been thus affected. Thus while there are numerous individual examples of cable samples which have been found to operate successfully with a large degree of damage to the insulation, there is actually in service a comparatively small number of feet of such cable. Thus there is not any extensive record of the serviceability of cable in considerably damaged condition. Furthermore, it is probable that such cable furnishes a large proportion of the operating failures that are not due entirely to external injury, an amount of failure insignificant in comparison with the amount of such cable in service. Furthermore, such cables may fail in service from injury due to causes which would not be harmful to good cable. Though examples of this sort are cited as evidence of how far the deterioration may be carried without causing electrical failure, we do not believe that it is the policy of operating engineers to recommend operation which may be expected to produce this condition in any short term of years.

Many of the cables known to have operated successfully after severe overheating have had very liberal insulation thicknesses. This fact has an important bearing on their successful operation after being damaged. Thus if an attempt were made to standardize an operating temperature which would produce any material deterioration of the insulation it would need take into account the liberality of insulation in proportion to the operating conditions.

One viewpoint of the operating companies is evidenced by the attitude of some of them with regard to cable specifications. We will refer particularly to the recently published specification of the N. E. L. A. Underground Systems Committee, which was produced after extensive conference with many engineers representing different parts of the industry. In the discussion preliminary to that specification, the operating engineers emphasized very strongly the importance of the ability of a cable to withstand installation under severe conditions, removal from the duct line if necessary and reinstallation, again under severe conditions. It is not to be thought that extreme sacrifices would be made to insure the ability to reinstall especially under severe conditions, but we know that it was emphasized as an important matter.

In view of this attitude, it would seem unreasonable for this Institute to standardize operating conditions which would materially reduce the serviceability of cables from this standpoint. It is proper however, for the Institute to recognize that operating conditions will sometimes exist which will make it a matter of economy and of good engineering to operate at temperatures expected to produce rapid deterioration and probable short life. It may be cheaper and better practise to replace cable at intervals when necessary than to put into service from the beginning, a much greater amount of cable. Or it may pay to load a cable to such an extent that there will be rapid deterioration, though reasonably long life will be expected provided it is not moved or mechanically disturbed. A single example of such a condition is where initial temperatures are very high and thus where a relatively slight increase of temperature would permit a very great increase of current rating. This subject is not for detailed consideration at this time, but is a matter which must be decided by each cable user on the basis of ultimate economy. The data furnished at this symposium regarding deterioration at higher than ordinary working temperatures, will be of great value in the analysis of such special cases.

As a definite suggestion in line with the above discussion, it is submitted that the Committee assign a temperature limit which may be expected to produce a reduction of 20 per cent of the original tearing resistance of the paper after a period of say five years' time. Supplementing this, higher temperatures may be named which will produce the same annual rate of deterioration if the temperatures are maintained for a certain corresponding number of hours per year.

This specific suggestion, together with the specific data in Fig. 5 will lead to the following temperature limits:

For continuously maintained temperature	78 degrees
For maximum temperature maintained five hours per day, temperature during remaining part of day low	85 degrees
For maximum temperature maintained two and one-half hours per day, temperature during remaining part of day low	90 degrees
For maximum temperature maintained one-half hour per day, temperature during remaining part of day low	100 degrees

It is to be expected that there will be available to the Committee additional information which will confirm or modify these suggested values.

It has been remarked that cable failures have resulted from the motion of cables due to contraction and expansion with variation of temperature, resulting in cracked sheath and ultimately in failure due to entrance of moisture. It has been reported that satisfactory means for preventing this difficulty have been found. Cable users should be cautioned in regard to this matter and should be informed as to the preventative methods.

Where data are available concerning any considerable length of cable which has been severely damaged in commercial service by overheating, it will be of particular value if any unusual phenomena are reported. For example, in tests made by one of the authors in 1913, a 100-ft. length of cable was heated to a temperature such as to produce rapid deterioration. It was found that a large amount of gas escaped from the ends which were at first unsealed. Accordingly, terminals were attached to the ends so as to prevent the escape of the gas, and a steam gage was attached so as to register the pressure inside the sheath. This pressure reached a value of about 100 lb. per sq. in. at which pressure the sheath burst and the pressure was relieved by the forcing out through the hole of a large amount of compound and gas.

In the recent series of tests, where samples were sealed in lead tubes, some difficulty was experienced in maintaining the seal tight, and there was considerable evidence of internal pressure. This information points to a possible limitation of amount of allowable deterioration quite aside from the changing properties of the paper itself.

It is worthy of particular note that, for ordinary conditions, much more is to be lost by operating at a temperature a few degrees too high than by operating at a few degrees lower than the maximum allowable temperature. For example, based on an earth temperature of 20 deg. and an operating temperature of 85 deg. a change of 5 deg. in the operating temperature will be produced by a change of current rating of only 4 per cent under ordinary installation conditions. But an increase of 5 deg. above the correct limiting temperature will result in a shortening of the life by one-half. Therefore, an accurate knowledge of actual temperatures of cables is a requisite for obtaining maximum performance without danger of material reduction in life of the cables.

Without a margin of safety in the temperature rating, the importance of accurate knowledge of temperature conditions or proper allowance for want of this knowledge is of fundamental importance. Neglect of this will lead to cable damage far more costly than a sacrifice of carrying capacity due to operating at even less than the safe maximum. Thus in rating cables for current it is important to leave whatever margin is necessary to insure that uncertainty in knowledge of conditions does not cause an excess of temperature.

Acknowledgment is made to Mr. F. E. Coxe for valued work during the series of tests just concluded and to Mr. N. C. Davis for the investigation of the "pop-tester."

APPENDIX

Machine No. 1 is essentially a very light vertical tension testing machine having a maximum reading, or automatic recorder. The scale was read as centimeters deflection but a calibration was made in grams by hanging weights from the dynamometer spring.

Standard samples were prepared for test as follows. Strips of paper usually one inch wide were cut in lengths of 7¼ in. Five holes ¼ in. in diameter were punched along the center line of the paper and about ⅝ in. between centers, the first hole being about ⅝ in. from one end. From the other end a cut was made with scissors to within ¼ in. of the last hole. From the end of that hole to within ¼ in. of the next a cut was made with a razor blade. This was repeated for each hole.

Test was made after clamping the free ends on each side of the scissors cut in the jaws of the testing machine. The maximum force required to tear from the cut into the next hole was read for each of the five holes. The average of fifteen readings taken on three samples of paper constituted a single test.

Other forms of test sample were used at an earlier date but the above was especially useful as giving a considerable number of tests so as to give a good average within a small sample and in a reasonable time.

In the description of the No. 2 machine, we quote largely from a statement by the maker of the machine.

The machine is known by the maker as the "Elmendorf Paper Tester." It was finally perfected in the Forest Products Laboratory of the United States Forest Service. It is the understanding of the writers however that the makers of the machine have added some improvement since making the statement which we quote in the previous sentence, and that these improvements are embodied in the machine with which we have worked.

The testing machine simulates the action obtained by one method of hand testing on paper when a sample piece of paper is torn between the fingers in order to "sense" the average tearing force. The instrument consists essentially of a weighted pendulum which, in swinging from a predetermined height, tears the sample to be tested and indicates the tearing strength of the paper by the amount its swing is retarded.

Briefly, the machine operates as follows. A certain number of samples of the paper to be tested (generally four in our tests) are selected, each 6 cm. long and 3 or 4 cm. wide. (Our tests were made on samples 1 in. wide). The samples are then set in the machine and held in the clamp as shown in Fig. 2. A knife on the machine is made to cut a slit in the paper, giving a start for the tear. The cut is a definite distance of 2 cm. thus giving a distance of 4 cm. for the tear.

The pendulum is then allowed to fall and as it does so, it tears the paper as indicated in Fig. 3. As the tearing action proceeds, the motion of the pendulum is retarded by an amount proportional to the work done in tearing the paper. For each grade of paper tested, the pendulum will therefore rise to a different height on the right. The lighter the paper and the less work required to tear it, the higher the pendulum will rise, and the heavier the paper, the less the pendulum will rise. The greatest height to which the pendulum rises on the right is registered by a pointer and can be read when the pendulum comes to rest. This reading is a measure of the work done in overcoming the tearing strength of the paper through the length in which it was torn. It is proportional to the average tearing strength of the paper when the number of papers and the distance torn are constant.

In using machine No. 2 for measuring tearing resistance, usually four pieces of paper were tested simultaneously and the total length of the tear was 4 cm. The individual readings thus gave the average resistance for the four papers. Most of the data recorded are the average of four individual measurements. As this gives an average of the tearing resistance of 64 cm. of paper, it may be expected that the results will be capable of very exact duplication for uniform paper. This is further illustrated by the following. On twenty different measurements, each the average of four or five individual tests, the numerical differences between individual measurements and the average of all were taken. This difference was expressed in per cent for each set of readings. The average of these average differences of twenty tests was 4 per cent, the maximum was 11 per cent. This was on a very brittle (aged) sample. No other difference exceeded 8 per cent. It seems reasonable therefore to expect that the error of the measurement of any sample taken should seldom exceed 5 per cent and that the probable error of any result did not exceed about 2 per cent.

However, it has been found that samples tested on different days under conditions considered identical have given differences of as much as 20 per cent. The difference is attributed to variation of paper at different parts of a roll which was evidently not entirely uniform in tearing resistance. Of course, wide variations are to be expected if moisture content is allowed to vary and it is very hard to keep this under control. The variation of 20 per cent was found however in the case of two sets of samples which were dessicated by drying in a vacuum at a temperature of about 20 deg. cent. It is not known at this time just how much influence small changes of temperature or small changes in the residual pressure in a vacuum chamber may have affected these results.

With the No. 1 machine for measuring tearing resistance, we considered the limit of probable error of the measurement of the actual samples under test, to be about 10 per cent.

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PERMISSIBLE OPERATING TEMPERATURES OF IMPREGNATED PAPER INSULATION IN WHICH THE DIELECTRIC STRESS IS LOW

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PRESENT day practise in the operation of low-tension cables (7500 volts or less) is mainly based upon the temperature limitations generally specified by cable manufacturers and others, who from extensive experiments and research have determined the temperature at which the physical structure of impregnated paper as used for cable insulation, suffers marked deterioration in both its mechanical and electrical properties.

Naturally the conditions thus observed have formed the basis for certain guarantees on cable, a course which has had the support and approval of large users of cables as the result of their observations and experience. As the result of this experience there was evolved the present Standards rule limiting the permissible conductor temperature in low-tension paper insulated cable to 85 deg. cent., with suitable reductions in temperature as the voltage is increased. There being no evidence before us that paper insulation has suffered injury at a temperature as high as 85 deg. cent., and as this limit is slightly lower than the temperature at which paper has been noted to suffer deterioration (93.5 deg. cent.) we may, therefore, assume that low-tension cables may be safely operated up to 85 deg. cent. for indefinite periods without injury.

We find an apparent conflict with this temperature limitation in another Standards rule covering fibrous or Class A insulation when used for the insulation of electrical apparatus. This rule in specifying 90 deg.

cent. as the permissible observable temperature for impregnated materials also permits an allowance of 15 deg. cent. for hot-spot correction or temperature gradient through the insulation, this raising the limit of conductor temperature to 105 deg. cent., or 20 deg. cent. higher than is specified for paper insulation in cables. For non-impregnated materials it is to be noted that this rule provides for a reduction of 10 deg. cent. in the above values.

It is questionable if the limit placed upon Class A insulation is not too high, since in the writer's experience it is possible to point out cases where Class A insulation has failed in modern apparatus, transformers and rotating machines, in which the temperature of the conductors has never been permitted to reach the observable limit of 90 deg. cent.

While the initial failure in these cases has been limited to a relatively small portion of the winding, the insulation on the balance of the winding has been found dried out to such a degree as to be too brittle to withstand the handling necessary to make replacements and an entire rewinding has been required.

There is a marked difference in the conditions under which insulation in electrical apparatus and in cables is operated. In electrical apparatus in general, excluding oil-cooled equipment, the insulation is largely exposed to the air at all times, and in many instances is cooled by forced ventilation, thus affording ideal conditions for the impregnating compounds between layers to be gradually dried out or expelled, leaving the entire body of the insulation to become more brittle as it is continued in service.

In the case of cable insulation wrapped in a waterproof covering or enclosed in a lead sheath, it may be contended that since evaporation is impossible, the insulating compounds will be retained in their original sticky or semi-fluid condition, and the insulation as a whole retain its original value if not otherwise injured.

This, however, is not always borne out in practise, as was noted recently when attempting to install some 1,500,000-cir. mil, 600-volt, single-conductor cable which had been held on the original reel as emergency stock for over ten years. The insulation on this cable, although never in service, was found to be too brittle to withstand installation.

Unfortunately, cables are not always laid in horizontal positions, thus affording opportunities for the compound to gravitate to the lower positions in the cable, leaving sections of cable at the higher levels free of compound and unsuited to heavy or maximum loading conditions. These conditions develop more rapidly in cables alternately heated and cooled, with resulting expansion of the sheath creating voids, thus permitting migration of the compound.

While these conditions are beyond the control of the user, he also must contend with the imperfections in manufacturing processes whereby the impregnation is sometimes imperfect, thus leaving dry sections of insulation which hazard the safety of cables so constructed when operated at the higher temperature limits.

Operating practise in the loading of low-tension paper-insulated cables as reported by various users varies so widely that it is impossible to draw exact conclusions or to establish any fixed rule as to the maximum temperature at which such cables may be safely operated.

Reports are presented from time to time showing that cables of sizes specified have successfully carried certain loads in amperes for stated periods either regularly or as occasion required, without apparent damage to the cables. The loadings thus specified have indicated that the commonly accepted ratings of such cables have been materially exceeded, even though the final effect on the cable could not be determined. Reports of such a character are valueless unless accompanied by the necessary supporting data clearly showing the conditions under which the record was made.

In the last analysis the sheath temperature is the only definite factor from which to determine the actual operating temperature of a cable, since the temperature of the conductor may be determined with a fair degree of accuracy from the sheath temperature.

It has been frequently suggested that the insulation normally used on heavy low-tension cables, 250 to 600 volts, while necessary for mechanical strength, is really unnecessary for the voltage employed, and that therefore a substantial amount of deterioration may occur without affecting the life of the cable.

If this view be accepted for low-tension cables, it cannot be accepted with the same degree of confidence for cables operating at 2300 - 4000 - 7500 volts, since in no case is the factor of safety, if based upon the thickness of insulation employed on the higher-voltage cables, in any manner comparable with that of low-tension cables.

To secure the same degree of safety the thickness of insulation must be increased many times, to do which is at once uneconomical and at times, a physical impossibility. That the same factor of safety is not attained in practise is amply demonstrated by the record of failures in cables from 2300 to 7500 volts, they being sufficiently numerous as to form a most powerful argument against any proposal to increase their loading by an increase in operating temperature.

For a number of years it has been customary to provide for very severe bending tests in all specifications under which the breakage of the paper insulation must be kept at a minimum. If as has been reported by a number of eminent investigators and cable manufacturers, paper when subjected to a temperature only slightly higher than 85 deg. cent (*viz.* 93.5 deg. cent) does actually become brittle and lose a substantial percentage of its original tensile strength, then it must of necessity be unable to withstand the bending tests specified for new cable.

Since it is not always possible to be sure that cable once laid, will never be disturbed or moved to new positions, it must follow that the users, when reinstalling cable which has been operated at temperatures sufficient to damage in some measure the insulation next to the conductors, must finally accept the cable in its new position under a materially reduced standard of perfection from that which was acceptable at the time of original installation.

If this is a fair statement, then it must be admitted that the original specification was too severe and that it is not unlikely that cables which may have been rejected under tests were at least as serviceable as cable reinstalled under the conditions suggested above.

To retain the present provisions for bending tests may therefore be regarded as an economic waste as reflected in the final cost of cable. It cannot be denied that if paper is subjected to high temperatures its useful life as insulation must gradually or rapidly be shortened as the case may be.

The real question for the cable user to decide is the rate of depreciation which he is willing to accept as the result of operating his cables at high temperatures. Various interests have contended for different rates of depreciation on underground plant, but it is contended by the writer that in specifying a rate to be applied to paper-insulated cable there should not be included any allowance for depreciation due to loading. Depreciation allowed for aside from any consideration of values at different periods should only include allowances for physical depreciation due to wear and tear in position, external injuries, electrolysis and similar agencies affecting the life of the cable sheath.

This point of view has been rigidly adhered to in the operations of the company with which the writer is connected in that loading of cables has been such that, so far as is known, the temperature limitation of 85 deg. cent. has not been exceeded. In the operation of its 230-volt d-c. system during the past eleven years, careful records of d-c. feeder loads have been maintained, from which the data in the following tabulation were obtained.

This record includes only those feeders which are composed either in whole or in part of one million single-conductor or one million concentric cables, and shows the number of hourly readings in excess of 800 amperes which have been observed each year. It is of interest to note that while a total of 75,800 readings have been noted in the eleven-year period, 53,040 or 70 per cent have occurred in the winter months, clearly indicating the seasonal load characteristics of the system which afford such favorable conditions for operating cables at relatively high load values during the period of lowest temperature.

In estimating probable temperatures from this record for comparison with the test records presented by Mr. Torchio allowance must be made for the lower sheath temperatures noted in this system, these resulting from uniformly lower earth temperatures and in some measure to the use of smaller conduit lines, none of which are sufficiently congested to create abnormal temperatures.

The relative values may be determined from a number of typical test readings here presented. Temperature readings were taken just inside ends of ducts in manholes and are comparable with readings taken from thermocouple No. 20 in Mr. Torchio's exhibit on page 175.

Observations on June 6, 1920 were taken after four days of very hot weather.

Viewing these data in the light of our operating experience and allowing the usual temperature gradient through the insulation, it is questionable if the conductors of any of the cables under observation have ever reached a temperature of 85 deg. cent. unless due to local hot spots of which there has been no evidence.

Summarizing our experience with this installation, it appears that in eighteen years of use of single-conductor and concentric low-tension feeder cables there is no record of a failure of these cables due to loading conditions. This may be declared to be evidence of too great conservatism in the use of the plant investment in question. We believe, however, that it is justified by freedom from interruptions of service in a city where rendering the best possible service at all times is considered the first duty of the company.

With this record behind us, we are loath to depart from our present practise and approve a higher degree of loading which must invariably develop new troubles,

RECORD OF LOADS ON 230-VOLT D-C. FEEDERS—1910—1920
FIGURES IN TABLE INDICATE NUMBER OF HOURLY READINGS OBSERVED IN EXCESS OF 800 AMPERES

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Totals for year	No. of feeders observed
1910	800 to 900	920	160	120	200	80	0	0	100	20	380	440	600	3900	32
	900 to 1000	220	0	20	0	0	0	0	0	20	60	120	220		
	Over 1000	0	0	0	0	0	0	0	0	0	80	20	120		
1911	800 to 900	720	740	280	280	60	40	0	0	220	140	500	1360	6140	36
	900 to 1000	240	300	80	20	0	0	0	0	20	40	140	560		
	Over 1000	100	120	0	0	0	0	0	0	0	0	0	180		
1912	800 to 900	800	480	280	280	100	120	20	20	100	280	580	960	6320	50
	900 to 1000	420	120	200	80	100	40	0	0	0	200	140	280		
	Over 1000	60	200	60	60	60	0	0	0	0	60	60	160		
1913	800 to 900	400	140	940	80	120	60	20	0	160	120	660	460	4240	39
	900 to 1000	80	100	140	40	100	0	0	0	0	40	220	200		
	Over 1000	20	0	40	0	0	0	0	0	0	0	60	40		
1914	800 to 900	300	160	40	100	60	0	0	40	160	180	240	540	2240	33
	900 to 1000	60	20	0	0	0	0	0	0	20	20	60	60		
	Over 1000	40	0	0	0	0	0	0	0	120	20	0	0		
1915	800 to 900	240	160	180	40	20	60	0	0	40	420	340	760	3280	33
	900 to 1000	140	40	80	0	0	0	0	0	0	100	140	360		
	Over 1000	80	0	0	0	0	0	0	0	0	40	0	40		

RECORD OF LOADS ON 230 VOLT D-C FEEDERS—1910-1920—*Continued*

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Totals for year	No. of feeders observed
1916	800 to 900	360	440	220	500	180	200	100	20	0	380	680	1020	5400	46
	900 to 1000	140	140	40	120	20	20	0	20	0	80	200	240		
	Over 1000	20	0	20	120	0	0	0	0	0	20	20	80		
1917	800 to 900	280	120	0	580	300	240	40	40	280	260	400	440	3520	31
	900 to 1000	120	140	0	20	20	0	0	0	0	20	120	100		
	Over 1000	0	0	0	0	0	0	0	0	0	0	0	0		
1918	800 to 900	120	520	360	460	280	380	220	140	100	880	680	1560	7760	39
	900 to 1000	0	80	100	80	100	120	0	20	140	160	280	680		
	Over 1000	0	60	0	0	0	0	0	0	40	20	60	120		
1919	800 to 900	900	1440	460	440	420	380	420	740	1040	960	1220	1300	13540	57
	900 to 1000	240	580	80	100	120	140	160	80	360	360	580	460		
	Over 1000	0	140	0	0	0	20	20	40	40	140	120	40		
1920	800 to 900	1560	880	1060	1600	1060	1640	1080	620	940	1260	1260	1000	19460	71
	900 to 1000	580	240	320	420	340	1080	60	220	580	300	440	240		
	Over 1000	140	0	40	0	140	80	0	20	140	40	60	20		
TOTAL	800 to 900	6600	5240	3940	4560	2680	3120	1900	1720	3060	5260	7000	10000	75800	
	900 to 1000	2240	1760	1060	880	800	1400	220	340	1140	1380	2440	3400		
	Over 1000	460	520	160	180	200	100	20	60	340	420	400	800		

Number of readings Oct. 1 to Mar. 31 = 53,040
Number of readings Apr. 1 to Sept. 30 = 22,760

until conclusive evidence is at hand which will justify increasing the present limit of 85 deg. cent. for low-tension cables as now incorporated in the Standards.

Viewing the data presented by Mr. Torchio in the most liberal light, I cannot agree that it is conclusive since the physical condition of some of the sections of cable submitted after completion of his tests leaves much to be desired if the cable in question was to be continued in service. Further, the exhibit in question clearly shows the risk involved in basing the loading of cable upon temperature observations at one point. It is almost a foregone conclusion that as shown in this case there are points in any cable, where, due either to local conditions of external temperatures or to the effect of dry spots in cable insulation, excessive heating develops with resulting rapid deterioration and final destruction of the insulation. To operate low-tension cables at higher temperatures than at present is permissible cannot be all gain, since the carrying capacity of other cables within the same conduit must be reduced owing to the higher duct temperatures which must prevail. That such conditions are not unlikely to develop new troubles cannot be denied, therefore in the interest of safety to plant and avoidance of cable failures in general it seems the better policy to adhere to conservative temperature ratings rather than to operate at the highest possible temperature.

Date	Load	Duration of load	Sheath temp.	Approx. temp. N. Y. cable sheaths with same loading. Thermocouple No. 20
Feb. 18, 1920	875 Amperes	6 hr.	16 deg. cent.	
Feb. 19, 1920	700 "	6 "	27 " "	
June 6, 1920	900 "	6 "	50 " "	
June 6, 1920	800 "	6 "	33 " "	60 deg. cent.
June 6, 1920	800 "	6 "	39 " "	60 " "
June 6, 1920	700 "	6 "	43 " "	
Dec. 23, 1920	800 "	6 "	30 " "	60 " "
Dec. 23, 1920	890 "	6 "	33 " "	

If, as seems quite likely, the existing temperature limit of 85 deg. cent. may be safely exceeded for short periods without injury to paper insulation, it would seem preferable to apply an overload rating to low-tension cables which may be taken advantage of as occasion requires rather than to operate such cables on a load factor basis.

The objection to the latter method lies in its impracticability of application to the operation of any system of distribution. In actual service each feeder operates on a load factor of its own which may or may not coincide with the system load factor, or whose maximum load period may be independent of the system peak load, hence each feeder must be treated as an individual case. Further, load factor makes no distinction between seasonal loadings, a most important factor in the operation of a cable system, since loadings which may be permissible in winter must be materially modified during summer periods. Finally while it may be possible to specify an allowable overload rating for this class of cables in terms of temperature, it is next to impossible to determine whether such limit is not exceeded in practise, a condition which should cause one to lean to a conservative standard such as the present Standards rule as the more desirable policy.

DISCUSSION ON "THE MAXIMUM SAFE OPERATING TEMPERATURE OF LOW-VOLTAGE PAPER-INSULATED CABLES" (DEL MAR), "PERMISSIBLE OPERATING TEMPERATURES OF IMPREGNATED PAPER INSULATION IN WHICH THE DIELECTRIC STRESS IS LOW" (TORCHIO), "PERMISSIBLE OPERATING TEMPERATURES OF IMPREGNATED PAPER INSULATION IN WHICH THE DIELECTRIC STRESS IS LOW" (ROPER), NOTES ON "THE EFFECT OF HEAT ON IMPREGNATED PAPER FROM CABLE INSULATION" (CLARK), "THE EFFECT OF HEAT UPON PAPER INSULATION" (FISHER AND ATKINSON) AND "PERMISSIBLE OPERATING TEMPERATURES OF IMPREGNATED PAPER INSULATION IN WHICH THE DIELECTRIC STRESS IS LOW" (ELDEN), NEW YORK, N. Y., FEBRUARY 17, 1921.

Frank M. Farmer: It is evident that we are having here a duplication of the situation which has existed in the various committees which have had to do with this subject for some time—just the same divergence of opinions. It seems to me that we are exhibiting here this morning something that might be classed as an indictment of the engineering profession. We have gone along all these years and have probably invested several hundreds of millions of dollars in underground cable and it is only just now that we are beginning to get data on the fundamental characteristics that are the basis of proper operation of such cables, namely, the relation between the temperature and the deterioration in definite, concrete, quantitative terms. That, it seems to me is not a very enviable situation for us as engineers to face, but that is what this situation means. However, we are now beginning to get information of this character and perhaps we will now progress.

Of course, after we get this relation between temperature and deterioration, our problem is not solved by any means, the application of the data to the operation of cables under service conditions is a very complicated problem involving for example the question of deciding what shall be the deterioration limit and the matter of measuring the actual temperature of the cables under operating conditions.

I wish to make a few remarks about physical tests of paper. I agree with Mr. Del Mar that the tensile tests are of little value. The tensile test and the bursting test—that is the Mullen test—are standard tests in the paper industry. The Mullen test has been discarded very largely in the paper industry because of its general unreliability and indeterminate physical basis. The tensile test is a thoroughly reliable test but it is not a good measure for our purpose, for the reasons given in these papers.

Another test which we have used a good deal in some of our work is the folding endurance test, a test common in the paper industry, that is, a strip is folded back and forth in an automatically controlled machine. That test is undoubtedly a most valuable test of that characteristic of paper, which is most important in the ordinary use of paper, namely the durability under repeated handling or manipulation. But that is not the sort of characteristic we are interested in in connection with cables.

The kind of test which has been proposed by Mr. Del Mar and by Mr. Atkinson, the tearing test, looks very promising. It has all the qualifications which a standard test should have, namely, the necessary precision and reproducibility, and for cable purposes, it has the very important feature that it is probably as near a measure of the most important characteristic we are interested in as we can get.

George B. Shanklin: I do not believe that anything that has been presented warrants any radical change in the Institute limit of 85 deg. cent. for this type of cable. Before any such change should be made the various phases of the problem must be more thoroughly settled. For instance, no one can say today whether the limiting feature of high temperature operation of low-tension cables is the physical deterioration of the paper insulation or the damage that might be caused by contraction and expansion of the cable length due to the wide range of temperature encountered. It would appear from present knowledge that both of these features play an important part.

All of the papers presented this morning with the exception of Mr. Torchio's ignore this factor of contraction and expansion and center their attention upon the physical deterioration of the paper. It seems to be the general concensus of opinion that the paper must not deteriorate to a degree whereby lengths of cable cannot safely be withdrawn and reinstalled in other positions without the necessary bending causing the insulation to tear. If this is to be the criterion for judging deterioration it is certain that it is a much more severe criterion than that applied to other forms of apparatus. No one would require, for instance, that armature coils that have operated for years at the limiting temperature of 105 deg. cent. be removed from a machine and then replaced. It is certain that the insulation would be far too brittle to withstand this abuse, and all that is required is safe continuous operation without disturbance of their position in the slots. Since, therefore, cable insulation cannot be allowed to deteriorate to the same degree as other forms of Class A insulation such as armature coils, distinction must be made and the temperature limit must be lower than that of 105 deg. cent. covering the more general forms of Class A insulation. This statement is made on the assumption that paper cable insulation deteriorates at about the same rate as the rest of the Class A materials. Another reason why the temperature limits should be lower is that cables are supposed to last for a much longer time than other forms of apparatus. Where a life of 10 years without renewed insulation for a motor or generator is considered reasonable a cable is supposed to last not less than 20 years, because its insulation cannot be renewed.

The results Mr. Del Mar gives on the aging of sample lengths of paper cable are very surprising when compared with those obtained from other sources. In four weeks time Mr. Del Mar found that the paper in these cable samples showed a decrease of 32 per cent in tensile strength, and 65 per cent in tearing strength. Mr. Clark's results are much more in line with others. He found that in twelve weeks' time at 100 deg. cent. there was a decrease in tensile strength of 25 per cent, and tearing strength of 41 per cent. In an article in the *E. T. Z.*, October 5, 1916, p. 535, Mr. L. Schuler gives some interesting results of aging cable paper in resin oil. He found that 22 weeks aging at 100 deg. cent. caused a decrease of only 15 per cent in tensile strength. The General Electric Company has in the past few years made some very extensive tests on the aging of various types of Class A insulation. The results have never been published as the work is not yet completed. We have, however, aged cable paper in mineral oil and found that 72 weeks at 100 deg. cent. caused a decrease of 60 per cent in tensile strength.

A general review of all sources of information would make it seem almost certain that paper insulation as used in cables deteriorates at a slightly greater rate than other forms of Class A materials, such as coil insulation.

In summing up it would appear—

1. That the general run of Class A materials have a temperature limit of 105 deg. cent. which is now accepted almost without question.
2. It is acceptable to allow these materials to deteriorate to a much greater degree than cable insulation.
3. Results up to the present time indicate that

cable insulation deteriorates at a faster rate than other forms of Class A insulation.

4. The maximum "hot spot" temperature in lengths of underground cable cannot be as accurately estimated from observed readings as in other forms of electrical equipment.

When these factors are considered, it is apparent that the temperature limit of paper cable insulation should be something less than 105 deg. cent. If the temperature limit of 85 deg. cent is to be raised, this change must be approached with caution and an increase to 90 deg. or 95 deg. cent. is all that should be attempted until more is known of the subject.

In his paper Mr. Torchio recommends graded temperature limits, varying from 105 deg. for a load factor of 33 per cent to 90 deg. cent. for all load factors above 66 per cent; he bases his recommendation on the fact that peak loads only continue for short periods of time and higher temperatures for these short periods are, therefore, allowable. There is no denying the logic of this assumption provided periodic contraction and expansion is ignored, but I believe that Mr. Torchio has lost sight of the principle upon which temperature rules have always been based. A given temperature limit is supposed to cover all possible conditions from the best to the worst. The flat temperature rule does not prohibit overloads for short periods of time. It merely specifies that these overloads must not continue after the temperature limit is once reached. The conditions, especially in the large operating companies, are sometimes such that it is safe to exceed the limit for short periods of time.

E. B. Meyer: Regarding the matter of safe operating temperature for low-voltage paper insulation cables, it is my belief that the whole question has been summed up in Mr. Del Mar's paper in which he says:

> This increase of carrying capacity may sometimes warrant the use of cables at destructive temperatures, and the operating engineers may rightly consider such a procedure justified. It is questionable, however, whether the Institute should make a rule to cover such cases, as an Institute rule necessarily represents an agreement between manufacturer and user and it is unreasonable to expect the manufacturer to share the risks resulting from operation at or beyond the limit of endurance of his product.

Mr. Elden's experience in operating the cable system of the Boston Edison Company shows that over a period of 18 years there has been no record of a cable failure due to loading conditions. While as stated this may be considered as evidence of too great conservatism, it seems justified by the freedom from interruptions and the fact that continuity of service is of prime importance to the utility company.

The matter of safe operating temperature is one on which there has been considerable difference of opinion for some years past and is a subject which is receiving a great deal of attention by various central station companies and engineering bodies, particularly during the last 18 months.

Mr. Torchio has submitted some evidence which tends to show that the Institute rule giving 85 deg. cent. as a safe operating temperature for low-tension cables, is too conservative. However, there are a number of factors to be considered before deciding upon any plan which involves the operation of cables at higher temperatures than the present rule permits.

As stated by previous speakers cable specifications provide for certain bending tests depending on the diameter of the cable. If the cable is installed and allowed to remain in the duct without being disturbed except by the natural expansion and contraction incident to load and temperature changes, it seems reasonable that a slight deterioration of the paper is not particularly harmful.

If, however, the cable is likely to be involved in a rearrangement necessitating its removal and reinstallation, a deterioration of the paper might prove to be the cause of a failure.

As I see it the problem is one which depends for its solution on the judgment of the individual operating engineer, who must arrive at a decision after balancing the probability of accelerated depreciation against the more intensive use of cables under a schedule of higher ratings.

If the manufacturers will consent to an upward revision of operating temperature for cables to be installed and left in place, the user would welcome such a revision, as he would get all the benefits.

It would seem to me that in any attempt to get a guarantee with a maximum temperature over a limited period and a low temperature the rest of the year, it would be impossible for the user to get an adjustment unless he had a practically continuous record of the actual operating temperature from the time the cable went into service.

W. Irving Middleton: The following tests show the deterioration both electrical and physical of the impregnated paper used in cables subject to temperatures above 85 deg. cent.

A 30-in. piece of 500,000 cir. mil single conductor with 6/32 in. wall of insulation lead covered with the ends sealed up was placed in an oven and heat applied. A temperature of 90 deg., 100 deg., 110 deg. and 125 deg. cent. was maintained at each point for one week of 50 hours, at the end of each week a piece was cut off and voltage, breakdown, tensile and tearing test made upon the strips of paper (Fig. 1). At the end of the first week the dielectric strength was 83 per cent of its original value and was 70 per cent at the end of the fourth week with the curve apparently flattening out.

The tensile strength at the end of the first week was 80 per cent of its original value and 43 per cent at the end of the fourth week and dropping rapidly. The tearing test showed greater deterioration than the others, being 73 per cent at the end of the first week and only 29 per cent at the end of the fourth week, bearing out the fact that the tearing test is a better test of deterioration.

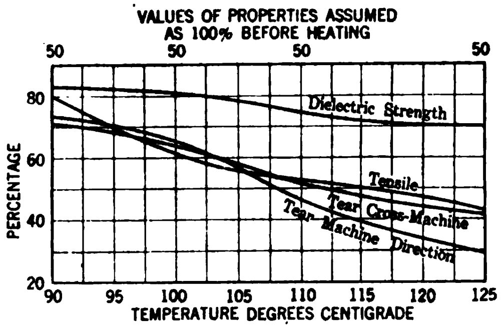

Fig. 1—Deterioration of Cable Paper with Heat.

Two tearing tests were made, one in the machine direction of the paper and the other crosswise of the machine. The crosswise test, while it started lower (71 per cent) only went down to 41 per cent. To all appearances, the paper was as good as before heating.

The above tests, while of short duration, would indicate that there was no very serious deterioration at 90 deg. to 100 deg. cent.

The objection to recommending that the present limit of 85 deg. be raised is that we do not know at present at what temperatures a great deal of cable is operating which we believe is well above this figure, and that many operating companies will feel that they should increase the load on their cables with disastrous results in many cases.

Similar research was started in England in 1914, the work being done by the National Physical Laboratory, Liverpool University and individuals. Mention is made of this work in the *Electrician* of December 24, 1920 as Buried Cable Research and again in the January 28th, 1921 number under Heating of Buried

Cables in which number it states that the final report might not be forthcoming for two to three years. I believe that we should take sufficient time to thoroughly investigate this very important matter before making any recommendation to change the present rules.

I might state along this line that within the last week I was called up by the engineer of quite a large operating company, who told me that he had some cables he thought were getting pretty warm. I asked him if he knew about what the temperature of the cables was, and he said yes, they measure 135 deg. on the outside. I asked him where he made the measurement, and he replied that he had made it inside the duct. I then asked him how much further in the duct he could go, and he replied that he did not know. A little while afterward he said that he went 20 ft. and got 154 deg.

W. A. Del Mar: Centigrade temperature?

W. Irving Middleton: No, Fahrenheit temperature. These figures show the position the ordinary engineer is in. He gets a temperature test on a cable at the point that is most accessible, but does not know what the temperature is further in the duct.

Comfort A. Adams: Rating of machinery or cables or apparatus should be based upon two considerations—first, the scientific facts underlying the phenomenon involved, and second, agreement. Assuming we know all the scientific facts, that we have complete knowledge of everything, for example, that we know exactly how long it takes insulation to deteriorate to an undesirable point, at each particular temperature—assuming we have all that information. Even then the rating must be a matter of agreement, and it does not make any difference, within reasonable limits, what the agreement is, or what the rating is, because, understanding what the rating means, the operating man and user can adapt the cable to service, by choosing a proper cable for the particular service.

The same considerations apply exactly to the whole question of machinery.

If we were to increase the temperatures, allowable operating temperatures, increase the ratings of the cables as suggested here by several of the speakers, then we would be in this position—that the uncertainty of how long the temperature exceeded the safe continuous point would put the manufacturer in a very undesirable situation. Moreover, we have not this complete knowledge. We are still in doubt on many of these points. The operating man does not know where the hottest spot in his system is, and from the operating man's point of view, as I see it, I should prefer very much to keep the rating down to a reasonably conservative basis.

So that it is my own conviction, until we have a great deal more information as regards the actual causes of deterioration, and the scientific underlying facts, and until we have a method by which the operating man can keep in closer touch with exactly what is going on in his cables, by which he can know where the hottest spots are, and all about them, that it is unwise to increase our safe temperature limits, and the rating of the cables any appreciable amount.

H. R. Woodrow: The current carrying capacity rating of cables is dependent on the permissible temperature rise and the permissible temperature rise is dependent on the ambient temperature in the duct system. Unfortunately, the limits of the ambient temperature of duct system or hot-spot correction factor have not been determined.

I agree with Mr. Torchio that 100 deg. cent. maximum temperature of paper cable for short duration would prove satisfactory and is a limit which could be specified if we were sure of the temperature conditions of the duct system in which the cable is to be installed. I therefore, feel that we should give the temperature gradients in the duct system thorough consideration before placing such a maximum limit for general standardization.

The temperature rise of a cable above the surrounding earth in a duct system, can be represented by the equation

$$T = \frac{W\,c}{K\,c}\left(1 - e^{-\frac{K\,c}{C}t}\right) + \frac{W\,b}{K\,b}\left(1 - e^{-\frac{K\,b}{B}t}\right) \quad . \qquad (1)$$

$K\,b$ = Average watts per duct foot of other cables in the bank per degree cent. rise above earth of cable, due to other cables under continuous load conditions.

$K\,c$ = Watts per cable foot per degree cent. rise of copper over earth under continuous load with other cables carrying no current.

B = The average watt hours per duct foot required to raise the temperature of cable and duct so that the temperature of the cable in question will be raised 1 degree cent. (energy supplied from other cables.)

C = The average watt hours per cable to raise the cable 1 degree cent. at copper (other material raised proportionately.)

$W b$ = The average watt loss per duct foot of other cables in the bank.

$W c$ = The average watt loss per foot of cable in question.

It is evident from this equation that such a large part of the variables entering into the temperature of cables is dependent on the duct conditions that a careful analysis should be made of duct systems for determining the ambient temperature of the cable in the duct system.

The savings to be effected by the operation of a cable at higher temperature are not in the same proportion to the savings in rotating machinery as the transmission efficiency of a low-tension cable is inversely proportional to the load, whereas, with rotating machinery the efficiency increases with increase in load up to a maximum point which is usually at full-load conditions or higher.

P. H. Chase: At least until we have more definite answers to the first three insulation problems, which Mr. Del Mar has discussed in his paper, his conclusions seem to be the only safe ones,—that the Institute should not establish in its standards, the principle of operating low-tension cable at temperatures destructive of its insulation.

The variables entering into cable applications are greater in number and greater in their effect on the operating temperatures than with apparatus. In the case of apparatus, factory test conditions are not often widely different from operating conditions. In the case of cables it may be said there is almost no relation between factory tests and operating conditions, so far as temperature is concerned. This is evident, solely considering the ambient, probably the most important single factor. With apparatus the ambient is air or water which carries off the heat largely by convection, that is, actual movement of the ambient, but with cables in duct lines, there is no true ambient for the duct line and soil absorb heat, and dissipate it only by conduction. Again in the case of cables, there is the great influence of the loading of neighboring cables.

For all these reasons the desirability of operating cables above their safe continuous temperatures seems to be primarily the operating engineer's problem.

Mr. Elden's point that the sheath temperature is the only definite factor from which to determine the actual temperature of the cable, offers to the operating engineer the best means of determining the proper loadings of his cables as actually installed. With proper allowance for hot spots and errors in readings, the loadings of cables can be determined accurately enough from the sheath temperatures.

Regarding the proposed determination of temperature limits by load factor, in addition to leading to the disadvantages mentioned in Mr. Elden's paper, I wish to present another objection; that the load factor in itself has no definite relation to the operating temperature of the cable.

For instance, if a cable has a 60 per cent load factor, on a daily basis, there may be full load for one hour, and 58.39 per cent full load for 23 hours, or there may be full load for 14.4 hours and zero load for the rest of the day. The load factor in each case is the same, but in the last case there is full load on the cable for fourteen times as long as in the first case. The same relation exists on annual load factors. These are the two extreme cases, but actually we will have load curves in different cables having the same load factors but with the maximum loading period, say, five times as long as for the other. The shape of the load curve determines the relation, not the load factor alone.

On account of these reasons we cannot determine ratings by loadings or hours of full load—we must go to ratings based on temperatures and time, properly weighted as shown by the results of further tests and experience with insulations. Then the operating engineer will have a definite means for determining how far he is justified in operating cables for short periods at excessive temperatures.

R. J. Wiseman: Sometime ago we were making some special electrical tests on a sample of dry paper cable to determine the effect of drying and then impregnation on the electrical properties. After making the desired tests we decided to run the temperature of a 3-ft. high-voltage cable up to 160 deg. cent. to see how much the cable would deteriorate. We took samples of paper from the belt and from the conductor and tested them for tensile strength and tearing resistance. To our surprise, the tearing resistance, which we also believe is to be preferred to the tensile strength as a guide to the quality of the paper, decreased to 62 per cent of its value prior to treatment. This was after both a heat and vacuum treatment.

As a comparison we took some impregnated paper from a cable which had gone through the regular factory treatment and its tearing resistance had decreased to 90 per cent of its value before treatment. We compared the tensile strength tests and we found that the impregnated paper had practically the same percentage of tensile strength as prior to the treatment, whereas the paper on the belt of the dry cable was 107 per cent and on the conductor 95 per cent of the before treatment values.

We do not believe that the tensile strength is a better criterion of the deterioration of the paper than the tearing test and are in accord with the views of Mr. Del Mar and Messrs. Fisher and Atkinson.

I am not inclined to accept Mr. Clark's method for conducting the tearing tests. His method of test is too closely a tensile strength test and not strictly a tearing test although he does get tearing action.

As to the effect of temperature on the operation of cables, I think it would be a good idea if Mr. Torchio would have some samples of paper taken from the four sections he ran the heat tests on, and have the samples of paper tested. I think he would find the deterioration was considerable and of such amount that he would question the use of these cables in the future.

I think Mr. Torchio's idea as to the use of load factor for determining the allowable operating temperature of cables can be improved upon. If we take the average yearly load factor shown by the curves in Fig. 21 in his paper we get an average of 43 per cent, his average winter load factor is 56 per cent and his summer load factor 34 per cent. On the basis he suggests we could run the cables up to a higher temperature in the summer time than in the winter time. I doubt if we should do so. I do think a better basis is to follow out the suggestion made by Mr. Elden and also Messrs. Fisher and Atkinson, namely, give the cable an overload rating for a short period. This is to be preferred to increasing the maximum operating temperature of the cables and at the same time meeting the desires of some operating companies for increase of load at urgent times on their cables. I would not advise putting an overload ruling in the Institute rules at the present time, but leave it as a tentative rule to see how it would work out.

The Cable Research Committee of the National Electric Light Association is conducting a very thorough investigation on the subject of temperature of operation of cables. Many of the operating companies intend to present data to this committee, showing their load conditions and the corresponding temperatures. I think it would be well if the Institute would wait until the Committee makes its report and recommendations, and then we surely will be in a better position to know what a cable can do.

William Maver, Jr.: I should like to answer Mr. Clark's question as to when the guarantee for cables was born. I think that perhaps I was present at the birth of that arrangement. Of course, operating engineers were just as human then, 1889, as they are today, and although the manufacture of underground cables was strictly in its infancy at that time, the operating engineers wanted guarantees. The manufacturer of one cable asked my advice as to whether they could safely give a guarantee and I advised him as follows:

"If you will exempt mechanical injury to the cable, and heat effects you can safely do it, in my opinion." But, of course, the heat effects I had in mind were not those you are discussing today.

An operating engineer of one of the large electric light companies, who was negotiating with a cable manufacturer for the purchase of a cable asked if I thought it would be safe to accept a guarantee of three years. I told him I thought it would be, and he took the cable. On another occasion I was asked by a cable manufacturer if he could safely guarantee his cable for three years if subjected to 10,000 volts. I replied "If you will let me write the specifications, why, yes," I specified a cable of 8/32ds India rubber. I believe the cable was in operation for over nine years, then owing to changes in methods it was taken out of the subways and put into use as service leads into buildings.

In 1890-1891, the only types of insulated cables used for high-tension electric lights and power circuits, were India rubber compounds, and oil impregnated fibrous cables. I think impregnated paper did not come until seven or eight years later. The high-tension circuits employed a maximum electromotive force of 4000 volts on direct current arc lighting circuits. Subsequently, alternating-current circuits of 1000 and 2000 volts were employed for arc and incandescent lighting. It was not until the fall of 1898 that an electromotive force of 6600 volts was used on feeders of the Edison Illuminating Co. If I am not mistaken the insulating material of these feeders was varnished cambric. Otherwise, it was oil impregnated paper.

The current employed in the arc lighting circuits was about 9 to 12 amperes. Hence—the current-carrying capacity of these arc lighting cables (which comprised the major portion of all the cables) so far as it related to increased temperature due to C^2R losses did not call pressingly for attention on the part of the officials of the high-tension arc lighting companies. The Edison Company no doubt had data on that point from its experience with high current-carrying capacity underground tubes or cables, but as these were "low-tension" cables, their operation did not come within my purview.

There was, however, a condition in the early years which related to heat effects. I refer to the high temperatures in the conduits due to the presence of defective steam pipes in many of the downtown streets of New York. By actual tests the temperature in some of the ducts was found to range at times from 100 deg. to 200 deg. fahr. The rules of the Board of Electrical Control required that the initial tests of the underground cables should have an insulation resistance of 15 megohms per 100 volts per mile, and thereafter a minimum of 5 megohms per 100 volts per mile. There were some data extant with regard to the effect of high temperature on the insulation resistance of fibrous cables, but so far as my knowledge went, nothing definitely was known on this point with regard to India rubber. It became known to me later that Sir William Thomson (Kelvin) had made certain tests which indicated that bare copper in contact with rubber when heated to 100 deg. cent., had a destructive effect upon the rubber, oxidizing it and rendering it brittle, while platinum had but little effect and silver and zinc had none on the rubber under similar conditions. It is assumed that tin would also have been neutral and as the copper used in rubber insulated cables was almost invariably tin coated, the effect noted by Sir William Thomson would probably not have been observed on tin coated copper. I undertook a series of tests in the early part of 1890 to obtain data on the subject. The results of these tests were published in the "*Electrical Engineer*," New York, August 12, 1891.

In the early days referred to I do not think it was generally anticipated that the current-carrying capacity of underground cables for electric light and power circuits would be raised to a point where the temperature would be likely to affect adversely the insulating materials of the cables. At least my own views on that subject, are disclosed in the following extract from a letter that I wrote to a cable manufacturer, November 17th, 1893. "The question of the effect of the temperature on rubber cables is occasionally brought up by those who overlook the fact that rubber cables are vulcanized at a temperature of about 300 deg. fahr. and the statement is sometimes made that under increasing temperatures the rubber softens, this permitting the conductor to decenter. It would certainly be poor policy to employ conductors, as feeders, of such small carrying capacity as to unduly raise the temperature of the conductor, but assuming that such a wasteful policy should be followed, the only effect upon the rubber insulation would be to increase slowly the degree of vulcanization of the cable On the other hand, the insulation resistance of fibrous cables falls enormously under heat and if such temperatures as those referred to had to be met continuously in the subways (fortunately they have not) the fibrous cables would not, in the matter of insulation resistance be able to meet the electrical requirements of the Subway Rules."

A. E. Kennelly: I want to make a plea for a conservative point of view in regard to cable temperatures in our rules, and also for the absence of overloads at this time. We have had so much trouble with overloads in the past, that we should eliminate them altogether from the rules. It seems to me all the evidence is in favor of the hottest spot applying to cables just as in dynamo-electric machines. It is the same material we are dealing with, cellulose, and we know from the books in our library, that cellulose is a durable material if it is kept cool and undisturbed, but we also know, as soon as the temperature reaches about 100 deg. cent., molecular decomposition or thermolysis, sets in, and produces brittleness, which is probably more easily manifested in a bending or tearing test, than in a tensile-stress test; so that we may expect as soon as the temperature reaches a certain point, that decomposition will set in. We should therefore endeavor to avoid exceeding the limiting temperature at the hottest spot. That is a simple statement, but the difficulty comes in not knowing what the temperatures of our cables are, as has been pointed out by various speakers and in the papers.

It seems to me that we should attempt to do what the manufacturers of dynamo machines have already done. They found it necessary not only to take observations upon machines in factories, and occasionally in the dynamo room, but also by inserting permanently recording temperature indicators in the large machines, and I think it will pay to put in temperature indicators in our ducts. Of course we know the problem is much more complicated in the case of underground duct systems than it is in the case of the simple machine, but we have, fortunately, the condition that whereas a machine's vibrations may play a detrimental part and tend to accelerate destruction under overheating, in the ducts the temperature changes are comparatively slow, and we do not have the agitation, and vibration to bring about breakdowns.

One of the slides this morning showed the interesting fact that Sunday was a day of grace, not only for human beings, but also for cables, and there is an advantage, therefore, in having a blue law for cables, but it may not be an unmixed advantage, because if we could keep the temperature absolutely constant on a cable, we should avoid all stresses due to expansions and contractions, and thereby we might be able to insure a longer period of life in cases where the limiting temperature has been exceeded, so that possibly the contraction that goes on on Sunday may offset some of the advantage of reducing the average temperature in starting the next week cool.

If we can run pressure wires inside multiple conductor cables, and if the cables were subject to the same environment throughout, we might expect to be able, by simple recording instruments, to measure the resistance, and therefore the temperature in the cables, and make a complete record of the temperature of the cable itself, making some small correction, perhaps, for the difference between the temperature of the pressure wires, and the temperature of the active conductor or conductors in the cable.

When alternating-current cables are to be considered, the difficulty is increased by inductive interference from the working wires on to the pressure wires, or temperature recording wires, but in the case of direct-current cables, that difficulty would be small. The temperature measuring wires are perhaps only applicable to new cables, and we want to find out what is going on in actual cables already in the ducts. It seems to me if we can find a duct section, between two manholes, which represents the hottest and most crowded condition, provide a spare duct, and run a special twisted-pair measuring cable in it, we can measure the average temperature of that special length of twisted cable by measuring its resistance. By connecting this test cable to a proper recording instrument, records can be kept of the temperature in the middle of the cross section of the duct, and the temperature so obtained should differ but little from the temperature of the cables adjacent.

A few measurements made in that way would enable us to obtain measurements of great value, without much expense, but until we do take steps to obtain continuous records, of the temperature in the ducts either by thermocouples or resistances, we shall be perpetually at sea, and wondering what the temperature is. It is most important, until we do obtain such information, that our standardization rules should be very conservative, and not attempt to run up to the maximum possible value.

In regard to the differences of summer and winter temperatures of cables in our streets, we know that they are very considerable, and that the temperature of the cables may be 25 deg. higher in summer than in winter, from observations which have been made, but that would be all automatically measured if we had a continuous record in the central station of the temperature in the duct, run, or of a short length thereof. Fortunately the heavy loads come on, as a rule, in midwinter, when the duct temperatures are lowest.

Frank D. Newbury: I would like to discuss this question from the general standpoint of our standardization rules. Numerous references have been made to the temperature limit of 105 deg., as now applied to Class A insulation in electrical machinery. I think it is dangerous to use a temperature limit established for one class of apparatus, or for one application in setting the limit for a radically different class of apparatus and application.

It might be interesting to refer briefly to the different factors that have influenced engineers in establishing this limit of 105 deg. The available information relating to the physical characteristics of the materials is one factor; another is the conditions surrounding the application. One difference between machines and cables has been brought out, in that cables are more frequently required to be removed and reinstalled than armature coils in machines. A third, and a very important factor in establishing any standard, is the personal equations of the engineers concerned in the discussion—the "agreement of minds" that Prof. Adams spoke of—all of our standards are necessarily compromises. A fourth, and probably the most important factor, is the concensus of opinion based on practical operation and experience. In the end, all standardization must stand the test of experience. A fifth factor is the economic factor of *cost.* All standards, to endure, must avoid the danger of undue conservatism on the one hand and unsafe operating conditions on the other hand. From this economic standpoint, different limiting temperatures can be justified for armature coils as compared with magnet coils, and, possibly, a lower limit is justified in cables than in either of these other cases, because the penalties of failure may be greater.

A number of the papers have disclosed very interesting information concerning physical tests of paper and other materials entering into cable insulation.

From what I have just said I think it is evident that that alone cannot be a criterion or guide in establishing safe limits. If we take the tearing test or other tests of the physical characteristics of paper, I think we would have to go down much below 85 deg. to be entirely safe in this respect. The English tests referred to by Mr. Torchio, made some time ago, showed at 75 deg. a marked deterioration, so that this factor, considered without regard to surrounding conditions, would be a rather pessimistic guide.

H. C. Dean: It seems to me that not enough stress has been laid on the economics of the problem. It is very interesting and desirable scientific information to know what you can do in an emergency or under unusual conditions; but as Mr. Woodrow pointed out, if you install your cables so as to obtain the most economical loading you will not, except in rare instances, have occasion to overheat them. When we have occasion to check the economics of a certain problem, we are usually surprised to find how much copper we should use for the most economical installation.

In particular Mr. Roper mentions 180 deg. cent. as being possibly the upper limit for operating cables, and I would like to ask whether he has checked an installation where this temperature would obtain to see whether it would not be more economical to double the whole cable installation, rather than to have the 180 deg., and the attendant energy losses. He showed a duct bank with about three empty ducts where temperatures considerably over 100 deg. were recorded. I would like to ask him whether it would not be more economical to fill up the empty ducts than to stand the large energy losses that must obtain with those temperatures.

D. C. Jackson: Upon reading these papers I was again much impressed by the importance of the nature of the insulation under consideration. Dr. Kennelly has stated that Class A insulation is fundamentally cellulose, but we must qualify that statement, for, in fact, Class A insulation is cellulose plus cementing materials. The Class A insulation that we put into electrical machines has certain cementing materials, and that we put into cables has other cementing materials. We have not learned much about the real effects of the cementing materials, and we therefore cannot say the insulation is the same in these two instances. The two may be and probably are different in the way they react to the effects of heat.

What the definition of the standard maximum temperature of a cable should be, depends on the way in which you look at it. It also depends upon what you consider a cable. As a rule, when one thinks of a cable, he thinks of a structurally simple affair, but that is not the correct view of the cable. For instance, consider a concentric low-tension cable. At the center there is a stranded copper conductor with a certain character of expansion and contraction with changes of temperature. Over this is wrapped paper insulation, which has another characteristic of expansion and contraction with changes of temperature. Laid over this is a spiral wrapping of copper wires composing the other conductor. Again over that is wrapped paper insulation. And outside of the whole, is a lead sheath. Each layer has its own characteristic expansion reactions when heat is applied, and the result probably is to produce a complex system of stresses.

When you begin to think how that thing expands and contracts, you find you do not know what is going on until you have studied it with great care experimentally, and that is a feature that we are only beginning to study effectively. Mr. Torchio has made a very considerable study of the matter, and he gives a little light on it in his paper.

A cable is not a simple thing at all when you heat it, but a very complex thing which acts in a very complex fashion. One has not only the deterioration due to the temperature, *per se*, but one also has the deterioration due to complex reactions due to expansion and contraction. For this reason it is proper to be cautious not to fix the standard maximum of temperature too high until all these features are sufficiently understood to be taken into account.

The standard maximum of temperature should be the highest within which we are sure the cable is safe for continuous running. Then engineers responsible for the design and operation of plant must individually take into account the economic factors (including amongst others, the effect of $I\ R$ drop on regulation, the cost of kilowatt hours converted into heat, and the relations of life and first cost of cable if overheated on peak loads) when they determine the manner of loading the cables under their control.

I believe that defining the standard maximum temperature for these cable structures as the maximum of temperature which is safely applicable to continuous loads, as adopted for the Standards Rules of the Institute is the correct procedure.

Wm. A. Del Mar: It is interesting to note that out of thirteen speakers who have discussed this group of papers, six favor the retention of the present temperature limit of 85 deg. cent., four are non-committal and only two desire it to be raised.

It is also interesting that Mr. Middleton's tests on sealed cables seem to be more consistent with mine than with Mr. Clark's.

Referring to the Fisher and Atkinson paper, it will be noted that their Fig. 5 is based upon certain experimental results which are given in Fig. 4 and that the range of time covered by the experimental results in Fig. 4 is quite limited as compared with the total time covered by Fig. 5. The curves have been extrapolated, where they are shown in broken lines, the scale of the curves is logarithmic. Hence, where tests have been made up to 1000 hours, by extrapolating a little distance on the diagram, values have been obtained for 20,000 hours. I do not think that is quite justifiable to take advantage of the peculiarities of logarithmic paper to extrapolate to such an extravagant degree. In my opinion, the curves of deterioration are not such as to form smooth curves on logarithmic paper. For example, if the curve in Fig. 7 of my paper were plotted on logarithmic paper, it would not run up smoothly like Mr. Atkinson's curves, but would turn sharply to the left. However, the method employed in the Fisher and Atkinson paper is a very valuable one as a suggestion to the committee, whatever misgivings we may have of the actual figures obtained by extrapolation.

Reviewing the group of papers and the discussion, it is clear that the industry is not in possession of all the facts necessary to solve the problem of temperature limits for impregnated paper. Research work is required and there is no reason why it should not be cooperative, both producers and consumers participating in both the control and the expenses of the work.

Philip Torchio: One of the speakers (in the original discussion) stated that one of the fundamentals in rating is the "hot spot" temperature; in laying out a distributing system, you will have a certain portion, say 10 per cent of the whole system, that will carry heavier loads or will operate hotter than all the rest. It is that 10 per cent that determines the average current density of all the rest. If you want to keep down the maximum temperature, you will have to lower the whole system. For instance, in New York the average loading at maximum system load, for the last twenty years, has been about 650 amperes, per thousand cir. mil, but in different years from three to ten per cent of the feeders carried in excess of 1000 amperes, ranging through to 1150. These feeders may have reached temperatures of 100 and 105, and perhaps 110 degrees in the winter months during the sharp short duration peak loads characteristic of the service. It may be possible that by rearrangement of buses, a more even distribution of load on all feeders could be secured, but even then with the existing subway conditions, as described by Mr. Maver, there will always be some cables having hot spots of 100 to 105 deg. To attempt to lower the maximum temperature of the system, the average current density for the feeders would have to be materially lowered and the cable investment largely increased notwithstanding the fact that over 90 per cent of the cables now have temperatures considerably below the 85 deg. cent. at all times, including the brief hours of system maximum load.

Manufacturers know, and their engineers have all here stated that they know that so-called high temperatures of 100-105 deg. have existed on some low-tension cables in this country. They have also referred to the responsibility of their guarantees as a convincing argument that they must play safe and oppose the demand for higher temperature guarantees, even for overloads only. Now, as you have admitted that you know that users have operated your cables at temperatures of 100-105 and 110 deg., will you not also state what have been the claims for damages? I do not recollect that any manufacturer has sustained one cent loss on such guarantees on any low-tension cable, because I do not know of any such failures.

Some of the speakers have claimed that the A. I. E. E. should rule that the limit of safety for cables is 85 deg. cent. because in practise, one does not know what will be the actual temperature of the cable installed in practical service. I expect that these gentlemen mean to intimate that temperatures of 100-110 deg. cent. may exist, but should not be recognized as legitimate elements of this discussion. I hope that I may remove their objections in my conclusions.

Some references have been made to the Kelvin law. That law has nothing to do with the physical characteristics of insulation; furthermore, if the speakers will consider carefully what are the conditions determining the "hot spots" in a distribution system, they will find that the Kelvin law has no bearing upon determining what is the safe temperature limit of paper impregnated cables for overloads or "hot spots." The Kelvin law applies to the average of the system. Design of network, voltage regulation or cable reserve requirements, buses and range of voltage available, arrangements of ducts in subways, loading of cables in same trunk ducts, soil characteristics in dissipating heat, and many other factors determine the hot spot temperature quite independently of the innocent Kelvin Law.

I want, with all emphasis, to refute the repeated assertions made by several speakers that I am advocating high temperatures for "normal rating." They all implicitly referred to normal rating. These speakers entirely overlooked the fact that I stated and I again repeat that 85 to 90 deg. cent. are the maximum safe limits for "normal rating" of fibrous insulation. I also repeat that for "2-hour overloads" aggregating, in duration, less than 10 per cent of the total hours in a year, 105 deg. cent. is an absolutely safe "overload rating" temperature. Most of you have declared that you know it to be a fact that many cables have safely operated at even higher temperatures. We confirm that understanding. Why should we now bury our heads in the sand?

The trouble with us electrical engineers is that, having been carried away by the fad of "single rating," we cannot see except through that small hole and are complacently oblivious to all the other factors and conditions which enter into the important problem of rating. We are headstrong against the evidence of satisfactory experience of over 25 years in the design and operation of electrical machinery, apparatus and cables under "continuous loads" and "overload rating."

The time has come to stop and take a reckoning of our course. Let us forget for a minute the commitments we have made in the past. Let us open our minds to consider the following simple facts:

In mechanics the "elastic limit" of a material is the definite unit stress which must not be exceeded even for a brief time because if that limit is exceeded the material is permanently impaired even if the excess stress is immediately removed.

If we know what is the maximum possible loading that will ever be applied to the material, we may build the structure on the basis of the elastic limit. This we do in the calculation of overhead cables for transmission lines, assuming the maximum stresses on certain conditions of temperature, sleet and wind velocity that may prevail in the territory transversed by the transmission line. In this case we do not apply any factor of safety as we assume that the stresses calculated on the worst condition of temperature, sleet and wind will represent the worst loading conditions.

In the development of standardization of machinery and cables, we have lately been applying the same principle for "single rating." According to this standard, the user, if he exceeds the limit, would assume all the responsibility, relieving the manufacturer from any obligation or guarantee. By taking the arbitrary figures of 105 deg. cent. for machinery and 85 deg. cent. for cable as the maximum limiting temperatures beyond which the user is warned that if he exceeds that limit he does it at his own risk and reponsibility, the engineers have implicitly assumed that the limits of 85 deg. for cables and 105 deg. for machinery mark a definite physical point, like the "elastic limit" in mechanics, beyond which it is impracticable to stress the material without impairing its safety. *This assumption is absolutely unwarranted and not representative of the true conditions.* In fact, in the case of cables, the exceeding of the temperature limit above given is, for instance, of no importance whatsoever if an excess of even 30 deg. or 40 deg. cent. is only of a temporary nature and not sustained for relatively long periods of time. In fact, the dielectric strength of the paper is not impaired at all at even prolonged sustained temperatures of 105 deg. cent. Only the tensile strength becomes gradually and slowly reduced after very prolonged application of temperatures of 105 deg. cent. or over.

The point that must not be lost sight of is that a temperature of 105 deg. cent., if applied only for a few hours in each year, will not reduce the useful life of the cable.

Mr. Del Mar has calculated that 105 deg. cent. temperature would increase the *continuous rating* of the cable 17 per cent. For *overloads of 2 hours or less*, the increased capacity of the cable would accordingly vary from 25 per cent to 33 per cent over the normal rating of 85 deg. From these considerations we can arrive at the conclusion that by adopting the "double rating" the user can with entire safety take advantage of 25 per cent to 33 per cent increased "2-hour overload" capacity in his cables whenever he finds it convenient or desirable to make use of such overload capacity. If you insist to condemn the double rating, you are depriving the user of this 25 per cent to 33 per cent increased capacity in the cables he installs. I do not see a single valid reason presented here today which militates against the double rating with the old standard 2-hour overload. When some of you speak of difficulties in determining the time duration of overloads or the actual temperature in ducts, or quote the Kelvin law and make arguments spurious to the subject, you are befogging the issue. No mechanical engineer would stand for lowering the elastic limit of copper or steel 15 per cent or 20 per cent below the *true elastic limit* on the argument that many users have not accurate means for determining the stresses or the elastic limits;

on the other hand, they would state that if you do not know accurately what the operating conditions are you must apply a factor of safety to the size of the apparatus but not underrate the unit strength of the material. To fool with the physical characteristics of the materials by misrepresenting them with arbitrary correction factors to take care of unknown conditions in application is a procedure that cannot prevail in the long run with good engineering practise. It is wrong in principle; it confuses understanding; and it retards progress.

I have produced clear evidence that impregnated paper in cables will have unlimited life if operated at limiting temperatures of 85 deg. to 90 deg. cent. for "continuous rating" and carry 25 per cent to 33 per cent overloads for two hours or less, giving 105 deg. cent. for "overload rating." The two largest electric power companies in this country have operated cables satisfactorily on the above basis for over 20 years and their engineers have given the industry the benefit of their experience. Will the Institute follow?

D. W. Roper: Discussion by the several authors this morning has exhibited the result that an attempt at some cooperation in investigating the subject has been made, and I want to bring before this meeting how the same subject is being handled across the water. There was organized the British Electrical and Allied Industries Research Association, and they have recently contributed to the Institution of Electrical Engineers a paper which contains a wonderful amount of interesting data.

In looking over this paper, it is found that in a few instances they have investigated very thoroughly, and have come to some conclusions regarding subjects that are still under consideration and investigation in this country, and that further some of the subjects they have listed as intending to investigate have been quite thoroughly covered and conclusions reached in this country.

On the other side they have a far more compact organization and formal way of proceeding, and they have the assistance of the British government in their research work. We have in this country a national research council which I understand is organized for a similar purpose, and if it is proper I should like to bring this point to the attention of the Chairman of the proper Committee, and the officers of the Institute to see if we cannot get the National Research Council to take some interest in this question of the maximum permissible operating temperature of paper insulation: and also to see if it is not feasible to institute some scheme of cooperation between the bodies on the two sides of the Atlantic Ocean that are working on identical problems.

The discussion following the presentation of the papers began with the physical characteristics of the paper. A little later questions of operation were introduced and then one speaker brings in questions of economics. The several authors and speakers exhibit a very wide difference of opinion on the facts regarding the physical deterioration of paper under the influence of heat and electric stress, and until some agreement can be reached upon the facts, it appears to be quite hopeless to reach any conclusion on questions based on these facts. The maximum operating temperature of the cables should be determined by the physical characteristics of the materials and it should be left to the judgment of the operators of the cables to determine in each particular case how much and how long it is economical for them to overload their cables.

Regarding the questions raised by Mr. Dean, it is a comparatively simple matter to draw a curve showing the relation of the current density to the total annual cost of operating the cables, and this is a flat "U" shaped curve. The most economical current for any particular set of conditions is readily determined from such a curve, but the curve is so flat that a rather wide change in current density from the absolute minimum makes very little difference in the total annual cost. The conditions which determine the curve, however, are not very steady. In times of business depression or when the cost of raising money is excessive, there is always a marked tendency to allow the current density to increase, and at other times the tendency is to lower the current density, perhaps to a point below the most economical density. The extra amount of copper installed under favorable economic conditions thus allows of additional load being carried later when the conditions change and the net result is that the current density fluctuates over a period of years, and the amount of the change is dependent upon the financial policy of the company as well as upon engineering conditions. During the past few years the conditions have been quite unusual. While the war was in progress the operating companies were unable to get any cable except for the purpose of supplying industries for carrying on the war. Later when the war was over, the price of materials soared so high that companies could not afford to buy very much cable, and somewhat later the price of money increased to such an extent that the companies could not raise the money to purchase cable. The conditions at the present time with most companies, therefore, follow a period in which the entire tendency was to overload their cables to the limit on account of these difficulties.

H. W. Fisher: There is no reason why we should believe that the current carrying capacity of the same type of cable made by different manufacturers should be materially different. Manufacturers have no immediate way of knowing how their cables will be loaded and for that reason we feel obliged to preserve a conservative attitude in regard to the currents and temperature rating of cables. If 100 deg. cent. were given as the maximum rating, there undoubtedly are many operators who would not hesitate to operate the cables at a considerably higher temperature where occasion demands overloads.

On more than one occasion, the speaker has examined cables, taken out of duct systems, the paper of which was extremely brittle, indicating that they were very much overloaded. Up to the time of withdrawing the cables, the operating engineers had no idea that the cables were overloaded. This would indicate how desirable it is to impress upon the minds of operators the great necessity of making periodic surveys of their duct systems in order to indicate the maximum rise of temperature. In many cases it is possible to place a maximum and minimum recording thermometer in duct systems and determine the maximum and minimum temperatures. I believe until operating engineers universally realize the necessity of making periodic surveys of temperature conditions in their duct systems and actually carry out this important investigation work, that it would be unsafe to materially change the A. I. E. E. rule which has proved to be a safe one.

R. W. Atkinson: Undoubtedly the comparatively meager information which there is regarding the aging effect of high temperature upon paper insulation is the result first of the long time required to make useful measurements, and second of the fact that no satisfactory apparatus for determining the aging effect has been available until recently. Thus, for example, if all of the data which have been obtained as to change in tensile strength due to aging, could be used, our knowledge of the subject would long ago have been very fair. On the other hand, now that we have available a fairly satisfactory method of measuring one of the effects of aging, namely the effect on tearing resistance, we need be careful that we do not overlook as important, but less easily measured effect of heat upon cables such as for instance that of longitudinal expansion and contraction of the whole cable due to changes of temperature.

The extrapolation of data in Fig. 5 was questioned by Mr. Del Mar. It is true that it is always dangerous to extrapolate and that extrapolated values can be used only with full reservation. However, it is a common engineering practise to extrapolate where better data are not available and is entirely allowable if the conclusions obtained in that way are used with the proper degree of caution. It is granted that the caution is very important.

During the discussion, mention has been made of cable for operation at 7500 volts and the fact that conditions are different for these, and perhaps different also for somewhat lower voltages, that is, 2000 or 5000 volts. It seems that such differences are actually outside of the sphere of the present discussion and that the expression "low voltage" should be defined for the purpose of the present discussion so as to exclude any operating voltage which imposes any more severe condition than say 500 or 600 volts operating pressure. Cables for operation at higher voltages would then come under this discussion only to the extent that the difference in voltage would produce no important change in the conditions. It is to be presumed that 2000 volts, or 5000, or 7000 volts will make comparatively little difference in the limiting temperature, but to whatever extent there is a difference, the question is taken outside of the present subject.

Mr. Roper made calculation of temperatures of cables on the basis of an article by the writer in the September 1920 JOURNAL. As I understand it, Mr. Roper has used the data given for temperature rise under continuous load, for determining the temperature rise attained by his cables under intermittent loading. He has used these data for indicating that certain very high temperatures were attained by the copper and the insulation next to it. Now, it is perfectly safe to calculate the temperature rise of a cable for intermittent load as though the load were continuous, if that calculation is used as a basis of limiting the load of the cable. On the other hand, if that calculation is intended as a basis for determining temperatures which have been attained in the past and which therefore are considered to be allowable in the future, incorrect and unsafe values are found. I do not know to what extent this comment may apply to the particular calculations just mentioned, but it is important enough to invalidate conclusions, where it is not given due consideration.

L. L. Elden: In its further study of this subject, it is hoped that the Institute may finally specify the permissible temperature at which paper insulation in cables may be safely operated, and that when so specified its decision will be accepted by all. Since the responsibility of operating engineers to their executives and the public they serve is a serious one, it is extremely desirable that the final decision in this matter as affecting the industry does not rest upon the judgment of those who will take the greatest risks, for in the end it is the public which finally pays all costs.

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CARRIER CURRENT TELEPHONY AND TELEGRAPHY

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Abstract of Paper

This paper briefly outlines first the history of the development of carrier multiplex telegraphy and telephony. The fundamental principles underlying particularly the newer developments of the art are then discussed. Consideration is likewise given to the propagation characteristics of open wire lines, including those containing intermediate lengths of cable. Commercial types of apparatus and actual installations are then described and a brief statement made as to further applications of the art.

THE carrier method of multiplexing telephone and telegraph lines is technically one of the most interesting and important of the developments which have been perfected in the art of electrical communications during the past few years. In this paper we are giving a brief sketch of the development of this art, an explanation of the principles on which it is based, and a description of the applications which have been made in the plant of the Bell Telephone System.

In a carrier multiplex system, a number of separate telephone, telegraph or signaling messages are superimposed simultaneously on a single electrical circuit by employing a separate alternating current, usually called a "carrier current," for each of the separate messages. This carrier current is made to vary in accordance with the variations of current representing the telephone, telegraph or signaling message. The different carrier frequencies which are superimposed on a circuit must differ sufficiently in frequency so that they may be separated from each other at the terminals by the use of proper electrical circuits. Each carrier may be of either audible or ultra-audible frequency, but its frequency must be higher than the highest frequency represented in the message to which it corresponds. These currents are known as carriers, since in a sense, they may be said to "carry" the telephone, telegraph or signaling currents by which they are controlled.

The underlying principles of such systems are old in the communication art and indeed go back to the date of the invention of the telephone itself, for it will be recalled that it was Bell's experiments with the vibrating reed type of multiplex telegraph system which led to his discovery of the telephone. A short history of the art during the forty odd years that have elapsed between the conception of its possibilities by the early communication pioneers and the present realization of their hopes is given below under the heading "Historical."

In looking back over the early history of the carrier art it is now clear that the development of successful multiplex carrier systems had necessarily to await not only the evolution of the fundamental ideas for carrier operation, but also the development of radically new types of apparatus and the developments in electrical wave transmission over wires which have characterized the recent progress of long-distance telephony.

The telephone and telegraph systems which are described in this paper are in daily use over long toll circuits in the Bell telephone system. The telephone installations in service furnish simultaneously as many as four two-way telephone conversations over each circuit in addition to the telephone and telegraph facilities normally afforded by the circuit. The telegraph systems in service are arranged to furnish as many as ten duplex carrier telegraph circuits over each circuit in addition to the telephone and telegraph facilities normally afforded by the circuit. These figures do not indicate the maximum numbers of facilities which it will be found economical to employ ultimately, but cover the facilities furnished by the systems which are now commercially employed.

The increased circuit facilities obtained in this way are, in general, up to the high standards set for the best grade of long-distance circuits. They are relatively stable and are maintained by the regular telephone plant personnel. The carrier circuits, both telephone and telegraph, are so designed that as circuits they fit in completely with the more usual circuit facilities of the telephone system. They may be connected with each other and with ordinary circuits, and, in general, present much the same degree of practicability and flexibility of operation as do the more usual forms of circuits.

While the development has thus succeeded in making available to the communication art new types of circuit facilities, these facilities can only be made to meet the high standards required in a public service plant by the use of correspondingly high-grade equipment which, unfortunately, is correspondingly expensive. Indeed, the cost of these systems, at least at present, is such as to make their use economical only over relatively long toll circuits. For short-distance toll service, and for local exchange service, the equivalent facilities can be provided more cheaply by the older methods.

HISTORICAL

As indicated above, the multiplex carrier art had its origin in the harmonic telegraph systems dating back to the time of the invention of the telephone itself. With such alternating-current telegraph systems are associated the names of Gray, Bell, Van Rysselberghe, Edison and Mercadier. The multiplex feature of these systems is well illustrated by Fig. 1, which is a reproduction of a diagram of Elisha Gray's system published[1] in 1886.

In this figure, the circles numbered 1, 2 and 3 represent vibrating reed transmitting instruments while those numbered 1′, 2′ and 3′ represent the corresponding receiving electromagnetic reeds. When one of the transmitting reeds is vibrated, the electrical waves sent out set into oscillation the correspondingly tuned receiving reed which thus gives out an audible note. The systems invented by these pioneers are

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[1] Leblanc, M., "Le Telephone Multiplex," *La Lumiere Electrique*, p. 97, Apr. 17, 1886.

all characterized by the use of the mechanical resonance of tuned reed instruments for generating and selecting the carrier frequencies involved. This type of system has been more fully developed by Mercadier.

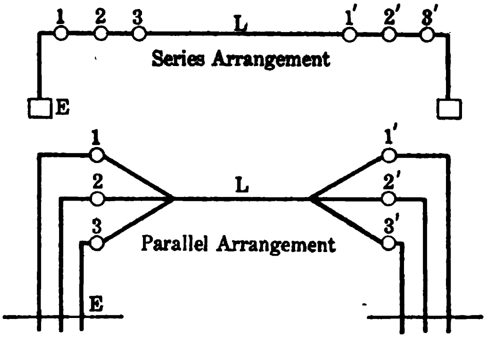

FIG. 1
(Multiple Harmonic Telegraphy)

The Art of the 1890's. Shortly after 1890 there occurred the next outstanding development in this art, namely, the use of electrical resonance instead of mechanical resonance for selecting the carrier frequencies. An interesting piece of technical history is

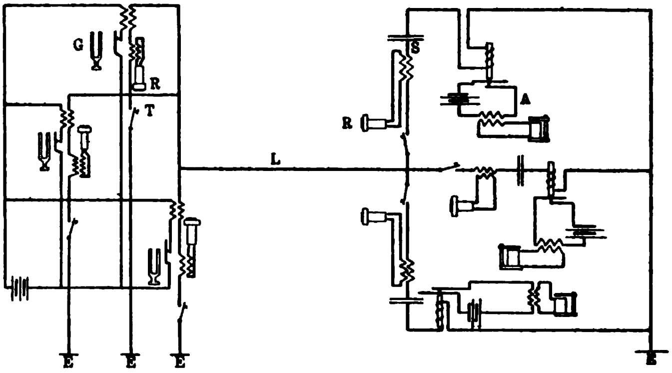

FIG. 2
(Pupin—1892)

disclosed in the manner in which several investigators, Professor Pupin, Hutin and Leblanc, and John Stone Stone, independently invented about the same time the electrical method of selection of a plurality of carrier frequencies. Pupin was adjudged the earliest inventor in the United States. His original system is illustrated in simplified form in Fig. 2.[2]

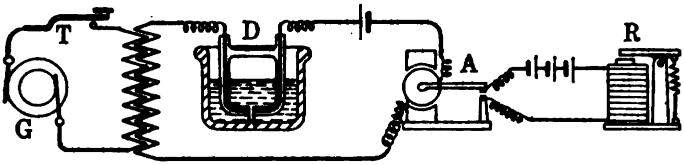

Fig. 3
(Pupin—1898)

In order to permit the successive figures in this historical discussion to be readily followed, a uniform system of lettering their important parts has been employed. These conventions are as follows:

G = Generator of carrier current.
T = Telegraph key, telephone transmitter or other carrier modulating device.
L = Line.
S = Selecting or tuned circuit.
D = Detector.
A = Amplifier.
R = Receiver.
D R = Detecting receiver.
E = Earth.

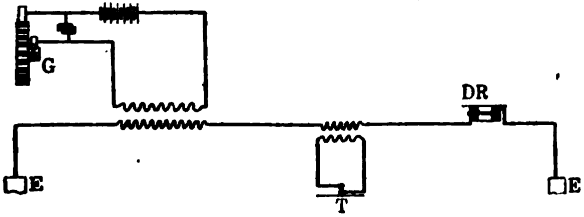

Fig. 4
(Hutin and Leblanc—1892)

By following this lettering Fig. 2 will be readily understood. It will be noted that at each end the line branches into three parts, and that each circuit is tuned by capacity and inductance to a particular

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[2] From U. S. Pat. No. 707,007, 1902.

frequency. It will be seen, furthermore, that each of the channels derived in this manner is arranged for sending in both directions, although not simultaneously. Each generator consists of a self-excited tuning fork driving a contact or a microphone transmitter. Receiving is accomplished either by a telephone receiver or by a vibrating reed device which is operated by a microphone amplifier.

Pupin also invented an electrolytic detector for use in such alternating-current telegraph systems as shown in Fig. 3.[3]

The function of this detector was to rectify the alternating current and thus enable a d-c. telegraph relay to be operated from the rectified current. This marked the beginning of the use of separate devices for performing the two primary functions of carrier receiving; (1) that of reproducing from the carrier the current variations which represent the original signals, and (2) that of indicating the signals, as by a relay or telephone receiver. The separation of these two functions is important in the carrier art because it permits the place at which detection is effected to be separated from that at which the indication or interpretation occurs.

While the contributions up to this time were concerned primarily with telegraphy, they were very soon carried over into the field of telephony (still in the early 90's) by such pioneers as Gibboney, Hutin and Leblanc, and Stone. Their predecessors were concerned with the use of carrier frequencies of the order of a few hundred cycles, whereas, these inventors appreciated the necessity of employing for telephony carrier currents sufficiently high in frequency to preserve the characteristics of the voice currents. Thus we find suggested at this early date the use of carrier currents in the tens of thousands of cycles, which values have since proved to be in the preferred frequency range. Hutin and Leblanc so simply illustrated the use of relatively high-frequency alternating currents for telephony that it is useful to reproduce

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[3] From U. S. Pat. No. 713,044, 1902.

their early diagram as shown in Fig. 4,[4] for the purpose of obtaining in our discussion an appreciation of the principles involved.

This is a carrier telephone circuit of the simplest type, arranged for a single one-way transmission. Connected in the line are three elements, the generator of the high-frequency currents *G*, the voice-actuated modulator *T*, and the detector-receiver *D R*. The generator is a high-frequency commutator; the modulator is a microphone transmitter; and the receiver which is of the dynamometer type serves the double function of detection and of translation into sound waves.

Multiplex operation of this type of carrier telephone channel as devised by these French inventors at the same time (about 1892) is also representative of these early contributions to carrier telephony and is reproduced in Fig. 5[5]. Here we have the carrier telephone channel of Fig. 4, arranged for multiplex operation by the use of electrical selection, each of the carrier circuits being tuned by capacity and inductance to its own carrier frequency.

As indicated the carrier currents of all the channels are introduced into the line at a common point through a transformer. At each terminal the line divides into four branches. Each sending branch contains a microphone transmitter *T* connected into circuit through a transformer. Each receiving branch contains a dynamometer receiver *D R*. The condenser in each transmitting circuit and the inductance in each receiving circuit were employed in tuning the channels.

The multiplex system invented by John Stone Stone[6] was very similar to those illustrated above for Pupin, and Hutin and Leblanc, and is therefore not illustrated. It did, however, contain an important improvement over those of his contemporaries in that he

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[4] From U. S. Pat. No. 596,017, 1897, British Pat. No. 23,892, 1892, French Pat. No. 215,902, 1891.

[5] British Pat. No. 23,982, 1892; French Pat, No. 215,901, 1891.

[6] U. S. Patents Nos. 726,368, 1903; 726,476, 1903; 729,103, 1903: 729,104, 1903.

tuned the local branch circuit individually instead of tuning the system from end to end for each carrier channel, as did Pupin, and Hutin and Leblanc (see their figures). This improvement is evident also in a system which he developed shortly afterward, especially for high-frequency transmission. This is illustrated in Fig. 6.[7]

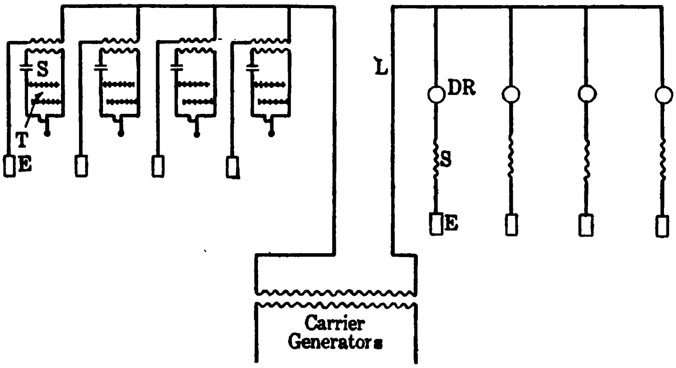

Fig. 5
(Hutin and Leblanc—1892)

Stone devised and tested this system in the laboratories of the American Bell Telephone Company in 1894. The high-frequency currents were generated by means of small arcs which were fed from a d-c. source through a suitable choke coil. One of the electrodes of each arc in Fig. 6 was made light in weight and was attached to a diaphragm which served, when acted upon by voice air waves, to modulate the high-fre-

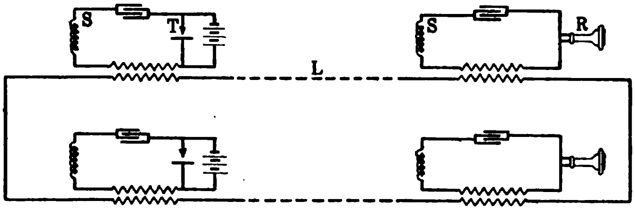

Fig. 6
(Stone—1894-96)

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[7] From U. S. Pat. No. 638,152, 1899.

quency currents generated by the arc. The particular arrangement illustrated is also of interest in showing the tuned circuits at both the sending and receiving ends as associated with the line in a series manner, an arrangement which is an alternative of the parallel connections previously illustrated.

It is also of interest to note in connection with these older multiplex telegraph systems that Van Rysselberghe recognized as early as 1886[8] the advantage of superimposing the alternating-current circuits on an ordinary d-c. telegraph circuit, thereby enabling the ordinary telegraph wires to be employed for the transmission of the multiplex system. While the idea of extending the range of frequencies employed in the multiplex system down to zero frequency and thereby including the d-c. signaling circuit would naturally be obvious in a more advanced stage of the art, its invention at this early date illustrates the clear engineering appreciation these earlier inventors possessed.

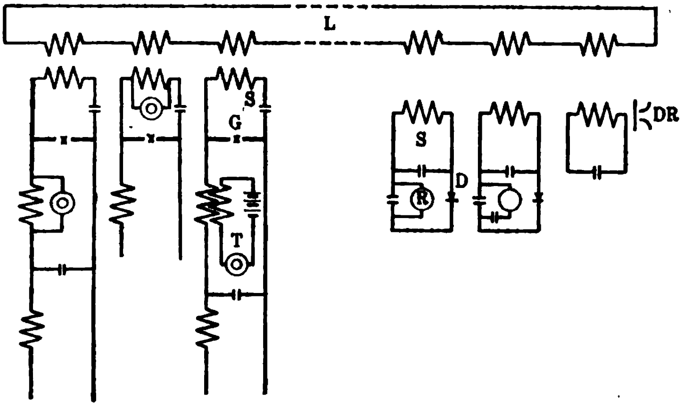

Fig. 7
(Ruhmer—1909-10)

It will be seen, therefore, that the foundation of the carrier art was laid back in the 1890's, at which time there had been contributed these cardinal features:

1. Electrical selection or tuning.

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[8] U. S. Patent No. 363,188, 1887.

2. The use of continuously generated high-frequency carrier currents.

3. Modulation of the carrier, as by a microphone transmitter.

4. Detection and indication of the high-frequency currents by means responsive continuously and proportionally to the received current.

Relations of Radio Developments. With the entrance of wireless telegraphy into the communication field, the attention of those scientists and engineers who might otherwise have developed the art of wire multiplex, so well begun, as indicated above, seems to have been diverted to the new found art. The wireless art started with the use of very high frequencies, generated discontinuously by the spark method, and gradually came to use waves of lower and lower frequency, and of increasing persistency. Finally, with the use of continuously generated waves, the radio-frequency range came to overlap the frequency range earlier employed in high-frequency wire transmission. The wire carrier art started with the use of audible frequencies and extended into the ultra-audible range, where it was later met by the radio frequencies. The similarity of the history of the two developments is illustrated by the fact that the major steps, which are noted above for the early carrier art, also mark the major steps of advancement of the radio art. By reading over the four points above, keeping radio in mind, the parallel will be seen to be quite complete.

These ideas of continuous wave telephone transmission were quite thoroughly appreciated in the radio art by about 1905, although they have not been fully attained in practise until quite recently. It was natural that radio engineers should carry these ideas over to wires, using radio instrumentalities which, while different in form, operated on the same principles as did the means employed by the earlier wire pioneers.

Simultaneously with this evolution of the radio art, attention continued to be given to the older wire carrier transmission by such other investigators as Vreeland in America and Bela Gati and Maior in Europe. About 1906 Vreeland, using his well-known mercury-vapor oscillator as a generator of sinusoidal carrier currents, devised a multiplex carrier telegraph system which embodied improvements in the use of loosely coupled tuned circuits in proper relation to the impedance of the line. An engineering and commercial development of this period, as distinguished from more purely laboratory or theoretical investigations, was the so-called "Phantoplex" system devised by engineers of the Postal Telegraph Company and quite extensively employed by that company. In this system a relatively low-frequency carrier telegraph channel was superposed on the ordinary direct-current circuit. In addition to the above, attention may be called to the disclosures by Ehret and Kitsee. Ehret shows[9] a multiplex carrier telephone system including amplifiers, and Kitsee shows[10] a carrier telegraph channel operating over an ordinary telephone circuit.

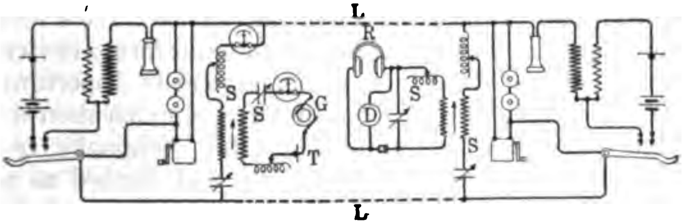

FIG. 8
(Squier—1910)

Previous to 1910, Dr. Ruhmer in Europe had undertaken experiments on high-frequency wire transmission, employing apparatus taken from the then current radio art. Ruhmer's system[11] is illustrated in Fig. 7.

He employed oscillating arcs as high-frequency generators, microphone transmitters as modulators, tuning at both the transmitting and receiving ends, and a radio detector in the receiving circuit.

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[9] U. S. Pat. No. 789,087, 1905.

[10] U. S. Pat. No. 666,883, 1901.

[11] Belgian Pat. No. 224,008, Mar. 31, 1910; *Zeitschrift fur Schwachstromtechnik* of February, 1911; *Electrical Review and Western Electrician,* July 1, 1911.

In 1910 and 1911 Major, now Major-General, Squier carried out a set of experiments employing a carrier channel operating over a short telephone cable circuit. The announcement of his work popularized interest in this art, and the paper which he presented before the Institute in May, 1911 brought out considerable discussion.

The system which he used in his experiments is illustrated by Fig. 8.[12] This figure shows a carrier telephone channel operating over the wires of an ordinary telephone circuit. A high-frequency alternator is employed to generate the carrier current, a microphone transmitter is used as a modulator, tuning is employed at the sending and receiving ends, and a radio detector is employed in the receiving circuit.

As a part of the evolution of the radio art, there was developed in its early and somewhat crude form a device which was destined to play an extremely important part, not only in radio, but in wire communication as well, that is, the thermionic tube. Originally invented by Edison, this device was first applied as a radio detector by Fleming about 1904. DeForest in 1906 made a vital contribution by adding the grid, and thereby laid the foundation for its use as an amplifier. The history of this very remarkable device is so well covered in recent technical literature that we will discuss it here only in connection with its specific application to the carrier art.

The preceding history brings us up to about 1912. About this time an important step was taken toward the adaptation of the vacuum tube as a non-distorting amplifier by the addition of a negative grid battery by Lowenstein.

Since the above date, in addition to the active developments which were carried out in the Bell System and are described below, certain other investigators have been working in this field, among whom may be mentioned the General Electric Company, U. S. Signal Corp Engineers, Lee DeForest and certain European investigators, especially in Germany and France. In the

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[12] From Fig. 6 of Squier's A. I. E. E. 1911 paper. Also Fig. 1 of U. S. Pat. No. 950,356, 1911.

attached bibliography will be found references to the more important publications which have been made by such investigators.

Bell System Developments. The most important developments, which have occurred since 1912 and are principally the work of the Research and Development Departments of the Bell System, may be stated as follows:

1. Development of the thermionic vacuum tube into a reliable and stable instrument for amplification, modulation and demodulation.
2. Development of the electrical filter and an improved technique of separating electrical currents of different frequencies.
3. Development of the technique of transmission over wires, particularly in connection with repeater operation and of methods for overcoming interference between circuits.
4. Development and operation of commercial carrier systems.

In considering the above developments which have led to commercial operation, it should be appreciated that in order for a carrier system to be commercially successful, it must compete on equal terms with the ordinary types of wire circuits, that is, it must have the same degree of reliability and stability, and must give the same degree of privacy and the same freedom from interference. Moreover, the system must be capable of being readily maintained and must be arranged so that it may be used interchangeably in the ordinary manner with any of the facilities furnished by the plant. All of these conditions must be met at a cost less than that of the ordinary types of circuits for similar service.

Developments in Thermionic Vacuum Tubes. The development of the thermionic vacuum tube as an amplifying element in a telephone repeater has already been described before the Institute,[13] as has also its application to radio telephony.[14]

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[13] Gherardi and Jewett, A. I. E. E. TRANS., pp. 1287-1345, 1919.

[14] Craft and Colpitts, A. I. E.-E. TRANS., pp. 305-343, 1919.

The success which attended these two lines of development indicated that in this one device was embodied the solutions of many of the controlling difficulties that had previously stood in the way of the commercial development of carrier systems. In connection with a resonant circuit, the vacuum tube provides a compact and reliable source of continuous oscillations of readily adjustable frequency. As an amplifier of both low- and high-frequency currents, it removes the necessity for excessive line currents. As a modulator and demodulator, it provides an ideal means of impressing the voice waves on the carrier current, and of restoring them to their original form at the receiving end. These tubes have, moreover, been developed into devices which are very stable and reliable in operation, and may be maintained with only routine periodic supervision.

Electrical Filters. Another development which has been of vital importance in the success of carrier telephone systems is that of the "band-filter" invented by G. A. Campbell.[15] Without such electrical filters, it would be impossible to utilize economically the relatively low-frequency range employed in the present carrier telephone systems, or to separate various channels in this range from each other or from the ordinary telephone and telegraph channels. The simple tuned circuits of the prior art would either introduce prohibitive distortion or, if made sufficiently nonselective to avoid distortion, would require placing the carrier channels widely apart in frequency. The Campbell filter, therefore, enabled the carrier channels to be squeezed closely together at comparatively low frequencies where the difficulties of transmission over lines are at a minimum.

Transmission over Wire Circuits. Since the attenuation over wire circuits is much greater at carrier frequencies than at the ordinary telephone frequencies, the successful operation of carrier systems is particularly dependent on the use of repeaters at comparatively frequent intervals in the line. This has required the development of high-frequency repeaters involving the

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[15] U. S. Patents No. 1,227,113, 1,227,114, of 1917.

application at high frequencies of all the developments of the repeater art which were described before the Institute in the paper on telephone repeaters already referred to. As in the case of telephone repeaters at voice frequencies, the amount of amplification which can be given by each repeater depends entirely on line conditions, such as the degree of line balance which can be maintained at the repeater point and the degree to which mutual interference between line circuits can be prevented.

This prevention of interference between line circuits required the development of more elaborate methods of transposing and adjusting them. In order to overcome the large transmission losses and irregularities introduced in open-wire lines by unavoidable sections of cable, new types of loading for cable circuits were developed for these carrier frequencies and put into practical use.

Development and Operation of Commercial Carrier Systems. In 1914, simple forms of carrier circuits, embodying the fundamentals of our present system, were successfully set up in the laboratory, and experiments carried out with them. In view of the favorable conditions which had resulted from the various developments noted above, it was decided to begin active work toward commercial carrier systems. Field measuring apparatus was developed with which the characteristics of existing telephone lines were carefully studied in the carrier-frequency range. At the same time in the laboratory the physical possibilities and limitations of the various types of apparatus and circuits were being studied. Based on these fundamental data there was developed in the laboratory a complete multiplex telephone system providing two-way telephone conversations, and operating over an artificial line. This laboratory apparatus was then taken into the field and tried out on a line between South Bend, Ind., and Toledo, Ohio. The practical difficulties always encountered were overcome, and satisfactory operation secured. At the same time satisfactory results were obtained on a simple type of carrier telegraph system between Chicago and Toledo.

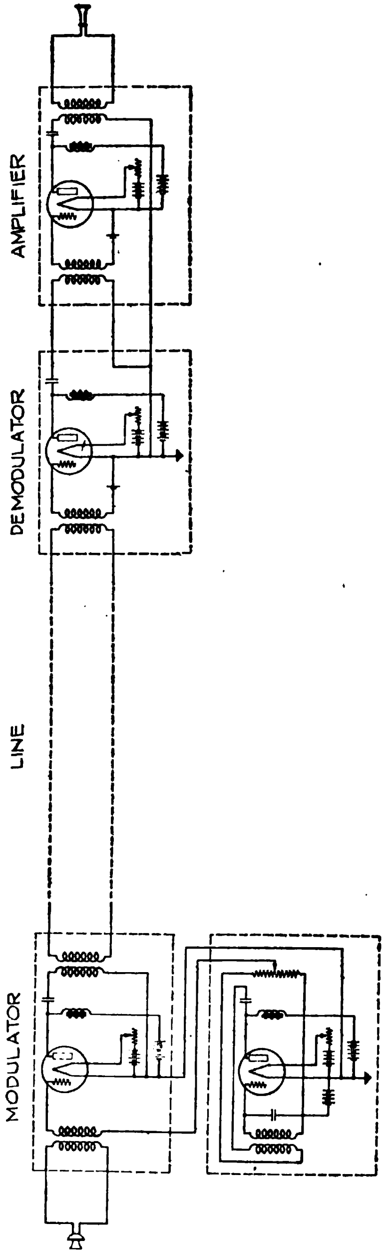

Fig. 9

The entry of this country into the war brought the work to a standstill for a time. However, the same cause created a demand for more telephone circuits between Washington and Pittsburgh. It was decided to meet this demand by a trial installation of a carrier telephone system between Pittsburgh and Baltimore, from which point cable circuits to Washington were available. In view of the urgency of the situation, the apparatus used in the earlier field experiments was adapted to equip the Pittsburgh terminal, while new apparatus was built for the Baltimore terminal. This carrier system went into service and has since been operating satisfactorily.

PRINCIPLES OF OPERATION

General. An adequate understanding of carrier systems requires a consideration in some detail of the fundamental principles underlying their operation. Some of these principles, which are also important in connection with telephone repeater operation and in connection with radio telephony, have already been discussed at some length before the Institute in papers[16] on those subjects as referred to above. Emphasis will therefore be placed on those features which pertain more strictly to carrier operation.

The underlying principles of carrier systems will be described in their application to carrier telephony. Their application to the somewhat different conditions of carrier telegraphy will be treated separately in a later section.

We will first discuss those features which are involved in a single one-way carrier telephone transmission channel, including generation of carrier current, modulation and demodulation or detection. Next will be considered multiplex operation in a single direction, involving separation of channels by selective circuits, followed by a consideration of two-way operation of single and multiplex channels. Next will be presented an explanation of another type of system in which no unmodulated carrier current is transmitted

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16. Gherardi and Jewett, loc. cit.
Craft and Colpitts, loc. cit.

over the line and of a special mode of carrier current generation particularly adapted to this system. Finally the repeaters used for amplifying the currents of carrier frequency at intermediate points, and certain other matters such as ringing and the assignment of carrier frequencies will be discussed.

Fig. 9 shows schematically the circuits involved in a single one-way channel. The source of carrier frequency shown is a vacuum-tube "oscillator." The operation of oscillator circuits in their many forms has been so thoroughly covered in the recent technical literature as not to require detailed discussion here.

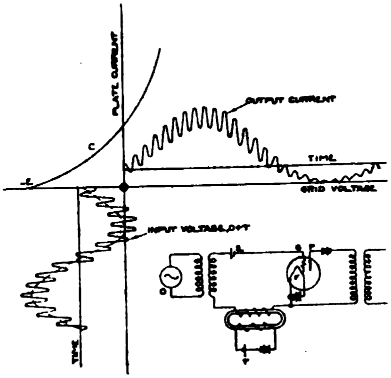

FIG. 10

Modulation. The process by which the carrier current produced by the oscillator is so combined with the voice currents from the telephone transmitter, that the variations of the latter are impressed upon the former, is known as "modulation," and the tube circuit in which this is accomplished is known as the "modulator."

It will be noted in the circuit shown that the potentials of carrier and voice frequencies are applied in series in the grid circuit of the modulating tube together with a steady voltage from a battery. Owing to the non-linear relation, which exists between the plate current and grid voltage, the output current of the tube is not simply a reproduction of the alternating voltages applied to the grid. In fact, the modulating properties of the tube result from the interactions between applied voltages which this non-linear relation introduces.

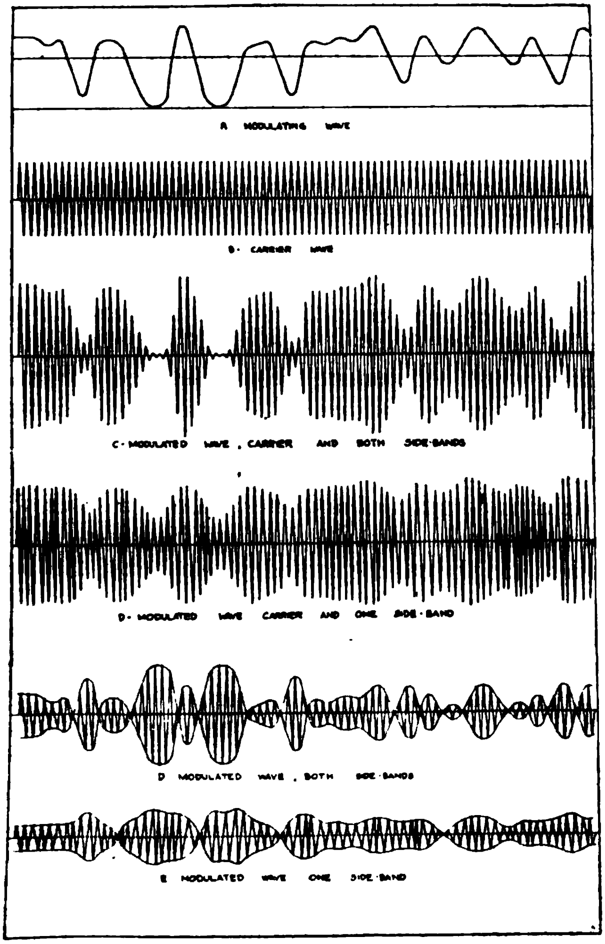

FIG. 11

The mechanism of this interaction is shown graphically in Fig. 10, which is reproduced above from the paper on Radio Telephony already referred to.[17] It is evident that while the output current includes both

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[17] Craft and Colpitts, loc. cit, page 312.

the modulating current (here a sinusoid) and the carrier current, the amplitude of the latter varies in accordance with the instantaneous value of the former. Hence, even though the relatively low modulating frequency itself be removed by a selective circuit, its variations are preserved in the wave form of the higher carrier frequency. The form of this modulated carrier wave is shown in Fig. 11. Here curve *A* shows a modulating wave of irregular form representing the voice current, curve *B* the carrier wave, and curve *C* the modulated carrier wave, whose envelope has the form of the modulating wave.

As it is not at once obvious from an inspection of this modulated carrier wave what must be the frequency characteristics of a circuit which is to transmit it to a distant station, it seems worth while at this point to consider what component frequencies are present in the carrier wave and which of these are essential. The case is exactly analogous to that of attempting to design circuits for ordinary telephone transmission from a consideration of an oscillogram of a voice wave rather than from an analysis of its frequency characteristics. In the case of ordinary telephony, the problem has been solved by analyzing the voice wave into its components of various frequencies and ascertaining which of these frequencies it is essential to preserve and which may safely be neglected. This analysis has been accomplished largely in an experimental way through the use of electrical circuits selective to particular ranges of frequency. As a result of these experiments, it has been determined that speech of satisfactory commercial quality may be secured if the circuit is capable of transmitting all sustained alternating currents whose frequencies lie, let us say, between 200 and 2000 cycles per second. These limits having been determined, the apparatus may then be designed on the basis of its meeting these requirements as to the transmission of sustained single frequencies. The information accumulated at voice frequencies can be applied directly to the solution of the carrier current problem and, incidentally, to radio telephony, provided we know what component frequencies are present in the modulated carrier wave and what relations exist between these components and the component frequencies of the modulating or voice wave. For a complete discussion of the analysis of a modulated wave into its component frequencies, reference may be made to a publication by Carson[18]; and for its application to vacuum-tube operation to van der Bijl[19]. While it is known that a modulated wave can be resolved into a large number of component frequencies, it is necessary to consider here only those components which are directly involved in carrier transmission.

Assume for the moment the complex voice wave to be replaced by a sinusoidal current of a frequency $\frac{q}{2\pi}$ lying somewhere in the voice range. The envelope of the modulated wave will approach closely a sine curve and we may assume the value of the current at any instant to be given by the equation:

$$i = P\,(1 + k \cos q\,t) \cos p\,t.$$

This equation represents a carrier current of frequency $\frac{p}{2\pi}$ whose amplitude varies sinusoidally between the values $(1 - k)\,P$ and $(1 + k)\,P$; k being proportional to the amplitude of the modulating wave. By simple transformation, this may be resolved into its components, giving

$$i = P \cos p\,t + P\,\frac{k}{2}\,[\cos\,(p + q)\,t + \cos\,(p - q)\,t]$$

The first term represents a component of carrier frequency whose amplitude, P, is altogether independent of q and of k; and therefore it has no part in conveying the characteristics of the modulating wave to the distant station. These characteristics are preserved by the remaining two terms, whose frequencies

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[18] *Proceedings I. R. E.*, Vol. 7, page 187, 1919.

[19] "The Thermionic Vacuum Tube," 1920, McGraw-Hill Book Co., Inc.

are respectively the sum and difference of the carrier and modulating frequencies, and whose amplitudes are proportional to the product of the carrier and modulating waves.

From this it follows that every component frequency of a modulating voice wave is represented in the corresponding modulated carrier wave by two components, one of which is greater in frequency than the carrier wave by the frequency of the voice component, and the other of which is less by the same amount. We may therefore be certain that all of the essential components of the voice wave will be preserved if those components of the modulated wave are transmitted whose frequencies lie within two frequency bands, one of which extends from the carrier frequency plus 200 upwards to the carrier frequency plus 2000 and the other from the carrier frequency minus 200 down to the carrier frequency minus 2000. These are known as the upper and lower side bands, respectively.

While the above discussion refers more specifically to the use of the vacuum tube as the means for effecting modulation of a carrier current, it should be understood that any device possessing a non-linear current-voltage characteristic will operate more or less effectively as a modulator.

Demodulation. By the term "demodulation" is meant the process of reproducing the original low-frequency modulating wave from the carrier wave upon which it has been impressed. Various methods of accomplishing this result have been known for many years, such as the use of the electrolytic detector of Pupin or of crystal detectors of various forms. All of these operate by virtue of their non-linear current-voltage characteristics. The instrument which has, however, come to be employed almost exclusively for this purpose is the three-element vacuum tube, and the following discussion presupposes its use.

For a concrete example of the use of the vacuum tube as a demodulator, reference may be made to Fig. 9, where at the receiving station a modulated wave is shown applied to the input circuit of a vacuum tube. This figure also shows a low-frequency amplifier in the output circuit of the demodulating tube. Because of the bearing of demodulation on the transmission requirements of the system as a whole, we will discuss this matter at some length. Anyone desiring to pursue the matter still further is referred to the publications[20] already cited under "Modulation."

The operation of the demodulating tube is exactly similar to that of the modulating tube, in that if voltages of two different frequencies are applied to its input circuit, there appears in its output circuit, a complex current wave. When the output current wave is resolved into its components, we find currents identical with the two frequencies which had been applied to the input, one component whose frequency is the sum of the applied frequencies, one component whose frequency is the difference of the applied frequencies, and a large number of harmonics and sum and difference frequencies. The amplitudes of the two currents whose frequencies are the sum and difference of the applied frequencies are proportional to the product of the amplitudes of the applied voltages. When, therefore, the received modulated wave is applied to the demodulating tube, we may determine the frequencies and relative amplitudes of the components of voice frequency in the output circuit of the demodulator by considering the interaction of the various pairs of frequencies in the modulated wave.

Obviously frequencies in the voice range can occur in the demodulator output circuit only as the difference of two components of the modulated wave. If we subtract the carrier frequency from any component of the upper side band, the result is the original speech frequency which produced that component. The interaction of the carrier and the entire upper side band therefore reproduces all the components of the voice wave with their proper relative amplitudes, since the amplitudes of the side band components are proportional to those of the original voice components, and that of the carrier is the same for all of them. The reproduction of the original voice wave also results

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[20] Carson, loc. cit.; van der Bijl, loc. cit.

from the interaction of the carrier with the lower side band.

It is evident that since speech can be reproduced from either side band alone, there is no necessity for transmitting both. Accordingly, the selective circuits to be described later can be so designed as to transmit only one side band. As this effectively halves the range of frequencies assigned to each channel, its great importance is at once obvious. The effect on the wave form of suppressing the upper side band is shown by curve *D*, Fig. 11. It is seen that in addition to the form of the envelope being changed, the times at which the current passes through zero are no longer equally spaced.

It is necessary to consider the interactions between the frequency components of the side band itself, for if, in the case of telephony, the voice wave includes components of more than one frequency, each will be represented by a corresponding component in the side band. The interaction of two of these component frequencies, simultaneously present in the side band, gives rise to a component in the output circuit of the demodulator, the frequency of which is the difference between those of the corresponding two components of the original voice wave. Such currents will have a serious effect on the quality of the reproduced speech, if their amplitude is comparable with that of the reproduced voice currents. The amplitude of this distorting component is proportional to the product of the amplitudes of the two side band components, whereas the amplitude of each of the two components of the desired voice current is proportional to the product of the amplitudes of its corresponding side band component and the carrier. The reproduced voice current can be made large compared with the distorting current only by insuring that the carrier is large compared with every component of the side band. As a result of this, it follows that in order to secure good quality it is necessary that the greater portion of the energy applied to the demodulator consist of unmodulated carrier frequency.

The behavior of the receiving apparatus—that is, the demodulating tube—to interfering currents, such as may be produced by induction from external sources of electrical energy, so-called static interference, etc., can be directly deduced from the above considerations. With properly designed selective circuits only those line currents whose frequencies lie in the range of the side band being transmitted can reach the demodulator. These can produce noise of voice frequency either by interaction with the currents normally associated with that channel or by interaction with each other. Unless the interfering currents are of greater amplitude than the carrier current, in which case commercial operation is impossible, the noise components of the greatest amplitude result from the interaction of the interfering currents with the carrier current. The noise current in the output circuit therefore bears the same ratio to the reproduced voice current as the interfering line current does to the side band current. It follows, therefore, that in designing a system it is the side band current, in which are preserved the characteristics of the speech, which must at all points along the line be kept large compared with the extraneous disturbing currents lying within its range of frequency. This consideration has a very important bearing on the

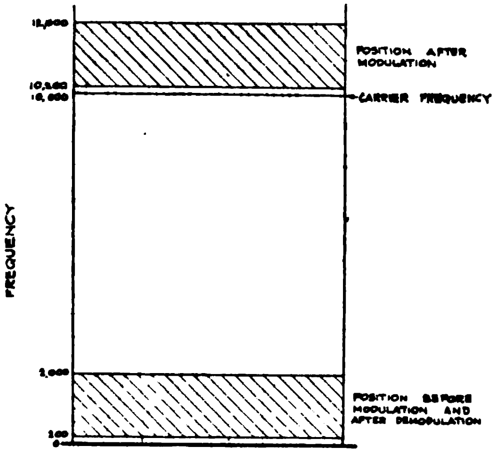


Fig. 12

electrical design of apparatus operating on the carrier principle, whether dealing with wire or radio transmission.

While our discussion of modulation and demodulation has been made as concise as possible, it is evident from the foregoing that these two are complementary processes. Modulation may be thought of as elevating the band of essential speech frequencies to a position adjacent to the carrier frequency, and demodulation may be regarded as the process of restoring this band to its normal position in the frequency scale. In Fig. 12, the band of voice frequencies is shown, below, in its normal position before modulation, and above, in the position adjacent to the carrier frequency to which it is raised by modulation.

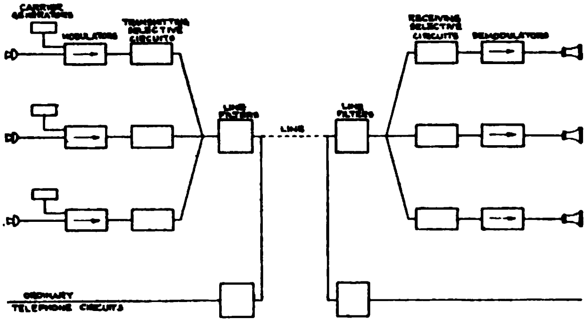
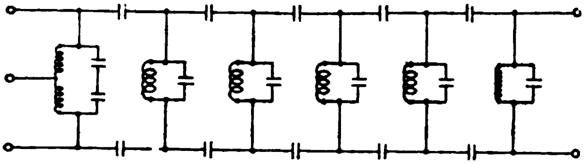
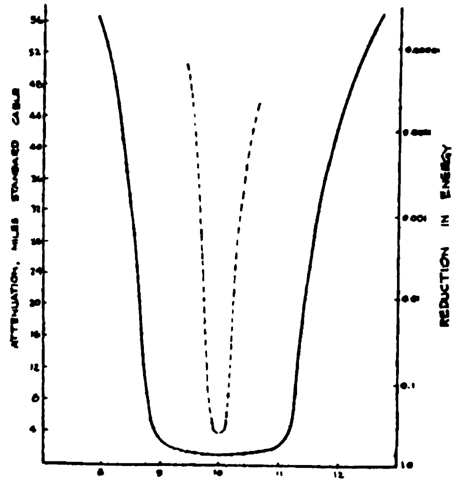


FIG. 13

Selection—Electrical Filters. When a number of one-way channels of the type schematically shown in Fig. 9, each employing a different carrier frequency, are operated by superposition on a common line, each channel must be connected with the line through selective circuits which transmit only the range of frequency assigned to that particular channel. Not only must the demodulator assigned to a given channel be prevented from receiving from the line the currents of other channels, but the sending modulator must be prevented from putting onto the line currents of frequencies outside of its assigned band for, as was pointed out in the discussion of modulation, frequencies other than those desired are developed in the output circuit of the modulator, and if these currents were permitted to reach the line, those whose frequencies fell within the transmission band of some other channel would be transmitted to the demodulator of that channel through its receiving selective circuit. The general position of the selective circuits in such a one-way multiplex system is indicated in Fig. 13.





Frequency - Kilocycles

FIG. 14

As will be brought out later in the discussion of the behavior of lines with respect to their transmission efficiency at carrier frequencies and with respect to cross-talk between adjacent circuits on a pole line, the most desirable frequency range is rather limited. For this reason, where it is proposed to secure a maximum number of channels simultaneously operating on a given circuit it is necessary to make the frequency interval between the adjacent carrier channels as small as possible. The first limitation to the frequency separation between carrier frequencies is determined by the fact that, as has already been pointed out, the width of the side band must correspond to the voice frequency range; that is, even with ideal apparatus the carrier frequencies must have at least a separation of approximately 2000 cycles per second. The ideal selective circuit which would permit this close spacing of frequencies is one which would transmit efficiently this side band, having a frequency range of 2000 cycles, and would absolutely block off frequencies outside of this band. Because it is not physically possible to secure such ideal circuits, we are obliged to make a greater separation in carrier frequencies than that made necessary by the width of the side band.

The nearest approach to this ideal selective circuit, particularly for carrier operation at moderate frequencies, is secured by the use of what has come to be known as an "electrical filter." This arrangement was invented and thoroughly studied by Dr. G. A. Campbell even before practical carrier operation was made possible by the perfecting of vacuum tubes and the development of their use as oscillators, modulators and demodulators. Campbell's electrical filter is a network composed of inductances and capacities which transmits with a minimum of attenuation, currents whose frequencies lie in a predetermined range and attenuates very greatly currents whose frequencies lie outside that range. While these filters may take a variety of forms to meet special needs, they are all alike in that the currents traverse a succession of meshes or "sections," the attenuating effects of which are cumulative. The discrimination against the frequencies which it is desired to exclude may be increased to any physically practical value by increasing the number of sections.

Fig. 14 shows a type of filter which has been used to great advantage in carrier telephony. As this filter transmits a band of frequencies, it has, for convenience, been termed a "band-pass" filter. The transmission characteristics of this filter are also shown in Fig. 14, where the attenuation introduced into a circuit by the insertion of this filter is plotted against the frequency of the applied current. The attenuation is expressed in miles of standard cable. For the convenience also of those not familiar with this usage there is shown at the right a scale from which may be read for any frequency the fractional reduction of the energy due to transmission through the filter. This particular filter is designed to transmit the upper side band of a carrier of 9000 cycles or the lower side band of a carrier of 11,000 cycles.

At this point it may be instructive to compare the performance of the filter just described with that of a pair of loosely coupled circuits resonant to a frequency in the transmission band of the filter. The attenuation characteristics of such a tuned circuit are shown by the dotted curve in Fig. 14. It is obvious from the attenuations of this circuit in the frequency range of the side band that such a circuit is very poorly adapted to the purposes of carrier telephony.

Referring again to the band-pass filter above described, it is of interest to consider the relation between its attenuation characteristic and the operation of the system. The form of the attenuation curve within its transmission range is important from the standpoint of the quality of the transmission of the carrier channel in which the filter is used. If the attenuation is uniform throughout the frequency range which the filter is designed to pass, the effect is merely the same as that of increasing the length of line by a corresponding amount, and the loss can be compensated for by amplification inserted somewhere in the system. If the attenuation is not the same for all frequencies within the band, as, for example, if it is greater at the edges than at the center of the band, then the difference in transmission equivalent for different components of the side band will introduce a similar distortion into the over-all transmission frequency curve for various voice frequencies, as measured from the modulator input to the demodulator output. Such a distortion would manifest itself by more or less impairment in the quality of the telephone transmission.

Both the magnitude of the attenuation within the frequency band transmitted and the variation with frequency are dependent upon the dissipation of energy in the coils and condensers, as well as upon the choice of their electrical constants, so that the problem of securing filters of desired transmission characteristics has been largely one of obtaining reactance elements of high time-constants and of high accuracy and stability. For the capacities mica condensers are largely used. For the inductances a special core material of finely divided iron has been developed which has made possible toroidal iron-core coils which are superior in time-constant to air-core coils for frequencies up to the highest values used by us. At the same time they are more compact and have less stray field. Transformers having similar iron cores are also used throughout the carrier system. A description of this type of core material and a statement of the results obtained by its use in the telephone plant will form the subject of an engineering paper to be published at an early date.

As has been indicated above, the attenuation of the filter outside of its efficient transmission band, determines the necessary frequency separation between the side bands of adjacent channels and therefore to a large degree also the number of channels which may be operated in a given frequency range. For example, if channel *A* is operating through the filter shown in Fig. 14, then the frequency band of channel *B* must be so chosen in the frequency range that the attenuation of the filter in channel *A* for currents of the frequencies of channel *B* is at least as great as some value fixed by the cross-talk requirements imposed on the system.

The attenuation outside of the transmission band is practically independent of the resistance of the coils and the dissipation in the condensers, but is determined almost wholly by the arrangement and values of the reactances employed in a section and by the number of sections. Numerous special arrangements have been devised for controlling the form of the attenuation curve and for giving to the filter an impedance best suited to the circuit with which it is connected. It has been found practicable to design filters which permit of operating with an interval of about 1000 cycles between adjacent telephone channels; that is, 3000 cycles between adjacent carrier frequencies.

In addition to separating the various carrier channels from each other it is found convenient from an operating standpoint to separate within the toll offices the carrier frequencies as a group from the frequencies used for ordinary telephony and telegraphy. For this purpose the portion of the line which is used in common is connected with the carrier apparatus through a "high-pass" filter, which transmits all frequencies above a predetermined value (in this case above about 3000 cycles), and suppresses all frequencies below this value (in this case below 3000 cycles). Similarly connection is made with the ordinary telephone and telegraph circuits through a "low-pass" filter, which in this instance passes frequencies

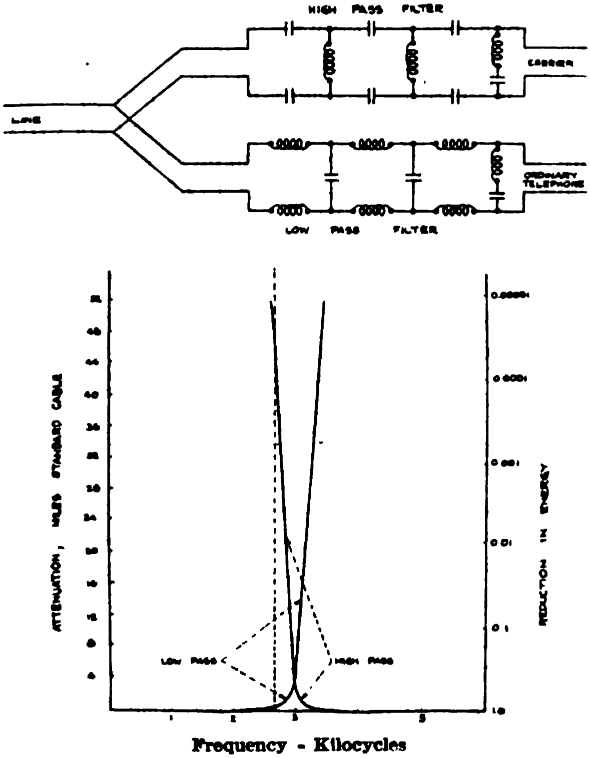


FIG. 15

below 3000 cycles and suppresses those above. This combination of carrier line filters, sometimes called a "high-frequency composite set," is shown in Fig. 15, together with the attenuation curves of the two filters. Referring to this figure, it will be seen that currents in the multiplex line divide between the low-pass and high-pass filters shown at the top of the figure. The division is determined at any particular frequency by the relative input impedances of these two branches. Accordingly, the high-pass filter is designed to offer a high input impedance to currents of ordinary telephone frequency, and to have an impedance equal to that of the line for currents within the carrier frequency range. Correspondingly, the low-pass filter is designed to offer a high input impedance to currents of the carrier frequency range and to have an impedance equal to that of the line for currents of ordinary voice frequencies. The attenuation of the high-pass filter is small for carrier frequencies and large for voice frequencies, while the reverse is true for the low-pass filter. Referring to the attenuation curves, which show, as indicated, the attenuation for both the high-pass and the low-pass filters, it is interesting to note how sharp a discrimination is obtained even for frequencies very close to the cut-off points of these filters. For instance, if we select a frequency of 2700 which happens to fall near the upper limit of the normal voice range, it is seen from an inspection of these curves that currents of this frequency are attenuated by about one mile of standard cable when passing through the low-pass filter, but are attenuated by about forty-five miles of standard cable when passing through the high-pass filter. Likewise, a frequency of 3200 near the lower limit of the carrier range is attenuated by less than one mile when passing through the high-pass filter, but is attenuated by about forty-five miles when passing through the low-pass filter. These differences in attenuation correspond roughly to a ratio of energies greater than ten thousand to one.

The location of these line filters in a carrier system is indicated in Fig. 13. A low-pass filter is also used in the output circuit of the demodulator to prevent currents of frequencies higher than the essential voice range from being transmitted to the subscriber.

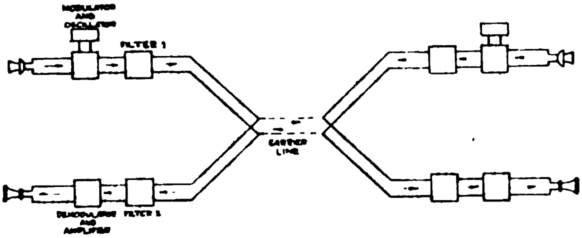


Fig. 16

Arrangements for Two-way Transmission. Thus far the discussion has been limited to transmission in one direction. Provision must be made, however, for associating these one-way channels with the connecting telephone lines so as to permit two-way conversation. In many aspects the problem resembles that encountered in adapting a one-way amplifying element to a two-way talking circuit by means of a telephone repeater. The similarity of the two problems consists not only in the fact that the carrier channel and the repeater element are both unilateral or one-way arrangements, but also that both involve amplification, and therefore the same possibilities of "singing" are present in the case of the carrier as in the case of the

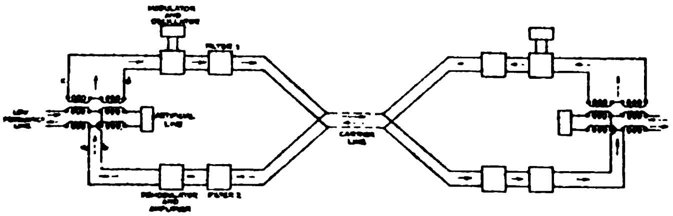


Fig. 17

repeater. The experience, which was gained in the development and engineering of telephone repeaters, has proved of very great value in connection with the development of carrier current systems. For details of the various circuit arrangements, and for a discussion of the fundamentals of the repeater problem, reference may be made to the paper on telephone repeaters mentioned above.[21]

In Fig. 16 there is shown schematically an elementary form of two-way carrier telephone circuit. Filters are included in the transmitting and receiving branches, as they are necessary in those branches for multiplex operation. This circuit is entirely operative between two fixed telephone stations. If the same frequency is used for transmitting in both directions, there will obviously be an excess of sidetone in the receiver circuits. It is plain that such a type of circuit has very limited commercial application, and it is shown here merely as a starting point for building up the more generally applicable types.

As in general it is desirable to be able to connect any desired telephone trunk or toll line to the section of line equipped for operation by the carrier current method, it is necessary to adopt for connecting these lines together a circuit of the type which has been studied for many years by telephone engineers, first in connection with subscriber sets, and second in connection with repeater circuits.

Fig. 17 shows schematically one such arrangement. At either terminal of the carrier frequency line, the sending and receiving branches, instead of terminating in a transmitter and receiver, terminate in what are, in effect, conjugate branches of an alternating-current bridge. If the impedance of the artificial line exactly simulates the impedance of the voice frequency line looking outward from the carrier terminal, an electromotive force applied between the points *a* and *b* does not cause any current to flow in the branch *c*-*d* of the carrier current circuit. This represents a condition of zero coupling between the input and output circuits of the carrier system; hence persistent oscillations, *i. e.* singing, cannot be set up. If, however, the balancing network does not accurately simulate the low-frequency line, either of two types of singing may occur. In the circuit arrangement in Fig. 17, if

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[21] Gherardi and Jewett, loc. cit.

the same frequency is used for transmission in both directions, the type of singing most likely to occur would be local singing at either terminal. This occurs for the reason that in general the amount of energy applied to the two terminals *c* and *d* is largely amplified in the course of passing through the circuit—modulator, filter 1, filter 2, demodulator and amplifier. If the unbalance in the bridge circuit is such that the fraction of this energy which is fed back to the points *c* and *d* is as large as that originally supplied, singing occurs. To avoid this type of singing different carrier frequencies may be chosen for transmission in the two directions. If this is done, local singing cannot be set up, for the reason that filter 2 acts as a block to the return of the output current on itself. End to end singing as distinguished from local singing may, however, occur provided the over-all transmission loss of the line and the terminal apparatus is made less than zero, and provided that there is sufficient unbalance between the artificial lines and the low-frequency lines at both ends. By "transmission loss of less than zero" is meant that the attenuation of the carrier line is more than compensated for by amplification introduced either at the terminal stations or at intermediate repeater stations. However, the accuracy of line balance necessary to prevent end to end singing with carrier circuits such as we have used is very much less than would be required to prevent local singing if the same frequency were used for transmission in both directions. It is interesting to note that in both of these types of singing the sustained oscillations in different portions of the circuit are of different frequen-

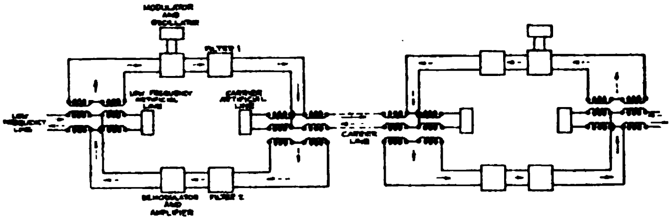

FIG. 18

cies. Those in the portions used for transmission at voice frequency have some value lying in the voice frequency range. Those in the portions used for transmission at carrier frequencies differ from the carrier frequency associated with that particular channel by the frequency of the oscillations in the low-frequency circuit.

Whereas, with the circuit shown in Fig. 17, local singing is prevented by the use of different carrier frequencies in the two directions, it is possible to prevent this type of singing without resorting to different frequencies, with the attendant reduction in number of channels, by the use of the arrangement shown in Fig. 18. In this arrangement the energy from the output of the modulator is prevented from reaching the input of its associated demodulator by placing the two in conjugate relation in an alternating-current bridge circuit, of which the carrier frequency line forms one arm, and a balancing network, designed to simulate the line impedance, the other arm.

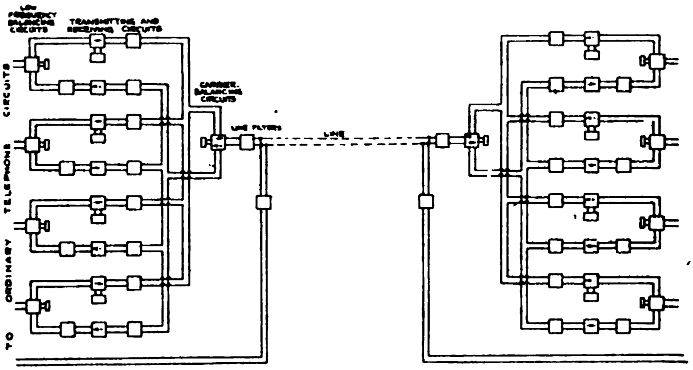

FIG. 19

Both the arrangements shown in Fig. 17 and that shown in Fig. 18 have been successfully employed for two-way carrier current transmission.

We have already discussed quite fully the selective characteristics of filters and their relation to one-way multiplex operation, and have, in the preceding paragraphs of the present section, pointed out the fundamental principles of two-way operation. In Fig. 19 is shown schematically an arrangement for two-way multiplex operation capable of giving four two-way carrier conversations in addition to the normal telephone facilities. It will be noted that, in this multiplex system, the basic two-way transmission system of Fig. 18 is employed. A similar two-way multiplex system could be built up employing the basic two-way transmission system shown in Fig. 17.

Carrier Suppression. One of the systems which has been developed, particularly for use on long high-grade circuits, involves certain fundamental principles in addition to those already discussed. It will be recalled, that as stated, the proper operation of the demodulator requires that the side-band currents, by which are transmitted the characteristics of the speech, be accompanied by a relatively large amount of unmodulated current of carrier frequency. When this carrier current is transmitted from the modulator, it is evident that only a relatively small part of the line current is actually used in conveying the characteristic variations of the voice current. If, therefore, this carrier current is supplied to the demodulator from a local source instead of over the line from the sending station, the amount of line current which it is necessary to transmit per channel is very materially reduced, for then only the relatively small side bands are transmitted. Curve *E*, Fig. 11, shows the wave form with the carrier suppressed when both side bands are present; and Curve *F*, Fig. 11, shows the wave form with the carrier suppressed when only one side

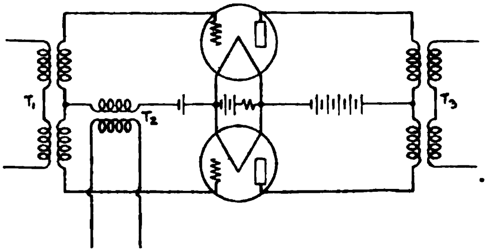

FIG. 20

band is present. In the application of this method, means must be provided for eliminating the carrier current at the sending end and for supplying it to the demodulator from a local source at the receiving end.

Elimination of the carrier frequency at the sending end can be accomplished by what is known as a "balanced modulator," a schematic circuit of which is shown in Fig. 20. In this arrangement two tubes are connected in a manner somewhat similar to the "push-pull" repeater circuit which is described later. The voice frequency potential is applied differentially to the grids of the two tubes by the transformer T_1. The carrier potential is applied through the transformer T_2 to the common portion of the input circuit in such a manner that the carrier frequency potentials of the two grids with respect to the filament are at any instant the same. The resultant carrier frequency currents in the plate circuits of the two tubes are then equal, and the fluxes which they set up in the core of the differential transformer T_3 are equal and opposite; hence no voltage of the frequency of the unmodulated carrier is induced in the output circuit. By a more detailed analysis it can be shown that the side-band currents resulting from the interaction of the carrier and speech-frequency currents are not balanced out but are reproduced in the output circuit. It should be noted that under these conditions, high-frequency current appears in the output circuit only when low-frequency telephone currents are being applied to the input circuit of the modulator.

Harmonic Generator. In order to insure that the carrier current applied to the demodulator in the above system, employing suppressed carrier, is of exactly the same frequency as that used for modulation at the sending end, an arrangement has been devised whereby both of these frequencies are derived from the same source. For this purpose at one terminal of the system a vacuum-tube oscillator generates a frequency somewhat above the voice range—say 5000 cycles. Current of this frequency is applied to the input of another vacuum tube in such a way as to overload it. This "harmonic generator," as it has been termed, is so arranged that the current in its output circuit has a distorted wave-form containing prominent components whose frequencies are exact multiples of the applied frequency. The various harmonics of the base frequency (in this case 10,000, 15,000, 20,000 cycles, etc.) are separated by suitably designed selective circuits and led into individual circuits where they are amplified and made available for use as carrier currents, each in connection with a different channel. At the same time, current of the base frequency from the controlling oscillator, in this case 5000 cycles, is amplified and transmitted over the line to the other terminal. Here it is separated out by a filter, amplified and applied to a second harmonic generator, which produces the same series of carrier frequencies as does the harmonic generator at the controlling station already referred to. These regenerated harmonics may not only be used for demodulating the transmissions received from the controlling terminal, but may also be used in connection with balanced modulators which send in the reverse direction. The demodulators at the controlling station, are supplied with carrier current from the harmonic generator at that terminal.

The suppressed carrier system, besides employing smaller line currents, has two other important advantages. One is the absence of audible beat notes resulting from interaction in the demodulating circuits between the carrier frequency normally present and others which may be present through cross-talk or lack of perfect balance. Where all of the carrier frequencies are generated separately, these combination frequencies may in certain cases give rise to disturbing tones within the voice range. With the harmonic arrangement, on the other hand, the only possible frequencies are differences of the base frequency itself and its harmonics, all of which are above the normal voice range, and accordingly are suppressed by the low-pass filter in the output circuit of the demodulator. As a matter of fact, this harmonic arrangement is practically essential where the same frequency range is used for both directions.

The second advantage arises from the fact that variations in the attenuation of the line, due to weather changes or other causes, have less effect on the transmission equivalent of the system where the carrier frequency itself is not transmitted. This will be clear when it is recalled that the magnitude of the voice current in the output of the demodulator is proportional to the product of the amplitudes of the carrier and side band currents. If, therefore, the change in line attenuation is such as to increase or decrease the side band current by a given ratio, the carrier current when transmitted will in general also be changed in the same ratio, and the resulting voice current will be changed by the square of this ratio. In the suppressed carrier system, on the other hand, while the side band is changed as before, the carrier is increased or decreased—not by the change in attenuation which occurs at the carrier frequency—but by the changes, in general much smaller, which occur at the base frequency, so that the voice current is less affected in this case.

Repeaters. From the discussion of the transmission characteristics of lines which will be given later in the paper, the very great practical importance of amplifying apparatus at intermediate points on a line employing carrier frequencies will be evident. For this purpose fortunately we have available, first, the vacuum tube, and, second, a large variety of methods of applying this tube which have been developed to a high state of efficiency in connection with the voice frequency telephone repeater. While, as just indicated, the same general considerations apply to repeaters for carrier current circuits as to repeaters on circuits operated at voice frequencies, the conditions peculiar to carrier current operation require that the repeaters for this service differ quite considerably from standard voice frequency repeaters.

In the first place, on a multiplex carrier current circuit a single repeater installation must handle the energy associated with a number of independent conversations. This could be accomplished by making the installation include a number of repeaters in parallel with suitably associated filter combinations, but it is at once obvious that it is much preferable to install but one repeater channel capable of amplifying all the carrier transmission. The requirements for the repeater set are made still more severe by the fact that modulation in the repeater tubes, which tends to increase with the load, introduces disturbing factors in carrier operation which are not serious in ordinary repeater operation. The reason for this is that the combination frequencies resulting from the interaction of the currents in two channels may lie in the frequency range of a third, in which case they are transmitted through the selective circuits of that channel and appear as an interfering noise or tone at the subscriber's

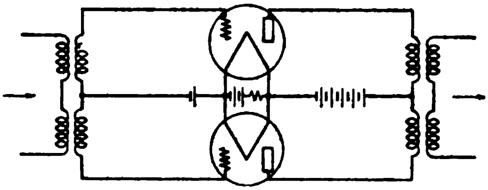

FIG. 21

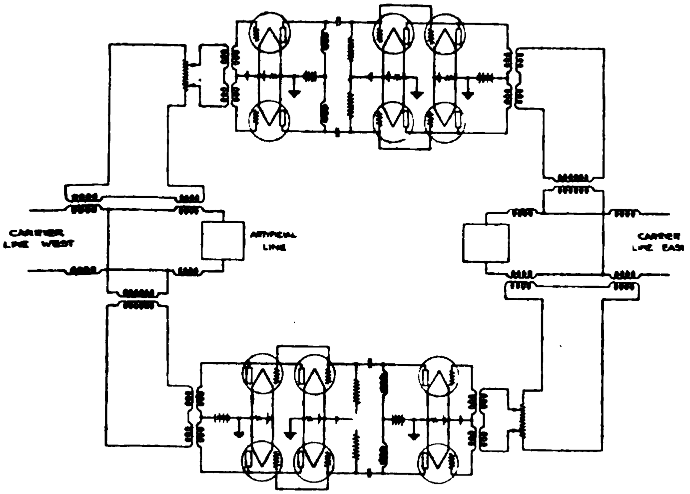

FIG. 22

station. To obtain sufficient energy carrying capacity, and to overcome to some degree this difficulty of intermodulation, we use a number of tubes in parallel in the so-called "push-pull" arrangement. The principle of the push-pull amplifier is shown in Fig. 21.

In this arrangement the input voltage is applied in such a way as to increase the grid voltage of one tube with respect to its filament at the same time that the grid voltages of the other is diminished. The plates are connected with the output circuit by a differential transformer, so that the useful amplified currents from the two tubes are added, while the more troublesome interfering components due to modulation are equal in amplitude and opposite in phase, and hence are balanced out. Instead of employing tubes in parallel to increase the energy capacity of the set, it would have been possible to have used a single tube of larger energy capacity. The scheme of using a number of tubes operating in parallel was adopted in order to avoid increasing the number of types of tubes in the plant.

In repeater operation at voice frequencies, the amount of amplification which can be secured on a given line and with given types of repeater apparatus is limited by the tendency to "sing." The same is true for repeater operation at carrier frequencies. To reduce the tendency of the repeater to sing, the same methods may be adopted as are employed at the terminals; that is to say, if the same frequencies are used for the transmission in both directions, the lines on either side of the repeater must be balanced and the same general type of repeater circuit used as for voice frequency telephone repeaters (see Fig. 22). If, however, different frequencies are employed for transmission in the two directions, filters may be used to prevent the currents sent out in one direction from passing into the input circuit of the repeater set which receives energy from that direction.

While the telephone currents at voice frequencies may be amplified in the same repeater along with the carrier currents, it has been found convenient for reasons of plant flexibility to separate voice frequencies from carrier frequencies by line filters similar to those used at the terminals. Due to the fact that the attenuation of voice frequencies is much lower than that of carrier frequencies, it is frequently not necessary to install a voice frequency repeater at all of the points where carrier frequency repeaters are installed. A number of arrangements are illustrated in the sections dealing with commercial systems.

Signaling over Carrier Telephone Circuits. For a carrier telephone channel to form an integral part of an ordinary telephone connection, it is in general desirable to be able to operate the normal signaling mechanism over the channel without the intervention of an operator at the terminals of the carrier section. This is accomplished by two distinct methods in the two types of system employed. In the type where carrier current is transmitted over the line, an auxiliary rectifier tube is associated with the demodulator in such a manner that the incoming carrier current produces in the output circuit of this rectifier a direct current sufficient to maintain a relay in its operated position. When the operator signals, the ordinary 16-cycle ringing current is received at the carrier terminal. This is made to operate a relay, which disconnects the source of carrier current from the modulator, thereby stopping its transmission over the line. As a result, at the distant terminal the relay controlled by the rectified current falls back, causing an ordinary 16-cycle ringing current to be sent out over the connecting line associated with that particular channel.

In the system where the carrier current is suppressed, the 16-cycle ringing current from the low-frequency line operates a relay which applies to the modulator, through the speech circuit, a current of 133 cycles from a vacuum-tube oscillator or other source. This current interacts with the carrier current in the modulator to produce a side band current, differing from the carrier by 133 cycles, which is transmitted to the distant terminal. Here it is demodulated and appears in the voice frequency circuit as a current of 133-cycle frequency. This current operates a relay tuned to this frequency, which in turn serves to send out 16-cycle ringing current over the low-frequency line.

Actual circuit arrangements showing these two methods of signaling are shown in the sections of this paper describing commercial systems.

Telegraph. Carrier current telegraphy is based on the same fundamental principles as carrier current telephony, but in actual operation it employs somewhat different physical arrangements, owing to the differences in the nature of the signals to be transmitted and to the differences between the operating conditions met in the two cases.

In ordinary telegraphy the signaling current consists of a succession of so-called "marking pulses" separated by intervals of zero or oppositely directed current representing spaces. In transmitting telegraph signals over a line by the carrier method, the signaling current, as received from the local telegraph trunk or from a connecting long-distance telegraph line, operates a relay which controls the application of carrier current to the high-frequency line. The usual arrangement is such that high-frequency current of uniform amplitude is sent out during the marking intervals only. At the receiving terminal this high-frequency current is rectified, generally after amplification, by a vacuum tube. The resulting rectified current operates a relay, which in turn sends signals over the connecting telegraph circuit or loop. Fig. 23 shows a simple, one-way carrier telegraph circuit with one-way direct-current telegraph loops at either end.

It has sometimes been assumed that the only frequency transmitted under these conditions is that of the carrier, and that therefore the only limitation on the frequency intervals between the carriers of adjacent channels is that imposed by the degree of selectivity possible of attainment with actual physical apparatus. That this is not the case is easily seen from a consideration of the building up and decay of current in a sharply resonant circuit. If the time required for the current to build up in such a circuit is comparable with the lengths of the marking and spacing intervals, the high-frequency current will not accurately reproduce the telegraph signals. This causes a rounding off of the signal, or, if it is sufficiently extreme, the signals disappear altogether.

To determine quantitatively the relation between the constants of the selective circuits and the speed and quality of the signals, it is most convenient to regard the problem as a case of modulation. As in telephony it was shown to be necessary to transmit a band of frequencies equal in width to the voice frequency range, similarly in carrier telegraphy it is necessary to transmit a band of high frequencies corresponding to the important frequencies present in the direct-current telegraph signals. An analysis of the ideal current wave representing a succession of telegraph signals reveals the presence of an infinite series of components whose frequencies extend to infinity and whose amplitudes decrease with increasing frequency. Ordinary telegraph circuits transmit only components of comparatively low frequency, with the result that the signals are rounded off. Reasonably good signals are secured, however, if those components are preserved whose frequencies are a few times the fundamental interruption frequency. The upper limit of this essential frequency band varies with different types of apparatus and with different grades of service required, but it is for any one set of conditions roughly proportional to the speed of signaling. For the cases so far met with in practise, it is oı the order of 100 or 200 cycles. It follows, therefore, that while a modulated wave, whose envelope approximates ideal telegraph signals, would require the transmission over the line of a very wide band of frequencies, satisfactory operation requires the transmission of a band of frequencies equal only in width to the essential frequency range of ordinary telegraphy. In case of multiplex carrier telegraph operation, the non-essential frequency components are accordingly suppressed by the selective sending circuits, so as to prevent them from interfering with other channels.

Referring again to Fig. 23, which shows one arrangement for sending and receiving, it will be seen that the transmission of the high-frequency current is controlled, by a relay whose winding is included in the low-frequency

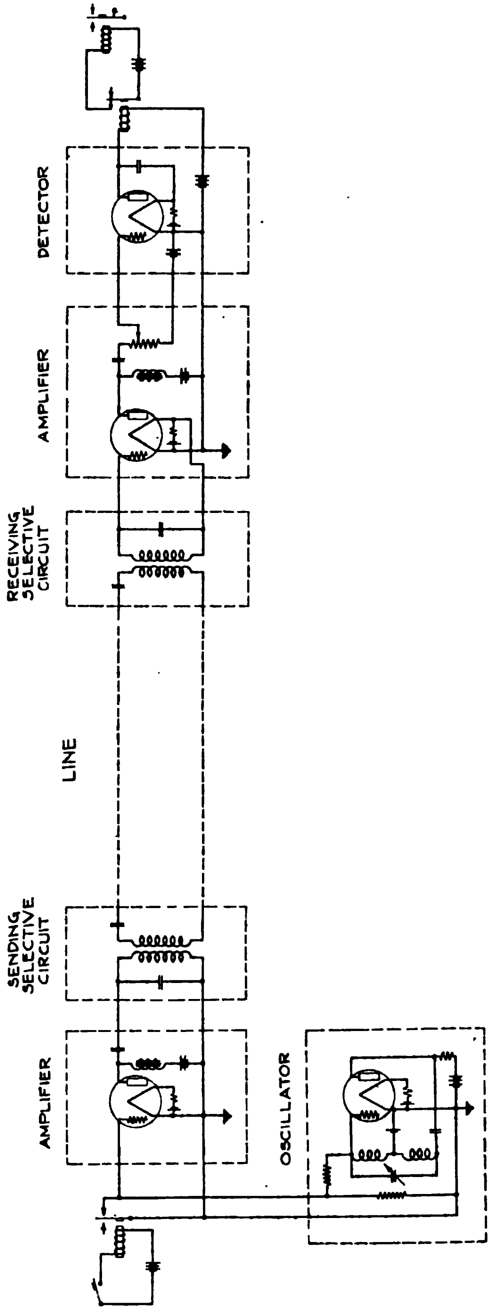
AMPLIFIER
SENDING SELECTIVE CIRCUIT
LINE
RECEIVING SELECTIVE CIRCUIT
AMPLIFIER
DETECTOR
OSCILLATOR

FIG. 23

line and the contacts of which short-circuit during the spacing intervals the output circuit of the oscillator which supplies energy to the line through an amplifier. At the receiving terminal the arrangement for demodulation or detection requires some further explanation. The carrier current, after suitable amplification, is applied to the input circuit of a vacuum-tube detector. The grid of this tube is made just sufficiently negative to prevent the flow of current in the plate circuit, which includes the winding of a relay, when no high-frequency current is being received from the line through the amplifier. During the marking intervals a high-frequency alternating potential is applied to the grid, causing a high-frequency pulsating current to flow in the plate circuit and operate the relay which is adjusted so as to be held in the operated position for the duration of the signal. The contacts of this relay control the sending of signals over the connecting telegraph circuit.

Referring to the question of multiplex operation, it may be mentioned that where the carrier frequency is of the order of several thousand cycles, the percentage difference in frequency between the extreme edges of the side band is so small, that it is not so readily possible to design circuits to suppress one of the side bands, as can be done in the case of telephony. For this reason, the frequency range assigned to a carrier telegraph channel has been twice that of the essential frequency range of the direct-current telegraph channel. As is obvious from previous consideration, the advantages of band filters largely disappear for narrow transmission bands at high frequencies, and in telegraphy it has been found more convenient, for the signaling speed so far met with, to use loosely coupled resonant circuits, such as are shown in Fig. 23.

A frequent condition of two-way operation involves what in ordinary telegraph working is termed "full-duplex operation," where the oppositely directed channels are used simultaneously for independent messages. In ordinary telegraphy this full-duplex operation is secured by balanced bridge arrangements which involve at each terminal a close balancing of the actual line by an artificial line. This close balancing at low frequencies is secured by rather close attention of a repeater operator and rather frequent readjustments of the artificial line constants. While it is possible to adapt such an arrangement to the carrier telegraph line, it has not been found economical to do so because of the ease of securing full-duplex operation by the use of different carrier frequencies for the two directions. The extension of this method to multiplex operation is obvious. A very convenient frequency arrangement for carrier telegraphy has been found to be that in which transmissions in one direction occupy a range of frequency from 3300 to 6000 cycles, and those in the other direction from very slightly above 6000 to 10,000 cycles. By proper terminal arrangements this will provide on a single pair of wires the equivalent of ten full-duplex telegraph channels. From what has been said, it will appear that there is left still available a substantial frequency range which may, if desired, be used to provide either other telegraph channels, or, if the needs of the service require them, additional telephone channels.

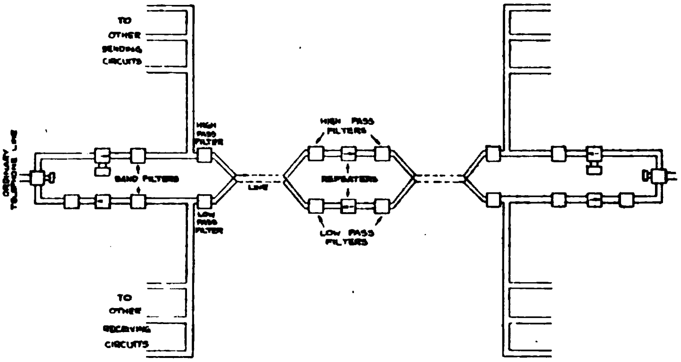

FIG. 24

Frequency Assignments. From the statements regarding filters and the methods of obtaining two-way operation, it will be evident that it is possible to select the frequencies for the various telephone and telegraph channels in a variety of ways. What assignment of frequencies to the various channels is best suited to a particular installation depends upon the engineering and economic considerations involved. For example, where there is only a single pair of wires available and it is desired to secure over this pair as many carrier telephone channels as possible, it may be economical to go to considerable expense in securing sufficient uniformity in the line so that its impedance can be readily balanced by the artificial line networks, thereby making it possible to use the same range of frequency for securing a two-way telephone channel. The harmonic frequency arrangement already described is particularly useful in such a case.

If, however, it is desired to operate carrier systems over a number of pairs of wires on the same lead, considerations of cross-talk, which will be explained more fully later in a section dealing with lines, make it highly desirable that different frequencies be used for operation in the two directions. Under this condition it is not necessary to secure the uniformity of line impedance which is required when the same frequency is employed in both directions. Of the possible frequency assignments for the oppositely directed channels, one which has proved very convenient is that in which all of the channels in one direction employ carrier frequencies below a certain value, and all the channels in the opposite direction carrier frequencies above this value. This grouped arrangement simplifies the selective circuits both at the repeater points and at the terminals; for the separation between oppositely directed currents which is accomplished by the balancing of the high-frequency line when the same frequencies are used in both directions can, with this grouped arrangement, be accomplished by a combination of high- and low-pass filters of the type shown in Fig. 15. Fig. 24 shows schematically a carrier telephone system employing filters of this sort both at the terminals and at an intermediate repeater station.

A very workable assignment of frequencies to telephone and telegraph on the same pair is shown in

Fig. 25. The arrows at the lower part of the figure indicate the positions assigned in the frequency scale to the different types of transmission. Beginning at zero frequency there is assigned to the direct-current telegraph a narrow band. The range extending from 200 to 2000 cycles and represented by the horizontal arrow is the frequency band of ordinary telephony. In the interval between 3333 and 6000 cycles is a group of eight one-way carrier telegraph channels indicated by vertical arrows. In the interval between 6000 and 10,000 are the eight oppositely directed channels, which with those of lower frequency may constitute eight full duplex telegraph circuits. The frequency range above 10,000 is assigned to three two-way carrier telephone channels. These are each designated by a vertical arrow indicating the position of the carrier frequency and the direction of transmission, and a horizontal arrow indicating the position of the side band with respect to the carrier frequency.

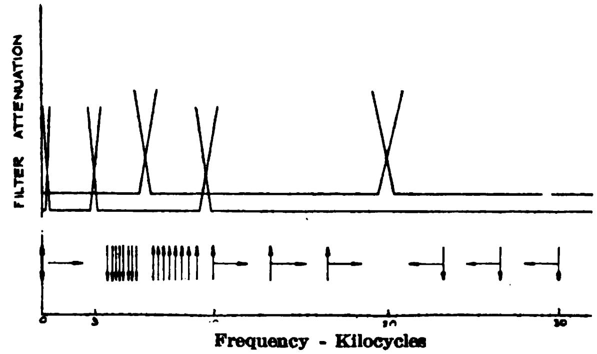

Fig. 25

Above there are given, one above the other, the idealized attenuation characteristics of a pair of separating filters for use with this assignment of frequencies. The lower of the two is so designed that each filter transmits only those frequencies which are assigned to one particular purpose. Such filters would be used for separating into individual circuits the currents used for carrier telephony, carrier telegraphy, ordinary telephony and ordinary telegraphy and thus facilitating their distribution in the central offices. The filters shown above are used, as is illustrated in Fig. 23, for separating in the carrier current circuits the currents transmitted in opposite directions.

LINES

General. The electrical design of carrier systems is determined in large part by the problems which arise in the transmission of the carrier currents over the line wires. The comparatively high frequencies used in carrier transmission attenuate much more rapidly in passing along the lines, and have a much greater tendency to cause interference in adjacent circuits than do the ordinary telephone frequencies. Both attenuation and interference increase rapidly with increase in frequency. Because of this it has been found most economical to make use of the frequency range commencing immediately above the voice range. The systems which have so far been put into commercial use employ frequencies up to about 30,000 cycles.

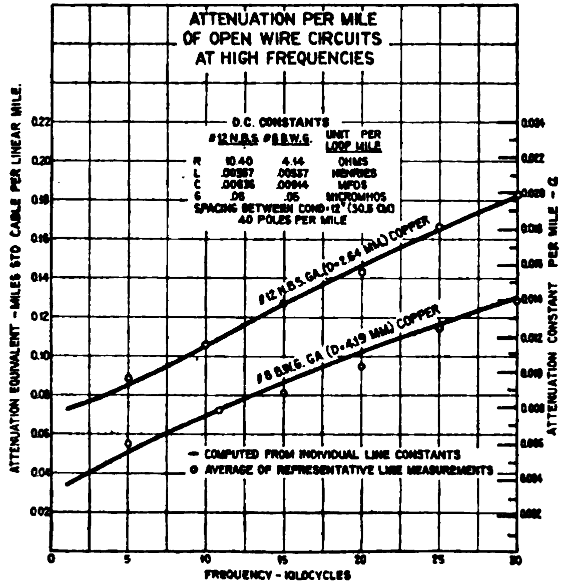

FIG. 26

Because of the high attenuation and interference, carrier transmission is particularly dependent on the use in the circuit of repeaters placed at comparatively frequent intervals. To indicate the importance of repeaters, it is interesting to note that if the Harrisburg-Chicago carrier telephone system, which spans about 750 miles, as described below, were operated without repeaters, it would be necessary under the most favorable line conditions to apply at the sending end of the highest-frequency channel a power of 60 kilowatts. By the use of intermediate repeaters the high-frequency power at no point exceeds 0.1 watt.

Some of the experimenters in this art have had the misconception that the mode of transmission of the high frequencies employed in carrier operation was different from that of the ordinary telephone frequencies, and that the carrier frequencies had some unexplained property whereby, although guided by the line wires, large energy losses in the line wires were avoided. There is, however, no theoretical or experimental basis for this idea. As a matter of fact, the line attenuation of carrier currents is considerably greater than for telephone frequencies and increases rapidly with frequency, due to the increased resistance of the line wires, and increased effective leakage between the line wires at the carrier frequencies. While it is, of course, proper to picture the mechanism of carrier transmission as one in which the energy is contained in the electromagnetic waves, which are guided by the line wires, this is no less true for the transmission of low frequencies. The difference between radio and wire transmission, whether of high or low frequency, is the difference between unguided and guided waves.

Open Wire Characteristics at Carrier Frequencies. The two sizes of wire in most common use for open-wire telephone lines in this country are No. 12 N. B. S. gage (0.104 in. diameter) and No. 8 B. W. G. (0.165 in. diameter). These wires are strung on pole lines with a normal separation of twelve inches between their centers.

The curves of Fig. 26 give the values of the attenuation constant[22] at different frequencies for circuits of these sizes of wire. The attenuation follows the usual line formulas. That is, the ratio of the currents i_1 and i_2 at two points on a transmission line separated by a distance l, assuming the line so terminated as to make reflection effects negligible, is

$$\frac{i_2}{i_1} = e^{-l\alpha}$$

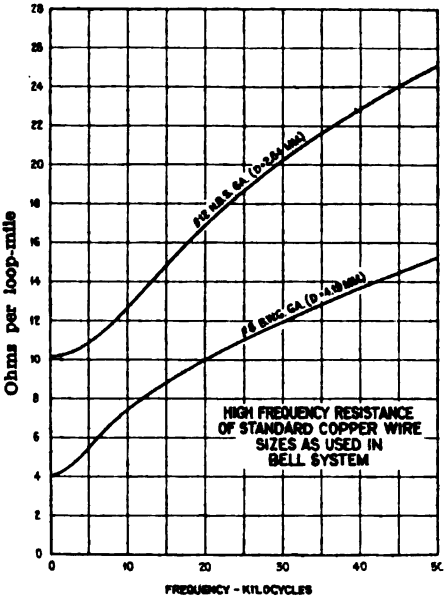

Fig. 27

in which α is the real part of the expression

$$\sqrt{(R + j\,p\,L)\,(G + j\,p\,C)}$$

In this expression R and L are the effective loop series resistance and inductance per unit length and G and C are the effective conductance and capacitance between the wires, per unit length.

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[22] Note: A convenient practical unit of attenuation which has gained large use in telephone engineering is that of the "mile of standard cable," in which α at 800 cycles equals 0.109. The attenuation at carrier frequencies is expressed in terms of the miles of standard cable which at 800 cycles has the same attenuation.

The formulas covering the action of transmission lines to alternating currents are so well understood[23] that the discussion here will be limited to certain features of particular interest in connection with carrier systems.

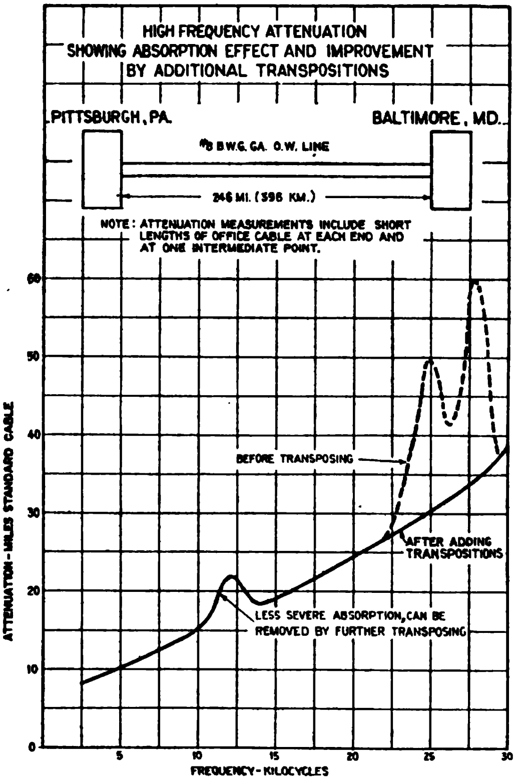

FIG. 28

It is found that the constants L and C are practically the same at high as at low frequencies. R may be computed by the usual "skin effect" formulas. Its

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[23] J. A. Fleming: "The Propagation of Electric Currents in Telephone and Telegraph Conductors."

A. E. Kennelly: "The Application of Hyperbolic Functions to Electrical Engineering Problems."

John Mills: "Radio Communication, Theory and Methods, with an Appendix on Transmission over Wires."

rapid increase in value with increase in frequency is shown in Fig. 27.

The determination of G represents a more difficult task since no theoretical relation has been established between the effective conductance between the wires and frequency. In computing the curve shown, the value of G was taken from measurements of the effective insulation of a group of glass line insulators exposed to ordinary weather conditions, and assumes therefore that the effective leakage occurs only at the insulators. The conductance, for example, at 25 kilocyles, under normal dry weather conditions, is found to be roughly 200 times that measured with direct current.

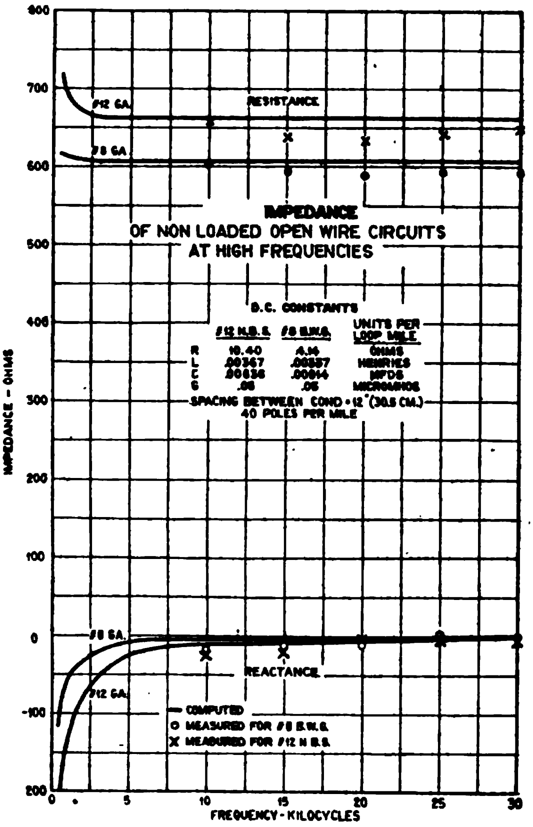

Fig. 29

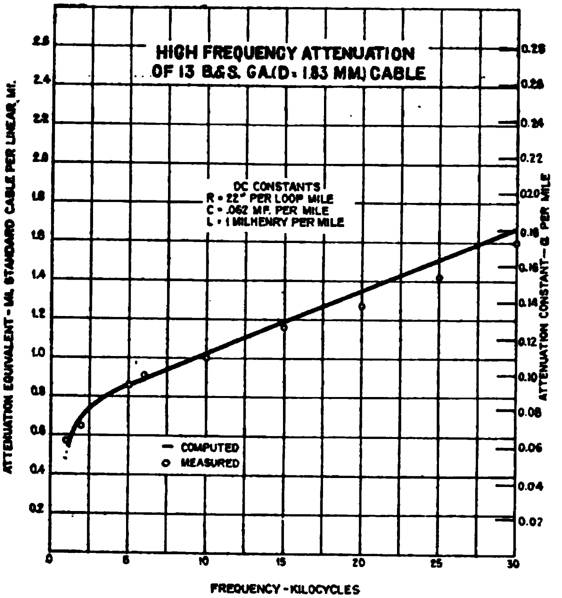

Fig. 30

It will be noted that the curves computed with the values of the constants so obtained are checked very closely by the actual field measurements which are indicated on the curves by small circles. Since the leakage plays a large part in determining

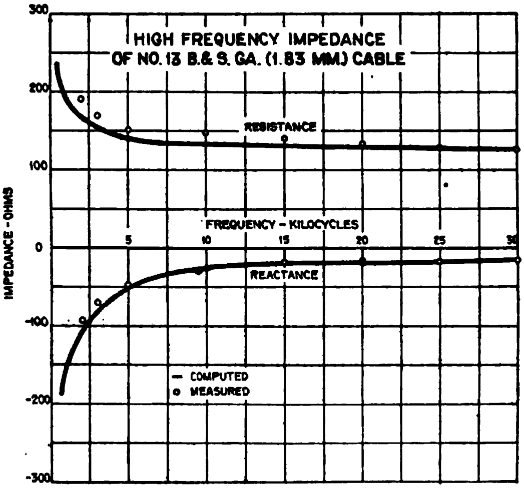

Fig. 31

the attenuation, substantial changes in attenuation occur for varying weather conditions. Under wet weather conditions the attenuation will rise materially higher than that shown in the above curve.

The apparent attenuation of a circuit may be largely increased by the setting up of induced currents in adjacent wires carried on the same pole line. This is illustrated in the curve of Fig. 28, which is for one of the circuits employed in the operation of the first commercial carrier telephone system between Baltimore and Pittsburgh. The dotted curve represents excess attenuation originally found in the circuit due to such absorption. After additional transpositions had been cut into the circuit it finally gave the attenuation shown in the full line curve. The smaller attenuation hump shown in the curve at about 12,000 cycles was not eliminated, as its effect was not considered sufficiently serious to justify the expense of further transpositions.

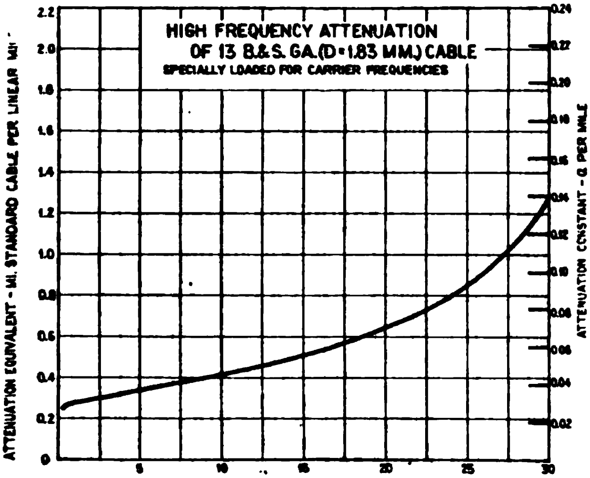

Fig. 32

The impedance of a circuit as viewed at terminal and intermediate repeater points is important in determining the proportioning of the connecting apparatus and in determining the amount of amplification which can be given, in systems depending on balance. Fig. 29 shows the impedance characteristic of a long No. 8 B. W. G. circuit. The curves follow the usual line formulas for characteristic impedance. It will be noted that the impedance is practically a pure resistance with a value of approximately 600 ohms. The fact that the reactance component is negligible makes it possible to design the selecting circuits regardless of the particular line over which a system is to operate.

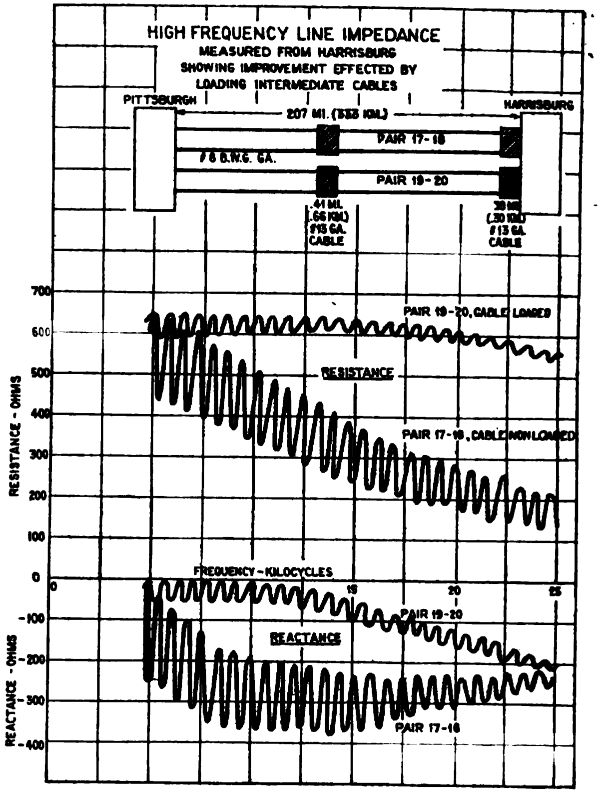

Fig. 33

The effect on repeater amplification of irregularities in impedance is covered in the section under "Line Balancing" below.

Cable. Transmission over cables will be discussed here in connection with the unavoidable use of short lengths of cable in open wire lines, for toll entrance in bringing the circuits into the central offices, at river crossings, in passing through cities, etc. Such lengths of cable have two effects:

a. They introduce a considerable transmission loss due to the inefficiency of cable circuits at these higher frequencies, and

b. They introduce a large irregularity in impedance characteristics which, in systems depending on balance for duplex operation, affects radically the amount of amplification which may be obtained at repeater points.

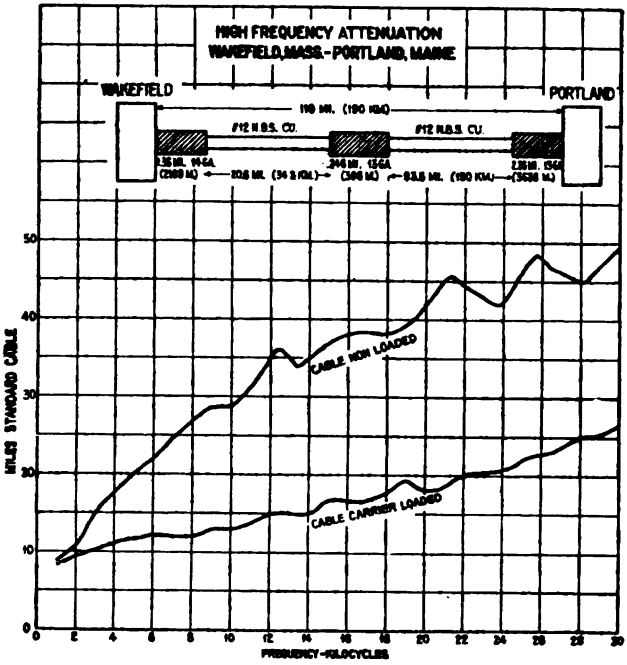

FIG. 34

Fig. 30 shows the attenuation, and Fig. 31 shows the impedance of a No. 13 B. & S. gage paper-insulated cable circuit of the ordinary telephone type.

To reduce both the attenuation of the circuits at these frequencies and the impedance irregularity which short lengths of cable introduce, there has been developed a system of coil inductance loading.

Loading for Carrier Frequencies. The loading systems which have been developed for cable are adapted to transmit frequencies up to about 30,000 cycles. The coils are spaced about 1000 feet apart, and the amount of inductance is chosen so as to give the cable circuits the same characteristic impedance as the lines to which they are connected. Fig. 32 shows the attenuation of a No. 13 gage cable so loaded.

Fig. 33 shows the impedance of a section of line between Harrisburg and Pittsburg as measured at Harrisburg, including two lengths of cable as indicated in the figure. It will be noted that the impedance when the cables are non-loaded is very irregular. The rapid variations in impedance are caused by reflections from the intermediate length of cable at Altoona, whereas the general drop of the complete impedance curve is due to the terminal cable at Harrisburg. It will be noted in this case that due to the terminal cable the reactance of the circuit as measured from the terminal is not negligible. The decrease in irregularity in impedance as the frequency increases is due to the fact that the attenuation increases with frequency, so that the cable at Altoona is electrically farther away at the higher frequencies. Since, however, the large attenuation has to be made up by larger repeater gains, the smaller apparent irregularity at the higher frequencies is of equal or greater practical importance than that at low frequencies. It will be noted furthermore that the loading largely overcomes the effect of the two lengths of cable. The slight remaining reactance component, which occurs at the higher frequencies, is largely due to the office wiring at the end where the measurements were made; and the slight remaining irregularity is due to some office wiring at Altoona.

Fig. 34 illustrates the effect on attenuation of the loading of intermediate lengths of cable. It shows the improvement introduced in the attenuation of a circuit between Wakefield, Mass., and Portland, Me., due to the loading of three lengths of intermediate cable. This section is a part of the circuit of a carrier telephone installation between Boston, Mass., and

Bangor, Me. The importance of loading will be appreciated in this case by noting that at 25 kilocycles the received energy is increased about two hundred times by the loading of the cables.

Under some conditions it has been found convenient to leave lengths of cable in carrier systems unloaded, and to install auto-transformers between the cable and the open-wire circuits to reduce the reflection losses introduced by the cables.

Line Balancing for Two-Way Operation. As already pointed out, two-way operation may be carried out either by the use of different frequencies in the two directions, or by using the same frequency for the two directions but using duplex balancing arrangements at the terminals. When different frequencies are used in the two directions it is sometimes convenient to employ line balance to supplement the selective circuits.

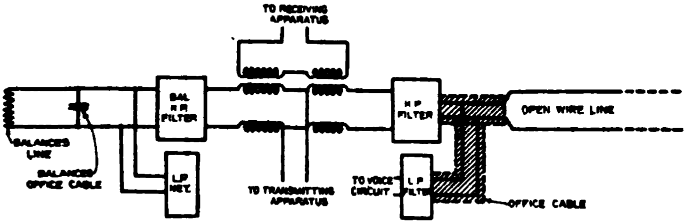

Fig. 35

The general problem of line balancing was discussed in some detail in the paper on telephone repeaters already referred to.[24] It will be noted by referring again to the impedance characteristic of a long uniform length of open wire circuit (Fig. 29) that a balance can be obtained by employing an artificial line consisting simply of a non-inductive resistance of about 600 ohms. Moreover, this resistance gives a good balance for all of the channels employed in a carrier system.

For systems requiring it, balance must be obtained not only at intermediate repeater points but also at each terminal, since the terminal set is itself inherently a repeater. Fig. 35 shows diagrammatically

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[24] Gherardi-Jewett, loc. cit.

a typical balancing arrangement in which the open-wire and connected apparatus on one side of the hybrid coil is balanced by a resistance and connected apparatus on the opposite side. The office wiring is balanced by a condenser and the high-pass and low-pass filters in the line are balanced by similar arrangements in the balancing line.

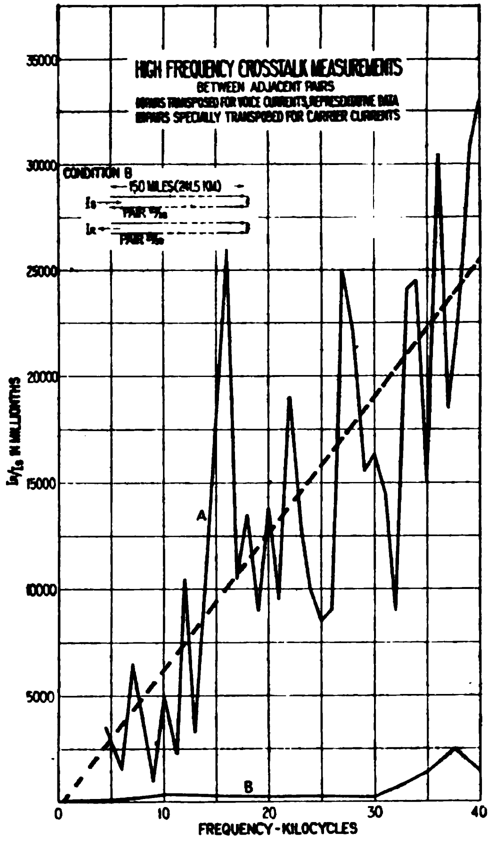

FIG. 36

There has already been pointed out in the section above the manner in which irregularities due to intermediate lengths of cable are cared for by loading. It is important that lines used for carrier operation shall be kept as free as possible from intermediate lengths of cable, lengths of twisted pair, etc. It will be noted that the irregularities in impedance so introduced are similar to those which occur at ordinary telephone frequencies, and were discussed in some detail in the paper on telephone repeaters.

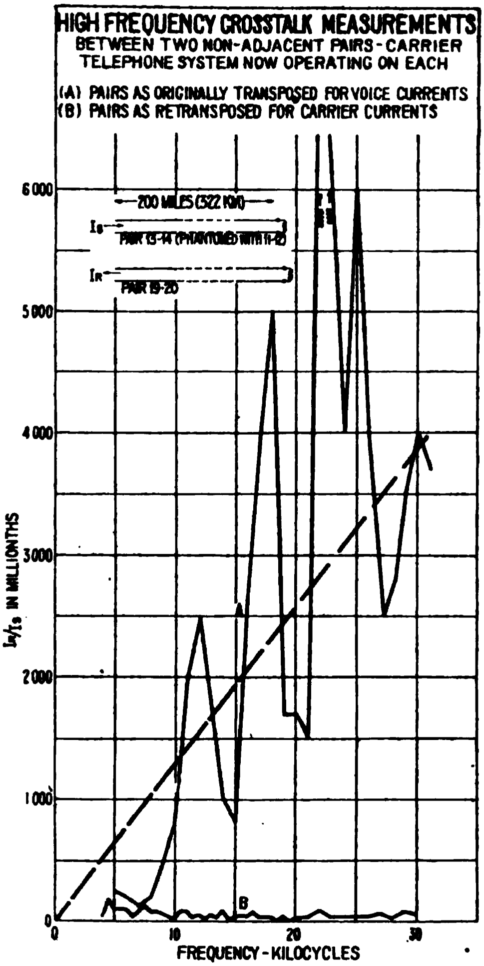

Fig. 37

Interference between Circuits—Transpositions. Any general use of carrier systems in the telephone plant requires that it be possible to operate a number of similar systems over the same pole line without mutual interference, that is, to transmit the same range of carrier frequencies over a number of circuits running closely together on the same line, with only negligible interference between channels of different carrier systems.

Inasmuch as the only means available for preventing interference between circuits where the same carrier frequency is employed in both directions is that of balance between circuits, effected by transpositions, it is obvious that where a number of carrier systems are to be operated on the same pole line, the circuits must be operated on the metallic and not on the ground return basis. Metallic circuits are also desirable for reducing foreign high-frequency interference, such as "static" and that from high-power radio stations employing frequencies in the carrier range.

The transpositions existing in open-wire telephone circuits are generally inadequate to balance the circuits sufficiently accurately for the higher frequencies of carrier transmission.

Fig. 36 shows the values of interference at different frequencies between two pairs of wires which are adjacent on the crossarm. Curve *A* shows typical values for circuits as measured with the ordinary telephone transpositions in them. Curve *B* indicates the great reduction made in the cross-talk by inserting transpositions in both of two circuits extending between Toledo, Ohio and South Bend, Indiana, making the average number per circuit about six per mile. Inasmuch as these circuits are adjacent pairs on the line, the exposure between them is the maximum possible.

In Fig. 37, Curves *A* and *B* show, in the same manner, the cross-talk between two circuits with the ordinary transpositions and after special transpositions had been cut into them. Here the circuits are not immediately adjacent but are separated on the crossarm by two other pairs of wires. The two pairs covered by this figure extend between Harrisburg and Pittsburgh, and are in commercial use for carrier systems.

As a result of a considerable amount of line measurements of the above types with different transposition systems, and from theoretical investigation of cross-talk at these frequencies, it has been determined that the interference limitations are roughly as follows:

Where carrier systems employ the same frequencies for transmission in the two directions, it would not be practicable to operate systems on all the pairs of a line, since the number of transpositions required would be prohibitively large. In fact, in a lead carrying a considerable number of circuits, the transpositions would have to be more closely spaced than are the poles under present standard construction. It is possible, however, to reduce greatly the effect of interference between circuits, by employing systems using different frequencies in the two directions, and arranging so that all of the systems employ the same range of frequencies in each direction. This reduces, of course, the number of two-way channels which may be obtained per pair. It is not certain, however, that even with this arrangement of carrier systems it would be economical to apply carrier to all pairs of a pole line.

Fig. 38

Much has already been accomplished, however, in transposing a limited number of pairs on a pole line for carrier operation, and this constitutes the practical problem in most of the present cases; for example, two carrier telephone systems and one carrier telegraph system are operating over the same pole line in the section of the New York-Chicago line between Harrisburg and Pittsburgh, a distance of about 200 miles. While the circuits involved in this case are not adjacent on the crossarm, the systems employ the same frequencies for transmission in opposite directions and therefore represent a severe condition as regards interference.

FIG. 39

Noise Interference. As the frequencies used in carrier systems are considerably higher than the harmonics which are generally present in power systems, these circuits are less subject to noise from power interference than are the ordinary telephone circuits. They are not free from such interference, however, since high frequencies may be set up in power systems by the charging of lightning protectors, switching, etc. Since the circuits cannot in general be as well balanced to ground at carrier frequencies as at ordinary telephone frequencies, the carrier channels have shown a certain amount of interference from atmospheric electrical effects—that is, so-called static. Some interference has also been experienced from high-power long-distance radio systems which are now employing frequencies within the same range.

Line-Measuring Apparatus. To put the lines in proper shape for carrier operation and to maintain them properly has necessitated the development of a suitable measuring technique and of portable measuring units, including a high-frequency oscillator, high-frequency impedance bridge, detector circuits, thermocouples, etc.

Fig. 40

A photograph of a portable high-frequency oscillator designed for testing work is shown in Fig. 38. This involves the use of four vacuum tubes and affords stable outputs as high as 50 milliamperes into an average line impedance. Its frequency range extends from 100 cycles to 50 kilocycles, and it is designed to operate on telephone-office power-supply sources.

Fig. 39 shows a high-frequency bridge of the differential-transformer type with a normal operating range covering that of the oscillator above mentioned. and capable of an accuracy throughout this range of one-quarter of one per cent.

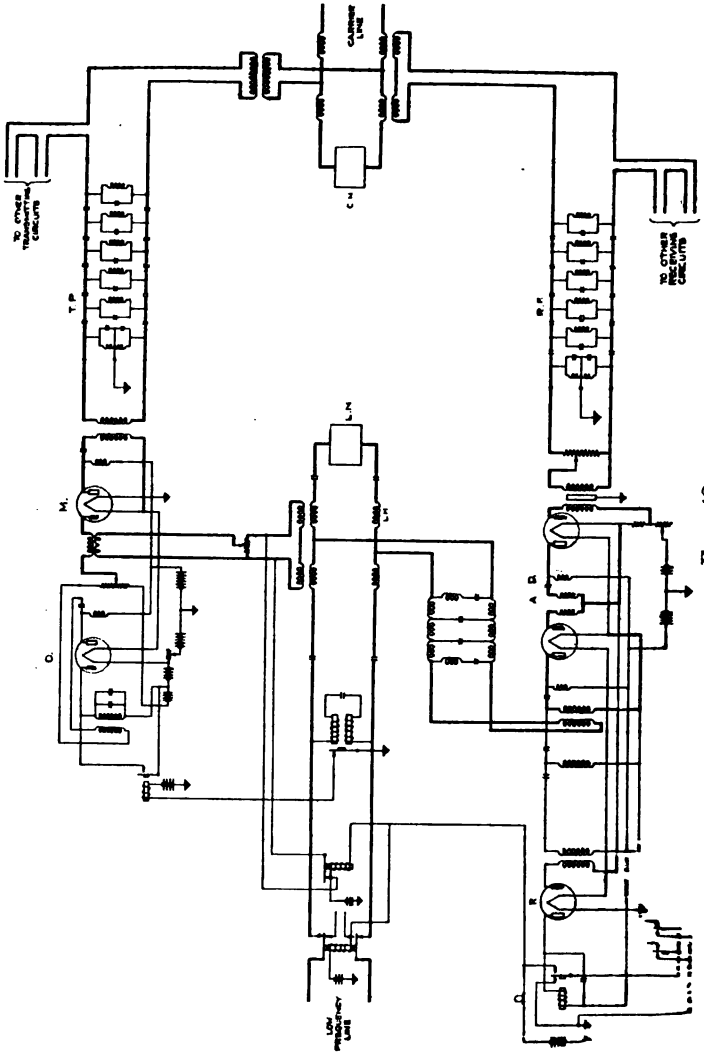
TO OTHER TRANSMITTING CIRCUITS
T.P.
M.
O.
CARRIER LINE
C.N.
L.N.
L.H.
R.F.
TO OTHER RECEIVING CIRCUITS
A.R.
R
LOW FREQUENCY LINE

FIG. 42

Fig. 40 shows a high-frequency detector unit for use in bridge measurements. This involves the use of several vacuum tubes in an amplifier-detector circuit with an optional detecting arrangement allowing either:

a. Recording on a direct-current galvanometer, or
b. The use of a telephone receiver.

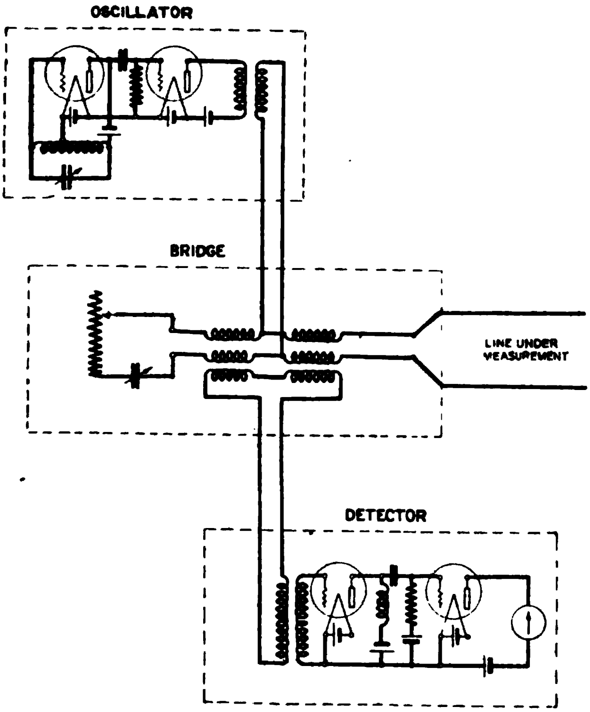

Fig. 41

Attenuation measurements have been carried out largely by the use of thermocouple meter circuits in conjunction with an oscillator of the general type above mentioned. This permits measuring directly the attenuations of lines up to about 250 miles in length. The current sent into the line is compared with the corresponding received current, with the circuit properly terminated. An over-all accuracy of about 1 per cent is usually obtained. Currents as low as 0.25 milliampere may be read with this method thus making it possible to measure attenuations involving current ratios up to 1:200, or a line length equivalent to approximately 50 miles of standard cable. For greater lengths of line circuits involving the use of the sensitive detector circuit above mentioned, have been employed using comparison methods.

Impedance measurements are made with the oscillator, bridge and detector circuits above noted. A schematic circuit arrangement is shown on Fig. 41.

COMMERCIAL APPARATUS AND INSTALLATIONS

Under this section there is given a description of the apparatus which has been developed for commercial service and of the manner of employing it in actual installations in the Bell Telephone Plant. To date there have been developed and put into commercial use, three distinct types of multiplex carrier systems, as follows:

1. A carrier telephone system in which the carrier is transmitted.
2. A carrier telephone system in which the carrier is suppressed.
3. A carrier telegraph system

There has also been developed a two-way repeater set employing vacuum tubes, and suitable for use with any one of these three systems.

We will consider these systems in the order noted above, including the repeater more specifically under the first system, and will then discuss the general considerations as to their practical uses which are common to all the systems.

Carrier Telephone System Employing Transmitted Carrier. The apparatus which characterizes this type of system is indicated diagrammatically in Fig. 42, which shows the terminal circuit arrangement of one two-way channel.

This circuit can perhaps be most simply explained by tracing the path of currents involved in telephone transmission, which is shown by heavy lines in the figure. Voice frequency currents originating in the low-frequency line on the left pass through the low-frequency hybrid coil, *L H*, into the vacuum-tube modulator, *M*. There is likewise fed into the modulator the carrier current from the vacuum-tube oscillator, *O*, shown in light lines. Of the components of modulation appearing in the output circuit of the modulator. the transmitting band-filter, *T F*, suppresses all except one side band, either the upper or lower as desired, and the carrier, which it transmits or passes into the circuit common to all of the transmitting channels. The transmitting currents from this and the other channels then pass through the carrier hybrid coil and out on the carrier line.

Fig. 43

The balancing networks, *L N* and *C N*, shown in Fig. 42, are important elements in determining the satisfactory operation of the system. The network, *L N*, on the left balances the low-frequency line and is similar to those used in ordinary telephone-repeater practise. The network, *C N*, on the right is of the type discussed above in the section on lines, and is illustrated in Fig. 35. It includes apparatus for balancing the office cabling and the line filters as well as the line itself.

The currents received from the line, which in the case of any given channel consist of one side band accompanied by its carrier, pass through the carrier hybrid coil and are selectively passed to the appropriate receiving circuits by means of the receiving band filters, one of which is shown at *R F*. The current passing through the filter *R F* is then amplified and demodulated in the two-stage vacuum-tube unit, *A D*, and the voice frequency currents appearing in the output circuit are selected from the other components of demodulation by the low-pass filter, from which point in the circuit they pass through the low-frequency hybrid coil, *L H*, to the connecting voice frequency line.

It should be pointed out that Fig. 42 indicates the points of connection for the transmitting and receiving circuits of the other two-way channels of the multiplex system, which are led to additional low-frequency lines through sets of apparatus which are exact duplicates of the one shown, except for the modifications necessitated by the use of different frequencies over the different channels.

The relays and the rectifier, employed in signaling by the methods already discussed, are also shown in the figure in light lines.

For convenience the apparatus itself is mounted on panels which are attached to relay racks in the central offices. The vacuum tubes peculiar to a two-way channel along with their immediately associated coils and other apparatus, are mounted on a panel by themselves, front and back views of which are shown in Figs. 43 and 44. At the top of Fig. 43 may be seen the oscillator and modulator tubes mechanically protected by wire cages, the control and dial of the condenser for adjusting the frequency of the oscillator, and similarly the potentiometers for controlling the supply of carrier and voice currents to the modulator. The jacks facilitate access to the various portions of the circuit for testing purposes.

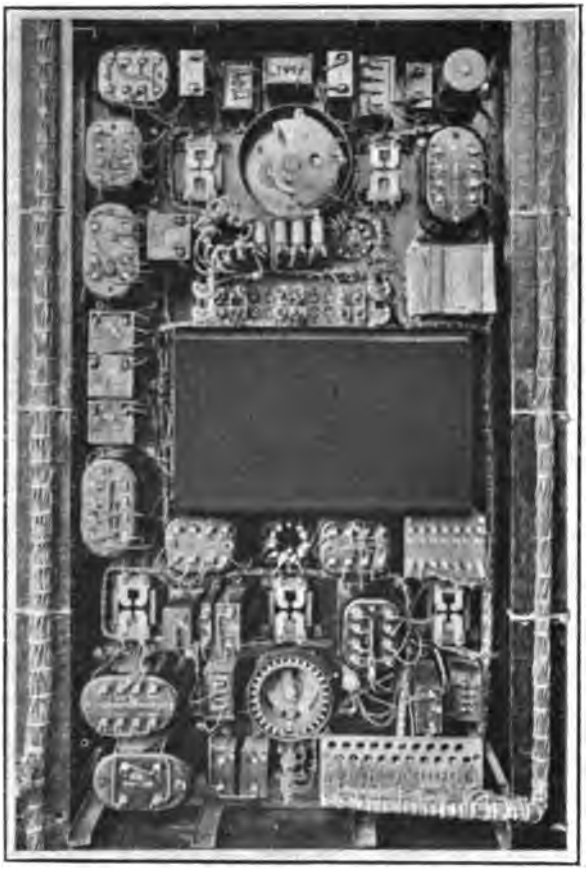

Fig. 44

Below are shown the three vacuum tubes of the receiving circuit, the potentiometer for controlling the line current supplied to the detector input, the filament-current rheostat and a signal lamp with cut-out key. The remainder of the apparatus is mounted on the back of the panel, Fig. 44, and when installed is protected by metal covers.

An assembly of panels of the type just described, each associated with an individual carrier telephone channel, together with other apparatus about to be described, is shown in Fig. 45. At the left may be seen four of the panels, three working in this instance and one spare, such as were shown in Fig. 43. The band-filters discussed above are mounted as individual units, of one of which a photograph is shown in Fig. 46.

FIG. 45

The coils and condensers are shown secured to a mounting plate; and this plate is clamped to the vertical rack immediately adjacent to the vacuum-tube panel with which it is electrically associated. In Fig. 45 these filter-units may be seen located just above and below the vacuum-tube panels. In the two bavs to the right are mounted the apparatus controlling the power supply to the tubes, the appara-

FIG. 46

tus used in the routine maintenance tests, and the hybrid coils and signaling relays.

The repeater set, which can be used with any of the

FIG. 47

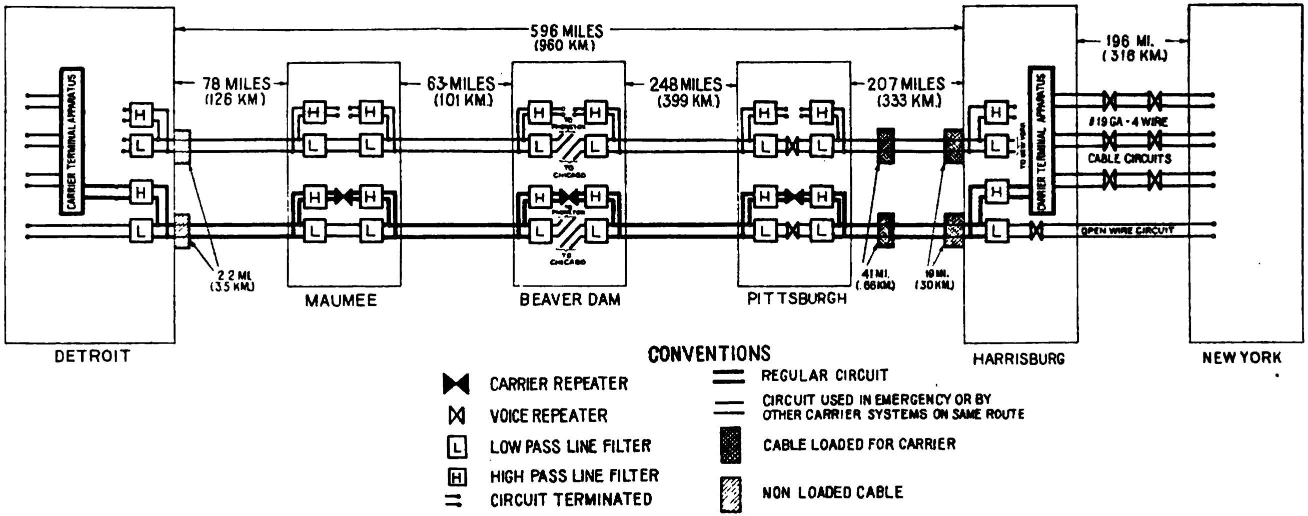
DETROIT
CARRIER TERMINAL APPARATUS
78 MILES (126 KM)
2.2 MI. (3.5 KM)
MAUMEE
63 MILES (101 KM)
596 MILES (960 KM)
BEAVER DAM
TO CHICAGO
TO CHICAGO
248 MILES (399 KM)
PITTSBURGH
207 MILES (333 KM)
41 MI. (66 KM)
19 MI. (30 KM)
HARRISBURG
CARRIER TERMINAL APPARATUS
196 MI. (316 KM)
#19 GA.-4 WIRE
CABLE CIRCUITS
OPEN WIRE CIRCUIT
NEW YORK
CONVENTIONS
CARRIER REPEATER
VOICE REPEATER
LOW PASS LINE FILTER
HIGH PASS LINE FILTER
CIRCUIT TERMINATED
REGULAR CIRCUIT
CIRCUIT USED IN EMERGENCY OR BY OTHER CARRIER SYSTEMS ON SAME ROUTE
CABLE LOADED FOR CARRIER
NON LOADED CABLE

Fig. 48

carrier systems so far employed, embodies the circuits shown in Fig. 22. A front view of an actual set is shown in Fig. 47. This set includes the two-stage push-pull amplifiers, one for operating in each direction, and the necessary filters and hybrid coils for associating the set with the line. The balancing networks are located on shelves of a nearby rack. Also there is furnished a testing unit which may be associated with a number of such repeaters, usually up to four.

An illustration of an installation of this type is afforded by the Harrisburg-Detroit system, which is planned for New York-Detroit telephone service. A diagrammatic layout of this system is given in Fig. 48.

The carrier terminals are located at Detroit and Harrisburg, and the three carrier channels are brought from Harrisburg into New York as voice frequency circuits of the four-wire cable type. The system is provided with three intermediate repeaters at the points indicated. An additional open wire circuit between Harrisburg and Detroit is equipped with the necessary line filters at the terminals and the intermediate points, to make it readily available as a spare line-circuit. This spare line-circuit may be employed subsequently for a second carrier system. In its course from Harrisburg to Detroit the carrier system is superimposed upon two different voice frequency circuits in turn. One of these is a New York-Chicago circuit, which the carrier system takes between Harrisburg and Beaver Dam, at which point it deviates from the route pursued by the carrier system. The remaining portion follows a different voice frequency circuit from Beaver Dam to Detroit. This illustrates the possibility of transferring the carrier systems from one voice frequency circuit to another en route. The separation of the carrier channels from the regular voice frequency channel, at each of the intermediate points, enables the two sets of channels to be handled entirely independently of each other in their operation and maintenance. For example, at Pittsburgh a repeater is inserted in the voice frequency circuit as well as in the carrier frequency channels, while at Beaver Dam and Maumee the repeaters are inserted in the carrier channels only. The occurrence of sections of intermediate cable in the system is indicated in the figure. The effect of the cable sections between Harrisburg and Pittsburgh was specifically referred to in the section on Lines.

Carrier Telephone System with Suppressed Carrier.

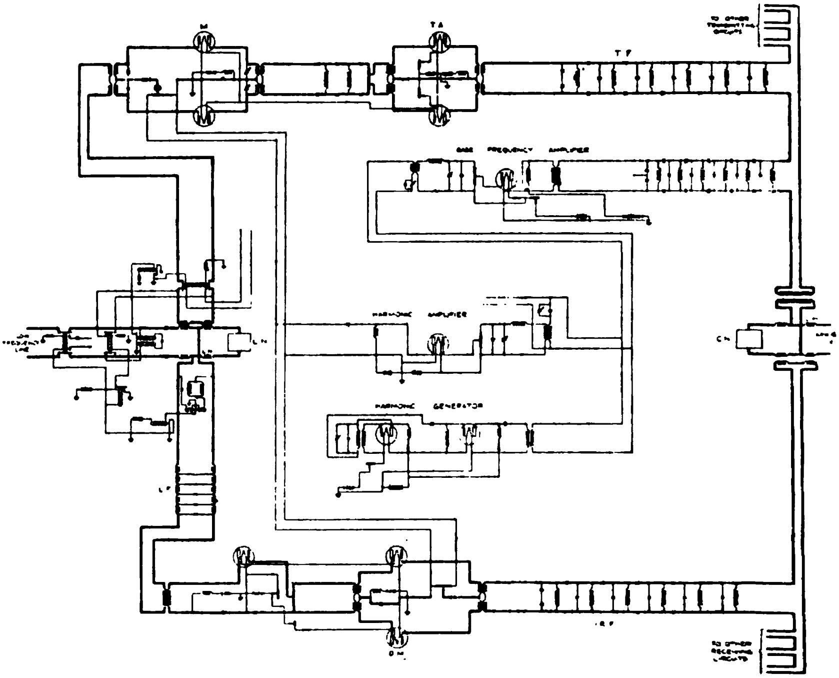

FIG. 49

The second type of carrier telephone system has been designed to operate on the principles of carrier suppression and harmonic carrier generation which were quite fully discussed above. In comparison with the system just described it is rather more complex and there is more auxiliary terminal apparatus common to all the channels. Fig. 49 is a circuit diagram of one terminal of one two-way channel together with the common carrier-supply circuits. As usual, the transmission circuits are indicated by heavy lines, while the light lines show the carrier-supply and the signaling. The system indicated is one designed to use the same carrier frequency for both directions of a two-way conversation. Therefore the harmonic generator is shown as feeding through the same selective circuit and harmonic amplifier, into the modulator, *M*, and the demodulator, *D M*. The harmonic generator is supplied with the base frequency from the oscillator, *O*, and in addition to supplying the harmonics it also supplies the base frequency to the terminals of the base-frequency amplifier which selectively amplifies this frequency and supplies it to the line as shown. In the transmission circuit it will be noted that in addition to the balanced modulator, *M*, already described, a push-pull amplifier, *T A*, is used to increase the volume of side-band current transmitted. The high-pass filter between the modulator, *M*, and amplifier, *T A*, prevents the latter from being overloaded by the voice currents in the output of the modulator. The balanced demodulator, *D M*, serves to prevent the transmission of the local carrier back over the line. The carrier-supply apparatus shown, including the harmonic generator, is that used at the controlling station. At the distant station the arrangement is modified to provide for amplifying the base frequency received from the incoming carrier line and supplying it to a harmonic generator which supplies the various frequencies through the amplifier to the modulators and demodulators associated with each channel.

The apparatus for this system has been mounted on unit racks of self-supporting type. One such unit holds the sending apparatus for one channel and another the receiving apparatus. Illustrations of these are shown in Figs. 50 and 51. Apparatus such as tubes and potentiometers is located with convenient accessibility and the space below is used for filters, condensers and other apparatus which requires practically no attention or adjustment. Similar racks are used for the base-frequency oscillator and harmonic generator, the harmonic amplifiers, the testing circuits and the auxiliary low-frequency apparatus.

This type of apparatus is employed, for example, in the Harrisburg-Chicago system, the circuits of which are extended into New York as voice frequency circuits in order to provide New York-Chicago service. This system spans a somewhat greater distance than the Harrisburg-Detroit and includes four intermediate carrier repeater stations. Fig. 52 shows diagrammatically the layout of the whole system. For insurance of service a second set of line wires is arranged for carrier operation as illustrated. In general the plant features are the same as in the case of the Harrisburg-Detroit installation

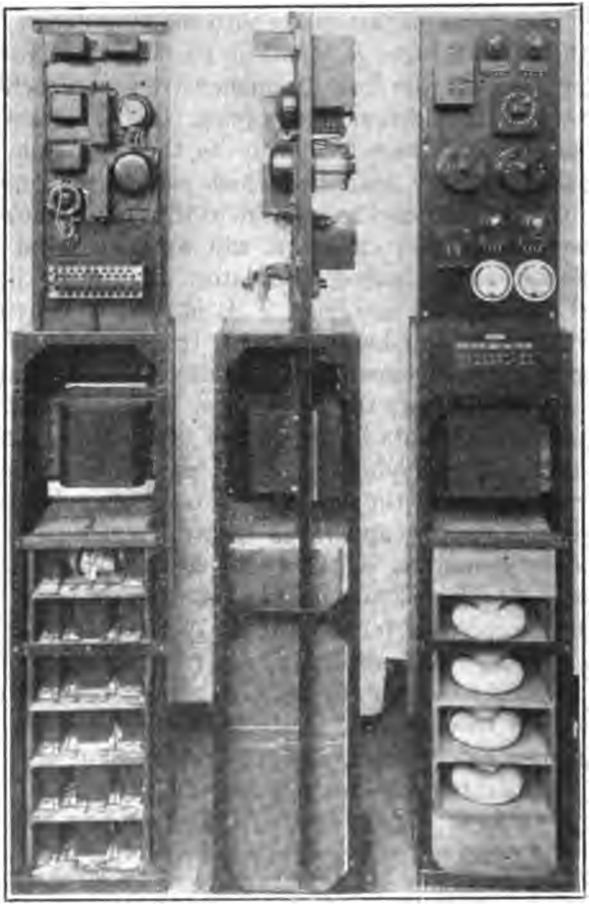

FIG. 50

above. Because each carrier circuit in this system employs the same carrier frequency for transmission in the two directions, greater care was taken to make

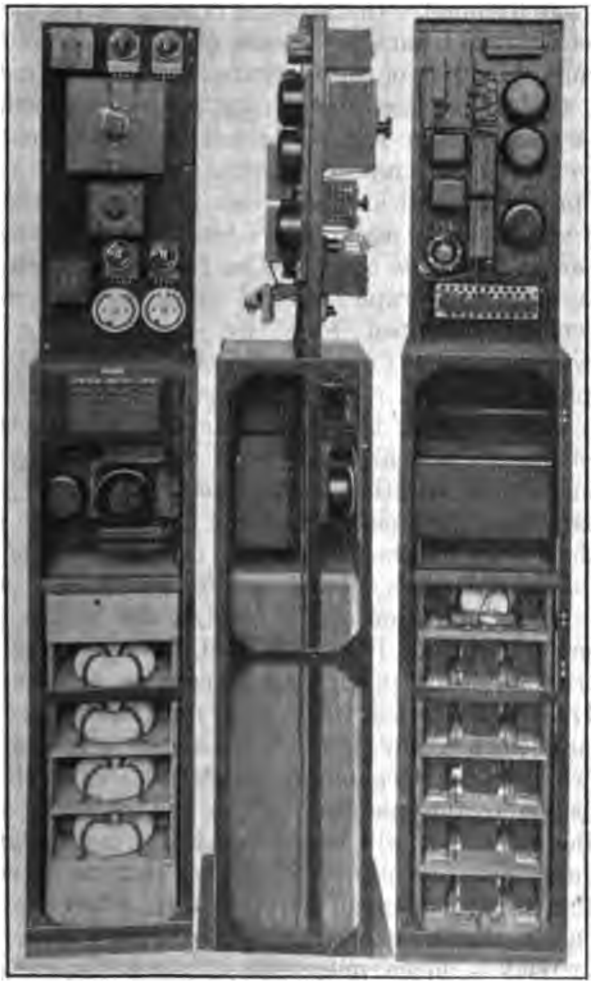

FIG. 51

the lines of uniform impedance and to simulate them with their associated balancing networks.

In the Harrisburg-Pittsburgh section, this system is operated over the same pole line as is the one previously described and also with a multiplex carrier telegraph, later referred to. This has required a special transposing of the line wires between these two points.

The appearance of the apparatus at the terminal offices is shown by Fig. 53, which is that located at the Chicago terminal. In the center of the group of panels is seen the test panel by means of which the routine maintenance tests of the apparatus and lines are made.

A typical repeater installation at an intermediate office is shown in Fig. 54, which is that located at Cleveland. Two repeater units, one a spare unit, are provided; and located beside them is the testing unit employed for maintenance tests and switching.

Carrier Telegraph System. The fundamental circuit of a carrier telegraph channel has already been shown in simplified form by Fig. 23. Fig. 55 shows the circuits for associating ordinary telegraph sending and receiving loops with one terminal of a duplex carrier telegraph channel. It also shows schematically the high-frequency side of the system including the selective circuits and the vacuum-tube apparatus. The operation of the high-frequency side of the system will be clear from a consideration of the simplified telegraph circuit and from what has been said of the operation of the very similar carrier telephone apparatus. It may be said, however, that the discrimination by tuned circuits between the sending and receiving channels which are of different frequencies is supplemented by the line-balancing arrangement shown, as in the telephone system first described above. Referring to the operation of the low-frequency side of the system, it will be seen that the manipulation of the sending operator's key controls the sending relay of the carrier apparatus which in turn impresses the signals on the carrier current. In receiving, a sensitive polar relay is shown, operated by the rectified current, which in turn transmits the signals into the local subscriber's loop in the form of the usual direct-current impulses. In the actual apparatus switches are provided by means of which the sending and receiving channels are associated with a common subscriber-loop for half-duplex operation.

The apparatus for one terminal of one full-duplex

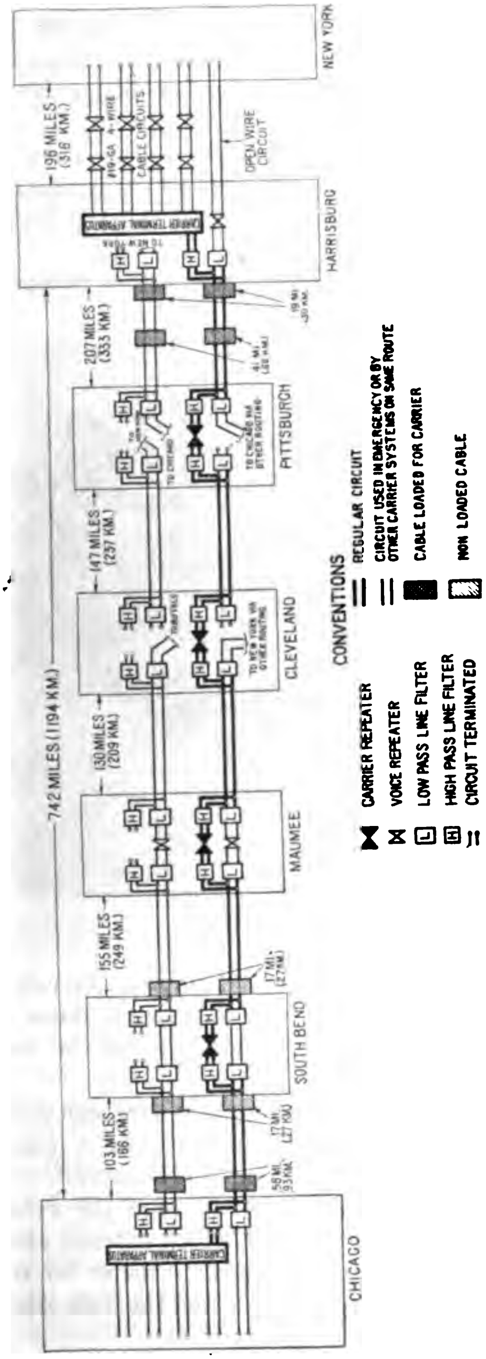
NEW YORK
196 MILES (316 KM.)
#19-GA 4-WIRE
CABLE CIRCUITS
OPEN WIRE CIRCUIT
HARRISBURG
CARRIER TERMINAL APPARATUS
TO NEW YORK
19 MI. (30 KM.)
207 MILES (333 KM.)
61 MI. (98 KM.)
PITTSBURGH
TO CHICAGO
TO CHICAGO VIA OTHER ROUTING
147 MILES (237 KM.)
CLEVELAND
TO NEW YORK VIA OTHER ROUTING
742 MILES (1194 KM.)
130 MILES (209 KM.)
MAUMEE
155 MILES (249 KM.)
17 MI. (27 KM.)
SOUTH BEND
103 MILES (166 KM.)
58 MI. 93 KM.
CHICAGO
H
L
CONVENTIONS
CARRIER REPEATER
VOICE REPEATER
LOW PASS LINE FILTER
HIGH PASS LINE FILTER
CIRCUIT TERMINATED
REGULAR CIRCUIT
CIRCUIT USED IN EMERGENCY OR BY OTHER CARRIER SYSTEMS ON SAME ROUTE
CABLE LOADED FOR CARRIER
NON LOADED CABLE

Fig. 52

carrier telegraph channel, represented in Fig. 55, is mounted on a self-supporting rack Fig. 56. On the front of the panel may be seen the vacuum tubes, the meters for observing the signaling currents, the sounders and key for monitoring; and the switches associated with the subscriber's loop circuit. The panel at the top is hinged to afford ready access to the apparatus mounted on the back. In the lower compartment are located the tuned circuits, the adjustable condensers of which are visible. Below these can be seen the cylindrical case which contains the sensitive receiving polar relay.

FIG. 53

Fig. 57 shows a group of carrier telegraph sets with an associated testing unit constituting a part of a complete installation located at Pittsburgh. At the top of the testing unit may be seen the relay and sounder of a regular test wire which extends along the route taken by the carrier system, a meter for measuring high-frequency line currents and the dials associated with an oscillator for testing purposes. The jacks afford access to circuits of any of the carrier telegraph panels grouped with the test unit.

The layout of the ten-channel Harrisburg-Chicago carrier telegraph system which includes the equipment of Fig. 57 is shown in Fig. 58. The circuits connecting the Harrisburg terminal to New York, where the most of the telegraph business terminates, are also shown. Pittsburgh, it will be noted, is not made merely a repeater station, as is Beaver Dam, but instead is equipped with two complete sets of carrier telegraph terminal apparatus. This is done to permit of connection between the through channels and local telegraph loops and also to permit of any one channel on one side being used independently of the corresponding channel on the other side.

Fig. 54

Fig. 59 shows the geographic layout of the three installations described above extending west from Harrisburg and connecting back to the seaboard cities through cable circuits. There is also indicated on this

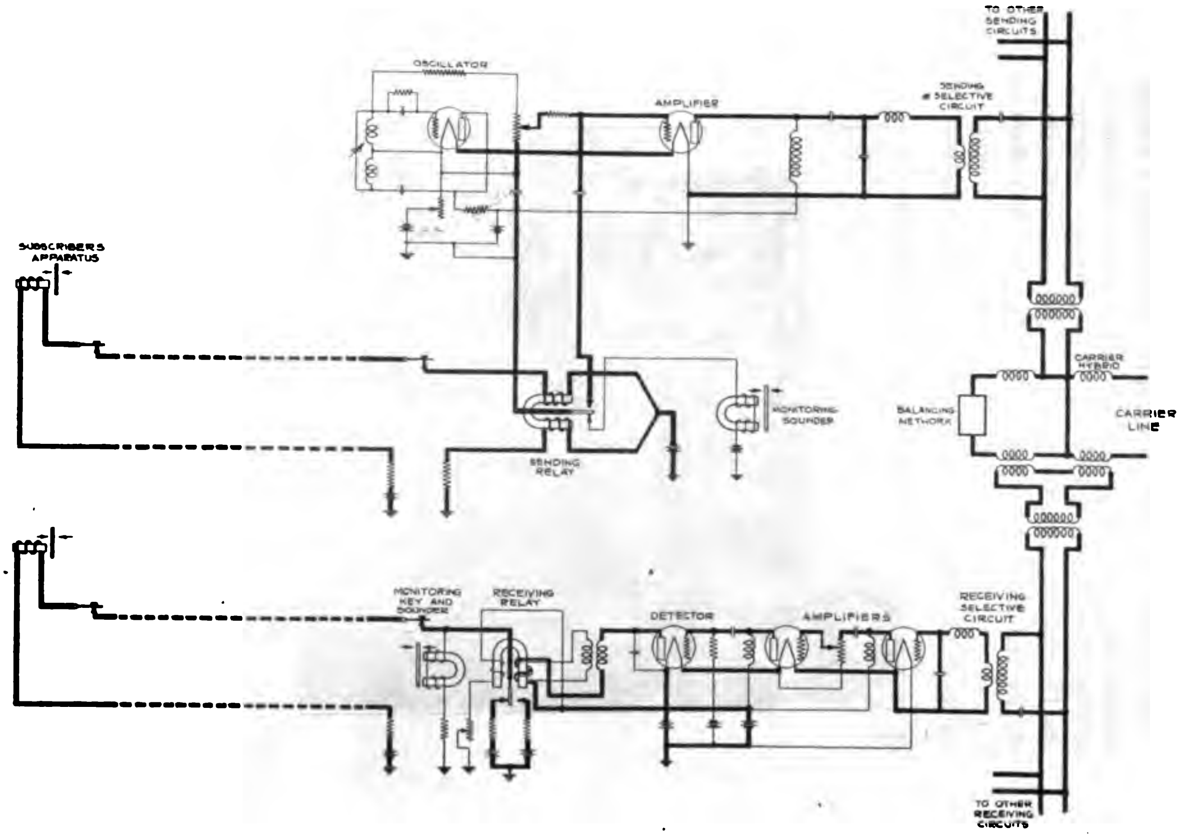
TO OTHER SENDING CIRCUITS
OSCILLATOR
AMPLIFIER
SENDING & SELECTIVE CIRCUIT
SUBSCRIBERS APPARATUS
CARRIER HYBRID
CARRIER LINE
BALANCING NETWORK
MONITORING SOUNDER
SENDING RELAY
MONITORING KEY AND SOUNDER
RECEIVING RELAY
DETECTOR
AMPLIFIERS
RECEIVING SELECTIVE CIRCUIT
TO OTHER RECEIVING CIRCUITS

FIG. 55

Fig. 56

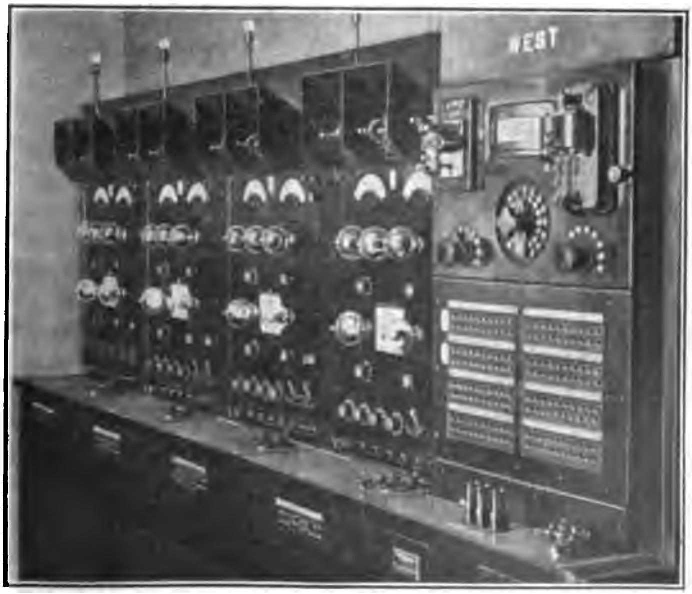

Fig. 57

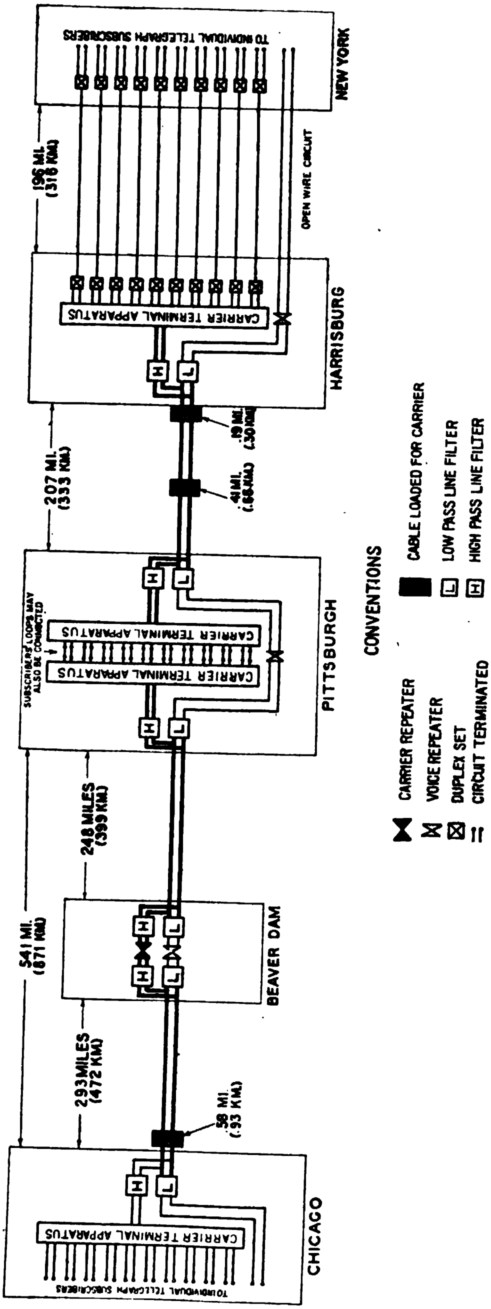
NEW YORK
TO INDIVIDUAL TELEGRAPH SUBSCRIBERS
196 MI. (316 KM.)
OPEN WIRE CIRCUIT
HARRISBURG
CARRIER TERMINAL APPARATUS
H
L
.19 MI. (.30 KM.)
207 MI. (333 KM.)
.41 MI. (.66 KM.)
PITTSBURGH
SUBSCRIBERS' LOOPS MAY ALSO BE CONNECTED
CARRIER TERMINAL APPARATUS
CARRIER TERMINAL APPARATUS
248 MILES (399 KM.)
541 MI. (871 KM.)
BEAVER DAM
293 MILES (472 KM.)
.58 MI. (.93 KM.)
CHICAGO
CARRIER TERMINAL APPARATUS
TO INDIVIDUAL TELEGRAPH SUBSCRIBERS
CONVENTIONS
CARRIER REPEATER
VOICE REPEATER
DUPLEX SET
CIRCUIT TERMINATED
CABLE LOADED FOR CARRIER
LOW PASS LINE FILTER
HIGH PASS LINE FILTER

Fig. 58

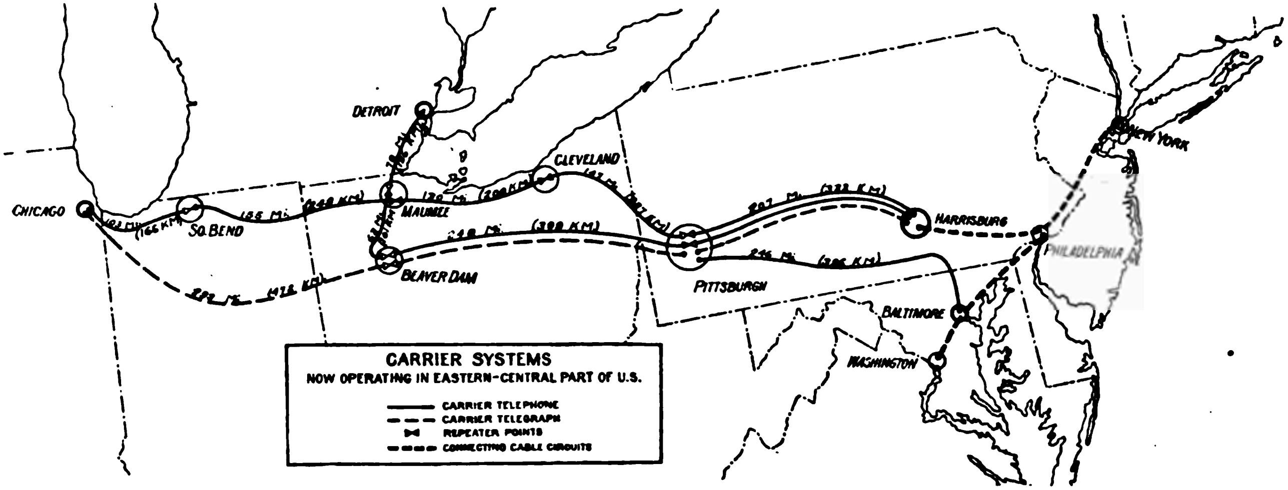
CHICAGO
103 Mi. (166 KM)
SO. BEND
155 Mi. (248 KM)
MAUMEE
DETROIT
129 Mi. (208 KM)
CLEVELAND
BEAVER DAM
248 Mi. (399 KM)
PITTSBURGH
207 Mi. (333 KM)
HARRISBURG
246 Mi. (396 KM)
PHILADELPHIA
NEW YORK
BALTIMORE
WASHINGTON
CARRIER SYSTEMS
NOW OPERATING IN EASTERN-CENTRAL PART OF U.S.
CARRIER TELEPHONE
CARRIER TELEGRAPH
REPEATER POINTS
CONNECTING CABLE CIRCUITS

Fig. 59

map the Baltimore-Pittsburgh telephone system, which was originally installed for giving Washington-Pittsburgh service.

General Considerations. An important aspect of the carrier developments described above is that they have placed the art upon a quantitative basis and enabled carrier installations to be engineered and put into operation in much the same way as is done for regular repeater telephone circuits. The transmission layout of the system is determined from a consideration of data on line characteristics and from the characteristics of the apparatus. In carrying out an installation, a certain amount of preparatory work must usually be done on the lines, including particularly the loading of intermediate sections of cable and transposition work. In the offices, the apparatus is installed in much the same way as are the more usual forms of telephone equipment, taking certain precautions, however, to minimize the lengths of office wiring included in the high-frequency circuits and to avoid cross-talk in the wiring interconnecting the individual apparatus units. The battery supply currents for the vacuum tubes are usually furnished from the existing 24-volt telephone batteries and 120-volt Morse batteries.

The grade of service given by carrier circuits, both telephone and telegraph, is as a rule quite up to the high standards which prevail for the long-distance circuits of the Bell plant. Not only is it possible to deliver the volume of transmission necessary for enabling the carrier circuits to be greatly extended by the addition of ordinary circuits at the ends, but also the naturalness and intelligibility of transmission is preserved to a very satisfactory degree.

The carrier telephone channels are terminated in the long-distance switchboards in the usual way as, for example, at New York and Chicago for the Harrisburg-Chicago system described above; and connections are put up by the long-distance operators, using the regular toll cords. In fact, to the operators such circuits are indistinguishable from the regular long-distance repeatered circuits. The operator rings at the terminals of the connecting circuits in the standard manner, and the signals are automatically relayed over the carrier telephone channel as indicated in the circuit diagrams above, so that each carrier telephone channel is provided from end to end with its own signaling channel. The satisfactory working out of such operating features as these has been of much importance in completing the commercial usefulness of carrier telephone systems.

As has been indicated above the carrier telegraph systems as well as the carrier telephone systems, are designed to fit as an integral unit into a comprehensive wire plant, the relay-circuit arrangements providing for automatic repetition between the carrier channels and the connecting circuits, whether the latter be subscribers' loops or an additional section of long-distance circuit. The carrier telegraph circuits are used in the Bell plant, as are the regular composited Morse circuits, to furnish leased-wire service. The requirements for this service are particularly exacting as regards continuity and quality. The carrier telegraph circuits have proved to be very satisfactory in meeting these demands.

Reference was made in the first part of the paper to the fact that the carrier apparatus required for meeting the high standards of operation of a public service communication system is expensive. The technique involved in the art is so fascinating that one may readily lose sight of the more practical matter of costs, but to the engineer the economics of the situation are all-important, for it avails nothing if it is not possible to accomplish by the new method the same, or better, results than were obtainable with the old, at no greater cost. Carrier telephone systems—at least in the present state of the art—are economical in a general public service communication system only for use over relatively long distances. Of course, whether carrier can be justified in any given case depends upon factors peculiar to that case; in some instances, for example, it may not be physically possible to provide additional wires over a given toll line or cable route, in which case the relatively high apparatus costs may be easily justified. The carrier telegraph system is also essentially a long-distance proposition, although it is sometimes possible to warrant its use for distances somewhat shorter than in the case of telephone systems.

The authors wish to state that this paper is based largely upon the results of the engineering and research work of a great number of engineers on the staffs of Col. J. J. Carty, Vice-President of the American Telephone and Telegraph Company, and of Col. F. B. Jewett, Chief Engineer of the Western Electric Company. They desire particularly to acknowledge their obligations to Messrs. R. V. L. Hartley and Lloyd Espenschied, who, in addition to their very valuable contributions to the development of the art, have rendered special assistance to them in the work of preparing this paper.

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SOME PHASES OF RAILROAD TELEGRAPH AND TELEPHONE ENGINEERING

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Abstract of Paper

Statement of size of N. Y. C. Lines telegraph and telephone plant and variety of engineering problems involved. Telephones used almost exclusively for train dispatching, not so general for message work, but growing. Automatic telephones used. Extensive local and long distance lines and switchboards. Telegraph system reaches all stations. Pole line is basis of plant, increasing in strength to meet safely the loads to which subjected. Railroad employs wire chiefs.

Problems include electric protection, inductive interference, electrolysis, transmission, traffic, necessitating continual experiment and investigation. Telegraph answer-back used with selectors. Phantom telephone circuits used. Single wires for railroad telegraph obsolete, all wires used in simultaneous telegraphy and telephony. Extra high impedance telephone used for train dispatching. Iron wire joints welded. Battery consumption data; unit type switchboards designed, supplant dry battery for main selector ringing battery; chemical rectifier also used. Oscillograms of single-line telegraph current waves, when line insulation varies. Railroad long-distance lines can be loaded.

Telephone selector current waves given. Gill local bell selectors used with repeat coil signaling to obtain low-resistance simplex. Duplex telegraph used on about 10,000 miles of circuit on N. Y. C. Lines. Polar duplex is approximate three-wire circuit. Self-balancing duplex designed especially adaptable at unattended repeater stations; oscillograms illustrating results in better balance of duplexes. No. 5-U retard coil of standard bridging duplexes and quads is auto-transformer as well as retard coil; is useful as retard, detrimental otherwise. Polar relay armature of differential duplex and quadruplex has more force than in bridging. Differentially connected relays are transformers to some degree. Inductive effects of differential sets. Standard quadruplex, common side, is too sluggish for hand-operated sending machines. Defects of quadruplex discussed. Limiting practicable lengths stated for various kinds of wire for telegraph and telephone circuits.

THE railroad telegraph and telephone department entered a new era when telephone train dispatching was adopted 13 years ago. In the last five years electrical engineers have been employed in this

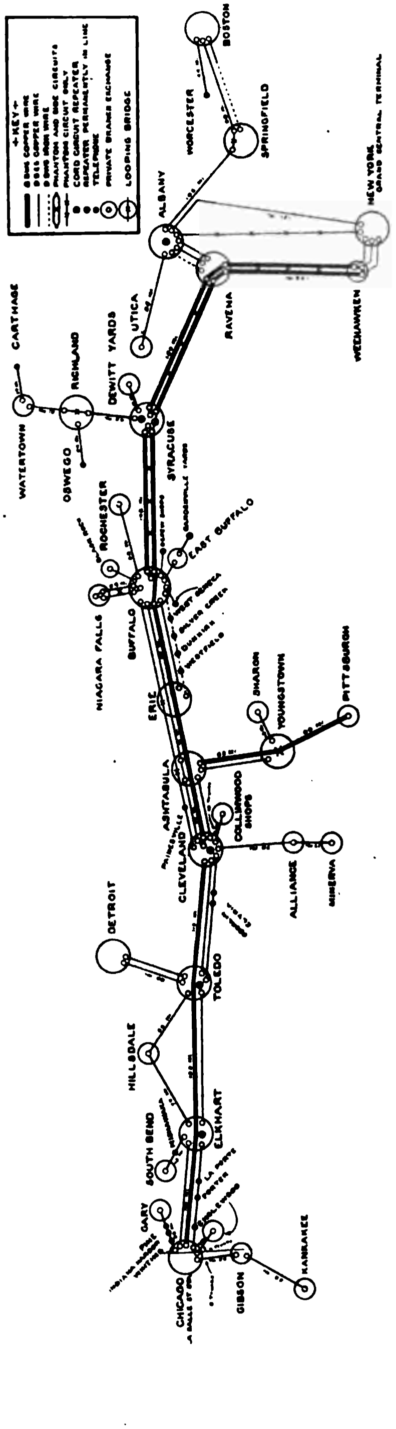


FIG. 1—NEW YORK CENTRAL LONG-DISTANCE TELEPHONE LINES

department in increasing numbers, and the development has become more rapid. Previously the telegraph and telephone departments of the railroads were content to depend on outside interests for ideas, equipment, methods of operation and development, and as a result the development was slow. The staff of one railroad telegraph department, with engineers continuously employed, has procured considerable advancement in the railroad telegraph and telephone plant in a space of four years, perhaps as much as was accomplished by all railroad telegraph and telephone departments in the four years previous to the period mentioned. This is attributed to the intensive application of electrical engineers to practical problems and obvious requirements of railroad service.

FIG. 2—C. C. C. & ST. L. RY., ST. LOUIS DIV. HEADQUARTERS RELAY TELEGRAPH OFFICE

A difficulty confronting the engineer in the investigation of a problem, is to learn the state of the art in relation to the particular problem in hand. It is somewhat with the idea of presenting some data on the state of the art, as applied to railroad telegraph and telephone systems, that data and results of investigations are given here. It is hoped that any incomplete investigations can be continued by the engineers of the New York Central Lines and others; that any false conclusions can be pointed out, and that the data here presented may suggest investigations along other similar lines and on related problems.

In order to interest others than railroad engineers in these problems, it can be said that the railroad telegraph and telephone engineer, particularly of the larger railroads, has problems of a variety that includes a little of about everything confronting the plant and traffic engineers of the large telephone and telegraph companies that have nation-wide service. The extent and distribution of the plant are the chief differences. This variety gives absorbing interest to the work. As the staff of the telegraph department is small, its engineers are obliged to handle any problem that arises as best they can.

NEW YORK CENTRAL LINES TELEGRAPH AND TELEPHONE PLANT

The plant under the supervision of the New York Central Lines Telegraph Department comprises 6 per cent of the total Western Union pole line and 12 per cent of the wire, and includes 12,000 miles of pole line with 80,000 miles of copper wire, of which 40,000 are used by the railroad; 76,000 miles of iron wire, of which 25,000 are used by the railroad on 12,000 miles of rail line. This includes a New York-Chicago long-distance telephone line, shown in Fig. 1, which has telephone repeaters, composite equipment, phantom circuits, and loaded cable. Practically all other important points from New York and Boston, to St. Louis and Chicago are connected in the network of service. Vacuum-tube telephone repeaters are installed at Albany, Syracuse, Cleveland, Toledo and Elkart, with one or two additional stations soon to be installed. These lines connect railroad telephone exchanges in some cases larger than required to serve the public in small cities. The total number of long distance calls handled is about 5000 calls per day. New York and Chicago have 12 position boards, and others are in proportion to the amount of business done. The New York Central Lines have about 5500 telephones on P. B. X. boards and 4000 direct exchange lines.

The number of local calls is enormous, but is not kept count of ordinarily. City calls are counted by the telephone companies in order to make the billing where this is on measured rates. These boards are operated by the railroad, but furnished and generally maintained by the Bell telephone companies. The railroad offices in large cities have numerous one-position sub-boards in various departments.

The railroad telegraph service with its network of 40,000 miles of copper and 25,000 miles of iron wire in its own service, reaches 3700 offices. The centers of operation at headquarters of the general staff of the railroads have large offices called general telegraph offices. The division headquarters telegraph offices are called relay offices. Such an office at Mattoon, Ill., is shown in Fig. 2. This office serves two telephone dispatching circuits, four telephone message circuits, two phantoms, four yard lines, two Western Union way Morse wires, four railroad single-line Morse wires, two of which are connected through repeaters, three duplex Morse wires, two of which are connected through repeaters. New York has a force of 20 telegraph operators, Indianapolis 18, Detroit 16, Chicago 14, Cleveland 13, and other cities in proportion.

The telegraph service is more extensive than the telephone long-distance system, because it must reach every station and office on the system; whereas, the telephone long-distance service is limited to the officers and employes who have Bell telephones that connect to the railroad telephone exchanges, and the way stations in general do not have access to the long-distance lines.

Direct through service is maintained between the important centers and in nearly every case between adjacent division terminals. For example, New York has a direct Cincinnati wire, also one each to Chicago, Detroit, Cleveland, Buffalo, Rochester, Syracuse, Watertown, Corning, Albany and Boston. Single Morse has the greater total mileage, duplex Morse next, but only a small amount of quadruplex is used because of its limitations.

The thirty New York Central Lines relay telegraph offices handle about 55,000 railroad telegraph messages per day. No attempt is made to count the messages handled by one way station with another, unless they are relayed or sent or received by the general or relay telegraph offices. The way-station operators receive and transmit Western Union commercial messages in addition to the railroad messages.

Some printing telegraph service is employed between relay offices. At present, this is limited to New York to Albany and Cleveland to Toledo. The operation is duplex, single channel, Morkrum type in both cases. In the hand operation, single, duplex and quadruplex service is employed.

The telephone is used almost exclusively for train dispatching on the New York Central Lines, consisting of 108 circuits, with 3020 selectors on 10,271 miles of railroad. It is also being extended for way-station message service on dispatching divisions, but is at present in use on 48 circuits with 1464 selectors, less than half the total New York Central Lines mileage. When business returns to normal it is expected that this service will rapidly extend until the railroad is on a complete telephone basis. Several different types of selectors and telephones are in use for these dispatching and message circuits.

Two railroad automatic telephone systems are in service, one at Detroit and one at New York in the electric division, neither of which is connected to the Bell telephone system. The New York installation comprises five interconnected exchanges, with 600 stations. The system centers in Grand Central Terminal but has exchanges connected by trunks, at West 72nd St., Mott Haven, Harmon, and White Plains. The latter two are each about thirty miles from New York. An immense volume of traffic is handled on this system. The Grand Central Terminal board handles about 2000 local calls per day, 500 incoming trunk calls, and 700 outgoing to and through Mott Haven. The high hourly load is between 3 and 4 p. m., during which period about 600 local calls are handled daily.

The privately owned telephone cable plant is gradually extending. It now extends nearly twenty miles out of New York on both the Hudson and Harlem Divisions, and will extend eventually thirty miles on each. In other cities the private cable plant is growing in proportion. In the New York territory loud-speaking telephones are used for train dispatching, also for train announcing between interlocking towers in the vicinity of Grand Central Terminal. "A" tower on the upper level of Grand Central Terminal has in use almost all practicable methods of wire communication, including, Bell and automatic telephones, telautograph, loud speaking telephone circuits, lamp signal annunciators, bell annunciators, private line telephones, and selector telephone train dispatching and message lines. Private line telephone connection is provided between ticket sellers at the stations in the larger cities and the Pullman reservation departments in the same cities, over which reservations are handled. The telephone system is specially designed for this service. Some lines are provided from the reservation desk to the regular telephone switchboard. Special boards or tables are provided for passenger train information at the larger terminals, connecting with the regular telephone switchboard, as well as direct to the Bell city exchange.

The construction and maintenance of the pole lines, except some private line and cable, is under the supervision of the telegraph department in accordance with the contract with the Western Union Telegraph Co. and under the specifications of the latter after approval by the railroad. The installation and maintenance of the inside telephone plant is under the supervision of the telegraph department and is performed under the railroad's own plans and specifications. The telephone companies install and maintain the rented telephones and switchboards. The inside telegraph plant is installed and maintained by the railroad chiefly under Western Union Telegraph Company specifications under the contract between the two companies.

The pole line is the backbone of the telegraph and telephone plant. Railroad pole line construction in the past has been very largely based on the average-strength plan, which for a given load of wires provides that the class of poles shall be the same regardless of the extent of the exposure to ice and wind. No estimate is available to indicate how much of the average-strength type of line is too weak, too strong or just strong enough. Lines that are stronger than necessary have cost the railroads more than was warranted for their construction, while those that are too weak will require large expenditures for maintenance, particularly after severe storms when stretches may be laid flat. Additional losses result from service interruption. Such interruptions not only consist of the loss of wire service, with the consequent train delays, but may result in a blockade when poles fall across main tracks, as has happened frequently.

FIG. 3A—LINE REPLACED MODERN POLE LINE

FIG. 3B—WAY-STATION INSTALLATION

In order to reduce the pole line damage and traffic interruptions to a minimum, railroad telegraph and telephone engineers have worked out an exact strength of line with an allowable factor of safety based on wind and ice data for the localities in which the lines are located or are to be built for use in construction and reconstruction work. Wind and ice data may be determined readily in any locality so that railroads can construct lines on an exact strength of line basis with a proper factor of safety which should result in economy.

The reconstruction of pole lines along the New York Central Railroad is now being handled on this basis. The desirable line consists of a cable and not more than two arms of open wires. Fig. 3A shows this type of line at Cleveland, Ohio, built on the factor of safety or exact strength design, also the old type of line which it replaced.

The type of telephone and telegraph installation now approved for way offices includes a metal box unit containing electrical protection, cross connections and terminal blocks; metal box units with porcelain panels and very substantial jacks, for patching and testing circuits; factory made cables; caustic soda primary battery common to transmitter and selector bells; and conveniently located table apparatus. Such an office is shown in the two views of Fig. 3B, in which the door of the metal box containing the electrical protection, is open.

The wire testing is performed by an organization of railroad wire chiefs, each testing office having about one operating division to supervise, which is, roughly, one hundred and fifty miles of railroad. Many of these points have three "tricks," that is, a wire chief is on duty at all times. Others have but two men per day and some have but one. Wheatstone bridge testing methods are used; also the voltmeter and milliammeter. The station linemen maintain both pole lines and station equipment on most of the New York Central Lines.

Problems arising from the construction, maintenance and operation of the railroad telegraph and telephone plant include electrical protection, inductive interference, electrolysis and telephone and telegraph transmission and traffic. Investigations and experimental work are continually necessary in various phases of the engineering. The oscillograph of the Electrical Engineering School of Purdue University has been available for about five years in these investigations, the major part of which has been made on actual working lines.

TELEGRAPH TRAFFIC PROBLEMS

Telegraph censors are employed on two of the New York Central Lines for the purpose of reducing unnecessary telegraphing and telephoning and reducing the number of words in necessary telegrams. A large part of the duty is educational in giving other departments an idea of the proper use of the telegraph. The results accomplished are more than enough to justify the expense. One failing that has been reduced is the tendency to let messages stay in the originating office until closing time at night, sending them to the telegraph office at the same time the train mail is sent to the mail-room. This overloaded the telegraph office at a time when outlying offices were closing for the day and many such late messages would be held over until the next day. The telephone traffic is more difficult to censor, as no record of subjects of conversation is made—an unnecessary message must be caught in the act of transmission. Rules are in effect which prevent unlimited use of the long-distance telephone service, calls for the higher officials being given preference.

No charge is made against any department for the railroad telegraphing done by it and no records are kept for that purpose, but a numbering scheme is employed to give a check on the volume of business and the cost of handling it. The railroads have quite generally adopted a numbering scheme for telegraph messages based upon counting one number for each message of three lines or less, an additional number for each additional three lines, and an additional number for each additional address if addressed to more than one person. Ten words are counted as a line; extra numbers are allowed for reports which are termed "make ups." Only the larger offices keep such a record;

that is, way stations do not. The division relay offices make a daily and monthly record of messages handled, which, on the New York Central Lines, are compiled and presented graphically as shown in Fig. 4, which shows total messages handled per month, the cost per message and the average number handled per man per hour.

An analysis of the messages handled on three different circuits is interesting and is tabulated below:

TABLE I

	New York-Albany Morkrum printer	New York-Chicago operator	Big Four Route operator
a. Number messages reported............	441	391	348
b. Correct number messages..........	367	387	357
(Difference between a and b is operators' error in recording numbers handlod.)			
c. Actual number pieces paper.............	259	245	261
d. Actual minutes required	165	379	328
e. Number per minute..	$\frac{367}{165} = 2.22$	$\frac{387}{379} = 1.02$	$\frac{357}{328} = 1.09$
f. No. per man per hour	66.72	61.25	65.25
g. Possible number per 8 hours...........	1065.6	490	522

The above mentioned printer circuit is duplexed and the total number of messages possible in eight hours includes the total sent in both directions. One man only, at each end, is needed and each can send one-half the total, or 533 messages, in eight hours. On the ordinary Morse circuit it requires two men, one sending and one receiving, to handle this number of messages.

The printer receives with scant attention, and the possible 1065.6 would be reduced if the circuit were in trouble or failed to transmit perfectly. The evidence is plain that the printer will handle about double the load with one man at each end, that a Morse wire will handle. Including all items of cost, operators will handle the business cheaper than the printer up to a total of about 400 numbers, including both sent and received, but this varies with rates paid operators, etc.

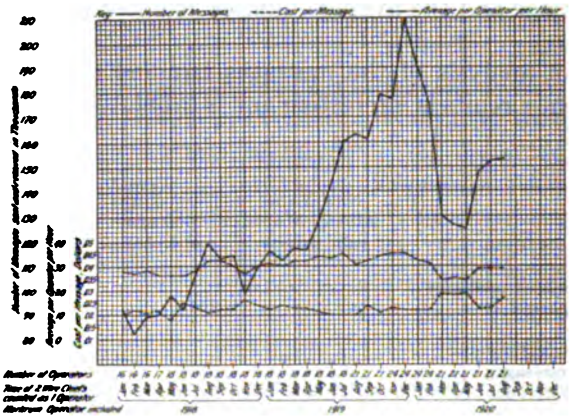


FIG. 4—TELEGRAPH TRAFFIC RECORD, "Q" TELEGRAPH OFFICE N. Y. C. R. R., NEW YORK

The averages of Table II indicate that nearly 35 per cent of railroad messages are one line or less; 35 per cent are one to two lines; perhaps, 15 per cent are two to three lines; 10 per cent are three to six lines and not more than 5 per cent are over six lines. This indicates that 85 per cent of the messages are less than

TABLE II

	N. Y.-Albany	% of 259	N. Y.-Chgo.	% of 245	Big 4	% of 261
Actual number pieces paper	259		245		261	
1 line or less..........	88	34.0	93	38.0	68	25.0
1 line to 2 lines.......	98	38.0	79	32.2	91	35.5
2 lines to 3 lines......	20	8.0	35	14.3	55	21.1
3 lines to 6 lines......	45	17.0	31	12.7	38	14.4
Over 6 lines..........	8	3.0	7	2.8	9	3.5
Extra count for excess over 3 lines........	66	....	49	....	79	....
Extra count for make-ups and joints......	42	....	93	....	17	....
Total numbers......	367	....	387	....	357	....

three lines and small error would result if only one number were counted per message regardless of the number of lines.

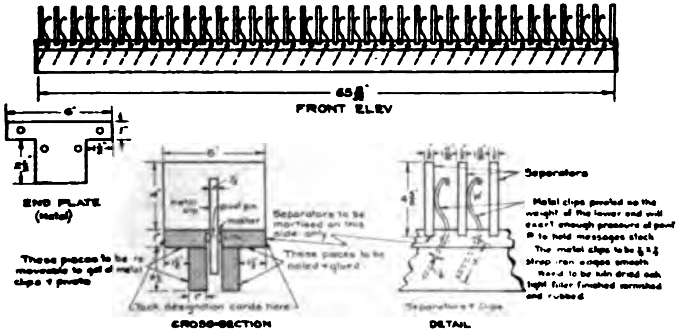


Fig. 5—Operators' Table Rack for Handling Messages to be Transmitted

A mechanical device, which the railroad designed for assisting in prompt handling of outbound messages, is shown in Fig. 5. It can also be seen on the telegraph operating table in Fig. 2. It is a gravity clip

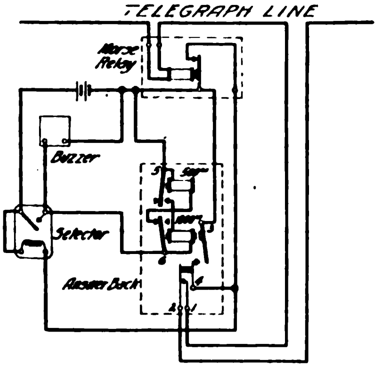


Fig. 6—Telegraph Selector Answer-Back, Type A, for Single Morse Circuits

message holder, from which messages can be reached from both sides of a quartette operating table. Each division of it has a designation card for some outlying office.

TELEGRAPH SELECTOR AND ANSWER-BACK

The telegraph selector has been a growing factor in railroad telegraph traffic in recent years, until it is now considered an essential part of a modern relay office and is growing in favor for way-station use. It is quite generally used in conjunction with the lamp signal concentration unit operating table for signaling offices. When the selector is operated by the distant station sending the proper code of impulses on the wire, it lights a lamp in the concentration unit. In concentration units many Morse wires are available to one or more positions of an operating table. Means of notifying the calling office that the selector had functioned was

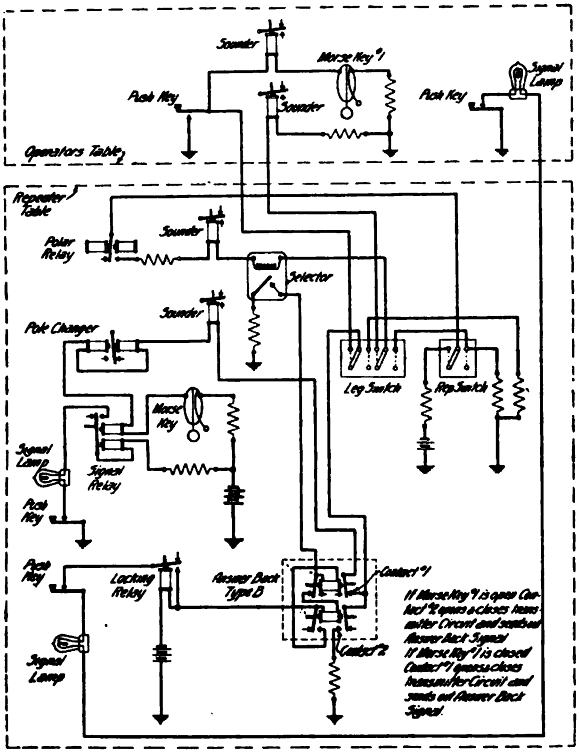
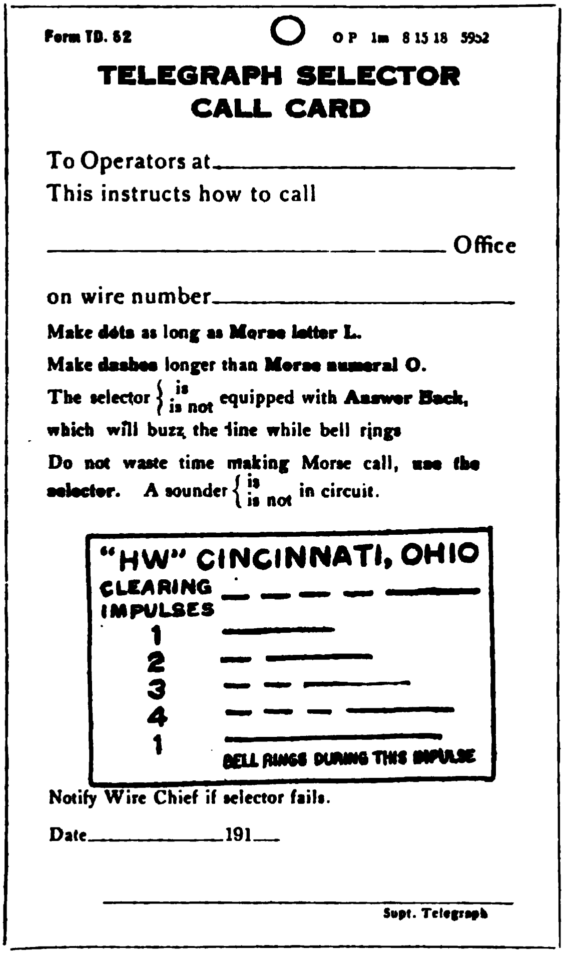


FIG. 7—TELEGRAPH SELECTOR ANSWER-BACK, TYPE B, FOR DUPLEX AND QUAD USE

lacking until the telegraph selector answer-back of Fig. 6 was produced by the railroad. The fundamental idea is to cause the telegraph circuit to open and close at a speed corresponding to rapid dots, which begin when the selector contact closes and continue until some one along the line opens the circuit; that is, the selector answer-back is under the control of any station. The two coils of the answer-back operate alternately to produce the speed of vibration



Form TD. 52 ○ O P 1m 8 15 18 5952

TELEGRAPH SELECTOR
CALL CARD

To Operators at____________________
This instructs how to call

________________________ Office

on wire number____________________

Make **dots** as long as **Morse letter L.**

Make **dashes** longer than **Morse numeral O.**

The selector $\left\{\begin{array}{l}\text{is}\\ \text{is not}\end{array}\right.$ equipped with **Answer Back**, which will buzz the line while bell rings

Do not waste time making Morse call, **use the selector.** A sounder $\left\{\begin{array}{l}\text{is}\\ \text{is not}\end{array}\right.$ in circuit.

"HW" CINCINNATI, OHIO
CLEARING IMPULSES — — — — ———
1 ————
2 — ————
3 — — ————
4 — — — ————
1 ————————
BELL RINGS DURING THIS IMPULSE

Notify Wire Chief if selector fails.

Date____________191__

____
Supt. Telegraph

FIG. 8—TELEGRAPH SELECTOR CALL CARD

desired at line contacts 1 and 2. Contacts 3 and 4 maintain the selector circuit closed while the Morse relay contact is released, which occurs when 1 and 2 open. The answer-back is also applied to duplexes as shown in Fig. 7 and will give a signal whether the key at the selector station is open or closed. The selector is operated in the local sounder circuit of the polar relay and the answer-back opens and closes the transmitter local sounder circuit to send the signals to the calling station. This device on either single line or duplex gives operators considerable satisfaction in knowing they waste no time in calling, and it promotes efficiency of service. The card sent out to notify stations of the combination and method of making it is shown in Fig. 8. The selector combination is placed on this with a rubber stamp, because, generally, only two or three score are needed and individual printing cannot be justified. It is found that the signal is easier to make with the combination printed in a vertical column, with one group of impulses below the other, than with the whole combination strung out in one line. At smaller offices where more than one selector is used but no lamp signal concentration unit is provided, a special design of visual signal box based on the railroad's design is used.

One of the best examples of the value of the telegraph selector is on the New York Central Lines on a telegraph train report wire extending from New York to Chicago and known as the "GX" wire. The wire is used for reporting the time that through passenger trains pass the several important points, to the recorder's office at New York. This office has a keyboard with Gill selector keys about the same as on a telephone train dispatching circuit. The selectors are distributed from New York to Chicago. The circuit has six sets of telegraph repeaters, which gave trouble in adjustment until the Chicago end was equipped with a selector and answer-back. This gives the recording office operator instant check on the repeater adjustment and continuity of the circuit. If he calls Chicago and gets the answer-back, it is evidence that the repeaters are fairly well lined up and that the circuit is unbroken.

RAILROAD SIMULTANEOUS TELEPHONY AND TELEGRAPHY

The railroad makes use of simultaneous telephony and telegraphy on practically all its wires, including station-to-station block telephone circuits, train dispatching circuits, message telephone circuits and long-distance lines. The station-to-station block telephone simplex is illustrated in Fig. 9 which indicates "single" Morse on the simplex, but this type of circuit is very successfully duplexed and has been quadruplexed with good results in some cases. This block telephone circuit is very seldom used in a phantom, because there is but one such circuit on any one pole line and this is looped in and out of every office, and further, being iron wire in nearly all cases, it would not give transmission up to the required standard, for the distances phantoms are required to cover in railroad service.

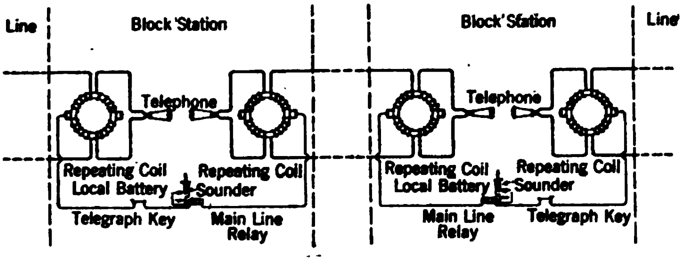
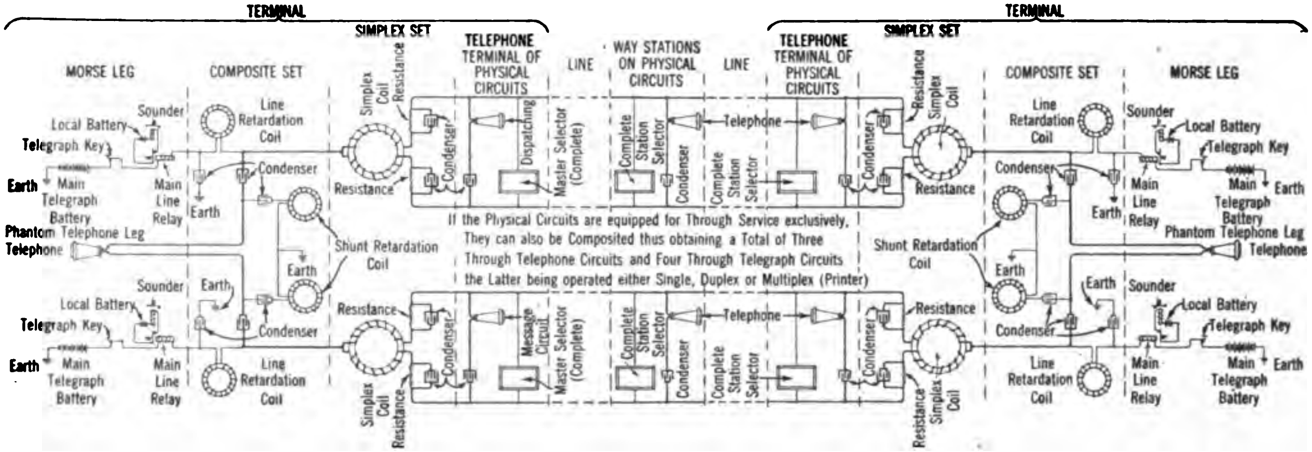


FIG. 9—STATION-TO-STATION BLOCK TELEPHONE SIMPLEX

Dispatching and message telephone circuits are like Fig. 10 in general, if direct-current impulse selectors are used. This figure indicates the added resistance that is necessary with the simplex coils to prevent the coils short-circuiting the direct-current impulses which operate the telephone selectors. A phantom composited is shown such as are made up from dispatchers and message circuits on one railroad division. This figure without the composite equipment and without the condensers around the added resistance in the simplex coil bridges, illustrates an ordinary high-resistance simplex. Straight Morse is shown but these are often duplexed in the service of the larger railroads to get better service in weather that would reduce



If the Physical Circuits are equipped for Through Service exclusively, They can also be Composited thus obtaining a Total of Three Through Telephone Circuits and Four Through Telegraph Circuits the Latter being operated either Single, Duplex or Multiplex (Printer)

FIG. 10—HIGH-RESISTANCE SIMPLEXES WITH COMPOSITED PHANTOM

the margin of a single Morse circuit to an unsatisfactory degree. The dispatchers and message telephone circuits on each division with few exceptions are paired into a phantom by proper transpositions, and composited. In recent high-resistance phantom installations two separate repeating coils are used on each circuit at each end, one for the telephone tap and the other for the telegraph. The No. 5-AA retardation coil combines the two separate Morse leg coils in one unit, likewise combines the shunt retardation coils in one unit, each unit having two separate and distinct magnetic circuits with but one cover and base. If alternating-current selectors, which are alternate positive and negative impulse selectors, are used, a repeating coil scheme of sending the impulses can be employed, in which case the same coil is used for the Morse and phantom connection to the physical pairs as indicated in Fig. 11. This gives a low-resistance simplex, generally 1000 ohms or more below the ordinary "high-resistance" simplex of Fig. 10, assuming 150-mile lines of No. 9 A. W. G. copper wire. The composite ringer is used for signaling between the terminals on phantom circuits which are composited.

Long-distance telephone lines are simplexed if the transmission losses incident to the use of composite apparatus are prohibitive; also if there are any intermediate telephones, or if there is no need of additional telegraph service. The railroads generally have no spare telegraph facilities and can use all they can get. The simplex can be single, duplex, or quadruplex. Two such circuits can be made up into a phantom without simplexing or compositing. This is frequently done in railroad service for trunk lines between outlying private branch exchanges and the main branch exchange. In some cases repeating coils are inserted in the phantom drop circuit and a Morse circuit connected to the middle of the line side, thus making a four-wire simplex telegraph circuit. This, in some cases, is done instead of compositing the phantom which would give two Morse circuits, in order to obviate composite ringers; in other cases it is to get more copper in the Morse circuit, for example when

No. 19 A. W. G. cable conductors are used, in trunks between offices in metropolitan districts.

If no intermediate stations are required on a long-distance line, and the transmission volume is ample, the two wires of the pair are composited with which composite ringers are used and with Morse legs carrying either single or duplex telegraph. Two of these long-distance composited pairs can be phantomed if properly transposed.

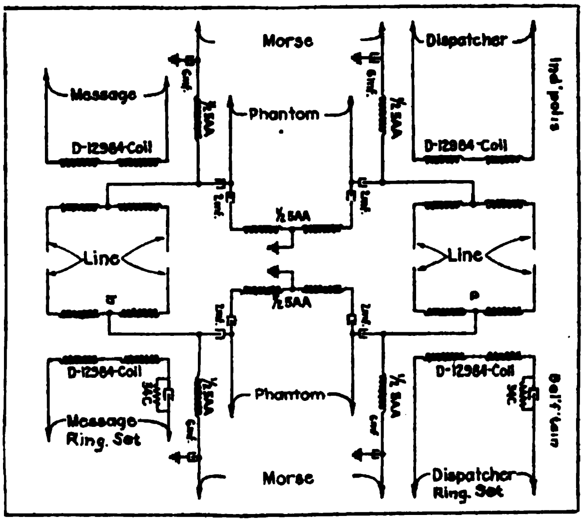


FIG. 11—LOW-RESISTANCE SIMPLEXES WITH COMPOSITED PHANTOM

Single wires for telegraph purposes only, are almost a thing of the past for railroad service along some of the large railroads. This is because of the economy in using all available wires for simultaneous telegraphy and telephony. Before the advent of telephone train dispatching there were very few long-distance telephone circuits. The New York-Chicago, New York Central No. 8 B. W. G. copper pair which was strung in 1904 was a notable exception. The division service on many trunk lines consisted of one iron Morse train wire, one iron message wire, and very rarely, an iron wire for station-to-station grounded telegraph block circuit. When a telephone dispatching copper pair was strung,

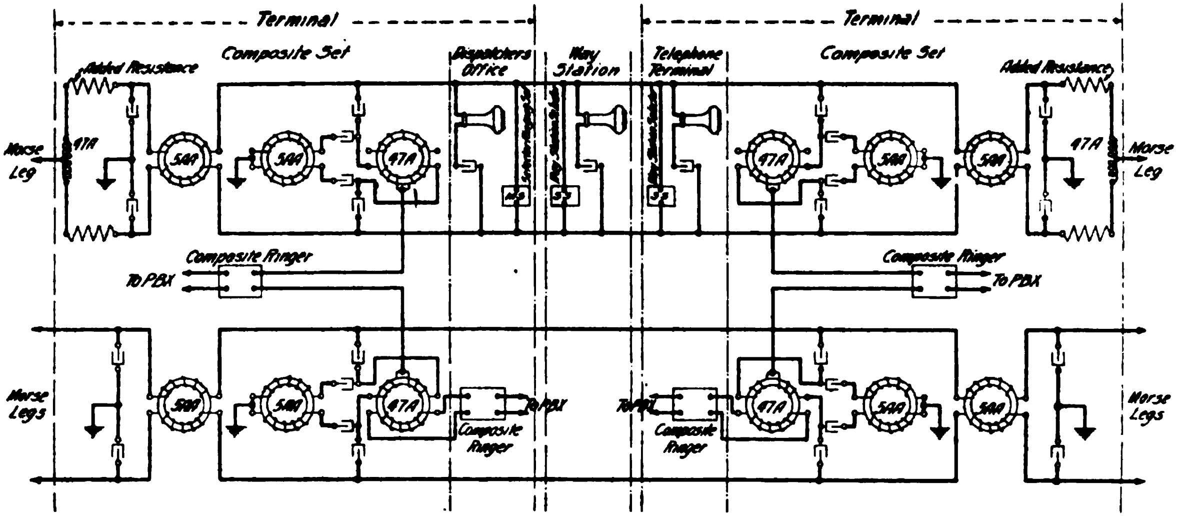


Fig. 12—Two Metallic Telephone Lines with Through Phantom, One Physical Simplex, and Equipped for Way-Station Telephone Service, Other Composited through Telephone Line

the old train wire and message wire were generally paired and made into a station-to-station block telephone circuit and simplexed for the way-station Morse message wire. The addition of a message telephone copper pair at a later date completed the division service and provided a long-distance phantom circuit which was generally as much needed as the way-station message telephone pair. This leaves many divisions with no single wire—nothing but pairs, simplexed or composited for telegraph.

A phantom made up of one composited pair and one dispatching circuit was developed by the railroad for a special situation between Indianapolis and Cincinnati, which points were connected for long-distance service by one No. 8 B. W. G. iron composited long-distance line and one No. 9 A. W. G. copper phantom, the latter consisting of the dispatching and message circuits. The phantom gave much better transmission, and because calls for the same party were first on the iron circuit and next on the copper, it resulted in complaints, some officials thinking the "connection was poor," when they were talking on the iron circuit. It was found that no circuit diagram was available for a combination of a composited pair and a simplexed pair for a phantom, and it was necessary to develop one by experiment. The result is shown in Fig. 12, which indicates that each side of the dispatching telephone line is treated as a composited wire; that is, there is one-half of a No. 5-A A retard coil in each wire. This was found necessary to give a quiet phantom terminal set. This type of circuit gave almost as good a phantom circuit as Fig. 10. The two retard coils in each end of the simplex did not reduce the speed of Morse service, because but half the telegraph current went through each. The capacity to ground on each side of the set at the retard coils was made three microfarads on the simplex and six microfarads on the composite. The equipment on the office side of the No. 5-A A coils has no effect on the circuit as far as phantom noise is concerned, which permits of the three microfarads on one circuit and six microfarads on the other.

EXTRA HIGH IMPEDANCE TELEPHONES

In arranging for the simplex-composite phantom, it was necessary to use the iron wire circuit as a way-station message telephone circuit, and use the copper pair formerly in this way-station service, as the composited pair of the phantom. This would not have been possible but for a recent advance in telephone transmission which resulted from the use of extra high impedance telephones. The improvement in telephones was the result of experiments made necessary by the emergency use of a one-hundred-mile No. 8 B. W. G. iron wire circuit as a dispatching circuit, in order to divide two dispatching districts into three parts for handling unusually heavy freight traffic that existed just previous to the entrance of the United States into the war. No means of calling stations was provided on this circuit, so that all stations continuously listened in. There were 30 of them, and the resultant "listening" losses were so great that stations at one end of the line could not hear those at the other end. This gave the clue to the cause of other transmission troubles, which were that at certain periods of the day, transmission on dispatching circuits was excellent and at other periods it was very poor. The evidence now is plain that in the evening hours, when the transmission was poor, many operators were listening in. At other times, particularly in the morning hours, transmission was good because the operators were busy with other duties and had the receivers on the hooks.

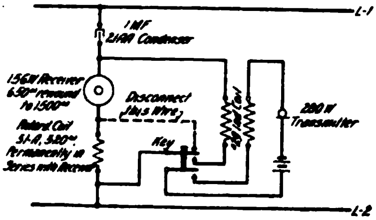


FIG. 13—295-AK AND 300-W SUBSETS CONVERTED TO EXTRA HIGH IMPEDANCE TELEPHONE BY USE OF 1500-OHM RECEIVER

The outcome of the investigation was the use of 1500-ohm receivers with a retard coil permanently in series as shown in Fig. 13. It was found that with these sets, all stations on the hundred-mile iron wire circuit could listen in simultaneously without noticeable diminution of transmission. The results on dispatching copper circuits, especially the ones with a large number of stations, were likewise gratifying. Some of these dispatching circuits have 60 to 65 stations, whereas the average over the country is but thirty, and the telephones previously in use, with 650-ohm receivers, were designed for a maximum of about 15 receivers off the hook at once. The 1500-ohm receiver is equally effective on the Wray-Cummings "booster" telephone, which also has a retard coil permanently in series with the receiver. The Western Electric Company had developed an extra high impedance set with a repeating coil and 70-ohm receiver, which was about ready to put on the market and which was put out very shortly thereafter. This gives the benefit of high impedance when in the listening position and also insulates the telephone from the line. In this set the repeating coil is not disconnected from the line by the hook-switch but is permanently connected across the line.

WELDED IRON WIRE JOINTS

Another step in the improvement of iron wire for telephone circuits is due to oxyacetylene welding of the joints. This has been successfully done on the No. 8 B. W. G. iron wires of the Hocking Valley, Zanesville & Western, and Cleveland, Cincinnati, Chicago and St. Louis Railroads. The resistance of a welded joint is 95 per cent of that of an unspliced wire, whereas the usual soldered joint is 112 per cent of the unspliced wire. Many apparently soldered joints are really not soldered and are about 200 times the resistance of the same length of unspliced wire. The joints are painted with red lead after welding. The work is not excessive in cost and the result is a considerable reduction in resistance and is of a permanent nature. A recent job of welding on the C. C. C. and St. L. Ry., cut the transmission equivalent of the circuit almost in half.

COMPOSITE RINGER

The operation of a type B composite ringer was investigated with the oscillograph with the results shown in Fig. 14. Oscillogram No. 193 is the simultaneous record of the outgoing signals when the home station operator rings. Trace No. 1 is the 16-cycle motor-generator ringing current from the operator's keys. Trace No. 3 is the 133-cycle current as produced by the interrupter and delivered to the line, and is flowing to a station 150 miles away over a No. 9 A. W. G. copper phantom circuit, composited.

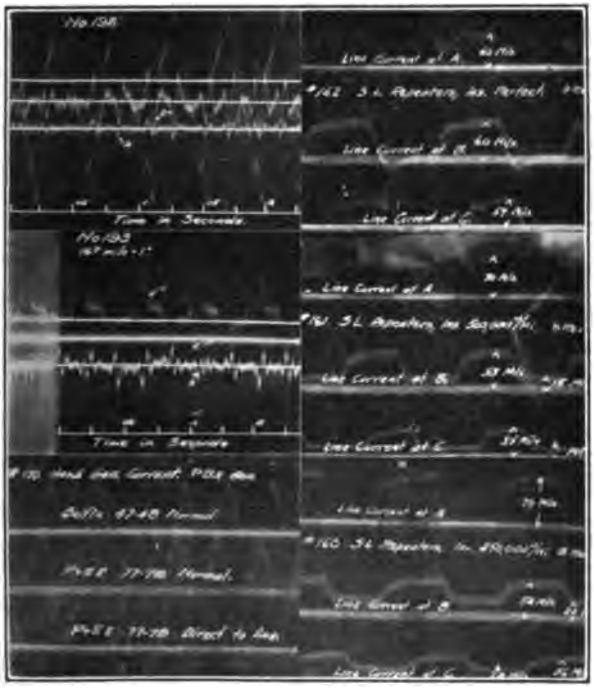


FIG. 14

Oscillogram No. 192 is the record of an incoming signal from the distant office. Trace No. 2 is the wave at a point in series with the high-frequency relay and is the deflection calibrated at 50 milliamperes per inch, whereas the No. 1 and No. 3 are 167 milliamperes per inch as in No. 193. The waves do not resemble sine waves to any noticeable extent but are distorted more like transformer magnetizing current. Oscillogram No. 170 is shown for comparison with hand generator ringing current and presents three separate exposures; the top one on a No. 8 B. W. G. iron wire way-station message selector telephone line, Indianapolis to Bellefontaine; and the middle one is the same generator ringing on a similar circuit, Indianapolis to Springfield, Ohio, through a No. 47-A repeating coil; and the lower trace is on the same line without the repeating coil. The calibration of the oscillograph vibrator elements was not alike in these three exposures.

ENERGY CONSUMPTION

Several tests have been made to determine the energy consumption of different circuits used in railroad service, particularly those which use primary battery, in order to compare costs of different types of battery. In general, the ampere-hour energy consumption was recorded by copper voltameters and in some cases by watt-hour meters, for periods of 24 hours, of days that were considered average. The number of calls on selector telephone circuits was registered automatically on Veeder counters. The records for several telephone dispatching circuits is given in Table III.

TABLE IV
Energy Consumption Data of Transmitters—for 24 Hours.
Gen. Telg. Office, Indianapolis, C. C. C. & St. L. Ry.

Transmitter tested	Battery supply	Ampere hours
Chi. Div. Dis. East	8 B. S.C.O. Cells	1.162
" " " West	8 " " "	1.499
" " Chf. Disp.	4 " " "	0.069
" " Msg. Opr.	4 " " "	0.1365
" " Car Dist.	4 " " "	0.0199
P. &. E. Disp. East	8 " " "	1.765
" " " West	8 " " "	0.845
" " Supt.-Car Dist.	8 " " "	0.0659
Supt. Terminals	5 Dry "	0.0265
Wire Chief	10 " "	0.0522
Short line	3 " "	0.00269
		5.55 total

The number of calls per day is interesting. It runs as high as 1223, which is as high as on any existing dispatching circuit, because it is an exceptionally busy line and one man could not do much more on one circuit.

TABLE III

Energy Consumption Data on Various Selector Telephone Circuits.

C. C. C. & St. L. Ry.

Division Name	Circuit No.	Length of Line, Miles	Kind of Wire C-Copper I-Iron	Size of Wire No. 9 AWG No. 8 BWG	Type of Selectors 4G5 = 5000, 4G16 = 1600, 4G7 = 7000	No. of Selectors	Voltage at Generator	Milliamperes at Generator	During 24 hours							
												Ampere hours				
									A. C. Motor kw. Hours	No. of Calls	No. of Trains	Call Box Battery	Main Line Battery	Selector Main Line Battery	Selector Local Battery	Main Line Volt Ampere Hours
Cincinnati	31-2	78.7	C	9	4 G 5	32	160	200	3.6	1223	85	0.716	0.245		0.154	39.2
Columbus	"	45.1	"	9	4 D 16	20	"	145		"	43				0.152	
Delaware	"	49.9	"	9	4 G 7	12	"	72		"	19				0.206	
Above three are operated as one circuit																
Cincinnati	73-4	78.7	I	8	" 5	43	330	218	5.1	403		0.275	0.496		0.145	163.5
Columbus	71-2	45.1	"	8	" 5	21	85	82		173		0.079	0 0199		0.27	16.9
Delaware	71-2	49.9	"	8	" 7	13	78	64		319		0.304	0.38	0.27	0.11	29.7
Sandusky	31-2	130.7	C	9	" 7	33	107	105	3.5	539	83		0.3	0.07	0.208	32.1
Sandusky	75-6	34.0	I	8	" 5	13	170	138	3.7	163		0.379			0.55	
Chicago East	31-2	109.6	C	9	" 16	32	210	250			45	0.095	0.085			17.8
Chicago West	31-2	139.8	"	9	102-C	35	180	260			35	0.162	0.094			16.9
Peoria & Eastern	31-2	211.5	"	9	102-F	55	300	285	13.3		22	0.076	0.130			39.0
Springfield	31-2	140.1	"	9	102-C	34	140	150			15	0.13	0.086			12.0
Chicago East	51-2	109.6	"	9	4 G 16	34	240	250				0.101	0.045			10.8

The record of transmitter energy consumption is given in Table IV for several offices in the C. C. C. & St. L. general office building, Indianapolis. The above record gives data for the total of all transmitters in the general office building, and a four-volt, 25-ampere-hour battery was set up which has since supplied all these transmitters.

The shunt field current of a motor of a dispatcher's selector-circuit motor-generator was found to be 0.3 ampere, which is eight ampere-hours per day, sufficient to charge the 24-ampere-hour battery on the transmitters. The storage battery was placed on continuous charge in this shunt field circuit without either affecting the other detrimentally.

It is quite general practise to feed all local battery transmitters around a railroad general office building from a four-volt or six-volt storage battery of small capacity, placed on continuous charge from the 110-volt d-c. lighting circuit or other available d-c. supply. No cross-talk results, if sufficient copper is used in the busbars from the battery to the distribution point and if the plates of the cells are not too far apart. This continuous charge method requires less supervision than a daily charge method.

It was noted in making the transmitter current tests that new transmitters of a given type use more current than old ones, in some cases twice as much. This is in conflict with the general belief that old transmitters are "packed" and consequently use more current. An explanation for the higher resistance of old transmitters is that the granules lose their many sharp edges and become more nearly round with fewer points of contact with other granules, which increases the resistance of the carbon as a whole with resultant smaller current flow.

Table V shows the record for a selector calling-key battery which was provided for by a twelve-volt, six-ampere-hour storage battery connected in the shunt field of a small motor of a dispatching-circuit motor-generator set.

A test was made on a 48-volt storage battery supplying a Western Electric Co. No. 10, private branch exchange with 45 stations at Beech Grove Shops. The board is operated from 8:00 a. m. to 5:00 p. m., except Sunday, and has six trunks to the main railroad exchange at Indianapolis. The record showed 5.27 ampere-hours per day. The charging rate was based on this at five amperes for eight hours, once per week, with suitable overcharge periods.

A four-ohm sounder used 1.25 ampere-hours in a 24-hour period on two gravity cells. The record for the Chicago Division message operator shows (Table IV), 0.1365 ampere-hour in 24 hours. This transmitter is in almost constant use, sending and receiving messages for the Division Superintendent's office. Therefore, it can be said to fairly represent the average busy local battery telephone on a railroad, consuming more energy than the average way station or block tower. On this record it could be predicted that a 300-ampere-hour set of batteries of equivalent voltage would last 2200 days—or six years. Actually, they would not last quite so long, but are known to last three years and more in this service. At an initial cost for four cells of $8.94 and renewal cost of $5.72 for consumable elements, the cost is less than $2.00 per year, based on three-year life of renewals. Dry cells, three per set, would last about three months and cost about $4.50 per year at 28 cents each. In addition to saving in cost, the caustic soda cells give desirable reliability and require less labor expense. It is standard practise to connect the transmitters of all telephones at any station, and all the telephone selector bells to the same set of caustic soda battery.

TABLE V

Energy Consumption Data of Call Boxes for 24 Hours, Gen'l. Telegraph Office, Indianapolis, C. C. C. & St. L. Ry.

Chi. Div. Disp. East	6 Dry Cells	0.0957
" " " West	7 " "	0.1625
" " Msg. Oper	8 " "	0.101
P. & E. Dis. East	8 " "	0.1326
" " " West	8 " "	0.0761
		0.567 total

UNIT TYPE POWER SWITCHBOARDS

The rapid and uncertain growth of dispatching and message telephone circuits has made it difficult to plan motor-generator sets for battery supply and keep a neat layout of power plant. The C. C. C. & St. L. Railway experienced this trouble and the unit type was adopted. This is shown in Fig. 15. Morse battery supply also has been installed on this plan at Springfield, Ohio, to fit in with the units for the selector lines.

FIG. 15—UNIT TYPE POWER SWITCHBOARDS FOR SELECTOR TELEPHONE CIRCUITS

The plan provides one square foot of power panel with the motor and generator line switches, line fuses for both generator and motor, field rheostat, circuit breaker and voltmeter for each machine and in close relation to it. The generator circuits are taken through a jack panel at the left end of the bench, where any machine can be put on any circuit. This type of power installation saves space and puts the control apparatus in close proximity to the motor-generator.

Dry cells have been supplanted by motor-generators and sodium-phosphate-aluminum-iron chemical rectifiers for selector telephone circuits, to a great extent. The motor-generators in the first installations had shunt-wound generators with the inherent characteristic of drop off in voltage with increase of load which was undesirable on selector telephone lines. The load on a dispatcher's circuit consists of series of twenty or thirty short impulses, seldom more than 1500 series per day, which is practically no-load from a power standpoint. The efficiency of a machine therefore, is of less importance than good voltage regulation. The compound generator has been used in all recent installations on the New York Central Lines, separately excited if the motor power supply is direct current.

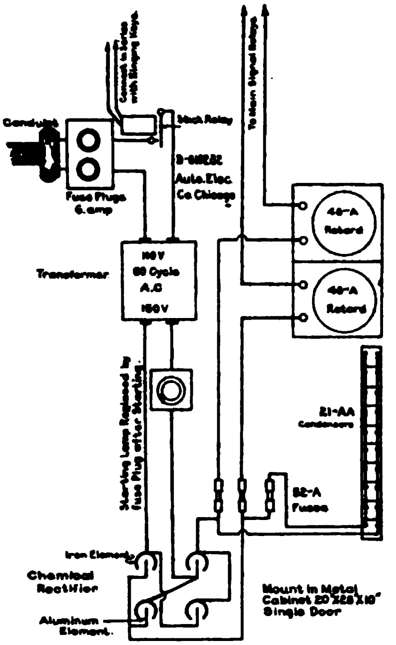


FIG. 16—WIRING OF CHEMICAL RECTIFIER FOR SELECTOR TELEPHONE CIRCUITS

Alternating current has been found better suited for the motor supply than direct current, because of its better regulation. The direct-current power from railroad shops has poor regulation, due to the arc welders, etc., in the shops.

Quick starting motors have been used in some installations, and while fairly successful, are not preferred to the constantly running sets, because of excessive wear of the commutator, due to heavy starting current. Four-bearing motor generators have been found to give better results than two-bearing type. Ring oilers are better than wicks.

CHEMICAL RECTIFIER

The use of the sodium-phosphate chemical rectifier is being extended. The first few sets were purchased but later installations are made up completely by the railroad installers. Four old type sal-ammoniac battery jars are used, containing a solution of commercial sodium phosphate, made up of one pound dissolved equally between the four jars of water, in which is suspended a semi-circular strip of iron separated about one inch from an aluminum strip. Fig. 16 shows the wiring of such an outfit for a dispatching circuit. The condensers and retard coils eliminate the hum of the alternating-current source on the telephone line. The stick relay normally disconnects the rectifier from the a-c. supply between calls on the dispatching line. Fig. 17 shows characteristic curves of such a set. The unmarked curve is the efficiency.

"SINGLE" MORSE CURRENT WAVES

Perhaps the best known phenomenon to the telegraph fraternity is the sharp snap of the relay when the "single" Morse circuit is closed and opened at the home station, as compared with the comparatively sluggish impulse received in the same relay when a distant station is sending. The comparison is evident in Fig. 18 in oscillogram No. 165 which has two separately made exposures. Trace No. 1 was made at Indianapolis on a single No. 8 B. W. G. iron way wire to Mattoon, Ill., 128 miles long, with forty 120-ohm main line sounder instruments cut in on it with

Indianapolis sending. Trace No. 2 is at the same place but with Mattoon sending. The peak of trace No. 1 is the line charging current that gives the snap

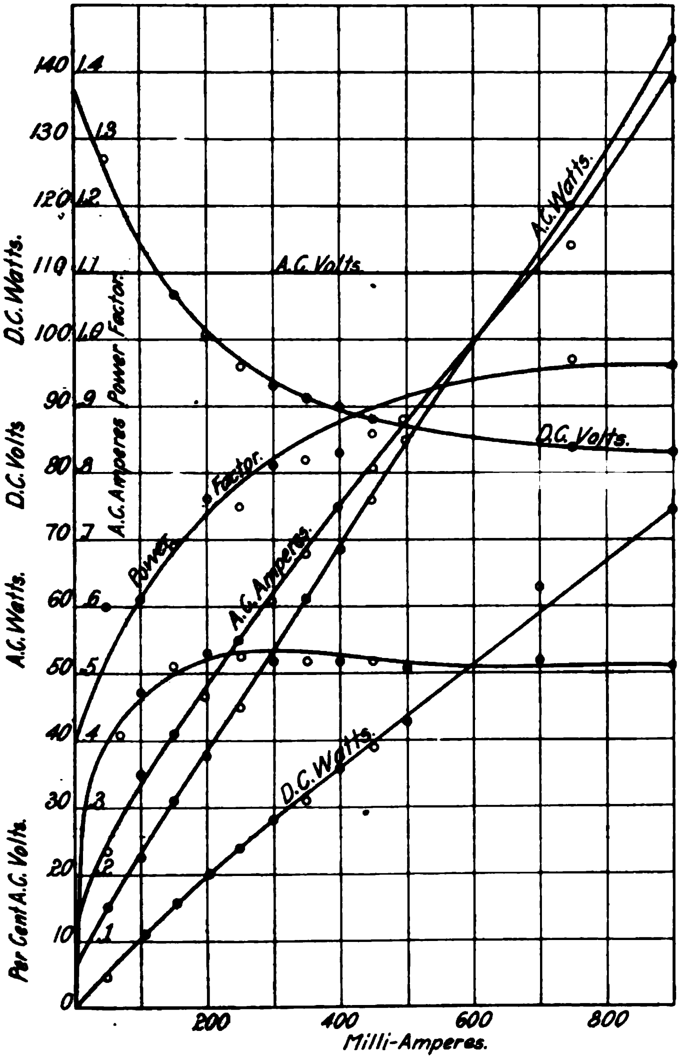


FIG. 17—CHARACTERISTIC CURVES OF CHEMICAL RECTIFIER

to the home relay but does not get to the distant station, due to its establishing the electrostatic flux of the line. The No. 163 indicates the current in a block simplex circuit composed of two No. 8 B. W. G. iron wires 140 miles long, Indianapolis to Bellefontaine, Ohio, with 45 Morse relays, 35-ohm, with 97 No. 47-A repeating coils as simplex coils. The upper trace is with Bellefontaine sending and the lower with Indianapolis. The middle trace is on a No. 8 B. W. G. iron simplexed selector telephone line between the same points.

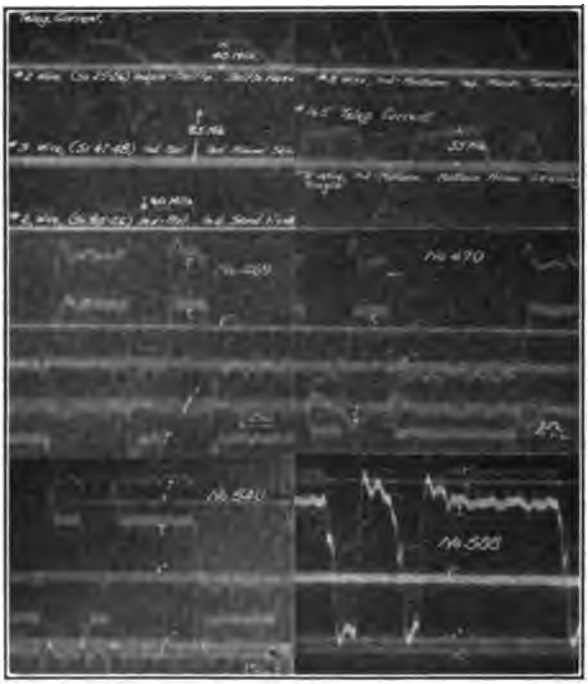


FIG. 18

TELEGRAPH REPEATERS

Some tests on telegraph repeaters were made upon an artificial line, shown in Fig. 19, which represented two 150-mile lines with telegraph repeaters connecting them. The line leakage was adjustable to either of three conditions, *viz.*, perfect insulation, ½ megohm per mile and ¼ megohm per mile, by means of switches. Shunt-locking repeaters were used. Oscillogram No. 162 of Fig. 14 records the current simultaneously at three points, with a condition of perfect insulation.

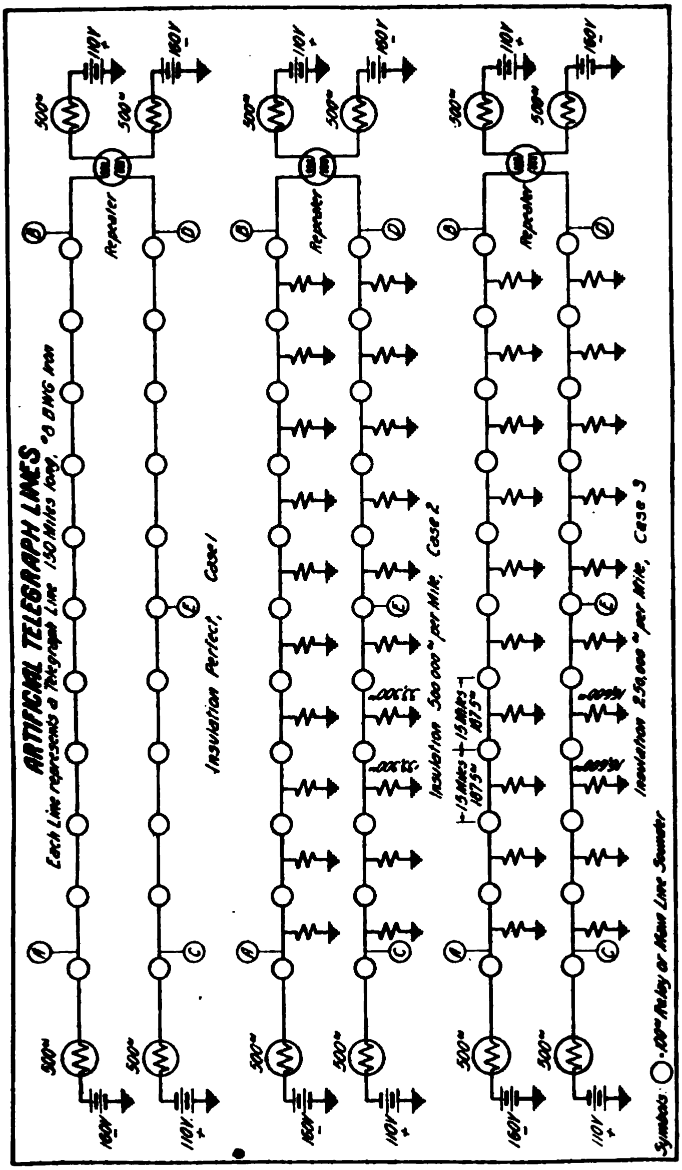


FIG. 19—ARTIFICIAL TELEGRAPH LINES

The line current at *A* is the current of the extreme end of one line with the station at that point sending the signals. The current at *B* is the resultant wave at the other end of the sending line. The line current at *C* is the resultant current wave that reached the far end of the second line, after being repeated by the station *B*. This record, compared with No. 165, indicates very close approximation to a real line, as the wave-shape at *A* is very much like the wave-shape in the upper trace of No. 165, which is under somewhat similar conditions; that is, it is the sending station on a line with several instruments and perfect insulation. The wave-shape at *B* is much like the wave in the lower trace of No. 165, and both are the received waves at the distant end of a line.

In No. 162 the time lag between the sending impulse at *A* and the received impulse at *C* is considerable. The records represent about one-tenth second to the inch, which indicates that it takes nearly one-twentieth second from the closure of key at *A*, until the impulse begins at *C*. The impulses were made with an impulse machine of clockwork with a governor for speed adjustment, and are uniformly 6 per second.

Oscillogram No. 161 is the record at the same points as No. 162, but with line leakage reducing the insulation to one-half megohm per mile. This value of insulation is as low as it is desirable to permit for satisfactory single Morse operation. In this record it is seen that the wave does not become zero at *B*, when the key opens at *A*, because the line battery at *B* causes leakage current to flow. The repeater adjustment is the same in this record as in No. 162. It was lined up for good Morse signals in No. 162 and was not further adjusted. Oscillogram No. 160 is the record with the insulation still further reduced to one-quarter megohm per mile, and shows that only little more than half the current was cut off at *B* by opening the key at *A*. The tests showed that the signals received at *C* were unreliable but could be made readable by slight readjustment of the relay at *C* and without any readjustment of the repeaters at *B*, which indicates the wide margin of the repeaters. This very low value of insulation is not often found on single wires even in the worst weather if the line is well maintained, but is more frequent on the simplexes with their two wires, which nearly halves the insulation resistance value.

It is not practicable to assume from the above tests that these repeaters will not require readjustment with changing weather conditions. It is seldom that a set of repeaters is adjusted to its very best with perfect line insulation conditions, but it will require attention with change of weather sooner than if perfectly adjusted for good insulation conditions. Table VI gives the current readings at various points in the two artificial lines as actually measured, for different key positions and the three conditions of line insulation resistance.

TABLE VI

Milliammeter location	Current—milliamperes		
	Insulation perfect	½ Megohm per mile	¼ Megohm per mile
A, line closed	60	70	78
A, open at *B*	0	32	52
B, line closed	60	55	54
B, open at *A*	0	15	22
C, line closed	57	55	56
C, open at *D*	0	17	28
D, line closed	57	63	70
D, open at *C*	0	30	50
E, line closed	57	55	50
E, open at *D*	0	8	10
E, open at *C*	0	15	20

LINE INSULATION

Low insulation apparently is due more to broken and chipped glass insulators than to smoked ones. A perfect insulator measured 40 megohms with a 500-volt megger meter and a similar one measured 10 to 15 megohms with a piece of the outer petticoat of about two inches width knocked off, with the same condition of rain in both tests. An insulator so badly shattered that the tie-wire was holding it together, measured 1 megohm in a drenching rain and when thoroughly water-logged. A mechanically perfect insulator but one very badly crusted by smoke, measured about 40 megohms, after a hard rain, which is about the same value a clean insulator shows. The crust deposited by smoke seems to have high resistance. The megger tests were made on actual lines from line wire to ground after cutting off the line wire about a foot each side of the tie wire. It was found that the resistance from line to pin nearly always equalled the value from line to ground, when the pole and cross-arm were wet. It is important to keep chipped and broken insulators off a line on which the working margin demands good insulation. This is especially important on simplexes, because of the reduced insulation of the two wires in parallel.

LEAKAGE FROM WIRE TO WIRE

Few references are available relating to the effect of line leakage of one wire on a pole line to a paralleling wire on an adjacent pin. This point came up in a study of a proposal to string a common return wire on an inter-calling selector telephone circuit to take the place of a ground return, installed on the Indianapolis Belt Railroad, semi-circling the city. The telephone selector ground return was affected badly by the city street railway return current, also leakage in wet weather made the ground return so unreliable that some other plan was necessary. The third wire was proposed but it was known that the insulation of the two wires to ground was very low in wet weather and it was feared that the leakage to the third wire would make the system inoperative at such times.

The experiences of telegraph and telephone men were obtained and the general opinion was that the leakage from the two line wires as a simplex to the third wire as a common return would be negligible. The effect was actually found to be less than one-third of the leakage current that existed with the ground return. Assuming that the wires of the telephone pair in wet weather had an insulation resistance of one megohm per mile each, which in parallel was ½ megohm to ground, the third wire with one megohm has its insulation resistance in series with the ½ megohm of the pair, which would make the result theoretically 1½ megohms or three times what it was between the pair and ground.

This type of inter-calling system is limited to very short lines of perhaps a maximum of ten miles, due to the variable operating current of the simplex connection resulting from insulation leakage. The permissible length is 100 per cent greater with a return wire than with a ground return. Circuits 100 to 150 miles have not proved successful.

The leakage from one wire of the pair to the other under ordinary conditions on selector telephone lines has no noticeable effect upon selector operation. The net resistance is the sum of the resistance of each, and the effective voltage to cause leakage current falls from the value of the main battery, usually 200 to 300 volts at one end, to less than 50 volts at the distant end, on most types of selectors, and the total leakage current causes very slight additional voltage drop on the circuits and no apparent effect on the selector operation.

The leakage from one telegraph wire to another can be detected by means of a voltmeter by opening one wire at the distant end, inserting the voltmeter at the home end between the line and ground, and applying voltage to the paralleling wire. The value of the leakage is so slight that it is seldom observed in the Morse relays of the circuits if worked as single Morse, or on the polar relays if worked as a duplex. The electrostatic induction from paralleling wires, apparently, is noticed more than the leakage.

It has been stated that, in the past, the insulation of railroad circuits was too variable and low to permit of successful loading of open wire lines. Judging from recent tests of insulation, it is now believed to be feasible to load the railroad long-distance lines, which are limited to through service. It would, probably, not be successful on phantoms made up of selector telephone lines.

SINGLE MORSE

Both theory and practise indicate that 30 to 35-ohm relays or main line sounders are more desirable than 100 to 150-ohm, for iron wire way-station telegraph circuits, whether single wire or simplex. The actual result has been demonstrated a number of times on the New York Central Lines by changing all the instruments from 100 or 150 ohms to 30 and 35 ohms with marked improvement in the service.

The operating current of telegraph relays, for satisfactory service on railroad way wires, should be something close to the following:

> 30 to 35-ohm relays or main line sounders, 65 milliamperes, closed circuit, to 40 milliamperes on open circuit. The difference between these values gives a margin of 25 milliamperes.
>
> 100 to 150-ohm relays or main line sounders, 40 milliamperes closed circuit, to 25 milliamperes on open circuit. This is a margin of 15 milliamperes.

Formulas for calculating telegraph line current values for the conditions of closed circuit and distant key open, are as follows:

1. For the condition of keys closed:

$$I = \frac{E}{R + \sqrt{\frac{r}{g}} \tanh \frac{L}{2} \sqrt{rg}}$$

2. For the condition of distant key open:

$$I = \frac{E}{R + \sqrt{\frac{r}{g}} \coth L \sqrt{rg}}$$

E is voltage at one terminal, R is terminal resistance of one terminal, r is average line resistance including relays, g is the leakage conductance, mhos per mile, and L is the length of line in miles.

Table VII gives the results of calculations made for the purpose of comparing the current values of single wires and simplexes with 150-ohm relays and 35-ohm relays; with 500,000 and 250,000-ohm line insulation resistance per mile, on No. 8 B. W. G. iron wire.

The two No. 8 B. W. G. iron wires in parallel, in a simplex, have the resistance of the No. 47-A repeating coils added. There are two coils at each intermediate station and one at each end. The intermediate station coils add 21 ohms per station, and the terminals 10.5 ohms, making the average resistance of the circuit 10.4 ohms per mile, which is not a great reduction below the value of a single No. 8 B. W. G. iron wire. The simplex has double the leakage current of a single wire, assuming the same insulation resistance values for both. wires. On these simplexes better insula-

TABLE VII

Computed current values, telegraph line 150 miles long with 30 relays comparison of single wire and simplex for three conditions of insulation.

			Current—milliamperes				
Computation Number	Resistance of relays ohms	Resistance of insulation ohms per mile. per wire	Line closed (a)	Line open distant end (b)	Margin *i. e.* difference between (a) & (b)	Margin required for satisfactory operation	Dry weather current perfect insulation
	Single No. 8 B. W. G. iron, 12.4 ohms per mile.						
1	150	500,000	52.3	28.9	23.4	15	46.
2	35	500,000	96.5	35.2	61.3	25	91.2
3	150	250,000	58.3	43.3	15.0	15	46.
4	35	250,000	101.5	57.1	44.4	25	91.2
Simplex, No. 8 B.W.G. iron, 10.4 ohms per mile, including simplex coils							
5	150	500,000	60.2	44.1	16.1	15	48.1
6	35	500,000	108.1	58.2	39.9	25	100.
7	150	250,000	70.6	62.3	8.3	15	48.1
8	35	250,000	110	86	24.	25	100.

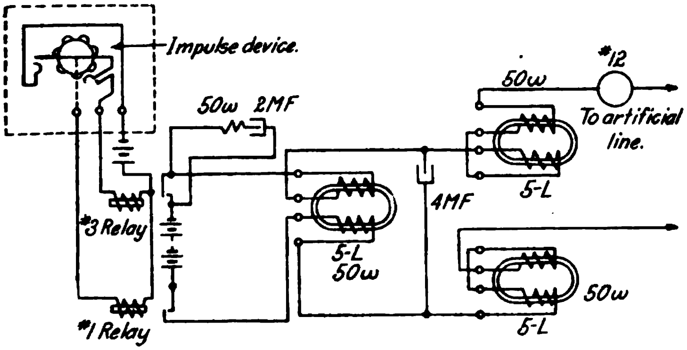


FIG. 20—SIGNALING SET FOR SELECTOR TELEPHONE CIRCUITS WITH 3-5*L* COILS

tion is desirable than can be permitted on single wires. Comparison of computations Nos. 4 and 6 of the table shows that the margin of a simplex with 500,000-ohm insulation resistance per mile is about the same as a single wire with half that insulation resistance.

The table shows that the 35-ohm relays have better margin than 150-ohm relays under the same conditions of insulation. Comparison of computations Nos. 3 and 4 shows, that the margin is at the limiting value with 150-ohm relays and 250,000-ohm insulation, whereas the 35-ohm relay margin at 44.4 milliamperes is still satisfactory. Comparison of computations Nos. 7 and 8 shows similar results on a simplex circuit.

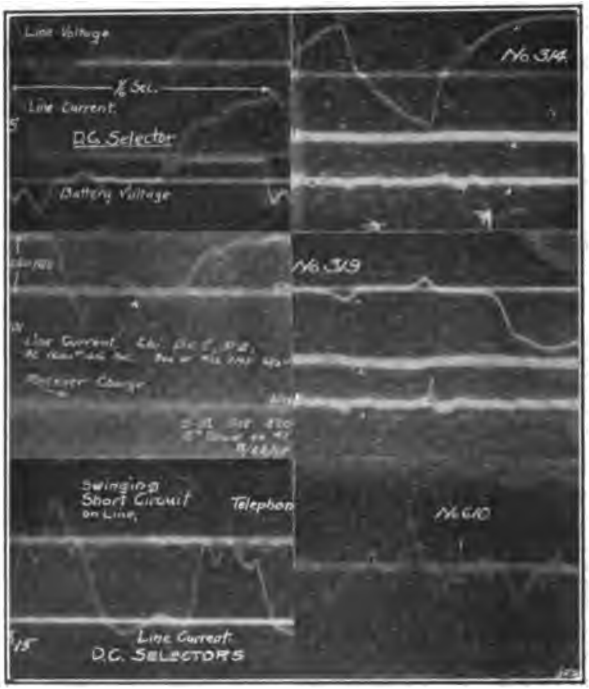


FIG. 21

It is found in practise that an entire circuit seldom has a uniform value of insulation resistance in wet weather, because of the variable rainfall rate. It is generally clearing at one end of a division when raining hardest at the other end.

TELEPHONE SELECTOR CURRENT AND VOLTAGE WAVES

In Fig. 20 retard coils and condenser are indicated in a telephone selector signaling circuit, which are for the purpose of modifying the voltage wave that is impressed on the line so that it will not give listeners on the telephones a disagreeable sound shock. Some investigations were made on an artificial line of Fig. 22 through the signaling equipment of Fig. 20 with the result shown in oscillogram No. 5. The oscillogram No. 5 of Fig. 21 shows the voltage on the battery side of the coils as trace No. 3 and the simultaneous result on the line side as trace No. 1. The line current is trace No. 2. This shows that the line voltage and current are practically in phase. Considerable delay in the progress of the wave on the line is indicated both at the make and break of the circuit. The condensers in the middle of the retard coils act as a storage battery and assist to prevent the sudden collapse of line voltage when the relay opens. They also cause high initial counter e. m. f. in the coil between them and the battery when the relay closes, thus rounding off and delaying the growth of the line wave. The resultant current wave on an actual line is shown in No. 101. This was taken on a 110-mile dispatching No. 9 A. W. G. copper wire circuit, Indianapolis to Cincinnati, equipped with 32 Sandwich type 4-G selectors, with a main battery of 220 volts. In No. 101, the capacity of the telephone condensers added to that of the line causes a decided oscillatory action at the end of impulses. This is aided by the capacity and retardation in the wave modifying set.

The cause of the vicious sound in the receiver which occurs due to a swinging short circuit on the line while selector impulses are being sent, is shown in oscillogram No. 15. The upper trace is the telephone condenser wave and the lower is the line current. The short circuit is removed at about the middle of the wave with sudden increase in line voltage with resultant rapid charging of the condenser in the telephone receiver circuit which causes the disagreeable sound shock.

The condenser signal sending set of Fig. 23 was recorded in No. 50 and No. 51 of Fig. 24 sending impulses into this artificial selector line, first with 125 volts main charging battery and then with 325 volts. This type of sending circuit is in use to a limited extent on some railroads. The brevity of the line current wave is the outstanding feature of these two records.

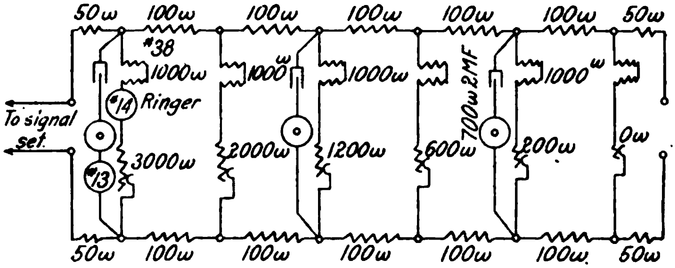


FIG. 22—ARTIFICIAL SELECTOR TELEPHONE CIRCUIT

The above mentioned Sandwich selectors on the Indianapolis-Cincinnati dispatcher's telephone line were replaced by 32 Western Electric Co. alternating-current selectors, type 60-A, with wiring as shown in Fig. 11; and oscillogram No. 380 shows the current in the battery side of the repeating coils as trace No. 1 and in the line as trace No. 2. This circuit has the condensers removed from the selectors and lumped in the battery side of the repeating coil. The impulses as registered in the line at the sending station on the Indianapolis-Kankakee dispatching telephone circuit, a 140-mile No. 9 A. W. G. copper circuit of 35 No. 60-A alternating-current selectors, is shown in No. 590, in which trace

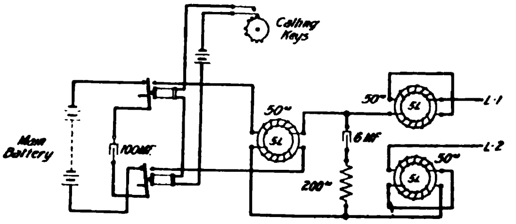


FIG. 23—CONDENSER TYPE SIGNALING SET FOR SELECTOR TELEPHONE CIRCUITS

is the line current. These selectors are operated with a condenser in series with each selector and with the main battery applied directly to the line. It will be noted that the first impulse, which is the closure of the No. 122-E W relay, is but half the amplitude of the following impulses. Oscillogram No. 591 is the Kankakee circuit line current with the repeating coil signaling set of the Cincinnati circuit sending impulses. The resulting impulses are only half the amplitude of the impulses of the regular signaling set, shown in No. 590. This method is now being experimented with. It is the more desirable plan because with condensers in the bridging selectors the wire chief can make accurate Varley loop Wheatstone bridge measurements for trouble. If the direct battery ringing set of the Kankakee line is put on the Cincinnati circuit which has the condensers removed from the selectors, the result is as

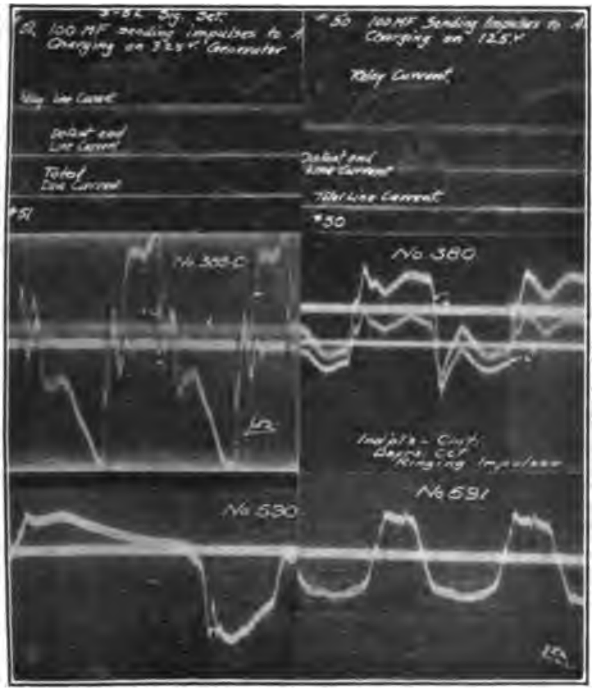


Fig. 24

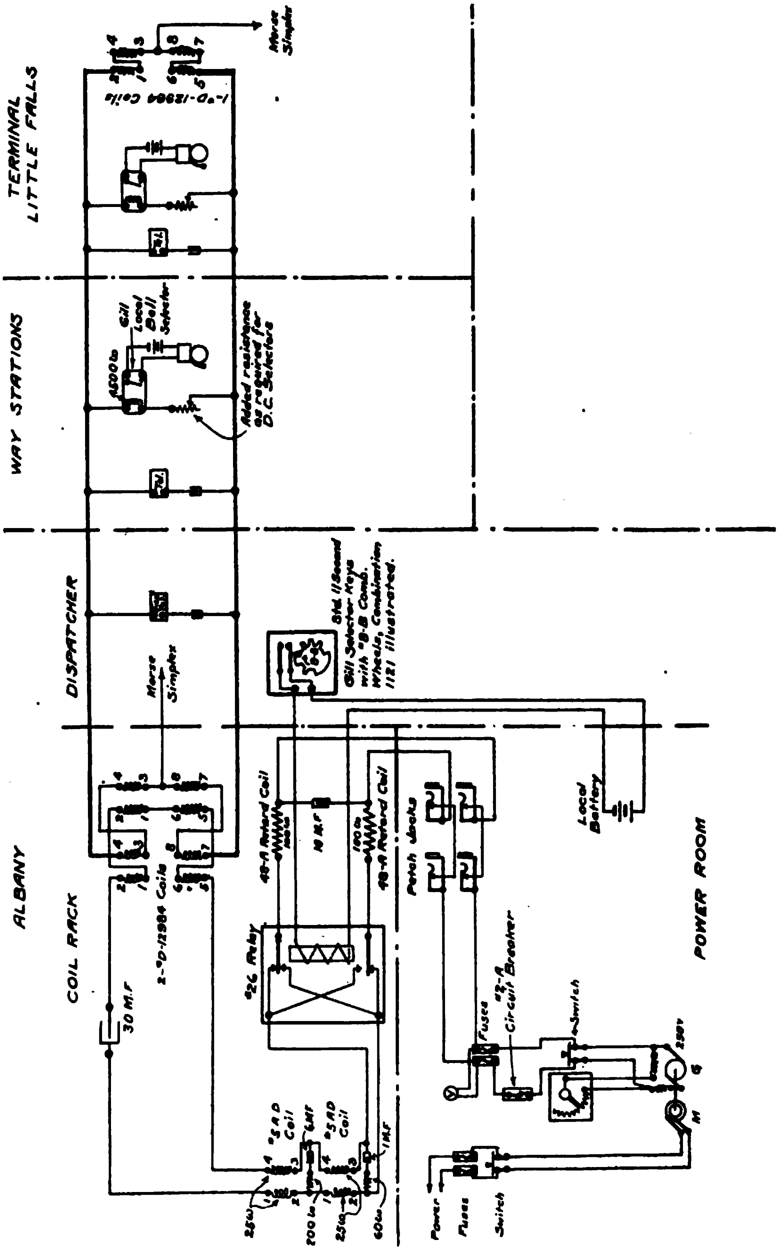


FIG. 25—GILL LOCAL BELL SELECTORS USED WITH REPEATING COIL SIGNALING TO OBTAIN LOW-RESISTANCE SIMPLEX—ALBANY—LITTLE FALLS—N. Y. C. R. R.

80 Miles No. 9 A. W. G. Copper—33 Model E-3 selectors.

shown in No. 388-C, trace No. 1, which is the line current.

Oscillograms No. 319 and No. 314 of Fig. 21 show the comparative impedance of a No. 47-A repeating coil and a D-12984 coil, which is used for the signal sending repeating coil for alternating-current selectors and also as a simplex coil for the "distant" end of such circuits. Trace No. 1 of No. 314 is the current in the No. 47-A coil at the Indianapolis end of an Indianapolis-Bellefontaine No. 9 A. W. G. copper alternating-current selector line 140 miles long, equipped with 45 a-c. selectors not operated through a repeating coil at the sending end, but with the battery applied direct to line at Bellefontaine.

Trace No. 2 is the current through the selector which had two microfarads capacity in series with it. Trace No. 3 is in the phantom telephone branch on this circuit. In No. 319, trace No. 1 is the current through a D-12984 coil. The lobes of this wave on the short impulses are much smaller than on No. 314, indicating much less effect on the line current, while the continuous impulse is somewhat the same shape in both.

No. 610 shows the current through the D-12984 coil at Indianapolis after the condensers from the selectors had been lumped in a repeating coil type of signal sending set of Fig. 11, at Bellefontaine.

GILL SELECTORS AS A-C. WITH LOW RESISTANCE SIMPLEX

The repeating coil method of operation is applicable to types of impulse selectors which do not require main line battery for ringing the selector bells. The Gill local battery selector, of which a great many are in use, is in this class and is successfully operated through the D-12984 repeating coil, as shown in Fig. 25. The circuit on which this was first used is the Albany-Little Falls dispatching telephone line, which was the first telephone train dispatching circuit in this country; the first one to have selectors, which were the Gill telegraph type, used on a third wire; the first to have selectors on the same wires as the dispatching circuit,

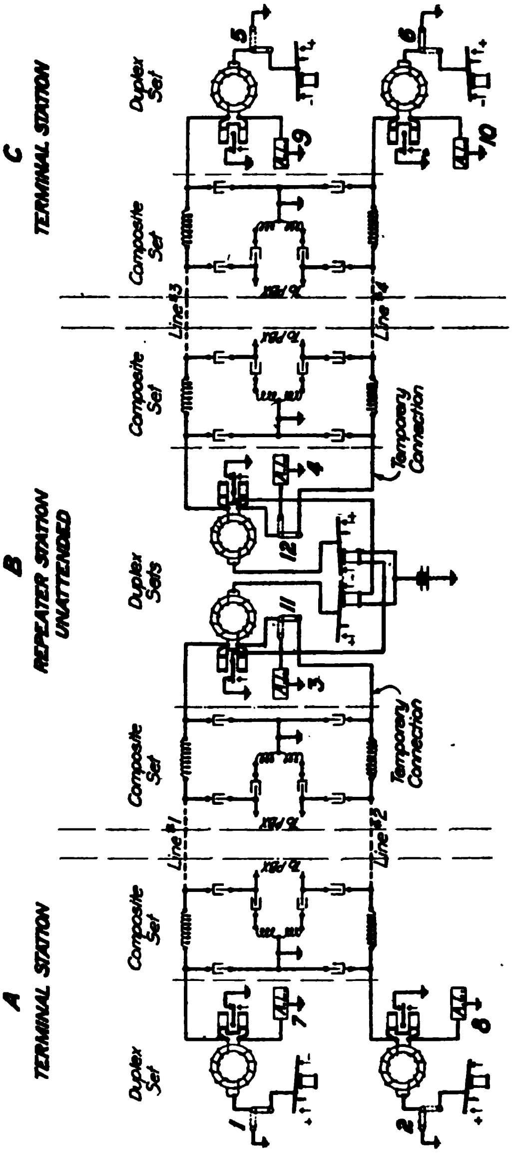


Fig. 26—Unattended Self-Balancing Duplex Applied at Repeater Station

which was the series Gill type with selectors in the line at one station in one wire and in the other wire at the next station, alternating first in one wire and then in the other, and operated by simplex current. These series selectors were later replaced by the first "bridging" Gill selectors which are still there and are now converted to "alternating-current" operation, so-called, and are the first circuit of Gill selectors to be so operated.

The No. 26 relay replaces the ordinary single-contact telegraph relays formerly used; the condensers and repeating coils were installed and new No. 8-B combination wheels were made for the dispatcher's calling keys, and designed so that one impulse is sent when the key contact makes and another when it breaks; otherwise, no change was made in the circuit. The added resistance in series with the selectors was not altered and the current distribution seems to be satisfactory. The circuit is No. 9 A. W. G. copper, 80 miles long with 33 selectors. About one microfarad per selector is enough capacity in the repeating coil circuit to operate the selectors properly. Slightly less main battery is required than before the change was made. The repeating coils reduced the simplex resistance 1000 ohms. It is believed that the method will be found successful on almost any selector circuit now equipped with this type of selector.

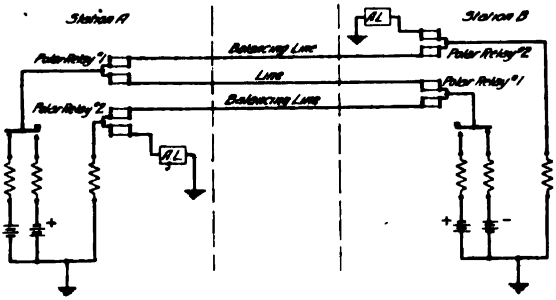


FIG. 27—THEORY OF A DUPLEX CIRCUIT SHOWING THREE WIRES

The No. 48-A retard coils and condenser were necessary to reduce the generator hum which was heard on the line without them, due to the generator being continuously connected through the back contact of the No. 26 relay, to the condenser and repeat coil. If a key is designed with a third contact, a relay can be inserted, as is used with the Western Electric Co. No. 60-A apparatus case to cut off the battery between operations of the calling keys. A few of the old Gill keys were slightly too fast in speed for the new combination wheels and had to be slowed down, but in future, the combination wheels can be cut to take care of this.

The advantages of repeat coil operation are that grounded sources of power, such as lighting circuit can be used for main battery; that more than one circuit can be connected to the same generator or power supply; and much lower resistance simplex telegraph circuits result.

POLAR DUPLEX AND QUADRUPLEX OPERATION

The standard polar duplex of the Western Union Telegraph Co. is in use on the N. Y. C. Lines, on a total of 36 circuits and on 9903 miles of circuit. The preferred type is convertible from bridging to differential. The differential is used on composited wires in which the retardation of the Morse leg is sufficient to round off the outgoing wave, and prevent induction trouble. The bridging set is used on simplexes and single wires.

The standard quadruplex is used to a limited extent. As with the duplex, the preferred type is convertible from bridging to differential, and the differential should be limited to use on composited wires.

The action of bridging duplexes and quadruplexes as installed in accordance with the Western Union Telegraph Company's specifications, has been studied to learn their characteristics and better their performance and speed of service, so that such circuits in railroad service can be relied upon to give full output as "double" duplexes and "four-cornered" quadruplexes.

A polar duplex or quadruplex is approximately a three-wire circuit, usually consisting of an actual line and two artificial lines. Actual lines may be substituted for artificial lines as indicated at station B of Fig. 26. Fig. 27 indicates the three wires of a duplex using actual lines in place of artificial lines to balance both No. 1 polar relays. As indicated in Fig. 27 actual or dummy duplex sets are needed at both points designated as No. 2 P. R. With these dummy sets, artificial lines are needed to enable the distant station to get the best balance practicable. Carrying the idea further, it would be possible to use actual lines in place of these artificial lines, also placing dummy sets at the distant ends. In turn, these dummy sets would require balancing lines. Thus, theoretically, the number of balancing lines could be multiplied infinitely. In practise, the balance is found to be practicable with but two balancing lines, and no dummy balancing sets are ordinarily used with artificial line boxes. Hence, the term "approximate" three-wire circuit seems to be a correct designation for a duplex or quadruplex. The artificial line can never exactly balance the real line because there is always one more wire between "home" battery and distant ground in the line side than in the artificial line side, as is readily seen in Fig. 27.

SELF-BALANCING DUPLEX

Based upon the idea of a duplex being a three-wire circuit, successful use has been made of a real line instead of the usual artificial line resistance box and condensers which are standard equipment in duplex sets. This "real" balancing line balances the regular line almost perfectly under changing weather conditions, needs no additional balancing at such times and hence can be designated "self-balancing." It also balances for inductive disturbances to which both line and balancing line are exposed and for line irregularities such as short lengths of cable. This assumes that the duplex line and its balancing lines are alike in characteristics; are on the same pole line; have the same length; kind of wire, and, in fact, are twins. The two sides of a composite are very good for this type of set-up, but the plan is also applicable to any two similar circuits, such as straight wires or simplexes provided they are reasonably alike in kind.

One difficulty experienced in lining up a duplex is to get an adjustment of resistance and capacity in the artificial line which will so nearly balance the actual line that no kick will be felt in the home polar relay when the home pole changer is operating. It is almost impossible to get such a balance, and furthermore, the balance must be changed for changing weather conditions. It is, therefore, unsatisfactory to work a duplex circuit having a repeater station on it that does not have an attendant the full period of the day in which the circuit is expected to give service.

This plan of self-balancing duplex is especially valuable for circuits that are unattended at repeater stations for a part of the day and on Sunday. It has been the custom in some instances to cut the repeater out during the hours the station is unattended, but this makes a long and unsatisfactory circuit.

The plan may be considered an extravagant use of wire, because it uses two wires for one duplex, but it is only suggested as an expedient for use where some circuits are idle after business hours, as many duplexes are at night and on Sunday, at which time they can be put to productive use for balancing a wire that must give twenty-four hour service.

Some oscillograms have been taken that illustrate the effect of lack of good capacity balance in the artificial line, and the perfection of the balance with a real line instead of an artificial line. It should be kept in mind that in the latter the balance is continuous and unchanging, whereas the artificial line needs attention intermittently.

In oscillogram No. 469 of Fig. 18 the outgoing line wave of a bridging quadruplex set on a 140-mile, No. 8 B. W. G. iron wire, high-resistance simplex, is trace No. 1 while the home key is operating. Trace No. 2 is the artificial line under the best balance that the attendant was able to get with the milliammeter as a guide. Trace No. 3 is the wave in the polar relay and shows plainly that the home pole-changer affects it considerably, evidenced by the kicks in trace No. 3 which occurred on the reversal of the line wave.

Oscillogram No. 470 is the same set on the same circuit with no difference except that all the capacity was removed, which greatly amplified the kick in the polar relay, trace No. 3, as would be expected. Oscillogram No. 540 is the same circuit with duplex sets. Oscillogram No. 588 shows the results with the self-balancing duplex on a 140-mile, No. 9 A. W. G. copper wire low-resistance type phantom, composited, in which it is readily apparent that the kick in the polar relay is very slight and a great improvement over the best balance that could be obtained on the artificial line. The slight waves in the polar relay wave between reversals of line current are probably reflected waves.

In Fig. 26, which indicates self-balancing duplexes applied at an unattended repeater station, the artificial line is cut off at switches No. 11 and No. 12, where the real lines to be used as balancing lines are cut in, which requires a special connection in existing duplex sets. Terminal stations are shown with duplex sets connected to these balancing wires, with no change except to cut off the battery at the seven-point switch and put on ground contact, which is regularly provided for in the seven-point switch. If lines No. 2 and No. 4 are regularly duplexed, their duplex sets are simply grounded at the seven-point switch. The resistance and capacity in artificial lines No. 8 and No. 10 can roughly approximate the values required in the artificial lines No. 7 and No. 9. This does not need to be exact, although it is about as easy to make it so as to have it inexact.

This set-up can be quickly arranged and, it is believed, is worth the trouble where circuits are idle, although the station may be attended, because it gives better service and needs no attention. It is quite often the case that the night and Sunday repeater attendants are the less experienced men of the force, and service will be better if they do not have to attempt adjustments of the duplex apparatus or repeaters. The plan is equally applicable and advantageous for differential and bridging duplexes.

NO. 5-U RETARDATION COIL IN BRIDGING DUPLEX AND QUADRUPLEX IS ALSO AUTO-TRANSFORMER

The action of the No. 5-U coil of bridging duplexes and quadruplexes was an object of curiosity, the work performed by the coil being difficult to determine with certainty, and a large number of oscillograms was taken to reach conclusions. From these it can safely be asserted that the No. 5-U coil functions primarily as an auto-transformer and incidentally as a retardation coil.

The traditional explanation ever since Brown designed this circuit arrangement is that an incoming wave from the line meets great opposition in its attempt to flow through the line side of the No. 5-U coil, because of the high impedance of the latter, and as a result almost all of the incoming current rushes into the polar relay which is connected across from line to artificial line. The explanation stopped at this point and neglected to state where this rush of current through the polar relay proceeds to. It does not go through the artificial line to ground, because the current is coming toward the No. 5-U coil at this time, and while this current is influenced slightly in value by the incoming line current it is not reversed nor is it greatly reduced. If the impedance of the line side of the No. 5-U coil were effective in stopping the inrushing line current, the artificial line side of it should be equally effective in stopping the rush that passes through the polar relay. No explanation has been made for the condition of outgoing current which also occurs due to the operation of the distant pole-changer.

In the quadruplex, the condition existing with the home keys and distant common key closed and distant polar key working will be discussed first. Oscillogram No. 471 of Fig. 28 shows the current in the line as trace No. 1, in the artificial line as No. 2 and in the polar relay as No. 3, of a bridging quadruplex on an Indianapolis-Bellefontaine, 140-mile, No. 8 B. W. G. iron wire telephone pair, simplexed with the ordinary high-resistance simplex used with direct-current selectors as shown in Fig. 10 but without the composite equipment, and balancing at 4400 ohms with one microfarad and 500 ohms in the first condenser, and 400 ohms and ¾ microfarad in the second condenser. The distant polar key is sending the impulses and the other keys are closed. It is apparent from No. 471 that the artificial line current is only slightly changed by the change of line current with operation of the distant polar key. Oscillogram No. 467 was taken under the same line conditions as No. 471 but shows the current in the line side of the No. 5-U coil as trace No. 1, the artificial line side as No. 2 and in the polar relay as No. 3. The difference in the values of current in the artificial line as shown in No. 471 and the artificial line side of the No. 5-U coil in No. 467 is very marked, and the difference represents the polar relay current.

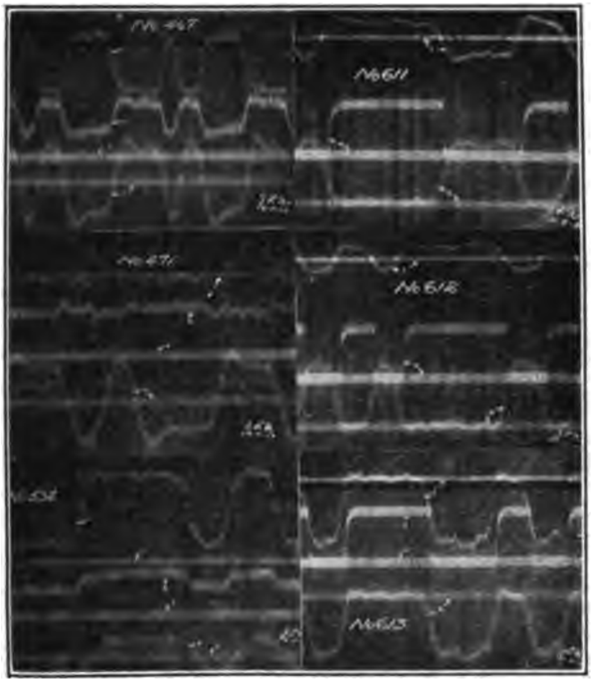


Fig. 28

With all keys closed the current is "upward" in the polar relay, *i. e.*, the direction indicated by an arrow

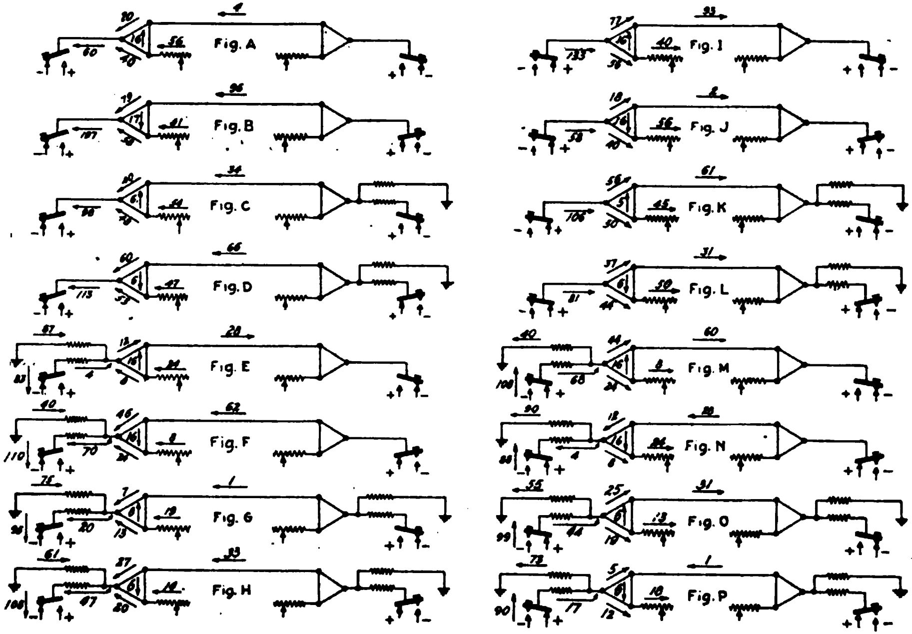


FIG. 29—APPROXIMATE CURRENT VALUES IN BRIDGING QUADRUPLEX FOR VARIOUS KEY POSITIONS

240 volts each end

Balance artificial line................2650 ohms
Home lamp resistance............−524 "
" " " ....+524 "
Distant lamp " ....−501 "
" " ....+486 "

Wires 57-58 No. 9 A.W.G. message simplex copper.
A-C. selector, low-resistance simplex.
Indianapolis-Bellefontaine

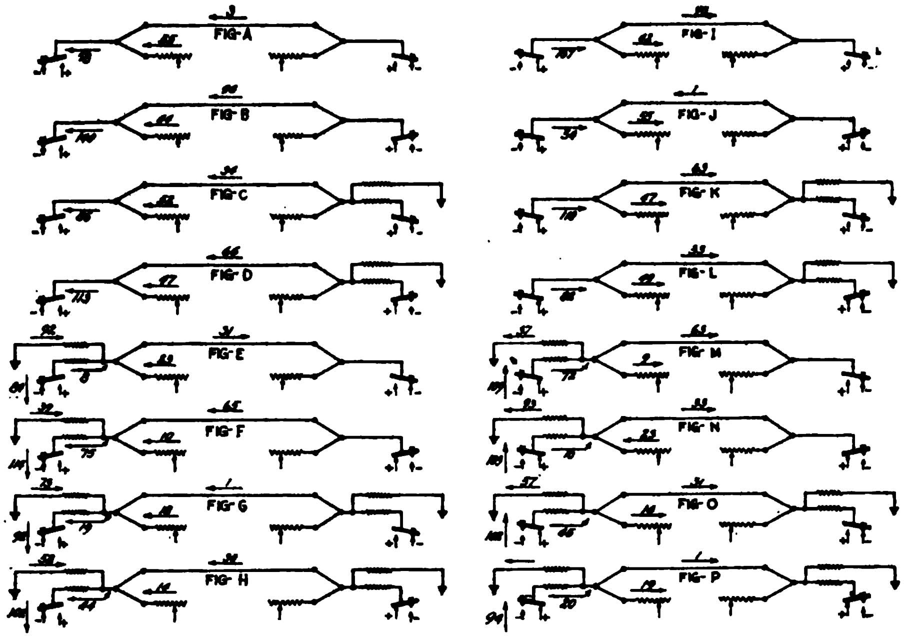


FIG. 30—APPROXIMATE CURRENT VALUES IN DIFFERENTIAL QUADRUPLEX FOR VARIOUS KEY POSITIONS

240 volts each end

Balance artificial line..................2900 ohms
Home lamp resistance.................−524 "
" " " ....+497 "
Distant lamp " ....−473 "
" " " ....+483 "

Wires 57-58 No. 9 A. W. G. message simplex copper.
A-C. selector, low-resistance simplex.
Indianapolis-Bellefontaine

on Fig. 29 pointing to the top of the page. It is also flowing toward the home pole-changer through the No. 5-U coil windings. Fig. 29 gives the current values and direction of flow on a bridging quadruplex during the steady state, for the different positions of the keys, as actually measured on a working circuit. Fig. 30 gives actual current values in a differential quadruplex on the same circuit, for comparison.

Now, if the distant polar key opens, positive potential is applied there and current begins to flow in from the distant station. The potential wave will cause current to flow through the line side of the No. 5-U coil and will quickly increase the potential across this coil, during which time the current will decrease through the polar relay, and when the potential across the line side of the No. 5-U coil equals the potential across the artificial line side, the polar relay current at that instant will be zero but rapidly changing in direction. The transient state continues, that is, there is no hesitation at the zero point and the current reverses in direction through the polar relay.

When the distant polar key closes again negative potential is applied there and the line current decreases and becomes nearly zero. The traditional explanation does not mention this action which leaves the impression that the movement of the polar relay armature both to and from the marking contact is due to "incoming" waves of current. In fact, the movement away from the marking contact is due to increase or rise of incoming current in the line, and the movement toward the contact is due to decrease or fall of line current, provided the home polar key is closed. If the home key is open, then the movement of the polar relay armature is due to just the reverse set of current actions, *i. e.*, the movement away from the marking contact will occur with decrease of outgoing line current and will move toward it with increase of outgoing line current. The current in the line will be flowing from the home station when the home key is open.

It will be remembered that the No. 5-U coil windings are both wound on the same core and have a common terminal. The incoming and increasing current in the line side when the distant polar key opens, tends to build up a magnetic field in this core. This induces current in the artificial line winding by mutual induction or transformer action and in the same directional relation as in the line side; *i. e.*, if the line current is increasingly flowing toward the common terminal of the two windings, the generated current in the artificial line side will be toward this point, as follows from the laws of mutual induction. The magnetic flux of this generated current is nearly equal and opposite to that in the line side, and hence, the net change in flux is slight. As the current rapidly increases in the line side of the coil, it also rapidly increases in the artificial line side, thus creating a large difference of potential between the two line terminals; it is to be remembered that the common terminal can have only a potential common to both. This change of potential across the line terminals, which is across the polar relay, causes the reversal of current through the polar relay and throws the armature to the spacing position.

The oscillograms fail to show any great "rush" considered as rate of change of current value, but do show that the current continues to increase in value after reversal has occurred, to perhaps 20 per cent higher value than it does if the No. 5-U coil is replaced by 500-ohm resistances. If the No. 5-U coil is removed and two 500-ohm non-inductive resistances are put in its place, the current through the polar relay loses its tendency to rise beyond the value it has after reaching the steady state. Oscillograms No. 611 and No. 612 illustrate this, with No. 1 as polar relay trace, No. 2 as the polar relay local sounder circuit trace and No. 3 as the line trace. The No. 611 has the No. 5-U coils and shows that the polar relay current at each reversal continues beyond its ultimate value considerably and then gradually recedes. The No. 612 has 500-ohm resistances and the current in the polar relay reverses and reaches the steady value without the tendency to "bulge" beyond that value.

These two oscillograms were taken on one side of the low-resistance composited phantom, Indianapolis to Bellefontaine, No. 9 A. W. G. copper a-c. selector telephone dispatching line with the bridging duplexes balancing at 1800 ohms, three microfarads and 100 ohms in the first condenser, and two microfarads and 600 ohms in the second condenser, with 160-volt main battery at each end. The polar relay has an ordinary or usual adjustment, and both No. 611 and No. 612 show that the polar relay armature is reversed before the current change has ceased in the polar relay, and it is evident that the bulge of current in the set with the No. 5-U coil serves no useful purpose other than to hold the polar relay armature more solidly against its contact after it gets over. From the evidence gathered in these investigations it is not apparent that the current changes at any greater rate in the set with the No. 5-U coil than in the one with the 500-ohm non-inductive resistance. A similar

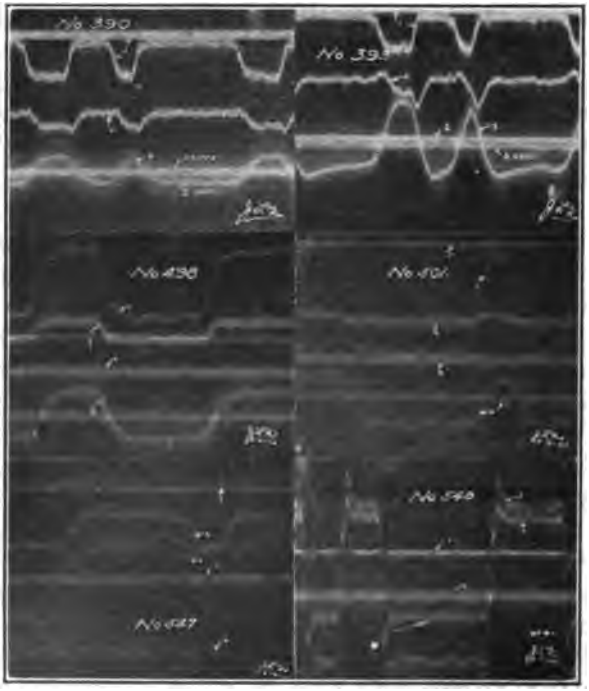


Fig. 31

record of a differential duplex and its polar relay local sounder circuit is given in No. 613 for comparative purposes. It was taken on the same circuit as were No. 611 and No. 612. In No. 613, traces No. 1 and No. 3 are both the line current.

For the bridging quadruplex the result of comparison of the No. 5-U coil and the 500-ohm resistances is shown by No. 469 of Fig. 18 for the No. 5-U coil and No. 534 of Fig. 28 for the 500-ohm resistances, both taken on the 140-mile, No. 8 B.W.G. high-resistance iron simplex circuit. In these, trace No. 1 is the line side of the No. 5-U coil, No. 2 is the artificial line side of the No. 5-U coil and No. 3 is the polar relay current. The common or neutral keys are closed.

This tendency to bulge or exceed the ultimate steady state value is more striking in the Goslin quadruplex, as illustrated in No. 390 of Fig. 31 for the non-inductive winding, and No. 393 with the No. 5-U coil. In this arrangement the polar relay and neutral relay are in series across the terminals of the No. 5-U coil and get less current in the bridge after the steady state is reached than does the regular quad, and due to the No. 5-U coil tending to equalize the current through its two windings during the transient state, the polar relay current is considerable.

It will be noted in No. 467 of Fig. 28 that after the first rush ends, the line side current in the No. 5-U coil continues to increase slowly and the artificial line slowly decreases, both changing by about the same amount, until the steady state is reached. The time to reach the steady state in these bridging sets is longer than the average dash, as seen in the letter "a" which is being repeated in these oscillograms.

Two quadruplex sets were made up of non-inductive resistances throughout, simply maintaining the skeleton outlines of the bridging quadruplex; that is, there were no coils or relays used, simply resistances of the same values as the pieces of apparatus they replaced. These were placed on the same No. 8 B. W. G. iron wire simplex circuit as that on which No. 467 and No. 471 of Fig. 28 were taken. No. 498 of Fig. 31 corresponds to No. 467 as to location of recording elements of the oscillograph, and No. 501 similarly corresponds to No. 471. In No. 498 and No. 501 it is evident that the rate of reversal of current through the polar relay branch of the circuit is the same as with the regular polar relay and No. 5-U coil, but the change ceases sooner with the non-inductive circuit, although the line waves are very closely the same in both arrangements.

Comparison shows clearly how the steady state is quickly reached in the polar relay in the non-inductive resistance circuit used in place of the No. 5-U coil illustrated in No. 498; whereas, there is considerable slant or gradual change in the inductive No. 5-U coil illustrated in No. 467.

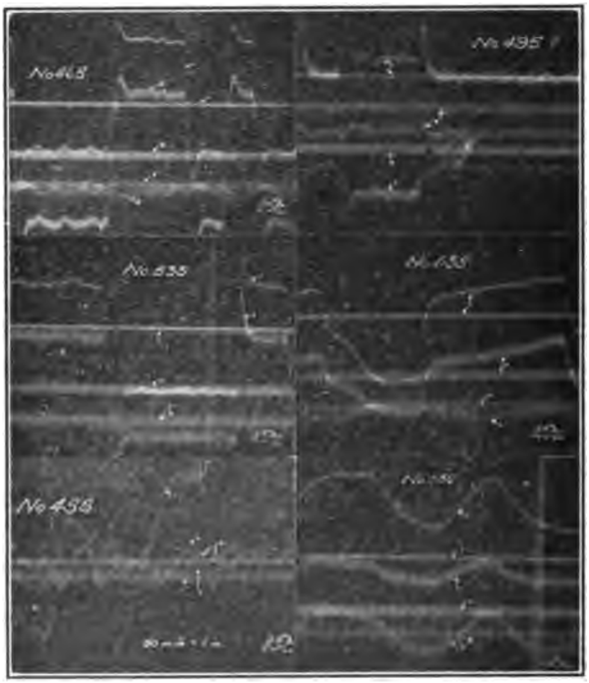


Fig. 32

A search coil of 250 ohms was wound on a No. 5-U coil of a duplex set and connected to the oscillograph, giving the result shown in No. 547 of Fig. 31 as No. 1 trace, with the distant station sending on the polar key.

This shows that the change in magnetism in the core of the No. 5-U coil is very slight, consisting of small humps in the trace No. 1 at each reversal of the line current, while the current in the two sides fluctuates widely, which indicates that the coil is a very efficient transformer and as in power transmission, comparatively large power is transformed with a relatively small magnetizing current.

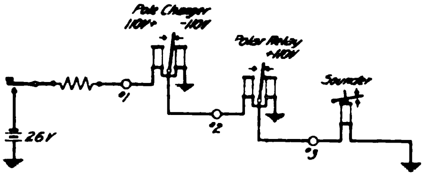


FIG. 33—POLAR RELAY TEST CIRCUIT

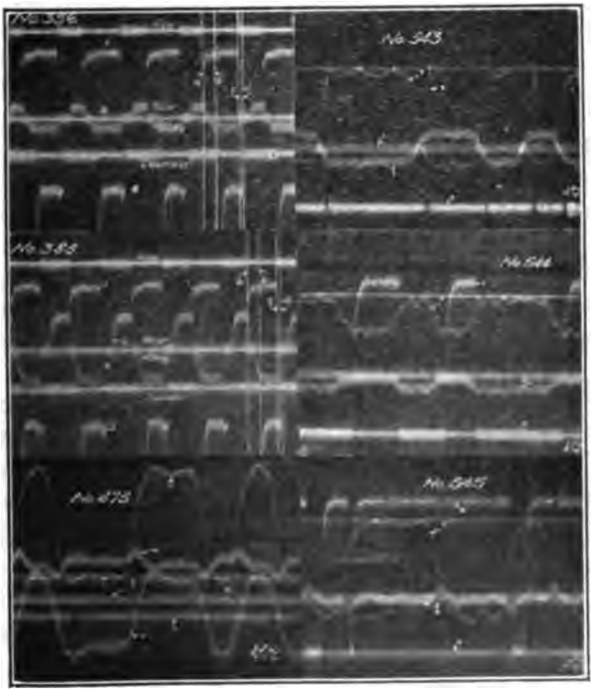


FIG. 34

In the case of the current waves set up by the action of the home polar key when sending as shown in No. 548 of Fig. 31, the magnetism is considerable, as shown by the large sharp peaks of trace No. 1 made by the search coil. This is somewhat due to the lack of proper and exact "balance," *i. e.*, the capacity, resistance and inductance of the artificial line is not exactly the same as the real line and the terminal apparatus at the distant end of the line.

These peaks of magnetism in the core of the No. 5-U coil cause the rounding off of the line wave of the home key operation, which is one of the chief features aimed at in the bridging sets. If no magnetic flux resulted due to the outgoing wave, the coil could be considered as non-inductive to outgoing waves and would show no great difference in the outgoing wave from that of the differential sets which have very sharp peaked out going waves. Tests with an actual line instead of an artificial line show that the kicks in the polar relay resulting from the home pole-changer are negligible, as illustrated in No. 588 of Fig. 18, but that the outgoing line current is rounded off as much as in sets that have artificial lines. Therefore, it is not lack of balance that causes the flux in the No. 5-U coil and the rounding off of the outgoing wave. It is, perhaps, the leakage flux in the No. 5-U coil which affects both the line and artificial line sides equally, if the balance is exact.

As a further illustration of the conclusion that the No. 5-U coil has effect in rounding off the outgoing waves No. 465, No. 495 and No. 533 of Fig. 32 can be compared. All three are records made on the previously mentioned 140-mile, No. 8 B. W. G. iron wire simplex circuit, and trace No. 1 is the line side of No. 5-U coils, No. 2 is the artificial line side of No. 5-U coil, and No. 3 is the polar relay circuit. The distant common key was open in all three, the home polar key sending and the other two keys were closed. The peaks of the outgoing waves are rounded off in No. 465, which is the regular bridging quadruplex. They are sharp in No. 495 which is a skeleton resistance quadruplex mentioned above and are also sharp in a regular quadruplex with 500-ohm resistances instead of a No. 5-U coil, as illustrated in No. 533.

In a quadruplex of either bridging or differential type and in the differential duplex, it is readily apparent that the relays which are in the line differentially, that is with one coil in the line and one in the artificial line, act as transformer to some degree. This follows because the two windings have a common core, and current in one winding cannot fail to generate current in the other winding. The extent of this action has not been definitely determined.

Two separate No. 5-U retardation coils were also tried in a quadruplex with one winding of each connected in circuit and the other winding standing open, on the 140-mile No. 8 B. W. G. iron simplex. The result is shown in No. 536. It was not possible to work this quadruplex, because it took too long for the current waves to build up and die out in the retardation coils. The result of the home polar key sending is shown in No. 535, which is plain explanation of the failure of the circuit to telegraph. Trace No. 1 is the line side coil, No. 2 is the artificial line coil and No. 3 is the polar relay. The home key causes wide variation in the current in the home polar relay. These two records disprove the theory that the No. 5-U coil is a retardation coil only.

Modification of the outgoing wave is necessary for circuits such as the bridging duplex is designed for, that is single wires and simplexes, and for these perhaps some suitable retardation coil and condenser can be designed for insertion between the pole-changer and the line relay. The ideal design would be inductive to home sending and non-inductive to received signals. The vacuum tube may solve the problem.

In comparison of bridging and differential duplexes it is seen that the received line waves are practically equal and alike in shape in both, if used on the same circuit and with the same voltage. A question is, which makes more efficient use of this wave? The polar relay has its coils in series on the standard bridging duplex. One coil of this relay would require twice as much current in order to have equal force. The net operating current in a differential set is the difference between the line and artificial line current and can be considered as acting in one coil only of the polar relay. If this net operating current is greater than the bridging set polar relay current multiplied by 2, it has greater force than the latter. Tracings from oscillograms Nos. 413 and 415 are given in Fig. 35, and clearly indicate that the differential relay net operating current of No. 413 is more than twice the polar relay current of No. 415. From the records taken it appears that the bridging polar relay does not get as much force as the line coil of a differential set, due to the divided circuit between the No. 5-U coil and polar relay, both of which share the line wave. Therefore, the differential probably makes more efficient use of the line wave than does the bridging duplex.

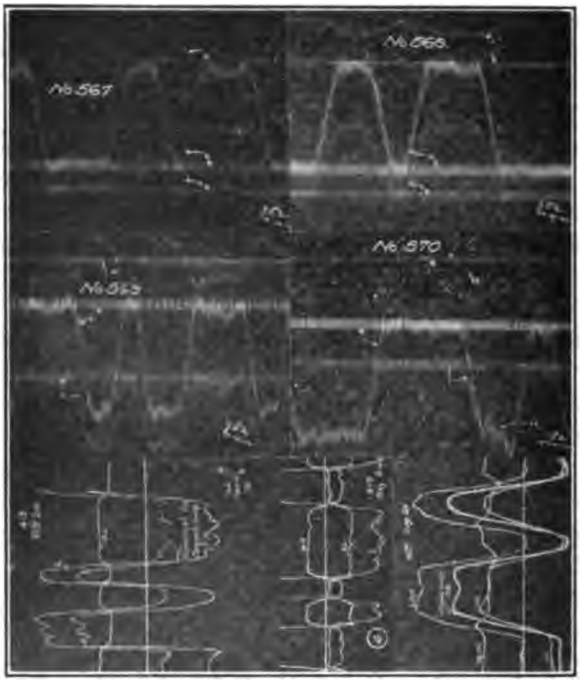


Fig. 35

POLAR RELAY SPEED OF REVERSAL

The quadruplex depends for its success upon the important fact that the fluctuations in the line current due to the insertion and removal of resistance in the distant station main battery, are not distinguishable to the ear in their effect upon the polar relay and its local sounder. The fluctuation is generally set at a 3 to 1 ratio, that is, the current is three times as great when the distant neutral key is closed and the resistance cut out as when it is open with the resistance in. In some cases the ratio of 4 to 1 is used. In a bridging quadruplex the bridging relay current will be 16 or 17 milliamperes with the distant neutral key closed and 5 to 6 with it open. The polar relay must and does follow the distant polar key without recording this 5 to 16-milliampere variation. Tests were made to demonstrate this, using the circuit of Fig. 33, with the result given in oscillograms No. 355 and No. 356 of Fig. 34. The key circuit was 150 milliamperes, the polar relay was 30 milliamperes and the sounder circuit, 325 milliamperes in No. 355. In No. 356 the polar relay current was reduced to 10 milliamperes. The distance *a-b* in both represents the reversal time of the polar relay armature when the key closes. The interval *c-d* is the reversal time when the key opens. There is no difference noticeable in the *a-b* intervals of the two records, and, likewise, very little difference in the *c-d* intervals of the two, which verifies what is known from listening tests.

DEFECTS OF QUADRUPLEX

The neutral side of a quadruplex depends upon increase and decrease of line current strength and should be independent of the direction of the current. One weakness of the standard quadruplex is that the neutral relay is not independent of the reversals of line current which are produced by the operation of the polar side of the circuit. Means are necessary to overcome the resulting opening of the neutral side local sounder circuit when the current reverses in the neutral relay. The present standard of the Western Union Telegraph Company appears to be a development of the Gerrett

Smith bridging condenser plan in combination with the Diehl "bug trap" repeating sounder. With the "bug trap" the contact point is the back-stop of the neutral relay armature, and therefore, this armature may, in fact, leave its front stop when a current reversal takes place, and if it pulls up again without striking the back contact, no false signal results. The bridging condenser holding circuit includes a coil on the neutral relay, which gives the armature a pull, due to the condenser charging current that occurs with change of line current, and this pull assists in keeping the armature from striking the back contact during current reversal.

The present design of neutral relay has the holding coils mounted above the line coils, and the armature is extended up to the pole faces of these coils. This results in a comparatively slow or sluggish relay due to armature inertia, and while fast enough for hand sending, for which it was designed, it is too slow for fast hand-operated sending machines or "Vibroplex" use, commonly called "bug" sending.

The standard Western Union bridging quadruplex has the polar relay bridged across the line and artificial line terminals of the No. 5-U coil with its two coils in parallel, and has one winding of the neutral relay in the line and the other in the artificial line. The current readings of small Fig. A of Fig. 29 indicate the steady current values which are with all keys closed, 16 milliamperes in the polar relay and 52 milliamperes, the difference between 56 and 4, in the neutral relay, which is net operating current in one coil of the latter. The 16 milliamperes in the polar relay with coils in parallel are equivalent to 16 milliamperes in one coil, if the same force were applied to one coil only as is the case with the neutral relay. The neutral relay, therefore, has a marginal advantage of 36 milliamperes acting in one coil, over the polar relay due to being in the line. Oscillograms, as well as direct-current measurements, confirm the above advantage claim as shown in the tracing of Fig. 35, at the bottom of the page, traced from oscillogram No. 475, using one base line for all three waves of current, on a bridging quadruplex on the 140-mile, iron wire simplex. On this tracing the difference between the line and artificial line current has been plotted and is marked "Resultant in N. R.," showing that the neutral relay net operating current apparently is greater than the polar relay current.

REVERSE QUADRUPLEX

The polar side of a standard bridging quadruplex is believed to be weaker than a differential duplex, because of smaller current margin, and in the endeavor to strengthen it, advantage was taken of the apparent higher current in the line, and the positions of the polar relay and the neutral relay exchanged, placing the polar relay differentially in the line and the neutral relay across the No. 5-U coil.

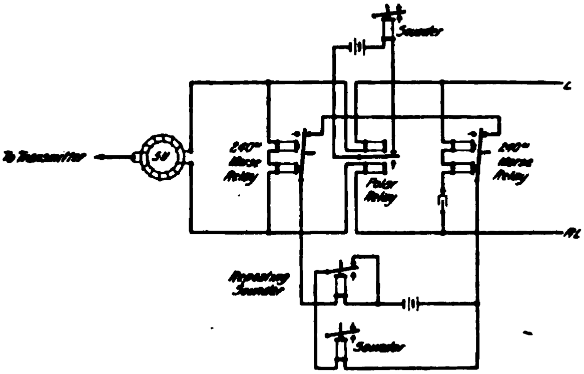


FIG. 36—REVERSE QUADRUPLEX

The neutral relay was next separated into two parts, consisting of two standard 240-ohm Morse relays, No. 4-C, one in the bridge and the other in the holding condenser circuit, with the result shown in Fig. 36 called a "reverse" quadruplex, which is a faster quadruplex than the one with the standard neutral relay. This novel arrangement of the holding relay in series with the holding condenser and separate from the neutral relay, functions when the line current reverses, due to the distant pole-changer operating, and pulls up the holding relay and opens the neutral relay local circuit at the moment it tends to close when the line current reverses. Tests were made with a reverse type quadruplex on the 140-mile iron wire simplex with the distant station sending on the polar key, first with the holding relay contact short-circuited and not functioning, and second with the neutral relay contact short-circuited and not functioning, but with the holding relay operating. The first is No. 543, of Fig. 34, in which trace No. 1 is line current, trace No. 2 is bridge relay current and trace No. 3 is the neutral relay local circuit. The relation of waves in traces Nos. 1 and 3 shows the time at which the neutral relay releases, due to line current reversal. The second case is No. 545, in which trace No. 1 is line current as in No. 543, trace No. 2 is holding relay circuit, which has the condenser in series with it, and trace No. 3 is the neutral relay local circuit. The break in the local circuit here comes at practically the same place in the line wave that the circuit tends to close in No. 543.

Actual results confirm the fact that these two circuits function in harmony, producing a practicable "bug trap." The repeating sounder is retained as in the standard quadruplex. The closure of the neutral relay local circuit with operation of the distant neutral key, is illustrated in No. 544 as trace No. 3, in which the line current is trace No. 1, and the bridging relay, in this case the neutral relay, is trace No. 3. This type of quadruplex will follow fast "bug" sending on the neutral side.

The second weakness of a quadruplex is lack of accurate artificial line balance, and a means of determining the accuracy of the balance better than the standard milliammeters is greatly needed for both duplex and quadruplex. It is not possible with the milliammeters to distinguish between a balance on an artificial line and the balance obtained by the use of an actual line. The results as observed on the Morse and as recorded by the oscillograph, show there is a very decided difference in the best artificial line balance and the actual line balance. A meter with a beam of light instead of a swinging coil and pointer, based on the oscillograph vibrator idea, is suggested. The undulator for multiplex circuits perhaps may be advantageously used with ordinary Morse duplexes.

TERMINAL RESISTANCE UNBALANCE

The terminal resistances, which are in the main battery taps as protection from short circuits at the pole-changer contacts, are a third detrimental factor in the quadruplex and also in the duplex, but more so in the quadruplex. In Fig. 29 it is seen that the current in the negative battery is 60 milliamperes with all keys closed, and is 137 milliamperes when the distant polar key is open. The 137 milliamperes cause a greater potential drop across the battery protection resistance and result in less effective voltage to the artificial line, which upsets the balance to a considerable extent as seen in the resultant neutral relay wave of No. 475 traced in Fig. 35. This causes the current to be light with the keys all closed and heavy when the distant polar key is open. If the home polar key is open, the conditions of heavy and light are the reverse, that is, the current is heavier when the distant polar key is closed than when it is open. The effect is apparent in the polar relay, and although less noticeable, is very detrimental in the neutral relay by reducing the working margin to the extent of the difference between the light and heavy current. The remedy suggested is to use No. 2-A or similar circuit breakers in place of terminal resistance, and use generators or battery with negligible internal resistance.

CAUSE OF LIGHT AND HEAVY WRITING

A fourth factor detrimental to good quadruplex results and also to duplex working, is the tendency for the polar relay to write heavy when the home polar key is closed and to write light when it is open, caused by the distant office pole-changer armature travel being too great, or its speed of travel too slow. This action is independent of and in addition to the terminal resistance unbalance. If all keys are closed, there is no current in the line. Assume that the distant pole-changer now opens; *i. e.* leaves the negative battery, and is held midway between contacts a definite length of time, that is, on neither positive nor negative battery.

The home battery and the stored energy of the line and equipment will be the only forces acting. The current values that existed the instant previous to opening the key, were comparatively small, there was no current in the line, and the magnetic inertia tends to keep the current flowing as it was, hence no great effect is noted, not enough to throw or start the home polar relay armature. Now, let the distant pole-changer strike the back contact which is positive battery, and the line current will jump up perhaps to 100 milliamperes and promptly throw over the polar relay armature. If the pole-changer is now "opened" again without making contact on either polarity, half the voltage causing the 100-milliampere line current will be cut off, the current will quickly decay, and the home battery will weaken the current in the polar relay and tend to start it in its reversal. If the pole-changer now closes, *i. e.* makes contact on negative battery, the line current will become zero and the polar relay will be reversed by the home battery. In this explanation the point is that when the distant pole-changer leaves the negative or closed pole, the effect is negligible until the positive pole is in action; this tends to lengthen the marking signal at the polar relay, and the movement of the pole-changer from the positive or open pole toward the closed or negative pole, causes quick action in the polar relay, tending to make it close. Thus, the effects are to lengthen marking signals by quick closing and delayed opening.

Assume both the pole-changers to be on the open or positive battery and the line current zero. Now, if the distant pole-changer opens and is held midway between contacts a moment, the spacing signal at the home station will continue. When the pole-changer is placed on closed or negative battery, the line current will jump up to about 100 milliamperes and the home polar relay will be reversed to the marking contact. If the distant pole-changer is now held open again, the 100 milliamperes will be cut off and the home battery also will tend to weaken the current in the home polar relay. When the open or positive pole is again put in action at the distant pole-changer, the force necessary to complete the action of reversing the home polar relay will be slight and the result prompt. In this explanation it is seen that slow or delayed movement of the distant pole-changer from the positive or open pole to the negative, tends to make the marking signal slow to begin, and the delayed action in closing again tends to cut off the marking signal almost as soon as if no delayed action occurred. Thus, by delaying the start and not delaying the end of a marking signal, the signal is made shorter, which is the reverse of the condition with the home polar key closed. The result is heavy signals with the home polar key closed and light signals with the home polar key open. The remedy is close adjustment of the pole-changer, but this will not change the terminal resistance unbalance trouble.

From oscillogram No. 455 of Fig. 32, which is the record of line current as trace No. 1, bridge relay as trace No. 2, and holding relay as trace No. 3, on the 140-mile iron wire simplex, it would appear, at first glance, beyond expectation for the relays of a quadruplex to follow such apparently senseless waves. The experiments so far made encourage the belief that it is not impossible. In the first place, if an artificial line as good as an actual line is obtained, half the problem is solved. The terminal resistance unbalance, pole-changer travel unbalance and unnecessary relay inertia are other factors which are capable of improvement.

INDUCTIVE DISTURBANCE IN TELEPHONES FROM DIFFERENTIAL SETS

It is the experience on the New York Central Lines that differential operation on some classes of circuits causes considerable induction in adjacent circuits, in some cases interfering to a serious extent with the operation of telephone circuits carried on the same pole lines. The increasing number of multiplex printer circuits which are differential-operated increases the disturbances.

Bridging duplexes do not seem to cause appreciable difficulty of this nature, but the speed of operation of the bridging sets may not be as high as with differential working. Certain tests have shown that the differential system is satisfactory from an induction standpoint on paralleling telephone circuits when used on composited phantom wires, that is, on the Morse legs of two pairs making up a phantom of which each pair gives one Morse circuit; also on Morse circuits made up of each of two wires which form a long-distance telephone pair. It is the intention, therefore, to use the differential system on composited wires and the bridging system on simplex and single wires, on the New York Central Lines. However, it is apparent from some oscillograms taken that bridging sets can be speeded up when used on composited circuits by removing the condensers and coils in the Morse legs of the composite sets, but because the efficiency of the differential is higher and the polar relay in it gets more current at lesser operating voltages, it seems preferable to use differential on composited circuits. The lessened voltage results in lessened disturbance in the telephone branch of the circuit.

Oscillograms No. 458 and No. 459 of Fig. 37 show the outgoing and incoming waves on a circuit made up of a 280-mile loop of simplexed telephone lines equipped with Western Electric Company straight step-up selectors, consisting of two so-called "high-resistance" simplexes—one 140-mile No. 8 B. W. G. iron pair, and the other 140-mile No. 9 B. & S. copper pair—connected together without repeaters at the junction point. That is, the circuit was arranged with two duplex sets at Indianapolis, Ind., on two simplexes to Springfield, Ohio, where the simplexes were tied together without repeaters. This permitted simultaneously recording both outgoing and incoming waves at Indianapolis. The sharpness of the differential waves in trace No. 1 of No. 459 is noticeable, compared with the more rounded wave of trace No. 1 of No. 458, which is the bridging duplex. The duplex sets used were standard Western Union instruments, installed according to that company's specifications. The simplex coils were Western Electric Company No. 46-A with No. 34-B non-inductive resistances added between the No. 46-A coil and the line.

A number of records were made to see if a differential set at one end of a line and a bridging set at the other had any effect upon the operation of the circuit, but no detrimental effect could be noted. One point noted was that the received wave is the same shape in both differential and bridging circuits. The sharp peak of the outgoing differential set is absorbed by the line, upon simplex and composites at least, which were the kind of circuits tested. This is illustrated in trace No. 2 of No. 567 of Fig. 35 for bridging set, and No. 568 for differential set, which were taken on a low-resistance phantom composite loop of Fig. 11. These two circuits were 140 miles each, No. 9 A. W. G. copper dispatching and message lines. Points *a* and *b* of Fig. 11 were connected at the Bellefontaine end, making a loop, Indianapolis to Bellefontaine and return. All the composite and telegraph equipment was cut off at Bellefontaine.

The effect of the grounded capacity and half No. 5-AA retard coils in the Morse legs was noted by cutting them out and taking No. 569 bridging and No. 570 differential, other conditions being the same as Nos. 567 and 568. In Nos. 567 and 568 trace No. 1 is the polar relay current, and trace No. 2 is the line current at the receiving station. In Nos. 568 and 570, No. 1 is the artificial line current and No. 2 the line current at the receiving station. Comparison of Nos. 567 and 569, bridging sets, indicates that the half No. 5-AA coils and six-microfarad condensers, as used in No. 567, appreciably round off the waves and slow up the circuit, and that they can be dispensed with and yet obtain fairly smooth waves as in No. 569. Comparison of Nos. 568 and 570, differential sets, indicates the necessity of having these coils, as No. 570 has rather sharp waves. No. 568 indicates that the differential waves are rounded out enough to prevent induction.

An interesting exhibit is shown in No. 463 and No. 464, which are records made on two working multiplex printing telegraph circuits. The No. 463 was taken at Indianapolis on a Chicago-Louisville multiplex wire, and No. 464 was at Indianapolis on an Indianapolis-Cincinnati multiplex wire. It is evident that No. 464 was being operated as a differential set, and it is probable that No. 463 was also, but as the record was made at the middle of the line, the waves are somewhat rounded off. No. 464 illustrates why induction is heard on telephone circuits from these multiplex circuits with their sharp waves.

Fig. 37

Records No. 403 and No. 404 of Fig. 37 show the result of 25-cycle induction from a single-phase trolley line on duplexes, used on a composite leg of a No. 9 A. W. G. copper, low-resistance phantom, Indianapolis to Cincinnati, 110 miles. The trolley line parallels the railroad from Indianapolis, 40 miles toward Cincinnati. The No. 403 is with duplexes with 500-ohm resistance in place of the No. 5-U coils. Trace No. 1 is line current, trace No. 2 is artificial line and trace No. 3 is the polar relay. The No. 404 is the same as No. 403, but has No. 5-U coils, which greatly amplify the induced waves, but the net operating current in the polar relay is about the same in both. The effect of an induced wave, if it should occur at a time of zero current in the polar relay, might cause false signals, with the No. 5-U coil set.

The investigations indicate that the one-microfarad condenser in duplex and quadruplex sets at the vertex of the No. 5-U retard coil, has but slight bearing on the wave shape of the circuit and is chiefly advantageous as a spark eliminator at the pole-changer contacts. Six microfarads were tried without noticeable effect.

It is noted in the bridging quadruplex that the holding condenser current affects a loop consisting of the condenser, the holding relay, line relay and bridge relay. No effect of it can be detected in the line, the artificial line or in the No. 5-U coil.

The "bulge" of the polar relay current is noted in both the duplex and quadruplex. In the quadruplex this is confined to the above mentioned loop consisting of the holding condenser circuit, line relay and bridge relay. In the duplex it is seen to a limited extent in the line and in the No. 5-U coil.

TELEGRAPH TRANSMISSION DISTANCES

On the N. Y. C. Lines three hundred miles are about the maximum a single No. 8 B. W. G. iron wire is used for single Morse in through service or semi-local service. If all way offices are cut in, the average distance is 150 miles. On iron wire block simplexes the distances are about the same as above. While the line wire resistance is halved in a block simplex, the leakage is increased and the simplex coil resistance is added, resulting in the wire being about as good as a single wire of similar material and gage for the same length. There are so few single copper wires in the N. Y. C. Lines in telegraph use, that no experience with them can be related. As indicated in the discussion of single Morse operation on page 339, these iron wires prove unsatisfactory for local way wires with many offices in wet and foggy weather. Iron wire should not be considered for main lines with heavy traffic because of the rapid deterioration from smoke.

Duplexes are used on the average for about one railroad division which is 150 miles, on high-resistance simplexes of No. 8 B. W. G. iron wire. Copper wire simplexes or composites, No. 9 A. W. G., high-resistance type, are good for more than this length but seldom for two divisions. Low-resistance copper simplexes or composites, No. 9 A. W. G., are good for 300 miles. Copper wire, No. 8 B. W. G., is used in simplex composite and phantom composite, low-resistance type, for 500 miles.

Quadruplexes are good for about 300 miles on single No. 9 A. W. G. copper wire; block simplex, No. 8 B. W. G. iron, for 150 miles; high-resistance No. 8 B. W. G. iron simplexes, 100 miles; copper No. 9 A. W. G. simplexes, high-resistance type, to perhaps 150 miles; and on low-resistance type 200 miles. Very little data regarding quadruplexes on composite circuits are available. This combination is seldom used. The above data are for circuits without repeaters.

Comparison of the telegraph transmission qualities of different gages and kinds of wires and types of circuits have been made and are recorded in Fig. 38. No. 616 is the record of a bridging duplex, first with the distant station sending, which is the trace above the base line, and second with the home station sending, which is the trace below the base line. The wire is a No. 9 A. W. G. copper single wire between Indianapolis and Mattoon, Ill., distance 129 miles. In this territory there is very little cable—hardly enough to be considered in such short duplexes. No. 617 is the same duplex on one side of a composited phantom between the same two points and recorded similarly. The circuit is No. 9 A. W. G. copper, low-resistance type simplex on the dispatcher's circuit, which is one side of a phantom. It will be seen that the current is greater on this than on the single copper wire and the wave shape is practically the same, indicating that the circuit is about as fast in dry weather as the single wire.

The duplexes were next moved to the No. 8 B. W. G. iron wire between the same points with the result given in No. 619. No. 618 is the result on a No. 8 B. W. G. iron wire simplex circuit between these points, low-resistance type, and indicates as good a dry-weather circuit as the single iron wire No. 619.

Fig. 18 gave the record of the way Morse wire on this division of the railroad, taken at the time when it was equipped with 120-ohm main line sounders. This wire was later made one side of the station-to-station block telephone circuit and simplexed for the way-station Morse service, at which time it was equipped with 30-ohm main line sounders. The record of its present transmission is No. 622. The Western Union way wire in this territory is No. 8 B. W. G. iron, with 120-ohm main line sounders, and is recorded in No. 621. The block simplex has more current but has 30 offices, whereas the W. U. Co. way wire has but 22 offices.

Fig. 38

TELEPHONE TRANSMISSION DISTANCES

Experience indicates that the railroad service requires ten-mile telephone transmission or better for the dispatching, message and long-distance lines. Dissatisfaction results if the equivalent in miles of standard cable is much greater than this. This shows that the railroad demands better transmission than is considered satisfactory in commercial service. From the standpoint of practical results and satisfaction to the users of the railroad telephone lines the following has been noted:

No. 8 B. W. G. iron for long-distance lines should not exceed 50 miles of line; for way-station message telephone lines using railroad telephones, 75 miles.

No. 9 A. W. G. copper for long-distance lines should not exceed 150 miles; for dispatching and message lines, 225 miles; for phantoms composited, 150 miles.

No. 8 B. W. G. copper for long-distance lines should not exceed 300 miles without repeaters.

The above figures are based upon average conditions such as obtain upon the New York Central Lines, and take into consideration that some of the P. B. X. stations are a considerable distance from the P. B. X. which limits the transmission distance because of the loop losses. Circuits are frequently used of longer distances than the above but at a sacrifice in efficiency and with some annoyance to the users.

The railroad telephones as used on dispatching and message lines produce considerably more volume of transmission than standard P. B. X. station telephones, and therefore have greater transmission distance, which experience indicates is 30 per cent greater than the standard P. B. X. stations for equal volume of received transmission.

The author wishes to express his cordial appreciation of the extensive assistance rendered by Mr. John L. Niesse, Telegraph & Telephone Engineer, C. C. C. & St. L. Ry., in making the oscillograms and for other assistance in preparing data for this paper, and to Professor C. Francis Harding, Head, School of Elec. Eng., Purdue University, for the use of the oscillograph.

DISCUSSION ON "CARRIER CURRENT TELEPHONY AND TELEGRAPHY" (COLPITTS AND BLACKWELL) AND "SOME PHASES OF RAILROAD TELEGRAPH AND TELEPHONE ENGINEERING" (RHOADS), NEW YORK, N. Y., FEBRUARY 17, 1921.

Major General G. O. Squier: The subject matter dealt with in the paper, entitled "Carrier Current Telephony and Telegraphy," is naturally of particular interest to me personally, and I am very much interested, indeed, to know that the development of my invention is receiving attention by a competent engineering organization in this country and is now used in practise by The American Telephone and Telegraph Company. I shall deal briefly with the technical aspects of the subject a little later on. Let me say in the beginning that in this discussion it is my aim to contribute something in a constructive way. I take due note of the fine engineering achievements of The American Telephone and Telegraph Company in the development of my system of multiplex telephony and telegraphy.

To begin with, I cannot agree in the choice of the name adopted by the A. T. & T. Co. "Carrier Current Telephony and Telegraphy" does not convey the basic idea of the principle employed in this system which differentiates it from the older systems of telephony and telegraphy. After all, even in the direct-current system, a carrier current is employed in the sense used in the paper. Certainly to the layman it does not convey a correct idea of the principle of the system. In this system of a-c. telephony and telegraphy, currents of comparatively high frequencies are employed, and it is the difference in frequencies which gives distinct character to the different messages sent simultaneously over the same line, and which enables us to sort them out and separate them at the receiving end. Surely the name ought to be in some way expressive of the underlying principle of the invention. Like every other new art, some confusion exists in regard to the name. It is at present variously designated, "High-Frequency Telephony and Telegraphy," "Guided Wave Telephony," "Wired Radio," and popularly known by its original name "Wire Wireless." Recently we have circularized the radio engineers of the Navy Department, the War Department, and the Bureau of Standards, and it was tentatively agreed that "Wire Radio" would be a proper name for this new art. I have proposed this name in a letter published in the *London Electrician* of December 17, 1920, which has led to considerable discussion in the correspondence columns of that journal. Many different names were suggested, but the one proposed by Dr. Louis Cohen, viz., "Line Radio," seems to me to meet more fully all the requirements. It is brief, euphonic, and at the same time conveys the idea of the transmission of currents of a radio character over a line, and the utilization of equipments, apparatus and engineering methods usually associated with the radio art.

I would suggest that the Institute Committee on Standardization and Nomenclature give some attention to this matter, deciding on a suitable name for this new art, and avoid further confusion which is likely to result from a multiplicity of names. Unless one is acquainted with the art, one would hardly suspect that "Carrier Current Telephony and Telegraphy," and "Wired Wireless" are different names for the same thing.

The historical aspects of the subject given in the paper interest me considerably. I really feel some delicacy in discussing this phase of the paper, Mr. Chairman, because I have been intimately associated with the invention and development of this new art for many years, and naturally should be obliged to refer to my own contributions to the subject, and open myself, perhaps, to the charge of being biased. I shall try, however, in the interest of historical accuracy, and as a matter of record, to present the facts as I know them. I appreciate that one may get into a sort of "polarized state of mind," seeing only one angle of a complex subject, and this is also true in the case of an organization—there may be such a thing as "group polarization." The best I can do is to give you my views on the subject.

In the discussion of the history of the subject, and also in the bibliography given, the authors of this paper take the year 1912 as the date on which active development of this new art of multiplex telephony and telegraphy was started. By indirection, it is implied that my contributions to the art are only of historical interest. It may be that the year 1912 is the time when The American Telephone and Telegraph engineers realized the importance of the use of my invention of high-frequency currents for telephonic and telegraphic transmission over lines, and started investigations along that line in their laboratories, but this should not blind us to the fact that work along that line had been done before, and successful results obtained.

I believe that the first successful experiments in

Multiplex Telephony and Telegraphy were carried out in the Signal Corps laboratories, under my direction, in 1910. We had commenced to make plans for these experiments in the early part of 1909. Our idea was to unite the two arts of "Line Telephony and Telegraphy" and "Radio Telephony and Telegraphy" by the simple expedient of connecting the transmitting and receiving stations by a line. The idea was that such a system would be much more efficient than an ordinary radio system, since the energy transmitted would be guided by a channel connecting the two stations, preventing it from radiating into space in all directions, and at the same time, offer the possibility of multiplexing. We accordingly took immediate steps to secure all the apparatus which might be required for these experiments. As a source of continuous high-frequency oscillations, we obtained a high-frequency alternator from Mr. Alexanderson of the General Electric Company, which had an output of 2 kw. at 100,000 cycles. We were also the first I believe to use the three electrode vacuum tube detector or audion on a physical line. In other words, we tried to obtain and secured the best equipments available at that time for that purpose, and with these means, and with our experience in the radio art, we had no difficulty in obtaining satisfactory results from the very start. It was easy to run a large number of experiments, due to the thorough preparations we had made, and in the course of a few days our experiments had established, beyond the shadow of a doubt that this matter was entirely practicable. These experiments attracted attention, and as the paper says, "excited popular interest in the subject." The reason for that popularity was that the experiments were successful. Those who were interested realized that that was the first time in the history of the art that telephonic transmission by means of electric waves guided by wires had been accomplished, practically, and for a number of months after that we had to keep the exhibit on view for various scientists and engineers who came to Washington to see it, use it, and be convinced. It was further realized that this matter offered the solution to the problem of multiplex telephony and telegraphy. It is true, as pointed out in this paper, that many able engineers had previously given considerable attention to the problem of multiplexing. Among those most prominently active in this field may be mentioned, Gibbony, Stone, Pupin, Hutin, le Blanc, and Ruhmer, but their work did not materialize into a practical solution of the problem.

In a very able paper entitled "The Practical Aspects of the Propagation of High-Frequency Electric Waves Along Wires," published in the *Journal of the Franklin Institute*, October, 1912, Dr. John Stone, who was himself interested in the solution of this problem at a previous time, and who was thoroughly familiar with the history of the art, makes the following statement:

> A new art has been born to us. The infant art of high-frequency multiplex telephony and telegraphy is the latest addition to a brood of young electric arts. It is certainly a most promising youngster, and should, after the manner of its kind, call lustily for its share of attention and sustenance.
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> More than 20 years ago, the advent of this new art was definitely prophesied by the late J. W. Gibbony, the author, in this country, and in France by the well known electrical engineers, Maurice Hutin and Maurice le Blanc. Though there was at that time a vigorous contest for priority which extended over a period of years, it is not with these earlier efforts, prophetic though they were, that we have to deal now. They are buried in the archives of the United States Patent Office. Our interest today is in the vital, practical aspects of the new art, based upon the propagation of high-frequency electric waves along wires, and though 20 years ago there seemed to be much promise of the new art, there were indeed surprisingly few practical aspects to the subject.

Let us consider for a moment what are the essential elements in this system. Briefly, the use of alternating currents or electric waves of relatively high frequencies, means for modulating high-frequency currents at the transmitting end, selective tuning at both ends of the line, separating the messages of different frequencies at the receiving end, and suitable means for rectifying and detecting the signals at the receiving end. These are the basic elements necessary and sufficient for the successful operation of the system, all of which I have made use of in my original experiments as described in my paper published by the War Department as Government Document No. 390 and reprinted in the TRANSACTIONS of the American Institute of Electrical Engineers of 1911, and disclosed in my original United States patents issued to me on January 3, 1911.

It is not my intention to minimize the importance of the contributions to the development of this art by the Bell engineers. I yield my place to no one in my admiration of the engineering skill of this able group of telephone engineers, but, after all, their work as embodied in this paper represents only modifications and improvements, very valuable and important to be sure, but, nevertheless, not basic.

The two elements in the system for which the credit is apparently due to the Bell engineers, and which are emphasized and elaborated on in this paper, are the repeater and the wave filter; and the repeater, of course, is a development of the De Forest audion. To be sure, with the aid of the repeater, greater transmission efficiency is obtained, less power is required, but it is not indispensable. The statement made in the paper that for a circuit 750 miles long, 50 kw. input would be required if no repeaters were used, seems to me to be exaggerated. Calculations made by the Signal Corps engineers would indicate that only a few watts would suffice, and this is further supported by results obtained in experimental tests carried on by the engineering staff of the Signal Corps laboratories, employing considerable range of frequencies and various distances up to about 250 miles. The fact is that we have used this system successfully for telephonic and telegraphic communications over distances up to 200 miles without the aid of repeaters. So, while the repeater is a valuable adjunct in the perfection of the system, it is not indispensable.

Similarly, in the matter of wave filters on which great stress is laid in the paper, the development of this device is certainly a remarkable engineering achievement, and Dr. Campbell deserves great credit for his work in perfecting this device, but in connection with this system it is only an adjunct, a very useful and valuable one, to be sure. With the aid of wave filters, band tuning is obtained, which makes it possible to isolate more effectively each individual message, and thereby utilize more channels within a given range of frequencies. This, of course, is very important, but again it is not basic. For some reason, the American Telephone and Telegraph Company engineers have apparently adopted 30,000 cycles as the upper frequency limit for telephonic transmission—why not extend that limit so that a larger range of frequencies may be employed to operate on, which will offer the opportunity for wider frequency separation between different channels, and thus make the system, if necessary, independent of the use of wave filters. We have already employed in the Signal Corps laboratories frequencies up to 600,000 cycles, and obtained good results over considerable distances. The choice of 30,000 cycles as the upper limit seems to me purely arbitrary, without any engineering justification for it.

The point I desire to emphasize is that while the A. T. & T. engineers have, as usual, accomplished a great deal in the matter of development, improvements, refinements in practical details, etc., the basic principles employed in the system are absolutely the same as described in my paper and disclosed in my patents.

In tracing the history of the art, I notice that the authors of the paper go back to the work of Gray and Bell in 1867. Why not go back to 1837, the date of Morse? After all, he was the first one to transmit intelligence by electrical means over a wire, and the wire is an essential element in my system, as well as in the older system of telephony and telegraphy. In tracing the history of any art, one can always find anticipation in a certain way, records of men of vision and intuition who suggested or hinted at this, that, or the other possibility, and sometimes there is a difference of several generations between the man who first proposed a certain idea, and the man who realized it, practically.

In a lesser degree, this is generally true in almost every art of importance, and certainly the art of multiplex telephony and telegraphy is no exception. Many people have attempted to solve this problem, many schemes were proposed, but apparently there was always lacking some fundamental element or elements in the proposed methods which made it impossible of practical realization. In my invention I have not introduced any new elements in the sense of new devices or new apparatus, but have taken advantage of the development of the radio art, and combined it with the older wire telephone art, and thus realized, I believe, for the first time, the successful operation of multiplex telephony. In my original paper above referred to, I have made the following statement:

> It should be noted that throughout these experiments not a single piece of new apparatus was designed or constructed, but the conventional apparatus as now employed in wireless telegraph engineering was adopted as a whole, although, as stated above, this apparatus could be very materially improved in the line of compactness of design for this range of frequencies.

I believe, therefore, that I am justified in my assertion that my original disclosure showed for the first time a combination in which were introduced all the elements essential for the successful operation of the system, and in addition, actual tests were carried out at that time in the Signal Corps laboratories which fully demonstrated the practical operation of the system.

I may call attention here to another advantage in connection with this system which is of considerable importance, and that is the elimination of inductive interferences from nearby power transmission lines, which has been the source of a great deal of annoyance and litigation in connection with the older system of telephony. And not only that, but it is possible to utilize the same line simultaneously for power transmission and telephonic communication. In fact, extensive tests of this phase of the subject have been conducted in Japan and Germany, and it was found to be entirely feasible. At the present time, regular telephonic communication is being carried on from Golpa to Rummerlsburg, a distance of 84 miles over a 110,000-volt power line circuit.

The fact that frequencies of several hundred thousand cycles per second are now successfully superimposed upon high-tension power lines immediately suggests the advisability of adding to your Committee on Telephony and Telegraphy of this Institute some engineers representing the power transmission field to consider the problems common to these two branches of engineering which were heretofore considered separate and distinct.

Tesla suggested many years ago the possibility of transmission of power by radio means and recently this subject has also been treated prophetically by Dr. Emil Mayer of the faculty of the University of Strasbourg, in which he suggested a modification of the Tesla method by guiding the high-frequency currents to their destination by transmission lines, essentially in the manner which I have adopted for telephonic and telegraphic transmission. I have always regarded the principles embodied in my system of line radio as offering great possibilities in connection with long distance power transmission.

In the original experiments in 1910 a number of circuits were successfully employed which so far as known have never been used as yet in practise. They are fully described in official laboratory note books which are on file in the archives of the Signal Corps.

I am constrained to address a word of encouragement to the young engineers present. I surmise that the general impression you will carry away from this meeting after reading the Colpitts and Blackwell paper, will likely be one of bewilderment at the complexity of the subject and how much has already been accomplished in this new field. But do not despair. I call to your attention that this whole paper from beginning to end is concerned only with the very small range of frequencies from zero to 30,000 cycles, whereas we are using in the Signal Corps every day efficient apparatus in the radio art involving frequencies as high as 4,000,000 per second, and in line radio frequencies up to 600,000 cycles per second.

You will see, therefore, that the whole subject of this splendid paper is restricted and covers only 0.7 of 1 per cent of the practical radio spectrum which is now in daily use, leaving 99.3 per cent still untouched for your consideration.

In other words, do not imagine that because this paper is limited to 30,000 as a maximum, that the rest of the range of frequencies is not equally important for future development. In fact, you will notice that the paper nowhere says that it is not; nor indeed do the Bell engineers take such a position, but I feel justified in calling your attention to it here.

The fact is that electric waves guided by conductors are destined in the near future to find a tremendous application, and will play an important part in the future in the development of various branches of engineering, entirely independent of telephony and telegraphy. Naturally the lower frequencies are better adapted for long distances, reserving the higher frequencies for shorter distances, precisely in the same manner as in radio communication today. The time will surely come when the allocation of frequencies or wave lengths throughout the entire spectrum for wire systems will have the same importance that it now has in space telephony and telegraphy throughout the world.

Arthur E. Kennelly: It is shown in the paper that it becomes feasible upon one pair of wires working up to 30,000 cycles per second, to employ 24 different channels, of which only a few are telephonic and the rest are telegraphic. That is, nearly one channel to every thousand cycles per second. The sketch shows that is only 7/10th of one per cent of the total range, so we are left to imagine what the full 100 per cent may be capable of doing in their respective fields, and it is very interesting to observe that this paper suggests the discarding of duplex for all multiple work in the sense we have ordinarily understood it. Heretofore, every multiple circuit, every circuit on which we endeavor to secure the greatest number of messages, has been duplexed as a matter of course, and may even be quadruplexed, but now it is suggested that it may be advisable to drop the duplex plan by reason of an embarrassment of riches. It is interesting to see, nevertheless, that the duplex principle is still employed, being embodied in the plan of simultaneous receiving and sending over the wire. That is, the duplex principle is availed of for ordinary single service, and is then discarded for the continuous transmission of messages in opposite directions simultaneously.

It is also very interesting to see how much wider the channels in the ether are for the telephone than for the telegraph. It is probably well worth while, but whereas a relatively very wide swath is necessary for the telephone, the telegraph channel takes only a little space. The telephone comes high, but we must have it.

Another very interesting feature is the delicacy of the balances suggested all the way through, as, for example, in Fig. 35 where you see the delicate balances as carefully represented and highly developed, although the duplex, as such, is not involved. It is very interesting to notice how a line becomes not merely a carrier in the sense that General Squier says is so overburdened—the carrier is a very overburdened word just now—but also becomes a transformer. In Fig. 28 you see that the curve of attenuation length versus frequency develops a hump due to transformer action. The line was acting as the primary of a transformer working into other lines as secondary circuits, whereas a line properly installed should have no transformer included. It should confine its attention entirely to its own circuit, and not try to develop current in neighboring lines.

It is evident that one pair of wires in the future may serve for a dozen pairs at the present, with ordinary simplex telegraph communication, but it is also evident that the type of wire chief who will be necessary, in order to maintain such a multiple system as is suggested in Fig. 25, will be a different wire chief from the one that would ordinarily be necessary at present, in order to operate simple simplex circuits.

Moreover, the paper suggests that, in time, the telegraph will be driven off the earth. The telephone long ago gave up the unequal task of keeping on the earth, and was obliged to double its wires and use a return conductor. The telegraph has held on, and no doubt in sparsely settled districts, it is likely to cling with its roots to the ground for a long time; but in more densely populated districts, where wires become nuisances, and where any such system as the paper suggests is put into effect, it will probably become necessary to get off the earth, and to operate wires in carefully balanced and transposed return-conductor pairs. Thus, the duplex, you see, foreshadows its end, and the ground-return circuit also foreshadows its end, in the possibilities that a more complete development of electrical engineering offers in the future.

Donald Mc Nicol: On page 216 of the paper by Messrs. Colpitts and Blackwell, it is stated that the thermionic tube was originally invented by Mr. Edison. I thought that written history had been corrected to show that Prof. Buff of Giessen University in 1852 or

1853 made the first recorded discoveries along this line. Also in the historical review I see no mention made of the Raymond Barker multitone system of 1907 utilizing the Cardew vibrator method and tape recorder reception. It seems to me that these should have had mention in the historical part of the paper.

E. C. Keenan: The New York Central Telegraph and telephone communication system, described by Mr. Rhoads in his paper was developed to keep pace with the demands of the railroad in properly handling its business. We endeavor to keep the communication facilities up to and a little in advance of the general traffic. Our long distance and telephone dispatching circuits, we believe, employ the best up-to-date equipment and arrangements. The success that we have achieved in this work was due, in a great measure, to the assistance we obtained from electrical engineers.

H. W. Drake: Mr. Rhoads states on page 339: "Both theory and practise indicate that 30 to 35-ohm relays or main line sounders are more desirable than 100 to 150-ohm ones, for iron wire way-station telegraph circuits, whether single wire or simplex." I am afraid that some of us would fail to agree with Mr. Rhoads in that statement. The question as to where to draw the line between low resistance and high resistance instruments on such circuits is one that telegraph engineers have struggled with for many years, and I feel sure that a further consideration of the matter will convince almost anyone that there are many way circuits having a small enough number of stations to fully justify the use of the 100 to 150-ohm instruments which have been standard for so long. One of the advantages of the high resistance instruments is the fact that a smaller operating current may be used. In many cases the way-station circuits are of such length that to provide the potentials necessary for higher operating currents, at terminals which are sometimes far from commercial power sources, is an expensive and difficult problem.

Mr. Rhoads' remarks in regard to the functions of the 5-U retardation coil, so commonly used in duplex and to a lesser extent in quadruplex circuits, are very interesting; but there again I think there will be some question as to whether the statement that the 5-U retardation coil functions primarily as an autotransformer, will receive full acceptance. Of course, that question, like a great many others, may simmer itself down into one of definitions. I suppose any retardation coil must function, to some extent, as an auto-transformer, but regarding the term "function *primarily* as an autotransformer" I am doubtful.

The plan of the self-balancing duplex mentioned is an ingenious one, that may find application where the attendants during certain hours of the day or perhaps on Sundays, are of such a character that real balancing by means of an artificial line is out of the question. That condition, I am quite sure, will be met with more frequently in very small railroad stations than in the ordinary commercial repeater offices, and I think, on the whole, the trend of the paper indicates that the growth in the activities of the railroad telegraph and telephone departments will gradually wipe out a condition of that kind. It does seem, as Mr. Rhoads says, an extravagance in the use of wire to take two wires in order to obtain a duplex, but there are occasionally peculiar conditions where that may be practicable.

There is one thing in which I think probably most engineers will agree with me, and that is, that one of the outstanding features of both the papers presented this afternoon is the testimony they bear to the achievements of the modern engineering research and development organizations. The practical application to the A. T. & T. lines of the composite and simplex methods of simultaneous telegraphy and telephony, mentioned in Mr. Rhoads' paper, was one of the remarkable accomplishments of the engineers who, 25 or 30 years ago, formed the nucleus of the present engineering and research organization of the Bell system. The methods used in the development of the earlier schemes for multiple use of wires, were undoubtedly similar to, although on a smaller scale than, those of the past few years, which have resulted in the carrier current system described by Messrs. Colpitts and Blackwell. In a smaller way, the telegraph and railroad companies, as amply illustrated by Mr. Rhoads' paper, are following these same methods, and I assume the same is true of other lines of communication activity outside of the railroads.

John L. Niesse: Mr. Rhoads' paper gives a statement of the size of the New York Central Lines' telegraph and telephone plant. It might be interesting to add that the telephone bill of the New York Central Lines for rented service and operation thereof, is probably one of the largest of any single individual consumer in the country, being nearly a million dollars.

The small metal box type of construction for way-station installations described and illustrated in Fig. 3B is now being used exclusively on the Big Four

Railway for its way station service. We have been experimenting with this type of construction and have reduced it to a unit basis, so that the equipment is wired complete in the shops by men who soon become expert in the work, and is arranged in such a manner that it can be shipped out and connected up in the field at minimum expense for installation.

In regard to the traffic studies and the method of numbering messages, the practise of taking one number for each three lines or less, and one number for each additional three lines has been modified in the last fortnight, and the New York Central Lines have now adopted the method suggested by Mr. Rhoads in connection with Table II, that is, the taking of one number for each message, one number for each additional address, and in case of long reports, of which there are quite a number on the railroads, one number for each station concerned in the report. This simplifies the method of counting, eliminates the practise of "padding" which we found had been indulged in, and also, I feel, gives a much more accurate check.

There are some additional advantages of the low resistance type of simplex not mentioned by Mr. Rhoads. By eliminating the connection of the ringing machine from the line, the possibility of crossing up the telegraph circuits through the ringing machine in case of simultaneous ringing, is prevented; the machines may be consolidated into one, and individual motor generators eliminated entirely,—the ringing current being taken directly from the power supply, if it is of the proper voltage and in the proper direction.

The low resistance type of simplex also greatly lessens the noise on the phantoms. We have quite a few phantoms, and the cross fire from the Morse has been lessened by this type, due chiefly to the decreased voltage it is possible to use on the Morse.

I think it may be of interest to mention a case of trouble that we recently experienced at Bellefontaine, Ohio. This place is the terminal of two phantoms, one from Cleveland and the other from Indianapolis. There are four Morse circuits operated on the composite principle, two from each direction. One of the Morse circuits, from each direction, is connected through as an intermediate composite at Bellefontaine, the other two are operated as terminal sets. Shortly after the service was put into effect, we noticed there was considerable noise on the phantoms, both east and west, and on investigation we found it was due to the 2 mf. condensers to ground we used on the Morse leg of the composite circuit at the intermediate station. By increasing the capacity to 7 mf. practically all of the noise was eliminated.

Another advantage of the low resistance type simplex method of operation is that it gives an emergency source of battery where the 220-volt three-wire d-c. grounded circuit is in use, as 110 volts is ample to operate any Morse circuit of the low resistance type, and the two sides of the 220-volt circuit will give the necessary polarity for working the duplex.

Mention is made of the oxy-acetylene welding. The circuit referred to on the Big Four was welded by means of the oxy-hydrogen blow torch. The oxy-acetylene is a much hotter flame, and I think the oxy-hydrogen is the preferable type of torch, because the possibility of burning the wires is not as great as with the oxy-acetylene.

The circuit was an old No. 8 B. W. G. iron telephone circuit, 140 miles long, having approximately 3900 joints. They were welded and after the welding the increase in transmission more than came up to our expectations. I should assume it was a 50 per cent improvement. Before welding the service was unsatisfactory from the P. B. X. telephones, but afterwards satisfactory service was obtained.

The fact that the 5-U retardation coil is a transformer is rather interesting. As far as I know, it has never been described before. It seems strange that the old view should have persisted so long unchallenged, and no one should have arrived at the correct solution. From a study of the oscillogram there seems to be no doubt it does function primarily as an auto-transformer.

R. D. Duncan, Jr. (by letter): The problem as presented to the Signal Corps engineers was not that of developing elaborate plant equipment or of establishing communication over very long lengths of line, but rather of studying and investigating the possibilities of adapting and converting certain of the strictly radio equipments to wire radio or carrier operation. In addition, it was necessary that foundational information be secured on the high-frequency properties of the telephone lines which could serve as a basis for the design and development of new equipment if such should be required. Furthermore, for military purposes, the wire radio equipment, in general, must operate on telephone lines which may not be tampered with, in fact, operate secretly in some instances, and hence the lines must necessarily be accepted in the condition in which they are found and in which they normally operate, viz., with intermediate connected apparatus, lengths of cable, normal transposition, etc.

From the standpoint of unification of types of apparatus (radio apparatus demanding small antenna capacities with consequent use of short wave lengths or high frequencies), training of personnel and for other reasons, what has been termed by the authors, the "carrier" frequency range, was restricted to the higher end of the radio spectrum.

The results which have been obtained at the high or radio frequencies have been entirely satisfactory and when considered in the proper light are not at all inconsistent with what is predicted by theoretical or experimental evidence. In this respect it is agreed with the authors that there is apparently no logical basis for the belief that a pair of telephone lines or one line with ground return should, at high frequencies, behave in a manner different from that predicted by low-frequency theory, provided that proper account is taken of all of the phenomena involved.

Accepting as correct, the standard *wire* transmission theory when extended to high frequencies, it is quite easy to show that results as predicted by theory are entirely in accord with those experimentally obtained. By further consideration of standard *radio* transmission theory, a logical basis of comparison, the two methods of communication are easily arrived at, from which their respective merits may be judged.

The transmission of speech over a pair of No. 9 A. W. G. copper wires, spaced 15 in., 100 miles in length, employing a frequency of 500,000 cycles per second wave length 600 meters), is considered for purpose of illustration. The constants, at the frequency in question, per loop mile of this circuit are very closely as follows:

Inductance—3.61×10^{-3} henrys; Capacity—0.802×10^{-8} farads; Resistance—74 ohms (including radiation); Leakage and Conductance—100×10^{-6} mhs.

The values of inductance and resistance given were computed, taking the "skin effect" into account. The leakage conductance at 500,000 cycles per second was assumed to be 2000 times that occurring at direct current, for which latter figure that given by the authors was assumed, viz., 0.05×10^{-6} mhos per loop mile. The factor 2000, it is believed, sufficiently allows for the increase in leakage over that occurring at direct current. The attenuation constant may be computed from the expression.

$$\alpha = \frac{R}{Z}\sqrt{\frac{C}{Z}} + \frac{G}{Z}\sqrt{\frac{L}{C}}$$

Substitution of the numerical values given for *R, L, C* and G, gives for the attenuation constant a value of 0.0886 per mile. The attenuation for a circuit 100 miles in length is therefore equal to $\epsilon^{-\alpha l} = \epsilon^{-8.86} = 0.000140$ (approximately). Elsewhere[1] it has been shown that the effective input impedance and resistance of such a pair of lines, at the frequency in question, is equal approximately to 350 ohms and 72 ohms respectively. Assuming a value of transmitting current equal to 0.10 amperes, the voltage impressed at the line terminals and the power input are respectively 35 volts and 0.72 watts. The voltage effective at the receiving terminus, 100 miles distance, neglecting the attenuating effect of the load is therefore, 0.0049 volts ($35 \times \epsilon^{-8.86}$). This voltage acting upon a tuned receiving circuit of 50 ohms resistance develops a power therein of $\frac{(0.0049)^2}{50}$ or 480×10^{-9} watts. From experiment[2] it has been determined by Dr. L. W. Austin that an average antenna power of 2×10^{-15} watts is required for the production of a signal of unit audibility with the three electrode vacuum tube detector, self heterodyning and without amplification; it was further determined that the sensitiveness of this type of detector in the self heterodyne and in the pure rectifying conditions is approximately in the ratio of from 600 to 1000 to unity. On the basis of the latter figure, it may be easily shown that the antenna power necessary for the production of a signal of unit audibility, when not heterodyning and without radio or audio frequency amplification, is very closely 4.5×10^{-9} watts. Comparison of this figure with that of 480×10^{-9} watts as computed for the case of wire radio communication shows that the power available for signal production is 100 times that required. This conclusion was corroborated by experiment; over a 100 mile length of line, with the transmitting conditions and current as stated, a very good quantity and quality of telephonic communication was obtained with a main frequency of 500,000 cycles per second, without the use of amplification.

Wire radio or carrier current communication may be compared with radio communication on the common basis of attenuation. In both methods of energy transmission the transmitted current or electromagnetic field is attenuated as it proceeds from the transmitting source. In the *wire* system, the attenuation may be computed from the well know expression;

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[1] *Journal* Franklin Institute, V. 191 p. 23, Jan. 1921.

[2] *Proc.* I. R. E. Vol. 5, p. 239, August, 1917.

in the *radio* system the attenuation may also be computed, probably not with the same accuracy however, from the semi-empirical Austin-Cohen expression.

Aside from consideration of fitting new to old and existing equipment, values of attenuation so determined serve as a basis for a study and comparison of the relative advantages of the two systems. Under some conditions the wire attenuation may be less than the radio attenuation and under others the reverse will be true. The two basic expressions are as follows:

For the wire system: $\frac{I_R}{I_T} = \epsilon^{-\alpha l}$

For the radio system:[3]

$$\frac{I_R}{I_T} = \frac{0.234\, h_T\, h_R}{R \,.\, \lambda \,.\, l}$$

where in the subscripts R and T stand respectively for *receiving* and *transmitting.* α, the attenuation per mile of the conductor system, l, the distance in miles, h_T and h_R the effective heights of the transmitting and receiving radio antennas in meters, R, the resistance of the receiving antenna system and λ the wave length in meters. In the second expression the absorption factor has been omitted since for short distances it is very nearly equal to unity.

In Signal Corps equipment, because of demands of portability, antennas of relatively small heights are employed. It is here assumed that $h_T = h_R = 6.10$ meters; $R = 75$ ohms; $\lambda = 600$ meters and $l = 100$ miles. The radio attenuation I_R'/I_T' therefore equals 0.000001932, or in comparison to the wire attenuation of 0.000140, as previously determined, for the same average transmitting current, the wire radio received current will be 70 times the radio received current.

The reverse may also be true. During the latter part of 1920 the Signal Corps conducted a series of wire radio experiments on a submarine telephone cable connecting Cape Henry and Smith Island, Virginia, at the entrance of the Chesapeake Bay. The frequencies employed ranged from 40,000 cycles per second upwards. From semi-empirical information which was available it was estimated that at a frequency of 500,000 cycles per second the attenuation constant per kilometer was 2, an enormously high figure. The length of this cable was 78,000 feet or 23.8 kilometers. The attenuation for this cable length is therefore $\epsilon^{-47.6}$ or approximately 0.2×10^{-20}. Needless to say, telephone signals were not received over the cable at this

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[3] Dellinger, Trans. A. I. E. E., 1919, p. 1347.

frequency. For this same distance the radio attenuation, with the same antenna heights as previously given, would be 13180×10^{-10} or approximately $\frac{1}{60{,}000 \times 10^{10}}$ times as great. It is easily shown that the amount of power received via radio over this distance is sufficient to produce a readible signal.

By further use of this information on the attenuation values, with increasing frequency it was possible to predict, with fair accuracy, the frequency at which signals would be lost, or for a given frequency the number of stages of audio frequency amplification required for the production of a readible signal.

These various facts bearing upon the power received at high frequencies and upon a comparative basis of wire radio and radio systems have been emphasized as it is believed that they have not been sufficiently recognized and considered previously. At least the records of the art so indicate this.

Louis Cohen (by letter): It would add greatly to the value of the paper if it could be supplemented by more detailed data and calculations of the many problems, connected with the transmission of high-frequency currents over wires, which have been touched upon in this paper. It is stated, for instance, that without the use of relays it would require 50 kw. to communicate over a distance of 750 miles. I am sure engineers would be interested to know how this value of the power required has been arrived at. A computation that I have made would indicate that not even a fraction of 1 per cent of that power is necessary.

By the ordinary transmission formulas, we have

$$V = \frac{E\left\{\epsilon^{q(l-x)} + \gamma\,\epsilon^{-q(l-x)}\right\}}{\epsilon^{ql} + \gamma\,\epsilon^{ql}},$$

$$I = \frac{\frac{E}{Z}\left\{\epsilon^{q(l-x)} - \gamma\,\epsilon^{-q(l-x)}\right\}}{\epsilon^{ql} + \gamma\,\epsilon^{ql}},$$

where E is the impressed electromotive force at the transmitting end,

$$\gamma = \frac{Z_0 - Z}{Z_0 + Z},$$

Z_0 is the receiving impedance, Z is the surge impedance or line characteristic, and q is the line propagation constant.

For the transmitting end

$$V_t = \frac{\frac{E}{Z}\left(\epsilon^{ql} - \gamma\,\epsilon^{-ql}\right)}{\epsilon^{ql} + \gamma\,\epsilon^{-ql}}\,.$$

For the receiving end

$$V_r = \frac{E\,(1+\gamma)}{\epsilon^{ql} + \gamma\,\epsilon^{-ql}}\,,$$

$$I_r = \frac{E\,(1-\gamma)}{Z\,(\epsilon^{ql} + \gamma\,\epsilon^{-q})}\,.$$

Taking the values of the constants for a No. 8 B. W. G. open-wire circuit as given in the paper; attenuation constant per mile $\alpha = 0.014$, $Z = 600$ ohms, for a line 750 miles long $\alpha\,l = 10.5$ and ϵ^{ql} is therefore very small in comparison with ϵ^{ql}, we have therefore approximately

$$V_t = E$$

$$I_t = E/Z$$

$$V_r = E\,(1+\gamma)\,\epsilon^{ql}$$

$$I_r = \frac{E}{Z}\,(1-\gamma)\,\epsilon^{ql}$$

Since Z the line impedance is practically a pure resistance, V_t and I_t are in phase and the power input at the transmitting end is

$$P_t = V_t I_t = E^2/Z.$$

The power delivered at the receiving end is

$$P_r = I_r^2\,Z_0,$$

$$= \frac{E^2}{Z^2}\,Z_0\,(1-\gamma)^2\,\epsilon^{-2ql},$$

$$= \frac{4\,E^2\,Z_0^2}{Z\,(Z_0+Z)^2}\,\epsilon^{-2ql},$$

and

$$\frac{P_t}{P_r} = \frac{(Z_0+Z)^2}{4\,Z_0^2}\,\epsilon^{2ql}\,.$$

Assume that the receiving apparatus is tuned to the carrier frequency and acts therefore as a resistance for which a value of 50 ohms is assumed, the values of the constants in the above equation are as follows:

$$\frac{(Z_0+Z)^2}{4\,Z_0^2} = 42.2, \quad \epsilon^{2ql} = \epsilon^{21} = 13.2 \times 10^8,$$

and

$$\frac{P_t}{P_r} = 13.2 \times 42.2 \times 10^8 = 5.6 \times 10^{10}.$$

For an input power of 1 watt the received energy would be about 2×10^{-10} watts. Now it is known that the power required to produce a signal of unit audibility with a three electrode vacuum tube detector without heterodyning and without any amplification is about 5×10^{-9} watts, with suitable amplification a great deal less power is required. It would follow, therefore, that a few watts input should be more than ample to signal over a line 750 miles long.

It is true that in the above calculations a uniform open wire circuit is assumed and no account is taken of the larger losses that occur in the short cable sections that must unavoidably be used in a circuit of this kind. Nevertheless the difference in power required between 50 kw. as given by the authors and only a few watts as indicated by calculations is so marked that some additional information in regard to the data and method used by the authors would be of the greatest interest and appreciated by engineers engaged in the investigation of similar problems.

Wm. Maver, Jr. (submitted after adjournment): I must take the opportunity to express high appreciation of Mr. Rhoads' valuable paper, which I am sure will be of much utility, especially to telephone and telegraph engineers.

The paper touches on so many features that one must perforce limit himself to those which most interest him, which, in my case, are certain of the sections relating to telegraphy. Mr. Rhoads states that he has found the studies and analyses described in his paper very absorbing. From my own experience, I can duplicate his remarks, since over thirty years ago I devoted much time to an analysis of the various changes occurring in the operation of the duplex and quadruplex systems, many of the results of which I have recorded in my writings. Mr. Rhoads apparently preferred the oscillograph in his investigations, and of which he has made excellent use. I had to be content with the aid of diagrams, which, however, I certainly found very useful. It may, in this relation, be of interest to state that after devoting several months to these analyses, I found I was able to call up in my mind and to analyze the action taking place in the circuits under almost any given condition, even without graphics, somewhat analogously, as I have heard that some train despatchers can see in their mind's eye every train in their division and its place on the main tracks and on sidings.

In my comments on Mr. Rhoads paper, if I should in one or two instances appear to express different views from those of the paper, it will be solely in the interest of what appears to me the further promotion of fuller knowledge of the telegraphic art, which the author laudably mentions as one of the objects of his paper. Mr. Rhoads further mentions in his opening remarks that a difficulty confronting the engineer in the investigation of a problem is to learn the state of the art in relation to the particular problem in hand, and that the information presented by him is intended to ameliorate that difficulty. To the same end I shall endeavor here and there to supplement Mr. Rhoads' information on certain points.

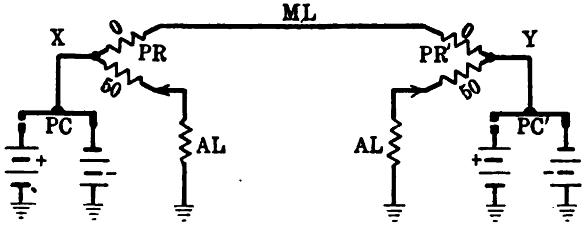


Fig. 1

Mr. Rhoads states that one of the factors detrimental to good quadruplex results and also to polar duplex working is the tendency for the polar relay to write heavy when the home polar key is closed and light when it is open, caused by the distant pole changer armature travel being too great, or its speed of travel too slow. Mr. Rhoads gives an analysis of the conditions that in his view cause the said defect. In my varied and extensive practical experience with duplex and quadruplex telegraphy I have never observed the light and heavy writing to which Mr. Rhoads refers.

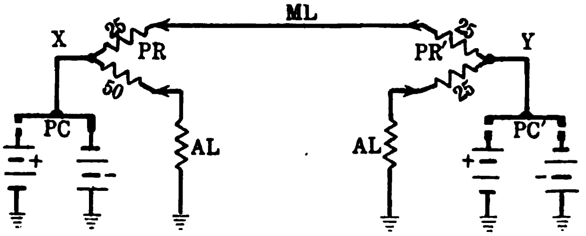


Fig. 2

I am quite sure that it did not exist prior to 1890 in commercial telegraphy. I do not, however, gainsay Mr. Rhoads' statement, because there must be reason therefore. In his analysis, Mr. Rhoads assumes, among other conditions, that during the time the distant pole changer is between contacts the amounts of current on the main line is negligible, and draws therefrom certain conclusions. A different analysis of the same subject may show that this is not necessarily so. Thus, assume the case of a differential polar duplex without other line apparatus than is outlined in Figs. 1, 2, 3; let *X Y* represent the home and distant station; *M L* and *A L* the main line and artificial line, respectively; *P R*, *P R'*, the home and distant polar relay, and *P C*, *P C'*, the home and distant pole changers. In Fig. 1, assume both pole changers to be closed, putting negative batteries to line at both stations. Assuming a well insulated line, there will then be no current on the line. But a current of, say, 50 milliamperes, to conform to Mr. Rhoads figures, from the home and distant batteries magnetizes the respective polar relays at each station by current through the artificial line coils. Of course, we are dealing ultimately with the magnetizing effects on the cores of the relays. Assume that in Fig. 2 the pole changer at *Y* now opens, disconnecting the negative battery, and is in transit between contacts a definite length of time. During this time, according to Mr. Rhoads, the home battery and the stored energy of the line will be the only forces acting and that they are slight or negligible. It is however, to be noted in Fig. 2 that when the distant pole changer is between contacts the negative current from battery at *X* under the conditions now assumed, finds a momentary circuit to ground at *Y* through the polar relay coils and the artificial line. As this doubles the resistance of the main line from *X*, the current will be 25 milliamperes

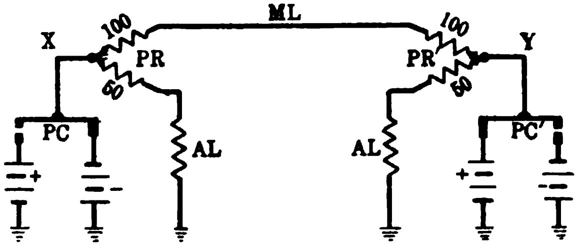


FIG. 3

on the main line at this instant. This reduces the pre-existing magnetic effect in the home polar relay *P R* by one-half, while the magnetic effect in the distant polar relay *P R′* remains as before, inasmuch as the 25 milliamperes in each of its coils are magnetizing its core to the same polarity. Without the 25 milliamperes on the line at this instant the main line would still be at practically zero current. The next instant the distant pole changer makes contact with the positive pole, and the current on the line jumps from 25 milliamperes to 100 milliamperes in positive direction from *Y* (see Fig. 3). This is, however, not so important as it may seem, because the actual reversal at *Y* found a coinciding current of 25 milliamperes in the line which had reduced the magnetizing current in the home polar relay from 50 milliamperes, to 25 milliamperes this presumably speeding up the reversal in that instrument. On the other hand, when the distant pole changer is again opened and is between its contacts the conditions shown in Fig. 2 are reproduced, the previously existing 100 milliamperes on the main line are reduced to 25 milliamperes and not to zero, this retarding the reversal of the home polar relay which reversal is completed when the distant pole changer makes contact with its negative pole, reducing the main line current to zero.

Further investigation of the conditions on the circuit, with the home key open and closed, by means of diagrams akin to Figs. 1, 2, 3, and assuming as before appreciable current on the main line at the no contact moment of distant polar key, will, it is believed, show that in each case the retarded actions mentioned by Mr. Rhoads in the home polar relay will be speeded up, while the accelerated actions will be retarded.

Without saying that the said accelerating and retarding actions, here assumed to be due to an appreciable current on the main line at the no contact moment, may account for the uniform polar relay signals in duplex and quadruplex operation of former years, it is suggested in explanation of the light and heavy writing in the polar relay to which Mr. Rhoads refers and in which it is assumed that the No. 5 U coil is used, that when the distant pole changer is between contacts, that coil, by introducing at that instant its 1000 ohms inductive resistance, together with the 1200 ohms inductive resistance of the polar relay, may act as a choke coil, preventing or diminishing the actions described in connection with the figures just shown, and in which, as stated, the absence of No. 5 U coils is assumed. Granting the existence of current on main line at the moment when the distant pole changer is between contacts, at which time it is assumed that current from the home stations flows through the coils of the distant relays in series, it seems evident that this current, in the absence of the No. 5 U coil, will perform in the quadruplex an important function in steadying the distant polar relay and in keeping the armature of the distant neutral relay forward against the pull of its retractile spring, at the no-contact instant in the distant pole changer, when the home transmitter is closed. It may be added that if the quadruplex transmitter is open at *Y* it will provide for the home battery at *X* a still shorter path to ground at *Y* through the "leak" of the field Key system, than is provided by the distant pole changer at the moment of no contact and perhaps with an improved result. (In this relation it may be pointed out that the Haskins duplex, U. S. patent 154479-1874 utilized practically the principle shown in Fig. 2 in its operation, it having no battery at back contact of key, but using differentially wound relays and artificial line.)

In discussing at length the No. 5 U retardation coil in the bridge duplex and quadruplex, Mr. Rhoads refers to a traditional explanation of the operation of this circuit arrangement to the effect that because of the high impedance of that coil almost all the incoming current rushes into the bridge polar relay. The author does not think the explanation goes far enough and he then gives an interesting explanation by oscillograms and diagrams of the action at the home station of a certain iron wire quadruplex circuit, 140 miles in length, in which a No. 5 U coil is used. In my own work I have found that a diagram such as shown on page 205, "American Telegraphy," gives quite a clear insight into the operation of the duplex and quadruplex at any given instant, and if, in the said diagram, the Smith condenser is displaced by the bridge polar relay, also affords a ready means of ascertaining the voltage at, and the direction of current to and through the coils of the bridge polar relay, due to home and distant reversal.

It may not be amiss to note here that the selection of a single more or less favorable condition in the operation of the quadruplex, as in the cases discussed, only represents a minute fraction of the multifarious conditions that exist with the quadruplex in full operation and employing its 16 key combinations, to say nothing of the main and artificial line static currents. Imagine, for instance, what the various co-ordinations taking place in the circuits and apparatus must be while the distant and home pole changer and transmitters are being opened and closed and while the main line static and artificial line condenser are functioning. That the multifarious operations are carried out without a hitch in successful quadruplex telegraphy has always seemed marvelous to me. Nearly forty years ago it was written in a book, "The Quadruplex," "There are many such combinations continually occurring on the quadruplex which at first sight will seem to be enough to entirely prevent the working of the system, but, an analysis of each combination will prove, what is known to be the case, that they do not so prevent." I do not wonder, therefore, that Mr. Rhoads' remarks in his paper read at Cleveland in reference to oscillogram, No. 455 of Fig. 32, that it would be beyond expectation at first glance for the relays of a quadruplex to follow such apparently senseless waves. The experiments so far made, he adds, encourage the belief that it is not impossible, presumably referring to the burden imposed on the quadruplex by the No. 5 U coil, etc. Otherwise, and if the causes that impair the operation of the present day quadruplex are not removable, possibly owing to the great demands for wire facilities, the fault need not be paid to the quadruplex system, *per se*, for in the nature of things it has limitations. Yet in these days of carrier current telegraphy and telephony, it may be unwise to arrive at hasty conclusions as to those limitations.

On page 360 of his paper Mr. Rhoads states that from the evidence gathered in his investigations it is not apparent that the current in the polar relay changes at any greater rate in the set with the No. 5 U coil than in the one with the 500-ohm non-inductive resistance. On page 373 of his paper, also, he gives the results of his experiments as shown by oscillograms, of placing separate retardation coils in a quadruplex circuit, namely, that this had a marked detrimental effect on the operation of the quadruplex. It may be of interest to note that in both instances the oscillograms appear to bear out the present writer's experience and analyses as described in *American Telegraphy,* page 563 b.

The author refers to the fluctuations in the line current due to the insertion and removal of resistance in the distant main battery of the quadruplex. Personally, I have always tried in writing on this subject, namely, the highly admirable Field Key system, to differentiate between the ordinary removal of resistance from a circuit and the variation of resistance in that Key system which produces a difference of potential at a desired point in the quadruplex circuit; the difference, I think, being important. Mr. Rhoads does well to emphasize, as he does, the importance, of keeping the protective resistance always at 600 ohms in the Field Key system.

Mr. Rhoads shows a neat device in which the usual Western Union Telegraph Company's holding relay is displaced by a separate neutral relay in the bridge wire of the quadruplex, the armature of which, when operated by currents from a bridged condenser is designed to open the repeating sounder circuit at the moment of no magnetism in the home neutral relay, due to distant reversals. Mr. Rhoads terms his device, probably for convenience, a holding relay. It is rather a local circuit opening device if it acts as intended. The present writer's extensive experience with devices of this kind is that it is difficult to insure exact co-ordination between them. In describing the operation of the Western Union holding relay, Mr. Rhoads states that the holding coil gives the armature a pull due to the condenser charging current that occurs with change of line current. Rather, the chief pull is probably due to the discharge current of the already charged bridging condenser, since I think it will be found that the bridging condenser is always charged before the distant reversal for a signal begins. This, if so, is fortunate, since in this very interesting operation the holding relay, getting the benefit of that discharge at an opportune moment, tends to hold the Western Union neutral relay armature forward against the pull of its retractile spring at the moment of distant reversal. Likewise, this discharge current of the condenser attracts the relay armature of the Rhoads device at an opportune time. This condenser current of discharge, however, probably weakens more rapidly than the previous magnetizing current in the coils of the home neutral relay, and when the moment of no magnetism in that relay arrives, at that instant, if not before, the zero moment also arrives in the holding condenser. Clearly, the retractile spring of the armature of the Western Union neutral relay and that of the Rhoads device will begin to act before the actual moment of no magnetism in the neutral relays and zero in the condenser arrives. At this time it is probable that the armature of the Western Union neutral relay and that of the Rhoads device fall back and rest on their back contacts for a brief instant, giving a tendency to a false signal, or split dots, in the reading sounder, which the repeating sounder should ordinarily prevent. The actual reversal current now begins, gradually magnetizing the line neutral relay. Simultaneously the holding condenser of the Western Union device begins to charge, setting up a current in the holding relay that tends to attract its armature, thereby perhaps giving back some of the energy taken by the holding condenser from the main or artificial line current. On the other hand, from the moment of no magnetism in the neutral relay and the zero moment in the condenser of the Rhoads device up to complete reversal seemingly no other function is performed. If its relay armature is fully attracted by the charging current of its condenser it may tend to open the local circuit which is then probably open also at the armature local contact of the line neutral relay.

A possible disadvantage of the use of devices of the foregoing nature is that when the short end of the distant battery is to line and when the tension on the retractile spring of the home neutral relay armature is weak, there may be a tendency, due to the charge and discharge current of the holding condenser, to open the repeating sounder contacts and thereby set up a chatter. All such points were carefully studied in connection with extraneous devices more than thirty years ago in quadruplex telegraphy. (See "American Telegraphy," page 207.) It is true as Mr. Rhoads notes, that the extended lever arrangement of the neutral relay adds to the inertia of the apparatus. To my ear the signals received on circuits on which extended lever armatures on the neutral relay were employed had a pronounced drag as compared with those received on the short lever relays. It was axiomatic with the present writer not to add to the circuit or apparatus devices that did not show a wide margin of advantage. Consequently, in my own practise while electrical engineer of the Baltimore and Ohio Telegraph Company, 1884-1888, I recommended on the quadruplex circuits of that company the use of the Edison short-core differential neutral relay without other devices than the Edison repeating sounder bug trap and with very successful results throughout. Thus the Boston-New York quadruplex circuits worked day in and day out like local circuits, while the second side of several New York-Chicago quadruplex circuits were leased for brokerage business, the exacting nature of which is well known. From personal experience, also, I may add that the Western Union Telegraph Company in the early days of quadruplex telegraphy, 1880-1884, did correspondingly well with its systems, in which only the short-core neutral relay, the Smith condenser arrangement and the Edison repeating relay were used. It is proper to say in this relation that on the quadruplex circuits then under my supervision there was no impedance in the lines except that due to the relays, and little or no interference from electric light and power circuits. There was, however, marked inductive effects from neighboring telegraph circuits.

In view of the great utility and wide employment of the combination of the extended lever of the neutral relay, in combination with the holding relay and bridging condenser, especially in commercial quadruplex telegraphy, it may not be out of place to state here, subject to correction, that the present writer was probably the first to suggest the use of this combination (see *Electrical World,* page 228, 1888), although he did not deem it necessary to employ it in his own practise, for reasons given previously herein, and it did not occur to him to attempt to patent the device before describing it.

Mr. Rhoads states that he employs the Edison repeating sounder bug trap with his device and that it functions perfectly. Such being the case, it might be suggested that the Edison repeating sounder be dispensed with, still keeping the neutral relay contact on the back stock, however. By so doing the inertia of an intermediate instrument will be dispensed with. It may be of further interest to try out dispensing with the repeating sounder since, in his paper the author adds that a critical examination of oscillograms Nos. 543 and 545 shows that the holding relay acts very slightly ahead of the neutral relay in the standard Western Union quadruplex. This result could be anticipated if the first action of that relay is due to the discharge current of the holding condenser and not to the current of charge. By dispensing with the repeating sounder the action would be speeded up to a certain extent and thereby perhaps meet the said advanced action of the holding relay.

Before leaving this feature of the paper it may be worth noting as showing what might indeed almost be expected, that Edison had also thought of utilizing the transit of a relay armature to prevent the false signal in the home neutral relay at the moment of distant reversal. Thus, in his U. S. patent No. 207724, 1878, Edison describes a local circuit opening device for this purpose, practically as follows: "The armature of the polarized relay which is in the circuit of the permanent retractile magnet (a substitute for the retractile spring of the neutral relay armature) being moved by reversals of current on the main line, opens the circuit of the retractile magnet momentarily and then closes the same, so as to neutralize as far as possible the risk of a false signal in the neutral relay armature by breaking the circuit of the retractile magnet at the instant of reversing the polarity of the distant battery."

It should be noted here that in a revised paper Mr. Rhoads takes cognizance of the successful operation of the quadruplex circuits in the past and the absence of the retardation coils, etc., in those circuits as the probable explanation. He also expresses surprise that such efficient quadruplex results were attained so long before the oscillograph was invented. In answer to this it may be remarked that the records will show that the telegraph engineers of over a quarter of a century ago did not consider that they were altogether in the dark as to what was taking place in a quadruplex, even without the aid of oscillograms. This is said without questioning the admitted value of the oscillograph. On the same page of his paper, Mr. Rhoads further remarks that "the investigations of the quadruplex and duplex indicate that it is the cumulative effect of little things which add up to an appreciable amount and prevent satisfactory operation. The battery taps must be equal in resistance, etc." On this point it may be urbanely remarked in passing that this conclusion would probably follow as a result of ordinary observation. At least, on page 233 of *American Telegraphy,* the present writer, in 1890, wrote: "To insure the successful working of a quadruplex constant attention to details is essential. One radical defect in a quadruplex circuit may be readily traced and eliminated but many trifling defects allowed gradually to accumulate, etc."

In other parts of his paper Mr. Rhoads discusses terminal resistance unbalance, telegraph transmission speeds, etc. In a classical paper presented to the American Institute of Electrical Engineers, by F. F. Fowle,(June 1911) entitled "Telegraph Transmission," these and other kindred subjects are treated at some length, and can I suggest be read to advantage in connection with Mr. Rhoads' paper by students of telegraphy.

It should have been stated herein that in the early days of quadruplex telegraphy in this country continuity preserving pole changers and transmitters were employed, and a single gravity battery was allotted to each circuit, before the advent of the dynamo machine. It is quite likely that the continuity preserving pole changer minimized the interval between reversals. Further, at this instant the gravity battery was short-circuited and the main line was put to ground at distant station. In this case a current of 50 milliamperes from the home battery at *X* would pass through the line coils of distant relays almost directly to ground, instead of 25 milliamperes as indicated in Fig. 2. This will cancel the 50 milliamperes flowing in the artificial coil of the home relay at *X* and leave that relay ready for reversal the moment contact is made with the distant positive battery, thus speeding up the actual reversal in the home relay almost as if the relay between reversals of the distant battery were negligible. Further, after contact with distant positive pole has been made and when the distant continuity preserving polechanger is again short-circuited in starting to place the negative pole to line, the previously existing 100 milliamperes on the main line is only reduced to 50 milliamperes and not to zero, as assumed in the paper under discussion at the moment of no contact in distant polechanger, this retarding the reversal of the home relay virtually until the actual reversal occurs at *Y*. The foregoing conditions assumed to occur in the operation of the continuity preserving polechanger, with home polechanger closed, and other conditions that follow with that polechanger open, appear to obviate still further the conditions which Mr. Rhoads, most likely properly assumes, have produced the light and heavy writing in the home polar relay operated by the dynamo polechanger in the modern quadruplex system to which he refers, namely that by delaying the start and accelerating the end of a marking signal when the home polechanger is open the signal is made shorter, which is the reverse of the conditions with the home polechanger closed. The analysis just made of the conditions assumed to prevail at the moment between reversals in the operation of the continuity preserving polchangers may also serve to further explain the uniformity of signals in the polar relay observed in the polar duplex and quadruplex systems of the eighties and early nineties.

In the section on Polar Relay Speed of Reversals, the author remarks that investigation, presumably recent, shows that there is no noticeable effect on the polar relay due to variations of potential at the distant station. It may be noted that this fact was well known from the earliest days of the quadruplex. See "The Quadruplex," 1888, page 44, in which this feature is quite fully discussed. Under the caption "Single Morse" in Mr. Rhoads' paper, there is a section on 35-ohm relays in which it is recorded that a change from the 150-ohm main line Morse relay to 35-ohm relays on the New York Central lines has demonstrated that marked improvement in the service resulted. It may be of some interest to note here that the Association of Railroad Telegraph Superintendents had the matter of displacing 150-ohm Morse relays by 35-ohm relays under discussion in 1896. At the convention of that Association in 1899, which the present writer had the pleasure of attending, a committee previously appointed to investigate the subject reported favorably at much length. A letter embodied in that report mentioned the case of a thirty year old iron wire circuit, 175 miles in length, with 30-150-ohm relays, measuring 7500 ohms. The current was supplied by a dynamo of 160 volts at Omaha and gravity battery of 170 volts at Sioux City. In wet weather this circuit was inoperative unless cut in two sections. The substitution of 37.5-ohm relays reduced the total resistance to 4740 ohm, with the result that in the worst weather the entire circuit was successfully operated. In the discussion of the report many of the superintendents present reported successful results from more or less similar changes. The chief objection at that time to the reduction of line resistance was that it involved expenditure for increased current, then mainly supplied by gravity battery. The most marked improvement due to the use of 35-ohm relays noted by the train dispatchers was that the character of the signals was changed from sluggish to sharp signals, a point also noted by Mr. Rhoads in his paper.

In this relation it may be remarked that the effect of wet weather on poorly insulated wires, operated as single Morse circuits, in making it difficult to keep the relays adjusted, was very well known many years ago and the cause was also known. In 1890 or earlier, P. B. Delany invented a device termed by him a line adjuster, which under attainable condition automatically opened the line at both terminals, thereby opening all the relays on the circuit. The Delany device is described and illustrated in *American Telegraphy,* p. 150. Apropos of this subject, reference may be made to the Stumm added resistance for use in wet weather on duplex and quadruplex railroad and commercial circuits. This device, it is well known, introduces at such times non-inductive resistance into the main line with remarkable improvement, apparently paradoxically, in the operation of the circuits. This improvement is perhaps due to the lessening of the variations of the line resistance caused by changes in the line resistance in stormy weather, thus steadying the adjustment of the system. It is understood that the Stumm resistance is now a part of the equipment of the Western Union rheostats used in duplex and quadruplex circuits, since it is also found to prevent undue heating. On the other hand, it is understood that the Postal Telegraph-Cable Company inserts resistance in the main line of such circuits in wet weather, by means of switch plugs carrying in their handles a desired resistance.

Stanley Rhoads: Mr. Maver's excellent book on "American Telegraphy" was before me when doing the work which formed the basis of my paper and was most useful in that work, in giving me the results of past experiences along the same lines. Also Mr. Fowle's paper has been in my possession since it was published. The two texts mentioned, as well as others that I consulted, did not give me enough facts as to the simultaneous conditions that take place in the various branches of the duplex and quadruplex circuits, and at this time, after taking nearly 500 oscillograms, I still find that there are conditions that I would like to investigate in order to arrive at a complete understanding of these simultaneous relations.

One of these things that needs further visualization is the relation of the simultaneous action of neutral relay armatures to the applied current wave, with different tensions in the retractile springs and with different adjustments of the air gaps. These two variables make it possible to cause a contact to close at various times in relation to the wave of current, and if the results were known, it might be possible to predict more closely than is now possible just what action would result with various circuit combinations.

Another thing that needs to be demonstrated to the eye, is the difference in wave shape of current (and voltage) on different kinds of lines. There is a decided difference between the different kinds of lines, and with proper experimentation, reducing the time of revolution of the recording drum on the oscillograph so that the recorded waves have a long slant, it may be possible to readily distinguish between the waves of different circuits. It is not possible to distinguish much difference in the results we have so far obtained, yet we know by ear from the results on the relays that there is considerable difference. By following out this line of experiments far enough and taking enough records, it would be possible to work out a set of telegraph transmission equivalents for various apparatus and kinds of wire and cable, like the transmission equivalents used in telephony, so that one could predict what the result would be with any particular combination of lines and apparatus. The difference between the wave shape, or rather wave front, using different kinds of telegraph sets on the same line, should be similarly investigated.

The books and papers so far available give us only approximations and do not give the actual condition during the transient state in the waves. A person can take paper and pencil and try to figure out the simultaneous transient conditions, but, in my opinion will come far from exact facts. This method of attack, backed up with the oscillograph, gives the proper present-day method.

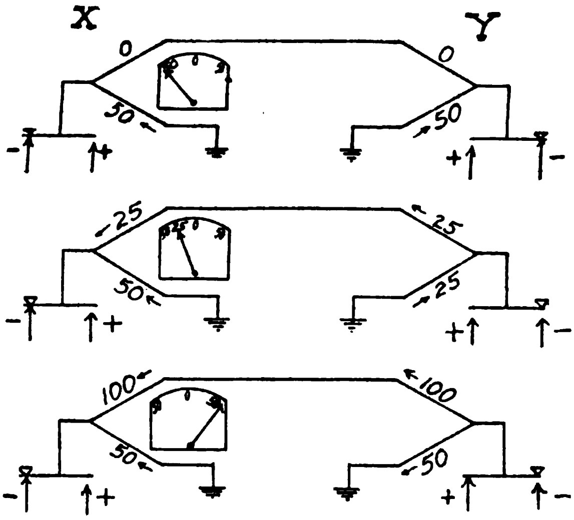
In regard to the light and heavy writing experienced in duplex telegraphy on the railroads, it is interesting to discover that this is a comparatively new phenomenon in the art. It is due perhaps, more to the greater time constants of the present-day lines, which to me means less steep wave front, which result from the increased amount of cable rather than to the 5-U coil or the wide polechanger travel, because it is experienced with differential as well as bridging sets.

It appears that Mr. Maver did not follow through on his own line of attack on the light and heavy writing problem. The six figures required for the full consideration of the matter are given. Nos. 4, 5 and 6, are the same as given by Mr. Maver. Nos. 7, 8 and 9 are for the reverse condition, which is with the home key open. For greater ease in following the current variations I have shown a milammeter at the home station which in each case indicates the current in the polar relay with the conditions as given.

I follow Mr. Maver in his discussion of Figs. 1, 2 and 3 up to a certain point. That is, with both keys closed the current in the polar relay will be 50 mils and in the marking direction, as shown in Fig. 4. When the distant polechanger is opened and held midway between the poles the condition will be as shown in Fig. 5 and the current in the polar relay will be but 25 mils but still in the marking direction and the marking signal will continue. Now, if the distant polechanger is closed on positive battery the condition becomes as shown in Fig. 6. Here comes the point that Mr. Maver failed to diagnose properly—to wit: when the distant polechanger is opened again and held open and not on either pole, the current is, as Mr. Maver says, 25 mils, but it is in the *marking* direction and has reversed the polar relay at the home station as shown in the milammeter. This means that when the distant polechanger changed from the condition of Fig. 4 to that as shown in Fig. 5 it did *not* change the signal, but that when it opened from the condition of Fig. 6 to the condition of Fig. 5 it *did* change the signal. The marking signal is thus lengthened by delay at the time the distant polechanger leaves the marking pole and by prompt action when it leaves the spacing pole to begin another marking action.

In Fig. 9 the distant polechanger is on the marking pole and the home key is open with the current 50 mils in the marking direction as shown in the milammeter. If the distant polechanger opens and is on neither pole the condition is as shown in Fig. 8 and it is seen that the polar relay has been reversed to 25 mils in the spacing direction. With the distant polechanger on spacing battery the condition is as shown in Fig. 7 and is 50 mils in the spacing direction. When the distant polechanger is again opened and not on either pole, the condition becomes as of Fig. 8 again and the spacing signal continues with 25 mils in the spacing direction through the polar relay at the home station. Closure of the distant polechanger on marking battery which is negative polarity, gives the condition of Fig. 9 again and changes the current from 25 mils spacing direction to 50 mils marking direction. This means that with the home key open, as soon as the polechanger leaves the marking pole the marking signal *does* end and that when it leaves the spacing pole it does *not* end the spacing signal. The marking signal is thus shortened by the reversal that occurs when the distant polechanger leaves the marking pole and by delay in reversal when it leaves the spacing pole to begin another marking signal. This is just the reverse of the results brought out in the preceding paragraph for the condition of home key closed.

This shows conclusively that the light and heavy writing has cause, but which may not exist in the sets formerly used which had circuit preserving polechangers. Computations show that the condition is improved by the use of lamp resistance in the battery leads and because these resistances are used jointly by the current through the line and from the artificial line. When the condition of Fig. 5 or 8 exist, if there is lamp resistance in the battery leads, the current in the artificial line will be reduced below what it is if no current flows in the main line because of the joint use of the lamp by the main and artificial line currents. In this case the milammeter would show some value less than 50 mils; that is, it would be farther in the direction it is wanted in, and the tendency will be to cause more prompt action of the polar relay in response to the action of the distant polechanger. It may be that the duplexes that used gravity battery with its high internal resistance were thus benefited thereby. It also would indicate that increase of terminal lamp resistance would benefit present day sets in this regard, but the difficulty is that many duplexes need all the current available and additional resistance would be disadvantageous, because the current would be reduced.

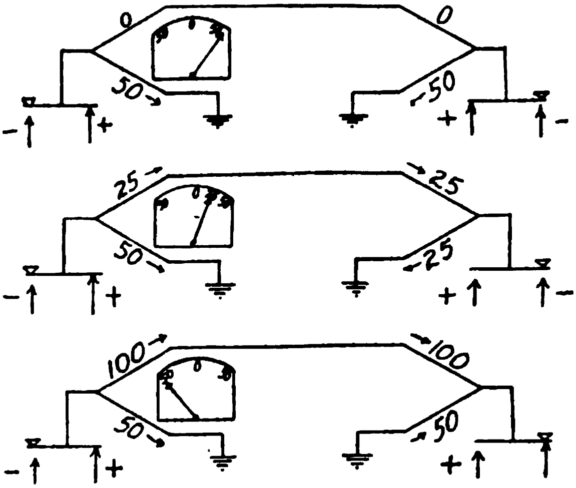


Figs. 5, 6 and 7.

The distinction that Mr. Maver has drawn between charging and discharging current in the holding condenser, to my mind, is not entirely correct, if considered as follows:

Assume a condition of closed keys on all corners fo a quadruplex; the holding condenser will be in a charged condition, of maximum value. Now, if the distant polechanger reverses, it starts a wave along the line, which causes a change of potential to occur across the holding condenser, which will cause the condenser to have the charge that was in it pushed out, so to speak, by another charge but the current that goes in to it to do the pushing is in the same direction as the current being pushed out and continues until the steady state is reached after the complete reception of the incoming wave from the distant station. The result is a pulse of current in the holding circuit, in phase with the line current, beginning when the line wave begins and ending when it ends. One oscillogram, No. 431, in the February 1, 1920, issue of the *Telegraph and Telephone Age*, page 66, shows the pulse in the condenser circuit in Trace No. 2 and its relation to the line wave. The point to this is that the condenser current at each reversal of distant polechanger is all charge going into, or rather through, the condenser. The charge and discharge are inextricably rolled into one pulse of current.

Considering the Rhoads relay as performing the function of holding the reading sounder circuit of the common side closed while a dot might otherwise be split by the neutral relay falling against the backstop when the distant polechanger reverses, makes the term "holding relay" appropriate.



FIGS. 8, 9 and 10.

Since the holding condenser pulse is in phase with the line wave that caused it, it is only necessary to get the holding circuit to pick up at the precise instant that the neutral relay would strike its backstop, and thus prevent a false signal. This is not as easy as it seems. It is necessary to know the action of the neutral and holding relays in relation to the current wave and to the air-gap and retractile spring tension, facts that are not definitely known at the present time, except, perhaps, in laboratories where the data is not made public, and which data we should obtain experimentally as stated in the early part of this letter. The best information obtained by me so far, is in oscillograms Nos. 543, 544 and 545; results which show the simultaneous action or coordination to be successful on single wire circuits. The current is maximum in the holding circuit at the very instant that it is zero in the neutral relay. This is at the middle of the reversal of the line wave. Consequently, the holding pulse of current comes at the desired time, but it is dependent upon the characteristics of the neutral and holding relays as to whether this pulse can be made successful use of.

No trouble has yet been experienced with the holding relay being actuated by current from the short pole reversals at the distant end. The reason is that the ordinary Morse relay has very wide margin of adjustment and, if adjusted so it just pulls up on a given current, there is no trouble from its picking up on one-third of this current, which it would have to do on a quadruplex which works on a 3 to 1 ratio.

In connection with the good service which the quadruplex gave years ago between New York and Chicago—points now beyond the range for quadruplex-working—it seems worth while to note that these lines were practically open wire from operating room to operating room, including open wire through the city streets and included but little cable; whereas at present there are untold amounts of cable and growing worse in this respect. The tests we have made indicate that it is the capacity effect that plays havoc with the speed of reversal of current, and which causes the trouble in the quadruplex. If the wave has a steep front, it causes a quick reversal in the neutral which is more easily bridged over by the holding devices. The capacity reduces the steepness of the wave front of the received wave.

The omission of the bug-trap relay was tried, and it was found to be indispensable at that time. Some further tests will be made soon on longer lines and omission of the bug-trap will be tried again. With 400-ohm local sounders operating on 110 volts the sluggish action in local circuits is greatly reduced, in our experience, and the bug-trap does not seem to cause appreciable lag.

That many statements that I made in my paper seem to be restatements of old facts, makes it timely to state that we will have to watch closely in the future to prevent wasted effort in reinvention and rediscovery of many things because of the rapidly increasing complexity of science. Science has been described as organized knowledge, and there is plenty of chance for improvement in this organizing and card indexing of facts, as anyone can testify who has tried to follow up some subject and has found that text as indicated by title is far from being what the searcher is led to expect. It also indicates the difficulties ahead of the index-maker.

The problem of low resistance instruments for heavy way Morse wires is an old one, as Mr. Maver says, and was brought out in my paper because of the special case of the use on block telephone simplexes and to indicate the matter of insulation as related to the problem. As I had in mind, way circuits with 30 to 50 stations, when the writing statement that low resistance instruments are preferable for way wires, I believe Mr. Drake will agree when the statement is thus limited.

I failed to give credit in my paper to the line resistance invented by Mr. Stumm, as when the early draft of the paper was made we were not making much use of it, because the wires in duplex service were generally high resistance simplexes on dispatching circuits and were worked on the highest current obtainable without excessive voltage but which current at best, was generally near the low limit for duplex working. Consequently, no benefit could be made by the insertion of resistance in bad weather. However, in recent months we have converted many dispatching telephone simplexes into low resistance types by the use of repeating coil operated selectors. These simplexers give ample margin of current, when duplexed, and in bad weather the Stumm resistance box is found valuable. Mr. Stumm, by the way, does not like the term line resistance box. He prefers the word "box" omitted.

In conclusion, it seems proper to say that the remarks herewith are fair indication that the performance in the quadruplex and duplex is to a great extent a matter of guess-work, if attempted by graphics and charts, and our attempt has been to help take the guesswork out of it, which attempt has only been partially successful up to date. One motive in the work has been to make visible many of the well-known audible phenomena. Two senses are better than one on a problem, or three are better than two, if eyes, ears and mind are counted as one each.

E. H. Colpitts: Before considering the technical questions raised in the discussion, there are two matters which require further notice. The first covers the claims made by General Squier in his discussion that he is the inventor of the carrier current system. The second covers the question as to the best name to apply to the system.

General Squier's claims were, of course, before us when we wrote the historical part of the paper. We recognized the obligation in the historical section to give as unbiased statements as possible. We carefully considered his claims and we believe the statements made in the paper give due credit to his contributions to the art.

General Squier, in his discussion, states:

"Let us consider for a moment what are the essential elements in this system. Briefly, the use of alternating currents or electrical waves of relatively high frequencies, means for modulating high-frequency currents at the transmitting end, selective tuning at both ends of the line, separating the messages of different frequencies at the receiving end, and suitable means for rectifying and detecting the signals at the receiving end. These are the basic elements necessary and sufficient for the successful operation of the system * * * * * "

It is exactly these essential elements of the system, each and all, which were invented, combined together and thoroughly understood, considerably previous to the work by Squier. A careful consideration of the facts presented in the paper will show this.

Frankly, we must look at the work by General Squier in the same way that he looks at the work of those who preceded him when he states, " * * * * * but their work did not materialize into a practical solution of the problem." The previous work was carried to a point permitting a technical demonstration of wire carrier telephony and telegraphy. The Squier tests went no further, although the great ability of General Squier to inspire popular interest in such matters brought his work into more wide-spread notice. The Squier tests did not "materialize into a practical solution of the problem." This was fully brought out at the time by Dr. Jewett.[4]

There are two things which have come into the art which above all others have been responsible for taking the carrier art out of the experimental stage in which it had been for many years and making it a commercially practical system. The first and the biggest thing is the wonderful art which has been built up around the three-element vacuum tube. This vacuum tube art includes dvelopments in the tube itself and its application as amplifier, repeater, modulator, demodulator and oscillator, and the numerous circuit and

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[4] Trans. A. I. E. E., 1911, Vol. II, p. 1666.

line developments which have been associated with these factors. Second, is the development of the electrical filter which has permitted the use for telephone purposes of the most advantageous frequency range for carrier use.

As regards the name given to this system, it seems to us that the terms "wired wireless", "wired radio" or "line radio" are particularly objectionable in that they ignore the fundamental difference between wire and radio transmission. The characteristic feature of wire transmission is that the electro-magnetic waves are guided by conducting wires, whereby the energy is prevented from spreading and is delivered to the one desired receiving point. The characteristic feature of radio is, of course, that the waves "radiate", that is, they are unguided and are permitted to spread out in all directions. If we speak of a "wired radio" or "line radio" system of transmission, we are in effect saying a "guided-unguided system." The term contradicts itself.

These names have arisen out of a misconception as to the transmission of high frequencies over wire circuits. For example, in his present discussion, General Squier states,

"I have always regarded the principles embodied in my system of line radio as offering great possibilities in connection with long distance power transmission."

In General Squier's paper of 1911 he states:

"The distortion of speech, which is an inherent feature of telephony over wires, should be much less, if not practically absent, when we more and more withdraw the phenomena from the metal of the wire and confine them to a longitudinal strip of the ether which forms the region between the two wires of metallic circuit.

The ohmic resistance of the wire as shown can be made to play a comparatively unimportant part in the transmission of speech and the more the phenomena are of the ether, instead of that of metallic conduction, the more perfectly will the modified electric waves, which are the vehicle for transmitting the speech, be delivered at the receiving point without distortion."

The facts are, of course, that the transmission of high frequencies over wire curcuits presents no new principles, either to the power engineer or to the telephone engineer. Quantitatively, the phenomena involved in the transmission of high frequencies are even somewhat less "of the ether" than are those involved in the transmission of the lower frequencies. By this we mean that there is more active dissipation of energy in the wires themselves and in leakage between the wires the higher the frequency. It is even true that the energy transmitted in the wires themselves increases with frequency although as pointed out below this is negligibly small.

In this connection it may be of interest to note where the actual transmission of energy takes place in an open-wire circuit. Fig. 10 shows a section across a pair of No. 8 B. W. G. copper wires spaced 12 inches on center, which is the largest gage open-wire circuit in common telephone use. Within the small dotted circles drawn around each wire is tranmitted 50 per cent of the total energy. Between the small circles and the larger outer circle is transmitted 40 per cent. The remaining 10 per cent is transmitted outside of the larger circle. This diagram holds true practically independent of frequencies, either for power transmission, ordinary telephone transmission or carrier transmission. The amount of energy actually transmitted longitudinally in the wires themselves is negligibly small for any frequency. For 60 cycles it is approximately 6×10^{-17} per cent, for 50,000 cycles 14×10^{-17} per cent.

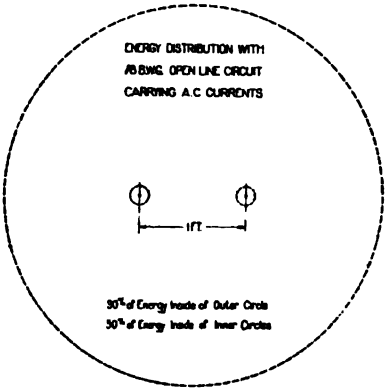

Fig. 10

For very low frequencies, as is well known, the current tends to distribute itself uniformly across the cross-section. As the frequency increases the current is crowded more and more into the outer layers of the wire. This does not mean at all, however, that there is less energy loss at the higher frequencies, but rather that there is more loss. For 1000 cycles, the guiding wires, (assuming 8 B. W. G. wires as above) due to their ohmic resistance alone, take a toll from the transmitted energy of 0.7 per cent per mile of travel. At 50,000 cycles they take a much greater toll of 2.6 per cent. Likewise the leakage losses increase greatly as the frequency goes up. The telephone engineer has gone to the higher and inherently less desirable frequencies involved in carrier use, because with the new facilities opened up by the art built around the vacuum tube he can sacrifice considerable in efficiency of transmission to obtain additional channels. The power engineer, however, is much more vitally interested in efficiency of energy transmission, and it is not now evident what advantages he can find in higher frequencies for power purposes to make up for their inherently poor transmission over wire circuits.

An appropriate name for the art should not only suggest the mode of operation, but should also differentiate between it and the two most closely allied arts, namely, ordinary wire telephony and telegraphy and radio telephony and telegraphy. We have already pointed out the fundamental distinction between it and radio.

The feature of the art which best distinguishes between it and ordinary telephony and telegraphy is that with it the signaling telephone or telegraph waves are impressed upon alternating current higher in frequency than the signaling waves, while with ordinary telephony and telegraphy the signals are transmitted at their own frequency. An alternating current on which the signaling variations are impressed in such a system has come rather naturally to be regarded as the "carrier" of the signaling variations, and therefore to be designated as the "carrier current."

If we wish then to set up a name which would fully differentiate this art from others, we could characterize it as "wire-a-c. carrier" system. From this name we can surely drop off the "a-c." for while the ordinary telephony and telegraphy may be considered to be impressed on direct current, the analogy, while instructive, is not an obvious one. It requires, for example, considering the permanent magnetism in the receiver of a telephone system as the "carrier" at the receiving end of an ordinary circuit. Without confusion then, the name can be shortened to "wire carrier" system. "Wire" differentiates it from radio. "Carrier" differentiates it from ordinary wire transmission. The two words taken together are suggestive of the mode of operation.

While carrier currents are employed in radio transmission, the term "radio" so well identifies that art that the term "wire carrier" has been further abbreviated in practise to "carrier". This has happened in connection with the development and operation of circuits of this kind by the Bell Telephone System in the United States. These circuits are already widely known to their operating as well as to their development and engineering forces as "carrier" circuits. For technical use the complete term wire-carrier is probably preferable.

Coming next to the technical questions raised by the discussion, we note that General Squier, Mr. Duncan and Dr. Cohen question the amount of power required to span various distances. The primary cause of this misunderstanding is that they are assuming that the energy "level" to which transmission may be permitted to fall, that is, the amount of energy at the receiving point (or point of amplification) is determined by the limits of audition and the amounts of amplification possible. However, in a commercial circuit the level to which the energy may be permitted to fall is determined solely by the level of the interfering energy which may be present in the circuit. For the carrier frequencies which we are using applied to a telephone line transposed in the usual manner, we find that the useful component of the energy must not be allowed to drop below about 10^{-5} watts. It is, furthermore, very desirable that the energy level be kept considerably above that value.

We appreciate that the ratio of this value to the interference is very much greater than that ordinarily experienced in radio transmission. The standards for commercial wire telephone circuits must be, of course, very much higher than those which are usually approached in radio.

Another factor which is important is that if extremely large ratios are permitted between sending and receiving energies, there will be undue interference from the powerful sending circuits into the sensitive receiving circuits where more than one system is operated on a pole line. Considering the fact that the crosstalk introduced into a circuit from any other circuit must not have more than a few millionths of the energy sent out on that circuit, it is evident that this requirement may be extremely important.

The discussion also raises the question as to why the frequency range below 30,000 has been exploited for commercial use. The primary reasons for this are, as pointed out in the paper, the lower attenuations, the greater ease in caring for inserted lengths of cable and the smaller interference between channels at the lower frequencies. As the frequencies increase not only does the attenuation increase rapidly, but the variations in attenuation with weather conditions become extremely large. The circuits rapidly reach a point with increase in frequency where the maintenance of stability becomes a very important factor.

Mr. Duncan presents computations of attenuation at 500,000 cycles over an assumed circuit of 100 miles length. At this frequency the leakage which he used was, as he stated, an assumption. We find the leakage factor varies tremendously with weather conditions. While we have no precise data giving the range at this frequency, we believe the value assumed by Mr. Duncan is a reasonable one for moderate weather conditions. For wet weather conditions, however, we believe the value is entirely too low; that it may be even increased by several times the assumed figure. Supposing the value was twice that assumed, we find that the received energy would be cut down by a ratio of approximately one hundred to one. For a two hundred mile length the ratio would be 10,000. This very well indicates what variations in received current would be possible with weather variations at this high frequency. Evidently there is a large difference between setting up a demonstration circuit under good conditions and obtaining satisfactory commercial efficiency and stability over the same circuit.

Our recent experience with carrier operation has shown an amount of interference from adjacent power circuits much greater than that which we had anticipated. Evidently while our carrier range is above the usual harmonics of power circuits, there are frequently set up in such circuits high-frequency oscillations and surges of considerable amplitude. We expect that further work will throw some interesting light on this subject.

Since writing the paper we have been glad to receive a letter from Professor Turpain of the University at Poitiers giving reference to early work carried out by him on carrier communication. He sent us a copy of a pamphlet entitled, "Recherches experimentales sur les Oscillations electriques," Paris, Herman, 1899. He also referred us to the following publications:

"La Telegraphi sans fil et les applications pratiques des ondes electriques, deux editions: 1902, C. Naud, Paris; 1908, Gauthier-Villars, Paris.

"Utilisation des ondes electriques a la solution generale du probleme de multicommunication en telegraphie et en telephonie.

"Soc. des Sc. P. N. de Bordeaux, 23 juin 1898, 10 mai 1900. C. R. Ac des Sc., 26 decembre 1898, 14 mai 1900. Soc. Fr. de Phys., 21 avril 1900. Congres de l'A. F. A. S., Boulogne, 1898; Paris, 1900; Angers, 1903; *Journal de Phys.*, aout 1900. Revue scienti-

fique (rose), 3 mars 1900. Congres de l'A. F. A. S., Rouen, 1921. Revue general Electricite, 24 Sept. 1921.
"Brevet francais No. 278719 du 13 juin 1918."

We regret that Professor Turpains contributions to the art were overlooked in our original statement. It is interesting to note that at an early date he applied to wires for multiplexing purposes the most effective methods then known in the radio art.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 18, 1921.

REGULATION OF FREQUENCY FOR MEASUREMENT PURPOSES

BY B. H. SMITH
Westinghouse Electric & Mfg. Co., E. Pittsburgh, Pa.

IT happens very often that it is desirable or necessary to transmit a quantitative indication to a more or less remote point. For instance, in a modern power system with its various sources of power, the load despatcher may wish to know the amount of power generated in a station perhaps several miles away, so that he may be able to better distribute his load. In addition, it may be desirable to regulate automatically the distribution of power as well as limit the amount that is received from a distant point. In this connection the problem may not be simply that of limiting the indicated power but of measuring and limiting the integrated demand over a definite time period. Of a different nature is the problem of recording at widely distributed points various operations in an industrial plant so that the results can be compared on the basis of the exact time of occurrence.

For all of the above problems frequency lends itself as a quantity which can be made proportional to a given indication and transmitted without any change for practically any distance. In this respect it stands out as being far superior to the transmission of energy or voltage or current. The transmission of voltage is affected by resistance in circuit, the transmission of current is affected by leakage and induction and the transmission of energy is affected by both of these quantities. Frequency is not affected by any of these quantities. The only problem is its satisfactory control and measurement. The speed control of a small

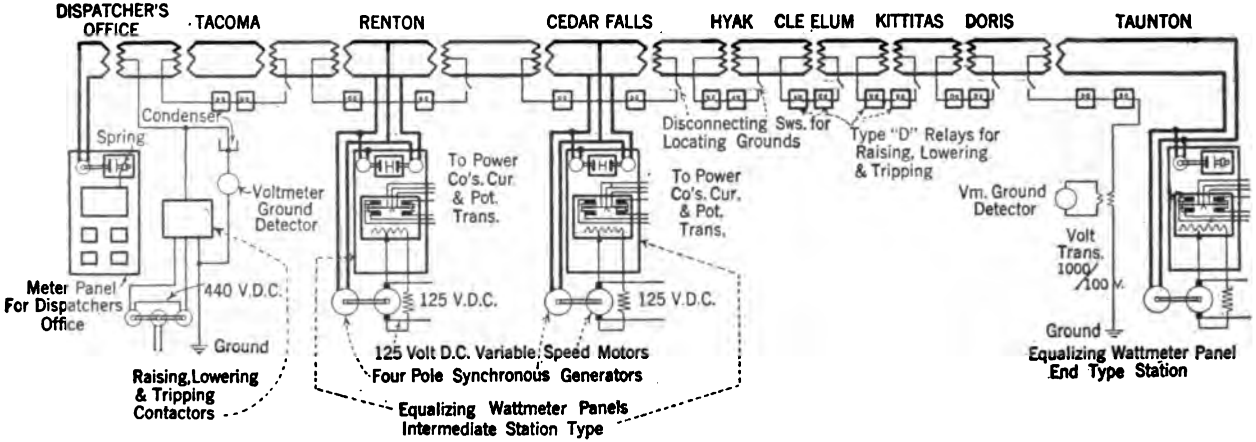

FIG. 1—DIAGRAM OF POWER INDICATING AND LIMITING SYSTEM, CHICAGO, MILWAUKEE AND ST. PAUL R. R. CO.

motor-generator set to give a desired speed within wide limits has been accomplished with more or less success in the past, but the frequency meter in its ordinary form is quite unsuitable for accurate measurement purposes. A new type of frequency meter of most satisfactory performance giving accuracy and high torque has been developed, making use of the automobile speedometer principle of a revolving magnet acting on an aluminum disk.

The purpose of this paper is to consider a number of metering systems where the frequency of a circuit is controlled in order to transmit an electrical condition to a remote point and to bring out the adaptability of this quantity for such purposes.

In 1917 the C. M. & St. Paul R. R. was confronted with the problem of measuring the power consumed on its latest electrified section extending from Tacoma and Seattle for a distance of about 200 miles east. It was decided to measure the power received at the various substations, Taunton, Cedar Falls, and Renton, and transmit the measurements to the dispatcher's office where they would be totalized and recorded. For much of the distance the climatic conditions are very severe and, especially along the coast, the weather is so wet that leakage of electrical energy from any kind of outdoor circuit is very great, and any method making use of quantitative transmission of current is out of the question.

The use of frequency was proposed as a suitable method, because frequency is a quantity which can be carried over a long distance without being subject to changes, and the details of the apparatus as installed some months ago are perhaps worthy of our attention as being an example of the most extensive application of the use of frequency for measuring purposes in service up to the present time. First of all, it is necessary to obtain from some source which will allow of regulation a frequency which can be made proportionate to the measured power. This is accomplished by connecting a wattmeter to a small a-c. generator in such a way that the speed, and hence frequency of the generator, is proportionate to the power received. This is done as follows:

At the first substation, Taunton, a small synchronous motor is driven from an a-c. generator, and through a revolving magnet acting on an aluminum disk produces a torque which over a wide range is proportionate to the speed. This torque is balanced with the wattmeter and maintained so that with any change in wattmeter reading the speed changes accordingly.

To take care of zero load a "base" frequency of 25 cycles is maintained, so that if the load is zero, exactly 25 cycles is sent out to the next station, and with various loads the frequency is increased up to a maximum of about 60 cycles. The outgoing frequency at approximately 100 volts is transformed to 2000 volts and transmitted to the next station. Here, and at three more stations, at intervals of about thirty miles there is no power received and the lines are brought into the station only for the purpose of bringing out the phantom or power control circuit which will be mentioned later.

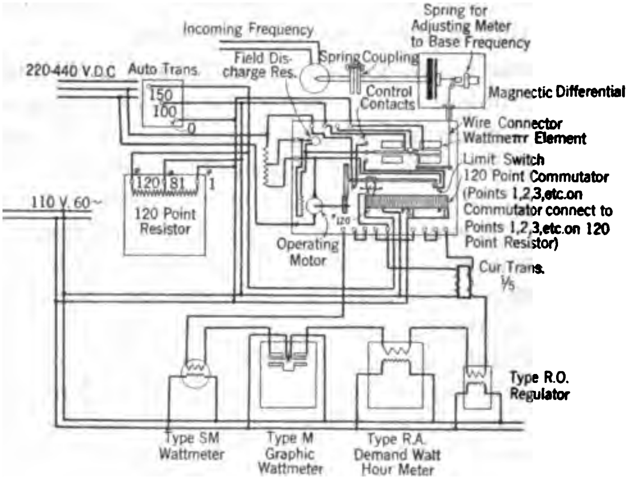

Fig. 2—Diagram of Dispatcher's Office Power Indicating and Limiting System

At the fifth station, Cedar Falls, the frequency is increased by an amount proportionate to the power being received at that station. It is not done directly however, but another generator is introduced and so controlled that its speed corresponds to the incoming frequency plus any power coming in on its own meter. The incoming frequency operates a synchronous motor similar to the one at Taunton and shown as the left hand motor in Fig. 8, its effect is added to the power incoming at Cedar Falls, and the outgoing frequency is balanced against it so that it represents the total power so far. The frequency is increased in like manner at the next station, Renton, and from there it is transmitted to the dispatcher's office. Here it is necessary to subtract the base frequency which is accomplished simply by a spring which opposes the effect of the incoming

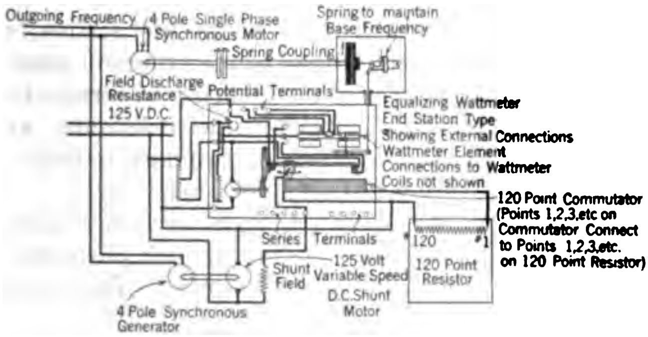

FIG. 3—DIAGRAM OF END STATION METER POWER INDICATING AND LIMITING SYSTEM—CHICAGO, MILWAUKEE AND ST. PAUL R. R. CO.

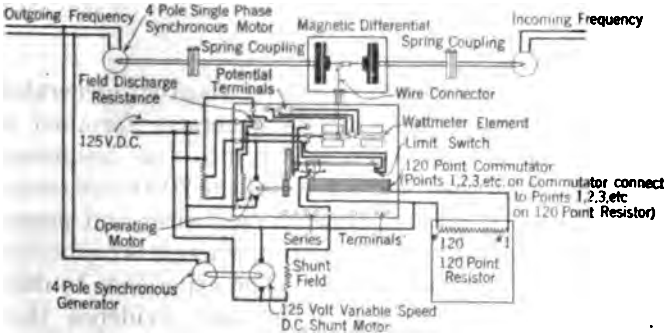

FIG. 4—EQUALIZING WATTMETER, INTERMEDIATE STATION TYPE, SHOWING EXTERNAL CONNECTIONS—POWER INDICATING AND LIMITING SYSTEM

frequency by an amount equivalent to a 25-cycle speed, and the remainder then represents the total power received by the railroad. The apparatus used to convert the frequency effect into a form which can be shown on ordinary meters both of indicating and watthour types, is similar to that at the first station, but the control mechanism, instead of operating on a motor-generator set only controls the quantity of current in a local circuit through suitable slide resistance, and this current is passed through standard indicating, recording, integrating and demand meters.

It was mentioned above that at certain stations, the metering circuit was led in only for purposes of bringing out the power control circuit. This circuit is supplied from a 440-volt direct-current generator at the dispatcher's office. One generator terminal is grounded and the other is led into the frequency circuit through the middle point of the 2000-volt transformer, then it divides between two wires and passes through the whole line to Taunton, where it is connected to ground as a return circuit. The experience to date with this circuit furnished the best evidence that quantitative measurement of a direct-current indication over a longer distance is out of the question under wet weather conditions. It was found in the very beginning, that about six milliamperes would leak from the line on an ordinary foggy morning. Perhaps by noon this leakage would entirely disappear. This quantity is small but the control impulses sent

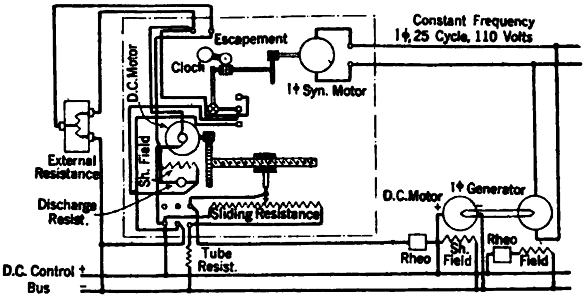

FIG. 5—DIAGRAM OF CONNECTIONS OF CONSTANT-FREQUENCY REGULATOR

over the line were only about 15 or 20 milliamperes, hence the percentage of leakage current was rather high. Later on there was evidence of much greater leakage, and at times it was impossible to get the proper control impulse through to the substations.

There was also found to be, especially along certain sections, a great deal of a-c. induction from the high-voltage power transmission line, and this tended to make the a-c. relays inoperative; but the effect on the metering frequency transmission was unnoticeable. This induction was, however, readily overcome by interposing in the circuit suitable resonant apparatus. It is not believed that the effects of ground potential have been serious, but recently there has been a great deal of apparent leakage from the 3000-volt power feeders into the circuit, so that the control impulses from the dispatcher's office at times are entirely overbalanced.

FIG. 6

The transmission of the frequency indications, however, has been practically unimpaired under all sorts of conditions except where the line itself has been broken or accidentally grounded, and so far it can be said that this application of frequency control and transmission for metering purposes has more than met the expectations of all concerned.

Another application of frequency control of more recent date is being worked out in a large industrial plant. Here it is desired to record various operations in widely separated areas about the plant in such a way that indications can be compared on a basis of the exact time at which they occur. The timing mechanism of the various meters are operated by small synchronous motors and these are supplied from a circuit, the frequency of which is controlled by a master clock so that the integrated frequency is proportional to absolutely correct time. Thus at any point a synchronous motor can be connected to the circuit and with proper gearing made to drive clock hands or timing devices, and these will indicate with no error.

FIG. 7

Fig. 5 is a diagram of the essential features of the control apparatus.

The speed of a small motor-generator set is balanced against a clock mechanism through a differential which operates the speed-controlling contacts. The differential is simply a sliding worm which moves forward slightly when the speed gets ahead of the clock, and backwards, if the speed falls behind, thus operating the contacts so that the speed is brought back to the proper value. The correct speed and frequency thus obtained are transmitted to the various parts of the plant, and small synchronous motors operate the various timing devices. By this system there is ample power for a high-speed timing device, the various meters will agree with each other to within a small fraction of a second, and the whole system may be kept within two or three seconds of standard time. The central apparatus can be regulated for fast and slow speed in the same manner as a watch, and if after running for a length of time the system is found to be slightly fast or slow it can be speeded up or slowed down quickly by hand control and brought to agreement with wireless signals or other indication of correct time. Then a slight adjustment of the regulator will suffice to keep the system as nearly correct as can be expected from a good timepiece.

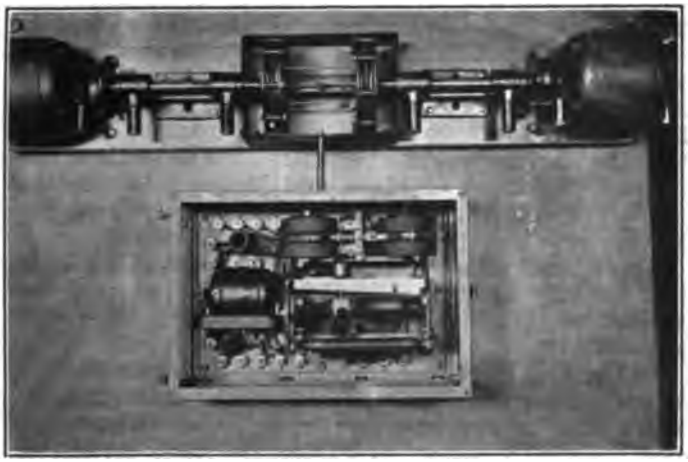

Fig. 8

DISCUSSION ON "REGULATION OF FREQUENCY FOR MEASUREMENT PURPOSES" (SMITH), NEW YORK, N. Y., FEBRUARY 18, 1921.

J. R. Craighead: I have been very much interested in Mr. Smith's presentation of the use of frequency for indications of the values of electrical quantities at a distance, particularly because of the advantages resulting from the use of a quantity which is practically unaffected by leakage.

Mention is made in the paper of the difficulties occurring due to leakage in the phantom circuit through which direct current is circulated for control purposes. I have had some experience in the transmission of similar values through direct current, and of control through the same means in a section further East than the one to which he refers. At that point we succeeded in transmitting through similar distances on two sections (about 220 miles) each with several operating substations and obtaining accuracies of a satisfactory nature with very little effect from leakage. This freedom from leakage trouble is partly due to the fact that the lines are not in a coast area. The sections run through the states of Idaho and Montana, where the rainfall is comparatively much smaller and where less leakage is to be expected.

There are, some rather particular advantages in the use of direct currents for similar purpose on account of certain features associated with the transmission.

In the first place, the transmission by direct current is not embarrassed by the inductance and capacity of the line to any extent. Second, the transmission uses the direct current only, and the same current is used at the same time for transmission of the indication and control of the substation apparatus. In consequence a smaller number of wires is necessary to supply the same conditions than where the system based on frequency is used.

If one side is grounded so that a ground return is used for the direct current, it is possible to use a single wire for the entire transmission. This tends to be objectionable, because it increases the leakage troubles and also because any inductive effect is very much increased, by the larger area enclosed. Two wires are all that are necessary to transmit and keep everything insulated from the ground.

To accomplish the same thing with the system mentioned here would require three wires,— the use of the ground return as stated in the paper reduces this to two wires. The number of motor-generator sets noted in the paper is quite considerable, and if applied to a greater number of stations in series, might become burdensome, because of the amount of rotating apparatus, to be kept not only in operative condition, but in condition of operation .sufficiently perfect so that the indications would not be affected.

When the d-c. system is used, the single generator is all that is required in connection with the indicating and controlling circuit. This is located in the dispatcher's office, and the controls in sub-points are simply resistance controls. There are also no phantom connections between different lines, which tends to reduce the difficulties of leakage. Since the current used for indication flows through all substations, it is possible to have the totalized value indicated in each station if desired.

We have some very interesting experiences as to the effect of inductive disturbances. On a d-c. line, supposedly, an inductive disturbance would have no effect; but practically all types of relays containing iron which are operated by direct current are partially sensitive to alternating currents. About the only exception to this, and this is not a complete exception, is the polarized type of relay. We found some difficulty in obtaining a reduction of inductive disturbances sufficient to avoid disturbing any of the relay controls, but this was accomplished rather simply in the long run by a few transpositions of the lines, and no alteration in the apparatus was necessary.

Mr. Smith speaks of a base frequency of 25 cycles' It is sometimes necessary in the transmission of railway intelligence of this character, to cover the fact that certain stations are running below the zero point, that is to say, are receiving power from the railroad and handling it back to the power company, instead of simply receiving power direct. In that case means must be provided for subtracting the value instead of adding it to the total. I should like to ask Mr. Smith how that is taken care of; whether it has been necessary on the circuit of which he speaks, and whether it involves the running of any of the machinery below the base frequency of 25 cycles?

Charles F. Scott: This paper, it seems to me, embodies what might be termed a bold attack on the whole problem of adding together the power that is incoming to a system at different points, and then adding to that the rather remarkable operation of so controlling automatically the operation of the whole railway system, by, for example, lowering the voltage, so that the power taken shall not exceed some predetermined maximum. If we had not this solution before us, if it were stated that some method of doing these things were required, we would think it almost impracticable to carry it out.

But as the previous speaker has indicated, it has been carried out by two methods, and in a method describing the use of frequency. We usually measure currents or volts or power, and we might under one of the rules proposed, add together the voltage generated at each of the several stations, and take that voltage, each one being proportional to the power at the station, as the sum which gives the-total which is desired, and which can be transmitted to and indicated in, the train dispatcher's office. But here we have brought in something new. We have brought in frequencies and added frequencies together.

Our worst troubles were in connection with the lines,—leakage, inductance, capacity. They can vary the currents or the power or the voltage, as it may be, but they do not affect the frequency. They may cut down or modify the amount of power which reaches the distant station, so that the receiving instrument will have to work with a smaller power impulse, but when it gets there, the thing we are trying to convey, to measure, namely, frequency, is not modified.

W. H. Pratt: I would like to challenge one of the remarks of the author in which he said that the accuracy of his apparatus was comparable with the accuracy of the house type meters. It would not be a sufficient proof of this to know that the record he referred to, was, over a period of time, the record of the totalizing meter, was the equal to the elements that went to make up that sum. It would seem from his description that the apparatus is subject to temperature errors by reason of the employment of an aluminum disk with the magnets dragging against it. As I understand the apparatus, the torque would vary with the conductivity of the material. If that is so, it can hardly be expected that the apparatus, as a whole, would give a very high accuracy, the high degree of accuracy that is given by the induction type meters.

B. H. Smith: In regard to the first discussion there are certainly some advantages to a d-c. system of measuring and there are some advantages to the frequency method. I might say that for about nine months of the year the climate is dry enough so that the leakage does not interfere a great deal, and on the d-c. system, over in Montana, I believe it is true that there has been little or no trouble from leakage. On the Pacific Coast section, on the last seventy or eighty miles of the circuit at times the leakage has reached a value of 94 milliamperes. For certain reasons it is desirable to keep the measured quantity, down around 20 or 30 milliamperes. The leakage is measured on a meter which measures the quantity of direct current going out over the line for the regulating impulse. A good deal of the time this regulating impulse is zero, but as soon as a salt fog comes along, the pointer gradually moves up the scale to perhaps 100 milliamperes, so that if one is using this indication as a quantitative measurement of power, it would be impossible to obtain accurate results on this Coast section. But the frequency is not affected by leakage, and in fact we have no trouble from frequency indication being affected at all.

The lines are affected by inductance and capacity. We have as high as 100 milliamperes alternating current induced from the high-voltage transmission line. For a long time we could hardly make the d-c. relays operate, and we had to very carefully install resonances at each station, so as to reduce the interference to a small value.

Now, about the base frequency, and the measurement of negative power. Fortunately, at the beginning of the line since we are always receiving about 10,000 horse power whether the railroad is running or not, power is measured in the positive direction, and then at Cedar Falls, about one hundred miles away, power flows away from the Railroad System, so right at the beginning the frequency is increased to 30 or 35, and we have a margin for reducing the frequency, at Cedar Falls, and since it is possible for the apparatus to run as low as 20 cycles, power flowing out may be greater than that coming in. The system has to take care of the regeneration of power on the mountains, and if a number of freight trains are running down hill, they may generate as much as 5000 horse power.

I wish to thank Mr. Scott for his kind remarks. I believe he has no questions about the system. It is a satisfaction to finally overcome the difficulties which this system brought out.

Now, Mr. Pratt questions the idea of comparing this system to the watt-hour meter. It is perhaps not to be expected that the accuracy will continue as great as it has appeared to be, and it is hard to believe that it really is as good as a watt-hour meter, and, of course, an error of one per cent is rather serious in the case of a watthour meter.

In regard to the temperature error due to the change in conductivity of the aluminum disks, I may say, first of all, that the disks are not purely aluminum, but an alloy of aluminum, which has a temperature coefficient about half of that of aluminum, so that the error of the disk is about itself 1/5 of a per cent per degree.

Now, at the first station we maintain this 25-cycle base frequency by means of a spring. If one balances the spring against the torque of a disk in a revolving magnetic field, this temperature error would be one per cent in five degrees, but this spring has some thermostatic metal on the end of it, and that takes care of the temperature error.

The temperature of the substation is fairly constant, and likely not to be far different from the temperature of the dispatcher's office. At the first station, and intermediate stations, where we balance the torque of the disk with the Kelvin balance, one would expect this temperature error, but in the voltage circuit of the Kelvin balance there is an external resistance, about half copper and half an alloy which has a zero temperature coefficient. Hence the temperature coefficient of the Kelvin balance is nearly the same as the disk, and the temperature error is practically negligible.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N.Y., February 18, 1921.

MEASUREMENT OF RELATIVE EDDY CURRENT LOSSES IN STRANDED CABLES

BY JAMES A. COOK
The New York Edison Company.

THE amount of energy dissipated by eddy currents in copper conductors is a matter of interest in many branches of the electrical industry. Eddy current losses in stranded copper cables constitute a source of heat. If the alternating flux density is high at usual operating frequencies, the eddy current losses may seriously restrict the conductor rating based on permissible temperature rise. This paper has been prepared, therefore, to describe a method

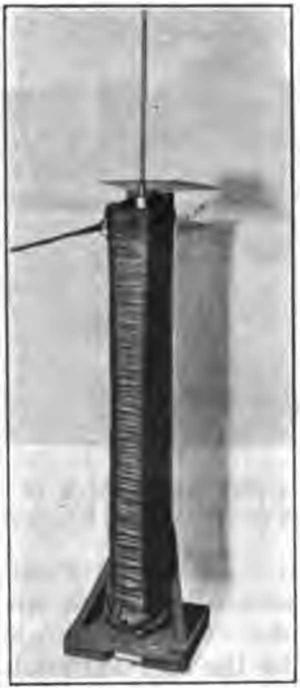

FIG. 1—FIELD WINDING FOR MEASURING RELATIVE EDDY CURRENT LOSSES IN STRANDED CABLE

which will provide accurate measurements of eddy current losses on a comparative basis. The method of test is not advanced as being original with the author, but represents the accumulated experience of the Test Department of The New York Edison Company with several series of tests of this character.

Investigations have been made at various times to determine the effectiveness of various expedients for reducing such losses. These include, for example, (1) impregnating bare cables with varnishes and compounds to insulate the strands from each other, and (2) insulating layers of strands from each other by wrapping the layers with asbestos tape during manufacture of the cable. The relative eddy current loss was determined for the bare and insulated condition; other factors held constant.

FIG. 2—SUSPENSION OF CABLE SAMPLE IN FIELD, SHOWING BIFILAR SUSPENSION AND SCALE FOR MEASURING DEFLECTIONS

Fig. 1 shows an air-core coil wound with three phases to produce a rotating field. The coils are on a five-inch fiber tube 36 inches long. The winding is full pitch, two-pole, each phase consisting of 100 turns of No. 22 A. W. G. insulated copper wire.

A two-foot length of cable to be tested is hung in the center of the coil by a bifilar suspension as shown in Figs. 2 and 3. Care is taken in cutting the sample not to disturb the lay of the strands. A pointer was mounted as shown in the illustrations to indicate the angular deflection of the cable from the free position.

Balanced field currents were then applied. The rotating field so produced set up eddy currents in the stranded cable sample, resulting in torque and rotation of the sample until balanced by the torque of the suspension. The angle of deflection is a measure of the torque which can be determined from the dimensions of the suspension as follows:

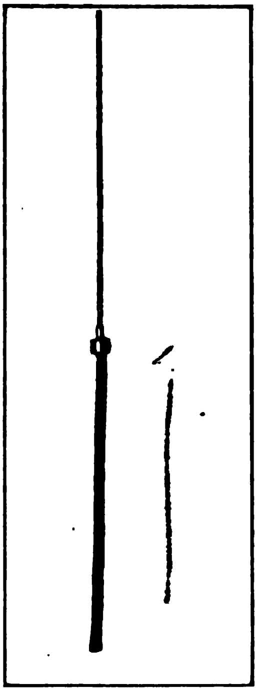

FIG. 3—METHOD OF ATTACHING CABLE SAMPLE TO BIFILAR SUSPENSION

l = length of suspension threads in cm.

d = distance between centers of suspension threads in cm.

m = mass of sample and suspension cap in gm.

g = acceleration due to gravity = 980 cm-sec.^{2}

θ = angle of deflection in degrees.

t = torque due to eddy currents.

$$t = \frac{m\,g\,d^2}{4\,l}\sin\theta \text{ dyne-cm. approximately} \qquad (1)$$

This relation is substantially correct for small deflections. If $l = 100$ cm., $d = 2$ cm. and $\theta = 30$ degrees, the error introduced by using the approximate formula is less than 1 per cent. In the actual tests described below, the error from using this approximate formula is less than in this assumed case.

With the torque determined, the watt loss by eddy currents p may be computed from the known speed of the rotating field.

$$p = 2\,\pi\,f\,t\,(10)^{-7} \text{ watts.} \qquad (2)$$

This use of a bifilar suspension assumes that there is no torsional moment in the suspension and for this reason silk threads are preferable to wire in constructing the suspension.

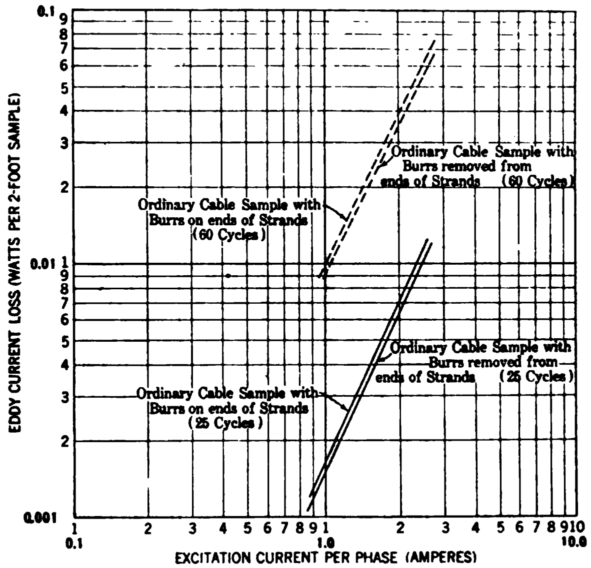

FIG. 4—EDDY CURRENT LOSSES IN COPPER CABLES
650,000-circular mil—37-strand cable

All cable samples were bound at each end and in the center before being cut from the piece. This was done to keep the strands as nearly as possible in their normal condition. The lashings were not disturbed during the test.

At the ends of the sample where cut, there was a slight burring of the strand ends which had an appreciable effect on the losses. These burrs were removed by immersing the end of the sample in sulphuric acid and the amount of error introduced by the burr was determined. The result of this test is shown in Fig. 4. It will be seen that the end effect is comparatively small.

Fig. 5 shows the relative eddy current losses in three samples of 650,000-circular mil, 37-strand cable.

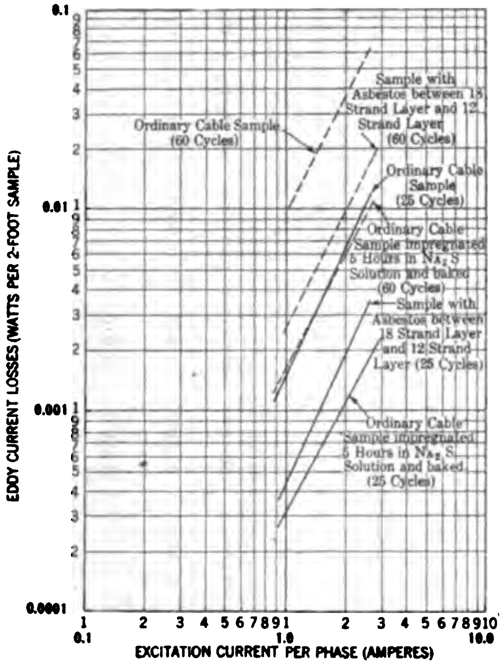

FIG. 5—EDDY CURRENT LOSSES IN COPPER CABLES
650,000-circular mil—37-strand cable

The samples were tested at 25 cycles and at 60 cycles after preparation as follows:

1. Sample cut from cable (no asbestos) and burrs removed from ends with sulphuric acid.
2. Same as in (1) except that the sample was also immersed for five hours in a sodium sulphide solution and then baked one hour at 105 deg. cent.

TABLE I—EDDY-CURRENT LOSSES IN WATTS FOR TWO-FOOT CABLE SAMPLE.
650,000-Circular Mil Cable 37 Strands
Excitation Current 2 Amperes In Each Test

	As cut from reel		After treating ends with H_2SO_4 to remove burrs		After immersion 5 hours in Na_2S solution and baking one hour at 105 deg. cent.		After bending samples treated with Na_2S solution to arc of circle and straightening			
	25 Cycles	60 Cycles	25Cycles	60 Cycles	25 Cycles	60 Cycles	Radius	No. of times bent	25 Cycles	60 Cycles
Ordinary cable sample........	0.0074	0.041	0.0066	0.037	0.0013	0.0061	14 inches	10	0.0011	0.0061
Cable with asbestos tape between 18-strand layer and 12-strand layer............			0.0020	0.010						

3. Same as in (1) except that sample was cut from a cable having asbestos tape separating the 18-strand layer from the 12-strand layer.

Reference to Fig. 5 shows the eddy current losses are very considerably decreased from normal by use of asbestos tape between the eighteen-strand layer and the twelve-strand layer. A greater reduction is effected by taking the bare cable and impregnating it with sulphide solution followed by baking. The effect of this impregnation is to form an insulating film of copper sulphide on the individual strands, thus reducing the eddy current losses. An examination of the samples after treatment showed thorough impregnation of the cable by the solution. The individual strands had copper sulphide coating of uniform thickness and at only very few points was the bare copper visible, thus indicating that adjacent strands had been in exceptionally close contact. To determine if the sulphide coating would withstand bending of the cable, strands were bent until the sulphide coating cracked off. It was necessary to bend to a radius of one or two inches before this resulted. The sulphide solution selected consisted of a 10 per cent solution by weight of sodium sulphide. To every 100 parts of this solution, 5 parts by volume of sulphuric acid (specific gravity 1.20) were added.

Samples of cable were bent to arcs of circles of 14-in. and 18-in. radii respectively, and were then straightened and eddy current loss again measured. One sample was bent to a radius of 14 in. ten times in succession. In this instance the losses were smaller than after one bending. This was probably due to the fact that the strands in the cable started to bulge and consequently were in less intimate contact. Table I gives the comparative results of the series of tests made under the conditions described above with excitation of two amperes per phase in all tests.

Sources of error to be avoided are:

1. Burring of cable strands in cutting sample.
2. Failure to suspend the samples in center of field.
3. Disturbance of strands of sample from their normal position, by bending or careless handling.

With suitable precautions, the results of the tests with apparatus described herein are correct within 5 per cent and serve to demonstrate the effectiveness of the various methods of treating stranded cable to reduce eddy current losses.

DISCUSSION ON "MEASUREMENT OF RELATIVE EDDY CURRENT LOSSES IN STRANDED CABLES" (COOK), NEW YORK, N. Y., FEBRUARY 18, 1921.

J. B. Whitehead: There are two features of this paper that are striking. The first is the method. The author does not claim that the method is new. It is in fact quite old. But I think that every instance of a method in which power is measured in terms of its simplest elements, is interesting. As applied here it is a particularly elegant method, one for determining what the author has called the relative eddy losses.

The second feature of interest is the nature of the losses measured. Where would one find in practise a stranded conductor placed in a symmetrical rotating field. Perhaps this question should not be raised since the method is claimed as being one to measure relative losses only. If the conductor is perfectly symmetrical, then the losses as determined in the rotating field would be proportional, it seems to me, to the losses in a single-phase unidirectional field; and therefore these measurements probably give a correct indication of relative losses in any unidirectional field.

If we look at the problem of the determination of losses in a unidirectional field, there at once comes to mind one of the early methods used for losses, namely, the calorimetric method It seems to me if determinations are to be made on short samples, such as we have here, it would be relatively easy to insulate as regards heat, and by such a method measure directly eddy current losses for unidirectional fields.

R. W. Atkinson: The method that Mr. Cook has outlined is very interesting and seems a very convenient one for measuring the quantities which are actually measured and it seems to have been very successful for this purpose. That is, it should give a relative measure of the eddy current losses in conductors due to alternating magnetic fields caused by currents external to the conductor itself.

However, I believe the method as described is not suitable for measuring eddy current losses in concentrically stranded cables as used for transmitting electric power, that is in other words, for measuring the skin effect in such conductors. Thus, the author shows that insulating the strands of a conductor from each other will reduce the eddy current losses under the conditions of this measurement. However, it can be shown quite simply that the insulating of the strands does not affect the distribution of current in the case of such a conductor while carrying current, except as the distribution may be affected by fields

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N.Y., February 18, 1921.

AN ELECTROMECHANICAL DEVICE FOR RAPID SCHEDULE HARMONIC ANALYSIS OF COMPLEX WAVES*

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IMPROVEMENT in an art requires perfection of detail. Investigation of the details is often delayed, even though the procedure may be well understood, by the large amount of labor involved in handling cumbersome formulas or mathematical processes. The fundamentals of alternating-current theory are based upon a pure sine wave. More careful analysis considers waves formed of many multiple frequencies, which are found to exist in most practical applications. Thus not only the fundamental sine, but its higher harmonics, must be dealt with. The process of splitting up any known wave into its various components is well understood, but is slow and laborious if more than one or two harmonics are required. In present methods of analysis, it is at once striking how many combinations must be made to obtain the result. In mathematical methods this involves the calculation of a host of sums and products, elementary in form, but laborious in procedure. Methods of selected ordinates require many readings of ordinates from the curve, different sets being required for each harmonic. Graphical methods require a large amount of constructional detail. Machines involve changes of gears or pulleys, and many tracings of the curve.

The great ease with which electric circuits may be combined by multiple switches, and the accuracy with

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* This Electric Analyzer was designed and manufactured in the Research Division Laboratories of the Electrical Dept., Mass. Inst. of Technology, where it has been in successful use for some time.

which electric measurements may be made, at once suggests the use of an electric network with some adjustable members to solve the curve under analysis (Bibl. 44). The device about to be described represents one way in which this may be done, and gives sufficient promise to indicate the possibility of great speed and reasonable accuracy with machines developed along these lines.

THEORY

The electric analyzer is based upon the schedule method of analysis, so called because the mathematical processes may be combined in a schedule and save duplication of operations. The fundamental solution of Fourier's series, upon which it is based, may easily be derived as follows:

The series: $y = c_0 + \Sigma\, c_n \sin [n\,\theta + \psi_n]$ may be transformed to

$$y = c_0 + \Sigma\,[b_n \cos n\,\theta + a_n \sin n\,\theta]$$

When substitutions are made of:

$$c_n = \sqrt{a_n^2 + b_n^2} \qquad \text{and} \qquad \psi_n = \tan^{-1}\left[\frac{b_n}{a_n}\right]$$

In all of which expressions a, b and c represent coefficients of the different terms, n represents the order of the term, or harmonic, and is any integer, and θ represents the time function usually expressed by $\omega\,t$. ψ is the phase angle of the harmonic, eliminated in the second expression by the introduction of both sine and cosine terms (Bibl. 4, 5, 6, 13 & 18).

If the area of the curve under analysis is the same on both sides of the zero line, then the term c_0 vanishes. If the curve is symmetrical with respect to its axis, then the even harmonics must be absent, and the values of n will be odd only. As these conditions are both true in most cases of alternating-current machinery, they will be the only ones herein considered.

By proper manipulation and integration, it is found that the coefficients sought are represented by the integrals:

$$b_k = 1/\pi \int y \cos k\,\theta\, d\,\theta$$

and

$$a_k = 1/\pi \int y \sin k\,\theta\, d\,\theta$$

where k is 1, 3, 5 etc.

In order to evaluate these integrals, an auxiliary curve may be obtained from the one under analysis by constructing curves of $y \sin k\,\theta\, d\,\theta$ and obtaining the area with a planimeter. This is the basis of many of the graphical methods. It also is possible to give a planimeter wheel such a motion that the vertical displacement is proportional to the values of y and the horizontal displacement is proportional to $\sin k\,\theta$ or $\cos k\,\theta$. In this case, the planimeter wheel will read the coefficient direct. This is the basis of most of the mechanical analyzers (Bibl. 65 & 82).

Both of these are indirect, however, and in order to obtain a direct mathematical method, further reduction of form must be obtained. It is shown in any text book upon the subject that the summation below represents the integral within certain limitations.

$$b_n/2 = 1/n\, \Sigma\, y_r \cos n/2\ \theta_r = 1/n\, \Sigma\, y_r \cos r\, \pi$$

$$b_k = 2/n\, \Sigma\, y_r \cos k\, \theta_r$$

$$a_k = 2/n\, \Sigma\, y_r \sin k\, \theta_r$$

All that is then necessary is to divide the curve into n equal parts, measure the $(n - 1)$ ordinates, multiply by the corresponding sine or cosine of the ordinate position, and add the results. The sum divided by $n/2$ will give the coefficient sought. The results are accurate, provided that there are no harmonics present of an order higher than the value of n.

The number of ordinates $(n-1)$ must be at least equal to the order of the highest harmonic, and, for waves containing only odd harmonics, need only be taken over one-half the wave. Thus for analyzing for the 1st, 3rd and 5th harmonics, the curve must be divided into six parts giving five ordinates, and if there are no harmonics present greater than the 5th, the results will be accurate within the error of measurement of the ordinates and of calculation. The method is quite old, and if worked out through all its stages, is quite laborious. It is interesting that Kintner

(Bibl. 7) published a set of tables to help the calculations, but did not seem to see the duplications of effort later pointed out by Carl Runge (Bibl. 6 & 16). It is evident that since a large number of sines and cosines are used as multipliers, and as these are taken for definite recurring angles and multiples of angles, there must be a recurring sequence of functions used as multipliers. Runge thus showed that the total number of multipliers necessary was equal to the sines of the angles of division of the curve between 0 and 90. The data thus developed were put into engineering form by S. P. Thompson (Bibl. 10) and became the now familiar harmonic analysis schedule. An eleven-ordinate schedule capable of giving the 1st, 3rd, 5th, 7th, 9th and 11th harmonic, both sine and cosine terms, is given in the Appendix, Table XI.

Probably one of the most serious errors likely to occur in this method arises from the fact that the cosine terms are obtained from the differences of what may be large numbers, and therefore the condition exists where the differences consist of numbers smaller than the accuracy of the original products, and so may themselves be entirely due to error. Steinmetz (Bibl. 14) has worked out a modification of the schedule method to eliminate this source of error, but while mathematically successful, it increases the labor very greatly and so is not generally used. Another difficulty in practical application arises from the fact that higher harmonics are neglected, and a schedule must be adopted which includes a sufficient number of ordinates, so that the higher harmonics may actually be negligible. With an unknown curve, this is more or less guess work, although the highest harmonic present may sometimes be fairly accurately estimated, or the type of curve may be sufficiently familiar for the general magnitude of results to be known. Thus with the magnetizing current of transformers, it is generally known that unless saturations are carried to very high values, the harmonics above the 11th are extremely small, while with alternator wave shapes, a tooth harmonic may be observed as a ripple whose order may easily be estimated. If no ripple is observed, it is probable that no harmonics higher than the 13th exist. The labor required to solve a curve by the schedule method rises rapidly as the ordinates or harmonics increase. The rate of increase of labor is at least proportional to the square of the order of the highest harmonic. Schedules as high as 35 ordinates are given in the California Railroad Commission Report (Bibl. 21). F. W. Gover (Bibl. 18) has also furnished some interesting data upon the error to be expected from neglecting higher harmonics which are present. His results seem to indicate that unless the neglected harmonics are very prominent, the error is chiefly confined to the highest of the harmonics determined by the schedule method, but an analysis of a series such as given by a rectangular wave where the harmonics theoretically extend to infinity, and which requires a relatively large number of terms to approximate the curve, will give an error in all the harmonics determined by the schedule method for eleven ordinates, the error increasing in magnitude as the harmonics determined increase in order. In general, if the schedule method is used intelligently, and with a knowledge of its limitations, it affords a very satisfactory method of analysis.

THE ELECTRIC ANALYZER

The new electric analyzer here described is based directly upon the schedule method, and is in substance an electrical network arranged to give the same result as that obtained by the mathematical processes. If an e. m. f. proportional to the ordinate y_r is impressed upon a conductance proportional to the sine or cosine of the ordinate angle $k\,\theta$, then the resulting current is proportional to their product, and it will be seen that this corresponds to one of the terms of the summation it is necessary to evaluate. Thus:

Let: $e = K_1 y$ and $R = 1/\sin k\,\theta_r$

Then $I = K_1 y \sin k\,\theta_r$

If a number of such circuits are connected in parallel, then the total current flowing will be the sum of the currents in each circuit. Thus, if a five-ordinate schedule is used as a basis, it will be necessary to have five adjustable voltages representing each of the measured ordinates, and a succession of resistances representing the various values of sines or cosines of the various angle multiples. As the ordinates remain the same for each curve, and only the angle functions change, it is evidently possible to have one setting of the adjustable voltages hold for the whole of one analysis, and the required values of resistance may be thrown in by multiple switches. In the use of the simpler schedules, dial switches may be used, but for more complicated schedules, gang switches are necessary to eliminate circulating currents. It will be understood that the current used for obtaining the solution of the schedule is direct current and bears no relation to the alternating-current wave under analysis.

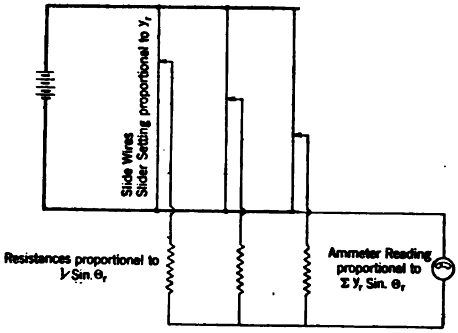

Fig. 1

The analyzer does not analyze an alternating-current wave directly, but an oscillogram must first be taken of it and then ordinates measured at the proper intervals, exactly as would be done for the mathematical schedule method.

The elementary principle is shown in Fig. 1, where three slide wires are used to provide the variable voltage and the sliders are connected from the sliding contacts through proper resistances to a common bus, to which is connected the indicating ammeter. Slide wires are the simplest means of obtaining variable voltage, but of course are subject to the objection that if current is drawn off at the sliding contact, the voltage distribution is no longer linearly proportional. The error involved in the assumption that the voltage is proportional is given by the equation:

$$\text{Error} = \left(\frac{l - x}{x}\right)\frac{R\,x}{r\,l}$$

where R is the resistance of the slide wire, r the resistance connected in series with sliding contact, x the position of contact and l the length of slide wire.

Thus it will be seen that if the series resistance is 500 times the slide wire resistance, the error is 0.1 per cent. As the accuracy of any harmonic analysis seldom exceeds 2 per cent, an error of 0.1 per cent is entirely negligible. Another point that brings in a difficulty is the fact that some of the angle functions are negative and some positive. Therefore, either the voltage or resistance must have two signs. Since negative resistance cannot be obtained for this purpose, it is easier to use a middle tap for the ammeter return circuit on each slide wire. As these middle taps will all be of the same polarity, there will be no current flowing and the position of the slider to the left or

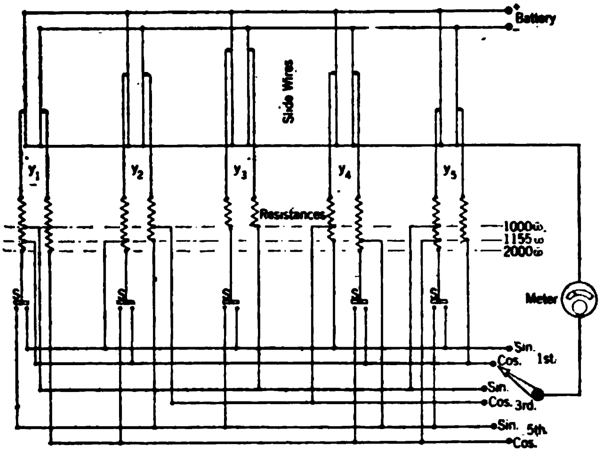

FIG. 2—WIRING DIAGRAM FOR 5-ORDINATE ANALYSER GIVING 1ST, 3RD, AND 5TH HARMONICS

The dial-switch is turned to proper point and coefficient read on meter. The switches marked S, S, S, are mechanically coupled so that they move in unison and are thrown to the right for fundamental components and the left for 5th harmonic. Slide wires 2 ohms each.

right of the middle tap will give an e. m. f. of opposing signs. Fig. 2 shows the connections for a five-ordinate analyzer, the slide wires being folded back at the middle point and two sliders being used, so that they may both be attached to the same member of the device, and the same scale setting used for either positive or negative values, the change being made by switching in the resistance connected to the proper contact, leaving the other one idle. The values of resistance are calculated so that the maximum inherent error due to voltage distortion will be 0.1 per cent. The maximum will only occur in some of the ordinates and so the average error for the instrument will be less than this. The greater the number of slide wires, the less this average error will be. In order to calculate the values of the resistances, the lowest one is taken as 1000 ohms and the others designed to bear the same proportion to this as the sine or cosine desired. Thus

Fig. 3

Fig. 4

the smallest sine is 0.50. The largest is 1.00. Therefore, if the smallest resistance corresponding to the sine value of 1.0 is 1000 ohms, the largest resistance will be:

$$\frac{1.0}{0.5} \times 1000 = 2000 \text{ ohms}$$

The analyzer shown in Fig. 2 will analyze any wave not containing higher than the fifth harmonic and one where the wave does not cross the axis within a half cycle, or, in other words, which has no negative ordinates, as no provision is made for ordinates of more than one sign. This may be taken care of very simply, however, by introducing a reversing switch in each slide wire, which is thrown over when a negative ordinate setting is required. The majority of curves met in ordinary practise do not require this additional refinement.

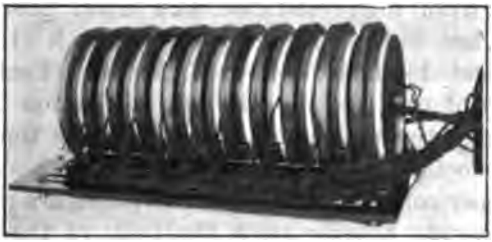

Fig. 5

CONSTRUCTION OF ELEVEN-ORDINATE ELECTRIC ANALYZER

The eleven-ordinate analyzer based upon this scheme is shown complete in Fig. 3, and connected for operation in Fig. 4. The double slide wires, similar to those in the five-ordinate diagram, are wound upon maple plywood disks, six inches, (15.25 cm.) in diameter, with a projecting flange for manipulation. The edge of the disk carries a scale divided into 100 parts for the length of the slide wire, which is a little less than the periphery of 18.8 (47.8 cm.) inches. The three connections to each slide wire are made by flexible cables and carried to busbars along the under part of the face plate, as seen in the front part of Fig. 5, showing the slide wire disks assembled upon the face plate. Each disk projects through the face plate, and the scale reading against a setting line, painted on the face plate, is read through a one-inch slot beside the flange, as may be seen from Fig. 3. The sliding contacts are mounted upon a bakelite platform on the bottom of the face plate just behind the busbars, and consist of two phosphor-bronze springs per disk, bearing upon the two parts of the slide wire. The slide wires are made of No. 25 B. & S. resistance wire having 1.65 ohms resistance each, and, being connected in parallel, give the whole slide wire system a resistance of 0.15 ohms. The resistances representing the angle functions are placed along the inside of the containing box. The resistances are wound from high-resistance wire upon fiber spools 2½ inches (6.35 cm.) long, with ½-inch (1.27-cm.) cores and 1¼-inch (3.18-cm.) flanges. Each spool consists of two sections, the bottom section for connection to the negative contacts and the top section for connection to the positive contacts. For making the proper connections, six gang switches are mounted in a separate housing upon the front of the box, as shown in Fig. 3. These consist of a brass rod with five crossarms which fit between five sets of jaws upon each side. The jaws are all insulated from each other, so that closing the switch to either side, closes ten circuits and connects them to a common bus.

Each switch represents one harmonic, closed to the left for the sine component and to the right for the cosine component. In the position shown in Fig. 3, it is set for the fifth sine component. In this particular machine, two dial switches are also provided for further isolation of resistances. These are shown upon the front edge of the face plate in Fig. 3. These are entirely unnecessary for the operation of the machine and were added purely for experimental purposes to determine the errors resulting from circulating currents, with the point in view of further simplification. The third dial switch on the left is a resistance in the battery circuit for adjusting the slide wire current.

The complete wiring diagram of this instrument is shown in Fig. 6, and the resistance data are given in the appendix.

METHOD OF OPERATION

The current chosen for the slide wires depends upon the instruments available. In Fig. 4, the battery is connected through an auxiliary resistance for adjustment and about 0.20 ampere per slide wire was used in the tests given below. The meter for reading the harmonics was a Paul unipivot milliammeter, the scales of 20 and 2 milliamperes maximum being used. It does not make any appreciable difference what the resistance of the meter is, so a meter of this type is very convenient, as the sensitivity may be increased by multiples of ten by simply turning a switch; and thus the smaller harmonic components read with greater accuracy on the meter than is warranted by the method. If the current in the slide wires is increased five times, which is allowable, the meter required would be a 200-milliampere maximum reading instrument which is of commercial size. The slide wire current will still not be in excess of that easily furnished by a portable storage battery, so the auxiliary devices required are of easily obtainable nature.

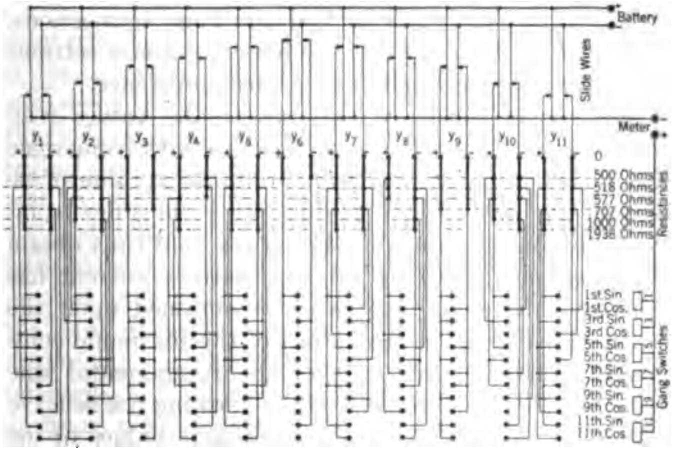

FIG. 6

To make the analysis, the instrument is first calibrated. This is done by setting the disks for a pure sine wave. Red marks are provided upon the scales, so that this can be rapidly done without reference tables. The first gang switch is then thrown to the left, or fundamental sine position, and the resistance in the battery circuit adjusted until the meter reads 100, or any other convenient amount. All other components should be zero. The switches are then turned successively through the other positions, and if the meter reads zero for all of them, it indicates that all connections are correct. This is a very rapid and invaluable check, for it can be made quickly any time and is an almost infallible indication of any open or short circuits, or poor contacts. All the resistances used in the sine fundamental position are used again in some other position, so that it includes them as well. Of course, it will not indicate poor connections, etc., that may develop for different ordinate settings but this has proved to be a very rare occurrence.

The eleven disks are next set to the values read from the curve, which should be done with some scale which will give the maximum ordinate a value of 80 to 100, or some decimal multiple of it, in order to insure the greatest range of slide wires, and thus obtain the maximum accuracy. If the battery current has remained the same, the readings obtained upon the meter will then give the values of the harmonic components directly, in terms of the fundamental sine wave used for calibration. Thus knowing the relative values of the scales used, the actual values of the coefficients may be easily determined. The readings are obtained by simply throwing one switch after the other, first to the left and then to the right, then returning it to the disconnected position and passing to the next switch. No change has to be made in the slide wire disk settings until another curve is analyzed.

Usually the relative magnitude of the harmonics is of more interest than the actual magnitude. This may be obtained directly from the instruments by adjusting the slide wire current, and this appears to be the only type of harmonic analyzer where this can be accomplished. After the disk settings have been made, instead of leaving the battery current the same as for the calibration and check, the fundamental switch is thrown to the sine position, and then the resistance in the battery circuit adjusted until the meter reads 100. Further manipulation of the switches then gives the harmonic coefficients directly in percentage of the fundamental sine. This machine also eliminates the chance of mathematical errors which creep in so easily with the multitude of operations necessary in the usual analysis by schedule.

TESTS UPON ELECTRIC ANALYZER

The tables give a series of tests made to determine the accuracy of the network analyser. A very simple curve was first taken, as given in Table III. The only error will be seen to be the 11th sine coefficient. This is due to an error in the value of one of the resistances connected for this combination, and it will be noticed that this error is repeated in all readings. Increasingly trying combinations of terms were analyzed, and it will be seen that the maximum error occurs in Table IX, and amounts to 3.7 per cent. The value for comparison was obtained by working out the schedule method upon a calculating machine and thus obtaining the best possible accuracy by this method. It is interesting to note that in Tables IX and X for the triangular and rectangular waves, neither method gives accurate results, due to the harmonics above the 11th being neglected, and these types of curves having an infinite number of theoretical terms. Tables VII and VIII give the analyses of an ordinary transformer magnetizing current wave, and a peculiar wave made up of a sine with a superimposed discontinuous function obtained from the thermionic conduction in a three-electrode vacuum tube with alternating current impressed upon the plate circuit. These two curves are similar to the types met with in general practise, and show quite good accuracy, the maximum error being 3.32 per cent in the 11th harmonic and 1.88 per cent in the other harmonics. The last harmonic within range of the schedule will always give the largest chance for error as it means that only one point per cycle is determined, and this is just the requirement for determining the size of the component. Thus a small error in measurement of the ordinate or setting of the machine will introduce relatively large errors in the results.

From these tests and the underlying theory, the conclusion may be arrived at that for the usual type of curve an accuracy of 2 to 3 per cent may be expected from this type of instrument, which is sufficiently accurate for most practical requirements and compares favorably with other methods of analysis. The error in the highest order of harmonic within range of the machine may be somewhat larger than this if the harmonic is prominent, but this is a characteristic of the method and not the particular instrument. The errors are all calculated against the value of the fundamental sine, as this is the fairest method. The importance of

TABLE I

Data on Resistance Coils for 11-Ordinate Harmonic Analyzer.
Arrangement of Coils:

Coil No.	Resistance Taps.
	Top Sections. Plus Connection
1	0 — 518 — 707 — 1938
2	0 — 500 — 518 — 577 — 1000
3	0 — 707 —
4	0 — 577 — 1000 — 1938
5	0 — 518 — 707 — 1938
6	0 — 500
7	0 — 518 — 707 — 1938
8	0 — 500 — 577
9	0 — 707 —
10	0 — 500 — 577 — 1000
11	0 — 518 — 707 — 1938
	Bottom Sections. Minus Connection
1	0 — 518 — 707 — 1938
2	0 — 500 — 577 — 1000 — 1938
3	0 — 707
4	0 — 500 — 518 — 577
5	0 — 518 — 707 — 1938
6	0 — 500
7	0 — 518 — 707 — 1938
8	0 — 518 — 577 — 1000 — 1938
9	0 — 707
10	0 — 500 — 518 — 577 — 1000 — 1938
11	0 — 518 — 707 — 1938

TABLE II

Connections of Resistances for Different Components in 11-Ordinate Harmonic Analyzer.

	Order of Harmonic											
	1		3		5		7		9		11	
Component:	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
Top Coils Plus Connection												
1	1938	518	707	707	518	1938	518	....	707	....	1938	....
2	1000	577	500	Inf.	1000	....	....	....	....	Inf.	....	518
3	707	707	707	....	....	....	....	707	707	707	707	....
4	577	1000	Inf.	....	....	1000	577	1000	Inf.	....	....	1938
5	518	1938	....	....	1938	518	1938	....	....	707	518	....
6	500	Inf.	....	Inf.	500	Inf.	....	Inf.	500	Inf.	....	Inf.
7	518	....	....	707	1938	....	1938	518	....	....	518	1938
8	577	....	Inf.	500	....	....	577	....	Inf.	500	....	....
9	707	....	707	707	....	707	....	....	707	....	707	707
10	1000	....	500	Inf.	1000	577	....	577	....	Inf.	....	....
11	1938	....	707	....	518	....	518	1938	707	707		518
Bottom Coils Minus Connection												
1		....	....	....	....	....	....	1938	....	707	....	518
2		....	....	Inf.	....	577	1000	577	500	Inf.	1938	....
3		....	....	707	707	707	707	....	....	....	....	707
4		....	Inf.	500	577	....	....	....	Inf.	500	518	....
5		....	707	707	....	....	....	518	707	....	....	1938
6		Inf.	500	Inf.	....	Inf.	500	Inf.	....	Inf.	500	Inf.
7		1938	707	....	....	518	....	....	707	707	....	....
8		1000	Inf.	....	577	1000	....	1000	Inf.	....	518	1938
9		707	....	....	707	....	707	707	....	707	....	....
10		577	....	Inf.	....	....	1000	....	500	Inf.	1938	518
11		518	....	707	....	1938	....	....	....	....	....	....

TABLE III

Curve of Equation: $y = \sin\theta + 0.5\sin 3\theta$

Ordinates:

y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
0.612	1.0	1.06	0.866	0.613	0.50	0.613	0.866	1.06	1.0	0.612

Harmonics	Electric analyser		Calculated		Error in per cent fundamental	
	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
1st.	+ 1.0	0	+ 0.9986	0	0	0
3rd.	+ 0.5	0	+ 0.4996	0	0	0
5th.	0	0	+ 0.0016	0	0	0
7th.	0	0	+ 0.0016	0	0	0
9th.	0	0	+ 0.0003	0	0	0
11th.	+ 0.02	0	− 0.0013	0	+ 2.0	0

TABLE IV

Curve of Equation: $y = \sin\theta + 0.8\sin 3\theta + 0.6\sin 5\theta + 0.4\sin 7\theta + 0.2\sin 9\theta + 0.1\sin 11\theta$

Ordinates:

y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
0.978	0.587	0.388	0.297	0.307	0.250	0.307	0.297	0.388	0.587	0.978

Harmonics	Electric Analyser		Calculated		Error per cent fundamental	
	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
1st.	+ 1.0	0	+ 0.9987	0	0	0
3rd.	+ 0.80	0	+ 0.8081	0	0	0
5th.	+ 0.59	0	+ 0.6040	0	− 1.0	0
7th.	+ 0.38	0	+ 0.3884	0	− 2.0	0
9th.	+ 0.195	0	+ 0.1920	0	− 0.5	0
11th.	+ 0.12	+ 0.005	+ 0.0990	0	+ 2.0	+ 0.5

TABLE V

Curve of Equation: $y = \sin\theta - 0.8\sin 3\theta + 0.6\sin 5\theta - 0.4\sin 7\theta + 0.2\sin 9\theta - 0.1\sin 11\theta$

Ordinates:

y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
0.0015	0.013	0.035	0.048	0.623	1.55	0.623	0.048	0.035	0.013	0.0015

(Actual values twice theses values)

Harmonics	Electric analyser		Calculated		Error in per cent fundamental	
	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
1st.	+ 1.0	0	+ 0.9998	0	0	0
3rd.	− 0.79	0	− 0.7980	0	− 1.0	0
5th.	+ 0.58	0	+ 0.5890	0	− 2.0	0
7th.	− 0.39	0	− 0.4030	0	− 1.0	0
9th.	+ 0.22	0	+ 0.2120	0	+ 2.0	0
11th.	− 0.12	0	− 0.1200	0	+ 2.0	0

TABLE VI

Curve of Equation: $y = \sin \theta + 0.2 \cos \theta + 0.5 \sin 3\theta + 0.1 \cos 3\theta + 0.1 \sin 9\theta + 0.2 \cos 9\theta$

Ordinates:

y_1	y	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
0.806	1.073	1.342	0.666	1.130	0.60	0.042	1.066	0.919	0.727	0.560

Harmonics	Electric analyser		Calculated		Error in per cent fundamental	
	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
1st.	+ 1.0	+ 0.18	+ 1.014	+ 0.189	0	+ 2.0
3rd	+ 0.49	− 0.10	+ 0.489	− 0.098	— 1.0	0
5th.	+ 0.018	+ 0.01	+ 0.004	+ 0.003	+ 1.8	+ 1.0
7th.	+ 0.023	− 0.028	+ 0.004	− 0.002	+ 2.3	+ 2.8
9th.	+ 0.013	+ 0.21	+ 0.090	+ 0.195	+ 3.0	+ 1.0
11th.	+ 0.011	− 0.023	+ 0.014	− 0.004	+ 1.1	+ 2.3

TABLE VII

Curve of magnetizing current in transformer

Ordinates:

y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
0.30	0.95	1.03	0.90	0.75	0.60	0.55	0.50	0.42	0.35	0.20

Harmonics	Electric analyser		Calculated		Error in per cent fundamental	
	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
1st.	+ 0.812	+ 0.22	+ 0.8121	+ 0.2165	0	0
3rd.	+ 0.199	− 0.160	+ 0.1933	− 0.1492	+ 0.74	+ 1.23
5th.	− 0.027	− 0.088	− 0.0280	− 0.0886	− 0.12	0
7th.	− 0.041	− 0.020	− 0.0407	− 0.0179	0	+ 2.45
9th.	− 0.041	+ 0.017	− 0.0401	+ 0.0158	+ 0.11	+ 0.12
11th.	+ 0.019	+ 0.038	+ 0.0086	+ 0.0233	+ 3.32	+ 1.85

TABLE VIII

Curve of Sinusoid plus discontinuous peak.

y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
0.60	0.725	0.775	0.775	0.725	0.65	0.75	1.07	1.25	1.15	0.725

Harmonics	Electric analyser		Calculated		Error in per cent fundamental	
	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
1st.	+ 1.065	− 0.165	+ 1.064	− 0.1630	0	+ 0.19
3rd.	+ 0.425	+ 0.098	+ 0.407	+ 0.0940	+ 1.7	+ 0.38
5th.	+ 0.037	+ 0.085	+ 0.037	+ 0.0833	0	+ 0.15
7th.	+ 0.044	− 0.012	+ 0.040	− 0.0098	+ 0.37	+ 0.19
9th.	+ 0 025	+ 0.005	+ 0.0009	+ 0.0050	+ 1.88	0
11th.	+ 0.037	− 0.020	+ 0.0024	− 0.0088	+ 3.30	+ 1.3

TABLE IX

Rectangular Wave:

$y = \sin \theta + 1/3 \sin 3\theta + 1/5 \sin 5\theta + 1/7 \sin 7\theta + \ldots\ldots$

Ordinates are all equal.

Harmonic	Electric analyser		Calculated		Error in per cent fundamental	
	Sin.	Cos.	Sin.	Cos.	Sin.	Cos.
1st.	+ 1.0	0	+ 1.000	0	0	0
3rd.	+ 0.325	0	+ 0.318	0	+ 0.3	0
5th.	+ 0.178	0	+ 0.172	0	+ 0.6	0
7th.	+ 0.099	0	+ 0.101	0	− 0.2	0
9th.	+ 0.058	0	+ 0.055	0	+ 0.3	0
11th.	+ 0.055	+ 0.014	+ 0.018	0	+ 3.7	+ 1.4

NOTE. Errors in above table are calculated against the calculated solution of the wave, since the fact that higher harmonics are neglected introduces large errors in the schedule method and the error figures are intended as a criterion of electric machine accuracy.

TABLE X

Triangular Wave: $y = 4/\pi\,(\sin\theta - 1/3^2 \sin 3\theta + 1/5^2 \sin 5\theta - \ldots\ldots)$

Ordinates:

y_1	y_2	y_3	y_4^{m}	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}
0.262	0.524	0.785	1.05	1.31	1.57	1.31	1.05	0.785	0.524	0.262

Harmonic	Electric analyser		Calculated		Correct	Error per cent fundamental	
	Sin	Cos	Sin	Cos	Sin	Sin	Cos
1st.	+ 1.27	0	+ 1.2805	0	+ 1.2732	− 0.3	0
3rd.	− 0.143	0	− 0.1489	0	− 0.1415	+ 1.2	0
5th.	+ 0.058	0	+ 0.0588	0	+ 0.0509	+ 0.8	0
7th.	− 0.034	0	− 0.0346	0	− 0.0259	+ 0.8	0
9th.	+ 0.025	0	+ 0.0266	0	+ 0.0157	+ 0.9	0
11th.	− 0.018	− 0.001	− 0.0222	0	− 0.0105	+ 0.7	+ 0.1

NOTE. It will be noticed that the errors in the calculated values are of the same magnitude as those in the electric machine. The percentages given in the error column are calculated against the correct coefficients and therefore are chargeable in a large measure to the method rather than the electric device for interpreting it.

TABLE XI

SCHEDULE FOR THE ANALYSIS OF A PERIODIC CURVE IN WHICH ONLY ODD HARMONICS APPEAR UP TO THE ELEVENTH HARMONIC

Note. The two half-periods will be similar, so that if the mean line be taken between the highest and lowest points in the curve, there will be no constant term. For further simplification the origin should be taken where the curve crosses the zero line.

(1) Divide the half-period into 12 equal parts, and measure the 11 ordinates $y_1\ y_2\ y_3\ \ldots\ldots\ y_{11}$; y_0 and y_{12} being each zero.

(2) Then arrange these ordinates as under:

$$\begin{array}{lcccccc} & y_1 & y_2 & y_3 & y_4 & y_5 & y_6 \\ & y_{11} & y_{10} & y_9 & y_8 & y_7 & \\ \hline \text{Adding}\ldots\ldots\ldots\ldots\ldots\ldots\ldots & s_1 & s_2 & s_3 & s_4 & s_5 & s_6 \\ \text{Subtracting}\ldots\ldots\ldots\ldots\ldots & d_1 & d_2 & d_3 & d_4 & d_5 & \end{array}$$

Note. s_1 stands for the sum of y_1 and y_{11}; d_1 for the difference between y_1 and y_{11}. Great care must be taken as to + and − signs throughout.

(3) Group numbers, to obtain values for use with third and ninth harmonics, as follows:

$$s_1 + s_3 - s_5 = r_1$$
$$s_2 - s_6 = r_2$$
$$d_1 - d_3 - d_5 = e_1$$

(4) Then select from the above numbers and put them in their places the table below, *multiplying each by the sine set down in the left-hand column before it is entered.*

Angle	Sine-Terms			Cosine-Terms		
	Harmonics			Harmonics		
	1 & 11	3 & 9	5 & 7	1 & 11	3 & 9	5 & 7
Sin 15° = 0.2588	s_1		s_5	d_5		d_1
Sin 30° = 0.500	s_2		s_2	d_4		d_4
Sin 45° = 0.707	s_3	r_1	$-s_3$	d_3	e_1	$-d_3$
Sin 60° = 0.866	s_4		$-s_4$	d_2		$-d_2$
Sin 75° = 0.966	s_5		s_1	d_1		d_5
Sin 90° = 1.000	s_6	r_2	s_6	...	$-d_4$	...
Total first column	...	...	...	...	...	...
Total second column	...	...	...	...	...	...
Sum	$6\ B_1$	$6\ B_3$	$6\ B_5$	$6\ A_1$	$6\ A_3$	$6\ A_5$
Difference	$6\ B_{11}$	$6\ B_9$	$6\ B_7$	$6\ A_{11}$	$6\ A_9$	$6\ A_7$

Check:

$$A_1 + A_3 + A_5 + A_7 + A_9 + A_{11} = 0$$
$$B_1 - B_3 + B_5 - B_7 + B_9 - B_{11} = y_6$$

the harmonic is usually comparable with its relation to the fundamental, and any method of measurements from a curve cannot be expected to give great accuracy upon a harmonic which may have a magnitude of the same general order as the error of the method of obtaining the curve or the measurement of ordinates. When the great saving of time is considered, what might be called the overall effectiveness of the instrument is quite great.

TIME REQUIRED FOR HARMONIC ANALYSIS BY DIFFERENT METHODS

Harmonic analysis may be effected by three general methods:

1. Mathematical
2. Graphical
3. Instrumental

The time required by graphical methods renders them practically useless except for determining one or two harmonics. They have the advantage of picking out anyone harmonic within the accuracy of the construction, but do not seem to lend themselves readily to large groups of analyses.

The two best known instrumental methods are the Henrici-Coradi machine (Bibl. 55, 65) and the Westinghouse-Chubb polar analyser, (Bibl. 51 and 52). The former consists of five glass spheres, rolling within a carriage so that their displacement is proportional to the ordinates of the curve. The curve in cartesian form is plotted to fairly large scale and followed with a tracer point. Motion of the tracer point in the time-axis direction rotates cages around the glass spheres, the cages carrying planimeter wheels in contact with the spheres. Thus the radius of the circle upon which the planimeter wheel rolls is proportional to sin $k\theta$ and the motion of the spheres is proportional to y. The resulting displacement of the wheel is the solution of the Fourier integral given in the first part of the paper. Each cage carries two wheels at right angles. Thus for one tracing of the curve, the sine and cosine components of five harmonics may be determined. Resetting of the pulleys upon the top of the cages allows another five to be determined with another tracing of the curve.

The Westinghouse-Chubb analyser requires a curve in polar form, obtained from the polar oscillograph, from which a template must be made of cardboard. This is placed upon a platen, which is given a combined rotational and harmonic translational motion. An arm carrying a roller traverses the edge of the template and guides a polar planimeter in its extremity. After one complete trace of the template the reading of the planimeter gives one component of the harmonic for which the machine was set. Gears are then shifted for another harmonic and the process repeated. Unfortunately, the author has no records of time required for analysis by this machine. If high order harmonics are required, the time is rather long, but this is not fair to the machine, since it may easily be motor-driven and other work done while it is grinding out the analysis. Transferring curves from cartesian form to polar form requires a good deal of time and introduces a good deal of chance for error, so it is not satisfactory unless used with polar curves.

Some of the times required for analyses are as follows:

Method	Time	No. harmonics determined	Minutes per coeff.	Authority
Steinmetz........	10 hr.	10	60	D. C. Miller
Schedule.........	3 hr.	8	22.5	D. C. Miller
Schedule.........	1 hr.	8	7.5	F. W. Grover
Schedule.........	2.5 hr.	17	10.6	Author
Schedule.........	15 min.	3	5	D. C. Miller
Coradi Mch.......	13 min.	10	1.3	D. C. Miller
Coradi Mch.......	7 min.	5	1.4	D. C. Miller
Schedule..........	30 min.	6	5.0	Author
Electric Mch......	3.5 min.	6	.6	Author

The figures are not all comparable. They should be corrected for the number of harmonics determined, as the labor is not proportional with the different methods. The figures for the Coradi machine assume the curve already drawn. If the curve has to be enlarged from an oscillograph film, the added time for this should be included. The last two sets of data are based upon the time for doing the actual calculation, the readings from the curve having already been made, and being the same in each case, both times being for analysis of the same curve. The schedule analysis was performed upon a Marchant calculating machine. It can be done quicker with a slide rule, but the errors in the cosine components are then liable to be very great.

CONCLUDING COMPARISON

In conclusion, it may be of interest to compare the advantages and disadvantages of the different methods.

SCHEDULE METHOD

ADVANTAGES	DISADVANTAGES
Simple	Very laborious and slow for more than a few coefficients
Requires only a small chart for direction	Not accurate where harmonics exist outside range of schedule.

Fairly accurate within theoretical limitations.	**Subject to error unless calculating machine used, particularly in cosine components.**
Reasonably fast for a small number of coefficients.	

WESTINGHOUSE-CHUBB

Accurate	**Requires cardboard template of polar form.**
Easy to operate	**Difficult to use with curves in Cartesian form.**
May be motor-driven and so require little labor.	**Requires separate trace for each component.**
Semi-portable	**Moderately expensive.**
Not difficult to obtain	Construction requires much machine work.
Easy to maintain	

HENRICI-CORADI

Accurate	Requires large curve.
Easy to operate	Special table, tracks, etc., must be provided.
Quick	Can only be manufactured by expert instrument makers.
Five harmonics completely determined with one trace.	Expensive.
	Difficult to obtain
	Requires care for maintenance.
	Not portable.

ELECTRIC

Easy and simple to operate.	Subject to limitations inherent with schedule method.
Moderately accurate and eliminates many chances for error.	Subject to usual difficulties of electric networks.
Very quick, as only one group of readings required from curve.	Not extremely accurate.
Reads coefficients either in actual values or per cent of fundamental sine component.	**Number of resistances increases rapidly with order of harmonics.**
Easy to construct, requiring common materials and little expert workmanship.	Requires storage battery and meter in addition to analyzer itself.
Inexpensive	
Easy to maintain	
Auxiliary apparatus of common form.	

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DISCUSSION ON "AN ELECTROMAGNETIC DEVICE FOR RAPID SCHEDULE HARMONIC ANALYSIS OF COMPLEX WAVES" (DELLENBAUGH), NEW YORK, N. Y., FEBRUARY 18, 1921.

V. Karapetoff: This device is of considerable interest, not only for the solution of the specific problem for which it has been designed, but also as opening new possibilities in the solution of other electrical problems. Now and then we have to solve a system of linear differential equations, or algebraic equations of the first degree, maybe two or five or more, depending upon the nature of the problem, and this is a tedious process. If we know of a physical phenomenon, which mathematically, is reducible say to a system of linear equations of the first degree, then we can set that apparatus and let the laws of nature solve the equations. To illustrate—in an electrical network with given sources of constant voltage and given resistances, the Kirchoff equations for the unknown currents are simultaneous equations of the first degree. So if you want to solve the network, as a rule you have to solve a system of such simultaneous equations.

Now, conversely, suppose that in some problem in engineering or in physics, we have to solve a number of simultaneous equations of the first degree; this may not be an electrical problem at all. Then, if we could arrange an experimental network of conductors with ammeters in various branches and set the e. m. fs. and the resistances of these branches to represent the constant coefficients of the given equations, the ammeter readings would give us directly the values of the unknown quantities. In this way we can make the laws of nature do work for us, that in pure mathematics would be tedious.

Mr. Dellenbaugh does not claim that his device is a universal substitute for all other methods and devices for harmonic analysis. As he himself states, it is only one of the methods which has certain advantages and certain disadvantages. Perhaps the most evident disadvantage is that of a limited number of disks and therefore of a limited number of ordinates, to be taken on the given curve. But I hope that he will continue to work on this idea, and will develop a device that will enable us to analyze harmonics with the highest possible precision, and also will enable us to take automatically into account smaller irregularities, due to much higher harmonics. For instance he mentions Prof. D. C. Miller's work on curve analysis which has been largely in acoustics, where harmonics of higher order are of prime importance. This problem of curve analysis will never be considered as completed until we develop an instrument by means of which the amplitude and the phase position of a desired harmonic can be obtained almost automatically with a comparatively simple setting of the device.

A. E. Kennelly: When in laboratory practise only an occasional oscillogram calls for analysis, it is ordinarily dealt with by some schedule method, and recourse to mechanical apparatus for deriving the harmonic components is not important. When however, many and frequent oscillograms have to be analyzed, the schedule routine becomes burdensome and tedious. In such cases, a device like that which Mr. Dellenbaugh has described in his paper becomes very useful, not merely because of the time saved in its use, but also because of the greatly reduced liability to accidental arithmetical errors. The device does nearly all of the arithmetic automatically, and indicates the answer on the dial of a milliammeter. If there is any question as to the accuracy of the results in a given recorded case, it becomes an easy matter to repeat the analysis with the device, and obtain a check on the numerical work; whereas the repetition of the work of arithmetical schedule analysis, when carried to a number of harmonics, is often a sufficiently serious task to make the attempt unlikely.

F. S. Dellenbaugh, Jr.: I do not wish to claim undue credit of originality for applying electricity to algebraic solutions of equations. Mr. Arthur Wright, (Bibl. 44.) has done some beautiful work along these lines and built a machine which was not only capable of the solution of ordinary equations but which could also introduce empirical curves. In this machine logarithmic resistances were built by winding wire around a logarithmic shaped form, which then was moved along a scale, forming a sort of electric slide rule. A carriage supported other wires making sliding contact with a bank of these logarithmic resistances. The position of the resistance determines the coefficients of each term and the slope of the sliding wire determines the exponents. By bending the sliding wires to special curves, variable exponents, and thus empirical curves, can be introduced.

As Dr. Karapetoff remarked, the ultimately most desirable machine for harmonic analysis is one which will give all the desired coefficients of the various terms of the Fourier series, after one trace of the curve. This is the ideal which I still hold before me, and undoubtedly some day it will be accomplished. One method of doing this which has occurred to me would be to have a rolling carriage which moves in the direction of the abscissas. This would carry a stylus moving in the direction of the ordinates. The method upon which it is based is the Kennelly or Fischer-Hinnen method of selected ordinates. With this type of analysis it is only necessary to add and subtract selected ordinates, but special ordinates must be selected in different places for each harmonic to be determined. Thus the rollers of the carriage could carry contact drums closing a circuit at the proper values of ordinates. The stylus could impress voltages in this circuit proportional to the ordinates by a drop wire and sliding contact moved by the stylus. If a fixed resistance and meter, of the Grassot Fluxmeter type, were connected in the circuit, then the reading of the meter after a trace of the curve would give any harmonic coefficient for which the parts were designed. A multiplicity of contact drums, circuits and meters would enable the determination of a multiplicity of harmonics. However, there are a number of practical drawbacks to this scheme, notably that the meter must be one with a large moment of inertia and zero restoring moment, which is a difficult thing to build, and maintain, and one of these would be required for each harmonic to be determined.

There are innumerable ways in which harmonic analysis can be done, all more or less successful and practical, but all having some features of cost, time, or inaccuracies which renders them undesirable. It is extraordinary that a process which can be done in so many ways has no quick and immediate solution.

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THE LIMITATIONS OF THE STOP WATCH AS A PRECISION INSTRUMENT

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IN MANY scientific and engineering measurements the quantity, time, is an important factor. Its value may be required within widely varying limits of accuracy. A high degree of precision can of course be obtained with our present-day astronomical clocks in proper environment and their usefulness greatly extended by electrically relayed circuits. This method, however, is cumbersome, leaves much to be desired and is not generally applicable to laboratory measurements, not to mention the wide variety of field work. The result is, the more convenient stop watch is frequently the criterion used in judging intervals of from a few seconds to periods between appointments with the dentist.

Believing that the characteristics are not generally appreciated by the user, it is the purpose of this paper to point out the limitations of the stop watch in precision measurements. It will not be necessary to discuss such relatively classical adjustments as "isochronal" and "thermal," as errors due to these sources are entirely masked by those due to the principle of operation, mechanical restrictions, and design.

The several types of watches to be discussed will serve to illustrate the sources and character of the errors in those commonly used. Claim is not made that all types are shown nor is it the purpose of this paper to choose among the types.

APPLICATIONS

A great majority of the stop watches made are sold to the non-technical public who put them to the use of an ordinary timepiece, and occasionally time sporting events. Obviously, they are designed and manufactured to meet the demands of this class of trade. As their use as timekeepers is of first importance, they are made in many grades. To these grades are added the start, stop, and reset mechanism of the sweep second hand, and which in the case of a given make, is the same for all grades. Therefore, the limitations of a given type of stop mechanism of a given make are the same in the low and high-priced watch.

As used by the technical public, the performance as a stop watch is the prime requisite. The accuracy of many scientific and engineering measurements is limited by stop watches' inaccuracies. Designed to meet the needs of the non-technical public, where the stop mechanism is used a few times a year, it is not robust enough to stand up under the demands of engineering tests, as for instance, the calibration of watt-hour meters, where a day's use exceeds several years non-technical use.

Experience of over twenty years in a manufacturing organization, with over four hundred stop watches, (including thirteen makes and nineteen models), shows that nearly all are in the repair shop every two months and in cases where the use is more nearly continuous, as in meter testing, operation tests, etc., the repair shop intervals do not exceed two weeks.

COST VERSUS TIME KEEPING

The ideas of the technical public as to what constitutes the best stop watch vary greatly. Many think the more costly the better. That this view, when applied to a stop watch, is wrong, will be made evident.

One of the big factors of cost of a modern timepiece is the adjustments for running in any position. Essential to these adjustments are the jewels of the train. Where the adjustments are approximate, only a few are required. Where the adjustments are to be precise, many are required and the cost is increased out of proportion. Precise adjustments cannot be made without many jewels and high cost, but it does not necessarily follow that with a large number and high cost one obtains precise adjustments; this idea is common as any jeweler can affirm, and accounts for the catch-penny watches of obscure make upon the market.

The function of the jewels, as you all know, is to reduce friction to a minimum, that the energy imparted to the balance may be the same with each tick, altered as little as possible by the variable wear, as time goes on. The disposition of these jewels and their bearing upon the requirements of a stop watch will be considered.

A very important timekeeping requisite is that the balance in its oscillations shall swing unhampered in any way. This requirement is an inherent source of error for a stop watch and will be considered together with the jewels at this point.

Fig. 1 is a diagrammatic sketch showing the disposition of the principal parts to be jeweled. Starting with the wheel marked "barrel" containing the mainspring, the force of which acts through the center or second wheel, the third wheel, the seconds or fourth wheel, the escape wheel, the pallet fork arbor to the balance, the speed of revolution increases in the order named. The force acting upon the bearings to produce friction, however, is greatest at the slowest speed. The disturbance, due to friction and wear, is greatest on the fast moving bearings. The importance of jewels is greatest at the balance and diminishes as the barrel is approached. The practise varies greatly. The most common, and certainly the most important is a seven-jewel movement. These jewels are disposed two at each end of the balance staff, the roller jewel and the two jewels of the pallet engaging the escape wheel. Of the two at each end of the balance staff

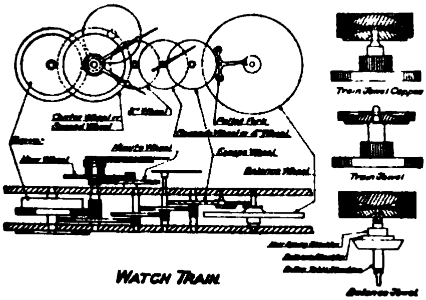


FIG. 1

one acts to center the staff (ring stone), and the other to limit end play (end stone). Their general shape and the staff are shown at *A*. The diameters of the pivots are made as small as possible, in some cases 0.002-in. diameter, to reduce friction. The roller jewel in the roller table is of special shape, varying in different makes.

The next common arrangement is the fifteen-jewel movement obtained by adding ring stones to the bearings of the pallet fork, the escape wheel, the fourth wheel, and the third wheel.

Seventeen jewels are obtained by adding two ring stone jewels to the center wheel.

Nineteen-jewel movement is obtained by adding two jewels to the barrel between the barrel and its staff, or by adding two cap jewels to the end of the escape wheel staff. An additional number of jewels is obtained by adding caps to the remainder of the train.

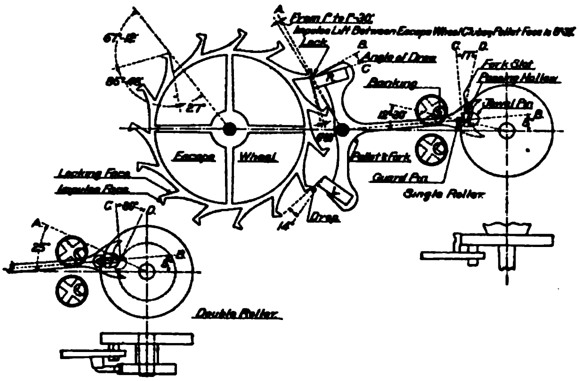


FIG. 2

Fig. 2 gives some of the more important characteristics of the modern escapement showing the escape wheel and its connection with the balance through the pallet and fork.

The escape wheel is shown locked against the pallet stone *R* at position marked "lock." The pressure of the mainspring at this point holds the fork against the upper banking pin.

The roller jewel marked "jewel pin" is shown carried into contact with the fork slot by the balance rotating in a counter-clockwise direction. Some of the energy in the balance wheel will be expended in carrying the fork through an angle of from one to one and a half degrees, the angle of lock, backing up the escape wheel against the mainspring. At this point the impulse face of the escape wheel club comes in contact with the impulse face of the pallet jewel *R* and energy is transferred from the mainspring to the balance carrying the pallet and fork against the lower banking pin, the jewel pin on the balance being released from the slot. The balance then continues free motion until its energy, minus that of friction, is transferred to the hair spring where the spring reacts to return the balance and the operations are repeated. The balance swings nearly a full revolution to the right and to the left from its position of rest. The actual excursion depends upon the force of the mainspring acting at the escapement, (friction losses in the balance and other moving parts, etc., are neglected). In general, the excursion of the balance is 680 degrees of motion. The roller jewel is in contact with the pallet and fork through 60 degrees of its motion. The pallet fork moves through an angle of ten degrees. Of this angle, a degree and a half to two degrees are necessary for lock and drop. Through the remainder of the angle the escape wheel, and therefore the train are in motion. The corresponding angle of the balance wheel is from 48 to 51 degrees. From this it will be seen that the train has an intermittent motion, being in motion during the time that the balance swings through its center position at its maximum velocity. The train is in motion while the balance swings through 0.07 of its excursion. The corresponding time is 0.01 of a second, the period of the balance being 0.2 sec. or a frequency of 18,000 beats per hour, 300 beats per minute.

ERRORS OF A MECHANICALLY PERFECT STOP WATCH

From the foregoing, it will be seen that the sweep second hand of a stop watch is in motion but a small part of the time during an observation. In timing an event the watch may be started just after the escape wheel has been released and stopped, just before the escape wheel is to be again released, in which case the time observed at the sweep second hand would be too short by one beat or $^1/_5$ of a second. The start and stop can also be so timed that the error will be one beat too much. Therefore, two mechanically perfect watches used to time the same event may disagree by $^2/_5$ of a second or 1.3 per cent in a thirty-second reading or both watches can be in error by half this amount plus or minus as the second limit.

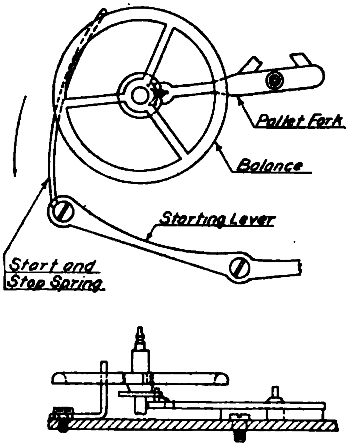


FIG. 3

RATE

Watches to be adjusted to keep time with extremely small variations must of necessity have many jewels. The cost of such a movement is not warranted in a stop watch. First, because the load to be carried by the train varies considerably whether the sweep second hand is running or not, and second, because careful adjustments made at the factory are almost invariably destroyed when the watch is repaired by the average jeweler.

An alarm clock without jewels can readily be regulated to keep time within one minute, in twenty-four hours. This rate for an interval of one minute, produces an error of ±0.04 second. The inherent error of a mechanically perfect stop watch is five times this amount. While the rate of an alarm clock as used is sufficiently precise for use as a stop watch, it is true that it cannot be carried about without seriously disturbing the rate.

The addition of a few jewels properly applied as in the case of the seven-jewel movement removes this objection and permits even a closer rate adjustment. The addition of more than seven jewels serves only to reduce an already negligible error.

ERRORS DUE TO METHODS OF APPLICATION OF START AND STOP MECHANISM AND MECHANICAL IMPERFECTIONS IN SOME TYPICAL STOP WATCH DESIGNS

The simplest, cheapest, and perhaps the most common stop watch is one without the usual hour and minute hands, having seven jewels. This watch, of Swiss make, is supplied to the trade under many names and models, differing slightly. The principle of operation is the same in all cases. The sweep second hand and minute hand, if any, are started and stopped by starting and stopping the balance.

FIG. 4—JOCKEY CLUB
Under the dial with hands removed.

Fig. 3 is a sketch showing how this is carried out in the type known as "Jockey Club." The balance and starting lever are shown in the stopped position. Pressing the stem, (not shown), starts the balance by snapping the starting lever about the right-hand screw, dragging the start and stop spring along the edge of the balance in the direction of the arrow, thereby setting the balance in motion.

Pressing the stem a second time stops the balance by returning the lever to the position shown.

Pressing the stem a third time returns the hands to zero by means of a "fly-back lever" and heart cams. These are shown in Fig. 4, a view with dial removed. The sweep second hand is removed from the small heart cam in the center of the plate and the small minute hand from the large heart cam. The fly-back lever as shown is ready to return the hands to zero by striking these cams.

Frequent pounding of these cams by the fly-back lever which strikes a heavy blow enlarges the holes in the plate and in the heart cam sleeves, which are of brass, causing the sweep second hand to jump forward or backward on being started or stopped.

The heart cams and hands cannot be rigidly attached to the staffs in this type of watch, as returning them to zero position must necessarily move the whole train, therefore, they are friction driven. The C-shaped springs seen on the heart cams provide this drive. One end passes around a pin at the point of the cam and the other end passes through a slot in the sleeve, bearing against the staff which is slightly recessed to prevent the heart cams moving along the staff.

The C-spring is an additional source of error, for if tension is too weak it will not drive, and if too strong, friction with the staff causes a rolling action between spring and staff while being returned to zero, producing a torque between the two members at zero. This torque results in the sweep second hand jumping ahead or back upon starting, the direction depending upon whether the hand returned to zero from the right or left. This error increases as the holes in the sleeves are enlarged. It is seldom less than $^1/_5$, usually from $^2/_5$ to $^3/_5$, and frequently $^4/_5$ of a second or more.

Another source of error common to all types using heart cam return is due to adhesion of different amounts between the fly-back lever and each cheek of the heart cam. This causes the sweep second hand to be pulled ahead or back as the fly-back lever recedes when the watch is started. This error would still further be increased by the magnetization of the fly-back lever and heart cams. Once magnetized, it is practically impossible to remove the last trace of magnetism unless heating is resorted to, which is out of the question.

The magnitude of this error can be determined in a given case by repeatedly pressing the stem while the balance is prevented from running with the aid of a camel's hair brush, meanwhile noting the position of the second hand. The added error, due to the C-spring, must be noted while the balance is free, as shown by trial, after returning the hand to zero from the right and left.

FIG. 5—JOCKEY CLUB

Still another source of error present in all types to a greater or less degree is the effect of the jar due to starting and stopping operations upon the unbalanced sweep second member. This error may produce a movement of the hand forward or backward when starting or when stopping.

Perhaps the most serious error in this type of watch, certainly the most disconcerting one for the engineer, is due to the method of starting and stopping. It is problematical at what position of the balance swing the stop wire will interfere with the balance as the starting lever returns to the stop position. If the interference results in turning the roller jewel out of the fork so far that when started it will carry the pallet fork to the opposite banking pin, all well and good, but it sometimes happens that when started, the roller jewel just returns to the fork without enough force to carry the fork over, and the watch does not start. More frequently the roller jewel returns to the fork with just sufficient force to carry it over, swinging a short distance beyond, with the result that an appreciable time is required for the balance to pick up to full motion. As the isochronal adjustment of these watches is in general very poor, considerable error results.

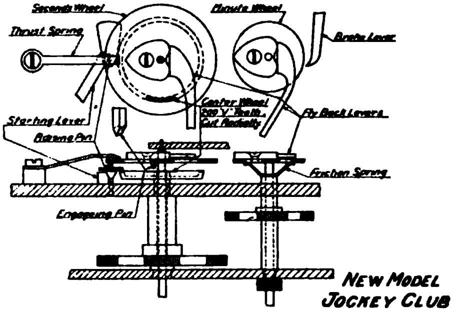


FIG. 6

Fig. 5 is a back view of this type where the start and stop spring can be seen projecting slightly beyond the edge of the plate to the right. This picture gives a good idea of the general appearance and the relative positions of the starting lever and balance.

Fig. 6 is a diagrammatic sketch of the new model Jockey Club. This model is without the usual hour and minute hands. The timing train runs continuously. The heart cams and hand are rigidly mounted on opposite ends of a staff forming the sweep second member. The staff of the seconds wheel of the timing train is hollow and surrounds the staff of the sweep second member. The parts shown in the sketch are in position ready to start. The operations are as follow:

Pressing the stem, first removes the fly-back levers from the heart cams an instant before the starting lever moves away from the cone on the staff beneath the friction disk on the sweep second member. The removal of the starting lever allows the thrust spring to force the sweep second member downward until the engaging pin on the friction disk engages with the center wheel of the timing train, thereby carrying the sweep second hand forward in unison with the timing train.

Pressing the stem a second time returns the starting lever to the position shown, striking against the cone, elevating the raising pin, which, in turn, disengages the engaging pin and stops the second hand.

Pressing the stem the third time causes the fly-back levers to strike the heart cams, returning them to the position shown.

Errors most noticeable in this type of watch are due to play in the bearings of the raising pin, aggravated by the hammer blow action of the starting lever. The friction disk to which the heart cam is attached is clamped between the end of the raising pin and the thrust spring. During the process of engaging and disengaging with the center wheel, the downward motion of this disk forces the cone along the surface of the starting lever, resulting in a torque at the disk. This is further aggravated by the fact that the thrust spring, in moving up and down, produces friction that is not applied radially. These torques cause the sweep second hand to jump forward or backward when started and when stopped.

As previously pointed out, the timing train has 300 positions of rest per minute and is in motion 1/100th of a second in each 1/5 of a second. The center wheel has 200 *V*-shape teeth. If these teeth are adjusted so that the pin falls directly into the tooth space with the fork against one banking pin, it will not again fall directly into a tooth space until the fork has made three trips.

The magnitude of these errors can be observed by repeatedly pressing the stem while the fork is held against each of the banking pins in succession. An additional difficulty is met due to the action of the brake lever on the minute wheel. This wheel is driven by a friction spring to the minute wheel of the train. The hook end of the brake lever is applied to ratchet teeth at the edge of the minute wheel holding it against the operation of the train through the friction spring. If the torque of the friction spring is too great, the motion of the balance will be greatly reduced. If too small, it will not drive.

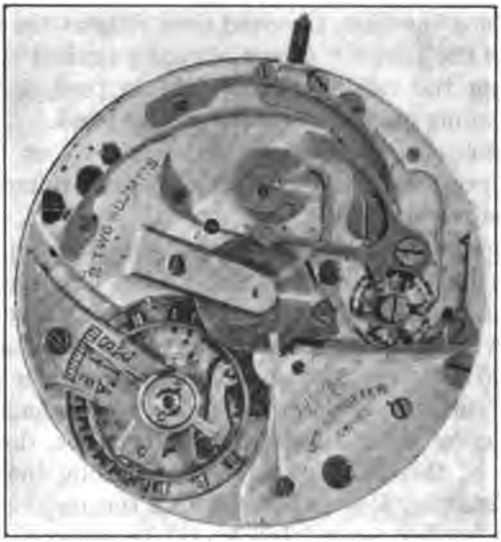


FIG. 7—NEW MODEL JOCKEY CLUB

Fig. 7 is a view of the back of the watch showing clearly the relative positions of the fly-back lever, heart cam friction, disk and spring.

Another method for starting and stopping the sweep second hand is one in which the sweep second member carries a toothed wheel. An intermediate shaft carrying a coarse tooth pinion at the lower end, engaging with the fourth wheel of the train running with it continuously, carries at its upper end a fine toothed pinion. This pinion is engaged with the toothed wheel to start, and disengaged to stop the sweep second hand.

Fig. 8 is a diagrammatic sketch of a watch of this type known as New York Standard. This type of watch has in addition to sweep second hand, the regular hour and minute hands.

Parts are shown in position ready for start. The operations are as follow:

Pressing the stem the first time turns the cam wheel, raising fly-back lever from heart cam just before intermediate is allowed to fall into mesh with the center seconds wheel starting sweep second hand.

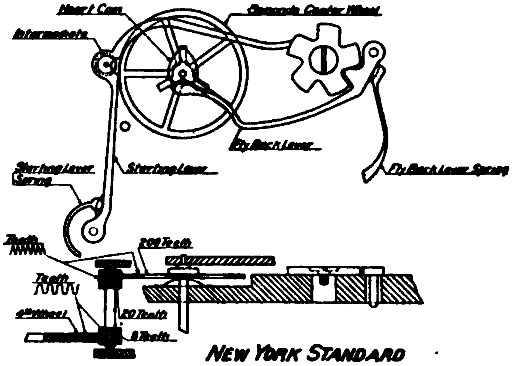


FIG. 8

Pressing the stem the second time disengages intermediate, stopping second hand.

Pressing the stem the third time allows fly-back hammer to strike heart cam, returning second hand to zero (position shown).

Sources of error in this type of watch are due to necessary play between the coarse tooth pinion and the fourth wheel, and play in the bearings of intermediate shaft. This amounts to $^4/_5$ of a second or more. The magnitude can be determined by putting parts in the running position, and with the balance stopped note freedom of sweep second hand necessary to take up lost motion to fourth wheel. If it were not for the three-legged friction spring, the sweep second hand would whip back and forth by this amount with each beat of the watch. The error due to this cause is uncertain both as to magnitude and sign within the limits specified.

Additional errors are due to the seconds center wheel having 200 teeth, while the intermediate has 300 positions of rest.

The intermediate gear strikes the same point on the seconds center wheel each time at starting.

Constant operation causes teeth to be deformed and produces jumping of the sweep second hand upon starting.

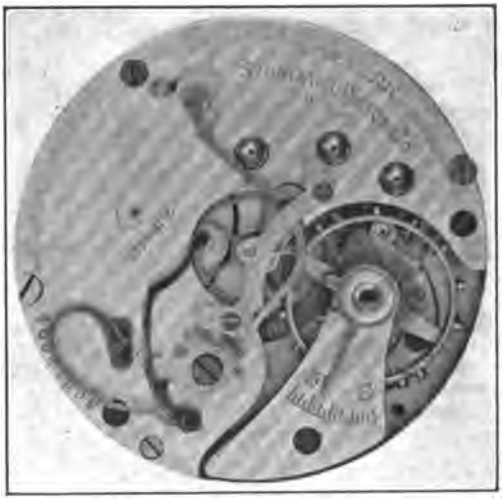


FIG. 9—NEW YORK STANDARD

A jar on starting and stopping affects the sweep second member.

Fig. 9 is a back view showing the relative position of intermediate, starting lever, fly-back hammer, and tooth wheel, on sweep second member.

Fig. 10 is a more complicated movement of the same type, of Swiss manufacture. This movement has, in addition to the sweep second hand, a minute counter advanced upon the completion of each revolution of the sweep second member. This is a regular fifteen-jewel movement with the addition of two ring stone jewels on the upper staffs of the sweep second member, and minute counter staffs, probably for appearance only as similar jewels are not found upon the lower ends.

Fig. 10—Swiss Watch
With similar acting parts to the New York Standard.

In another type of movement the sweep second member is started and stopped by an intermediate gear running continuously with a similar gear mounted on the fourth wheel arbor above the back plate. The

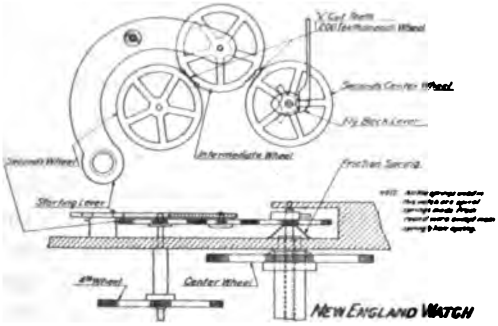


Fig. 11

intermediate gear is thrown into and out of mesh with a tooth wheel on the sweep second member.

Fig. 11 is a diagrammatic sketch of a watch of this type known as the New England. Sequence of operations is the same as described for the New York Standard type. The principal errors in this movement are due to 200 V teeth being used on all three wheels while the balance has 300 positions of rest. The intermediate gear strikes the same point on second center wheel deforming the teeth. Play in teeth of intermediate and fourth wheel, play in the teeth between intermediate and seconds center wheel, which play must be quite large as intermediate is carried bodily about a pivot located not at the center of the seconds wheel. The intermediate in engaging with the center seconds wheel is made to rotate about the seconds wheel on the fourth wheel arbor. This usually causes the second hand to jump forward or backward upon starting, depending upon the distribution of the three wheels in different types of watches. This jump is augmented by the errors previously noted and frequently amounts to $^2/_5$ of a second.

FIG. 12—NEW ENGLAND WATCH

Fig. 12 is a back view showing the relative position of seconds wheel intermediate, center seconds wheel heart cam, and fly-back lever.

Fig. 13—Allion à Versailles
For aviation in France.

Fig. 13 is a Swiss movement of a similar type, showing the relative positions of parts.

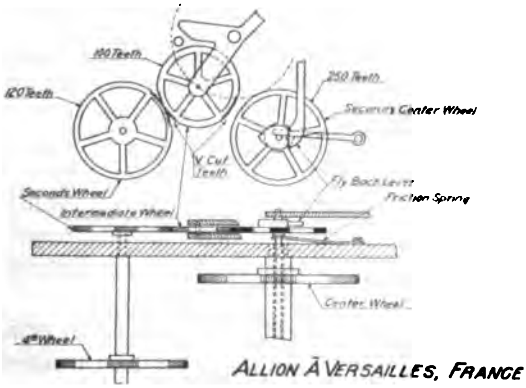


Fig. 14

Fig. 14 is a diagrammatic sketch of the same watch known as "Allion a Versailles," France. The criticism of the New England watch applies to this type.

It will be noted that the intermediate swings about a pivot, less favorably located for accuracy, and that the number of teeth is still not in agreement with the train positions of rest. The majority of the high-grade watches, (by that meaning high price) follow this general principle of operation.

Another principle of operation is that a small intermediate is made to engage with seconds wheel and second center wheel.

FIG. 15—SPLIT SECONDS SWISS WATCH WHICH HAS ONLY THE TWO SWEEP SECOND HANDS AND MINUTE HAND

The parts shown here control one sweep second hand and the minute hand. Balance runs all the time.

Fig. 15 is a back view showing the distribution of parts of a split second timer without the usual hour and minute hand. It shows clearly the imitation compensated balance.

Fig. 16 is a view with the dial removed showing the distribution of parts necessary to operate the secondary sweep second hand that can be stopped independently of the main hand.

Fig. 17 is a diagrammatic sketch of a watch of this type known as the Trenton watch, manufactured in this country many years ago.

The starting and stopping operations are as follows: Parts are shown in the running position. Pressing the stem the first time stops the sweep second hand by causing the starting lever to move to the left, striking the upper edge of the disk clamped to the staff supporting the intermediate, thereby turning the intermediate about this staff out of contact with seconds center wheel. This event takes place an instant before the brake lever falls in contact with the seconds center wheel, thus securely holding the sweep second member in position.

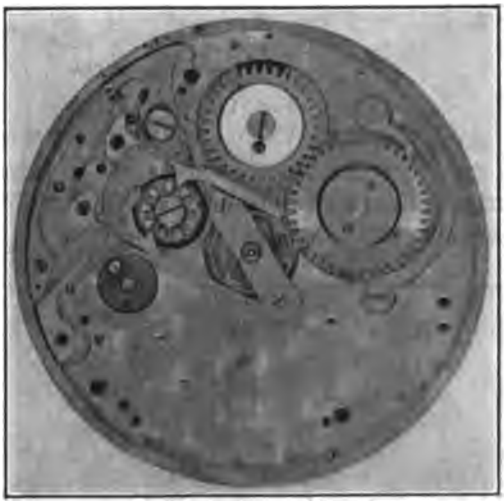


FIG. 16—SPLIT SECONDS SWISS WATCH

The parts shown here control the second sweep second hand. The function is to stop the hand, and release to continue in step with the other sweep second hand to a point at which it is to be stopped again. In other words this hand can only be stopped or released to run with the other sweep second hand.

Pressing the stem the second time causes the sweep second member to return to zero position by the fly-back hammer striking heart cam, the brake lever having been removed from sweep second member an instant before.

Pressing the stem a third time starts second hand by removing the starting lever from the disk on the intermediate, allowing the intermediate to engage, the fly-back lever having been removed from heart cam an instant before. In this watch it will be noted that the

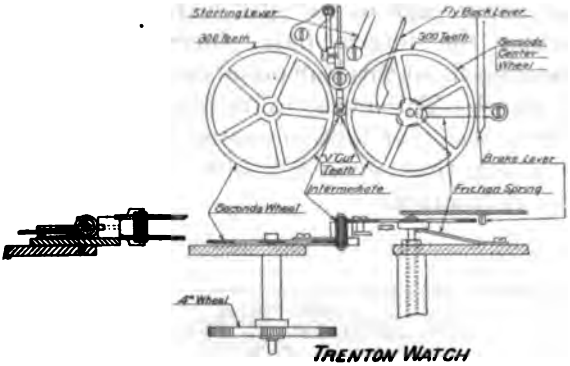


FIG. 17

seconds center wheel and seconds wheel on fourth wheel arbor have each 300 V-teeth: the error due to this source is consequently negligible.

FIG. 18—TRENTON WATCH

The source of errors in this type are due to the intermediate striking at the same point on sweep second member repeatedly at start and end play in the supporting member. Movement of staff of sweep second member, due to application of either brake or intermediate upon stopping or starting, causes the hand to jump forward or backward. This is due to the necessity for clearance between the staff of the sweep second member and the hollow staff of the train, having no bearing provided above seconds center wheel.

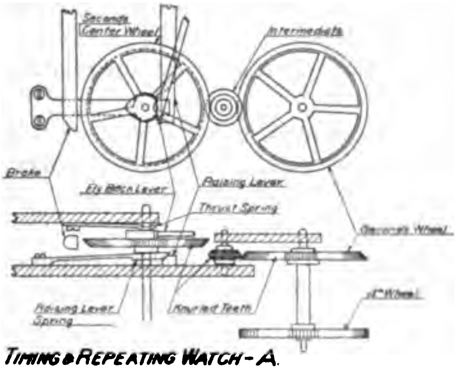


FIG. 19

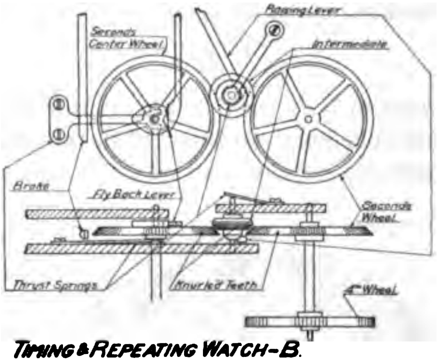
FIG. 20—TIMING AND REPEATING WATCH—A

The difficulty met with in adjusting this watch is due to necessity for play in the support of the intermediate. Without this it would be impossible to have the upper edge of the intermediate engaged with the seconds center wheel at the top to the right, and at the same time with the seconds wheel at the bottom to the left, and remain engaged while the wheels make a complete revolution.

Fig. 18 is a back view showing the relative positions of parts.

Fig. 19 is a diagrammatic sketch of another type known as "Timing and Repeating," in which parts are shown in the stopped position, ready for starting. The operations are as follows:

Pressing the stem the first time removes the fly-back lever from the heart cam just before the raising lever is removed from beneath the raising lever spring, allowing the thrust spring to force the second center wheel into contact with the intermediate, carrying it also in contact with the seconds wheel.



TIMING & REPEATING WATCH-B.

FIG. 21

The principal source of error in this type is due to teeth being knurled. The number is indefinite. The intermediate strikes repeatedly at the same point at start. The thrust spring bears on sweep second member at all times; the result is that unless the wheels are nearly perfectly true, the watch stops because there is not sufficient power in the train to force the sweep second member up against the thrust spring. The starting and stopping are accomplished by raising and lowering the sweep second member. The method described produces torques, causing the sweep second hand to jump forward or backward when started and when stopped. The extent of this error is in general 2/5 of a second and frequently more.

Fig. 20 is a back view showing the relative positions of parts. This watch has regular hour and minute hands in addition to sweep second and minute counter.

Fig. 21 is a diagrammatic sketch of a later model of the same make in which the starting and stopping are accomplished by raising and lowering the intermediate.

Fig. 22—Timing and Repeating Watch—B

This is a marked improvement over the previous model as it avoids the necessity for raising and lowering the staff carrying the sweep second member. With this exception the errors remain as in the previous model.

There is, however, a difficulty met with in adjusting the tension of the thrust spring at the top of the intermediate and beneath the seconds center wheel so that the former will have sufficient torque to oppose the latter and at the same tine carry the intermediate into contact with the seconds wheel. Any irregularity in either of the large wheels causes slipping. The freedom that must be allowed for the bearings of intermediate, second wheels, and center second wheel, causes a wedging action due to springs and rotation of parts. Any inequality in the teeth of the big gears will force a pair of members out of contact, and slipping results. This source of error is difficult to discover. For this reason, and for many others, at least two watches should be used for timing all observations.

CONCLUSIONS

Due to inherent errors of timing train, and those due to mechanical limitations and design, practically nothing is gained in accuracy by increasing the number of jewels beyond the standard seven-jewel movement.

An attempt has been made to reduce the inherent error in at least one instance by increasing the rate of vibration of the balance, but the price at which it was offered was out of all reason considering the accuracy gained and the cost of manufacture.

Some of the larger errors do not follow the law of probability, for while the errors may be either plus or minus, and vary somewhat in magnitude, some at least depend upon the interval of time being measured, as for instance, in the case of the Jockey Club type of stop watch if the interval being timed is less than thirty seconds, the hand will jump forward upon being started again. If the interval is more than thirty-five seconds the hand will jump backward on starting again.

The sources of error in a watch are such that at least two watches should be used simultaneously for timing an event, timing intervals of varying length if possible, the mean of all observations to be taken.

The stop watch applied to engineering measurements is not sufficiently robust for the purpose, and it is to be hoped that manufacturers will make a special effort to produce a stop watch suitable for this class of service.

DISCUSSION ON "THE LIMITATIONS OF THE STOPWATCH AS A PRECISION INSTRUMENT" (ELLIS), NEW YORK, N. Y., FEBRUARY 18, 1921.

V. Karapetoff: There is a common belief among watchmakers that there is such a thing as a seasonal breakage of mainsprings. They believe that mainsprings break in particularly large numbers during the season of thunderstorms, and of course they are bound to ascribe this to some mysterious action of the atmospheric electricity or magnetism. Professor S. R. Williams of Oberlin College, has become interested in this question of seasonal breakage of mainsprings and he writes me that he has made an investigation and actually confirmed the fact that there are numerous breakages of watch mainsprings during the thunderstorm season. However, a microscopic examination of mainsprings has shown the reason to lie in minute cracks which are always present in such springs. During the shower season the humidity is high, moisture gets into these cracks and starts incipient rust, so that the spring really breaks because of the rusting of the skin and not because of any electric or magnetic action. He therefore recommends a thorough oiling of mainsprings to prevent moisture from getting in the cracks.

H. M. Smith: I believe some mention ought to be made of a watch which we have found very satisfactory, and that is a Swisss watch in which the indicating hand makes a revolution in 30 seconds, and I believe the balance wheel makes 600 beats a second, instead of 300 beats a second which all these other watches have, so that the accuracy, I suppose, is quite as good, I am certain they do give very good results. It is very interesting to hold one of the watches to your ear and listen to the tick—it gives the impression of a six-legged duck walking along very fast. It is a very fast tick, and the dial is graduated on one-tenth seconds, so that apparently it is supposed to have an error not greater than one-tenth second, although I do not know what the error is. I cannot recall the name of the watch, but it is a fairly priced watch, I think they sell for $25.00.

W. J. Hammer: I would ask to what extent the author has gone into the question of magnetization. Many of these stopwatches are used around electrical apparatus. We are all familiar with the early experiments made by Sir Hiram H. Maxim, in which by suspending a watch in a magnetic field gradually moving it therefrom as the watch was revolved he demagnetized it. We know that watches are made which are non-magnetic. I have the pleasure of owning a watch, upon which various experiments were made many years ago in England, resulting in the first three non-magnetic watches which were made for Lord Kelvin, Sir William H. Preece and Sir Frederick Bramwell. Palladium balances were used and alloyed hair-springs and other things were tried in this watch with success. I know from my own experience around electrical machinery, that in our watches there is a possibility of considerable error and I would like to know to what extent the author of the paper has taken this matter into consideration and with what results.

L. M. Potts: I have done some work with a device which, while not a stop watch, is similar and may be of interest in this connection. The work was part of a printing telegraph development. A balance and escapement was used to establish synchronous operation between the machines at the two ends of the line. The balance had a period of about 1800 or six times that of a watch and was stopped in a definite phase position at the end of each signal and started at the beginning of each signal, like a stop watch. It was driven by a motor and friction clutch. A change of 250 per cent in the speed of the motor made less than 1/10 per cent change in the rate of the balance.

A. L. Ellis: I am very much interested in Professor Karapetoff's remarks concerning the seasonal breakage of main springs, subject of investigation by Professor Williams of Oberlin College, and his suggested remedy.

Main springs in watches are thoroughly oiled to reduce the friction due to rubbing between the surfaces of the various convolutions as the spring unwinds in driving the movement. A watch put up with a thoroughly dry main spring would soon fail due to friction at this point.

In this country at least, watch main springs have been very highly developed, and the process of manufacture so standardized that watch spring manufacturers will replace, free of charge, any watch spring sent to them that has broken in service, or has been soft enough to set.

Mr. Smith mentions a watch that beats 600 beats to the minute. The watch mentioned in this paper is of Swiss manufacture also, but is nearly double the size of an ordinary watch and is sold for about $400.

Watches today of the Jockey Club type can be obtained for from $4 to $5 wholesale: the intermediate grade from $7 to $12 and the most expensive watch considered from a stop watch viewpoint is $15 to $20. These watches will probably retail at an advance of about 100 per cent because a great deal of care and consideration on the part of the jeweler goes with the watch when it is sold. He usually has to make some minor repairs, and almost invariably is obliged to regulate it and take care of it after it has been dropped on the floor, etc., until such time as he can convince the purchaser that the difficulty is not due to a structural defect of the watch but is partly due to the purchaser's negligence.

It does not do to believe that a watch is reliable to 1/10th of a second just because the dial is marked in one-tenth second divisions. I would suggest that Mr. Smith may get some interesting results if he will check the concentricity of the dial markings with the second hand. The dial markings are usually printed on a porcelain surface and glazed in firing. If the divisions were true to begin with, they probably are not true after the firing process. Very noticeable errors are due to this cause in high grade watches as well as those of ordinary type. The variations over the dial frequently amounts to one-fifth of a second.

In regard to the magnitude of the errors that occur in a stop watch, a mechanically perfect stop watch, as pointed out, cannot be depended upon closer than one beat, which, in a thirty seconds' reading is 1.3 per cent. The error may be nearly double this or nearly two beats. To this error must be added the errors due to jumping forward and backward at starting and stopping of the sweep second hand. These errors can be observed, when holding the balance wheel still with a camel's hair brush, by repeatedly pressing the stem. With the sweep second hand standing at zero the amount of jump varies from one-fifth to four-fifths of a second. It is suggested that this experiment be tried with the stop watch one has been swearing by. I do not believe that a stop watch can be relied upon for an accuracy better than two-fifths of a second. Individual readings may come closer, but in general the uncertainty due to play in the bearings, the behavior of the fly-back hammer and heart cam, as the fly-back hammer is pulled away causes the hand to jump considerably either forward or backward on starting and stopping.

In reply to Mr. W. J. Hammer's remarks, the question of magnetic disturbance has caused us a great deal of trouble. It is not mentioned in this paper as it was not its purpose to cover all sources of error, as for instance, one of the greatest difficulties in watches is to adjust for temperature and another is to adjust for the unequal torque in the main spring. These are really problems when it comes to getting a watch in condition to keep time for a week or a month, but when wanted to keep time for a minute or two their effect is too trivial to be considered. These remarks, however, do not apply to the effect of magnetism, and I am very glad that Mr. Hammer has raised the question.

Errors due to magnetism in ordinary types of watches are very considerable and may be sufficient to actually stop the balance. The effect of magnetism in general is to vary the time keeping qualities as though there had been an increase in the force of gravity or an increase in the inertia of the balance. The watch the speaker refers to is probably one of the very high grade non-magnetic watches, containing a palladium balance and palladium hair spring. Such watches cost much more than the type we are discussing. The magnetism is a considerable source of error due to the effect on the steel lever parts of a stop watch. Such parts having once been magnetized are very difficult to de-magnetize to a point where they do not interfere with the operation of the watch. It is practically impossible to get rid of the last traces of magnetism except by heating the parts to the recalescence point. which of course is out of the question for watch parts, Subjecting a magnetized watch to the usual demagnetizing processes, such as an a-c. coil in which the current and frequency is gradually reduced to zero, or spinning the watch on a spring before the pole of a permanent magnet and while spinning drawing away from the pole, will in general reduce the magnetism to a point where it will not interfere seriously with the operation of the escapement but there will still be a sufficient amount left in the flyback hammer and heart cam to cause an undue amount of jumping forward and back when the watch is started from zero. Many of the so-called non-magnetic watches are not non-magnetic. This is not the only deception that is passed upon an unsuspecting public.

From the cuts in the paper you will see that some balances have timing screws. Timing screws are very necessary as are also temperature adjustments. The general public knows that a watch to keep accurate time should have a balance compensated for variations in temperature, but a great many of the balances are imitation compensated balances that apparently contain two metals, and some times do actually contain two, though often the balance is not split at the bridge, and therefore, cannot possibly compensate for change in temperature. Some makers even go so far as to cut a notch part way through the rim at the point where the balance should be split that the deception may be even more complete. Generally, the public knows that a watch that has a lot of jewels is probably a better watch than one having only a few. Some makers put jewels in the top plate where they would be readily seen when the back of the watch is open, but fail to put a corresponding number on the bottom plate where they cannot be seen as the dial would cover them.

These are all points that should be looked into when purchasing a watch for stop watch purposes, particularly in view of the fact that nothing is to be gained in purchasing a high-grade expensive movement for this class of work.

H. M. Smith: In regard to the concentricity of dial, we have tried to take readings for about one minute, so that the pointer comes back to pretty nearly the same place—I am speaking of checking watt-hour meters, and then we always use two watches, and I think it is quite likely, even so that the error perhaps is greater than one-tenth of a second. I have an idea that the error of this watch (600 beats) is about half the error of those which have 300 beats, so it is some error.

A. L. Ellis: The errors due to the beats are half as great, but the inherent errors, due to the stop mechanism in general, as you have seen by the paper, are several times the errors due to the beats.

H. M. Smith: There are certainly some errors, although the watch is apparently well made, indeed, and it sells at a higher price than the other watches, about $25.00.

A. L. Ellis: I would like to add the question of measuring time to a high degree of accuracy was not the purpose of the paper. We have, however, measured time, we believe to a millionth part of a second of one per cent, and we hope at some time to be permitted to present these facts in the form of a paper before this body.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 18, 1921.

SHORT-CIRCUIT CURRENT OF INDUCTION MOTORS AND GENERATORS

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ABSTRACT OF PAPER

There has been a rather prevailing opinion that a sudden short circuit of an induction generator would not cause a serious initial rise in current such as occurs in synchronous generators. This has led to the proposal of the use of such machines as a partial solution of the short-circuit problem on a-c. systems. Theoretical considerations and experimental data given in the paper show that, on the contrary, there is in the induction generator, just as in the synchronous machine, a serious initial rush of current which is limited only by the leakage reactance of the machine. The only difference is that the transient is shorter in the induction machine, and the current dies down of course, to zero instead of to the sustained value which occurs in an excited synchronous generator.

THE problem of short circuits on alternating-current systems is ever becoming more pressing. The calculation of the short-circuit current of the generating apparatus is therefore of utmost importance. This calculation for synchronous machines has been covered in an Institute paper[1] presented in 1918. The present paper deals with the induction machine. This study was prompted by the suggestion, which has now and then been proposed, that the installation of induction generators might possibly be a partial solution of the short-circuit problem. The basis for the suggestion was, of course, the supposition that the initial short-circuit current of this type of machine was negligible. This supposition rested on the idea that, unlike the synchronous machine, the induction generator has no permanent excitation, and therefore when the terminals are short-circuited and all electrical connection thus removed,

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[1] "Reactance of Sychronous Machines and its Application," by R. E. Doherty and O. E. Shirley, TRANS. A. I. E. E., 1918, Vol 37, Part 2, page 1209.

the existing small current will die out exponentially. A study of the problem however, indicated that this was not the case. Subsequent tests given herewith confirm that view and show that on large induction generators serious initial short-circuit currents may be expected, just as on synchronous machines.

From a search of the literature it appears that very little has been published on this subject. In 1910 Messrs. Spooner and Barnes[2] published an article on "The Induction Generator," giving the results of comparative short-circuit tests on synchronous and induction generators. Quoting from the article, "Theory would indicate that a short circuit would be equivalent to a withdrawal of the exciting current from the induction generator and hence it would cease to deliver energy. The accompanying oscillogram, which is a typical current record, shows this to be the case." These tests, however, were made on a small machine (10 h. p.) of relatively high resistance and therefore are not, as will be pointed out later, representive of conditions that would exist in large induction generators. In the same year a paper[3] by G. W. Meyer stated that, "If induction generators are used, a short circuit in the line does not cause an abnormal rise of current in these machines. They simply cease to generate."

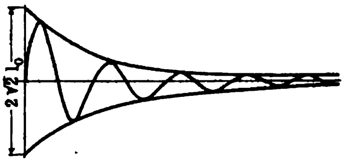

FIG. 1—DIAGRAM SHOWING METHOD OF DETERMINING THE SHORT-CIRCUIT CURRENT

The present investigation, however, shows that the sudden short circuit of an induction generator or motor, like that of a synchronous machine, is initially

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[2] *Electrical World*, February 24, 1910.

[3] "Short Circuits in Alternating-Current Mains: Their Reaction on Generators and Means for Diminishing their Harmful Effects," by G. W. Meyer in *Elektrotechnische Rundschau*, October 19, November 3, November 24, 1910.

many times normal, and depends in value upon the total leakage reactance. Unlike the synchronous machine, there is no "sustained" current. Instead the current decreases in a few cycles, from the high value existing in the moment of short circuit to zero. This is shown in Fig. 1.

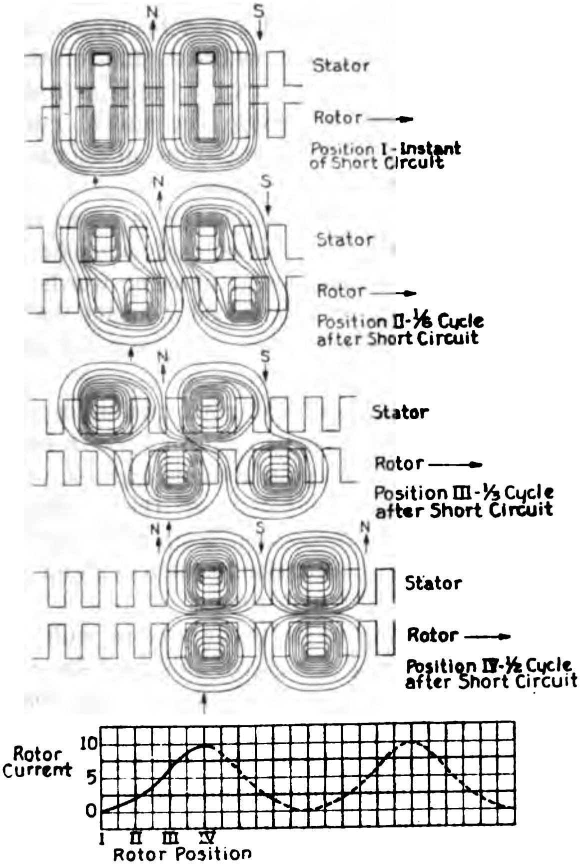


FIG. 2—DISTRIBUTION OF PRIMARY AND SECONDARY FLUX FOR DIFFERENT POLE POSITIONS AFTER SHORT CIRCUIT

The comparison of the *initial* short-circuit currents of induction and synchronous machines is really a comparison of practically identical phenomena. In either case, the relation of the flux in the machines to the stator and rotor windings is in fundamental respects the same. In either, the poles of the magnetic flux rotate at synchronous speed with respect to the stator windings, and at the same time the flux is linked with the closed rotor winding. The fact that in normal operation the flux of the induction machine "slips" with respect to the rotor winding, does not change the circumstance that it is nevertheless at all instants linked with the closed winding. Neither does the fact that the rotor winding of the synchronous machine has direct-current excitation whereas that of the induction machine has not, alter in a fundamental way the conditions which determine the initial current; although it does, of course, determine altogether the difference between the final values.

It is shown in the Appendix that *in a closed electric circuit without resistance the number of magnetic interlinkages must remain constant.* In other words, such a circuit must, as long as it is closed, contain the same number of interlinkages which it contained at the instant of closing.

While both the stator and rotor windings of an induction machine of course do contain some resistance, it is yet small enough to make possible at least a qualitative study of initial conditions on the assumption that the resistance is zero; and from that, one may form an idea of the modification which a small value of resistance would involve.

Suppose an induction motor is running at full voltage no load, and that the terminals of the stator winding are suddenly short-circuited. For convenience assume that when this happens, no flux is linked with the stator coils. Then, by the assumption of zero resistance, no flux can enter those coils. The rotating flux attempting to enter the winding causes sufficient current to flow in the winding, *i. e.* sufficient m. m. f., to force the flux out. But this field, being linked with the closed rotor circuit, can not die out. It can not decrease at all, since doing so would involve a change of interlinkages. Neither could the flux cease rotation for the same reason. Therefore, since the flux can not enter the stator and yet must emanate from the rotor surface and remain linked with the rotor coils, it follows that it must pass through the leakage paths, largely along the air gap and tooth tips between the stator and rotor winding and return to the rotor. Now the m. m. f. required to maintain normal flux in the leakage paths is greater than the m. m. f. of normal current in the ratio of normal flux to the leakage flux produced by normal current. Hence the m. m. f. at short circuit depends directly upon the leakage reactance of the machine.

It is clear that the stator current, generated by the rotating flux, is alternating, whereas the rotor current, being that required to maintain a direct flux, is itself direct.

The foregoing assumed that the stator interlinkages were zero when the short circuit occurred. Actually, in a polyphase machine, the entire flux of each pole is linked at all instants with some phase or phases. Hence the stator interlinkages must always be the same, *i. e.,* those due to normal flux regardless of the instant of short circuit. This means that there must always be two sets of magnetic poles of practically equal intensity. See Fig. 2. One, just mentioned, linked with the closed stator winding and therefore stationary in space; the other, described in the foregoing, linked with the rotor winding and therefore rotating in space. And just as the latter causes direct current in the rotor and alternating current in the stator, so does the former cause direct current in the stator and alternating current in the rotor. Thus the total current in any phase of either the stator or the rotor is the resultant of an alternating and a direct component.

The magnitude of the alternating component in each phase is the same, but the direct component depends upon the flux linked with the particular phase at the instant of short circuit, and can therefore be any value between zero and a maximum equal approximately to the maximum value of the alternating component.

The resultant m. m. f. of the stator, considering all phases, is therefore composed of two components: one stationary, and of constant magnitude produced by the direct current in the turns (all phases) surrounding the stationary, stator pole; the other rotating and also of constant magnitude, produced by the alternating current in the turns (all phases) directly opposing the rotating poles of the rotor.

The resultant m. m. f. of the rotor, considering all phases, is likewise composed of two components, one stationary, the other rotating with respect to the rotor.

Obviously these components must be roughly of the same magnitude, since the m. m. f. in either case is that required to maintain normal flux in the leakage paths.

It is clear from the above considerations, that, assuming the same leakage inductance, the initial value of short-circuit current will be the same in a given machine whether it is operating as induction motor, or as a synchronous motor with direct-current excitation in the secondary winding. There would, of course, be some difference in the leakage inductance when operated as an induction machine and when operated as a synchronous machine.

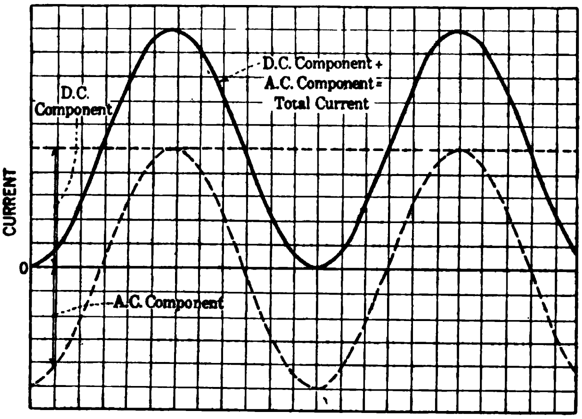


Fig. 3—Curve Showing the Sudden Short-Circuit Current of Induction Motor Assuming Zero Resistance and Short Circuit Occurring when the Circuit Enclosed Maximum Flux

The effect of shaft load upon the value of the short-circuit current is small. The primary flux per pole is a fixed value for a given voltage. At no load all of this flux, except 5 per cent or so, is linked also with the secondary pole, the 5 per cent being the leakage due to the exciting current. Under load the per cent by which the remaining 95 per cent linked with the rotor is reduced is not in direct proportion to the increase in the stator current on account of the phase difference between the exciting current and the load current.

Assuming no resistance, the general shape of the short-circuit current wave would be as shown in Fig. 3.

With resistance, which is present in every case, the flux linked with the two members will die out as an exponential function of time. Such a short-circuit current wave is plotted in Fig. 4. In this case the d-c. component of the primary is:

$$i_1 \text{ d-c.} = \sqrt{2}\, I_{01}\, \epsilon^{-\frac{r_1}{L_0} t}$$

and the a-c. component is

$$i_1 \text{ a-c.} = -\sqrt{2}\, I_{01}\, \epsilon^{-\frac{r_1}{L_0} t} \cos \omega t$$

Then the total primary current is

$$i_1 = i_1 \text{ d-c.} + i_1 \text{ a-c.} = \sqrt{2}\, I_{01}\, \epsilon^{-\frac{r_1}{L_0} t} (1 - \cos \omega t)$$

Where,

i_1 = instantaneous primary current

I_{01} = r. m. s. of the initial value of a-c. component

$$\text{in primary} = \frac{\text{(normal voltage per phase)}}{\text{(impedance per phase)}}$$

$$= \frac{E}{\sqrt{r^2 + x^2}}$$

r = total resistance per phase = $r_1 + r_2$

r_1 = resistance per phase of primary

r_2 = resistance per phase of secondary reduced to primary terms

x = total leakage reactance per phase (primary terms)

$L_0 = x \div 2\pi f$

The above equations apply when the ratio $r_1/L_0 = r_2/L_0$, that is, when $r_1 = r_2$.

Resistance does not appreciably affect the initial value of short-circuit current since the resistance is usually small compared with the reactance. For example in a case where $r = 5$ per cent and $x = 20$ per cent the error due to neglecting r in the impedance would be only 3 per cent, which is negligible. Resistance does, however, affect the duration of the short-circuit current, since, in this case, r appears as a factor of direct proportionality in the attenuation factor r/L.

In general, the primary and secondary members are magnetically very similar. That is, the ratio L/r is very nearly the same for either member. Hence the two fluxes die out at about the same rate. A conception of this rate can be had from the following illustration. Take, for example, a 60-cycle machine with 2.5 per cent resistance loss in each member,

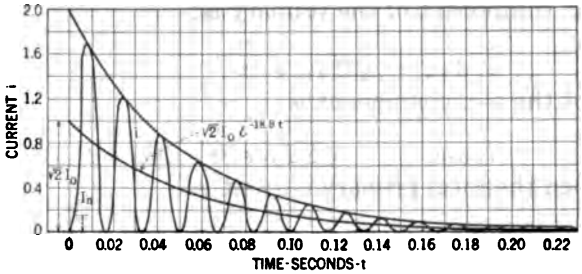


Fig. 4—Calculated Curve of the Sudden Short-Circuit Current of an Induction Motor

Equation of short-circuit current

$$i = \sqrt{2}\,I_0\,(\epsilon^{-18.9t} - \epsilon^{-18.9t}\cos\omega t) = \sqrt{2}\,I_0\,\epsilon^{-18.9t}(1 - \cos\omega t)$$

Assumed Constants

Stator		**Rotor**
	$r = 1$ per cent	$r = 1$ per cent
Total	$x = 20$ per cent	
	$\frac{r}{L_0} = 18.9$	$\frac{r}{L_0} = 18.9$

I_N = normal rated current

$$I_0 = \frac{100}{20}\,I_N = 5\,I_N$$

(*i. e.* 2.5 per cent resistance drop in each member at normal current) and a leakage reactance of 20 per cent. Then the time constant is,

$$\frac{L_0}{r} = \frac{\frac{20}{2\pi f}}{2.5} = \frac{20}{2\pi \times 60 \times 2.5}$$

$$= 0.021 \text{ second}$$

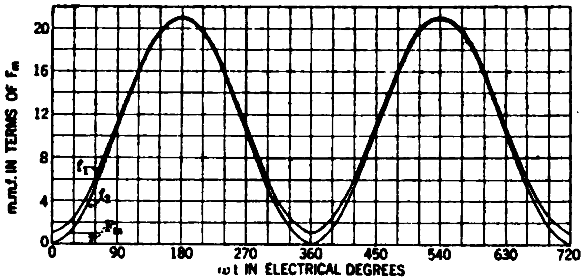


FIG. 5—CALCULATED CURVE OF M. M. F. AT SHORT CIRCUIT OF A POLYPHASE INDUCTION MOTOR

$$\text{Primary m. m. f.} = f_1 = \frac{F_m}{\dfrac{P_1 P_2}{P_m^2} - 1}\left[\frac{P_1 P_2}{P_m^2} - \cos\omega t\right]$$

Assumed Constants

$$\frac{P_m}{P_1} = \frac{P_m}{P_2} = 0.95$$

$$\text{Secondary m. m. f.} = f_2 = F_m \frac{P_1}{P_m}\left[\frac{1 - \cos\omega t}{\dfrac{P_1 P_2}{P_m^2} - 1}\right]$$

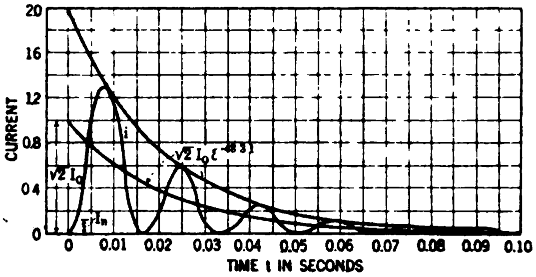


FIG. 6—CALCULATED CURVE OF THE SUDDEN SHORT-CIRCUIT CURRENT OF A 150-H. P. THREE-PHASE, 60-CYCLE, 720-REV. PER MIN., 440-VOLT INDUCTION MOTOR. SEE TEST CURVE IN FIG. 7.

Equation of short-circuit current

$$\begin{aligned} i &= \sqrt{2}\,I_0\,(\epsilon^{-48.3t} - \epsilon^{-48.3t}\cos\omega t) \\ &= \sqrt{2}\,I_0\,\epsilon^{-48.3t}\,(1 - \cos\omega t) \end{aligned}$$

Design Constants

Stator **Rotor**

$r = 2.1$ per cent $r = 2.1$ per cent

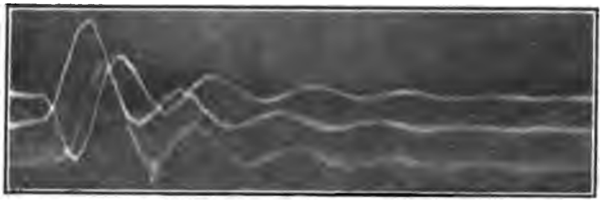
Total $x = 16.5$ per cent

$$\frac{r}{L} = 48.3 \qquad \frac{r}{L} = 48.3$$

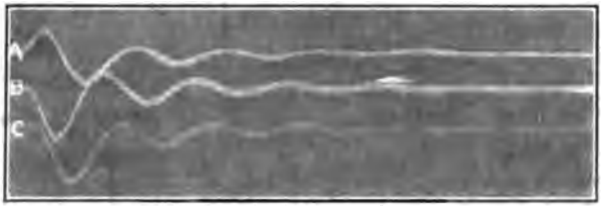
I_N = normal rated current

$$I_0 = \frac{100}{16.5}\,I_N = 6.06\,I_N$$

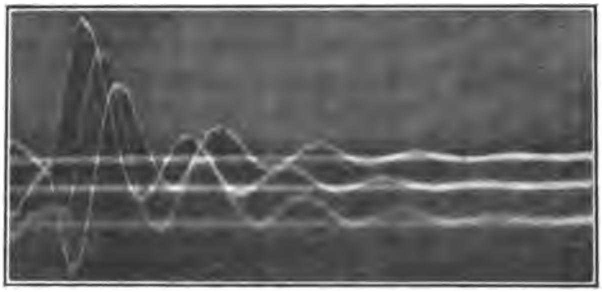
which means that in four times 0.021 second, or 0.084 second, that is five cycles, the flux, and therefore the current, will have practically died out. It is very important to note that at one-half cycle



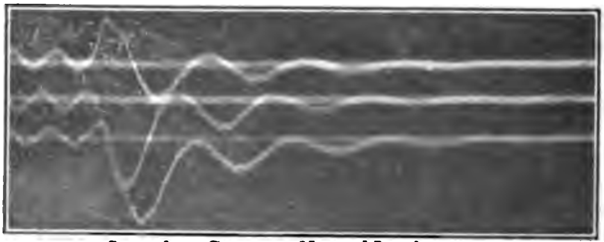
Primary Current—No Load.



Secondary Current—No Load.



Primary Current—Normal Load.



Secondary Current—Normal Load.

Fig. 7—Oscillograms of the Short-Circuit Current of an Induction Motor

150-h. p., three-phase, 60-cycle, 720-rev. per min., 440-volt three-phase short circuit at 440 volts.

(0.0083 sec.) when the current reaches the maximum peak (that is, when assuming no transient, sufficient m. m. f. would necessarily exist to support twice normal flux in the leakage paths) the flux has already decreased to 70 per cent of its initial value. This is important because if the resistance is less, say 1 per cent, as in the case of large induction generators, the flux, and therefore the current at this critical instant, would be higher. Moreover, the leakage paths would be more nearly saturated, thus causing an additional increase in current. Using 1 per cent resistance in the above illustration, the flux at the end of one-half cycle would be only 85 per cent instead of 70 per cent initial value. Such a case is plotted in Fig. 4.

In connection with this investigation four conditions of short circuit have been considered. The calculated curves of m. m. f. are plotted for each case and accompanying oscillograms show the actual current curves for two cases. Equations are developed in the Appendix for each of the cases and are as follows:

Case I. Polyphase short circuit on a polyphase induction motor or generator. The equation for the primary m. m. f. is,

$$f_1 = \frac{F_m}{\dfrac{P_1 P_2}{P_m^2} - 1} \left[\frac{P_1 P_2}{P_m^2} - \cos \omega t \right]. \tag{9}$$

and for the secondary m. m. f. is,

$$f_2 = F_m \frac{P_1}{P_m} \left[\frac{1 - \cos \omega t}{\dfrac{P_1 P_2}{P_m^2} - 1} \right] \tag{10}$$

Fig. 5 shows the calculated curves plotted from these equations.

This case of a polyphase short circuit is the most important and the equations have, therefore, been reduced to terms of current instead of m. m. f., and the effect of resistance is taken into account by introducing the transient factor. The equation for the primary current is,

$$i_1 = \sqrt{2}\, I_{01}\, \epsilon^{\frac{r_1}{L_0} t} \,(1 - \cos \omega t) \tag{26}$$

and for the secondary current is,

$$i_2 = \sqrt{2}\, I_{02}\, \epsilon^{-\frac{r_2}{L_0} t} \,(1 - \cos \omega t) \tag{27}$$

The curve in Fig. 6 is plotted from equation (26) and Fig. 7 shows the oscillogram of the current from test.

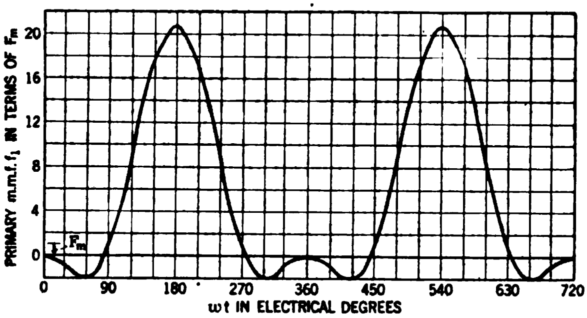


FIG. 8—CALCULATED CURVE OF PRIMARY M. M. F. AT SUDDEN SHORT CIRCUIT OF A POLYPHASE INDUCTION MOTOR HAVING THE SECONDARY EXCITED WITH THE DIRECT CURRENT.

$$f_1 = F_m \frac{P_m}{P_1}\left[1 - \frac{1}{\frac{P_1\,P_2}{P_m{}^2} - 1}\left\{\frac{P_1 P_2}{P_m{}^2}\cos \omega t - \frac{1}{2}\,(1 + \cos 2\,\omega t)\right\}\right]$$

Assumed Constants

$$\frac{P_m}{P_1} = \frac{P_m}{P_2} = 0.95$$

Case II. Polyphase short circuit on a polyphase induction machine having one phase of the rotor excited with direct current, that is, operating as a synchronous machine. The equation for the primary m. m. f. is,

$$f_1 = F_m \frac{P_m}{P_1}\left[1 - \frac{1}{\frac{P_1 P_2}{P_m{}^2} - 1}\left\{\frac{P_1 P_2}{P_m{}^2}\cos \omega t - 1/2\,(1 + \cos 2\,\omega t)\right\}\right] \tag{32}$$

and for the secondary m. m. f. is,

$$f_2 = F_m \frac{\frac{P_1 P_2}{P_m^2} - \cos \omega t}{\frac{P_1 P_2}{P_m^2} - 1} \tag{31}$$

These equations are plotted in Fig. 8 and Fig. 9. The test curve is shown in Fig. 10. The difference between the test curve for f_1 and the curve of stator current in Fig. 10 can probably be accounted for by the fact that the rotor resistance is increased by a rheostat and an exciter in the circuit. This causes the secondary flux to die down rapidly, thus causing the a-c. component of fundamental frequency in the primary to die down faster than the second harmonic in the primary.

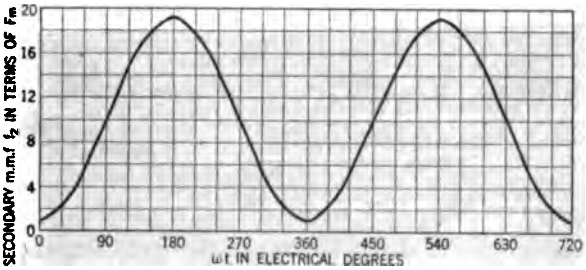


FIG. 9—CALCULATED CURVE OF SECONDARY M. M. F. AT SUDDEN SHORT CIRCUIT OF A POLYPHASE INDUCTION MOTOR HAVING THE SECONDARY EXCITED WITH DIRECT CURRENT

$$f_2 = F_m \left[\frac{\frac{P_1 P_2}{P_m^2} - \cos \omega t}{\frac{P_1 P_2}{P_m^2} - 1} \right]$$

Assumed Constants

$$\frac{P_m}{P_1} = \frac{P_m}{P_2} = 0.95$$

Case III. Single-phase short circuit on a polyphase induction machine under the assumption that the third line is opened at the instant the other two are short-circuited. The equation for the primary m. m. f. is,

$$f_1 = F_m \frac{\dfrac{P_1 P_2}{P_m^2} \cos \delta - \cos \omega t}{\dfrac{P_1 P_2}{P_m^2} - 1} \tag{36}$$

and for the secondary m. m. f. is,

$$f_2 = F_m \frac{P_m}{P_2} \left[1 - \frac{1}{\dfrac{P_1 P_2}{P_m^2} - 1} \left\{ \frac{P_1 P_2}{P_m^2} \cos \delta \cos \omega t - 1/2 \, (1 + \cos 2 \, \omega \, t) \right\} \right] \tag{39}$$

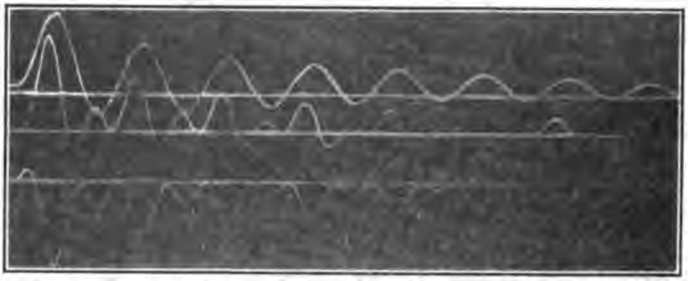


FIG. 10—OSCILLOGRAM OF THE SHORT-CIRCUIT CURRENT OF AN INDUCTION MOTOR WITH ONE PHASE OF ITS SECONDARY EXCITED WITH DIRECT CURRENT

50-h. p., three-phase, 60-cycle, 900-rev. per min., 550-volt—three-phase short circuit at 550 volts, no load.
Secondary excited with direct current.
Upper curve—current in rotor.
Middle curve—primary current.
Lower curve—primary current.

It will be noted that the curves from these equations with $\cos \delta = 1$, would be identical with those of Case II except that in this case f_1 corresponds to f_2 of the other, and *vice versa*. No test was made under these conditions.

Case IV. Single-phase short circuit on an induction machine with direct current in one phase of the secondary and the other phases open, that is, operating as a single-phase synchronous machine. The equation for the primary m. m. f. is,

$$f_1 = -F_m \frac{P_2}{P_m} \quad \frac{\cos \omega t}{\frac{P_1 P_2}{P_m^2} - 1/2\,(1 + \cos 2\,\omega t)} \qquad (44)$$

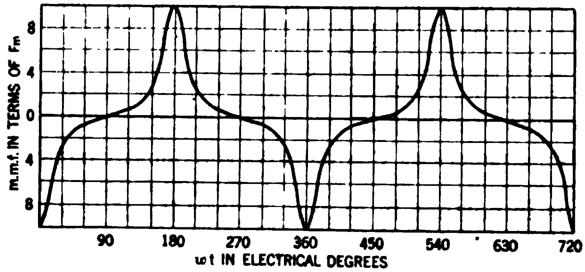


FIG. 11—CALCULATED CURVE OF PRIMARY M. M. F. AT SUDDEN SHORT CIRCUIT OF A POLYPHASE INDUCTION MOTOR WHEN OPERATING SINGLE-PHASE

$$\text{Primary m. m. f.} = f_1 = -F_m \frac{P_2}{P_m} \left[\frac{\cos \omega t}{\frac{P_1 P_2}{P_m^2} - \frac{1}{2}\,(1 + \cos 2\,\omega t)} \right]$$

Assumed Constants

$$\frac{P_m}{P_1} = \frac{P_m}{P_2} = 0.95$$

and for the secondary m. m. f. is,

$$f_2 = F_m \frac{P_1 P_2}{P_m^2} \quad \frac{1}{\frac{P_1 P_2}{P_m^2} - 1/2\,(1 + \cos 2\,\omega t)} \qquad (45)$$

Fig. 11 is the curve for f_1 plotted from equation (44). A test was not made under these conditions.

TESTS

The tests in connection with this investigation were made on a 150-h. p., three-phase, induction motor. The short circuits were made with the machine operating at normal voltage, no load, and normal voltage, full load. Fig. 12 shows the diagram of connections indicating the position of the oscillograph shunts and the short-circuiting switch. About 50 oscillograms were taken. Typical results are given in Table I.

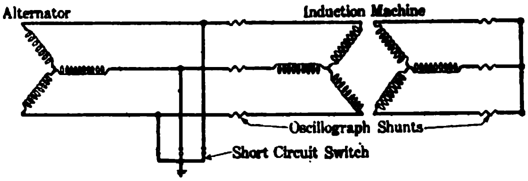


FIG. 12—DIAGRAM OF CONNECTIONS FOR SHORT-CIRCUIT TESTS

It is important in appraising results of short-circuit tests to note the method by which the "short-circuit current" is determined from the oscillogram. The

TABLE I

Results from Analyzed Oscillograms
Short-Circuit Tests on 150-H. P., 720-Rev. per Min., 440-Volt, Three-Phase Induction Motor

Nature of Load	Test No.	Initial Current*		Per cent† Reactance
		Primary	Secondary	
No load	36	1340	1180	13.8
	45	1420		13.0
	46	1170		15.8
	47‡	1560	1175	11.9
	48	1270		14.6
	49	1380	1150	13.4
	54	1380	1080	13.4
	55	1660	1180	11.1
	56	1390	865	13.3
	58	1190		15.5
	61	1290	916	14.3
Full load				
	50	1560		11.8
	51	1525	635	12.1
	52‡	1360	890	13.6
	53	1510	893	12.2

*Intial Current = r. m. s. of the a-c. component of initial short-circuit current.

†Per cent reactance = $100 \times \dfrac{\text{normal current}}{\text{initial current (primary)}}$

‡Oscillogram shown in Fig. 7.

method used in these tests is illustrated by Fig. 1. The curves joining the crests (both positive and negative) of the wave are projected backward to the axis of zero time. The same exponential is used to extend the curve back from the first crest to the axis of zero time as was found to apply to the curve between the first two crests. The intercept at the axis of zero time is taken as twice the maximum value of the a-c. component.

In the more general aspects these tests confirm the theory outlined in the foregoing. The particulars in which the tests do not agree, but which for the most part can be explained, are:

1. The attenuation factor r/L is higher than measured by the ohmic resistance and the inductance from the impedance test. That is, the current dies down in about 75 per cent of the calculated time. The calculated curve, Fig. 6, shows that six cycles are required for the current to die out, while the test curve, Fig. 7, shows that the current died out in four and one-half cycles.

This discrepancy can be explained by the facts that on account of eddy losses, etc., the effective resistance is greater than the measured ohmic resistance, and that on account of saturated leakage paths, the inductance is lower than that indicated by impedance test taken at near half voltage: both of these would shorten the transient.

2. The secondary m. m. f. at short circuit is apparently 60 to 75 per cent of the primary m. m. f. For this there seems to be no adequate explanation. This result, although roughly indicated by the tests, should, for reasons already given, be accepted with reserve.

3. The leakage reactance from results of these tests is about 25 per cent lower than that calculated from ordinary impedance tests (*i. e.* calculated reactance = 17 per cent, reactance from short-circuit tests = 13 per cent). This is explained by the fact that under short-circuit conditions the leakage paths are highly saturated, hence more current is required to maintain the flux. The amount by which the leakage reactance is reduced depends upon the extent

to which the flux has died down at the end of the first half cycle after short circuit (at which time the greatest flux exists in the leakage paths). It therefore depends upon the time constant x/r.

In such a machine as the present 150-h. p. motor, in which x/r is about 6, the flux dies down to about 60 per cent of its initial value in the first half cycle, and completely disappears, as shown in Fig. 7, in four or five cycles. On the other hand, in a machine with $x/r = 20$, the flux would die down to only 85 per cent of its initial value in one-half cycle. This would mean not only more current on account of saturated leakage paths, but also an additional increase because it is now necessary to maintain 42 per cent more flux in those paths (*i. e.* $85/60 = 1.42$). Hence in large machines of relatively low resistance the total leakage reactance under conditions of short circuit would be less than the reactance from impedance test by a difference greater than the 25 per cent noted in this test. On the contrary the difference would be *less*, if x/r were smaller.

CONCLUSIONS

1. The sudden short-circuit current of a polyphase induction motor or generator, like that of a synchronous machine, is initially many times the normal rated current, and consists of an a-c. and a d-c. component, of approximately equal magnitudes in both primary and secondary.

2. The initial value of the r. m. s. of the a-c. component is equal to the impressed voltage divided by the total leakage reactance.

3. It follows that, assuming the same leakage inductance, the initial current will be the same whether the machine is short-circuited as an induction machine, or as a synchronous machine with the secondary excited with direct current.

4. The leakage reactance under short-circuit conditions is lower than indicated by ordinary impedance tests. As pointed out in paragraph (3) under TESTS,

this is an important point to be considered in the design of certain large induction generators in which relatively low values of resistance may exist.

5. The actual duration of the transient is less than that indicated by the ohmic resistance and the reactance from impedance test, both because eddy currents increase the effective resistance, and saturation of leakage paths decrease L. Hence, r/L is increased.

6. Adding resistance to the primary winding will cause the d-c. component of that winding, and therefore the a-c. component of the secondary, to die out rapidly, and it will prolong the transient of the primary a-c. component and secondary d-c. component.

7. The effect of load upon the value of the short-circuit current is practically negligible.

The authors wish to acknowledge the assistance of Messrs. H. Maxwell, A. E. Averett, C. M. Davis and E. J. Burnham in making this investigation.

APPENDIX

Assumed Conditions

The following assumptions are made in the development of the equations of short-circuit current: (1) Sine wave, m. m. f., (2) Zero shaft load, and (3) Zero resistance.

The first assumption is true in polyphase machines so far as the practical calculation of short-circuit currents is concerned. There are, of course, harmonics which exert appreciable influence in other problems of design, but little evidence of them is seen in oscillograms of short-circuit current.

Regarding the second assumption it has been pointed out in the preceding theory that the effect of load upon the initial value of short-circuit current is negligible.

The third assumption (zero resistance) does not appreciably affect the initial value of the short-circuit current in the ordinary machine, since the resistance is usually less than 3 or 4 per cent of the impedance. It does, however, affect the duration of the short-circuit current. Therefore, by neglecting r in the impedance and multiplying the resulting expression for current by $\epsilon^{-\frac{r}{L_0}t}$ the effect of resistance is, for practical purposes, taken into account.

METHOD OF ATTACK

At the instant of short circuit the primary (stator) flux ceases to rotate since it must remain linked with the particular turns with which it was linked at the time the short circuit occurred. For the same reason, the secondary flux must continue to rotate. In a polyphase winding these fluxes are, at all times, supported by a resultant m. m. f. made up of ampere turns in each of the phases of the winding.

The problem at hand is to determine how the resultant m. m. f. in either member must adjust itself during rotation to maintain the constant value of flux. There are two sets of poles of practically the same magnitude, one stationary, the other rotating. The center lines of these poles afford references at which flux summations may be made involving equations including instantaneous values of m. m. f. For example, in Case I, where a polyphase short circuit is considered on a machine with a polyphase rotor, it is possible to sum up the following known values of fluxes in terms of known permeances and unknown instantaneous m. m. fs.

1. The total flux of the primary. The center line of this flux is, of course, the center line of the primary pole.
2. The primary flux in line with the secondary pole.
3. The total flux of the secondary.
4. The secondary flux in line with the primary pole.

In the case of a single-phase winding, since the current in all turns is in time phase, the direction of the resultant m. m. f., unlike the polyphase case, must be fixed by the position of the winding. Thus if both primary and secondary are single-phase only two equations are required. If one member is single-phase and the other polyphase three equations are required. In any case the reference lines are the same.

NOTATION

Φ_1 = flux linked with primary at instant of short circuit (stationary after short circuit).

Φ_2 = flux linked with secondary at instant of short circuit (rotating after short circuit).
F_m = magnetizing m. m. f. corresponding to the magnetizing current I_m in normal operation.
P_1 = permeance of primary = total primary flux per effective primary ampere turn (neglecting the effect of secondary).
P_2 = permeance of secondary = total secondary flux per effective secondary ampere turn (neglecting the effect of the primary).
P_m = permeance of mutual path = mutual flux per effective ampere turn of either primary or secondary.
ωt = electrical angle = $2 \pi f t$
f = electrical frequency corresponding to speed of rotation.
f_1 = total primary m. m. f. (at any time t) linking the primary flux and in line with the primary pole.
f_2 = total secondary m. m. f. (at any time t) linking the secondary flux and in line with the secondary pole.
f'_1 = the component of f_1 that is in line with f_2.
f'_2 = the component of f_2 that is in line with f_1.
I_m = magnetizing current at normal voltage.
I_n = normal rated current.
E = normal voltage per phase (*i. e.* per leg).
r_1 = resistance per phase of primary.
r_2 = resistance per phase of secondary reduced to primary terms.
r = resistance per phase = $r_1 + r_2$.
x = total leakage reactance per phase in primary terms.

X_p = per cent total reactance = $x I_n$ divided by the normal voltage per phase (expressed as a fraction 0.1 = 10 per cent.)
L_e = $X \div 2 \pi f$ = coefficient of total leakage induction.
i_1 = instantaneous primary current.
i_2 = instantaneous secondary current.

I_{01} = r. m. s. of initial value of a-c. component of primary short-circuit current.

I_{02} = r. m. s. of initial value of a-c. component of secondary short-circuit current.

CASE 1. POLYPHASE SHORT CIRCUIT

Polyphase primary, polyphase secondary.

At the instant of a no-load polyphase short circuit the total flux of the primary is,

$$\Phi_1 = F_m P_1 \tag{1}$$

and the total flux of the secondary is,

$$\Phi_2 = F_m P_m \tag{2}$$

Assuming zero resistance, Φ_1 and Φ_2 must remain constant and linked with the particular turns with which they were linked at the instant of short circuit.

At any time t after the short circuit, the rotor will have turned through the angle ωt. Then the primary flux in line with the rotor pole is,

$$\Phi_1 \cos \omega t = F_m P_1 \cos \omega t \tag{3}$$

and the secondary flux in line with the stator pole is,

$$\Phi_2 \cos \omega t = F_m P_m \cos \omega t \tag{4}$$

The equation for the total flux of the primary is,

$$f_1 P_1 + f'_2 P_m = F_m P_1 \tag{5}$$

and for the secondary flux in line with the stator pole is,

$$f'_2 P_2 + f_1 P_m = F_m P_m \cos \omega t \tag{6}$$

The equation for the total flux of the secondary is,

$$f_2 P_2 + f_1' P_m = F_m P_m \tag{7}$$

and for the primary flux in line with the rotor pole is,

$$f_1' P_1 + f_2 P_m = F_m P_1 \cos \omega t \tag{8}$$

Solving equations (5) and (6) for f_1 gives

$$f_1 = \frac{F_m}{\dfrac{P_1 P_2}{P_m^2} - 1} \left[\frac{P_1 P_2}{P_m^2} - \cos \omega t \right] \tag{9}$$

and solving (7) and (8) for f_2 gives

$$f_2 = F_m \frac{P_1}{P_m} \left[\frac{1 - \cos \omega t}{\dfrac{P_1 P_2}{P_m^2} - 1} \right] \tag{10}$$

The direct component of f_1 is,

$$f_{1d\text{-}c.} = \frac{F_m}{1 - \dfrac{P_m^2}{P_1 P_2}} \tag{11}$$

the a-c. component is,

$$f_{1a\text{-}c.} = -\frac{F_m}{\dfrac{P_1 P_2}{P_m^2} - 1} \cos \omega t \tag{12}$$

The direct component of f_2 is,

$$f_{2d\text{-}c.} = \frac{\dfrac{P_1}{P_m} F_m}{\dfrac{P_1 P_2}{P_m^2} - 1} \tag{13}$$

the a-c. component is,

$$f_{2a\text{-}c.} = -\frac{\dfrac{P_1}{P_m} F_m \cos \omega t}{\dfrac{P_1 P_2}{P_m^2} - 1} \tag{14}$$

Both f_1 and f_2 are a maximum at $\omega t = \pi$. At this instant f_1 is

$$f_1 \max = F_m \frac{\dfrac{P_1 P_2}{P_m^2} + 1}{\dfrac{P_1 P_2}{P_m^2} - 1} \tag{15}$$

and f_2 is

$$f_2 \max = F_m \frac{P_1}{P_m} \left[\frac{2}{\dfrac{P_1 P_2}{P_m^2} - 1} \right] \tag{16}$$

Thus, if $P_1 = P_2 = P$, and $P_m \div P$ is greater than 0.9, the maximum values of f_1 and f_2 are equal within one-half of one per cent. Fig. 5 shows calculated curves for f_1 and f_2.

Before Case II is considered, equations (9) and (10) which give the m. m. f. of the primary and secondary for this case, will be expressed in terms of current instead of m. m. f. These equations involve the permeances P_1, P_2, and P_m, and the magnetizing m. m. f., F_m, which are related to the total per cent reactance X_p and normal current I_n as follows:

Let $P_1 - P_m$ = leakage flux of the primary per ampere turn,

and $P_2 - P_m$ = leakage flux of the secondary per secondary ampere turn.

Per cent reactance of primary

$$= \frac{\text{(leakage flux of primary at normal current)}}{\text{normal flux}}$$

but $F_m P_1$ = normal flux

and $F_n (P_1 - P_m)$ = leakage flux of primary at normal current.

Therefore, the per cent reactance of the primary is

$$\frac{F_n (P_1 - P_m)}{F_m P_1}$$

And since $\dfrac{F_n}{F_m} = \dfrac{I_n}{I_m}$

the per cent reactance of the primary is

$$\frac{I_n (P_1 - P_m)}{I_m P_1}$$

Assuming $P_1 = P_2 = P$, and that the primary and secondary ampere turns are equal, then the total reactance corresponding to normal current will be two times the primary reactance.

Therefore, $$X_p = \frac{2 I_n (P - P_m)}{I_m P} \tag{17}$$

The initial value of the short-circuit current is equal to normal rated current divided by the per cent total reactance.

Therefore, $I_0 = \dfrac{I_n}{X_p}$

And substituting the value of X_p from (17)

$$I_0 = \frac{I_m}{2\left(1 - \frac{P_m}{P}\right)} \qquad (18)$$

Since $\frac{F_m}{f_{1a\text{-}c.}} = \frac{\sqrt{2}\,I_m}{i_{1a\text{-}c.}}$

Equation (12) may be rewritten in terms of current as follows:

$$i_{1a\text{-}c.} = \frac{\sqrt{2}\,I_m}{\frac{P_1 P_2}{P_m^2} - 1} \cos \omega t \qquad (19)$$

In the ordinary machine P_m/P_1 is about 0.95, so I_0 may be substituted in (19) for

$$\frac{I_m}{\frac{P_1 P_2}{P_m^2} - 1}$$

without a significant error because the difference between I_0 from this expression (assuming $P_1 = P_2$) and I_0 from equation (18) is only 2 1/2 per cent. Likewise all the m. m. f. equations may be rewritten in terms of current as follows: from (11)

$$i_{1d\text{-}c.} = \sqrt{2}\,I_{01} \qquad (20)$$

and from (12)

$$i_{1a\text{-}c.} = -\sqrt{2}\,I_{01} \cos \omega t \qquad (21)$$

The total short-circuit current in the primary is the sum of the two components. That is,

$$i_1 = i_{1d\text{-}c.} + i_{1a\text{-}c.} = \sqrt{2}\,I_{01}\,(1 - \cos \omega t) \qquad (22)$$

Also from (13)

$$i_{2d\text{-}c.} = \sqrt{2}\,I_{02} \qquad (23)$$

And from (14)

$$i_{2a\text{-}c.} = -\sqrt{2}\,I_{02} \cos \omega t \qquad (24)$$

And the total short-circuit current in the secondary is the sum of the two components.

$$i_1 = i_{2d\text{-}c.} + i_{2a\text{-}c.} = \sqrt{2}\,I_{02}\,(1 - \cos \omega t) \qquad (25)$$

These equations were developed on the assumption of zero resistance. Multiplying (22) by

$$\epsilon^{-\frac{r_1}{L_0}t}$$

and (25) by

$$\epsilon^{-\frac{r_2}{L_0}t}$$

takes into account the effect of resistance. The final equations then become:

$$i_1 = \sqrt{2}\, I_{01}\, \epsilon^{-\frac{r_1}{L_0}t}\,(1 - \cos \omega t) \qquad (26)$$

$$\text{and } i_2 = \sqrt{2}\, I_{02}\, \epsilon^{-\frac{r_2}{L_0}t}\,(1 - \cos \omega t) \qquad (27)$$

CASE II. POLYPHASE SHORT CIRCUIT

Polyphase primary, one phase of secondary excited with direct current.

This case requires only three equations for the solution since the secondary is single-phase. The equations summing up the flux in the machine are as follows:

1. Total flux of the primary,
   $$f_1 P_1 + f_2 P_m \cos \omega t = F_m P_m \qquad (28)$$
2. Total flux of the secondary,
   $$f_2 P_2 + f_1' P_m = F_m P_2 \qquad (29)$$
3. Primary flux in line with the rotor pole,
   $$f_1' P_1 + f_2 P_m = F_m P_m \cos \omega t \qquad (30)$$

Solving equations (29) and (30) for f_2 gives

$$f_2 = F_m \frac{\dfrac{P_1 P_2}{P_m^2} - \cos \omega t}{\dfrac{P_1 P_2}{P_m^2} - 1} \qquad (31)$$

Solving equations (28) and (31) for f_1 gives

$$f_1 = F_m \frac{P_m}{P_1} \left[1 - \frac{1}{\dfrac{P_1 P_2}{P_m^2} - 1} \left\{ \frac{P_1 P_2}{P_m^2} \cos \omega t - 1/2\,(1 + \cos 2\,\omega t) \right\} \right] \qquad (32)$$

CASE III. SINGLE-PHASE SHORT CIRCUIT

Polyphase induction motor or generator. It is assumed that the third line is opened at the instant the other two are short-circuited.

Let δ = angle between center line of flux and center line of short-circuited phases at the instant of short circuit.

The flux caught in the short-circuited phases is,

$$\Phi_1 \cos \delta = F_m P_1 \cos \delta$$

The flux in the rotor is,

$$\Phi_2 = F_m P_m$$

Summing up the flux as in the previous cases gives the equations necessary for the solution.

The total flux of the primary is,

$$f_1 P_1 + f_2' P_m = F_m P_1 \cos \delta \qquad (33)$$

The total flux of the secondary is

$$f_1 P_m \cos \omega t + f_2 P_2 = F_m P_m \qquad (34)$$

The secondary flux in line with the stator pole is

$$f_1 P_m + f_2' P_2 = F_m P_m \cos \omega t \qquad (35)$$

Solving (33) and (35) for f_1 gives

$$f_1 = F_m \frac{\dfrac{P_1 P_2}{P_m^2} \cos \delta - \cos \omega t}{\dfrac{P_1 P_2}{P_m^2} - 1} \qquad (36)$$

and solving (36) and (34) for f_2 gives

$$f_2 = F_m \frac{P_m}{P_2} \left[1 - \frac{1}{\dfrac{P_1 P_2}{P_m^2} - 1} \left\{ \frac{P_1 P_2}{P_m^2} \cos \delta \cos \omega t - 1/2\,(1 + \cos 2\,\omega t) \right\} \right] \qquad (37)$$

If the short circuit occurs at $\delta = 90$ deg., that is, at maximum voltage, (36) becomes

$$f_1 = -F_m \frac{\cos \omega t}{\dfrac{P_1 P_2}{P_m^2} - 1} \qquad (38)$$

and (37) becomes

$$f_2 = F_m \frac{P_m}{P_2} \left[1 - \frac{1}{\frac{P_1 P_2}{P_m^2} - 1} \right.$$

$$\left. \left\{ - 1/2\,(1 + \cos 2\,\omega\,t) \right\} \right] \qquad (39)$$

CASE IV. SINGLE-PHASE SHORT CIRCUIT

Single-Phase Stator, Single-Phase Rotor.

Let δ = angle between center line of stator pole and center line of rotor pole at the instant of short circuit.

The total flux of primary at the instant of short circuit is

$$\Phi_1 = F_m\,P_m \cos \delta$$

and the flux of secondary

$$\Phi_2 = F_m\,P_2$$

At any time after short circuit the primary flux is

$$f_1\,P_1 + f_2\,P_m \cos \omega t = F_m\,P_m \cos \delta \qquad (40)$$

and the secondary flux is

$$f_1\,P_m \cos \omega\,t + f_2\,P_2 = F_m\,P_2 \qquad (41)$$

Solving these equations for f_1 gives

$$f_1 = F_m \frac{P_2}{P_m} \quad \frac{\cos \delta - \cos \omega\,t}{\frac{P_1 P_2}{P_m^2} - 1/2\,(1 + \cos 2\,\omega\,t)} \qquad (42)$$

Solving for f_2 gives

$$f_2 = F_m \frac{\frac{P_1 P_2}{P_m^2} - \cos \delta \cos \omega\,t}{\frac{P_1 P_2}{P_m^2} - 1/2\,(1 + \cos 2\,\omega\,t)} \qquad (43)$$

If the short circuit occurs at $\delta = 90$ deg., that is maximum voltage, the equations become

$$f_1 = - F_m \frac{P_2}{P_m} \quad \frac{\cos \omega\,t}{\frac{P_1 P_2}{P_m^2} - 1/2\,(1 + \cos 2\,\omega\,t)} \qquad (44)$$

and

$$f_2 = F_m \frac{1}{1 - 1/2 \frac{P_m^2}{P_1 P_2} (1 + \cos 2 \omega t)} \qquad (45)$$

INDUCTION MOTOR DATA

150-h. p., three-phase, 60-cycle, 720-rev. per min.,........	440-volt.
Normal current 185.. amperes..........	
Resistance per phase of primary........	0.027 ohms—2.1 per cent
Resistance per phase of secondary	0.029 ohms
Voltage Ratio:	
Primary volts per.. phase...........	254
Secondary volts per phase............	250
Excitation, 58 amperes at..................	440 volts
Impedance, 175 amperes at..................	71 volts
Total reactance in primary terms,...........	0.227 ohms, or 17 per cent

PROOF THAT UNDER SHORT CIRCUIT THE MAGNETIC INTERLINKAGES OF THE CLOSED CIRCUITS MUST REMAIN CONSTANT IF RESISTANCE IS ZERO.

Consider an n phase, star-connected, induction generator with terminals suddenly short-circuited during normal operation. Then the voltage across *any* phase, say phase 1, between terminal and neutral is

$$e_1 = i_1 r_1 + \frac{d}{d t} (L_1 i_1 + \Sigma M_p i_p + \Sigma M_s i_s) \qquad (46)$$

where i, r, L are respectively the current, resistance, total inductance of the particular phase under consideration.

M_p = mutual inductance of other primary phases with respect to the phase under consideration.

i_p = current at any time t in any of the other primary phases.

M_s and i_s = similar quantities for secondary circuits. Neglecting resistance, this becomes,

$$e_t = \frac{d}{d\,t}\,(L_1 i_1 + \Sigma\, M_p\, i_p + \Sigma\, M_s\, i_s) \qquad (47)$$

By Kirchoff's laws

$$\Sigma\, i = 0$$

and

$$\Sigma\, i_s = 0 \qquad (48)$$

Adding the family of equations (47),

$$\frac{d}{d\,t}\,[(L_1 i_1 + L_2 i_2 + L_3 i_3 + \ldots\ldots L_n i_n) + \sum_{0-n} M_p\, i_p + \sum_{0-n} M_s\, i_s] = n\, e_t \qquad (49)$$

Consider $\sum\limits_{0-n} M_p\, i_p$. It is

$$\begin{aligned}
&M_{12} i_2 + M_{13} i_3 + M_{14} i_4 + \ldots\ldots M_{1n} i_n \\
&+ M_{21} i_1 + M_{23} i_3 + M_{24} i_4 + \ldots\ldots M_{2n} i_n \\
&+ M_{31} i_1 + M_{32} i_3 + M_{34} i_4 + \ldots\ldots M_{3n} i_n \qquad (50)\\
&+ \ldots\ldots \text{etc. up to} \\
&+ M_{n1} i_1 + M_{n2} i_2 + M_{n3} i_3 + \ldots\ldots M_{n(n-1)}\, i_{(n-1)}
\end{aligned}$$

But by symmetry

$$\begin{aligned}
M_{12} &= M_{23} = M_{34} = \ldots\ldots = M_{n1} \\
M_{13} &= M_{24} = M_{35} = \ldots\ldots = M_{(n-1)1} \qquad (51)\\
M_{14} &= M_{25} = M_{36} = \ldots\ldots = M_{(n-2)1} \\
&\text{etc. to} \\
M_{1n} &= M_{21} = M_{32} = M_{43} = \ldots\ldots M_{n(n-1)}
\end{aligned}$$

Hence

$$\sum_{0-n} M_p\, i_p = M_{12}\,\Sigma\, i + M_{13}\,\Sigma\, i + M_{14}\,\Sigma\, i + \ldots\ldots M_{1n}\,\Sigma\, i = \Sigma\, i\,(M_{12} + M_{13} + \ldots\ldots M_{1n}) \qquad (52)$$

But by (48)

$$\Sigma\, i = 0$$

Therefore,

$$\sum_{0-n} M_p\, i_p = 0 \qquad (53)$$

Consider $\sum\limits_{0-n} M_s\, i_s$. Identifying the secondary currents i_s in the different secondary phases by i_1, i_2, i_3, etc., and also designating the variable mutual inductances M_s between the several secondary phases and any particular primary phase by subscripts, the first indicating the particular primary phase, the second, the secondary phase, the following relations can be written:

$$\sum_{0-n} M_s i_s$$
$$= M_{11} i_1 + M_{12} i_2 + M_{13} i_3 + \ldots . M_{1n} i_n$$
$$+ M_{21} i_1 + M_{22} i_2 + M_{23} i_3 + \ldots . M_{2n} i_n$$
$$+ M_{31} i_1 + M_{32} i_2 + M_{33} i_3 + \ldots . M_{3n} i_n \qquad (54)$$
$$+ \ldots . \text{ etc. to}$$
$$+ M_{n1} i_1 + M_{n2} i_2 + M_{n3} i_3 + \ldots . M_{nn} i_n$$

But by symmetry

$$M_{11} = M_{22} = M_{33} = \ldots . = M_{nn}$$
$$M_{12} = M_{23} = M_{34} = \ldots . = M_{n1}$$
$$M_{13} = M_{24} = M_{36} = \ldots . = M_{n2} \qquad (55)$$
$$\text{etc. to}$$
$$M_{1n} = M_{21} = M_{32} = M_{43} = \ldots . = M_{n(n-1)}$$

Hence

$$\sum_{0-n} M_s i_s = M_{11} \Sigma i_s + M_{12} \Sigma i_s + M_{13} \Sigma i_s$$
$$+ \ldots . M_{1n} \Sigma i_s = \Sigma i_s (M_{11} + M_{12}$$
$$+ M_{13} + \ldots . M_{1n}) \qquad (56)$$

etc.

But by (48)

$$\Sigma i_s = 0$$

Hence $$\sum_{0-n} M_s i_s = 0 \qquad (57)$$

Assuming constant permeability and neglecting tooth ripples,

$$L_1 = L_2 = L_3 = \ldots . = L_n = L \qquad (58)$$

Therefore

$$L_1 i_1 + L_2 i_2 + L_3 i_3 + \ldots . L_n i_n = L \Sigma i$$

But $$\Sigma i = 0$$

Hence $$\Sigma L i = 0 \qquad (59)$$

Therefore, by (53), (57) and (59)

$$e_t = 0$$

and

$$L i + \Sigma M_p i_p + \Sigma M_s i_s = \text{constant.}$$

That is, the magnetic interlinkages of any particular phase must be constant, under short circuit, if the resistance of that phase is zero.

DISCUSSION ON "SHORT-CIRCUIT CURRENT OF INDUCTION MOTORS AND GENERATORS" (DOHERTY AND WILLIAMSON), NEW YORK, N. Y., FEBRUARY 18, 1921.

V. Karapetoff: As Mr. Doherty stated there has been a mistaken impression among engineers that an induction generator or motor has no "kick" to it, that is, when short-circuited it dies passively. The oscillograms given in the paper conclusively show a large transient current which is a superposition of an alternating and direct current in each phase, and of course, the initial values are those of the regular current at the instant of short circuit. Insofar as these experimental results are concerned we have to be grateful to the authors, and the only suggestion I would make would be to have these oscillograms provided with scales, so that we could judge about the absolute values of the currents.

When it comes to the theoretical part of the paper, I am not sure whether the fundamental assumptions are correct or not. I made some search among the standard works on electro-magnetism, but could find no clear statement of a physical law that applies exactly to the conditions in this case. For that reason I regret that the authors started with one or two assumptions which may be correct—maybe not. I should like to see these assumptions supported by the classical fundamental equations of electro-dynamics, in order that we may start this new branch of investigation on a solid ground.[1]

You will notice that the whole treatment of the theory is based on Lenz's law. There are as many statements of Lenz's law as there are books on electricity. At any rate, Lenz's law does not cover in its original form the case of an inter-connected stationary system of conductors with another interconnected electrical system in an inductive relationship thereto, and in a relative motion with respect thereto. Perhaps the law can be extended to cover the case, but I should like to see it so extended and definitely stated, before applying it.

The authors state that the total linkages of the flux with the primary at the instant of short circuit, remain constant, or, as they put it in another place, the flux which has been revolving before the short circuit, becomes stationary with respect to the stator winding.

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[1] The author in his closure to this disscussion has met the objection cited and Prof. Karapetoff has agreed to withdraw his criticism.—EDITOR.

This can be readily shown to be the case in a system of individual windings, not inter-connected into a three-phase system, and provided that the primaries and the secondaries are stationary. But is the same condition true in the case under consideration?

I shall use an analogy, and I shall begin with one phase in the primary and one phase in the secondary. This is case No. 4 in the paper. Suppose we make this case analogous to the movement of a single material point. If the material point has been under constraint of certain external forces, and then at a certain instant let go by itself, the subsequent motion can be simply described in terms of the velocity at the last instant of the constraint. Now suppose that you have two or more inter-connected windings. This corresponds in our analogy to a system of several material points connected by rods to form a system. Let this system at first be moving under the influence of some external forces, and then let these forces disappear at a certain instant. It is not correct to state that each point will move along a straight line in the same direction and at the same velocity as it did before the change in the conditions. No,—you have to consider the motion of the center of gravity of the system and the motion of the individual points about the center of gravity.

Now, an interconnected electrical system like the three-phase stator, has certain degrees of freedom, electrically speaking, in that the linkages of the flux with each individual phase may vary, and yet the total linkages may vary in such way that the system as a whole will satisfy certain fundamental differential equations of electro-mechanics. I expect to discuss this matter more fully with Mr. Doherty, and then write a mathematical contribution to the discussion.

While this may seem like splitting hairs and going too far back to the fundamentals, I should like to see it done just once, in order either to prove or to disprove the fundamental assumptions of the authors. Then those of us who wish to pursue this problem further will be absolutely sure that they are working on the correct foundation.

L. E. Widmark: The subject brought up by the authors is a very interesting one and so are the results obtained, but I most heartily disagree with the mathematical treatment of the problem and will herewith suggest a quicker and more general solution.

What is in fact the main difference between the complete short circuit of a synchronous generator and that of the induction variety?

Is it not that in a synchronous generator the excitation and main current are located in *different* circuits with *highly different time constants* and in an induction generator in *one,* meaning the same time constant?

Applying this last condition to the ordinary differential equation containing exponentially dying away sinus-function of the voltage opposed by the ohmic and reactance terms, the complete and general solution immediately will appear.

We get

$$i = \frac{E}{2\pi L \sim}\,\epsilon^{-\frac{R}{L}t}\ \{C - \cos(2\pi \sim t)\}$$

(short circuit started at maximum voltage, otherwise add an angle β to the cosine expression)

The following interesting results will at once be at hand.

$$E\,\epsilon^{-\frac{R}{L}t}\sin 2\pi\,\omega t = [R i + L\frac{di}{dt}$$

$$i = n v \quad \frac{di}{dt} = \frac{n\,dv}{dt} + v\,\frac{dn}{dt}$$

$$E\,\epsilon^{-\frac{R}{L}t}\sin 2\pi\,\omega t = R n v + L\left(\frac{n\,dv + v\,dn}{dt}\right)$$

$$R n v + L n\frac{dv}{dt} =$$

$$n\left(R v + L\frac{dv}{dt}\right) = 0$$

$$v = k\,\epsilon^{-\frac{R}{L}t}$$

$$E\,\epsilon^{-\frac{R}{L}t}\sin 2\pi\,\omega t = \epsilon^{-\frac{R}{L}t}\,L\,v\,\frac{dn}{dt}\ .k$$

$$\frac{1}{k}\ \frac{E}{L\,2\pi n}\ \{C - \cos(2\pi\,\omega t)\} = n$$

$$n v = \frac{E\,\epsilon^{-\frac{R}{L}t}}{2\pi n L}\ \{C - \cos(2\pi\,\omega t)\} = i$$

The authors are right when it comes to the general shape of the current. They are even more right than they themselves believe they are, because the expression holds good not only under assumption of zero resistance, but irrespective of the relation between R and L. Especially interesting is that, what the authors term the initial current, is only determined by

L, no matter the value of *R*. That does not mean however, that the maximum amplitude is independent of *R*. The attenuation factor takes care of that.

We note further how well this equation takes care of the d-c. component. We have it embodied in the integration constant and it requires only a simple subtraction to get it determined for any value and time position of the current at the start of the short circuit.

Now, I want to draw attention to another interesting feature. Comparing voltage and current we find that the current is 90 degrees apart from the voltage and still represents energy. I repeat it, *Zero power factor and wattful current!* Enough power to melt down the machine—*but zero power factor*. The explanation, of course, is found in the fact that the decreasing amplitudes of current and voltage produce decreasing watt waves and the succeeding wave cannot knock out the preceding one, as is the case with equal amplitudes. There is something over, that is enough to supply the more or less destructive development of heat that constitutes a real short circuit.

At last a few words in regard to the most important case—the single-phase short circuit. In practise this one will be the most important one, because you cannot expect "the fellow that is going to drop that monkey wrench" to hit all the three phases at the same time.

We will now get a combination of the induction and synchronous short circuits. The original revolving field will, step in step with the dying away of the one-phase excitation, dissolve itself in two rotating fields revolving in opposite directions. Conditions will now be exceedingly complicated, but it is safe to say that the induction generator will not be in a better position than an ordinary synchronous generator, maybe worse.

As this last case, as said before, has the most practical importance, it seems to me that the hope to get a more or less fool-proof generator by using the induction type, is only a technical illusion.

M. I. Pupin: I was much pleased by the statements made by my friend, Prof. Karapetoff. There are engineers who do not think that way. The very method that Prof. Karapetoff brought out so beautifully is one that I follow in my classroom, and I worked out the theory of the single-phase induction motor and the polyphase induction motor following that method and the result is so simple that even the average undergraduate student could understand it. The best test of a method is that which has been applied to the undergraduate student. If he likes it, it is all right. Do not serve it to grown engineers, who have a lot of things in their heads that they got in the shop. It is easy enough to write what is called the mathematical theory of certain electrical phenomena when you have the blueprints before you, and know beforehand what you ought to get. Start with the fundamental principle and get what you ought to get, and then you are perfectly sure that you are right. Besides, going back to the fundamental principles is a thing that we ought to encourage. What do we see here in these fundamental principles represented in the equations put on the blackboard by Prof. Karapetoff? What do they say? They say that the rate of variation of magnetic momentum gives you a reaction. Who said that? Newton, Faraday and Maxwell. It is their formulation of the fundamental laws which we always ought to repeat at every step.

When you say that there is a drop—I hate that term "drop," I always called it the dissipative reaction. You are dealing in electrical circuits with nothing but reactions, and we have dissipative reactions and non-dissipative reactions. That dissipative reaction was discovered by two great men in science, Ohm and Joule. Let us remember these two men every time we measure the reaction of a wire due to the heating produced in it by the electrical current; do it and you will never go astray.

N. S. Diamant: A very important practical question raised in this paper, and which the writers state prompted them to undertake the study of sudden short circuits of induction motors and generators seems to be: Is the suggestion correct that the installation of induction generators may prove a partial solution of the short-circuit problem? I think it would be quite interesting to have some information in regard to this point. For example, I wonder if the writers could give us in a tabular form the average, high and low values of reactance, and armature and field attenuation factors of ordinary synchronous and induction type machines ranging from 100 kv-a. to the largest commercially successful machines. From this sort of average data one could easily calculate the maximum sudden short-circuit current that different types and sizes of machines could deliver; also the attenuation factors would give us an idea as to the rate of decay of current in each case.

It seems to me that the size of machine or the available power back of a circuit are important as far as "danger" of short circuit is concerned, but the theory and underlying principles of the phenomenon, I believe are the same irrespective of size. Thus oscillograms obtained from small machines, having comparatively high resistance, may and do appear quite different from those obtained from large machines.

Referring to the *physical* explanation given in the paper, some readers may find the following due to Boucherot interesting and easy; Starting from actual facts we know that the field flux *changes* from, let us say, 100 per cent before the short circuit to zero at the end of the short circuit; similarly the flux enclosed by a given phase may be anything between let us say 100 per cent (on a different percentage) and zero, depending on its position at the instant of short circuit. Now this *change* or *decay* of flux manifests itself as a direct current which dies down according to the attenuation factor of the field or armature depending on whether the *change* of flux is in the field or armature. Thus, turning to the current equations given by Berg or Boucherot we find:

$$i = (A \cos \theta_1)\, \epsilon^{-\alpha_a(\theta - \theta_1)} + (A \cos \theta)\, \epsilon^{-\alpha_f(\theta - \theta_1)}$$

where α_a = attenuation factor of armature

α_f = " " " field

θ_1 = ωt_1 = time angle at which machine is short-circuited

A = constant = e. m. f. divided by impedance or reactance.

Now if the short circuit occurs when the e. m. f. wave is passing through zero so that $\theta_1 = 0$ then the first term of our equation is maximum and represents the decaying direct current which is due to the *change of flux* in the phase under consideration. If the short circuit occurs when $\theta_1 = 90$ deg. then there is no change of flux and no direct current in the phase under consideration. Also, it will be noted that this decaying direct current dies down according to α_a. The second term is due to the change of flux in the field and dies down according to α_f, and is independent of the time of short circuit; it is a decaying symmetrical alternating current and the total short-circuit current will be more or less symmetrical depending on the value of the first term. Finally it is clear how the direct current represented by the first term will induce an alternating current in the field, etc.

Another point I would like to touch upon is the mathematical derivation given by the authors. They start with ideal circuits without resistance and get their a-c. and d-c. components and then add them together to get the total current. This can hardly be called derivation of an equation. Here is the way Berg, for example derives the current equation: Start from the fact that,

$$\text{e. m. f. in a circuit} = i\, r \text{ drop} + i\, x \text{ drop}.$$

Now then, the e. m. f. which is $E \sin \theta$ before the short circuit dies down according to $(E_1 \sin \theta)\ \epsilon^{-\alpha_f(\theta - \theta_1)}$ because the flux, as we have just seen is reduced from 100 per cent to zero; furthermore the flux in the field dies down or can be assumed as a good approximation to die down according to the attenuation factor α_f. If we let a brother mathematician solve this equation for us: e. m. f. = $i\,r$ drop + $i\,x$ drop, we get a long expression for the current which was given above in its simplified form and which tells us that there is a d-c. component and an a-c. component etc. Boucherot's derivation is a good and beautiful derivation a little more complicated than the above; for further details the reader can consult Berg and Upsons, first course in E. E. p. 303 or the 1915 TRANS. A. I. E. E., p. 2237 where further references are given. In this connection referring to eq. (**26**) and (**27**) I would like to ask the authors why both the a-c. and d-c. components depend upon α_a or r_1/L_0 as they call it. Also is the short-circuit current independent of the time angle θ_1 at which the short circuit occurs? According to their equations it is.

Under the heading of tests and conclusions, the authors take up the question of what "the attenuation factor r/L" is and also what r is and what L is. I think an excellent idea of this can be obtained as follows. Take a synchronous or non-synchronous machine and connect across its field let us say a source of direct current and by means of an oscillograph determine the rise of current in the field with the machine (a) stationary (b) running full speed and armature open and (c) running full speed and armature dead short-circuited. This is a simple test which has nothing to do with short circuits, etc., and will give you α_f. You can reverse the tests and find the rate of rise of direct current in the armature under conditions similar to (a), (b) and (c) as given above. Thus you can obtain α_a. In every case you will find that the values of α_f obtained from (a) and (b) differ very little but they are *several times* smaller than α_f obtained from (c). The same is true of α_a. The reason for this is the fact that in (a) and (b) the rise of current in the field or armature as the case may be depends upon α_f or α_a where:

$$\alpha_f = \frac{\text{ohmic resistance of field, approx.}}{\text{self-inductive reactance of field circuit, approx.}}$$

and

$$\alpha_a = \frac{\text{ohmic resistance of armature, approx.}}{\text{self-inductive reactance of arm., approx.}}$$

But, in case (c) we have the *effect* of the field on the armature and vice-versa, so that, in this case

$$\alpha_f = \frac{\text{effective resistance of field, approx.}}{\text{total leakage reactance of field and armature reduced to field, approx.}}$$

Similarly for α_a, and let me add that the above are fundamental to all transients and so far my remarks had reference to the rise of direct current. Now, as shown in my paper, A. I. E. E. TRANS. 1915, p. 2237, if with the machine running full speed and the armature or field dead short-circuited, α_f and α_a be determined from the rise of direct current. These values of α_f and α_a are found to be very close to the actual α_f and α_a obtained from sudden short-circuit oscillograms.

In this connection those interested in these problems may find it profitable to refer to Prof. Karapetoff's discussion and my own given in TRANS. A. I. E. E., 1918.

Finally in closing I would like to ask the writers if they can tell us more definitely what is the difference in average values of α_f and α_a for wound and squirrel cage type machines. In their title and certain paragraphs they refer in general to either type but in their tests and conclusions they seem to have in mind the wound type of machine only.

Selby Haar: In my opinion the short-circuit tests would have been less open to doubt, if the generator had been disconnected from the motor at the moment of short circuit. I cannot help but feel that some of the short-circuit current recorded is generator current.

R. E. Doherty: Following the suggestion of Prof. Karapetoff, the paper has been slightly revised, proving the fundamental premise by the classic equations of electro-dynamics. That premise is: *in a closed electric circuit without resistance the number of magnetic interlinkages must remain constant.*

In the paper as originally presented, this was taken as following from Lenz's Law. That is, in such a circuit an incipient change in interlinakge would, by Lenz's Law, cause currents to flow *in a direction to oppose* the change; and it seemed obviously unnecessary to prove that the resistance being zero, the *magnitude* of that current would be limited only by the condition that the reaction or opposition be complete. This, however, is proved in the following; also, the Appendix has been extended to cover the proof of what, in the original paper, was taken as a corollary to the above premise; namely, that the magnetic interlinkages must remain constant in *each phase* (or leg) of a short-circuited, star-connected, polyphase induction motor or generator. This is true, even if as is the case, each phase is not individually short-circuited but instead is short-circuited in pairs (each two forming a closed circuit) provided the rotor and stator windings are each symmetrical polyphase systems of the same order: which is the particular condition under consideration. The proof can not however, be extended to cover unsymmetrical phases, or a different number of phases on the stator and rotor, unless each phase is individually short-circuited. Then it falls under the general case and the principle rigidly holds.

Even in a three-phase star-connected alternator, with a definite pole field winding, the principle approximately holds. In such a case, for instance, third harmonic (or multiple) variations of interlinkages could occur in each phase under short-circuit conditions.

Consider any closed electric circuit

(a) in relative motion to secondary circuits.

(b) in multiple connection with other circuits.

Let

i_a, i_b, i_c, etc. be the currents in the several individual lengths of the closed circuit.

L_a L_b, L_c, etc. be respectively the inductances and

r_a, r_b, r_c, etc. the resistances of those lengths;

M_1, M_2, M_3, etc. be the mutual inductances between the closed circuit and the secondary circuits;

i_1, i_2, i_3, etc. be the currents in the secondary circuits.

All the quantities are considered as variables.[2]

By Kirchoff's Law,

$$\Sigma e = 0$$

Thus,

$$(i_a r_a + i_b r_b + i_c r_c + \ldots\ldots) + \frac{d}{dt}(L_a i_a + L_b i_b + L_c i_c + \ldots . M_1 i_1 + M_2 i_2 + M_3 i_3 + \ldots) = 0$$

That is

$$\Sigma i r + \frac{d}{dt}(\Sigma L i + \Sigma M i') = 0$$

neglecting resistance this becomes

$$\frac{d}{dt}(\Sigma L i + \Sigma M i') = 0$$

What is the quantity in the paranthesis? It is the number of magnetic interlinkages of the circuit. The

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[2] *M's* variable by relative motion; *L's* may be variable either by saturation or by proximity to moving iron of secondary circuits.

equation says that the rate of change of the number of interlinkages is zero; *therefore the number is constant.*

Now if the turns in the closed circuit are not concentrated, then it does not follow that the number of interlinkages in each turn is constant; but it does follow that the total number *in the closed circuit* is constant. Thus, the distribution of interlinkages per turn may be anything so long as the total number in the closed circuit is constant.

Thus far no constraint has been placed upon the character of the circuits except that they are closed and contain no resistance or capacity. The equations show, therefore, that the number of interlinkages in any such circuit cannot be changed, either by a change in the reluctance of the magnetic path or by the effect of *any* secondary coil or coils.

Consider then the closed circuit formed by any two bars of a squirrel cage winding. It follows that neglecting resistance, the flux linked by the circuit must remain constant, regardless of rotor position or of currents in the other bars of the squirrel cage winding or in the coils of the primary winding.

For the same reason, the interlinkages of *any* short-circuited phase of a polyphase winding must remain constant, provided that the phase is closed on itself and therefore does not depend upon another phase for return. In a Y-connected 3-phase winding short-circuited at the terminals, the closed circuit is not a single-phase but includes two. *Any* two of the 3 phases form a closed circuit in which, for the above reasons, the number of interlinkages must be constant. The question remains whether the interlinkages *of each phase* must in this case also be constant. This is proved in the Appendix.

Referring to Mr. Widmark's discussion: he disagrees with the mathematical treatment of the problem. The author's method is to neglect resistance and thus determine the initial current wave; than approximate the effect, of resistance by introducing the well known exponential factor $\epsilon^{-\frac{R}{L}t}$. Mr. Widmark *assumes* a sine wave voltage multiplied by this exponential to be the particular integral of his differential equation for the voltage in the closed circuit, the same R and L are assumed as in the exponential term of the inducing circuit. Still further, the important term representing the mutual induction between primary and secondary is omitted.

Now the solution of the differential equation which really applies to the conditions is not easily solved.

They are, taking the simplest case of single-phase stator and single-phase rotor:

$$i_1 r_1 + L_1 \frac{d\,i_1}{d\,t} + M \frac{d\,i_2}{d\,t} = 0$$

and

$$i_2 r_2 + L_2 \frac{d\,i_2}{d\,t} + M \frac{d\,i_1}{d\,t} = 0$$

$$M = M_0 \cos \omega t$$

These reduce to the second order equation with variable coefficient, thus

$$\frac{d^2\,i_2}{d\,t^2} (L_1 L_2 - M_0^2 \cos^2 \omega t) + \frac{d\,i_2}{d\,t} (r_1 L_2 + r_2 L_1) + i_2 r_1 r_2 = 0$$

which is obviously not as simple as the equation offered by Mr. Widmark. For polyphase, it is still more difficult. The very object of the scheme of neglecting r as first approximation, is to obtain a practical solution of a practically hopeless equation.

Mr. Diamant's discussion consists largely of a recitation of the work done by Berg and Boucherot which he has from time to time written about. There are, however, a few points to be answered. He asks why both the a-c. and d-c. components depend upon the same factor α_a or r_1/L_1. Because the windings of the stator and rotor are practically the same; that is, have relatively the same resistance loss and reactance. This is, of course, only an approximation. The paper states, "The above equations apply when the ratio $r_1/L_0 = r_2/L_0$, that is, when $r_1 = r_2$." If r_1 and r_2 are significantly different, the components obviously would die out at the different rates of r_1/L_0 and r_2/L_0.

Mr. Diamant objects to the use of the theory of superposition in arriving at final equations. The objection is touched upon here, not because that was the method followed in the paper for it was not; but because it is an unusual viewpoint, not generally held by engineers. If direct proportionality is assumed between mechanical stress and deflection, or between current and voltage, or between leakage flux and m. m. f. then it is a perfectly safe and logical procedure in such cases to calculate each component separately and add them to obtain the resultant. But the authors didn't do that, and they would answer the objection by referring to equations (**9**), (**10**), and (**26**), (**27**) and their derivation.

He asks if the current is independent of the time of short circuit. The equations are developed in terms of resultant m. m. f. and not of current. For polyphase short circuit the resultant m. m. f. *is* independent of the time of short circuit. For single phase short circuit, it is dependent upon the time, and is shown in the equations for the single-phase case, *i. e.* Case III. The angle δ in equation (37) accounts for the time of short circuit. In the current equations (**26**) and (**27**) derived from m. m. f. equations (**9**) and (**10**), maximum values are taken.

The results obtained on squirrel cage machines as compared with phase-wound rotors are practically the same. The only difference being a relatively higher resistance in the squirrel cage, and therefore a correspondingly shorter rotor transient.

In reply to Mr. Haar, if the supply lines between generator and motor are short-circuited, the potential between *any* two lines at that point must be zero. Hence, no transfer of current could occur across the switch.

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 18, 1921.

HYSTERESIS EFFECTS WITH VARYING SUPERPOSED MAGNETIZING FORCES

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AND
W. H. MARTIN
American Telephone & Telegraph Co.

THE hysteresis effects discussed in this paper occur when magnetic fields are produced in iron by electrical circuits carrying simultaneously currents of different frequencies. Investigations have shown that when two currents of different frequencies are so superposed, the losses in the iron corresponding to each frequency may differ greatly from those obtained when each frequency is acting alone in the circuit. These effects are, therefore, particularly important in the electrical communication field because of the practise of transmitting over one circuit currents of different frequencies. Predictions of the behavior of iron-cored inductance coils and transformers in such a circuit may be erroneous if based on measurements of the iron losses which have been made in the usual way with single-frequency test currents.

These effects first became of importance in the plant of the Bell Telephone System as a result of the long established practise of arranging practically all the long telephone toll lines for simultaneous operation of telephone and telegraph circuits over the same wires. This system of "compositing" the lines has been generally arranged to provide one grounded telegraph circuit over each of the two conductors used for the telephone circuit. Each of these telegraph circuits can be operated either "full duplex" or "half duplex". In full-duplex operation a telegraph circuit is used to send messages simultaneously in both directions. In half-duplex operation the circuit is operated in only one direction at a time but may be used in either direction. Thus as many as four independent trains of direct-current telegraphic signals may be passing over the two conductors provided for the telephone circuit.

The compositing of a line is accomplished by the use of networks which transmit currents of frequencies in one range and discriminate against currents of frequencies in another range. A standard form of "composite set" is shown in Fig. 1. In the two wires of the line is inserted the network *a b c d*, consisting of inductances L_1 and capacitances C_1 and C_2, which transmits efficiently between the line and the telephone terminals, currents of frequencies in the range above 100 cycles. Connected to each of the line conductors are shown selective networks *a e* and *d f* each consisting of L_2 and C_3, which discriminate against this range of frequencies, but transmit efficiently the lower frequencies, including direct current, used for the operation of the telegraph circuit. Each of the line conductors thus provides a grounded telegraph circuit. To each telegraph terminal of the circuit is connected a duplex telegraph set which, by means of the usual balanced bridge arrangement, permits two-way operation.

With the application of this compositing system to loaded telephone lines[1] in which the inductance of the circuit is increased by the insertion at uniform intervals of toroidal iron-core inductance coils, it was observed that the operation of telegraph over long loaded circuits materially impaired the transmission of the telephonic currents. The effect was manifested by an irregular breaking up of the speech sounds which seriously interfered with the intelligibility of the telephone conversation, and in addition, the average volume of the received speech sounds was materially reduced. When a sound was sustained over the telephone system during operation of the telegraph circuits, a rapid undulation or fluttering of the tone was observed.

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[1] B. Gherardi. "Commercial Loading of Telephone Circuits in Bell System," TRANSACTIONS A. I. E. E. 1911, Vol. XXX, page 1743.

This effect has become known as "flutter" and will be so designated here.

LINE TESTS

To obtain a quantitative measure of this flutter, tests were made to determine the effects which the telegraph currents had on the transmission of single-frequency currents in the telephone range. In what follows currents of frequencies in the range from 200 to 2000 cycles will be referred to as "telephone" or "audio-frequency" currents. Currents corresponding to the usual d-c. telegraph signals or single-frequency currents in the range from 0 to 100 cycles will be called "telegraph" or "low-frequency" currents.

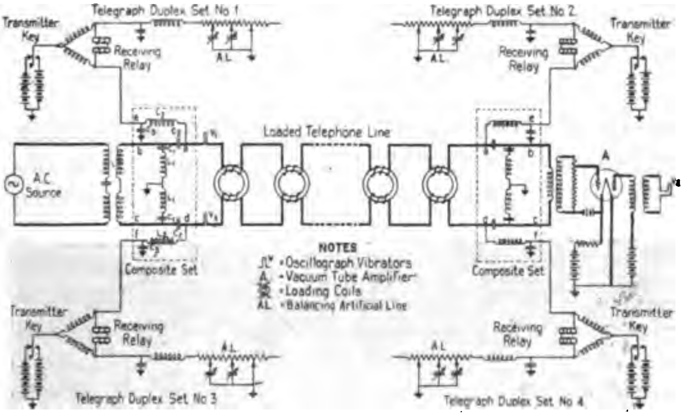

FIG. 1—COMPOSITED LOADED TELEPHONE LINE ARRANGED FOR RECORDING EFFECT OF TELEGRAPH OPERATION ON TRANSMISSION OF TELEPHONE CURRENTS

For these tests, a circuit such as shown in Fig. 1 was employed. This circuit consists of a loaded telephone line at each terminal of which is connected the standard compositing arrangement for providing one duplex telegraph circuit over each conductor. The telephone apparatus at one end of the cable is replaced by an oscillator capable of sending into the line, currents of frequencies in the telephone range. For recording the received current wave, there is connected to the other end of the telephone circuit an oscillograph vibrator, V_2. This is operated through a step-down transformer or, in the later measurements of flutter, a multi-stage vacuum-tube amplifier, in order to obtain enough current through the oscillograph to give suitable amplitudes on the records. The vibrators V_1 and V_3, of the oscillograph are connected directly into the line to record the telegraph currents over each conductor. The record of the telegraph current obtained is a combination of both the telegraph and the telephone current, but the magnitude of the latter is small compared to the former. With this circuit, data regarding the flutter are obtained by making oscillograph records of the single-frequency telephone current received over the line with the telegraph operating, and also with the telegraph not operating.

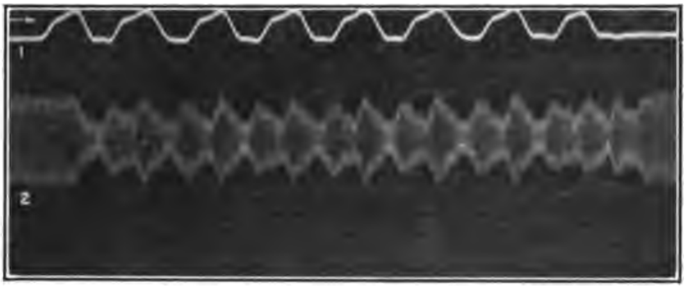

Fig. 2—Flutter Effect with Cable Circuit Loaded with Inductance Coils Having 60-Permeability Cores

V_1 Telegraph current, half duplex, 17 dots per second.
V_2 800 cycle telephone current.

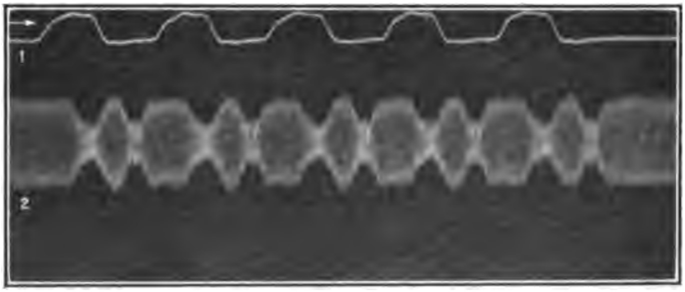

Fig. 3—Flutter Effect with Cable Circuit Loaded with Inductance Coils Having 60-Permeability Cores

V_1—Telegraph current, half duplex, 9 dots per second.
V_2—800-cycle telephone current.

Such tests were made in 1912 in connection with a loaded telephone cable between New York and Philadelphia of about 90 miles in length. In this cable, coils having an inductance of 0.25 henry are inserted at intervals of 1.25 miles. These "loading" coils are of an early type developed for cable circuits. They were made up on toroidal cores consisting of a number of turns of fine iron wire. These cores have an effective initial permeability of approximately 60. For a current of 800 cycles the ratio of received to sent currents over this circuit is about 0.31. The circuit has an attenuation per mile at this frequency of 0.013 and

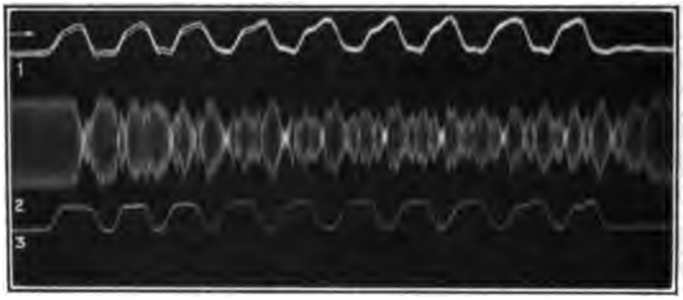

FIG. 4—FLUTTER EFFECT WITH CABLE CIRCUIT LOADED WITH INDUCTANCE COILS HAVING 60-PERMEABILITY CORES

V_1—Telegraph current, half duplex, 17 dots per second.
V_2—800-cycle telephone current.
V_3—Telegraph current, half duplex, 18 dots per second.

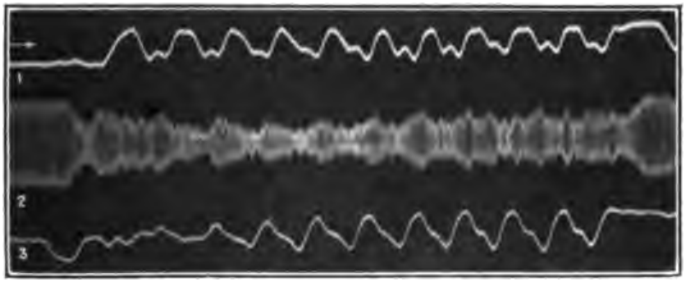

FIG. 5—FLUTTER EFFECT WITH CABLE CIRCUIT LOADED WITH INDUCTANCE COILS HAVING 60-PERMEABILITY CORES

V_1—Telegraph current, full duplex.
V_2—800-cycle telephone current.
V_3—Telegraph current, full duplex.

corresponds in its total attenuation effect to a length of 10.7 miles of standard No. 19 A. W. G. cable (88 ohms resistance and 0.054 microfarad capacitance per loop mile).

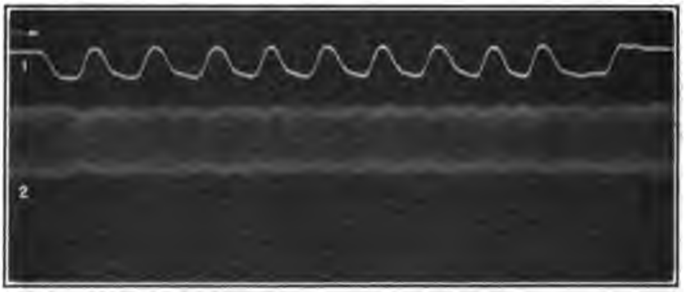

FIG. 6—FLUTTER EFFECT WITH CABLE CIRCUIT LOADED WITH INDUCTANCE COILS HAVING 30-PERMEABILITY CORES

V_1—Telegraph current, half duplex, 17 dots per second.
V_2—800-cycle telephone current.

Fig. 2 is an oscillogram showing the flutter obtained over a circuit in this cable with an 800-cycle telephone current of 0.002 ampere sent out on the line. The telegraph was operated in one direction over only one wire, that is, half duplex on one wire. The telegraph current is that corresponding to a succession of "dots" sent at a rate of 17 per second, and the maximum current reached is 0.055 ampere. The

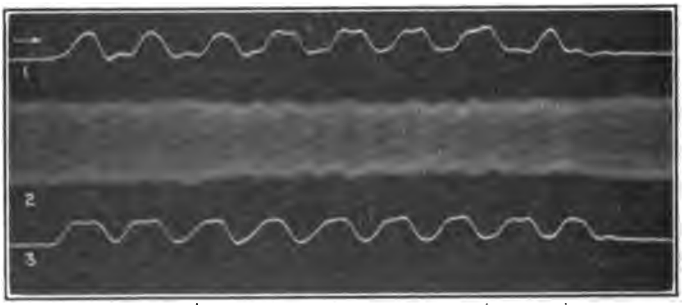

FIG. 7—FLUTTER EFFECT WITH CABLE CIRCUIT LOADED WITH INDUCTANCE COILS HAVING 30-PERMEABILITY CORES

V_1—Telegraph current, half duplex, 17 dots per second.
V_2—800-cycle telephone current
V_3—Telegraph current, half duplex, 18 dots per second.

oscillogram was started with the telegraph not operating, and then by means of a commutator on the oscillograph the telegraph signals were placed on the line and removed near the end of the record.

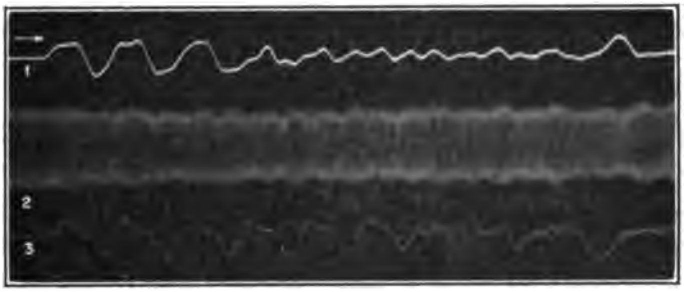

FIG. 8—FLUTTER EFFECT WITH CABLE CIRCUIT LOADED WITH INDUCTANCE COILS HAVING 30-PERMEABILITY CORES

V_1—Telegraph current, full duplex.
V_2—800-cycle telephone current.
V_3—Telegraph current, full duplex.

It will be noted that the 800-cycle wave is constant in amplitude at the start, but that during telegraph operation, the amplitude is at times materially reduced. Fig. 3 is a record of the same conditions as Fig. 2 with the exception that the frequency of the telegraph "dots" has been reduced to nine per second. From these records it is seen that a marked diminution of the 800-cycle wave is obtained at intervals corresponding to changes in the magnitude of the telegraph current,

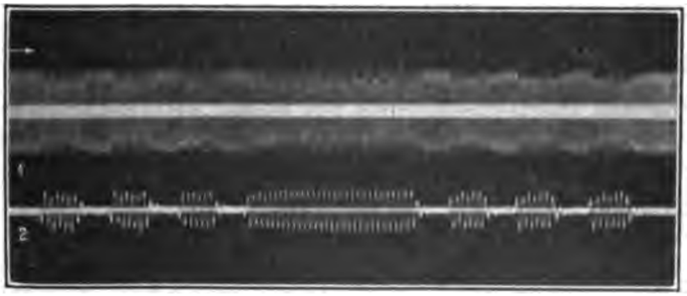

FIG. 9—FLUTTER EFFECT OF 800-CYCLE AND 200-CYCLE CURRENTS SUPERPOSED ON LOADED CABLE CIRCUITS

V_1—800-cycle current.
V_2—200-cycle current.

that is, when the telegraph current is increasing at the beginning of a telegraph signal or decreasing at the end of a signal. The time lag indicated on the oscillogram between a change in the telegraph current and the corresponding diminution in the telephone current is due to the fact that the telegraph record is taken at the sending end of the cable and the telephone at the receiving end. An appreciable time is required to propagate a wave over the loaded circuit.

Fig. 4 shows for the same circuit the effect of half-duplex telegraph operation on each wire of the telephone circuit, that is, one set of telegraph signals passing over each wire. The signals on the two wires are sent at slightly different speeds, (17 dots per second on the first wire, oscillograph vibrator V_1, and 18 dots per second on the second wire, vibrator V_2) and the flutter effect is rather irregular. The combined effect of the two sets of telegraph pulses is greater than that obtained on the oscillogram of Fig. 2.

Fig. 5 shows the effect with full-duplex telegraph operation over each wire, that is, when four sets of telegraph signals are simultaneously passing over the wires. In this case, also, each set of signals is a succession of dots. The records of the telegraph currents show for each wire the combination of the signal currents which are flowing in the two directions.

Figs. 6, 7 and 8 are oscillograms taken over a No. 13 A. W. G. cable circuit of the same length as that used for the above oscillograms but loaded with inductance coils of more recent design. These loading coils are made up on cores which have an effective initial permeability of about 30. The flutter effect with these coils is much smaller than that with the 60-permeability core coils.

Fig. 9 shows an oscillogram in which the telegraph current has been replaced by pulses of 200-cycle current. While the 200-cycle current is superposed there is on the average a diminution of the 800-cycle current received over the circuit. This oscillogram was taken over a different circuit from those described above and therefore the results are not directly comparable.

Two ratios may be used to express numerically the effects shown on these oscillograms. One is the ratio of the average amplitude of the high-frequency wave obtained during telegraph operation to the amplitude with the telegraph not working. The second is the ratio of the minimum amplitude obtained during telegraph operation to the amplitude of the undisturbed portion of the wave. The first ratio may be taken as a measure of the reduction in the volume of the transmitted speech sounds and the second as a measure of the distortion to which these sounds are subjected by the flutter.

Table 1 below gives these ratios for the oscillograms of Figs. 2, 4, 5, 6, 7 and 8, showing for both cable circuits the three conditions of telegraph operation namely, (1) half-duplex operation on one wire, (2) half-duplex operation on two wires, and (3) full-duplex operation on two wires.

TABLE I

Ratio of Amplitudes of Received 800-Cycle Current With and Without Telegraph Operation

Telegraph operation	60-Permeability coils		30-Permeability coils	
	Average amplitude	Minimum amplitude	Average amplitude	Minimum amplitude
1. Half-Duplex operation on one wire.........	0.63	0.34	0.92	0.81
2. Half-Duplex operation on two wires.........	0.53	0.11	0.90	0.78
3. Full-Duplex operation on two wires.........	0.42	0.08	0.88	0.75

Similar investigations of longer circuits have shown that the flutter effect increases with the length of the circuit. Its magnitude depends upon the type of loading coil, being less for coils having the lower permeability cores and also for those with lower flux density in the core. Tests on loaded open wire lines showed results similar to, although materially smaller than, those obtained in cables. The loading coils in open wire lines are spaced about seven times as far apart as in cable and are made up on large cores.

It was observed, in addition, that the amount of flutter was affected by the following factors: The frequency and amplitude of the telephone current, the speed at which the telegraph signals are sent, and the amplitude and wave shape of the telegraph signals. By studying these factors, it was found that the diminution of the received telephone current increases as the frequency of the telephone current is increased, and for any frequency decreases as the amplitude is increased. When the speed of sending the telegraph signals is increased, or when the magnitude of the telegraph currents is increased, or when the rate of change of the telegraph current at the beginning and end of a signal is increased, the flutter in the telephone current becomes greater.

Since the flutter occurred only in loaded circuits, it was naturally assumed to be due to changes in the "constants" of the loading coils and therefore to changes in the total inductance or effective resistance of the circuits. The effects are transient changes in the magnitude of the received current or, since the current sent into the line is constant, there is a decrease in the ratio of the received to the sent current. Calling the received current I_2 and the sent current I_1, the relation between this ratio and the attenuation a per unit length of the circuit is given by the formula

$$\frac{I_2}{I_1} = e^{-la} \qquad (1)$$

where e is the base of the natural logarithms and l is the length of the circuit. For telephone frequencies well below the critical frequency (that is, the frequency beyond which the coil loaded line has practically infinite attenuation) the attenuation constant is given by the relation

$$a = \sqrt{1/2\,\sqrt{(R^2 + p^2L^2)\,(G^2 + p^2C^2)} + 1/2\,(RG - p^2LC)} \qquad (2)$$

in which R, L, C and G are respectively the total effective resistance, inductance, capacitance and conductance per unit length of the circuit and p is 2π times the frequency f. For the case of the loaded line, where $p\,L$ is large compared to R, a close approximation of equation (2) is

$$a = \frac{R}{2\sqrt{L/C}} + G/2\,\sqrt{L/C} \qquad (3)$$

For the circuit having the 60-permeability core loading coils the first term on the right-hand side of this equation is about eight times as large as the second term and the former is therefore controlling. Neglecting this last term in equation (3), the change in attenuation may be caused by an increase in the resistance or a decrease in the inductance. Referring to the average reduction in the received current given in Table 1 for the oscillogram of Fig. 2, there would be required an average increase in the resistance per loading coil of 200 per cent, or reduction in the inductance per loading coil of about 60 per cent, to account for the attenuation obtained.

The characteristic impedance of a coil loaded telephone circuit for the frequencies for which the above attenuation formula applies is given by the relation:

$$Z_0 = \sqrt{\frac{R + j\,p\,L}{G + j\,p\,C}} \qquad (4)$$

Since for telephone frequenc es $p\,L$ and $p\,C$ are large compared to R and G respectively, the relation may be reduced to the approximation

$$Z_0 = \sqrt{L/C} \qquad (5)$$

Equation (5) shows that the impedance is affected by a change in the inductance of the loading coils, but, for the relative magnitudes of R and $p\,L$ stated above, is insensitive to changes in resistance. Measurements of the impedance of the loaded circuits for frequencies in the telephone range had shown only a small change in the impedance when the telegraph was operated. On this basis then it is apparent that the flutter effect is not primarily the result of a change in inductance of the loading coils, but is due to a change in their effective resistance

LABORATORY TESTS

In the investigation to determine the explanation of this change in the resistance of the loading coils, consideration was given to data which had been accumulated on the various types of coils showing the effect of superposing direct current. The communication engineer is primarily interested in the inductance and effective resistance of a loading coil to alternating current within the range of telephone frequencies. A characteristic curve showing how the constants of a 60-permeability core coil are affected by superposed direct current is given in Fig. 10. The ordinates are percentages of the original inductance and effective resistance increment respectively, and the abscissas are strengths of superposed direct current in terms of current *I* or magnetic field *H*. The relationship was obtained by using a special bridge circuit which enabled superposing direct current on the alternating current. In this bridge the loading-coil core was subjected simultaneously to the action of a telephone frequency current and of a desired value of direct current.

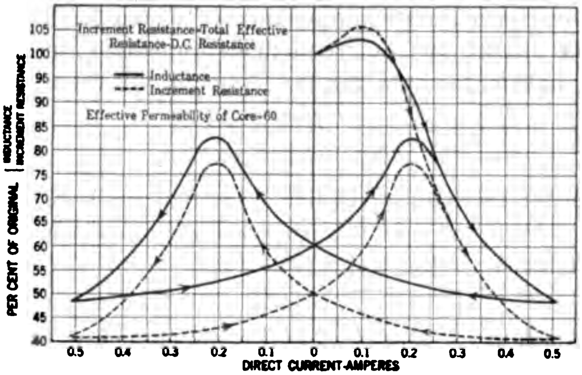

Fig. 10—Variation of Loading Coil Inductance and Effective Resistance with Cycles of Direct-Current Magnetization

The inductance and effective resistance of the loading coil were measured with a 1000-cycle current of 0.001 ampere. The values of *L* and *R* when there was no superposed direct current are taken as the original magnitudes from which the percentage change is calculated. In the curve of Fig. 10 the resistance which is plotted is not the effective resistance, but is the increment in resistance due to alternating current losses *i. e.*, the measured effective resistance less the direct-current resistance of the coil. From Fig. 10 it is seen that there is only a slight change in the inductance and effective resistance to the telephone current for a constant current strength not exceeding 0.1

ampere. For larger values of superposed direct current there is a marked decrease in both of these quantities.

The analysis of the attenuation and impedance relations of a coil loaded line which was given above indicated that the increased attenuation which accompanied the telegraph current could be accounted for only by substantial changes in the effective resistance or inductance of the loading coil. However, it has been standard practise in the plant of the Bell system, in order to guard against permanent magnetization of the coil cores, to limit the telegraph current to a maximum of 0.1 ampere. We need, therefore, consider only the part of the curve in the region from zero to 0.1 ampere direct current. For the oscillograms referred to above only that part between 0 and 0.055 ampere is pertinent, since the latter is the maximum value of telegraph current used. It is evident, that the percentage changes in these quantities shown in Fig. 10 would not account for the observed attenuation effects.

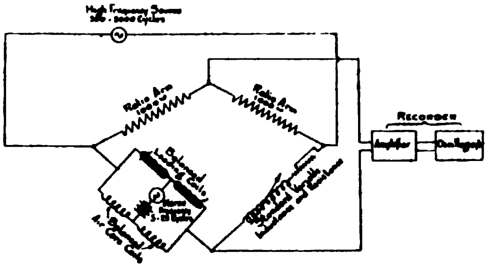

FIG. 11—SIMPLIFIED DIAGRAM OF SPECIAL BRIDGE FOR DETERMINING FLUTTER EFFECTS

It is further to be noted that the magnetic conditions pictured in Fig. 10 are due to the simultaneous passage through the loading coil winding of an alternating current and a fixed value of direct current. The condition of the iron so far as concerns the superposed direct current is "static." In a composited telephone circuit, however, the loading coil has its audio-frequency magnetization superposed on iron which is in a "dynamic" state due to the changing magnetization which the telegraph current produces. Such considerations early indicated the necessity for devising means for observing the effects on the loading-coil characteristics of the superposed magnetization due to telephone and telegraph current when both were passing through rapid cyclic changes.

It has long been known[2] that when an alternating magnetization is superposed on a slowly varying magnetization, the hysteresis loss of the latter is diminished. The energy expended in the iron to diminish this hysteresis must come from a source other than that of the low-frequency current. The flutter effect is recognized then as a manifestation of the interdependence of the high and low-frequency hysteresis losses. If, in any case of superposed magnetizations, there is a suppression of hysteresis for one magnetization, there is found an accompanying complementary phenomenon, the flutter effect, in the higher frequency magnetization. The present paper we believe to be the first publication of quantitative information on the reaction on the higher-frequency circuit of the hysteresis suppression in the low-frequency circuit.

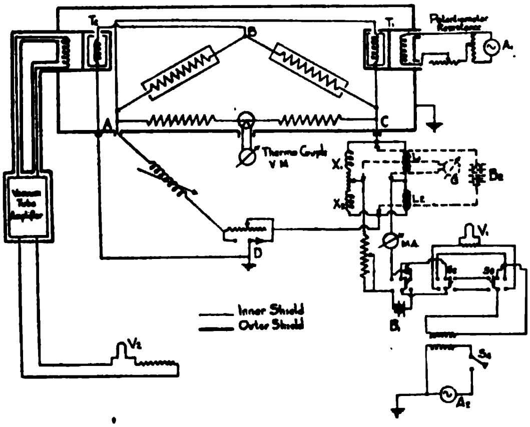

FIG. 12—CIRCUIT OF SPECIAL BRIDGE FOR DETERMINING FLUTTER EFFECTS

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[2] Finzi. *Electrician* Vol 26, p. 672, 1891, also, Gerosa and Finzi-Rendiconti del R l'stituto Lombardo Vol. XXIV fasc. X April 1891.

Mr. John Mills, an engineer of the Bell System whose analysis had indicated the importance of the resistance component, suggested a form of alternating-current bridge to investigate these transient or flutter effects. After considerable experimental work a form of alternating-current bridge was developed for the direct measurement of the effective resistance and inductance of the loading coils, for any desired instantaneous value of the superposed telegraph current.

Description of Flutter Bridge. A simplified diagram of the bridge is shown in Fig. 11. The actual circuit employed is shown in Fig. 12. Two similar coils are tested simultaneously in series. Bridge arms $A\ B$ and $B\ C$ are non-reactive 1000-ohm ratio arms. Arm $A\ D$ consists of a variable inductance of known effective resistance. Arm $C\ D$ comprises the coils which are under test together with an auxiliary circuit in the form of a secondary bridge. The variable resistance between arms $A\ D$ and $C\ D$ may be switched into either arm at will. The alternator A_2 is a source of telegraph current of a frequency of approximately 16 cycles. The recording system comprises an oscillograph and a multi-stage vacuum-tube amplifier through which the oscillograph is connected to the bridge circuit $B\ D$. The audio-frequency generator, A_1, and the recording circuit are connected to the bridge through double shielded transformers T_1 and T_2. The bridge itself is thoroughly shielded electrostatically in order to avoid false balances due to extraneous disturbances or unbalanced admittances to ground. The junction D is grounded so that under conditions of balance the terminals of the recording circuit are at ground potential.

The method of superposing the telegraph current on the secondary bridge circuit of arm $C\ D$ requires some detailed consideration. The magnetic material under investigation is the core of a toroidal inductance coil. Two such similar coils are wound and connected in series. These are designated X_1 and X_2 in the drawing. Two air-coils, L_1 and L_2, also balanced as to inductance and effective resistance, form the other two arms of the secondary bridge. The pair of junctions $X_1 L_1$ and $X_2 L_2$ are obviously points of zero difference of potential provided electromotive forces are impressed between the junctions $X_1 X_2$ and $L_1 L_2$.

In duplex telegraph operation over telephone lines the telegraph current in the line may have a variety of wave forms, as illustrated by the oscillograms of Figs. 2 and 5. Owing to the presence in the circuit of composite sets the telegraph pulses are rounded off. In the general case the telgraph current may be represented by an alternating current of low frequency.

In the operation of the flutter bridge the equivalent of a telegraph current is derived from a circuit comprising a generator and a battery in series. The generator gives an approximately sinusoidal wave and can be made to generate frequencies from 6 to 25 cycles per second. The e. m. f. of the battery is adjusted to equal the amplitude of the generator voltage. The series connection thus results in a current which pulsates between zero and a maximum positive value. The instantaneous current is, therefore, of the form $i = I_t (1 + \sin q t)$, where $q = 2 \pi$ times the frequency of the generator and $2 I_t$ is the maximum current output. This pulsating current was used instead of an alternating current, because it corresponds more closely to the wave form in half-duplex operation, which is in more general use than is full-duplex operation. It was also found to give more severe flutter than an alternating-current wave.

Special precautions are necessary to maintain the distribution of capacitances in the bridge circuit as a whole unchanged throughout the operation test. For this reason switches S_1 and S_4 are used to cut off the telegraph current without disconnecting any apparatus from the bridge. Switches S_2 and S_3 serve to pass the current through an oscillograph vibrator so that the telegraph wave may be observed and the relative values of the direct and alternating components properly adjusted. The milliameter $M A$ measures the telegraph current.

With the bridge circuit described, measurements of the instantaneous changes in inductance and effective resistance could be made with an accuracy of approximately 5 per cent.

In making the test it is necessary to observe the telegraph wave in its time relation to the current through the recording circuit. This is accomplished by having the low-frequency generator direct-coupled to the oscillograph mirror, thus making the telegraph wave "stand" in the field of view.

When the telegraph current is zero and the bridge is balanced to the telephone current, there will be no difference of potential across the terminals *B D*. However, as soon as the telegraph current is applied a recurring unbalance is produced. The period of this phenomenon is double the frequency of the telegraph pulse.

It will be recognized that the bridge as described comprises sources of two frequencies, a balanced magnetic system which modulates the higher frequencies by the lower, and a bridge connection which transmits to the recording apparatus only the modulated current.

Fig. 13—Recorder Current with Bridge Balanced for Zero Point of Telegraph Wave

Operation of Bridge. The actual procedure in making a test is as follows: The main bridge is first balanced with the selected value of audio-frequency current of the desired frequency. The secondary bridge is also balanced for direct current after adjusting the current strength to the desired value. The telegraph current is then adjusted to the required strength and frequency by switching in the oscillograph vibrator V_1 which gives a standing wave on the scale in the oscillograph field of view. The telegraph current is then replaced in the oscillograph (using vibrator V_2) by the amplified current in the recording circuit, which is essentially the unbalanced audio-frequency current modulated by the telegraph current. During this observation switch S_2 is thrown to the right and S_3 to the left.

Fig. 13 is an oscillograph record of the unbalance current and shows the variations in its amplitude during the making of a telegraph "dot," *i. e.*, during one complete pulsation. It will be noted that the two constrictions occurring in the current are separated by a time interval corresponding to the frequency of the telegraph pulses, 16.6 cycles per second.

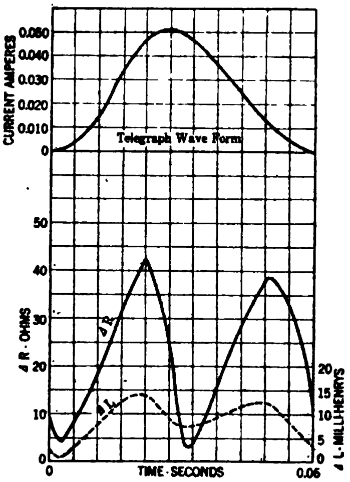

FIG. 14—VARIATION OF INCREMENTS OF EFFECTIVE RESISTANCE AND INDUCTANCE WITH PHASE OF TELEGRAPH CURRENT

By suitable adjustment of L and R in the bridge arm $A\ D$, a balance can be obtained corresponding to any point of the telegraph wave, thus giving the instantaneous values of the effective resistance and inductance of the secondary bridge arm $C\ D$ corresponding to each point of the telegraph wave. The difference between these values and those required to balance at zero telegraph current are used to obtain the instantaneous changes in the iron-core coils by means of the following formulas:

$$\Delta R = \frac{\Delta R'}{2} \cdot \frac{(L_1 + L_2 + X_1 + X_2)^2}{(L_1 + L_2)^2}, \qquad (6)$$

$$\Delta L = \frac{\Delta L'}{2} \cdot \frac{(L_1 + L_2 + X_1 + X_2)^2}{(L_1 + L_2)^2} \qquad (7)$$

where ΔR and ΔL are the changes in effective resistance and inductance respectively of the loading coils, L_1 and L_2 are the inductances of the air-core coils, X_1 and X_2 are the inductances of the loading coils, $\Delta R'$ and $\Delta L'$ are the changes in resistance and inductance respectively, required to balance the bridge at the selected point of the telegraph wave.

These equations are an approximation as they neglect the resistance of the coils. This is permissible as the ratio of reactance to resistance in these coils at the test frequencies employed is very large (about 100:1).

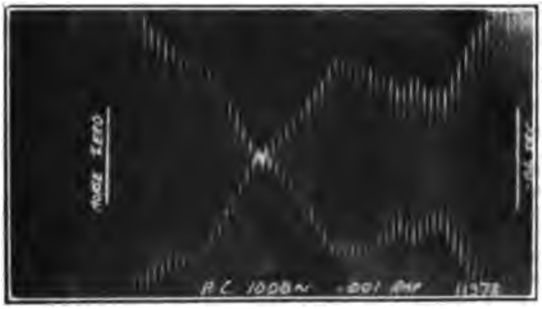

FIG. 15—RECORDER CURRENT WITH BRIDGE BALANCED AT FIRST PEAK OF ΔR CURVE OF FIG. 14.

Using this method the curve of Fig. 14 was obtained. It will be seen that the changes from L_0 and R_0 during the interval of a single telegraph pulse take the form of a double peaked curve, the maximum values corresponding to the time in which the telegraph current is experiencing its greatest rate of change, the first when it is increasing and the second while it is decreasing in value. In the upper part of the figure the telegraph wave is shown in its proper time relation to the flutter increments. Fig. 15 is an oscillogram of the recorder current, when the bridge is balanced for the part of the telegraph wave, corresponding to the first peak.

TABLE II

Flutter Effect with Varying Telephone Current in a 60-Permeability Core Coil. Constant Telegraph Current of 0.05 ampere, 16.6 cycles.

Telephone current (Frequency 1600 cycles)		Increments per henry in telephone circuit		
Current amperes	Magnetizing force H-c. g. s. units	Resistance ohms	Inductance millihenrys	Power loss watts × 10^{-6}
0.0005	0.023	780	74	195
0.0010	0.045	530	43	530
0.0015	0.068	390	29	880
0.0020	0.091	300	21	1200
0.0025	0.114	230	18	1438
0.0030	0.136	165	15	1485

TABLE III

Flutter Effect with Varying Telegraph Current in a 60-Permeability Core Coil. Constant Telephone Current of 0.001 ampere, 1600 Cycles.

Telegraph current (16.6 cycles)		Increments per henry in telephone circuit		
Current amperes	Magnetizing force H-c. g. s. units	Resistance ohms	Inductance millihenrys	Power loss watts × 10^{-6}
0.01	0.48	37	3	37
0.02	0.96	105	8	105
0.03	1.44	200	14	200
0.04	1.92	340	22	340
0.05	2.40	500	39	500
0.06	2.88	660	67	660

TABLE IV

Flutter Effect with Varying Telephone Current in a 30-Permeability Core Coil. Constant Telegraph Current of 0.032 Ampere, 16.6 cycles

Telephone current (1600 cycles)		Increments per henry in telephone circuit		
Current amperes	Magnetizing force H-c. g. s. units	Resistance ohms	Inductance millihenrys	Power loss watts × 10^{-6}
0.0005	0.035	180	39	45
0.0010	0.070	110	24	110
0.0015	0.106	80	18	180
0.0020	0.141	65	15	260
0.0025	0.176	60	14	375
0.0030	0.212	59	14	580

TABLE V

Flutter Effect with Varying Telegraph Current in a 30-Permeability Core Coil. Constant Telephone Current of 0.001 Ampere, 1600 Cycles

Telegraph current (16.6 cycles)		Increments per henry in telephone circuit		
Current amperes	Magnetizing force H-c. g. s. units	Resistance ohms	Inductance millihenrys	Power loss watts × 10^{-4}
0.01	0.70	18	3	18
0.02	1.41	54	10	54
0.03	2.11	98	18	98
0.04	2.82	150	28	150
0.05	3.52	204	40	204
0.06	4.22	265	58	265

The curve of Fig. 14 shows the increments of effective resistance and of effective inductance during one cycle of telegraph current for a definite value of the high-frequency current. For the purposes of the present investigation it was important to ascertain the effect of varying the values of both the telegraph and the telephone frequency current. This was necessary in order to determine the laws for the variation of flutter, first with different telephone currents under fixed telegraphic conditions, and second, with different telegraph currents under fixed telephonic current. In making these tests only the peak values were recorded, as these are of the most importance in comparing different core materials for flutter effects. The data given in Tables II, III, IV, and V were thus obtained. The values of increment resistance and

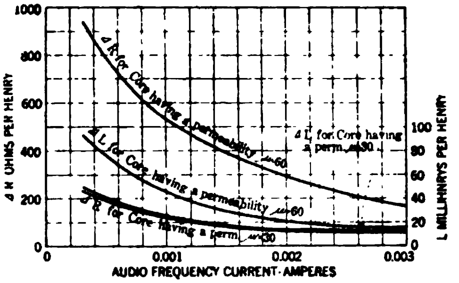

Fig. 16—Variation of Flutter with Telephone Current

inductance are the averages of the two successive peak values.

The hysteresis losses for the 30 and 60-permeability core materials were determined for conditions of zero telegraph current from measurements over a range of telephone frequencies and current strengths. For the telephone conditions of Tables III and V, *i. e.*, 0.001 ampere and 1600 cycles, the total iron loss for the 60-permeability material was found to be 70 ohms per henry, of which 38 ohms is hysteresis loss. For the 30-permeability material the total loss is 37 ohms per henry, of which 17 ohms is hysteresis loss. It will be seen by reference to Table II that the resistance increment (peak value) due to flutter in the 60-permeability material is approximately 14 times the normal hysteresis loss resistance.

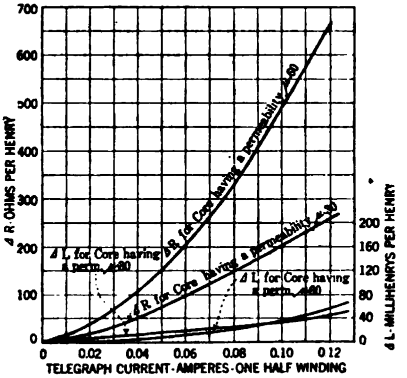

FIG. 17—VARIATION OF FLUTTER WITH TELEGRAPH CURRENT

From the tabulated data the curves of Figs. 16 and 17 have been plotted. Fig 16 shows the relation of flutter to telephone current, while Fig. 17 shows the variation in flutter for a constant value of telephone current as the telegraph current is increased. The current values used for the latter curves are twice those given in the table for the reason that the telegraph current actually flowed through one-half of the coil winding. It will be noted that in these tests a telephone frequency of 1600 cycles was used. This frequency was chosen rather than the one usually considered as representative for telephonic measurements (*i. e.* 800 cycles) in order to magnify the flutter values, which increase with the frequency used. This is shown in Fig. 18 and 19, which give the flutter increments for varying telephone and telegraph frequencies respectively.

Discussion of Results

In the experiments, the audio-frequency magnetizing force had, on the average, a value $H = 0.05$ *c. g. s.*, corresponding to a normal telephone current in the loading coil windings. This is a very small force, yet it exceeds that for which the molecular displacements may, according to Ewing's molecular theory,[3] be taken to be perfectly elastic, *i. e.* without hysteresis. The strength of audio-frequency current used develops only the initial permeability of the iron. The hysteresis loss in this region for hard iron is very small and can be detected only by careful bridge measurements.

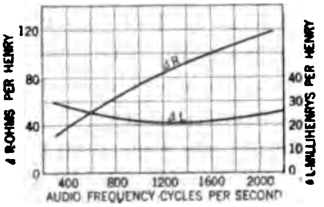

FIG. 18—VARYING AUDIO FREQUENCY

Telegraph current = 16.6 pulsations per second, 0.10 ampere in one line winding. Audio-frequency current, 0.001 ampere.

Curves show peak values.

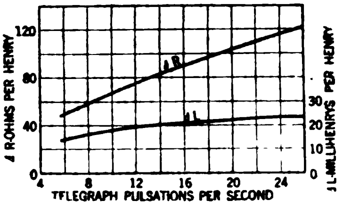

FIG. 19—VARYING TELEGRAPH FREQUENCY

Telegraph current = 0.10 ampere. Audio-frequency current = 0.001 ampere (1600 cycles per second).

Curves show peak values.

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[3] Ewing, Magnetic Induction in Iron and other Metals 1900, p. 302.

Such measurements can be used to separate the hysteresis from the eddy-current losses by the method referred to above.

Computations based on a loss separation show that the increase in eddy-current loss due to the small increase in high-frequency inductance during the telegraph cycle would account for only a small fraction of the increased effective resistance. The balance of the increase must be charged to an augmented hysteresis loss. That such a loss is due to the high-frequency current assisting the low-frequency current to execute its hysteresis cycle is in accord with the work of previous investigators.

The results of the tests described above are summarized in part by the following empirical equation, which in terms of power, satisfies fairly well the ΔR curves of Figs. 16 and 17.

$$W/L_0 = k\, H_t^{1.6}\, H_{ac}^{1.2}$$

in which,

W = maximum watts increment (taken as the product of ΔR and the square of the current for the corresponding point), for audio-frequency,

H_t = magnetizing force due to telegraph current,

H_{ac} = magnetizing force due to audio-frequency current.

The inference has already been drawn that the increased power loss in the high-frequency circuit represents a transfer of energy from the higher-frequency to the lower-frequency magnetization. It will be interesting therefore to review briefly the work of previous investigators on the subject of superposed magnetization in iron. The earliest work, already referred to, is that of Geroza and Finzi[4], who observed that there was a tendency to suppression of the hysteresis of a direct-current magnetization when alternating-current magnetization was superposed. In their experiments the direct-current magnetization was produced by a coil surrounding an iron wire, the alternating current having its path through this wire. The induction due to the current in the coil gave a "longitudinal"

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[4] Loc. cit.

magnetization, while that due to the current in the iron wire produced a "circular" magnetization. These experiments also showed an increased initial slope of the *B-H* curve, indicating a greatly increased permeability of the iron to weak forces.

Maurain[5] in an investigation of the action of the Marconi magnetic detector made experiments in which the specimen was subjected to two longitudinal magnetizations, one due to direct current, the other to an oscillatory current. He found that under proper conditions the hysteresis could be completely suppressed in soft iron.

Probably the most striking experiments involving hysteresis effects were those by Madelung[6], who used a Braun tube to obtain on a flourescent screen the effect of superposing a rapidly oscillating magnetic force on the hysteresis cycle produced by a slowly varying magnetic force.

Goldschmidt[7] investigated the effect of combined longitudinal and circular magnetization, the former being produced by direct current and the latter by an alternating current. He also remarked that the area by which the d-c. hysteresis loop is reduced exceeds that of the normal loop of the superposed circular magnetization. Waggoner and Freeman[8] examined the extent of hysteresis suppression with a superposed alternating longitudinal field for a series of iron-carbon alloys. The results showed the reduction of hysteresis to be proportional to the carbon content.

The present paper has dealt with the reaction in the high-frequency circuit instead of with the previously known effect on the low-frequency magnetization cycle. The basis for our conclusion that the so-called flutter in composited telephone circuits is complementary to a suppression of the hysteresis normal for a magnetization by telegraph currents, appears from the following restatement of our experimental results:

1. The resistance increment is proportional to the frequeney of the telephone current.

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5. C. Maurain. *Comptes Rendues*, Vol. 137, 914-916, 1903
6. E. Madelung *Annalen der Physik*, Vo'. 17, 861, 1905.
7. R. Goldschmidt. *E.T.Z.* 31, 218, 1910.
8. Waggoner and Freeman. *Gen. El. Review*, Vol. 21, 143, 1918.

2. It is proportional for different grades of iron to the hysteresis loss normal for these respective grades.
3. For larger telegraph loops having a greater average slope, the flutter loss increases correspondingly.

The findings of this investigation have been of immediate practical importance in the design of the plant of the Bell system. The fact that flutter depends upon hysteresis has led to the employment of materials of low intrinsic permeability in the coils used for loading the important long toll lines. The cross-sectional area of the core has been proportioned so as to work the iron at very low flux densities. These requirements affect also the design of other iron-cored induction coils and transformers which are used in circuits carrying currents of different frequencies.

For long loaded cable circuits there has been developed a telegraph system which has permitted a large reduction in the magnitude of the operating current. As a result of these factors the simultaneous operation of telegraph and telephone over a loaded cable circuit is satisfactorily free from flutter. A similar condition has also been obtained for the open wire lines.

It has been suggested that a current of frequency above the telephone range be superposed on the loaded lines to suppress the hysteresis and thereby reduce the iron losses for the telephone currents. This would tend to reduce also the flutter caused to the telephone currents by telegraph operation. This proposal was considered some years ago, but has difficulties in the way of its practical application. For instance, the frequency of the superposed current must be much higher than the frequency in the important telephone range to be effective. This would require that the spacing of the loading coils be decreased to transmit the higher-frequency waves, because the upper frequency limit of the transmission range of a coil loaded circuit is, for a given inductance per mile, inversely proportional to the spacing of the loading coils. There is also the problem of transmitting over very long circuits the amount of high-frequency power necessary to effectively suppress hysteresis.

Reference has been made to the presence of hysteresis suppression in the Marconi magnetic detector. The test results discussed above indicate that this suppression causes a power loss in the high-frequency circuit, which we have termed "flutter." These two effects, for flux densities well below saturation, are accompanied by a material change in permeability to the slowly varying magnetizing force. This change in permeability, it should be noted, is not merely that due to a shift along the normal magnetization curve, but results from a change in the form of the magnetization curve itself. The principle of operation of the various forms of magnetic amplifier and detector for radio telephony and telegraphy is such as to involve all of these actions.

The experiments described in this paper deal with two longitudinal magnetizations of different frequency and apply directly to conditions encountered in the telephone and telegraph plant. The determination of the actual form of the magnetization curve under the action of two magnetizations presents an interesting field for further investigation. The most direct mode of attack appears to be the use of the Braun tube to obtain the dynamic magnetization curve in a manner generally similar to that employed by Madelung. Such an investigation could well be directed toward obtaining accurate data as to the relation of the total hysteresis with two or more magnetic forces acting simultaneously to the hysteresis for each force acting alone. The investigation should include an examination of hard as well as soft iron, to determine the effect on B_{max} for both forces as well as the change in area of the hysteresis loops. With a number of superposed magnetic forces differing in their magnitudes and rates of change the further problem is presented of determining the interaction of any two of the forces in the presence of the others.

DISCUSSION ON "HYSTERESIS EFFECTS WITH VARYING SUPERPOSED MAGNETIZING FORCES"(FONDILLER AND MARTIN), NEW YORK, N. Y., FEBRUARY 18, 1921.

M. I. Pupin: The problem of magnetization has interested me for the last 25 years. The question of the high permeability of iron is a subject which has never been completely investigated. What is that which we call permeability? Why should iron have that great distinction of having high permeability, so much higher than anything else? All other members of the iron group like nickel and cobalt and manganese have also their fairly good permeability, but nothing like the permeability of first-class iron. Within the last ten or fifteen years people have succeeded in making iron by a particular kind of cooling or heating, etc.,—cooling in a vacuum, that has a permeability of 60,000. Perfectly enormous? Now what is it that gives the iron that enormous permeability? Well, we do not know; but it is a question which is being investigated by several men at the present time.

Five years ago, for reasons I need not explain here, I proposed to test the following proposition first made by Lord Rayleigh, and mentioned by Ewing in his book. Lord Rayleigh found that if you take an iron core, and magnetize it by direct current, and then superpose upon it a feeble variable magnetizing force, that the permeability for the feeble, variable magnetizing force is practically the same whether the iron be in a magnetized state or not, provided that the already existing magnetization established in the iron core by direct current be not too strong. That is a rather remarkable result.

When you increase the magnetization by the direct current and go beyond a certain limit, then the permeability for the feeble magnetizing force begins to diminish. That was found by Lord Rayleigh; it is correct, but the question which I proposed to myself was this: Suppose that the magnetizing force which is strong, is not due to a direct current, but to an alternating current and then if the superposed feeble variable magnetizing force is of higher frequency what happens then? I found to my surprise that Lord Rayleigh's rule does not hold—that both the permeability and the iron losses as determined by the Wheatstone bridge by measuring the effective resistance would be very much increased, particularly the resistance due to iron losses.

Well, I believed that I made a little discovery and I believe still I made a little discovery, but I believe Mr. Fondiller made it also, independently of myself.

Mr. Fondiller, who had, as a pupil of mine, charge of the development work with loading coils, was bound to make that discovery, whether he wanted to or not. He stumbled into it. I did not. I walked into, you know, with my eyes open. Now, that is the difference, but then he is a young man, and I a n not. But what I found in the laboratory on a small scale, he found on the actual line on a larger scale. It is a wonderful effect. He found that when a loaded line is used for telephony and telegraphy at the same time, that you had to know a little more, you had to have a little more knowledge than I disclosed in my patent. I did not intend the loaded line to be used for telegraphy and telephony simultaneously because if I had intended it for use both for telephony and telegraphy, they would have had to pay a little more. I intended it only for telephony or only for telegraphy. They wanted to do something for which they did not pay, and they could not do it. It served them right. They found something they did not expect to find. They found that strong excitation imposed by the low-frequency telegraph current produced for the superposed feeble telephone frequencies a high resistance. The iron responded to be sure, to the high-frequency currents of telephony, but it responded differently. It had a different permeability and a different iron loss resistance on account of the large hysteresis loss, consequently the line did not work so well when the telegraph was on as when it was off, that is there was this flutter which has been referred to. The flutter then indicates that what I found is correct—that iron has a different permeability, different resistance, that it has a very much increased resistance for high-frequency currents, when a low-frequency fairly strong and independent magnetizing force is imposed upon the iron core.

That subject I gave to a graduate student of mine, for a doctor's degree because when the war broke out we had other work to do. I made preparations to take it up again when the war was over, and I now have a student of mine who is working on it.

Charles W. Burrows: This paper is very valuable in that it presents actual oscillograph records of a comparatively little known phenomena. I feel constrained, however, to take issue with the authors of this paper on the matter of their conclusions. At the middle of page 574 statement is made that the resistance increment due to the presence of the lower frequency magnetizing current, is 14 times the normal hysteresis loss resistance. This is equivalent to saying that the low-frequency magnetizing current mulof the same amplitude as an alternating current produces a greater flutter than the alternating current. In this case the pulsating current shows a greater variation from zero of the magnetizing current and would be expected to show a greater variation in permeability.

In Table II the magnetizing force is 45 times the magnetizing current. In Table III the magnetic force is 48 times the magnetizing current. These two tables deal with the same toroid. The reason for the difference is not evident.

To present the full argument in support of my contention would require careful consideration and more time. However, I believe I have presented the case with sufficient fullness to warrant the statement that the authors are in error when they conclude the following:

1. The flutter effect produces approximately 14 times the normal hysteresis loss.

2. The flutter effect is a manifestation of the interdependence of the high-frequency and the low-frequency hysteresis losses, and furthermore that they have fallen into these errors by failure to consider some of the minor but in this case important fundamental magnetic properties of iron.

B. A. Behrend: Hysteresis effects in iron depend on many conditions and one of the most interesting phenomena in connection with hysteresis is that observed by Bailey and described in a paper about the year 1896 before the Royal Society. Bailey showed that at high inductions of 18,000 C. G. S. units and above, hysteresis loss in iron begins to disappear-and usually vanishes almost altogether at the point of saturation. This phenomenon is observed, however, only where the hysteresis is of the "rotatory" kind. Prof. Ewing in his book discussed this matter briefly and very generally without adding to it in any way and, in spite of the great importance of the subject, no laboratory tests have been made in confirmation of Bailey's observations. Some twenty odd years ago, I made a series of tests which were conducted with fair accuracy and confirmed in every respect Bailey's observations. However, it has seemed to me that this is a subject which has been neglected to an extent which is surely not warranted, and I have repeatedly called the attention of the professors in charge of university laboratories to the desirability of going over this field anew and recording the facts.

W. Fondiller and W. H. Martin: We were very much interested in Prof. Pupin's account of his work with two magnetizing forces of differing frequencies in iron. His work gives a valuable confirmation of the conclusions given in the paper.

With regard to Mr. Burrow's discussion, this is based on his assumption that the observed change in loading coil constants can be accounted for by a change in the permeability. On this basis Mr. Burrows takes issue with our conclusion that the increased power loss in the high-frequency circuit represents a transfer of energy from the higher frequency to the lower frequency magnetization. In predicating his discussion on this premise Mr. Burrows completely overlooks the results of tests on actual transmission lines given in the paper. These tests show that the line impedance is substantially constant, while marked changes in attenuation occurred when the telegraph current was superposed on the telephone current. Mr. Burrows also disregards data included in the paper, when he states that we assume the permeability to be constant. We will take up his objections to our conclusions in the order in which they are given.

1. Mr. Burrows states, "The assumption has been made that every alternating m. m. f. is accompanied by a particular hysteresis loss independently of any other m. m. f. acting." This statement is surprising since, in fact, we have aimed to prove the contrary to be true, viz., that an alternating m. m. f. causes a hysteresis loss which is dependent on the presence of other m. m. fs. Mr. Burrows also states that the paper assumes that if two m. m. fs. act conjointly, the sum of the hysteresis energies is constant even though the distribution of hysteresis losses attributable to the individual m. m. fs. varies, and that this conclusion is not justified. The data cited in the paper apply specifically to the iron losses and change in permeability to the high-frequency magnetizing forces. We did not state that the sum of the hysteresis energies is constant, as we did not measure the hysteresis loss for the low-frequency magnetization. Whether the sum of the hysteresis energies is constant is a matter for conjecture at the present time. What we do know is that a considerable increase in the hysteresis energy for the high-frequency magnetization takes place when it coexists in the iron with the low-frequency magnetization. Clearly, this is a reaction on the high-frequency source, due directly to the superposition of the lower frequency magnetization and the inference that the high-frequency source supplies energy which assists the low-frequency force to execute the low-frequency hysteresis cycle, is, in our opinion, wholly justified by the experimental data. It will be observed furthermore that this conclusion is not in conflict with the work

done by Dr. Lloyd of the Bureau of Standards, which Dr. Burrows cites.

2. Mr. Burrows states that it is assumed, the "permeability conditions" are constant, and that they probably vary in fact from an initial value of 30 or 60 to a final value of 1000 or 2000. This is not correct if we consider the permeability to the high-frequency force, which is the one under examination in the paper. The permeability in question was not assumed to be constant, but actually measured under a variety of conditions. The change in both the 30 and 60 permeability cores is about 5 per cent and is indicated in Tables 2 to 5 inclusive, in terms of the inductance increments per henry in the telephone circuit. This is very different from the percentage change of 3000 per cent which Dr. Burrows suggests. This as noted above checks the line measurements which showed very slight changes in line impedance. If there were any large changes in inductance of the loading coils, these would be reflected in the line measurements.

The magnetizing force of over 4 gausses to which Dr. Burrows refers applies to the telegraph current and not to the high-frequency or telephone current. It should be stated at this point that in working out equations (6) and (7), simplifications were made in the formulas by neglecting a permeability change where it appeared as a small quantity in comparison with other quantities in the same factor. This should have been stated in explaining the derivation of the equations.

3. With regard to the criticism that the differential permeability should be considered rather than the normal permeability, Dr. Burrows has apparently confused the permeability to the telegraph current with that to the telephone current. His remarks applied to the telegraph loops but have a very limited application to the telephone loop. We have actually measured the effective permeability to a small high-frequency force superposed on a large d-c. loop, using for the purpose a special bridge and the ratio between the maximum value for increasing d-c. magnetizing force, and minimum value for decreasing d-c. magnetizing force is surprisingly close to unity. This will be evident from Fig. 10. The ratio of several hundred to which Dr. Burrows refers is not realized with magnetic materials of the kind considered in the paper.

4. Dr. Burrows points out that the first cycle from a small alternating m. m. f. does not show the same characteristics as subsequent cycles. This criticism does not apply, since in our experiments we measured the average effect of a train of cycles and did not deal with separate first cycles.

5. With regard to the suggestion that part of the bridge reading reported as flutter effect is due to the telephone current unsettling the balance between the loading coils there is, of course, a theoretical possibility that the difference in relative phase of the telephone and telegraph currents in the two iron core coils might produce an unbalance foreign to the effect which we have described. This cause of unbalance would be a second order quantity, and would in our opinion, not be of sufficient magnitude to be measurable in the test circuit used. This follows from the magnetic characteristics of loading core material referred to above, namely that the differential permeability varies but little when the magnetizing force varies over a range from 0 to 5 gausses, the latter being the maximum employed in our tests. Data bearing upon this characteristic of very hard iron have since been presented in an Institute paper by Speed and Elmen, on "Magnetic Properties of Compressed Powdered Iron," June 1921, published in this volume.

In regard to the difference in magnetizing force of the coils in Tables 2 and 3, this was due to the difference in their windings, the cores alone being the same.

In conclusion, it should be noted that the measurements recorded in the paper cover only a small part of a relatively unexplored field. The investigation of the mutual reaction of two or more magnetizing forces in iron varying in their relative strength and frequency affords an extremely interesting subject for future research. It may well be that such further tests would shed light on the significant question propounded by Prof. Pupin, "What is that which we call permeability"?

Presented at the 9th Midwinter Convention of the American Institute of Electrical Engineers, New York, N. Y., February 18, 1921.

LONGITUDINAL AND TRANSVERSE HEAT FLOW IN SLOT-WOUND ARMATURE COILS

BY CARL J. FECHHEIMER

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IT has long been recognized that the heat generated in embedded armature conductors by the I^2R and eddy current losses in part escapes by transverse flow through the insulation from the copper to the iron (possibly, to a more limited extent, to the air at the ducts) and in part flows longitudinally along the copper to the ends of the coils exposed to the cooling air. The importance of a solution of the combined transverse and longitudinal heat flows has been realized, for upon these the internal copper temperatures must necessarily be dependent. Thus, it has long been known that in a machine of short core length, the iron temperature and temperature at the center of the machine by detector between coil sides could usually be reduced by increasing the volume of air blown upon the ends, but in machines of long lengths (say 50 inches or more), the temperature at the middle could not be so reduced. Again, it has been recognized that as a machine of a given diameter is lengthened, assuming a short core length (say 10 inches for the shortest) the temperatures increased, although the losses per inch of length remained nearly the same.

Nor is a knowledge of the maximum copper temperature, (say at the middle of the machine), the only temperature that is of importance. Some of the large a-c. generators of today are designed for maximum copper temperatures of the order of 150 deg. cent. and then, whether or not the core length be great, the temperature of the copper at the end of the core may be above 105 deg. cent., which temperature may reduce the life of the fibrous insulation which is used on the end windings starting near the end of the core.

Inasmuch as designing and operating engineers are interested in the linear expansion of the straight part of the armature coil due to temperature changes, and are consequently interested in the average temperature of the length of the coil located in the armature slots they may find one of the derived equations (**33a**) to be of value. Again equation (**33**) gives a means of calculating the average temperature of the entire winding, that is, the temperature as measured by the change in resistance.

The maximum copper temperature has usually been taken as the iron temperature plus the drop through the insulating wall, the influence of the temperature of the copper upon the I^2R loss being assumed, and possibly the calculation is then repeated to allow for the new value of temperature. In this paper the condition for infinite length gives an equation (**13**) which brings in the temperature coefficient. The longitudinal flow has been solved by a number of engineers on the basis of constant losses; and Symonds and Walker have taken account of the temperature coefficient.[1]

As is subsequently shown in this paper, none of the above equations is complete, and a general determination of the internal temperature cannot be obtained with any reasonable degree of accuracy (except the maximum and minimum temperatures in long machines) unless the simultaneous transverse and longitudinal flows be considered. A solution of that problem is offered in this paper, and it is hoped that the equations may be useful to the designer who is frequently confronted with decisions in regard to the temperatures of the embedded copper in the armature. So far as is known, there are no other formulas published today which are solutions of this problem.

The mathematical solutions offered in this paper

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[1] The equations derived in this paper reduce to the above. Thus, equation (**14**) gives the temperature drop considering only the transverse flow and neglects the temperature coefficent. Equations (**35**) and (**36**) are the usual longitudinal heat flow equations, neglecting temperature coefficient, and equations (**37**) and (**37a**) are for longitudinal flow taking the temperature coefficient of resistance into account.

were derived a little over three years prior to the writing of the paper, but they were not published at an earlier date, because there were no experimental data available to check calculated temperatures along the copper. The mathematical solutions and data on the experimental checks are both given in this paper.

METHOD OF ATTACK

The method of attack employed in this paper consists in solving two independent differential equations for heat flow, one for the embedded part of the coil and the other for the end winding, and then combining these two solutions at the point common to the two, viz., the copper at the end of the core. The method of combining the two solutions consists in equating the heat flowing longitudinally from the embedded part at the end of the core to the heat received by the end windings at the same point; in other words, the slopes of the two curves are equal at that point. In general, the temperature of the copper is at its maximum value at the center of the core, so that point is taken as zero for X; similarly the minimum temperature is usually not far from the extreme end of the end winding, and that point is chosen as zero for the independent variable for that part. (This is discussed further under "The points of Maximum and Minimum Temperature"). Then, considering the total heat generated by I^2R and eddy currents between the zero of reference (point one) and some other (second) point longitudinally as being equal to the sum of the transverse flow between those points and the longitudinal flow beyond the second point, the fundamental equations are easily written.

All of the equations are based upon the conditions which obtain after the steady state has been reached. Consideration of the additional independent variable, time, changes the ordinary differential equations to partials, and complicates them so much even with constant iron temperature, that a solution in practical form has not been obtained. Although the partial differential equations are linear, and admit of integration without difficulty, the combination of the equation for the ends and slot portion bring about equations which are too complicated to be employed readily.

THE IRON TEMPERATURE

In writing the equations for transverse flow, it has been assumed that the temperature of the iron adjacent to the outside surface of the coil is known. For most machines, especially those of short core length, it is sufficient to consider this temperature as the average of the temperatures axially, and the first equations are worked out on that assumption. However, it is realized that in some of the longer machines, this assumption may not be admissible and that the iron temperature may perhaps approximate a straight line relation with the length, reaching its maximum value at the center of the core; whereas, in other machines, the axial distribution of iron temperatures may not be far from a parabola, again with the maximum temperature at the center of the core. Equations have been solved in which all three assumptions of distribution of iron temperature have been considered. The general method of solution is the same for all three. Inasmuch as the assumption of constant core temperature is the one which, in all probability, will be used most extensively because of its greater simplicity and sufficient accuracy, the supplementary derived equations are given for that case only.

It is hoped that methods for predicting the iron temperatures with greater accuracy than at present will be forthcoming. Such methods will probably include the rate of generation of heat in the various parts of the iron, the rate of flow of heat from the embedded copper to the iron, the transfer of heat from one part of the iron to another, and finally the dissipation of heat from the iron surface; the constants for which, must of course, be determined experimentally. In the meantime, however, it should not be difficult to secure fairly complete data of the tooth temperatures of machines, having stationary armatures of various proportions, by means of, say, embedded thermocouples placed between laminations. Such thermocouples should be so placed as to give information axially and radially; for with the deep slots employed at present the variation in temperature of the iron radially is not always negligible. If the upper coil in the slot (the one nearer the air gap) has materially higher eddy current loss than the lower, and if in addition the temperature of the tooth adjacent to the upper coil is at somewhat higher temperature than the portion of the tooth adjacent to the lower coil, the upper coil will be at higher temperature as a result of the influence of both effects. In the machine, the tests of which are given in this paper, the lower temperatures of the lower coil are due almost entirely to the lower temperature of that part of the tooth. Fig. 11 gives an idea of the variation of tooth temperature with depth. Undoubtedly, this variation in tooth temperature was largely due to the not inconsiderable difference in induction density at the different depths; (the diameter of the machine was quite small).

In many machines, it will possibly be sufficient to take as the iron temperature that of the core measured in the ordinary way by thermometer; a small correction may be added. This should apply to machines like many of our standard induction motors and low-speed alternators having shallow cores and teeth, in which the temperature gradient radially cannot be very great. In the paper "Some Practical Experience with Embedded Temperature Detectors[2]," data are given on a 12,000-kv-a. alternator, in which the average difference between detector readings near the back of the core and in the core at nearly full load was only about three deg. cent.

In employing the temperature figures for the iron, allowance may be made for the cooling of the outside of the coils in the vent ducts in radially ventilated machines. In this calculation, the following should be allowed for:

1. The increase in temperature of the air above the ingoing air;

2. The difference in temperature between the outside coil surface and the air impinging upon it;

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[2] See paper by F. D. Newbury and C. J. Fechheimer, Trans. A. I. E. E. 1920, Vol. I, p. 971.

3. The weighted mean of the iron temperature and the outside coil surface.

1. More specifically may be approximately determined by considering the losses absorbed by the air before the air encounters the coil; (remembering that the air rise is about one deg. cent. when 1765 cubic feet per minute absorb one kw.).

2. May be approximated by means of an equation like (38) in this paper.

3. The weighted mean for constant core temperature is equal to:

$$\frac{\text{Width of vent} \times \text{av. temp. of outside of coil} + \text{width of iron pkg.} \times \text{av. temp. of iron}}{\text{Width of vent} + \text{width of package of iron}}$$

In general, a rough approximation is sufficient. The cooling of the outside coil surfaces at the vents tends to introduce irregularities in the copper temperature curve, but the high thermal conductivity of the copper undoubtedly practically obliterates them.

EDDY CURRENTS

In most large a-c. machines, and in some d-c. machines the eddy current loss due to the load currents may augment the $I^2 R$ loss materially. This loss is not the same for the two coil sides in a slot, and is lower in the end windings than in the embedded part. The formulas derived by Mr. R. E. Gilman[3] are quite accurate but they necessarily involve the temperature coefficient of resistance of copper. In using the equations derived in this paper, it is first necessary to calculate the eddy current factor, and for this a first approximation of the copper temperature must be employed. The eddy current factor in the equations is considered to be constant, and its values should be calculated with the use of the average temperature of the copper in the slots or ends, as the case may be.

It is of interest and value to note that the length of the core of the machine is not the only factor which affects the difference between the maximum temperature as computed by transverse flow only, and the

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[3] Eddy Current Losses in Armature Conductors, TRANS. A. I. E. E. 1920, Vol. I, p. 997.

maximum copper temperature which actually obtains. If the section of copper be large,(that is, so large as to secure a nominally low density) but the eddy current loss in the embedded portion be high, the large cross-section of copper permits of flow of heat at a fairly rapid rate to the ends; consequently, even for long core lengths, the longitudinal heat flow may be quite effective in reducing the copper temperature at the middle of the machine. Thus, in a machine, which was built about ten years ago, the nominal density in the copper at full load is 1200 amperes per sq. in., and the calculated eddy current loss plus $I^2 R$ is a little more than twice the $I^2 R$ loss. Even though the core length of that machine is 58 inches, the longitudinal heat flow lowers the temperature, as calculated by means of equations in this paper, 50 degrees below the temperature calculated by means of the transverse equation (on the basis of no longitudinal heat flow).

THERMAL CONDUCTIVITIES

The most unsatisfactory constant which is involved in equations of heat flow in electrical machinery is that of the transverse thermal conductivity of the insulating material. Unlike the electrical conductivity of metals, we are never sure within a large percentage what value to choose. Thus ordinary fish paper has been found to vary in transverse conductivity from 0.0047 to 0.0064 watts per sq. in. per in. per deg. cent. When built up in wrappers, with say the addition of mica, such as used on the straight parts of some coils, the combined conductivity is materially reduced, (due to the introduction of short paths of low conductivity from layer to layer), and the variation in conductivity is greater than that of paper or other material[4]. For the ends, for which varnished cambric is used, with varnish between layers, which varnish reduces the influence of air pockets and contact resistance, the conductivity

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[4] Some data on Thermal Conductivity of Insulating Material may be found in articles by T. S. Taylor in the *Electric Journal* for December 1919, and the *Elec. World* for Feb. 14, 1920; also in paper by Symonds and Walker "Heat Paths in Elec. Mach.," I. E. E., 1912.

is higher, and the variation less than for the embedded portion.

Owing to the fact that a slight amount of volatile matter is driven off at the higher temperature, the thermal conductivity may change with time, especially if the machine be operated at temperatures above 100 deg. cent. The driving off of the volatile matter does not change the thermal conductivity of the individual layers of insulating material so much as it changes the structure of the insulation between layers, thereby changing the conductivity from layer to layer. Naturally, the variations are erratic.

Therefore, it is quite possible that the temperatures of the copper of machines may change slightly after having been in service for some time, and this is also one reason why the internal temperatures on the same machine differ when made under identical conditions, but on different days.

Furthermore, for most insulating materials, the conductivity changes with the temperature, increasing slightly with increasing temperature. When built up in wrappers, the value of the temperature coefficient of thermal conductivity is quite indefinite and on some tests, its value has been found to be zero. In the equations, the thermal conductivity has been taken as a constant, partly because of uncertain value of the temperature coefficient but more especially because of a desire to avoid further complications in the equations.

Owing to the great importance of the transverse thermal conductivity of insulating materials, laboratory tests of the value of thermal conductivities are of great value. Such tests should be made upon a large number of coil wrappers imitating as closely as possible the conditions that obtain in the machine, and the temperatures in such tests should be maintained at values approximating those in service, and be thus maintained until constant conditions are reached.

The thermal conductivity of the copper (longitudinally) is so high compared with the longitudinal conductivity of the insulation (of the order of 1000) that the neglect of any heat flow longitudinally through the insulation may well be justified. The conductivity of copper has been taken as 9 watts per sq. in. per in. per deg. cent. in the calculations to be found in this paper, and, as in the case of insulation, the temperature coefficient of heat conductivity has been neglected. Various authorities give somewhat different figures for the conductivity of copper, and the value of 9 chosen may be a little lower than that given by most of them. The Smithsonian tables, for example, give, about 9.6 whereas Symonds and Walker used as low value as 7.6.

Emissivity from End Windings

Next to thermal conductivity of the insulation, the most unsatisfactory constant which is employed in the equations is that of emissivity from the end windings. Every electrical manufacturer has an enormous amount of data on temperatures taken by thermometer on the surfaces of the ends of the coils, but none of such data can be directly applied. The reasons therefor are:

1. Most of the temperatures were taken after shutdown, and some of the heat flowed out from the embedded portion of the coil, and thereby influenced the reading;

2. The temperatures of the copper inside the coils at the particular spot where the thermometers were placed were not known; and if they were known the watts per unit surface would have to be calculated from the drop in temperature through the wall of insulation and from a supposed knowledge of the conductivity of the insulating wall;

3. Most data do not give the spacing between coil ends;

4. There were no records taken of the air velocities upon which the rates of heat dissipation are very largely dependent;

5. There are no records of the angles of incidence of the air.

It is believed to be best to make such emissivity tests on suitable models in a laboratory, using dummy coil ends. A description of one set of such tests is given in a recent number of the *A. S. M. E. Journal.*[5] Those tests are far from complete, as they were made on one coil only; however, data from that set of curves should be helpful until more complete data are available.

In the equations which are given in this paper, the watts per sq. in. per deg. cent. have been taken to be constant, although with variable spacing, with supports for the coil ends at intervals, with variable air velocity, with different angles of incidence of the air, etc., that factor must be quite far from being constant; it is probable, however, that the value chosen (0.04)5 is sufficiently close approximation to the average value which obtained in the machine. Nevertheless, some of the departures between test and calculations may be in part due to the inaccuracy of the value chosen, and to the variability of that factor. Fortunately, in many machines in which the air velocity is fairly high, or the wall of insulation is rather thick, the variation of the emissivity factor along the coil, and the incorrect choice of its average value, do not have so much influence on the final results as might at first thought be supposed; because the drop through the insulating wall on the ends is usually of considerably greater influence than the drop from the external surface to the cooling air.

THE POINTS OF MAXIMUM AND MINIMUM TEMPERATURE

One of the terminal conditions for evaluating one of the integration constants for the embedded portion is that at the center of the core, or for $X = 0$, the temperature is at its maximum value. This assumption is usually in fairly close keeping with the conditions that actually obtain in the machine. However, with certain constructions it may be advisable to choose some other point for that of maximum temperature. For example, in most large axially ventilated turbo generators, there are fairly large radial vent ducts near the middle of the machine. The cooling air which

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[5] "The Dissipation of Heat by Various Surfaces" by T. S. Taylor, abstract in A. S. M. E. *Journal* for April, 1920. The complete paper contains useful curves not appearing in the abstract.

passes over the coil surfaces near the middle of the machine reduces the temperature there, so that in such cases, it is considered advisable to take the end of the iron adjacent to the first vent duct as the point of maximum temperature; that method has been employed in the calculations to be found in this paper.

The point of minimum temperature that has been chosen in the equations for evaluating one of the integration constants in the end windings, is the extreme end of the winding. Such assumption is quite accurate provided that the temperature curves for the upper and lower coils are identical. As is usually the case, however, the upper coil temperature in the embedded part is higher than that for the lower coil, owing to higher tooth temperature adjacent to the upper coil and the higher eddy current loss in the upper coil. If, then, the rate of cooling the ends of the upper and lower coils be the same, the point of minimum temperature is on the lower coil at a short distance from the coil-end. Thus, in Fig. 9, the test curve for the particular coil located in slot numbers 9 and 21 has been drawn in dot and dash, for the 300-ampere heat run; and it will be noted that the minimum temperature is about 28.5 inches, instead of 32.5 inches, from the center of the core.

If the difference in temperature between the upper and lower coils be considerable, it may be advisable to calculate the temperatures on the assumption that the point of minimum temperature is beyond the extremity; that is, that L_b[6] for the upper coil is greater than L_b for the lower coil. Otherwise, the calculated curves for the upper and lower coils will not meet at any point, a condition which, of course, must be fulfilled, in the machine. It is further of interest that the moving of the point of minimum temperature from the extremity of the winding to some point on the end of the lower coil, has the effect of reducing the maximum temperature of the upper coil, and of raising the maximum temperature of the lower coil, although such changes are too small to be of consequence. In fact, if the

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[6] L_b is the length of winding from the core to the extremity. See list of Symbols.

maximum temperature is the only one sought, it is believed that the error introduced by taking the minimum temperature at the end of the winding is quite negligible in machines of usual proportions.

THE TRANSVERSE AREA

The area per unit length through which the heat flows has been taken as the average area of the part of the perimeter from which the heat is dissipated, and the corresponding perimeter of the copper. For the embedded part with two coil-sides per slot, the two sides adjacent to the teeth plus one of the other sides are taken as the area (see Fig. 2). This assumes that there is no heat escapment from the two coil sides adjacent to each other. Such assumption is not strictly correct, for as was shown in the paper on "Embedded Temperature Detectors,[7]" the heat flow to the slot-sides has an appreciable influence upon the reading of the detector placed between coil-sides in the usual way. The magnitude of such heat flow is, however, very small, compared with the total transverse heat flow. Especially when consideration is given to the uncertainty of such important factor as the transverse thermal conductivity of the insulating material, the assumption is well justified.

For the end windings, in the special case for which the solution is given, the outside surface from which the heat is dissipated (for unit length) is taken as the external perimeter of one coil; and the average area through which heat flows is taken as the average of the external perimeter and the copper perimeter. In the particular problem adjacent coils were fairly well separated, so that the cooling air was effective in reaching all sides of the coil. However, such assumption may not be admissible in some machines (as many small induction motors) in which practically no air can pass between adjacent coil ends. The areas which should be chosen for the external surface Q' and that offered for transverse flow Q_b in the ends, must be decided after study by the designing engineer.

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[7] Loc. cit.

The question has been raised as to the inaccuracy of the "average area" equation, instead of the more exact logarithmic expression. The derivations and comparisons are given in the appendix, and it is there shown that with typical high-voltage (say 13,200) dimensions, the difference is less than 1 per cent. With low-voltage insulation, the difference is even less than for high-voltage.

LIST OF SYMBOLS

$A_a = \dfrac{1}{k_e N q}(K_a - \epsilon_a I^2 r \alpha)$

$A_b = \dfrac{1}{k_e N q}(\gamma K_b - \epsilon_b I^2 r \alpha)$

$b = \dfrac{x}{1 - \dfrac{\theta_i}{\theta_m}}$ = constant used in equations for linear variation in iron temperature.

$\dfrac{B_a}{A_a} = \dfrac{K_a \theta_i + \epsilon_a I^2 r}{K_a - \epsilon_a I^2 r \alpha}$ = temperature of embedded copper if all heat flowed transversely.

Note: Use θ_m instead of θ_i with linear or parabolic variations of iron temperatures.

$\dfrac{B_b}{A_b} = \dfrac{\gamma K_b \theta_0 + \epsilon_b I^2 r}{\gamma K_b - \epsilon_b I^2 r \alpha}$ = temperature of copper in ends if all heat flowed transversely.

C_1, C_2, C_3, etc. = integration constants.

D_a = thickness of single wall of insulation in embedded portion—taken as distance from bare copper to tooth.

D_b = thickness of single wall of insulation on ends of coil.

$f = \dfrac{x^2}{1 - \dfrac{\theta_i}{\theta_m}}$ = constant when assuming iron temperature axially to be parabolic.

$G = \dfrac{\theta_m K_a}{b k_e N q}$ = constant used with linear variation in iron temperature.

H = $\dfrac{\theta_m K_a}{f k_c N q}$ = constant used with parabolic iron temperature axially.

I = current (amperes) per conductor.

K_a = $\dfrac{k_a Q_a}{D_a}$ = conductivity constant for particular coil (embedded portion).

K_b = $\dfrac{k_b Q_b}{D_b}$ = conductivity constant for particular coil (end winding portion).

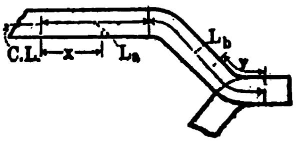
k_a = thermal conductivity of insulation (embedded portion).

k_b = thermal conductivity of insulation (end windings).

k_c = thermal conductivity of copper in watts per unit area per unit length per deg. cent.

k' = emissivity constant for heat dissipation from end windings in watts per unit surface per deg. cent.

L_a = distance from point of max. temp. to end of core; this is usually 1/2 core length.



L_b = half end winding length, at one end only.

L_t = sum of L_a and L_b.

N = number of conductors per coil.
($N q$ = cross-section area of copper in one coil.)

Q_a = average surface (in embedded portion) of one coil through which heat flows transversely, per unit length axially.

Q_b = average surface (in end windings) of one coil through which heat flows transversely, per unit length axially.

Q' = outside surface of one coil in end winding per unit length longitudinally.

q = area of cross-section of one conductor.

r = resistance in ohms of copper in one coil per unit length axially at zero deg. cent.

W = heat (expressed in watts) generated between zero point of reference and some other point (x or y).

W_1 = heat (expressed in watts) flowing transversely through insulation from point 0 to x (or y).

W_2 = heat (expressed in watts) flowing longitudinally along copper from point x (or $y + dy$) to point $x + dx$ (or y).

x = distance from point of max. temp. (usually center of core) to point x.

y = distance from point of min. temp. (taken as extreme end) to point y.

Greek Letters

α = temperature coefficient of copper = 0.00427 at zero deg. cent.

$$\beta = \frac{\sqrt{A_b}\tanh\sqrt{A_b}\,L_b}{\sqrt{A_a}\tanh\sqrt{A_a}\,L_a}.$$

$$\gamma = \frac{1}{1 + \dfrac{K_b}{k'\,Q'}}$$

Δ = current density in copper amperes per unit area.

ϵ_a = eddy current ratio for embedded portion = ratio of actual loss to nominal $I^2 R$ (See Gilman's formulas and curves A. I. E. E., June, 1920)

ϵ_b = eddy current ratio for end winding portion.

$\theta_{a0} = \dfrac{B_a}{A_a}$

θ_a = temperature, deg. cent. of copper, at a point x in embedded portion.

$\theta_{b0} = \dfrac{B_b}{A_b}$

θ_b = temperature, deg. cent. of copper at a point y in end winding.

θ_e = temperature, deg. cent., of external surface, at a point y in end windings.

θ_i = temperature of iron adjacent to coils at a point x axially, or the average iron temperature when constant iron temperature is assumed.

θ_L = temperature of copper at end of core.
θ_m = temperature of iron, maximum, when parabolic or linear variation of iron temperature is assumed.
θ_{max} = maximum temperature of copper (embedded portion).

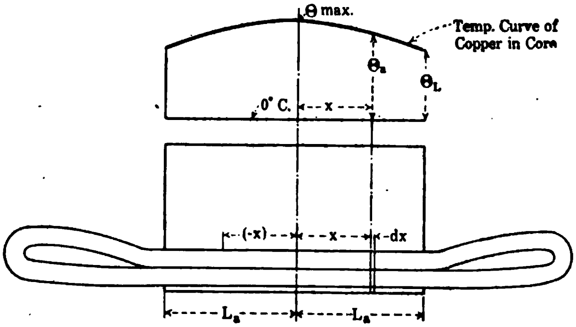


Fig. 1

θ_{min} = minimum temperature of copper (end windings)
θ_0 = temperature of air striking end windings.
θ_{av} = average temperature of winding.
ρ = resistance of unit volume of copper at zero deg. cent. (= 0.625×10^{-6} ohms per inch per sq. in.)

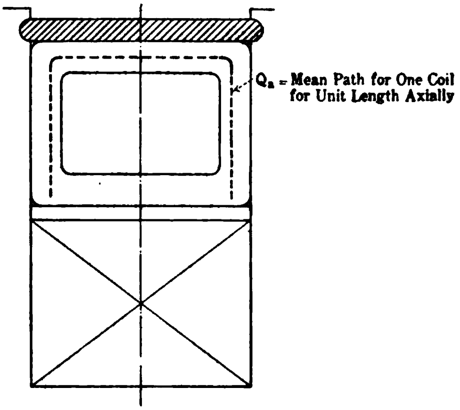


Fig. 2

CASE I—CONSTANT IRON TEMPERATURE STEADY STATE

If the machine has run for a long enough period of time to secure constant temperatures (steady state), power expressed in watts may be used instead of energy, expressed in joules or calories, for the heat generated, dissipated, etc. Calling W the heat generated by $I^2 R$ and eddy currents in the copper, the total heat generated from $x = 0$ to $x = x = \int_0^x dW$. (See Fig. 1.) This heat must either flow transversely through the insulation, or longitudinally along the copper toward the coil ends. If W_1 is the transverse flow, that heat flow from 0 to $x = \int_0^x d\,W_1$. After deducting the transverse heat flow from the total generated heat, the remainder must be the longitudinal heat flow; or if W_2 is the heat which flows longitudinally beyond x,

$$W_2 = \int_0^x d\,W - \int_0^x d\,W_1 \tag{1}$$

The loss in thin lamina $d\,x$ is:

$$d\,W = \frac{\epsilon_a\,\rho\,(1 + \alpha\,\theta_a)\,I^2\,N\,d\,x}{q} \tag{2}$$

Considering the average heat path through the insulation to have area of Q_a for unit length axially, the area for length "dx" is $Q_a\,dx$, and the traverse heat flow is (Fig. 2):

$$d\,W_1 = \frac{k_a\,(\theta_a - \theta_i)\,Q_a\,dx}{D_a} \tag{3}$$

If "$d\,\theta_a$" is the difference in temperature between the two sides of lamina "dx," the heat flow from one side of the lamina to the other is:

$$W_2 = -\,k_c\,(N\,q)\,\frac{d\,\theta_a}{dx} \tag{4}$$

The negative sign is used in (4), because θ_a decreases as x increases.

Substituting the values for W, W_1, and W_2 from (2), (3), and (4) in (1), and differentiating,

$$- k_c N q \frac{d^2 \theta_a}{d x^2} = \frac{\epsilon_a \rho (1 + \alpha \theta_a) I^2 N}{q} - \frac{(\theta_a - \theta_i) k_a Q_a}{D_a} \qquad (5)$$

Or,

$$\frac{d^2 \theta_a}{d x^2} - \frac{1}{k_c N q}\left(\frac{k_a Q_a}{D_a} - \frac{\epsilon_a \rho I^2 N \alpha}{q}\right)\theta_a = - \left(\frac{\epsilon_a \rho I^2 N}{q} + \frac{k_a Q_a}{D_a} \theta_i\right) \frac{1}{k_c N q} \qquad (6)$$

Writing

$$A_a = \frac{1}{k_c N q}\left(\frac{k_a Q_a}{D_a} - \frac{\epsilon_a \rho I^2 N \alpha}{q}\right)$$

$$= \frac{1}{k_c N q} (K_a - \epsilon_a I^2 r \alpha) \qquad (7)$$

and

$$B_a = \frac{1}{k_c N q}\left(\frac{k_a Q_a}{D_a} \theta_i + \frac{\epsilon_a \rho I^2 N}{q}\right)$$

$$= \frac{1}{k_c N q} (K_a \theta_i + \epsilon_a I^2 r) \qquad (8)$$

equation (6) becomes:

$$\frac{d^2 \theta_a}{dx^2} - A_a \theta_a = - B_a \qquad (9)$$

Or,

$$\frac{d^2}{dx^2}\left(\theta_a - \frac{B_a}{A_a}\right) - A_a\left(\theta_a - \frac{B_a}{A_a}\right) = 0$$

Considering $\left(\theta_a - \frac{B_a}{A_a}\right)$ as the dependent variable a general solution will be recognized as:

$$\left(\theta_a - \frac{B_a}{A_a}\right) = C' e^{\sqrt{A_a}\, X} + C'' e^{-\sqrt{A_a}\, X}$$

Since $e^u = \cosh u + \sinh u$
and $e^{-u} = \cosh u - \sinh u$,
the solution in more convenient form may be written as:

$$\theta_a = C_1 \cosh \sqrt{A_a}\, x + C_2 \sinh \sqrt{A_a}\, x + \frac{B_a}{A_a} \qquad (10)$$

In most machines, the temperature is a maximum for $x = 0$, that is at the center of the core. That is, one terminal condition is that $\frac{d\,\theta_a}{d\,x} = 0$ for $x = 0$.

$$\frac{d\,\theta_a}{d\,x} =$$

$$\sqrt{A_a}\,C_1 \sinh \sqrt{A_a}\,x + \sqrt{A_a}\,C_2 \cosh \sqrt{A_a}\,x = 0$$

Thus $C_2 = 0$ for $x = 0$.

The other terminal condition is determined by making $\theta_a = \theta_L$ for $x = L_a$ (see Fig. 1). Method for evaluating θ_L is given subsequently.

$$\theta_L = C_1 \cosh \sqrt{A_a}\,L_a + \frac{B_a}{A_a}$$

Or $$C_1 = -\frac{\theta_{a0} - \theta_L}{\cosh \sqrt{A_a}\,L_a}$$

Where θ_{a0} has been written for $\frac{B_a}{A_a}$.

Then $$\theta_a = \theta_{a0} - \left(\frac{\theta_{a0} - \theta_L}{\cosh \sqrt{A_a}\,L_a}\right) \cosh \sqrt{A_a}\,x \qquad (11)$$

Putting $x = 0$ for maximum temperature,

$$\theta_{max} = \theta_{a0} - \frac{(\theta_{a0} - \theta_L)}{\cosh \sqrt{A_a}\,L_a} \qquad (12)$$

For very long cores, $\cosh \sqrt{A_a}\,L_a$ increases and becomes so large that the temperature at the middle of the core becomes:

$$\theta'_{max} = \theta_{a0} = \frac{B_a}{A_a} = \frac{\left(\frac{k_a Q_a}{D_a}\right)\theta_i + \frac{\epsilon_a \rho I^2 N}{q}}{\frac{k_a Q_a}{D_a} - \frac{\epsilon_a \rho I^2 N}{q}\alpha}$$

$$= \frac{K_a \theta_i + \epsilon_a I^2 r}{K_a - \epsilon_a I^2 r \alpha} \qquad (13)$$

Equation (13) is quite important, as it is the expression for transverse heat flow without considering the longitudinal flow, and takes into account the influence of the temperature coefficient α. If α is neglected, (13) becomes:

$$\theta'_{max.} = \theta i + \frac{\epsilon_a I^2 r}{K_a} = \theta i + \frac{D_a}{k_a Q_a} \epsilon_a I^2 r \qquad (14)$$

This is a well-known form, being the sum of the iron temperature and the transverse thermal drop.

In order that θ_L be evaluated, it is essential to consider the heat flow from the embedded portions of the coils to the ends, and then the flow along the copper, as well as the transverse flow in the ends and the heat dissipation from the coil-end surfaces must be brought into the equations. The equations for temperatures in the end windings must be combined with those applying to the embedded portion. The assumption was made in solving the heat flow problem for the embedded portions that the temperature of the outside of the coil in contact with the iron was the same as the temperature of the iron, θi. The parallel assumption for the ends is scarcely admissible, inasmuch as the temperatures of the outside surfaces of the coil-ends are somewhat higher than the surrounding air.

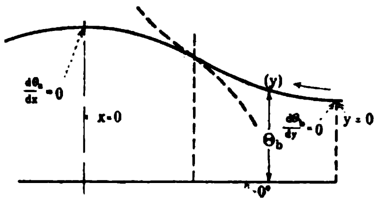


FIG. 3

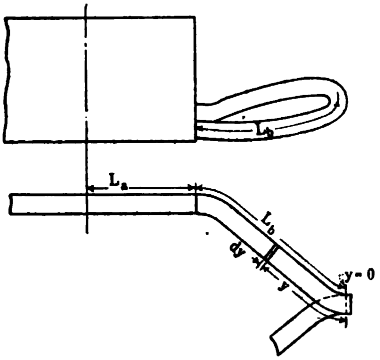


FIG. 4

Calling k' the emissivity from the coil end surfaces in watts per unit surface per degree difference in temperature between the surfaces and the surrounding air, Q' the surface per unit length of end connection, and $d\,W_1$ the watt dissipation to the air in length $d\,y$, the difference in temperature between the coil-end surface and surrounding air is:

$$(\theta_e - \theta_0) = \frac{1}{k'\,Q'}\;\frac{d\,W_1}{d\,y}$$

And as previously,

$$d\,W_1 = \frac{k_b\,(\theta_b - \theta_e)\,Q_b\,d\,y}{D_b}$$

Combining these two equations,

$$d\,W_1 = \frac{(\theta_b - \theta_0)\,k_b\,Q_b\,Q'\,k'\,d\,y}{k'\,Q'\,D_b + k_b\,Q_b}\;.$$

$$= (\theta_b - \theta_0)\;\gamma\,\frac{k_b\,Q_b}{D_b}\;d\,y \qquad (15)$$

Where $\gamma = \dfrac{k'\,Q'\,D_b}{k'\,Q'\,D_b + k_b\,Q_b}$

$$= \frac{1}{1 + \dfrac{k_b\,Q_b}{D_b}\;\dfrac{1}{k'\,Q'}} = \frac{1}{1 + \dfrac{K_b}{k'\,Q'}} \qquad (16)$$

The heat generated in thin lamina $d\,y$, is, as before:

$$d\,W = \frac{\epsilon_b\,\rho\,(1 + \alpha\,\theta_b)\,I^2\,N}{q}\;d\,y \qquad (17)$$

Taking y to be zero at the end of coil (Fig. 4), and to be positive to the left, it is clear that the heat (expressed in watts) that flows along the copper from the point $y + d\,y$ to the point y is:

$$W_2 = +\,k_c\,N\,q\,\frac{d\,\theta_b}{d\,y} \qquad (18)$$

In this case W_2 is positive because θ_b decreases as y decreases.

Evidently, the heat that flows into the copper longitudinally at point y (from left to right), (W_2), + the heat generated in copper from o to y, $\left(\int_o^y dW\right)$, must flow through the insulation to the outside surface of the coil where it is dissipated (by forced air convection currents in the usual case)[8]. That is:

$$W_2 + \int_{y=o}^{y=y} dW = \int_{y=o}^{y=y} dW_1 \qquad (19)$$

Substituting in (19) from (15), (17) and (18),

$$k_c N q \frac{d\,\theta_b}{d\,y} + \frac{\epsilon_b \rho I^2 N}{q} \int_o^y (1 + \alpha\,\theta)\,d\,y$$

$$= \frac{\gamma\,k_b Q_b}{D_b} \int_o^y (\theta_b - \theta_0)\,d\,y \qquad (20)$$

Differentiating and combining,

$$\frac{d^2\,\theta_b}{d\,y^2} - \frac{1}{k_c N q}\left(\frac{\gamma\,k_b Q_b}{D_b} - \frac{\epsilon_b \rho I^2 N}{q}\,\alpha\right)\theta_b$$

$$= - \frac{1}{k_c N q}\left(\frac{\gamma\,k_b Q_b}{D_b}\,\theta_0 + \frac{\epsilon_b \rho I^2 N}{q}\right) \qquad (20)$$

Or

$$\frac{d^2\,\theta_b}{d\,y^2} - A_b\,\theta_b = - B_b \qquad (21)$$

Where

$$A_b = \frac{1}{k_c N q}\left(\frac{\gamma\,k_b Q_b}{D_b} - \frac{\epsilon_b \rho I^2 N}{q}\,\alpha\right)$$

$$= \frac{1}{k_c N q}\,(\gamma\,K_b - \epsilon_b I^2 r\,\alpha) \qquad (22)$$

and

$$B_b = \frac{1}{k_c N q}\left(\frac{\gamma\,k_b Q_b}{D_b}\,\theta_0 + \frac{\epsilon_b \rho I^2 N}{q}\right)$$

---

[8] Another way is to consider y as negative, reverse limits of integrals, and W_2 then as negative. That is, however, slightly more difficult to follow, and has, therefore, not been employed. The result is the same.

$$= \frac{1}{k_c \, Nq} \left(\gamma \, K_b \, \theta_0 + \epsilon_b I^2 r \right) \qquad (23)$$

Equation (**21**) is of same form as equation (**9**), so that a general solution is:

$$\theta_b = C_3 \cosh \sqrt{A_b}\, y + C_4 \sinh \sqrt{A_b}\, y + \frac{B_b}{A_b} \qquad (24)$$

The terminal conditions for evaluating the constants of integration C_3 and C_4 are that for $y = 0, \frac{d\,\theta}{d\,y} = 0$ (that is, the temperature is at minimum value for $y = 0$); and that $\theta_b = \theta_L$ for $y = L_b$.

As for the embedded portion, the first condition gives $C_4 = 0$; and the second:

$$C_3 = \frac{\theta_L - \theta_{b0}}{\cosh \sqrt{A_b}\, L_b}$$

Therefore,

$$\theta_b = \theta_{b0} + \frac{(\theta_L - \theta_{b0})}{\cosh \sqrt{A_b}\, L_b} \cosh \sqrt{A_b}\, y \qquad (25)$$

Where θ_{b0} has been written for $\frac{B_b}{A_b}$

The minimum temperature is for $y = 0$:

$$\theta_{min} = \theta_{b0} + \frac{(\theta_L - \theta_{b0})}{\cosh \sqrt{A_b}\, L_b} \qquad (26)$$

With very long ends, L_b approaches infinity, so that

$$\theta'_{min} = \theta_{b0} = \frac{\gamma \, K_b \, \theta_0 + \epsilon_b I^2 r}{\gamma \, K_b - \epsilon_b I^2 r \, \alpha} \qquad (27)$$

Equation (**27**) is similar to (**13**) and is the expression for temperature when the generated heat at any spot flows transversely through the insulation, uninfluenced by any longitudinal flow.

The equation for temperature in the embedded portion may now be united with the equation for temperature in the ends. The curves for temperatures for the two portions join at point $x = L_a$, or $y = L_b$. (The continuation of those curves beyond that point are shown by the dotted curves in Fig. 3).

The heat flowing from the embedded portion to the ends at the point $x = L_a$ is $- k_e N q \left.\frac{d\,\theta_a}{d\,x}\right]_{x\,=\,L_a}$ (equation (4), and the heat received by the ends at $y = L_b$ is $+ k_e N q \left.\frac{d\,\theta_b}{d\,y}\right]_{y\,=\,L_b}$ (equation (18)). These two must be equal to each other. Substituting for θ_a from (11) and for θ_b from (25), performing the differentiation, equating and substituting L_a for x and L_b for y, the value of θ_L is obtained after simplifying:

$$\theta_L = \frac{\theta_{a0} + \dfrac{\sqrt{A_b}\tanh\sqrt{A_b}\,L_b}{\sqrt{A_a}\tanh\sqrt{A_a}\,L_a}\,\theta_{b0}}{1 + \dfrac{\sqrt{A_b}\tanh\sqrt{A_b}\,L_b}{\sqrt{A_a}\tanh\sqrt{A_a}\,L_a}} \qquad (28)$$

Writing

$$\beta = \frac{\sqrt{A_b}\tanh\sqrt{A_b}\,L_b}{\sqrt{A_a}\tanh\sqrt{A_a}\,L_a} \qquad (28a)$$

and

$$\theta_L = \frac{\theta_{a0} + \beta\,\theta_{b0}}{1 + \beta} \qquad (29)$$

With the use of equation (29), θ_a, θ_{max}, θ_b and θ_{min} may be evaluated by substituting for θ_L in (11), (12), (25) and (26) respectively; or θ_L may be eliminated between (29) and the other equations, and the following obtained:

$$\theta_a = \theta_{a0} - \left(\frac{\theta_{a0} - \theta_{b0}}{\cosh\sqrt{A_a}L_a}\right)\frac{\beta}{(1+\beta)}\cosh\sqrt{A_a}\,x \qquad (30)$$

$$\theta_{max} = \theta_{a0} - \frac{(\theta_{a0} - \theta_{b0})}{\cosh\sqrt{A_a}\,L_a} \cdot \frac{\beta}{(1+\beta)} \qquad (31)$$

$$\theta_b = \theta_{b0} + \left(\frac{\theta_{a0} - \theta_{b0}}{1 + p}\right)\frac{\cosh\sqrt{A_b}\,y}{\cosh\sqrt{A_b}\,L_b} \qquad (32)$$

In many machines, $\sqrt{A_a}$ may be taken equal to $\sqrt{A_b}$, and L_a equal to L_b; then $\beta = 1$, and the arithmetical work is simplified somewhat. Then

$$\theta_L = \frac{\theta_{a0} + \theta_{b0}}{2} \quad \text{and}$$

$$\theta_{max} = \theta_{a0} - \frac{\theta_{a0} - \theta_{b0}}{2 \cosh \sqrt{A_a}\, L_a}\text{, etc.}$$

The temperature measured by resistance is the average temperature,. which may be calculated as:

$$\theta_{av} = \frac{1}{L_a + L_b}\left[\int_{x=o}^{x=La} \theta_a\, dx + \int_{y=o}^{y=Lb} \theta_b\, dy\right]$$

Substituting for θ_a and θ_b from (30) and (32), integrating, and simplifying, calling $L_a + L_b = L_t$,

$$\theta_{av} = \frac{1}{L_t}\Bigg[\theta_{a0} L_a + \theta_{b0} L_b + \left(\frac{\theta_{a0} - \theta_{b0}}{1 + \beta}\right)\left(\frac{\tanh \sqrt{A_b}\, L_b}{\sqrt{A_b}} - \frac{\beta \tanh \sqrt{A_a}\, L_a}{\sqrt{A_a}}\right)\Bigg] \qquad (33)$$

For the slot portion,

$$\theta_{av} = \theta_{ao} - \left[\left(\frac{\theta_{a0} - \theta_{b0}}{L_a}\right)\left(\frac{\beta}{1 + \beta}\right)\frac{\tanh \sqrt{A_a}\, L_a}{\sqrt{A_a}}\right] \qquad (33a)$$

If A_a be taken equal to A_b, and L_a equal to L_b,

$$\theta_{av} = 1/2\,(\theta_{a0} + \theta_{b0}) \qquad (33b)$$

That is, under the assumptions, the average temperature is simply the arithmetical mean of the maximum and minimum copper temperatures obtainable with very long coils.

EQUATIONS DERIVED FROM THE PRECEDING

Before leaving the equations for constant core temperature, a number of other solutions will be treated. The first will be to show how some of the equations given in the foregoing reduce to some forms previously derived. The second will be the derivation of an equation for calculating the temperature of the external surface of the coil-ends while the machine is in operation under steady conditions. The third will be the derivation of equations for calculating (a) the heat (in watts) flowing along the copper at any point; (b) the heat flowing through the insulation between the center and any points; (c) the heat generated between the center and any point.

If in equation (6), the temperature coefficient α be taken as zero, and assume that the wall of insulation offers so much resistance to the flow of heat that there is longitudinal flow only, that is, if Q_a be taken equal to zero, the equation reduces to:

$$\frac{d^2\theta}{dx^2} = -\frac{\epsilon_a \rho}{k_e}\left(\frac{I}{q}\right)^2 = -\frac{\epsilon_a \rho}{k_e}\Delta^2 \qquad (34)$$

For the first integral,

$$\frac{d}{dx}\left(\frac{d\theta}{dx}\right) = -\frac{\epsilon_a \rho}{k_e}\Delta^2, \qquad \text{or}$$

$$\frac{d\theta}{dx} = -\frac{\epsilon_a \rho}{k_e}\Delta^2 x + C_5$$

Integrating again,

$$\theta = -\frac{\epsilon_a \rho}{2k_c}\Delta^2 x^2 + C_5 x + C_6$$

When $x = 0$, $\theta = \theta_{max}$. Therefore $C_6 = \theta_{max}$.

When $x = 0$, $\frac{d\theta}{dx} = 0$. Therefore $C_5 = 0$.

Hence the equation becomes:

$$\theta = \theta_{max} - \frac{\epsilon_a \rho}{2k_c}\Delta^2 x^2 \qquad (35)$$

If $x = L_a$, and $\theta = \theta_L$

$$\theta_{max} = \theta_L + \frac{\epsilon \rho \Delta^2}{k_c}\frac{L^2}{2} \qquad (36)$$

This is a well-known equation.

If similar assumptions are made, except that α be not taken as zero,

$$\theta_{a0} = \frac{B_a}{A_a} = -\frac{1}{\alpha} \text{ (for } Q_a = 0\text{)}, \qquad \text{and}$$

$$\sqrt{A}_a = \sqrt{-\frac{\epsilon_a \rho I^2 \alpha}{k_e q^2}} = j\Delta\sqrt{\frac{\epsilon_a \rho \alpha}{k_e}}$$

where $j = \sqrt{-1}$ and $\Delta = \frac{I}{q}$

Substituting in equation (**12**), and remembering that $\cosh j\,u = \cos u$, the expression for this special case becomes:

$$\theta_{max} = \frac{1/\alpha + \theta_L}{\cos\left(\Delta\,L_a \sqrt{\dfrac{\epsilon_a\,\rho\,\alpha}{k_c}}\right)} - \frac{1}{\alpha} \qquad (\mathbf{37})$$

It is interesting to compare equation (**37**) with an equation in the paper by H. D. Symonds and Miles Walker: "The Heat Paths in Electrical Machinery" Institution of Elęc. Eng. 1912. Using same values for constants as they used, $1/\alpha = 273$, $\epsilon_a = 1$, $\Delta =$ amp. per sq. cm., $\rho = 1.6 \times 10^{-6}$, $k_c = 3$, and taking θ in absolute deg. cent. (**37**) becomes:

$$\theta_{max} = \frac{\theta_L}{\cos\left(\dfrac{4.43}{10^5}\,\Delta\,L_a\right)}\,, \qquad (\mathbf{37a})$$

the same as in their paper.

The temperature of the coil end surface may be calculated while the machine is in operation—to check the ordinary thermometer measurements, the location of the thermometer bulb (y) being known, by solving the equations preceding equation (**15**) for

$\theta_e \left(\text{thus eliminating } \dfrac{d\,W_1}{d\,y} \right)$

$$\theta_e = \frac{K_b\,\theta_b + k'\,Q'\,\theta_0}{K_b + k'\,Q'} \qquad (\mathbf{38})$$

In using this equation it is necessary to first determine the internal temperature θ_b at the particular point on the end windings by means of equation (**25**) or (32). The formula is not applicable after shutdown, because then the internal temperatures no longer show the temperature gradients as given by the equations derived, but heat flows from high to low temperatures, thus equalizing, to some extent, the copper temperatures. The external surface temperatures are influenced somewhat by this equalization, and that is one reason why the thermometers on the coil ends frequently show an increase in temperature after shut-down.

The heat flow along the copper is [equation (4)] from $x = 0$ to $x = x$ given by $W_2 = - k_c N q \dfrac{d\,\theta_a}{d\,x}$.

Substituting for θ_a from (30), and differentiating,

$$(W_2)_a = k_c N q \sqrt{A_a}\, \beta \frac{(\theta_{a0} - \theta_{b0})}{(1 + \beta)} \; \frac{\sinh \sqrt{A_a}\, x}{\cosh \sqrt{A_a}\, L_a} \tag{39a}$$

The transverse heat flow is [equation (3)]:

$$(W_1)_a = \int_0^x K_a (\theta_a - \theta_i)\, d\,x = K_a \Big[(\theta_{a0} - \theta_i)\, x - \frac{(\theta_{a0} - \theta_{b0})}{\sqrt{A_a}} \; \frac{\beta}{(1 + \beta)} \cdot \frac{\sinh \sqrt{A_a}\, x}{\cosh \sqrt{A_a}\, L_a} \Big] \tag{40a}$$

The heat generated between $x = 0$ and $x = x$ is

$$(W)_a = \int_0^x \frac{\epsilon_a \rho I^2 N}{q} (1 + \alpha\, \theta_a)\, d\,x$$

$$= \epsilon_a I^2 r \Big[(1 + \alpha\, \theta_{a0})\, x - \frac{\alpha\, (\theta_{a0} - \theta_{b0})}{\sqrt{A_a}} \left(\frac{\beta}{1 + \beta} \right) \left(\frac{\sinh \sqrt{A_a}\, x}{\cosh \sqrt{A_a}\, L_a} \right) \Big] \tag{41a}$$

$\left(\text{For } x = L_a, \; \dfrac{\sinh \sqrt{A_a}\, x}{\cosh \sqrt{A_a}\, L_a} \text{ becomes } \tanh \sqrt{A_a}\, L_a \right)$

Similar equations may be derived for the ends as follows:

$$(W_2)_b = k_c N q \sqrt{A_b} \frac{(\theta_{a0} - \theta_{b0})}{(1 + \beta)} \; \frac{\sinh \sqrt{A_b}\, y}{\cosh \sqrt{A_b}\, L_b} \tag{39b}$$

$$(W_1)_b = \gamma K_b \Big[(\theta_{b0} - \theta_0)\, y + \frac{(\theta_{a0} - \theta_{b0})}{\sqrt{A_b}\, (1 + \beta)} \; \frac{\sinh \sqrt{A_b}\, y}{\cosh \sqrt{A_b}\, L_b} \Big] \tag{40b}$$

$$(W)_b = \epsilon_b I^2 r \left[(1 + \alpha\, \theta_{b0})\, y + \frac{\alpha\, (\theta_{a0} - \theta_{b0})}{\sqrt{A_b}\,(1 + \beta)} \; \frac{\sinh \sqrt{A_b}\, y}{\cosh \sqrt{A_b}\, L_b} \right] \tag{41b}$$

It may also be of interest to determine the rate of generation at any point; this is given from equations (**2**) or (**17**), thus:

$$\frac{d\,W}{d\,x} = \epsilon_a I^2 r\, (1 + \alpha\, \theta_a) \text{ watts per unit length.}$$

$$\frac{d\,W}{d\,y} = \epsilon_b I^2 r\, (1 + \alpha\, \theta_b) \quad \text{“} \quad \text{“} \quad \text{“} \quad \text{“}$$

Similarly the rate of flow of heat transversely through the insulation is from (**3**) and (**15**):

$$\frac{d\,W_1}{d\,x} = K_a\, (\theta_a - \theta_i) \text{ watts per unit length.}$$

$$\frac{d\,W_1}{d\,y} = \gamma\, K_b\, (\theta_b - \theta_0) \quad \text{“} \quad \text{“} \quad \text{“} \quad \text{“}$$

CASE II. LINEAR VARIATION OF IRON TEMPERATURE STEADY STATE

In some machines, as for example in certain axially ventilated armatures, the core and tooth temperatures are at maximum value at the center, and decrease in linear relation from the center to the end of the core, as indicated in the upper part of Fig. 5. The equation of the straight line may readily be written, if the values of the temperature are known at two points, say for $x = 0$, and for $x = L_a$, thus:

$$\theta_i = \theta_m \left(1 - \frac{x}{b} \right) \tag{42}$$

θ_m is the maximum tooth temperature, and b is a constant.[9] The transverse heat flow is (see equation (3)):

$$d\,W_1 = (\theta_a - \theta_i)\, \frac{k_a Q_a}{D_a}\, d\,x$$

---

[9] "b" has been placed in the denominator to simplify numerical calculations.

$$= \left(\theta_a - \theta_m + \theta_m \frac{x}{b} \right) \frac{k_a Q_a}{D_a} \, d\,x \qquad (43)$$

The loss in thin lamina $d\,x$ and the longitudinal flow are the same as before (see equations (2) and (4)). Also the fundamental equation co-ordinating $d\,W$, $d\,W_1$ and W_2 is the same as previously (equation (1)). Substituting for $d\,W$, $d\,W_1$, and W_2 in equation (1):

$$- k_c N q \frac{d\,\theta_a}{d\,x} + \int_0^x \left(\theta_a - \theta_m + \frac{\theta_m}{b} x \right) \frac{k_a Q_a}{D_a} \, d\,x$$

$$= \int_0^x \frac{\epsilon_a \rho I^2 N (1 + \alpha \theta_a)}{q} \, d\,x$$

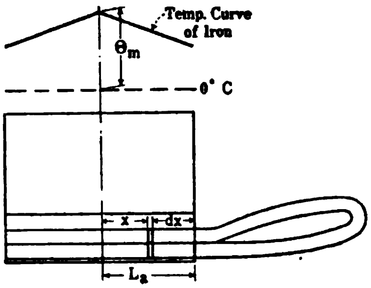


FIG. 5

Differentiating and combining,

$$\frac{d^2 \theta_a}{d\,x^2} - \left(\frac{k_a Q_a}{D_a} - \frac{\epsilon_a \rho I^2 N \alpha}{q} \right) \frac{1}{k_c N q} \theta_a$$

$$= \frac{\theta_m}{b} \frac{k_a Q_a}{D_a} \frac{1}{k_c N q} x$$

$$- \left(\frac{\epsilon_a \rho I^2 N}{q} + \frac{k_a Q_a}{D_a} \theta_m \right) \frac{1}{k_c N q} \qquad (44)$$

$$\text{Or} \quad \frac{d^2 \theta_a}{dx^2} - A_a \theta_a = G\,x - B_a \qquad (45)$$

Where A_a and B_a have the same values as previously, (equations (7) and (8)), except that θ_m appears instead of θ_i, and

$$G = \frac{\theta_m}{b} \; \frac{k_a Q_a}{D_a} \; \frac{1}{k_c N q} \tag{46}$$

Equation (45) may be written:

$$\frac{d^2}{dx^2}\left(\theta_a - \frac{B_a}{A_a}\right) - A_a\left(\theta_a - \frac{B_a}{A_a}\right) = G x$$

This linear differential equation may be solved by the well-known method of undetermined coefficients, and a general solution is:

$$\theta_a = C_7 \cosh \sqrt{A_a}\, x + C_8 \sinh \sqrt{A_a}\, x - \frac{G}{A_a} x + \frac{B_a}{A_a} \tag{47}$$

As in the case for constant core temperature, one terminal condition may be taken as $\frac{d\,\theta}{d\,x} = 0$ for $x = 0$. Then:

$$C_8 = \frac{G}{A_a \sqrt{A_a}} \tag{48}$$

And the other terminal condition is $\theta_a = \theta_L$ for $x = L_a$:

$$C_7 = \frac{- \theta_{a0} + \theta_L + \frac{G}{A_a} L_a - \frac{G}{A_a \sqrt{A_a}} \sinh \sqrt{A_a}\, L_a}{\cosh \sqrt{A_a}\, L_a} \tag{49}$$

Where θ_{a0} has been written for $\frac{B_a}{A_a}$. The solution may now be written as:

$$\theta_a = \theta_{a0} + \frac{G}{A_a \sqrt{A_a}} \sinh \sqrt{A_a}\, x - \frac{G}{A_a} x - \left[\theta_{a0} - \theta_L + \frac{G}{A_a}\left(\frac{\sinh \sqrt{A_a}\, L_a}{\sqrt{A_a}} - L_a\right)\right] \frac{\cosh \sqrt{A_a}\, x}{\cosh \sqrt{A_a}\, L_a} \tag{50}$$

As in deriving equation (28), the slope of the curve for the embedded portion $\left(- \frac{d\,\theta_a}{d\,x}\right)$ for $x = L_a$, is equal to the slope for the ends $\left(+ \frac{d\,\theta_b}{d\,y} \right)$ for $y = L_b$, obtained by differentiating equation (25), (the condition for longitudinal flow from the embedded portion at the end of the core being equal to the heat received by the ends at the same point). Thus:

$$- \frac{G}{A_a} \cosh \sqrt{A_a}\, L_a + \frac{G}{A_a} + \left[\theta_{a0} - \theta_L + \frac{G}{A_a} \left(\frac{\sinh \sqrt{A_a}\, L_a}{\sqrt{A_a}} - L_a \right) \right] \sqrt{A_a} \tanh \sqrt{A_a}\, L_a = (\theta_L - \theta_{b0}) \sqrt{A_b} \tanh \sqrt{A_b}\, L_b$$

Bringing in β as given by equation (28a), the above equation may be written as:

$$\theta_L = \frac{1}{1+\beta} \left(\theta_{a0} + \beta\, \theta_{b0} - \frac{G}{A_a} \left[L_a - \frac{\sinh \sqrt{A_a}\, L_a}{\sqrt{A_a}} + \frac{\cosh \sqrt{A_a}\, L_a - 1}{\sqrt{A_a} \tanh \sqrt{A_a}\, L_a} \right] \right)$$

The expression in brackets may be reduced to:

$$L_a + \frac{- \sinh^2 \sqrt{A_a}\, L_a + \cosh^2 \sqrt{A_a}\, L_a - \cosh \sqrt{A_a}\, L_a}{\sqrt{A_a} \sinh \sqrt{A_a}\, L_a} = L_a - \frac{\cosh \sqrt{A_a}\, L_a - 1}{\sqrt{A_a} \sinh \sqrt{A_a}\, L_a}$$

Then:

$$\theta_L = \frac{1}{1+\beta} \left[\theta_{a0} + \beta\, \theta_{b0} - \frac{G}{A_a} \left(L_a - \frac{\cosh \sqrt{A_a}\, L_a - 1}{\sqrt{A_a} \sinh \sqrt{A_a}\, L_a} \right) \right] \qquad (51)$$

This value of θ_L could be substituted in equation (50), and θ_a and θ_{max} found; or if substituted in equations (25) or (26), the temperatures of the ends may be found. The resulting expressions are quite complicated, and they are consequently not given here. It is believed best, to solve (51) and then substitute the numerical value found in the other equations.

If in equation (50), $x = 0$, $\theta_a = \theta_{max}$.

$$\theta_{max} = \theta_{a0} - \left[\theta_{a0} - \theta_L + \frac{G}{A_a} \left(\frac{\sinh \sqrt{A_a}\, L_a}{\sqrt{A_a}} - L_a \right) \right] \frac{1}{\cosh \sqrt{A_a}\, L_a} \tag{52}$$

It will be noted that these equations reduce to those for constant core temperature if $G = 0$.

CASE III. PARABOLIC VARIATION OF IRON TEMPERATURE. STEADY STATE

In most machines, especially those with radial ventilation, the core and tooth temperatures may be approximately represented by a parabola, with its maximum value at the center of the core, as indicated in Fig. 6. The equation of this curve for temperature may be written, if the values of θ_i are known at two points, say for $x = 0$, and for $x = L_a$; thus, if "f" is a constant,

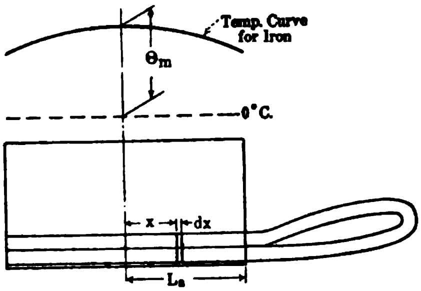


FIG. 6

$$\theta_i = \theta_m \left(1 - \frac{x^2}{f} \right) \tag{53}$$

The transverse heat flow is:

$$d W_1 = (\theta_a - \theta_i) \frac{k_a Q_a}{D_a} d x$$

$$= \left(\theta_a - \theta_m + \theta_m \frac{x^2}{f} \right) \frac{k_a Q_a}{D_a} d x \tag{54}$$

Substituting this value of $d W_1$ and those for $d W$ and W_2 (as found in equations (2) and (4) in equation (1),

$$-k_e N q \frac{d\,\theta_a}{d\,x} + \int_0^x \left(\theta_a - \theta_m + \frac{\theta_m x^2}{f}\right)\frac{k_a Q_a}{D_a}\,dx$$

$$= \int_0^x \frac{\epsilon_a\,\rho\,I^2 N\,(1 + \alpha\,\theta_a)}{q}\,d\,x$$

Differentiating and combining,

$$\frac{d^2\,\theta_a}{d\,x^2} - (K_a - \epsilon_a I^2\ r\ \alpha)\,\frac{1}{k_e N\,q}\,\theta_a =$$

$$\frac{\theta_m K_a}{f\,k_e N\,q}\ x^2 - (K_a\ \theta_m + \epsilon_a\ I^2\ r)\,\frac{1}{k_e N\,q} \tag{55}$$

Or

$$\frac{d^2\,\theta_a}{d\,x^2} - A_a\,\theta_a = H\,x^2 - B_a \tag{56}$$

Where A_a and B_a are the same as previously (equations (7) and (8)), except that θ_m appears instead of θ_i, and

$$H = \frac{\theta_m K_a}{f\,k_e N\,q} \tag{57}$$

A general solution of this linear differential equation is:

$$\theta_a = C_9 \cosh\sqrt{A_a}\,x + C_{10} \sinh\sqrt{A_a}\,x + \frac{B_a}{A_a} - \frac{H}{A_a}\,x^2 - \frac{2\,H}{A_a^2} \tag{58}$$

When $x = 0$, $\dfrac{d\,\theta}{d\,x} = 0$, whence $C_{10} = 0$.

For $x = L_a$, $\theta_a = \theta_L$, whence

$$C_9 = \frac{\theta_L - \theta_{a0} + \dfrac{H}{A_a}L_a^2 + \dfrac{2\,H}{A_a^2}}{\cosh\sqrt{A_a}\,L_a} \tag{59}$$

And,

$$\theta_a = \theta_{a0} - \frac{H}{A_a}\,x^2 - \frac{2\,H}{A_a^2} -$$

$$\frac{\theta_{a0} - \left(\theta_L + \dfrac{H}{A_a}\,L_a^2 + \dfrac{2\,H}{A_a^2}\right)}{\cosh\sqrt{A_a}\,L_a}\,.\cosh\sqrt{A_a}\,x \tag{60}$$

For $x = 0$,

$$\theta_{max} = \theta_{a0} - \frac{2H}{A_a^2} - \frac{\theta_{a0} - \left(\theta_L + \frac{H}{A_a} L_a^2 + \frac{2H}{A_a^2}\right)}{\cosh \sqrt{A_a}\, L_a} \tag{61}$$

Equating the heat flow in the embedded part to that received by the ends at $x = L_a$, and $y = L_b$, after simplifying,

$$\begin{aligned} \theta_L = \frac{1}{1+\beta}\Big[\, \theta_{a0} + \beta\, \theta_{b0} - \frac{H}{A_a} \\ \left(L_a^2 + \frac{2}{A_a} - \frac{2 L_a}{\sqrt{A_a} \tanh \sqrt{A_a} L_a}\right)\Big] \end{aligned} \tag{62}$$

Having found the numerical value of θ_L, the other quantities, θ_a, θ_{max}, θ_b and θ_{min} may be found by substituting in equations (60) (61), (25) and (26) respectively.

CALCULATIONS BY EQUATIONS AND TEST RESULTS

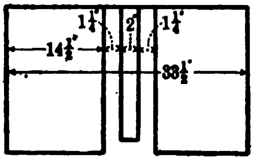
In order to check the equations derived, thermocouples were placed in the armature (stator) coils of a 2400-volt, three-phase, 60-cycle, 3600-rev. per min., turbo generator. The following are the proportions of the generator:

Length of core 33½ inches.

Number of slots 48.

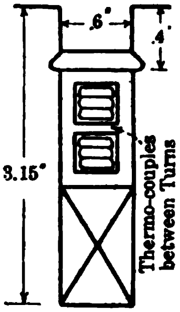
Size of slot 0.6 in × 3.15 in.

Number of conductors per slot = 4 ($N = 2$).



Size of conductor = three 0.144 in. by 0. 325 in.

Connection one circuit star.



Throw of coils, slot 1 to slot 13.

Approx. length of ¼ mean turn = 32.5 in.

Currents in upper coils in which thermocouples were embedded were out of phase by 120 electrical degrees with currents in coils in bottom of slot.

The ends of the coils were separated from one another between layers as well as circumferentially. The cooling surface was therefore taken as the perimeter of the coil (per inch longitudinally).

Thermocouples were also placed in the iron, about half-way down the tooth. The temperatures rises in the iron are shown in Fig. 7 for distribution of temperatures axially.

It will be seen that the temperature distribution in the iron is nearly that of a parabola, if the origin for x be taken as the end of the radial duct near the vertical center line, thus making L_a 14 ½ inches.

Embedded Portion

D_a = Insulation thickness $= \frac{0.6 \text{ in.} - 0.325 \text{ in.}}{2} =$ 0.138 in.

Gaged size of outside of coil = 0.549 in. by 1.197 in.

Outside surface of two sides plus width = 1.197 in. × 2 + 0.549 in. = 2.943 in.

Bare Copper surface = 0.144 in. × 12 + 0.325 in = 2.05 in.

Q_a = Average of above = 2.5 sq. in. (one inch axially)

ϵ_a = Eddy factor for upper coil = 1.092.[10]

ϵ_a = Eddy factor for lower coil = 1.065.

To avoid figuring twice, with so small difference in loss the eddy factor has been taken as 1.08 = ϵ_a.

k_a = thermal conductivity taken as 0.0025 watts per sq. in. per in. per deg. cent.[11]

L_a = length of embedded portion considered = 14.5 in.

End Windings

Gage size of ends = 0.57 in. by 1.28 in.

Q' = external surface = 2 (0.57 in. + 1.28 in.) = 3.7 sq. in.

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[10] Figured by formula in paper by R. E. Gilman, "Eddy Current Losses in Armature Conductors." TRANS. A. I. E. E. 1920, Vol. I, p. 997.

[11] Data on transverse thermal conductivity of coil wrappers consisting of cement paper and mica are given in article by T. S. Taylor in *Electrical World* for Feb. 14, 1920 as about 0.00245 for 6600 volts. Any figure must be regarded as approximate. The low values are largely due to contact resistance between layers of insulation.

Internal surfaces = 0.144 in. × 12 + 0.325 in. × 2 = 2.48 sq. in.

Q_b = average of 3.7 and 2.48 = 3.1 sq. in.

D_b = insulation thickness = $\frac{0.57 \text{ in.} - 0.325 \text{ in.}}{2}$ = 0.122 in.

ϵ_b = eddy current factor for ends = 1.03

k_b = thermal conductivity of ends taken as 0.0035 watts, per inch per sq. in. per deg. cent.[12]

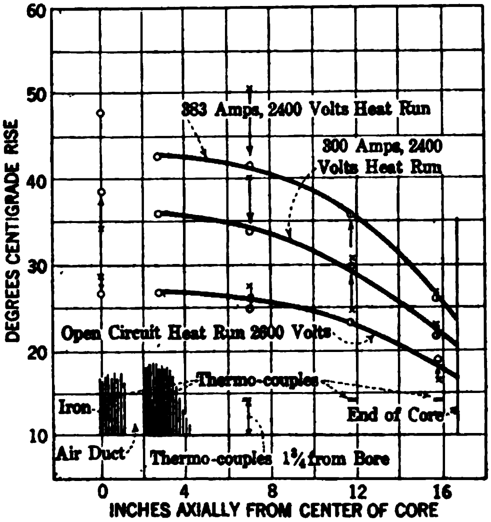

FIG. 7—CURVES SHOWING VARIATION OF TEMPERATURE RISES OF IRON (AXIALLY)

k' = emissivity from coil-end surfaces taken as 0.045 watts, per sq. in. per deg. cent.[13]

L_b = length from end of core to end of winding = 15.75 in.

General Data

k_c = thermal conductivity of copper taken as 9 watts per sq. in. per in. per deg. cent.

q = cross-section of conductor = 0.138 sq. in.

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[12] From unpublished data on transverse thermal conductivity of varnished cambric and linen tape used on ends.

[13] From unpublished data. See some data and description of tests, by T. S. Taylor in A. S. M. E. *Journal*, April 1920.

θ_e = air temperature around coil ends in test = 30.7 deg. cent.

Average ingoing air temperature = 23.7 deg. cent.

Heat Run at 300 *Ampere,* 2400 *Volts*

$$I^2 r = \frac{\rho N I^2}{q} = \frac{0.625 \times 2 \times 300^2}{10^6 \times 0.138} = 0.818 \text{ watt.}$$

$$K_a = \frac{k_a Q_a}{D_a} = \frac{0.0025 \times 2.5}{0.138} = 0.0453.$$

$$K_b = \frac{k_b Q_b}{D_b} = \frac{0.0035 \times 3.1}{0.122} = 0.089.$$

$$\gamma = \frac{1}{1 + \dfrac{0.089}{0.045 \times 3.7}} = 0.652 \text{ (equation (16).}$$

From Fig. 7, $\theta_m = 36.3 + 23.7 = 60^\circ$ $(x = 0)$

From Fig. 7, $\theta_i = 20.5 + 23.7 = 44.2$ for $x = L_a = 14.5$ in.

Assuming parabolic distribution of tooth temperatures, from equation (**53**),

$$f = \frac{x^2}{1 - \dfrac{\theta_i}{\theta_m}} = \frac{14.5^2}{1 - \dfrac{44.2}{60}} = 800$$

This value for f gives very close agreement between the iron temperature curve figured from equation (**53**) and test.

$$\theta_i = 60\left(1 - \frac{x^2}{800}\right)$$

Calculations for Constant Iron Temperature

Figuring on basis of constant iron temperature, the average iron temperature is:

$$\frac{1}{14.5}\int_{x=0}^{x=14.5} \theta_i \, dx = \frac{1}{14.5}\int_0^{14.5} 60\left(1 - \frac{x^2}{800}\right) dx$$
$$= 54.75 \text{ deg.}$$

$$\theta_{a0} = \frac{B_a}{A_a} = \frac{0.0453 \times 54.75 + 1.08 \times .818}{0.0453 - 1.08 \times 0.818 \times 0.00427}$$

$$= \frac{3.364}{0.04152} = 81 \text{ deg. (Eq. } \mathbf{13}\text{).}$$

$$A_a = \frac{0.04152}{9 \times 2 \times 0.138} = 0.01672; \ \sqrt{A_a} = 0.1292$$

(Eq. **7**)

$\sqrt{A_a}\, L_a = 0.1292 \times 14.5 = 1.876$

Tanh 1.876 = 0.953

Cosh 1.876 = 3.33

Values of the hyperbolic functions may be read from Fig. 8.

$$\theta_{b0} = \frac{B_b}{A_b}$$

$$= \frac{0.652 \times 0.089 \times 30.7 + 1.03 \times 0.818}{0.0652 \times 0.089 - 1.03 \times 0.818 \times 0.00427}$$

$$= \frac{2.63}{0.0545} = 48.3 \text{ deg.} \quad \text{(Eq. } \mathbf{27}\text{.)}$$

$$A_b = \frac{0.0545}{9 \times 2 \times 0.138} = 0.02192; \ \sqrt{A_b} = 0.148$$

(Eq. **22**).

$\sqrt{A_b}\, L_b = 2.335$

Tanh 2.335 = 0.98

Cosh 2.335 = 5.2

$$\beta = \frac{0.148 \times 0.98}{0.1292 \times 0.953} = 1.178 \text{ (Eq. } \mathbf{28a}\text{).}$$

$$\theta_L = \frac{81 + 48.3 \times 1.178}{1 + 1.178} = 63.4 \text{ degrees (Eq. } \mathbf{29}\text{)}$$

$$\theta_a = 81 - \left(\frac{81 - 63.4}{3.33} \right) \cosh (0.1292\, x)$$

$$= 81 - 5.29 \cosh (0.1292\, x) \text{ (Eq. } \mathbf{11}\text{).}$$

$\theta_{max} = 81 - 5.29 = 75.71$ degrees, or 52 degrees rise.

$$\theta_b = 48.3 + \left(\frac{63.4 - 48.3}{5.2} \right) \cosh (0.148\, y)$$

$$= 48.3 + 2.9 \cosh (0.148\, y) \text{ (Eq. 25).}$$

$\theta_{min} = 48.3 + 2.9 = 51.2$ degrees or 27.5 degrees rise.

The solid curves in Fig. 9, were figured from the above equations for θ_a and θ_b, allowing for the ingoing air temperature of 23.7 degrees. Using equation (33),

$$\theta_{av} = \frac{1}{30.25} \left[81 \times 14.5 + 48.3 \times 15.75 + \frac{81 - 48.3}{1 + 1.178} \left(\frac{0.98}{0.148} - \frac{1.178 \times 0.953}{0.1292} \right) \right]$$

$$= 62.9 \text{ deg., or } 39.2 \text{ deg. rise.}$$

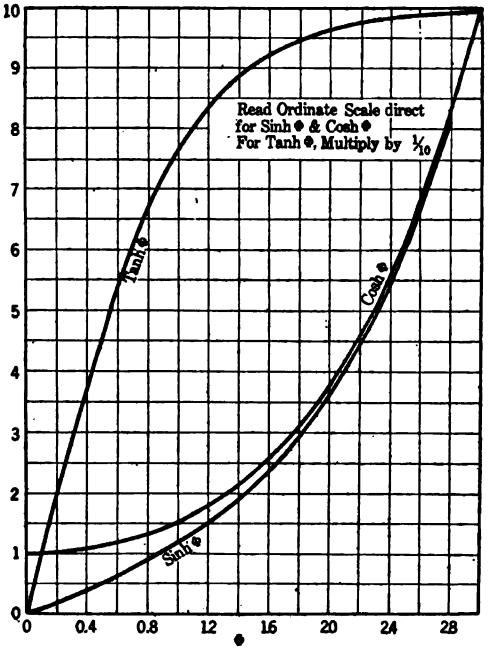

FIG. 8

The 39.2 deg. average rise applied to 30.25 in. of coil length, which is 2.25 in. less than the quarter length of the mean turn, since the zero point of reference was taken at the end of iron adjacent to the radial vent duct near the vertical center line. If the temperature for those 2.25 in. be taken to be the same as the maximum (θ_{max} calculated = 52 deg. rise), the average temperature should be,

$$\frac{39.2 \text{ deg.} \times 30.25 \text{ in.} + 52 \text{ deg.} \times 2.25 \text{ in.}}{32.5 \text{ in.}}$$

$$= 40.1 \text{ deg. rise.}$$

The temperature rise measured by resistance as soon as possible after shut down was 35.3 deg., the difference being due at least in part, to the cooling of the winding before the resistance could be measured.

The average temperature in the embedded portion by equation (33a) is 48.3 deg. rise. Allowing for the 2.25 in. at 52 deg. rise, this average rise becomes 48.8 deg. rise.

Calculations for Parabolic Variation in Iron Temperature

The constants are the same as for constant core temperature.

$k_c = 9, q = 0.138, N = 2, I^2R = 0.818, D_a = 0.138,$ $Q_a = 2.5,$ $\epsilon_a = 1.08,$ $k_a = 0.0025,$ $L_a = 14.5,$ $K_a = 0.0453,$ $D_b = 0.122,$ $Q_b = 3.1,$ $\epsilon_b = 1.03,$ $k_b = 0.0035,$ $L_b = 15.75,$ $K_b = 0.089,$ $Q' = 3.7,$ $k' = 0.045,$ $\gamma = 0.652,$ $f = 800,$ $\theta_m = 60,$ $\theta_0 = 30.7.$ $A_a = 0.01672,$ $\sqrt{A_a} = 0.1292,$ $\sqrt{A_a}L_a = 1{,}876,$ $\tanh 1.876 = 0.953,$ $\cosh 1.876 = 3.33,$ $A_b = 0.02192,$ $\sqrt{A_b} = 0.148,$ $\sqrt{A_b}L_b = 2.335,$ $\tanh 2.335 = 0.98,$ $\cosh 2.335 = 5.2.$

$$\text{Then } H = \frac{60 \times 0.0453}{800 \times 9 \times 2 \times 0.138} = 0.00136 \text{ (Eq. 57)}$$

$$\theta_{a0} = \frac{B_a}{A_a} = \frac{0.0453 \times 60 + 1.08 \times 0.818}{0.0453 - 1.08 \times 0.818 \times 0.00427}$$

$$= \frac{3.604}{.04152} = 86.7 \text{ deg. (or 63 deg. rise).}$$

For end windings, $\theta_{b0} = 48.3$, and $\beta = 1.178$ as previously.

$$\theta = \frac{1}{1 + 1.178}\left[86.7 + 1.178 \times 48.3 - \frac{0.00136}{0.1672}\left(\overline{14.5}^2 + \frac{2}{0.01672} - \frac{2 \times 14.5}{0.1292 \times 0.953}\right)\right]$$

$$= 62.6 \text{ deg. (Eq. } \mathbf{62}\text{) or } 38.9 \text{ deg. rise.}$$

$$\theta_a = 86.7 - \frac{0.00136}{0.01672}\,x^2 - \frac{2 \times 0.00136}{(0.01672)^2}$$

$$- \frac{1}{3.33}\left[86.7 - 62.6 + \frac{0.00136}{0.1672} \times \overline{14.5}^2\right.$$

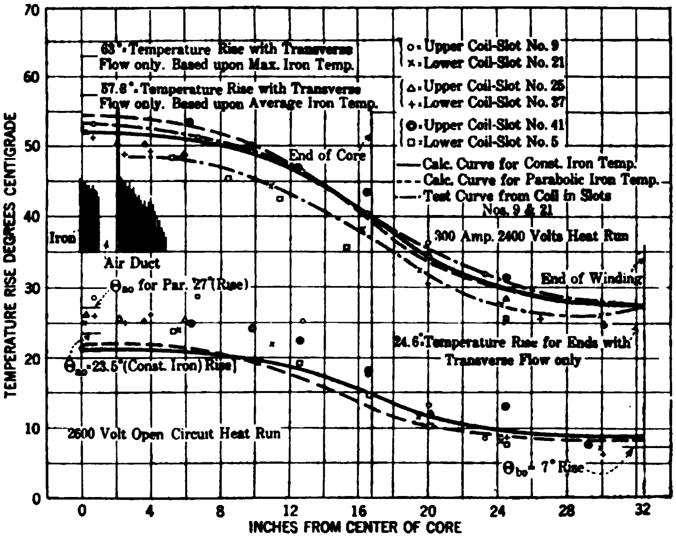

Fig. 9

$$\left.+ \frac{2 \times 0.00136}{(0.01672)^2}\right]\cosh\,(0.1292\,x)$$

$$= 77 - 0.0813\,x^2 + 0.81 \cosh\,(0.1292\,x) \text{ (Eq. } \mathbf{60}\text{).}$$

For $x = 0$, $\theta_{max} = 77.8$ or 54.1 deg. rise

$$\theta_b = 48.3 + \left(\frac{62.6 - 48.3}{5.2}\right)\cosh\,(0.148\,y)$$

$$= 48.3 + 2.76 \cosh\,(0.148\,y) \quad \text{(Eq. } \mathbf{52}\text{)}$$

For $y = 0$, $\theta_{min} = 51.1$ or 27.4 deg. rise.

The points calculated from the above for θ_a and θ_b will be found plotted in Fig. 9. As will be seen there is comparatively little difference between the curves for constant core temperature and for parabolic core temperature. In fact there is so little difference that it is questionable which is in closer agreement with the test points. In the calculations which follow, the constant core temperature figures are, in general, used.

Numerical Calculations Using Supplementary Equations

If equation (36) is employed, which assumes only longitudinal flow without allowing for the temperature coefficient, and if $\theta_L = 63.4$ deg., (as computed for constant core temperature, and if $\rho = \dfrac{0.825}{10^6}$ corresponding to 75 deg.,

$$\theta_{max} = 63.4 + \frac{1.08 \times 0.825 \times \overline{2175}^2 \times \overline{14.5}^2}{9 \times 2}$$

$$= 112.4 \text{ deg. total, or } 88.7 \text{ deg. rise.}$$

If equation (37) is used, which also assumes only longitudinal flow, but allows for the temperature coefficient,

$$\theta_{max} = \frac{\dfrac{1}{0.00427} + 63.4}{\cos\left(2175 \times 14.5\sqrt{\dfrac{1.08 \times 0.625 \times 0.00427}{10^6 \times 9}}\right)} - \frac{1}{0.00427} = 119 \text{ deg. or } 95.3 \text{ deg. rise.}$$

Had k_e been taken as ($2.54 \times 3 =$) 7.6 as in paper by Symonds and Walker, the temperature rise by same formula would have been 121 degrees; by Symonds and Walker's formula, the rise is 98.3 degrees. Or, using $k_e = 9$ in Symonds and Walker's formula, the rise is 87.3 degrees.

A comparison of these results is given in the following table:

TABLE I.

Maximum temperature rises by various means:

Longitudinal flow only				Transverse flow only		Combined flow		Test
Equa. No. 36	Equa. No. 37	Symond & Walker formula		Const. Core Temp.	Parabolic Core Temp.	Const. Core Temp.	Par. Core Temp.	
		$k_c = 7.6$	$k_c = 9$					
88.7	95.3	98.3	87.3	57.3	63	52	54.1	50.5 to 53.2

It should be noted that neglect of the transverse heat flow may lead to very considerable errors; even in a machine of medium core length the error introduced by considering only the longitudinal flow is very great, and in longer machines the error is even greater. Also, if the iron temperature be taken at its maximum value and the longitudinal flow be neglected, the calculated rise is 63 degrees; or there was an error, even in this machine of moderate length of core of about 11 degrees, or 21 per cent. If the longitudinal flow be neglected, and the average iron temperature be considered, the error in this particular machine or perhaps in longer machines is not very great. But it would be dangerous to draw any general conclusions, for as is pointed out in another part of this paper, under the subject of Eddy Currents, even in certain rather long machines, and certainly in short machines, the longitudinal flow has very material influence upon the maximum temperature. On the other hand, the close agreement of the maximum temperatures calculated either by means of the equation for constant core temperature or by the equation for parabolic core temperature with the test results shows the possibilities of estimating the maximum temperature by means of the equations derived in this paper.

The calculated temperature of the external surface of the end windings is given by equation (38), while the machine is in operation. Substituting in that equation,

$$\theta_c = \frac{0.089\ \theta_b + 0.045 \times 3.7 \times 30.7}{0.089 + 0.045 \times 3.7} = 0.349\ \theta_b + 20.2 \text{ deg.}$$

(The ingoing air temperature (23.7) deg.) must be deducted to secure rise).

Taking θ_b as the average of the two calculated curves in Fig. 9, (there are very slight differences), a comparison of calculated and test is given in Table II.

TABLE II

Distance along Copper from Center of Core	θ_b (Rise)	Calc. θ_c (Rise)	Test θ_c (Rise)
22.25	31.2	15.7	11.25
23.25	30.5	15.2	10.25
24	30	15.0	8.25

The test figure of 11.25 deg. is the average of three readings: 7.25, 9.75, and 16.75 deg. The lower temperatures by thermometer are probably largely due to the influence of the air striking the pad over the bulb of the thermometer, thereby lowering its reading. All engineers agree upon the inaccuracy of this method of judging temperatures.

The losses and the quantities of heat dissipated will now be accounted for. From equations **39a**, **40a** and **41a** calling $X = L_c$, and using figures for constant iron temperature.

$$(W_2)_c = \frac{9 \times 2 \times 0.138 \times 0.1292 \times 1.178\ (81 - 48.3) \times 0.953}{1 + 1.178} = 5.4 \text{ watts.}$$

$$(W_1)_c = 0.0453 \left[(81 - 54.75)\ 14.5 - \frac{(81 - 48.3)\ 1.178}{0.1292\ (1 + 1.178)} \times 0.953 \right] = 11.32 \text{ watts.}$$

$$(W)_c = 1.08 \times 0.818 \Big[(1 + 0.00427 \times 81)\ 14.5$$

$$- \frac{0.00427\,(81 - 48.3)}{0.1292} \times \frac{1.178}{1 + 1.178} \times 0.953 \Big]$$

$$= 16.72 \text{ watts.}$$

Thus, in the embedded portion, the total watts generated (16.72) equal the watts dissipated by transverse flow (11.32) plus the watts flowing to the ends at $X = L_a$ (5.4). See eq. (**1**)).

Similarly, by substituting in equations (**38b**,) (**40b**) and (**41b**).

$(W_2)_b = 5.4$ watts.
$(W_1)_b = 21.8$ watts.
$(W)_b = 16.4$ watts.

Thus, the total watts dissipated from the end (21.8 watts) = the watts generated in the ends (16.4 watts) plus the watts received from the embedded portion (5.4 watts). (See eq. (**19**)). Note also the agreement between $(W_2)_a$ and $(W_2)_b$.

Another interesting check is that based on the total wattage. It was previously found that the average temperature for the 30.25 in. considered was 62.9 deg., so that the average watts per inch
= (1 + 0.00427 × 62.9) 0.818 = 1.039 exclusive of eddy loss. The average eddy factor is,

$$\frac{1.08 \times 14.5 \text{ in.} + 1.03 \times 15.75 \text{ in.}}{30.25 \text{ in.}} = 1.054.$$

Thus, the total loss for the 30.25 in.

$$= 1.039 \times 1.054 \times 30.25 = 33.15 \text{ watts.}$$

From the previous calculations, the loss

$$= 16.72 + 16.4 = 33.12 \text{ watts.}$$

The rate of generation of heat in the embedded portion is,

$$\frac{d\,w}{d\,x} = 1.08 \times 0.818\,(1 + 0.00427\,\theta_a)$$

For $\theta_a = 75.7$ degrees (that is for $X = 0$),

$$\frac{d\,w}{d\,x} = 1.17 \text{ watts per inch.}$$

For $\theta_a = 63.4$ degrees ($X = L_a$),

$$\frac{d\,w}{d\,x} = 1.12 \text{ watts per inch.}$$

In the ends, $\frac{d\,w}{d\,y} = 1.07$ watts per inch for $y = L_b$.

In the ends, $\frac{d\,w}{d\,y} = 1.03$ watts per inch for $y = 0$.

The average rate of generation of heat in the embedded portion is

$$\frac{16.72 \text{ watts}}{14.5 \text{ in.}} = 1.15 \text{ watts per inch.}$$

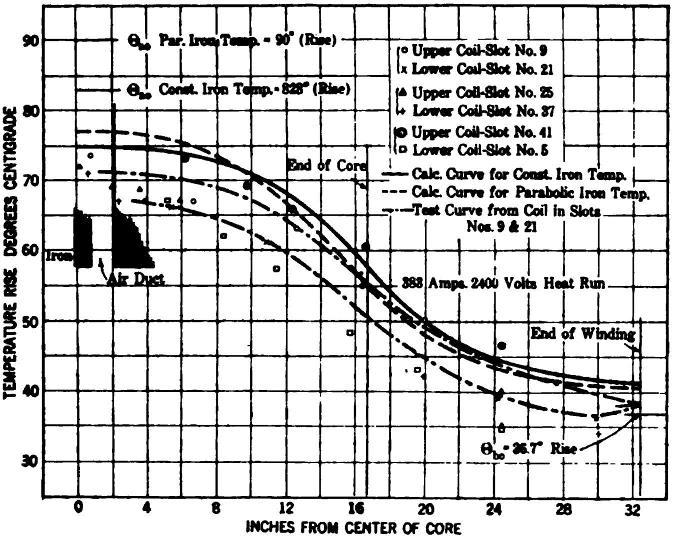

Fig. 10

The average for the ends is

$$\frac{16.4}{15.75} = 1.04 \text{ watts per inch.}$$

In accordance with the method of calculating eddy current loss, there is an abrupt change at the end of the core, and therefore the rate of generation of loss changes abruptly there also; that is, from 1.12 to 1.07 watts per inch. This abrupt change is more noticeable in machines with high-eddy current loss in the copper. The figures for watts per inch given above are the maxima and minima for the embedded and end portions.

The transverse rate of flow of heat in the embedded portion is,

$$\frac{d\,w_1}{d\,x} = K_a\ (\theta_a - \theta_i)$$

$$= 0.95 \text{ watts per inch for } X = 0$$

$$= 0.392 \text{ watts per inch for } X = L_a \text{ (end of core).}$$

$$\text{The average} = \frac{11.32 \text{ watts}}{14.5 \text{ in.}} = 0.78 \text{ watts per inch.}$$

For the ends,

$$\left(\frac{d\,w_1}{d\,y}\right) = \gamma\,K_b\,(\theta_b - \theta_0)$$

$$= 1.89 \text{ watts per in. for } y = L_b \text{ (end of core).}$$

$$= 1.19 \text{ watts per in. for } y = 0 \text{ (end of winding).}$$

$$\text{The average} = \frac{21.8}{15.75} = 1.384 \text{ watts per inch.}$$

Thus, the maximum rate of transverse flow (and therefore of heat dissipation) is, in this particular case, about twice as great from the ends as from the embedded portion, and there is a very great change when passing from the embedded to the end winding portion.

The longitudinal flow is maximum at the end of the core (5.4 watts) and is zero for $X = 0$, and for $Y = 0$. Its relative values at any points can be determined from the slope of the curve for temperature in Fig. 9, or may be obtained by substituting in equations (**39a**) and (**39b**).

COMMENTS ON TESTS AND CALCULATIONS

In addition to the tests made with 300-ampere load, and plotted in Fig. 9, tests were also made at no-load, open circuit at 2600 volts (Fig. 9), and with 383 amperes, 2400 volts, nearly zero power-factor, plotted in Fig. 10. The same constants, such as thermal conductivity, emissivity from the end windings, areas for transverse flow, etc., were used in the no-load and 383-ampere calculations as for the 300 ampere load calculations, with the exception that the eddy loss constant for the 383 ampere curves was taken slightly lower than for 300 amperes because the temperature was higher.

In Fig. 11 will be found some curves showing iron temperatures radially. They were measured 0.5 in. from one of the radial vent ducts. There is an unmistakable drop in temperature from the bore outward. The axial temperatures were measured 1¾ in. from the bore (Fig. 7), or a little more than half way down the tooth. The calculated curves in Figs. 9 and 10 were based upon the measured axial iron temperatures plotted in Fig. 7. The difference in tooth temperatures for the different depths undoubtedly explains much of the difference between the copper temperatures in the upper and lower coils. The constants used in the calculations were of such values as to give quite close agreement with the test curves for the upper coils. A comparison of Figs. 9 and 10 with Fig. 11 will show nearly the same difference in maximum temperature between the upper and lower coils as there was between the tooth temperatures for the corresponding regions.

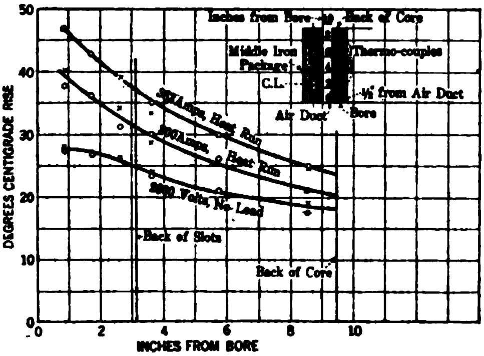

FIG. 11—CURVES SHOWING VARIATION OF TEMPERATURE RISES, RADIALLY IN THE IRON

One of the principal differences between test and calculation appears in the no-load curve (Fig 9).

Evidently, with no I^2R and eddy current loss in the copper, some heat from the iron flows transversely from the iron to the copper, and is transmitted longitudinally to the coil-ends where it again flows transversely to the coil surfaces, and is taken up there by the air. In order for heat to flow from the iron to the copper, the copper must be at the lower temperature; this appears in the calculated curves. (See Figs. 7 and 9). On the other hand the test data plotted in Fig. 9 for the no load heat run, show maximum temperature rise of 28.5 deg. for the copper, whereas the maximum iron temperature (by curve) from Fig. 7 was 27.5 deg. rise. Since the large number of couples embedded in the iron necessitated the placing of them in various teeth, in all probability the iron temperatures used for calculating the curves in the no-load curve in Fig. 9 were lower than some of the iron temperatures adjacent to the coils. This statement is further proved by the fact that in Fig. 7 some of the test points were not on the curves as drawn.

The 383-amperes calculated curves (Fig. 10) show slightly higher temperatures than most of the test points. The slight increase in thermal conductivity of the insulation with the higher temperatures then

TABLE III.

Heat Run	2600 Volts, N.L.	2400 V., 300 Amp.	2400 V., 383 Amp.
Calc. Max. Temp. Rise Par. Dis. of Iron Temp.	21.9	54.1	76.8
Calc. Max. Temp. Rise Const. Iron Temp.	21.1	52.0	74.8
Test Max. Temp. Rise (Slot No. 9)	28.5	53.3	73.5
Calc. Max. Temp. Rise Trans. Flow Only based on Max. Iron Temp.	27	63	90
Calc. Max. Temp. Rise Trans. Flow only Based on Av. Iron Temp.	23.5	57.3	82.8
Calc. Min. Temp. Rise Ends. (Const. Iron Temp.)	8.3	27.5	40.9
Test Min. Temp. Rise Ends. Approx. (Slot 21)	7.0	25.5	36.3
Calc. Min. Temp. Rise Ends. Trans. Flow only	7	24.6	36.7
Calc. Copper Temp. Rise End of Core (Const. Iron Temp.)	14.7	39.6	57.6
Test Temp. Rise End of Core (Slot No. 9.)	17.3	39.8	55

obtaining but which were not allowed for in the calculations, may explain some of these differences.

For convenience, in Table III the principal points of interest are recorded. Attention is called to the close agreement between calculations and test for maximum temperature, minimum temperature and temperature at the end of the core; the exception being the maximum temperature at no-load. It will further be noted that there is but slight difference between the calculated minimum temperature, considering transverse flow only, and the minimum temperature by test. On the other hand there may be quite a large difference between the calculated maximum temperature, considering transverse flow only, and the maximum test temperature; especially is this the case at the 383-ampere load test when the temperature is figured on the basis of the maximum iron temperature (90 deg.) instead of 73.5 deg. rise). And this applies even though the machine is of medium length, and the copper, at this load was worked at the fairly high nominal density of 2780 amperes per sq. in., with nearly negligible eddy current loss. (See the second paragraph under subject "Eddy Currents"). Thus, it may be misleading even in medium length machines, to ignore the longitudinal flow.

Further comparisons will be found under "The Average Coil Temperatures."

THE AVERAGE COIL TEMPERATURE

The temperature of the winding measured by resistance after shut-down is the average temperature at the particular time of measurement. Owing to the fact that there is necessarily a lapse of time between the removal of the load and the measurement of resistance, and since there is usually a difference in temperature between the copper and surrounding iron or air (the copper being usually at higher temperature), there is necessarily heat flow after shut-down and before the resistance is measured. Consequently, the average temeperature at the end of the heat run is usually higher than measured. At no-load the average temperature of the winding at the end of the run may be lower than the measured temperature, owing to the winding being at lower temperature than the iron.

Equation (**33**) enables the calculation of the average temperature (based upon constant iron temperature); with the use of equation (**33a**) the average temperature of the embedded part may be calculated. The results for the three heat runs are given in Table IV.

TABLE IV.

Heat Run	2600 Volt, N. L.	2400 V., 300 Amp.	2400 V., 383 Amp.
Calc. Av. Temp. Rise Embedded Part.	19.3	48.9	70.4
Calc. Av. Temp. Rise Entire Winding.	14.9	40.1	58.3
Av. Temp. Rise Test. (Res. Meas.)	15.5	35.3	44
Max. Temp. Rise Test. (Slot No. 9.)	28.5	53.3	73.5

An especial effort was made in these tests to allow as little time as possible to elapse between shut-down and measurement of resistance. (A Kelvin bridge was used). It will be noted, from an inspection of Table IV that the calculated average temperatures for both load runs were higher than test, whereas at no-load the reverse is the case, although the difference is slight.

Referring to Fig. 9, the average of the 300-ampere test curves for slots 9 and 21 (average of upper and lower curves) is 39 deg. rise, which is only 1.1 deg. lower than the calculated rise (40.1 deg.) The temperature rise by resistance was 35.3 degrees or 3.7 degrees lower than the test average rise. This difference is undoubtedly largely due to error in measurement due to loss of time.

The average rise from test curves on Fig. 10, (383-amperes load), as found by averaging the test curves for the coil in slots 9 and 21, is 54.1 degrees. The calculated average from the calculated curve is 58.3 deg., a difference of 4.2 deg. The temperature rise measured by resistance was 44 deg., or 10.1 deg. lower than actual. Thus there was an error, probably due to loss of time, of 23 per cent. It will therefore appear that the average temperatures as determined by resistance are not reliable.

The figures in Table IV show that the average temperature rise determined by resistance is certainly no means of judging the average temperature of the embedded part of the winding. Thus, in the 300-ampere run, if 1.1 deg. are deducted from the calculated rise (48.9 – 1.1) to allow for the difference between the calculations and test, then the difference between the average embedded copper temperature rise and the measured average temperature rise of the entire winding is (47.8 – 35.3 =)12.5 deg. At the higher load the difference is approximately [(70.4 – 4.2) – 44 =] 22.2 deg. or about 50 per cent of the measured temperature rise. Certainly the resistance measurement affords no means of judging the maximum temperature, and an inspection of Table IV is sufficient proof of that statement without further comment.

THE INFLUENCE OF THE CORE LENGTH

It is felt that a paper on longitudinal and transverse heat flow would not be complete without illustrating the influence of core length upon temperatures, thereby helping to clarify the physical picture. It is believed that further assistance is obtained by showing the influence of the core length upon the watts generated, the watts transmitted transversely, and the watts transmitted longitudinally. It must be borne in mind that one set of curves of this character are not of general application, but to obviate this, sets of curves for various proportions of slots, copper section, insulation thickness, current density, etc., could be worked out, if believed to be sufficiently useful.

The particular proportions adopted were those of the turbo generator, for which the tests and calculations are given in this paper. The particular load selected was the one for 300 amperes 2400 volts. The conditions for constant average iron temperature of same value as in other calculations were assumed. Inasmuch as, in laying out a line of machines, it is usual to have some relation between pole pitch and core length, and since the length of the coil end is proportional to the pole pitch, the ratio of length of coil end to embedded portion was taken to be constant. Such assumption is not generally justifiable; as for instance, with changing length, (and proportionate diameter) the cooling of the end windings must also change (their cooling rate was taken to be constant); with increasing diameters the peripheral speed in such machine would eventually become prohibitive; and in commercial practise the length of core is frequently changed without changing the diameter.

In Fig. 12 will be found "Curves Illustrating the Influence of Core Length upon Temperature Rise." The particular machine described in this paper has a nominal core length of (2 × 14½ =) 29 in. as plotted in these curves. For these proportions, there is practically no change in temperature if the core length is increased beyond 50 in.

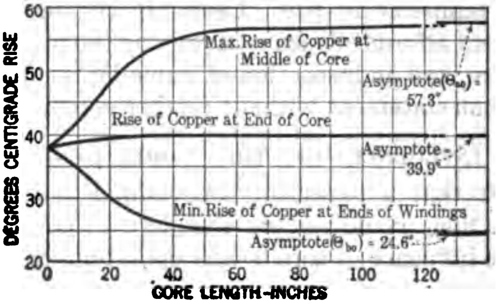

FIG. 12—CURVES ILLUSTRATING INFLUENCE OF CORE LENGTH UPON TEMPERATURE RISE

Based on constant ratio of length of ends to embedded parts.

In Fig. 13 are plotted curves illustrating the losses in one half of the embedded portion of one coil, and the heat paths for same. Thus, for very short core lengths, most of the heat flows longitudinally, to be dissipated from the ends; for about 7-in. length of core about twice as much heat flows longitudinally as flows transversely; for 16-in. length the same quantities flow along the two paths; and beyond that, the longitudinal heat flow increases but little, whereas the transverse flow increases indefinitely. The total watts must always be the sum of the transverse and longitudinal flows, at any given length of core, and would be directly proportional to the core length, but for the influence of temperature increasing the rate of loss generation.

In Fig. 14 the average rates of heat generation and the heat flows per inch of core length are plotted as functions of the core length. These curves of longitudinal and transverse flows illustrate the "usefulness" of the two for dissipating the generated heat; thus, as is well-known, the influence of the longitudinal flow is of maximum benefit for zero core length, and rapidly diminishes until for infinite length it becomes zero. The transverse flow is of minimum benefit for zero core length and approaches the same asymptote as the total generated watts approach; that is for infinite length all of the watts flow transversely.

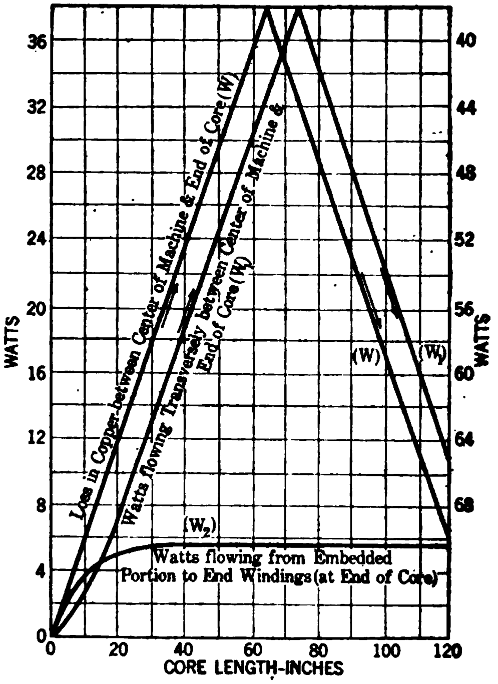

FIG. 13—CURVES ILLUSTRATING THE LOSSES IN ONE-HALF OF THE EMBEDDED PORTION OF ONE COIL, AND THE HEAT PATHS FOR SAME

Based on constant ratio of length of ends to embedded part.

APPENDIX

AREA FOR TRANSVERSE FLOW

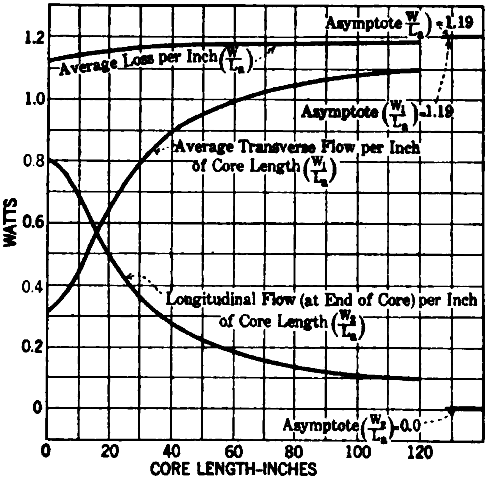

FIG. 14—CURVES ILLUSTRATING THE LOSSES IN ONE ARMATURE COIL AND THE HEAT PATHS PER INCH OF CORE LENGTH
Based on constant ratio of length of ends to embedded part.

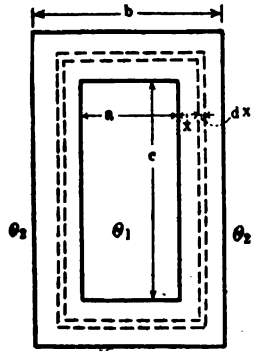

FIG. 15

Let Fig. 15 represent the section of a coil, the single insulating wall being $\frac{b-a}{2}$. If W is the wattage flowing transversely, k the thermal conductivity $d\,\theta$ the temperature drop through small thickness $d\,x$, and the area of flow is $2\left[(a + 2\,x) + (c + 2\,x)\right]$, then:

$$W = -k\,2\,(a + c + 4\,x)\frac{d\,\theta}{d\,x}$$

The negative sign appears because θ decreases with increasing x. Then:

$$\int_{\theta=\theta_1}^{\theta=\theta_2} d\,\theta = -\frac{W}{2\,k}\int_{x=0}^{x=\frac{b-a}{2}} \frac{d\,x}{a + c + 4\,x}$$

$$(\theta_1 - \theta_2) = \frac{W}{8\,k}\log_e (a + c + 4x)\Big]_0^{\frac{1}{2}(b-a)}$$

$$= 0.288\,\frac{W}{k}\log_{10}\left(\frac{2\,b + c - a}{a + c}\right)$$

Now, figuring on *average* area basis,

$$W = k\left[2\left(a + \frac{b-a}{2}\right) + 2\left(c + \frac{b-a}{2}\right)\right]\frac{\theta_1 - \theta_2}{\frac{(b-a)}{2}}$$

Or,

$$(\theta_1 - \theta_2) = \frac{W}{4\,k}\,\frac{(b-a)}{(b+c)}$$

Suppose the coil be intended for high voltage, and $a = 0.5$ in., $b = 1$ in., $c = 2$ in. By the more exact logarithmic expression, $(\theta_1 - \theta_2) = 0.0419\,\frac{W}{k}$.

By the second, average area formula, $(\theta_1 - \theta_2) = 0.0416\,\frac{W}{k}$. The difference is less than one per cent, thus justifying the use of the approximate equation. With thinner insulation, the error is less than with thick insulation.

DISCUSSION ON "LONGITUDINAL AND TRANSVERSE HEAT FLOW IN SLOT-WOUND ARMATURE COILS" (FECHHEIMER), NEW YORK, N. Y., FEBRUARY 18, 1921.

M. A. Savage: The author deals exclusively with the axially ventilated machines. The data and formulas, therefore, are less valuable to the large number of designers of radially ventilated machines.

In the axial type of ventilation where the core is cooled by means of axial ducts running back of the teeth it is readily seen that the temperature of the air, and hence the core, will vary with the distance from the ends of the core. With this type of ventilation we might expect to see a gradual rise in core temperature as we progress toward the center of the core. This is without the influence of the longitudinal transfer of heat which the author discusses.

In the radial type of ventilation this condition does not hold due to the fact that the factors which exert the greatest influence in the temperature of the iron can be made to vary with the distance from the end of the core, the greatest radiating surface being the sides of the teeth, and stator coil in air ducts. In nearly all machines of this type it has been found that the velocity of air through the ducts near the center is much greater than through the ducts near the ends, and since the temperature drop from the surface is proportional to this velocity of air, it will readily be seen that a condition of design may be reached where the core is actually cooler at the center than near the ends. In other words, by increasing the number of air ducts to compensate for the rise in air temperatures, the temperature of the core can be kept practically constant throughout its length.

In a 60-cycle machine having a core length of approximately 40 in. the theoretical temperature rise was found to be about 60 deg. By changing the air duct spacing so as to pass a greater amount of air through the center of the machine this temperature rise was reduced to approximately 50 deg. cent.

The author is to be complimented on the rather pretty mathematical solution of a difficult problem. The number of variables encountered in a problem of this sort are so great as to deter the average designer from putting them in mathematical form. There is the matter of core length to the overall length of the coils; the type and manner of blocking the ends; the percentage of coils actually exposed to the air at the ends; the loss in the heads of the machines due to cross fluxes, etc.; and finally to the velocity and temperature of the air over the exposed surfaces. All of these directly affect the longitudinal transfer of heat, and make it quite difficult to predict from one type of machine to another just what value should be given to the transfer of heat to the ends. In the core proper there is the variable of iron temperature both in the axial and radial type of ventilation and as has been pointed out in the case of the latter this variable is for certain limits in the hands of the designer. It would, therefore, seem that while there are certain mathematical laws which may be laid down, still there remains a vast amount of experimental data which must be collected on each type of machine before the constants used in this formula will make them useful to the average designer. The problem, therefore, remains as it always has been largely a matter of experience or familiarity with the type of machine involved.

It is gratifying, however, that a step has been made toward the analysis of copper temperatures. The incentive to collect data for the purpose of supplying mathematical solutions will undoubtedly lead to the collection of a large amount of it which will enable the designer to predict more closely the temperatures which exist in the various types of machines.

R. B. Williamson: Calculations regarding heating are, on the whole, about as unsatisfactory as any that the designer has to deal with; and any paper, such as the present one, that puts such calculations on a more rational basis than they have been, is of very great value.

The great increase in the size of a-c. generators that has taken place within the past five or six years has necessitated the construction of machines for both steam turbine and hydraulic turbine drive, having stator cores very much wider than was formerly considered feasible or desirable. With the safe limits of peripheral speed in many cases already reached with the materials at present available, the only way of increasing the output is to increase the axial length of the machine. This in turn has forced a careful consideration of the methods of ventilation and also of the probable hot spot temperatures and temperature distribution in the various parts of the winding.

In the present paper the author has developed a method of estimating the temperature rise of copper inside the coil above the surrounding iron or air as the case may be, for any point between the center of the machine and the end of the coil projections. While formulas have previously been developed for estimating the hot spot temperature at the center of a machine, none, so far as we know, have been published by means of which the temperautre at various points along the coil could be estimated. As pointed out by the author it is difficult with our present knowledge to evaluate some of the constants entering into the formulas and before full use can be made of the latter, it will be necessary to accumulate data of a suitable kind obtained from tests on a large number of machines. For example, assuming that the difference in temperature between copper and iron or between copper and outside surface of coil can be calculated for any point, there still remains the problem of estimating the temperature of the surrounding iron or air with which the portion of the coil in question is in contact, in order to determine the actual operating temperature which the designer is primarily interested in. Tests on a large number of machines of various types and sizes will have to be made, using temperature detectors at numerous points in order to accumulate data of the kind shown by Mr. Fechheimer in the case cited in the latter part of the paper. The fact that such data must be accumulated before full advantage can be taken of the formulas does not in any way detract from their value. It simply means that the enormous amount of test data on heating obtained in the past by the usual thermometer readings is not complete enough for general use in determining ultimate temperatures in the manner developed in the present paper. However, the amount of such data, as determined by temperature detectors is rapidly increasing and the methods and formulas proposed will become increasingly useful in the future. Aside from numerical calculations, the formulas in themselves are of special value in that they show clearly the various quantities that determine the temperature difference at any given point of the winding, and even if they may not be immediately available for estimating ultimate temperatures on account of lack of information regarding iron or air temperatures, they indicate to the designer the relative importance of the various factors entering into the problem and the way in which the final result is affected.

The calculation of temperatures in generators is always a difficult one for the designer, largely because of the great effect of variations in ventilation. Even with the same system of ventilation used on machines of various speeds and ratings, the results may be quite different from those expected. The subdivision of the stator core and the relative arrangement of air ducts and sections of core iron have a decided influence on the core temperature and its value at different points throughout the length of the stator. All of these things introduce complications into the problem and have an effect on the internal coil temperatures. The author of the present paper recognizes these difficulties but we believe the methods given cannot help but be of great value to those who have to deal with these problems.

B. A. Behrend: I should like to illustrate the conditions existing in the interior of an armature coil covered heavily with insulation in the following manner: Imagine a man in a diver's suit of very heavy material the thermal conductivity of which is low. The blood temperature of this man may be, say, 98 deg. fahr., and this blood temperature may be tolerably uniformly distributed over the entire individual.

The temperature on the *surface* of this man, however, may be quite different if the thermometer is placed in contact with his feet, or with his head, or with any other portion of his body.

Outside the diving suit the case is very different. If a stream of cold air is directed against the feet, the temperature measured on the outside where the jet of air strikes the feet may be very low. This temperature would be no indication of the temperature on the inside of the diving suit on the surface of the man who is inside it. This simile will make a little clearer the curious conditions which exist inside the armature coils of an electric generator.

Mr. Fechheimer's paper is valuable for two reasons: First, it is agreeable to note that this subject is discussed at last with perfect frankness and intellectual integrity. There is no longer any playing at hide-and-seek on the subject of concealed internal temperatures. Secondly, it is valuable because Mr. Fechheimer applies Fourier's theory of conductivity of heat to an intricate and interesting engineering problem. The fact is brought out in this paper that the distribution of temperature on the inside of the coil, measured by thermocouple in contact with the copper, is not at all uniform. It is shown that this temperature, which is lowest at the outside ends of the end connection, increases as one approaches the center of the machine. Then, Mr. Fechheimer analyzes the reasons for such distribution of temperature and he traces the temperature grades by making certain assumptions for the temperature distribution of the iron core surrounding the armature coils. He makes three assumptions for the distribution of temperature in the core: *A*. A uniform distribution of temperature; *B*. A distribution of temperature according to a straight line; *C*. A distribution of temperature according to a parabolic curve. Very simple results are obtained with the assumption A, and the results of calculations based on this assumption seem to tally well with the data. In cores of greater length, we are assured the degree of error is apt to be greater and, therefore, it has become necessary to consider also cases B and C. This has made the investigation appear a little more complex, but it may be well to keep in mind that the fundamental reasoning process by means of which Mr. Fechheimer has arrived at his interesting results is the same in all three cases.

Carl Hering: Some years ago I made some analytical and experimental researches concerning the flow of heat, which involved somewhat similar conditions, though they have no bearing on armatures. They referred to the proper proportioning of the electrodes of electric furnaces so as to make the total heat losses through and in them, a minimum. As in the two halves of an armature the heat flow is from the inner ends to the outer ends, and I^2R heat is also being generated in them. The results have been published[1] and I will repeat here merely that the total energy loss in them was least when they were so porportioned that the I^2R heat set free in them by the current, was equal to twice the heat flow through them if there were no current in them. This means that the current heats the electrode to such an extent that its inner end is raised to the temperature of the furnace, in which case no heat from the interior of the furnace will flow out through the electrodes, hence even less than flows out through an equal surface of the walls. The total loss of energy then is the I^2R loss.

The present paper deals with a flow of heat which is generated electrically. Heat being generally measured in calories, a flow of heat is measured in calories per second which is the same kind of a physical quantity as watts, namely power or rate of energy. In this class of calculations, dealing with electric heat, I showed some years ago[2] that it is often very convenient to use thermal resistances, and that by far the most convenient unit to use is that thermal resistance through which one watt will flow (as heat) when the difference of temperature at the two ends is one degree centigrade. The name proposed for this unit was the thermal ohm; calculations concerning heat flow are then like those with Ohm's law, there being no conversion factor necessary. When such simple units exist it is often a

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[1] The Proportioning of Electrodes for Furnaces, TRANS. A. I. E. E., Vol. XXIX, 1910, Part I, p. 485.

[2] *Met. and Chem. Eng.*, January 1911, Vol. 9, p. 13.

great convenience to use them, even if one has to first define them, which in this case takes but a few words.

The paper refers to the flow of heat between different metals, like copper and iron. I do not think it is generally known that the flow is far less from iron to copper than from copper to iron. There appears to be something analogous to a counter e.m.f. at the junction which opposes the flow when it is from iron to copper, and "boosts" it when from copper to iron. It seems to depend on the specific heats of the two metals and has apparently no direct connection with the Peltier effect as no electric current is flowing, but when it is, the thermoelectric e. m. f. is greatly affected when heat flows across such a junction, hence in using a thermocouple it is important not to have any heat flow across the junction.

G. E. Luke: The predetermination of temperatures in electric machines has been and probably always will be a difficult problem to the designer due to the vast number of factors involved. A rigid mathematical solution of the problem as a whole is more or less hopeless, however, certain parts of the problem can be analyzed and a practical solution obtained.

This paper by Mr. C. J. Fechheimer is the result of analyzing the heat flow from the copper based upon the fundamental physical constants. Naturally the accuracy of the solution depends upon the correct values of these constants. Nevertheless even if the constants can only be approximated an analysis of this part of the heat flow is well worth while, since it gives the designer a better idea of how the heat is carried away and how the hot spot can be reduced.

It is a well known fact that the ventilation of the armature end windings in electric motors and generators of short core lengths plays an important part in the cooling of the machine. For instance, the writer has seen examples of induction motors in which the stator iron temperatures were substantially reduced by improving the ventilation of the end windings.

Again tests on a small shunt d-c. motor with the open-type form wound armature coils gave a rating almost twice that which could be obtained with the hand wound "mush" winding for the same temperature rise.

For the purpose of showing the magnitude of this heat flow along the winding, calculations are given, see Fig. 1, on a typical induction motor rated 500 h. p., at 2200 volts, 8 poles, 60 cycles.

This sketch gives the results of the calculations. As shown the calculated average copper temperature was 48 deg. cent., while the test value by resistance was

51 deg. cent. There was a total of 13.2 deg. cent. difference in temperature between the embedded copper in the center of the core and the copper at the extremity of the end winding. This gradient was sufficient to transfer 1695 watts or 64 per cent of the total embedded copper loss from the copper in the core to the end windings. The dotted lines give the copper temperatures on the basis of no longitudinal heat flow.

The above is a good example of what takes place in machines with well ventilated end windings and short core lengths. On the other hand the conditions are exactly the reverse in a large number of railway motors where the conditions of operation make it necessary to carefully enclose the end winding in order to protect them from the possibility of water getting into the insulation.

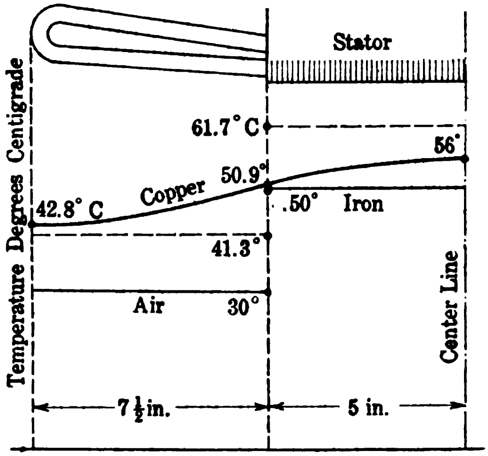


Fig. 1

The calculations, Fig. 2 were made on a d-c. railway motor with a one hour rating of 50 h. p. at 600 volts. The calculations were based upon the continuous rating with the iron temperatures taken from test.

The calculated average armature copper temperature was 106 deg. cent., the actual test value by resistance was 100 deg. cent. The copper in the center of the core had a temperature of 103.9 deg. cent., while the copper at the extremity of the end winding had a temperature of 110.7. It should be noted that in this case the heat flow was from the end windings to the core. The method of calculation developed by

C. J. Fechheimer is perfectly general in this respect and gives the proper direction of heat flow depending only upon the conditions. Thus, in this case the longitudinal heat flow came out negative, that is the heat flow was from the end windings to the core.

In the above example 109 watts or 21.6 per cent of the total copper loss in the end winding was conducted from the end winding to the embedded copper and then conducted to the core. The dotted lines give the copper temperature based upon no longitudinal heat flow under this condition the maximum temperature (in the end windings) would have been 135.4 deg. cent. instead of 110.7 deg. cent.

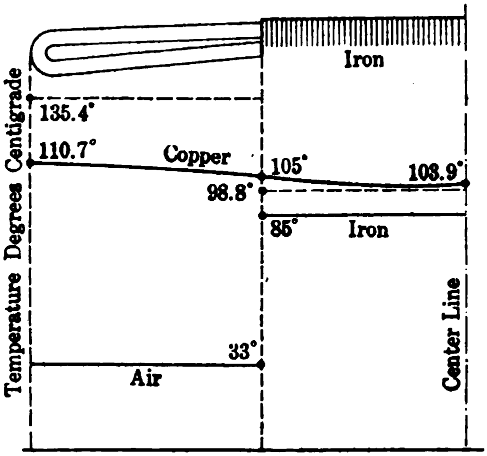


FIG. 2

C. J. Fechheimer: Mr. Savage has evidently misunderstood much of the treatment of the subject as given in the paper. In no place do I state or imply that the equations are applicable only to axially ventilated machines; the formulas are applicable to any type. Mr. Savage states that "by increasing the number of air ducts—the temperature of the core can be kept practically constant throughout its length." The first case treated in the paper is that of constant core temperature. The particular machine on which tests were made as a check on the equations was an axially ventilated turbo-alternator, and it is probable that Mr. Savage's statement followed from an inspection of some of the illustrations.

Mr. Williamson has called our attention to the importance of obtaining more data. In that I heartily concur. But I do not entirely agree that only accumulating data on complete machines will help us materiaally. Of course, we need some of those data, but I think that data obtained on models imitating particular parts of the machine, if suitably combined, could be checked against the temperatures in the final machine; then we would have a fairly complete solution. (For example, we are now conducting researches on the rates of dissipation of heat from dummies imitating coil ends.) In other words, I would analyze each factor or element and then combine and check against test results. That method is in contradistinction to the usual and generally unsuccessful way of taking final test results on a machine, and then analyzing them. The problem is too complicated for the latter procedure.

Mr. Behrend's comparison of temperatures as frequently measured in machines with the various measureable temperatures of the man in the diving suit is quite interesting. Most of us have realized for many years that only tests by detectors on the bare copper tell us what are the maximum temperatures in machines. Most of the discrepancies and their causes are brought out in a recent paper.[3]

Dr. Hering has indicated the desirability of using the "Thermal Ohm." I recall that Dr. Hering has previously advocated the use of that unit. I have always been reluctant to adopt terms that had not been universally accepted, and I feel that the individual writer has no authority to do so. I believe that the paper is made more difficult, rather than simpler, for the reader, if he is called upon to learn terms with which he is entirely unfamiliar.

In Figs. 12, 13 and 14 in the paper are illustrated the influences of the length of the machine upon the temperatures, total heat, and rates of generation and flow, the assumption then being that the ratio of length of ends to embedded parts is constant. An equally interesting set of curves may be drawn, assuming the length of ends to be constant; most manufacturers build a number of lengths for a given diameter, in which case the length of the ends do not change, if the throw of the coils remains fixed. In the following, the same proportions (conductor, insulation thickness, surfaces, etc.) were used as for calculating Figs. 12 to 14.

Some practical Experience with Embedded Temperature Detectors," of Newbury and Fechheimer, TRANS. A. I. E. E. 1920 Vol. XXXIX, Part 1, p. 971. Reprinted in the *Electrical Journal*, September 1920.

In Fig. 3 the temperatures of the copper at the middle of the core, the end of the core, and the end of the winding are shown. For zero core length, all three temperatures are necessarily the same and equal to that corresponding to infinite length of ends, since there is heat generated in no other part. The maximum temperature in the embedded part for infinite length (condition for transverse flow only) is essentially the same for either case (57.3 degrees). The temperature at the extremity of the windings is necessarily influenced by the loss in the embedded part—as the ends are of constant-finite-length, and as some heat flows to the ends from the embedded part. Hence, the temperatures of the end windings rise as the core length increases, and at the extremity approaches the value of 27.5 degrees. The temperature of the copper at the end of the core is between the maximum and the minimum, and the shape of its curve is consequently similar to the other two; theoretically, for very great length, that temperature approaches a value slightly higher than for the case of constant ratio, since the average temperature of the ends is slightly higher.

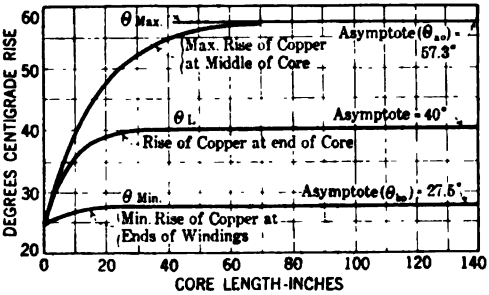


FIG. 3—CURVES ILLUSTRATING INFLUENCE OF CORE LENGTH UPON TEMPERATURE RISE

Based on constant length of end windings.

Fig. 4 is comparable with Fig. 13 in the paper. A hasty inspection would show the two sets of curves to be nearly identical; there are differences, however, the principal one being that the total watts which flow transversely (W_1) for very short core lengths, are actually negative on Fig. B, and are always positive in Fig. 13. This means that, with the particular proportions and constants, the rate of dissipation of heat from the ends is sufficiently great to produce lower coil end temperatures than iron temperatures. Consequently, for short core lengths, some heat flows transversely from the iron to the embedded copper, longitudinally along the copper to the ends, where it flows transversely through the walls of insulation to the outside coil surface, and then is taken up by the moving air. As the core length increases, however, the embedded copper temperature rises, and at about 4 inches, the average embedded copper and iron temperatures are equal—then an amount of heat, equal to the total generated in the embedded part, flows longitudinally to the ends; near the center of the core there is transverse flow from the copper to the iron, and near the end of the core there is transverse flow in the reverse direction, but the *average* transverse

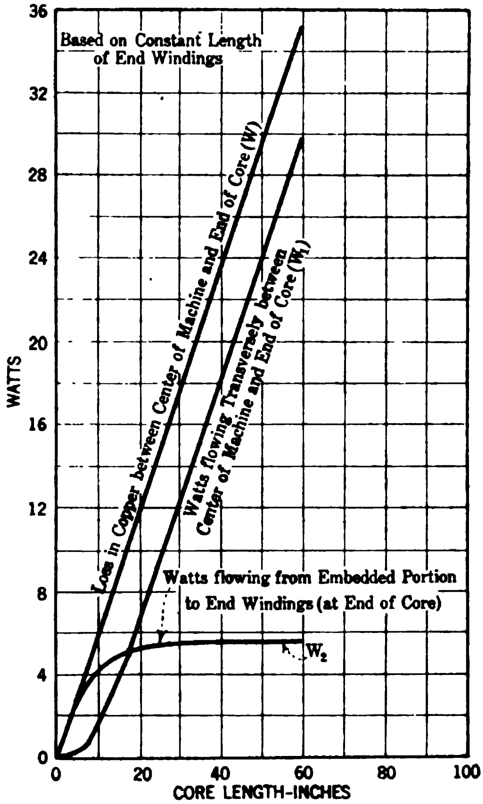


FIG. 4—CURVES ILLUSTRATING THE LOSSES IN ONE-HALF OF THE EMBEDDED PORTION OF ONE COIL, AND THE HEAT PATHS FOR SAME.

Based on constant length of end windings.

flow is zero. For longer lengths the embedded copper temperature continues to rise, and as its average value then exceeds that of the iron, the transverse flow is positive; that is, from the copper to the iron.

In Fig. 5, are plotted the average losses and flows, similar to Fig. 14 in the paper. The negative transverse flow for very short lengths is now more marked than in Fig. B. The very rapid rate of change of "usefulness" of the two flows for carrying away the generated heat with change in length for the shorter cores is particularly to be noted. The values for flow per inch on Fig 4 for short lengths, where the ends play a large part in the cooling, are quite different than in Fig. 14, but the sum of the transverse and longitudinal flows are equal to the generated loss for any length. On the two sets of curves the flows per inch become nearly equal for the greater core lengths, and approach the same asymptotes.

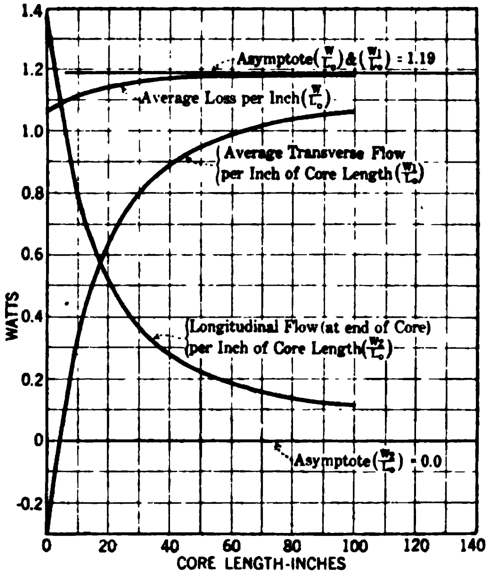


FIG. 5—CURVES ILLUSTRATING THE LOSSES IN ONE ARMATURE COIL AND THE HEAT PATHS PER INCH OF CORE LENGTH.

Based on constant length of end windings.

An attempt will be made to present a physical picture of the combined transverse and longitudinal flows, and given an interpretation of the differential equation for constant iron temperature. (The curves and picture refer to the turbo-alternator for which the tests are given in the paper, the particular load being 300 amperes, 2400 volts.)

In Fig. 6 are shown the summation of watts generated or flowing transversely and the longitudinal flow for the length of the embedded and end portions, taking the end of the air duct as the starting point. At any value of X the total watts generated equals the sum of the watts flowing longitudinally and transversely; thus at the end of the core, $16.72 = 5.4 + 11.32$, the same as worked out in the paper. The longitudinal flow is a maximum at the end of the core, and is zero at the starting point and at the end of the winding. Consequently, all of the generated heat must escape transversely when the end of the winding is reached, but for intermediate points, some heat flows longitudinally and some transversely. In other words, the longitudinal flow simply acts as a means for producing more uniform temperatures than would obtain were the flow only transverse, but it affords no means for heat escapement from the coil.

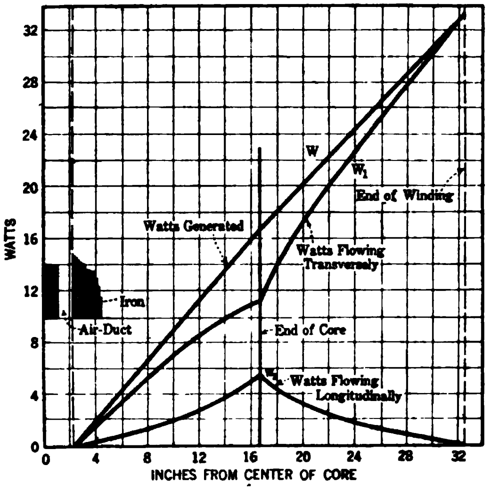


FIG. 6—CURVES ILLUSTRATING THE TOTAL WATTS GENERATED AND FLOWING AT ANY POINT

In Fig. 7 the physical picture is perhaps clarified. Here the shading shows the density of heat flow. Thus, the transverse flow is at one maximum near the center of the core, where the copper is at maximum temperature, and decreases toward the end of the core as the difference between copper and iron temperature decreases. For a slightly greater value of X the effect of the cooling air on the ends causes their surfaces to be at considerably lower temperature than the iron, so that the rate of transverse heat flow changes abruptly and reaches its maximum value at the beginning of the ends. Then it diminishes again as the copper temperature decreases, thereby decreasing the difference in temperature between the copper and the cooling air streams. The longitudinal flow is zero at the center of the core, because there is then zero change in temperature of the copper longitudinally; it increases up to its maximum value at the end of the core, and then decreases again, becoming zero at the end of the winding; see Fig. 6.

The armature coil may be compared with a channel into which water is fed at nearly uniform rate, say by springs, distributed throughout its length; the water fed into the channel is the generated heat; the springs,

FIG. 7—HEAT FLOW IN ONE-FOURTH OF AN ARMATURE COIL.

as sources of water, correspond to the $I^2 R$ and eddy current losses. There is no top to the channel, so that the water spills over the sides, thus imitating the transverse flow. Both ends are closed, to that no water can flow out at the ends, (near the middle of the machine and the end of the windings.) At some point between the two ends, there is an abrupt change in the height of the side walls, so that the rate at which the water spills over the side walls suddenly increases. (This abrupt change in side wall height corresponds to the change at the end of the core). Owing to the greater depression of the right end side walls (the end windings) the crest of the water is not so high there as in the end to the left. Consequently, some water flows from the left to the right end, and there it spills over the walls, together with that fed from springs at the right end. This flow from the left to the right end corresponds to the longitudinal flow. The height which the water reaches anywhere along the channel is comparable with the temperature (thermal potential) of the copper. If there were linear relations between the rate of flow and pressure in hydraulics as in heat, the curve of the height of water in the channel would probably be comparable with the temperature curve, as in the upper part of Fig. 4 in the paper.

Considering the embedded part, the heat generated by $I^2 R$ and eddy currents (corresponding to the springs) either flows transversely or longitudinally. At any value of X, the heat generated per unit length must equal the heat per unit length transmitted transversely plus the heat "picked up" per unit length for longitudinal transmission. In the hydraulic analogy, there are, say, A gallons per second per inch of length fed in at X, of which B gallons per second per inch are spilled over the sides, and the remainder, C gallons per inch, are turned into the longitudinal flow.

Referring to equation (9) in the paper, substituting the proper values for A_a and B_a, and rearranging, the equation may be written as:

$$- k_c N q \frac{d^2 \theta}{d x^2} + (K_a - \epsilon_a I^2 r \alpha) \theta_a = (K_a \theta_i + \epsilon_a I^2 r)$$

Comparing the terms in this equation with equations (2), (3) and (4) in the paper, it may be rewritten:

$$\frac{d w}{d x} = \frac{d w_1}{d x} + \frac{d w_2}{d x}$$

Or, the rate of generation of heat equals the rate of transverse flow plus the rate of "picking up" of heat for longitudinal transmission. Thus, we have a physical picture of the differential equation for the embedded part. A similar course of reasoning may be applied to the ends; but then the longitudinal flow is "converted to" transverse, so that the sum of the rate of such converted heat flow and the rate of the generated heat equals the rate of transverse flow. (A little caution must be observed in the signs of terms in the differential equation for the ends.)

These relations are clearly shown in Fig. 8, wherein the ordinates are the slopes of the curves in Fig. D. Furthermore, the picture in Fig. 7 may be compared with Figs. 6 and 8, and the changes in the manner of flow for various values of X will be then better understood. The rates of generation of heat would be constant but for the influence of temperature in changing the resistance, and for the abrupt change in eddy current loss at the end of the core. The shapes of the curves for transverse flow have been previously explained; again there is an abrupt change at the end of the core. The rate of picking up of heat for longitudinal flow is not zero for $X = 0$, nor for $y = 0$, as are the actual longitudinal heats (see Fig. 6). The "picking up" becomes negative for the end windings, that is, it is then conversion from longitudinal to transverse flow.

In all three curves on Fig. 8 there are discontinuities between the embedded parts and the ends; that is, the functions are discontinuous. The quantities which may be equated at the end of the core are the temperature of the copper, and the longitudinal flow. In the differential equations for the embedded and end portions, there are a total of four constants of integration, two in each equation. These four constants may be considered as being determined by the following four conditions:

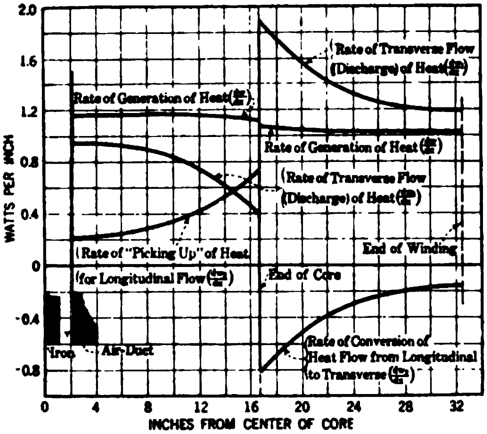


FIG. 8—CURVES ILLUSTRATING THE RATE OF GENERATION OF HEAT AND THE RATES OF DISCHARGE AND "PICKING UP" OF HEAT

1. The copper temperature is maximum for $X = 0$.
2. The copper temperature is minimum for $y = 0$.
3. The temperature of the embedded copper equals that of the ends for $X = 1/2$ length of core or $y = 1/2$ length of one end coil (at the end of the core).
4. The longitudinal flow from the embedded part to the ends equals that received by the ends for $X = 1/2$ length of core or $y = 1/2$ length of one end coil (at the end of the core).

In the paper the statement as regards the constants of integration are slightly different, but the same terminal conditions were used.

Presented at the 368th Meeting of the American Institute of Electrical Engineers, New York, March 11, 1921.

DEVELOPMENTS IN CONVERSION APPARATUS FOR EDISON SYSTEMS

BY T. F. BARTON AND T. T. HAMBLETON
Both of the General Electric Co.

ELECTRICAL energy for Edison systems is most efficiently produced and distributed to substations in the form of alternating current. At the substation it is converted into direct current and distributed to a three-wire network at a suitable voltage.

Conversion apparatus for Edison systems has taken the form of motor-generator set, synchronous converter and dynarotor. The voltage-range requirement of this service caused the development of several schemes for effecting voltage range with a synchronous converter. The tap changing switch with the transformer, the induction regulator, the regulating pole construction, the synchronous booster and field control are the forms which have been or are in commercial use.

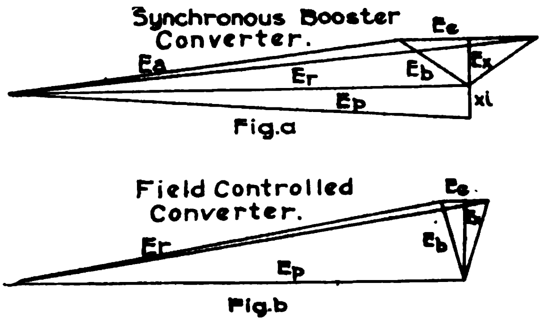


FIG. 1—VECTOR DIAGRAMS, SYNCHRONOUS BOOSTER AND FIELD-CONTROLLED CONVERTER

Edison systems operating at 25 cycles have used synchronous converters almost entirely. At 60 cycles the motor-generator set, both synchronous and induction has been used extensively on account of the questionable performance of the early 60-cycle converter.

Conversion apparatus for Edison systems must provide sufficient voltage range to maintain constant voltage at the load centers. The range depends on the amount of copper in the feeders and network, location of substations and load density.

In order to present the facts which should be considered in selecting the more suitable type of conversion apparatus for a particular service, the characteristics of the synchronous converter and the modern motor-generator set will be discussed.

SYNCHRONOUS BOOSTER CONVERTER

The synchronous booster has superseded the induction regulator because of lower first cost, greater reliability, and simpler substation layout. Its characteristics will be considered in detail for comparison with other types.

Fig. 1*a* represents vectorially the relation of the voltages in the converter, booster and transformer at full load. For simplicity, the resistance drops have been omitted. Unity power factor is assumed at the collector rings. The following table specifies and gives the values of the voltages.

E_R	—Collector ring voltage	100
E_x	—Booster reactance voltage from load current	10
E_e	—Booster energy or field voltage	15
E_b	—Booster armature voltage	18
E_a	—Converter armature voltage	85 or 115
$x\,i$	—Reactance drop in transformer and leads.	7.5
E_p	—Primary voltage	100. +

The principal component of E_x, the reactance voltage of the booster, is generated by the armature conductors cutting a magnetic field set up by the armature reaction of the load current in the neutral space and adjacent pole tips. It is 65 to 70 per cent of the designed voltage of the average booster.

Fig. 2 is an oscillograph record showing the voltage at the collector rings, voltage of booster armature and of an exploring coil in the booster armature. The latter indicates the field form of the flux set up by the armature reaction. Such a field form will cause high core loss and eddy current loss in the armature conductors. The eddy current loss is materially reduced by the use of stranded cable conductors in which the individual strands are adequately insulated.

The power factor at any point in the circuit can be determined from the relations shown in Fig. 1*a*. For unity at the collector rings the converter is furnishing 10 per cent leading kv-a. (99.4 power factor). For unity at the primary terminals of the transformer, the converter armature must furnish leading kv-a. to the amount of 10 per cent for the booster reactance, 7½ per cent for the transformer and lead reactance, and 5 per cent transformer magnetizing current,—totaling 22½ per cent (97.5 power factor).

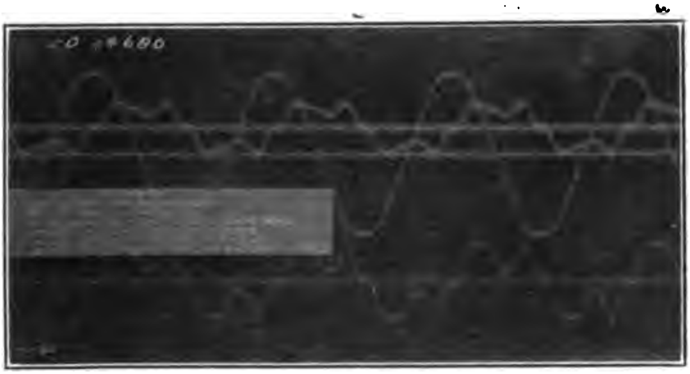


FIG. 2—OSCILLOGRAPH RECORD, 1000-KW., 25-CYCLE SYNCHRONOUS BOOSTER CONVERTER

Uper curve—Booster armature voltage
Middle curve—Collectior ring voltage
Lower curve—Booster armature exploring coil voltage

The values here assigned to reactance and magnetizing current are a minimum for modern designs; therefore, combinations, especially at 60 cycles, will be found where the converter armature must operate as low as 95 per cent power factor leading to hold unity at the transformer primary.

Fig. 3 shows the effect of power factor and booster on the average $I^2 R$ loss of the armature conductors.

Fig. 4 shows the effect on the $I^2 R$ loss in the armature conductors in the tap zone. The tap zone includes the armature conductors in which the greatest average $I^2 R$ loss occurs and is therefore the hottest spot in the converter armature. It is here taken as the tap slot and the adjacent slots on either side. The greatest loss occurs in the tap coil at unity power factor. The greatest average loss at any leading power factor takes place in the conductors in the slot next ahead of or in the direction of rotation from the tap slot. The converse is true for lagging power factor.

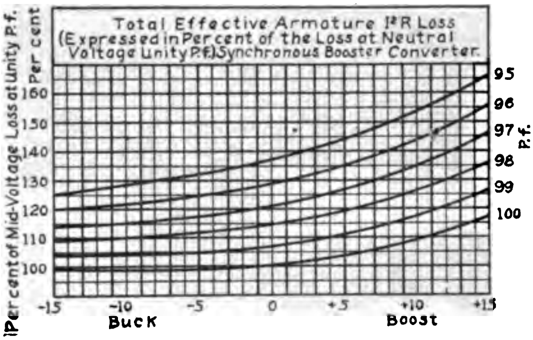


FIG. 3

The $I^2 R$ loss in the tap zone of a converter increases at a much greater rate for a change in power factor than in any other type of alternating-current machine. It is, therefore, of the greatest importance that a converter be operated within the power factor limits for which it has been designed.

The transformer capacity is usually 5 to 10 per cent greater than the converter. The high-voltage winding is arranged with four 2½ per cent full-capacity taps below rated voltage. The low-voltage winding is provided with a 50 per cent tap for connecting to the neutral of the Edison system. Suitable taps and lead arrangement are provided in either winding if a-c. starting is required.

The reactance and exciting current are a minimum consistent with conservative transformer design. An upper limit of 7½ per cent for each is set for continuous rated machines. The rated secondary voltage should be as high as the range of the booster, together with the application requirements, permits, for such an arrangement gives the best efficiency, lowest heating and most stable operation.

In the simple converter there is a fixed relation between the direct and alternating currents. The resultant armature reaction under the commutating pole, therefore, varies directly with the load current and may be neutralized by a series winding. This relation exists also in the synchronous booster converter when the booster field is not excited. The series winding alone maintains commutation at the mid or neutral voltage.

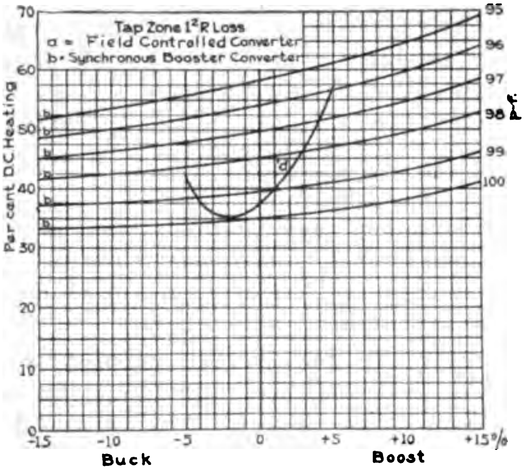


FIG. 4

When raising or lowering the voltage, the booster operates as an alternator or motor; the converter as converter and motor or as converter and d-c. generator. The armature reaction of the motor current in the converter armature magnetizes, and, of the generator current, demagnetizes the commutating pole. To maintain correct commutation, these effects must be neutralized. This is accomplished by a second winding on the commutating pole properly excited and controlled. This winding, in the case of a 15 per cent booster, is approximately 40 per cent of the series winding. Its control, therefore, must be accurate and reliable.

FIELD-CONTROLLED CONVERTER

The field-controlled converter was developed to meet the need of a limited voltage range machine. The voltage range of certain buses in large substations is small although the range of substation voltage is large.

Fig. 1*b* represents vectorially the relation of the voltages in the converter, reactance and transformer at full load. The resistance drops are omitted as in Fig. 1*a*. Unity power factor is assumed at the transformer primary. The following table designates and gives the value of these voltages:

E	—primary voltage	100
E_x	—reactance drop from load current	17½
E_e	—energy voltage of reactance	5
E_r	—converter ring or armature voltage	95, or 105
E_b	—total reactance voltage	18.2

It is evident from a comparison of the two figures that the total reactance of each type of equipment is approximately the same.

Fig. 12 shows the inherent regulation of synchronous booster and field-controlled converters for several equal voltage ranges. For the synchronous booster type 7½ per cent reactance is assumed for transformer and low-voltage connections. For the field-controlled converter 2½ per cent is assumed for the low-voltage connections (60 cycles may be 3½ to 5 per cent) and the additional reactance in the transformer required for the several voltage ranges.

It should be noted that the inherent regulation of the 5 per cent field-controlled converter is no greater than the 5 per cent synchronous booster converter. Slightly different assumptions of reactance and resistance would make little change in the results.

The voltage range determines the amount of reactance and reactive current, and the converter is designed to carry this current at full load. At fractional loads, it may be increased, with a corresponding increase in the voltage range without exceeding full-load armature heating. Fig. 5 shows additional marking on a d-c. ammeter scale to indicate the maximum reactive kv-a. permissible at any load.

The field-controlled converter at unity power factor is a simple converter and the commutation requirements are as previously described. When the power factor is leading, there is a change in the armature reaction which demagnetizes the commutating pole; the converse is true for lagging power factor. To neutralize this effect, a second winding is required on the commutating pole. This winding is approximately 10 per cent of the series winding on a converter of average proportion used for a 5 per cent voltage range by field control. The disturbance in the armature reaction is proportional to the reactive current which, in turn, is proportional to the main field current. The second winding is, therefore, excited and controlled from the main field rheostat.

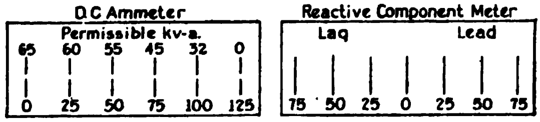


FIG: 5—MARKING OF D-C. AMMETER SCALE TO SHOW THE OPERATOR THE CAPACITY OF THE CONVERTER

The shunt-wound converter can be operated with equal stability over a greater range of reactive current and with more reactance in the a-c. circuit than the compound-wound machine. The usual design of 250-volt converter gives about 50 per cent reactive current at no-load and with zero field. To get the best efficiency over the voltage range, maximum obtainable reactive current is used at no-load minimum voltage. The converter armature loss on this basis, over a 10 per cent voltage range, is shown in Fig. 6, Curve *a*.

Fig. 7 gives results from test showing the relation of reactive current at the converter collector rings at no-load, half load, and full load over the voltage range. The loss shown in Fig. 6, Curve *a* is based on results of test.

Fig. 8 shows the conventional voltage range, that is, the range from no-load minimum to full-load maximum; also the additional range at lower voltages with increase in load, and the additional range at higher voltages with partial loads. The curves are from test on a 4200-kw. unit. It may be argued that only the conventional range is of any commercial value, but additional lowering of voltage under load is useful for load shifting and limiting. The higher voltage will often provide for the requirement of a higher bus on which the load is small.

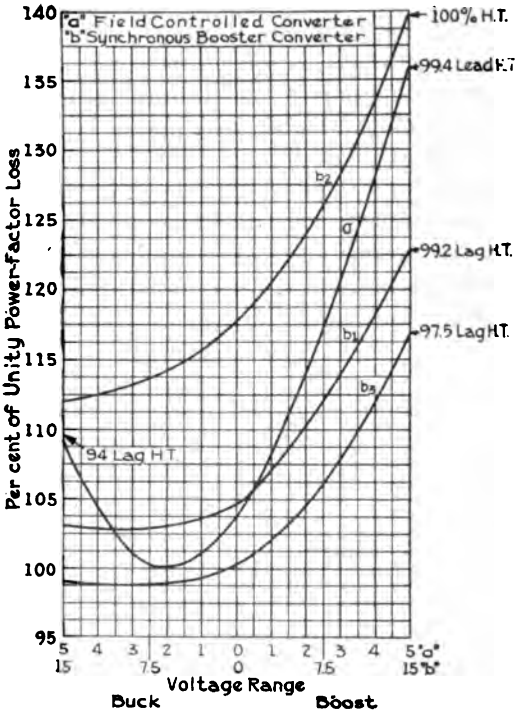


Fig. 6—Comparison of $I^2 R$ Armature Losses over the Voltage Range of the Field-Controlled and the Synchronous Booster Converter with Unity Power Factor, High-Tension Collector Rings and Converter Armature

In the larger substations, three d-c. buses are often used. During light load periods, all buses are tied together, giving in effect, a 24-hour load at nearly constant voltage. (Fig. 9 low bus).

The voltage of the main and high bus is also shown. Attention is called to the voltage range indicated by x and y. This is an important consideration where a number of machines are operating in parallel on a bus. The wide-range machines are connected first and the narrow-range machines are connected last and disconnected first. Suitable switches for changing the transformer connections with the transformer unex-

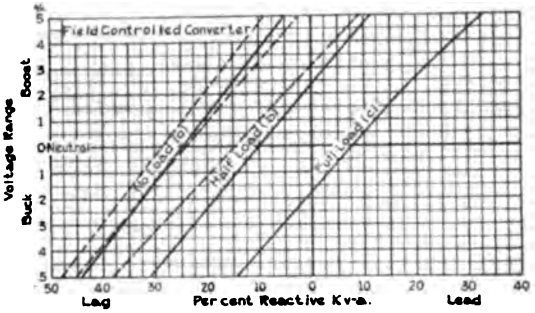


Fig. 7—Relation of Voltage Range to Reactive kv-a.—4200-kw. 25-Cycle Field-Controlled Converter

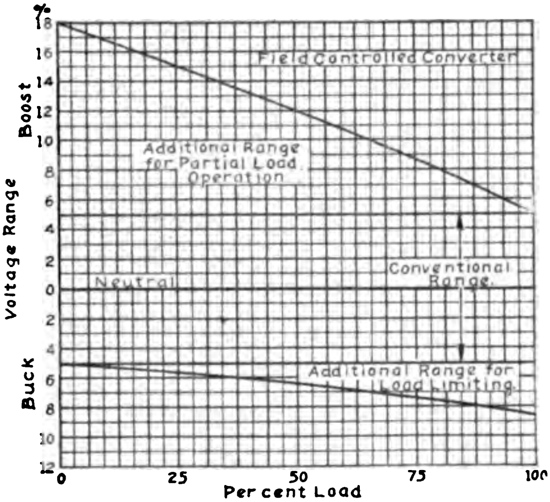


Fig. 8—Relation of Voltage Range to Load—4200-kw. 25-Cycle Field-Controlled Converter

cited makes a narrow-range machine available for any bus. To change from one bus to another, the load must be removed, the transformer line switch opened, ratio adjuster operated to the desired position, machine synchronized, and loaded.

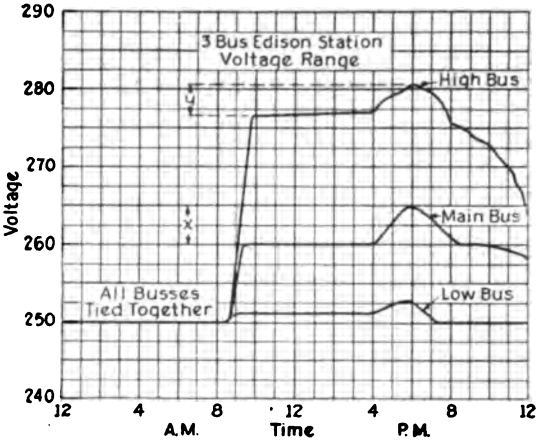


FIG. 9

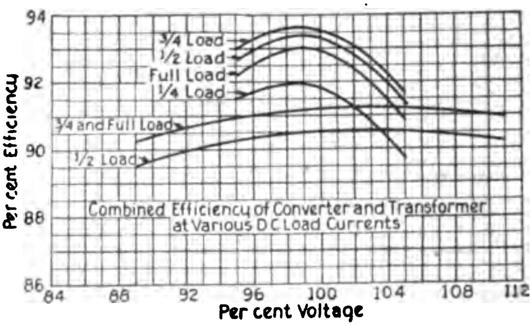


FIG. 10—COMBINED EFFICIENCY OF CONVERTER AND TRANSFORMER

Upper 10 per cent voltage range curves, 4200-kw. 25-cycle field-controlled converter equipment.

Lower 22 per cent voltage range curves, 3500-kw. 25-cycle synchronous booster converter equipment

The transformer is designed for approximately 15 per cent reactance. The equipment is designed for a total range of 20 per cent (± 10 per cent) with five running points on the transformer. The available range from any running connection is 10 per cent (± 5 per cent) resulting in a very flexible arrangement. The high-reactance transformer is a very satisfactory design, and, in many cases, costs little more than the low or normal-reactance type.

The following is a comparison of the field-controlled and synchronous booster types:

1. Higher efficiency of field-controlled type as shown in Fig. 10. The values are from tests on a 4200-kw.

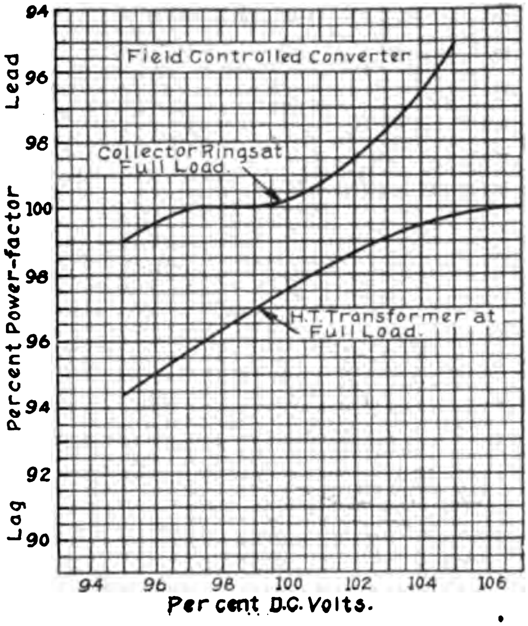


FIG. 11—RELATION OF POWER FACTOR TO VOLTAGE RANGE AT FULL LOAD, FIELD-CONTROLLED CONVERTER

field-controlled and 3500-kw. synchronous booster converter and transformer. The transformer efficiency in each case is approximately the same and the loss in the low-voltage connections has been deducted. The efficiency of the types over their respective voltage ranges is shown at one-half, three-quarter and full load. The efficiency of the field-controlled converter varies considerably over the voltage range. A transformer connection should be chosen to give highest efficiency at the operating voltage.

Designing the synchronous booster converter for the same range as the field-controlled converter gives but slight improvement in efficiency because the losses in a synchronous booster do not decrease in proportion to the reduction in range.

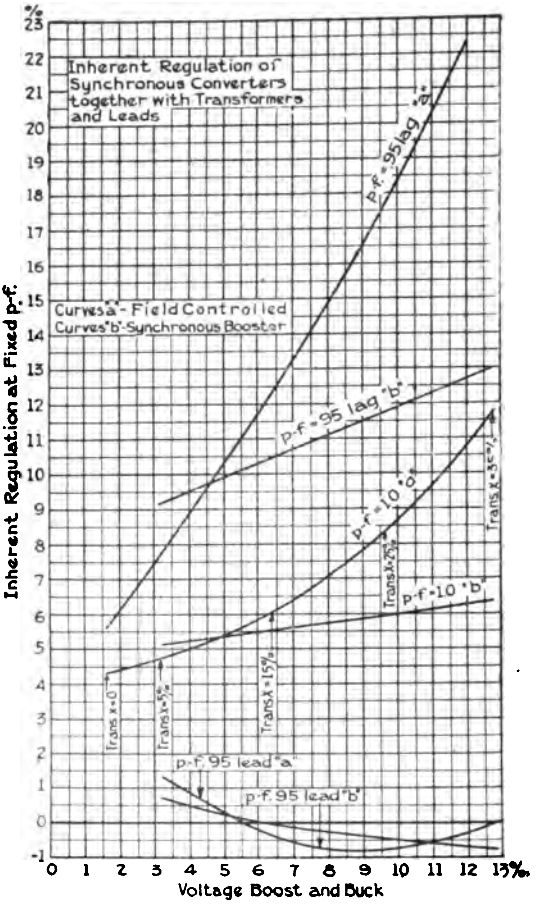


FIG. 12—INHERENT REGULATION OF CONVERTER EQUIPMENTS DESIGNED FOR SEVERAL VOLTAGE RANGES

2. Successful commutation over the voltage and load range of the field-controlled converter is obtained without the use of relays or special rheostats.

3. Better ventilation and accessibility of the field controlled converter.

4. Cost is in favor of the field-controlled converter for a voltage range not to exceed 10 per cent (± 5 per cent). The cost of the synchronous booster converter is reduced about 1 per cent in lowering the booster voltage from 15 to 10 per cent, and 2 per cent in reducing from 15 to 5 per cent.

5. Saving in floor space is in favor of the field-controlled converter.

6. The synchronous booster converter allows operating at unity power factor at the collector rings over its range of voltage; also it can be designed, at additional cost, to hold unity power factor at the transformer primary. The power factor of the field-controlled converter can not be adjusted independently of voltage, and the power factor at the transformer primary may be as low as 94 per cent lagging at full load minimum voltage, and about unity at maximum voltage. At partial loads the power factor will be lower; however, the reactive kv-a. should be considered, as it is a better guide than power factor. Fig. 11 shows the power factor at the transformer primary and the collector rings at full load over the voltage range.

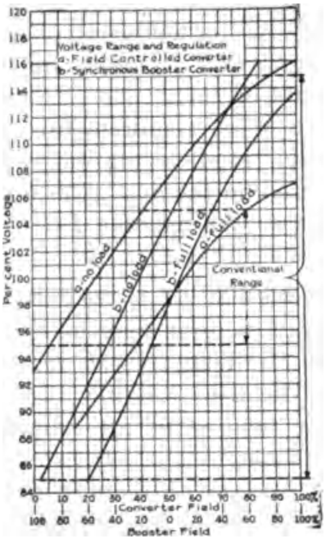


FIG. 13

7. The synchronous booster converter can be designed for a large voltage range while the field-controlled is limited to approximately 10 per cent. If the a-c. line has poor regulation (resistance drop) or is subject to voltage fluctuations, the net range is reduced in proportion. The a-c. range should, therefore be considered in connection with d-c. range required, in selecting the proper type of apparatus.

8. When starting d-c., it is not possible to change the a-c. voltage of the field-controlled converter for synchronizing and the d-c. supply should be tripped immediately before closing the a-c. circuit. This method of synchronizing is desirable on the synchronous booster converter as well.

9. Simplicity of the field-controlled converter.

10. Fig. 13 shows voltage range and regulation from test on large units of each type. Close regulation is not necessary to meet requirements of Edison service, furthermore broad regulation, especially when batteries are floated on the bus, gives greater stability.

11. Fig. 6 shows the average I^2R loss in the converter armature of each type.

MODIFIED SYNCHRONOUS BOOSTER CONVERTER

The synchronous booster may be excited either by direct current in the field coils or reactive current in the armature. The field winding may, therefore, be omitted and the field structure somewhat reduced. It is not practicable to furnish as much excitation through the armature as through the field windings and therefore this type of booster has a smaller voltage range.

The effects on commutation of the synchronous booster and field control are approximately equal and opposite for machines of equal range. Both these effects are present in the modified booster and no auxiliary commutation devices are necessary.

TRANSFORMERS

Transformers for synchronous converters may be single- or three-phase, shell or core type, air-blast, water-cooled, or self-cooled.

The secondary winding is designed for low voltage with high amperage. This requires a winding consisting either of a large number of multiple coils or a helical winding containing many individual multiple strands. The first case requires multiple connections between coils and between coil groups; also provision for obtaining equal current division anong the circuits. The second case combines mechanical difficulties of coil support and of winding. A new type of coil has been developed and is now in commercial service that is well suited to large units at 25 cycles. Some 4550-kv-a. shell-type, air-blast transformers with 150 per cent load for two hours have been built using solid copper bar 7/16 in. (1.11 cm.) thick by 13 1/2 in. (34.3 cm.) wide for the low-voltage winding. This type of winding has the advantage of ideal mechanical construction, no danger from unsupported turns or strands, coils supported and braced with straight moulded channels and spacers, efficient cooling with air in direct contact with copper, small air-duct requirement, and improved space factor. There is the disadvantage of additional eddy current loss. The full-load efficiency of the 4550-kv-a. unit is 98.14 per cent. Fig. 26 is an illustration of the solid bar coil.

At 60 cycles, it is often desirable on large machines to provide twelve conductors between transformer and converter so as to obtain low reactance and uniform heating. Careful consideration should be given to the location of the transformer so that the low-voltage connections are short and properly arranged to give minimum losses. The transformer may be placed below the converter. For the minimum length of low-voltage connections the air-blast transformer can be placed immediately below the converter on its side to simplify the problem of ventilation.

DYNAROTOR

Low-voltage connections between transformers and converters are costly in large size units, and considerable loss and reactance are found in many cases. The motor generator has the advantage in this respect. Going a step forward, the motor and generator can be combined into one machine using a common armature core; and going a step backward with the synchronous converter, the direct and alternating current may be carried by two separate windings in a common core. The a-c. winding may be designed for the voltage of the bus not to exceed 13,200 to which it is connected through a suitable collector. The d-c. winding connects to a commutator. By providing a leakage path for flux between the two windings, reactance is obtained, and voltage range is obtained as in the field-controlled converter. The commutating-pole field strength is effected and compensated for as in the field-controlled converter.

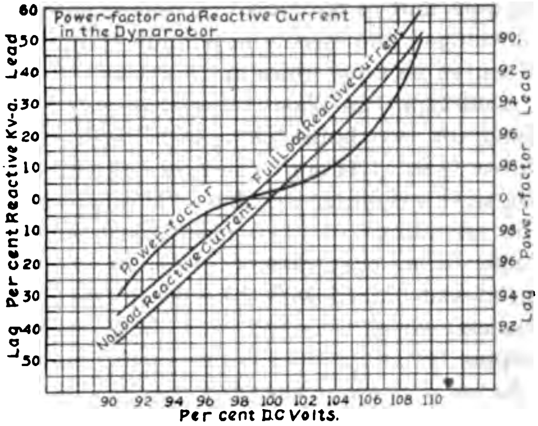


FIG. 14

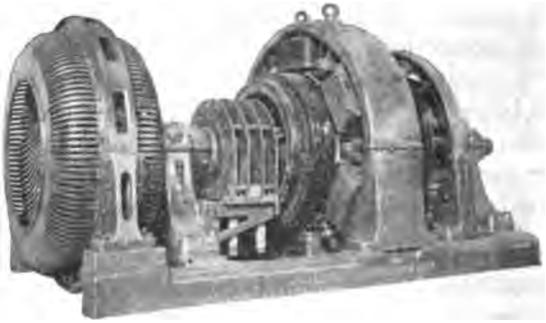


FIG. 15—1000-KW. 6600-VOLT THREE-PHASE 250-VOLT D-C. 25-CYCLE DYNAROTOR WITH SYNCHRONOUS A-C. BOOSTER

There are certain apparent limitations due entirely to the usual forms of construction. The high-voltage a-c. winding is difficult when built on a rotor, especially if the voltage exceeds 6600. Since the a-c. and d-c. windings are in common slots, a failure in the bottom winding involves removing both windings for repairs.

The over-all efficiency of such a unit is slightly higher than the synchronous booster converter with its transformer and connections, higher than the motor-generator, but lower than the field-controlled converter and transformer.

Fig. 14 gives characteristic curves from actual test on a 1000-kw. 250-volt unit. Fig. 15 is an illustration of the unit with a-c. synchronous booster. The booster was removed before the machine was installed since the necessary voltage range was obtained without it.

A-C. STARTING

There have been no recent important developments in direct-current, induction-motor or secondary-tap

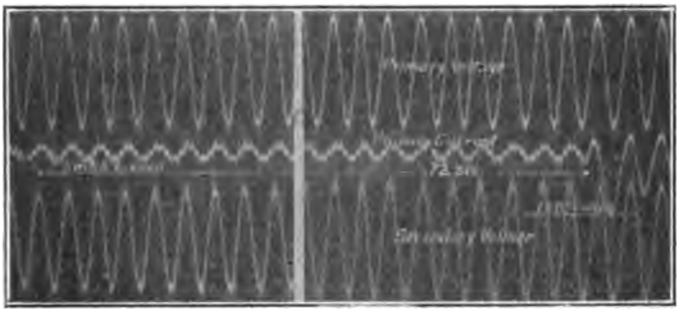


FIG. 17—OSCILLOGRAPH RECORD, SECONDARY-TAP STARTING 2500-KW. 60-CYCLE SYNCHRONOUS BOOSTER CONVERTER

Switching from 75 per cent tap to full voltage

starting. High-tension starting simplifies the low-voltage connections and eliminates heavy current switches.

Three methods are available: series-multiple, *Y*-delta and extended primary windings. Series-multiple offers the greatest advantage on two-phase-six-phase transformation; *Y*-delta on three-phase-six-phase, and extended-primary windings in conjunction with reactors for switching under load.

Y-delta is the cheapest. It requires two triple-pole switches only when 58 per cent starting voltage is suitable. For other voltages three primary taps must be added. The connections should be so chosen that the time phase displacement of 30 electrical degrees between the *Y* and delta connections will allow the converter armature to drop back a certain angle depending on the ratio of its losses to stored energy. This reduces the 30-degree phase displacement.

The starting kv-a. will be the same with low-tension or high-tension starting. The kv-a. on switching to full voltage depends on the voltage and phase difference of supply and converter. If the time in switching were zero, then the low-tension starting would have the advantage with no phase displacement against 30 degrees for *Y*-delta. The time in switching tends to equalize this difference.

Fig. 16 is an oscillograph record of the current in starting and switching, for secondary-tap starting, on a 2500-kw., 60-cycle, synchronous booster converter. The kv-a. at the instant of start is 150 per cent, dropping immediately to 110 per cent. On switching to full voltage, the inrush is 110 per cent. As a matter of interest, the complete starting and switching event is shown.

Fig. 17 shows the time of switching (0.72 sec.), also the phase displacement between line and converter, amounting to 20 electrical degrees behind.

Fig. 18 is an oscillograph record of starting current, for *Y*-delta high-tension starting, on a 3700-kw., 60-cycle, booster converter. The inrush kv-a. is 100 per cent, dropping immediately to 69 per cent. The inrush on switching to full voltage is 75 per cent.

Fig. 19 shows the time of switching (0.38 sec.), also the phase displacement between line and converter amounting to 20 electrical degrees ahead.

Fig. 20 shows that there is no noticeable effect on the voltage of the system (140,000-kv-a. connected capacity) when a 3700-kw. 60-cycle unit is started.

MOTOR-GENERATOR

In selecting between synchronous motor-generator or synchronous converter for Edison service, costs, floor space, efficiency, parallel operation with existing

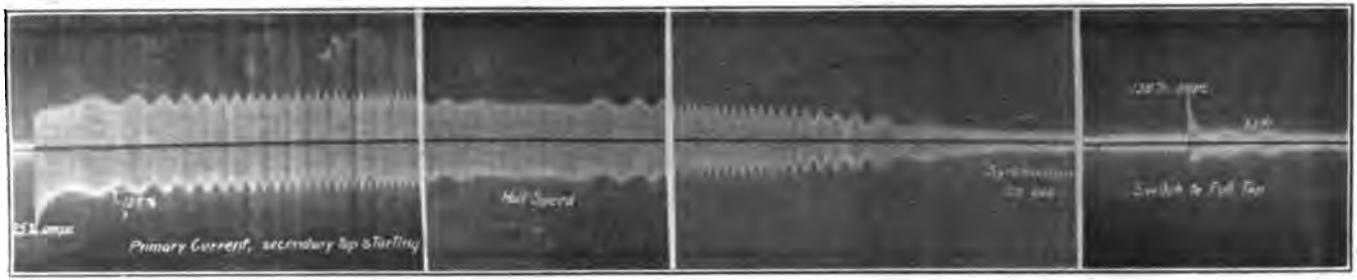


FIG 16—OSCILLOGRAPH RECORD, SECONDARY-TAP STARTING, 2500-KW. 60-CYCLE SYNCHRONOUS BOOSTER CONVERTER

apparatus, and synchronous condenser capacity have been the determining factors. The characteristics of the two types of apparatus are, however, radically different under certain conditions. The converter once out of synchronism with the supply can not remain connected to the d-c. system because of its changing polarity. The synchronous motor can drop out of step without affecting the generator in any way except to drop its speed and therefore its voltage and load.

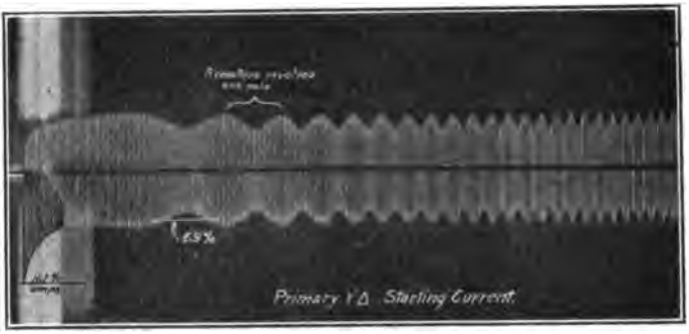


FIG. 18—OSCILLOGRAPH RECORD, HIGH-TENSION *Y*-DELTA STARTING, 3700-KW. 60-CYCLE SYNCHRONOUS BOOSTER CONVERTER

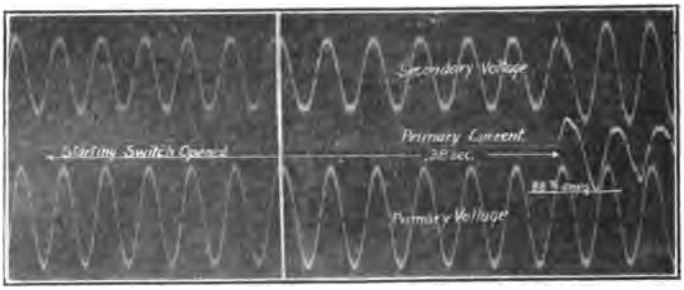


FIG. 19—OSCILLOGRAPH RECORD, HIGH-TENSION *Y*-DELTA STARTING, 3700-KW. 60-CYCLE SYNCHRONOUS BOOSTER CONVERTER

Switching 72 per cent to full voltage

Motor-generator sets now in operation on Edison systems have not been designed with special regard to load limiting of the generator or a-c. starting and synchronizing of the motor. Generators in the main have been built shunt-wound, a few compound-wound and a number with series windings for differential-generator or compound-wound motor operation. The differential generator was thought necessary for succesful parallel operation with batteries, but in actual practise it has been found that the regulation of the generator operating shunt-wound with series winding short-circuited is sufficient to give the desired results under normal conditions. Under abnormal conditions, however, it would be desirable to make use of this winding controlled so as to bring it into action on overload or reverse current to give increased stability.

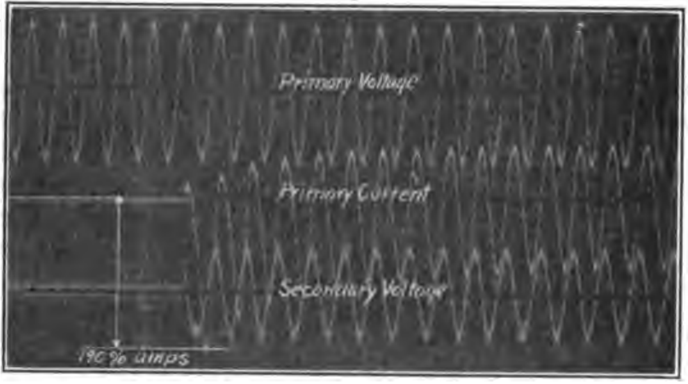


Fig. 20—Oscillograph Record, High-Tension Y-Delta Starting, 3700-kw. 60-Cycle Synchronous Booster Converter

Both generator and motor designs have advanced to the stage where certain desirable characteristics can be obtained at reasonable cost.

The synchronous motor can be designed to give sufficient torque to synchronize with full load on the generator. Figs. 21 and 22 show the relation between available motor torque and torque required by the generator, from which it is clear that the motor will synchronize with full load on generator if the supply voltage is normal. Reactance is connected in the motor circuit so that, in restoring service, full voltage may be impressed. The kv-a. required for starting with such an arrangement is high and would be warranted only under abnormal conditions. The usual switching arrangement with compensator would be used for normal starting duty.

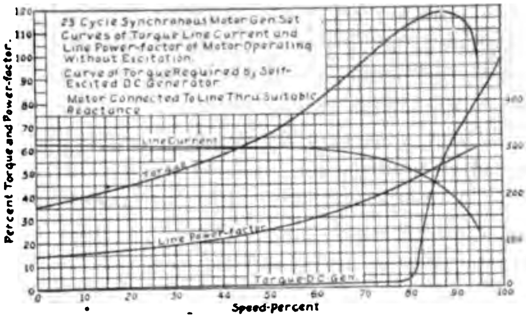


FIG. 21

The amount of reactance required for the 60-cycle motor would increase the cost of the set from 2 to 3 per cent, and lower the efficiency from 0.1 to 0.3 of one per cent. At 25 cycles, from 4 to 6 per cent in cost and 0.25 to 0.5 of one per cent in efficiency. The loss in the reactor under normal conditions could be eliminated by use of a short-circuiting switch, the switch controller to open for or under abnormal conditions.

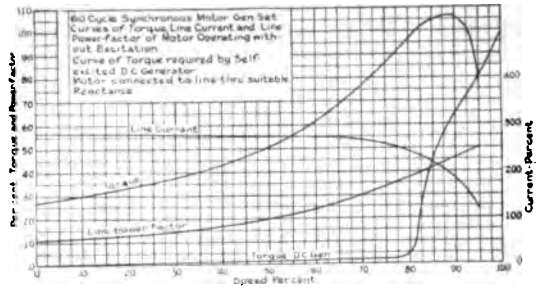


FIG. 22

The motor torque shown is that of the amortisseur winding. The motor field should be energized at about 95 per cent of synchronism, giving additional

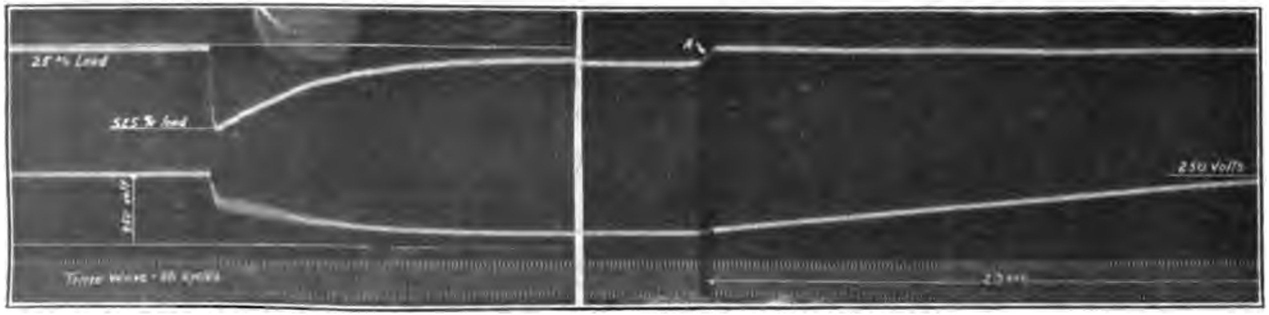


Fig. 23—Oscillograph Record, Short-Circuit Test on a 1000-kw. Generator

torque at the higher speeds, and finally synchronous torque. Below this speed, the torque would be greatly reduced if the field were excited.

The field circuit of the motor is controlled by a device that is responsive to "slip" between the motor and the supply; adjusted to open the motor field circuit at a predetermined slip and close it at a slightly higher value. This scheme makes available the maximum motor torque at all speeds.

The stator winding is protected against overheating by a thermal relay, the amortisseur winding by a time setting; that is, when the motor field is opened due to slip a time-delay relay will allow the motor to run as an induction motor for a definite time (probably three minutes.) If the motor field does not re-energize indicating synchronism, the time-delay relay will function to open the generator or motor connection to the line. The torque required at no-load is so small that any voltage that will start the set will bring it to synchronism. Also if the set is running at a voltage not sufficient to bring it to speed at no-load, the amortisseur winding will not overheat

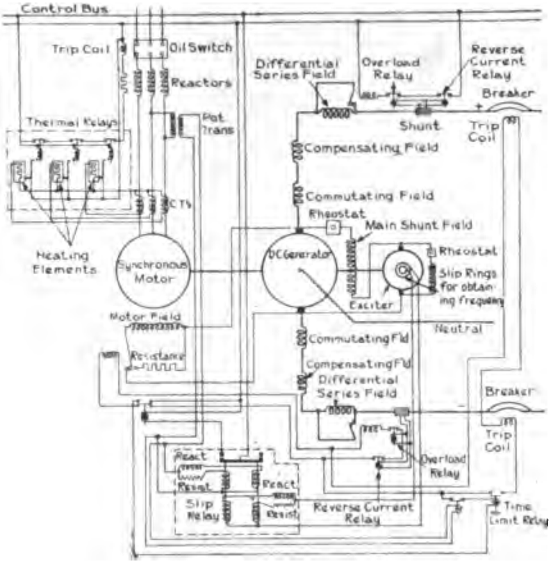


FIG. 24—SPECIAL CONNECTIONS OF SYNCHRONOUS MOTOR-GENERATOR SET FOR EDISON SERVICE

for a considerable period of time. If the motor field is re-energized in the predetermined time, then the time-delay relay resets and is ready for the next operation.

Disconnecting the generator, the motor, or both, from the line to protect the amortisseur winding of the motor gives a definite protection against dangerous heating. To insure synchronizing at voltages less than normal and thereby feeding the d-c. system all the available power an unloading control for the generator (not shown in Fig. 24) is used. A motor-operated rheostat of suitable resistance is connected in series with the shunt field of the generator and is controlled by a double acting instantaneous relay which is energized simultaneously with the time-delay relay used for disconnecting the generator from the line. This causes a lowering of voltage and current until the motor synchronizes. The speed of the rheostat is very slow so as to reduce the generator output a minimum amount for the motor to pull into step. With the closing of the motor field the unloading rheostat resistance is slowly cut out, giving normal field circuit resistance.

The generator characteristics can be made such as to limit its output in current, and withstand a short circuit at its terminals without flash-over. Fig. 23 shows an oscillograph record of current and voltage of a 1000-kw. 250-volt generator with connections as shown in Fig. 24.

This scheme of connections gives generator characteristics that limit its current output at any voltage from zero to normal that a system may require. The generator is arranged with a series winding that is connected in opposition to the shunt winding and normally short-circuited. The shunt winding is connected to the generator and exciter terminals connected in series. The generator is therefore, partly self- and partly separately-excited. The separate excitation gives stability and the self excitation and differential series excitation give elasticity to the system of voltage and current control. The separate excitation is balanced against the series differential excitation to give a limited output in current on short circuit (usually 125 per cent on continuous rated machines). Where generators are operated in parallel with batteries, exciters are not necessary.

Fig. 25 gives the characteristic curves of a generator with connections as shown in Fig. 24. Voltage in this case is automatically held constant up to full load, beyond which no further change is made in field rheostat setting. The short-circuiting device of the series differential winding opens, giving an initial drop in voltage and load. With a further reduction in resistance of the external circuit, the voltage gradually decreases to zero and the current increases but slightly. This characteristic is required of a machine that is to be connected to an Edison system after a complete interruption of power (bus voltage zero).

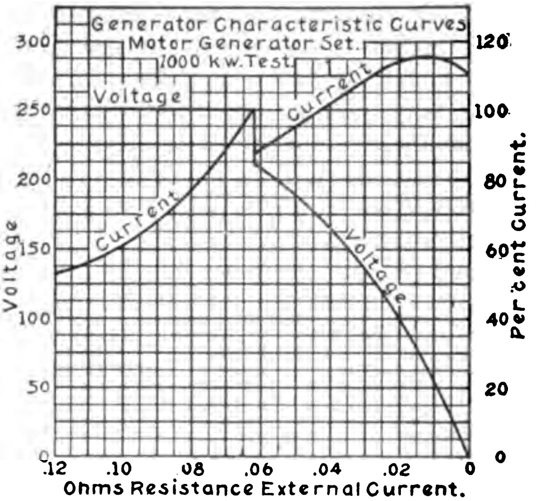


FIG. 25

Fig. 23 gives results as measured by oscillograph of a short circuit on the generator. The test simulates a short circuit on a d-c. system near the substation in which the generator is installed. The current increases to 525 per cent load instantly, then decreases to a constant value of 110 per cent load. The short circuit is removed at *A*. The current drops to zero and reverses. The generator operates as a compound-wound motor until voltage is restored approximately to normal.

The motor-generator with such characteristics will give continuity of service on an Edison system equal to that of the generating system supplying the power. The motor-generator, therefore, supplements the storage battery and can be used to reduce the amount of battery capacity required to give a system protection against a momentary interruption of a-c. supply.

Alternating-current power systems are constantly being developed to give continuity of service, also to localize the effects of disturbances and promptly to clear the fault from the system. Each improvement made in the a-c. system is reflected directly in the Edison system if the motor-generator is used. This does not mean that all conversion apparatus must be of the motor-generator type. A very careful study of any system will be necessary to indicate the proper capacity relation of converter, motor-generator, and storage battery to meet a desired service.

Restoring service on an Edison system after a complete shut-down is promptly and smoothly accomplished by the motor-generator set after the restoration of a-c. voltage. Each set connects to the d-c. system, delivers a predetermined amount of current and, as additional units connect, the voltage will increase until normal conditions are reached.

In general, the efficiency of the motor-generator at full load is approximately 2 per cent lower than the synchronous booster converter equipment, and at half load about 5 per cent. Floor space is about equal at 1500 kw., in favor of the motor-generator in smaller sizes and in favor of the converter in larger sizes. The difference is considerable at 4000 kw. The motor-generator is cheaper and more efficient as a three-unit set above 1500 kw. capacity. Generators controlled as shown in Fig. 24 can be connected permanently in parallel, which simplifies the switch-gear.

AUTOMATIC SUBSTATIONS

The advantages of automatic operation of substations for railway work have been fully demonstrated during the last six years, as is evidenced by the rapid increase in the number of such installations. Semi-automatic, remote control was demonstrated at Detroit in 1912 in the application of a 500-kw. synchronous converter equipment for lighting and power work. Edison systems to date have taken little or no advantage of developments for automatic control of conversion apparatus. The economy of the automatic substation for the interurban electric railway was obvious; its application to railway substations for city work was questioned and after six years, this field is being developed. The Edison substation differs but slightly from the latter, and, in the case of several moderate-size systems where a complete analysis has been made, the automatic operation of the entire system is not only favorable but highly desirable. In one case, it was necessary to vacate existing substations and change all converting apparatus to operate from 60 instead of 25 cycles. Here the a-c. system was developed and protected sufficiently to warrant the omission of batteries provided the automatic substation could be depended upon to handle the situation normally and under any emergency.

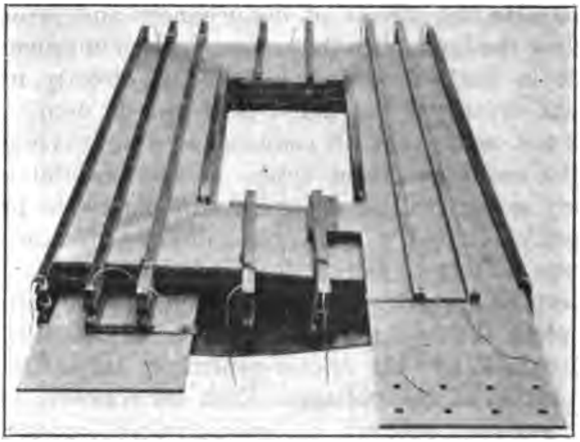


FIG. 26—215-VOLT SECONDARY COIL AND INSULATION, 4550-KV-A. AIR-BLAST TRANSFORMER

In another case, the main substation was located on very valuable property. By sub-dividing a saving can be made in substation and property cost, in addition to a large saving in distribution losses and operating costs.

Every system has its specific problems. There are large substations located in high load-density areas where automatic operation is neither desirable, economical or advisable; there are stations where duties aside from operating would require attendance, but there is probably a place on every Edison system for an automatic substation.

The existing d-c. area may be encroached upon by the a-c. system because there is not enough load for an additional manually operated station, because feeder losses are high to the nearest d-c. substation, or because a booster or special machine would be required at the existing substation; yet d-c. service might be very desirable in such a locality. The automatic substation is the answer.

The operator who goes about his duties quickly makes every move with precision and accuracy, is not confused by emergencies, exercises good judgment and is constantly alert to the situation, is too valuable a man for operating, and such insurance can be given the apparatus and service by automatic control. Confidence in the operation of automatic substations comes with experience in operating them.

The small and medium-size automatic substation would be provided with load-limiting equipment. In case of complete shut-down of the system the automatic substation starts promptly on the return of a-c. power, connects to the d-c. system and delivers its full current output, raising its voltage as the system permits until normal conditions are restored. For larger automatic substations, conversion apparatus with sufficient voltage range for load shifting when converters are used, and individual feeder protection by a suitable form of re-closing device, will be the most economical arrangement if the capacity of such automatic substations is not essential in restoring service after a complete system shut-down.

The automatic substation can at times be justified by the saving in operating costs, if converters are used and no-load limiting equipment is required. To secure the maximum return, however, the substations and distribution should be worked out to give a proper balance between cost of losses and capital investment.

No-load limiting equipment is required in the case of the motor-generator set as has been described. Also the motor can be designed to give motive power under all except the most abnormal conditions of power supply. This form of conversion apparatus is therefore very suitable for automatic substation application.

Load-limiting equipment for the converter is most economical in the form of series resistance. The type of resistor depends on the machine capacity and the number of steps required. In general, above 500 kw., water cooling is provided if resistance metal is used; metal resistance with suitable short-circuiting device if the number of steps does not exceed four and the current capacity does not exceed 19,000 amperes. A liquid rheostat with an infinite number of steps to the point of short-circuiting is used for higher capacities or more exacting requirements. Provision should be made to exhaust the vapors from the substation with either of the latter forms of resistors.

The authors desire to express their thanks to Mr. E. O. Shirley for help in preparing this article.

DISCUSSION ON "DEVELOPMENTS IN CONVERSION APPARATUS FOR EDISON SYSTEMS" (BARTON AND HAMBLETON), NEW YORK, N. Y., MARCH 11, 1921.

B. G. Lamme: In the early days of direct-current machinery, voltage control meant, largely, holding the voltage constant with change in load. When the synchronous converter came into use, about the middle nineties, one of its meritorious features was that it tended to give constant potential at its d-c. terminals when the a-c. supply voltage was held constant, and, as most of these early converters were for railway service, this condition was really quite satisfactory.

However, when we got into other fields of endeavor with the synchronous converter, it soon developed that this supposedly meritorious feature of the converter was really a serious handicap in some ways, and means were soon attempted for overcoming it. The earliest of these was the use of reactance in the a-c. supply system. It was discovered, as early as 1890, that a synchronous motor could set up leading, as well as lagging currents in its supply system, by suitable adjustment of its field excitation. Tests made in 1890, showed that a synchronous motor with heavily overexcited field, could maintain full voltage at the terminals of its driving generator, even with the excitation entirely removed from the latter. The reasons for this were understood, and, consequently, when synchronous converter voltage regulation came up for consideration, naturally the earliest method considered was that of controlling the voltage supplied to the converter by means of variations in the field excitation of the converter itself. As a "compounding" effect was really wanted on the earliest converters, this was obtained by series coils in the fields. However, it was well known that similar voltage control could be obtained by variations in the shunt field strength, with suitable reactance in the a-c. system. This general method was covered by patents as early as 1896, and in the following years it was used commercially to a great extent in railway work, and it is even the standard method today. Also, about 1896 or a little later, several installations were made with regulation by means of variation in the shunt field excitation, these being principally cases where only a moderate range of voltage was required. In one or two instances, a range of 10 to 15 per cent up and down was attempted, but it was found that this was too great a range, as it meant very bad power factor under some conditions of operation. Consequently, the method was dropped chiefly on account of its limited range. It was followed by the use of induction regulators in the a-c. supply circuit for varying the direct-current voltage and this practise was the standard between 1898 and 1904 or '05. This allowed almost any desired voltage range up and down, depending upon the range of the induction regulator itself. The principle of this method was entirely satisfactory, but, in practise, it was complicated and expensive and both manufacturers and operators were always on the lookout for a more satisfactory device.

About 1904, the so-called "split-pole" or "regulating-pole" synchronous converter was brought out with a view to eliminating the induction regulator. This was undoubtedly a big step in advance and, for a time, it showed evidence of dominating the field. However, some two years later, the synchronous-booster converter (an old scheme) was brought out commercially and for several years there was warm competition between these two types. The synchronous-booster machine, as the name implies, was simply a converter with a synchronous booster or alternator in its a-c. circuit, for controlling the voltage supplied to the rotary. It was a simpler arrangement than the regulating pole type and admitted the ready application of commutating poles, which came several years later. It was largely on account of the latter, that the synchronous-booster type finally won out over the regulating-pole type.

These three types of regulation, namely, the induction regulator, the regulating pole, and the synchronous booster were all applicable for rather wide ranges of voltage, such as 15 per cent up or down from the mean. This was necessary in those days for two reasons, namely, to correct variations in the supply voltage of the system, and to cover, in addition, a certain working range in the d-c. voltage, particularly in connection with three-wire d-c. systems. To cover both of these variables required apparently a range of 10 to 15 per cent up and down from the mean. All of these regulating means were much more complex and more expensive than the plain field control of the earliest method. However, with the growth of the systems, both in capacity and constancy of load there have been improvements in the service. In certain congested districts and small areas supplied from one substation, recent experience has shown that much smaller ranges in voltage than 10 to 15 per cent up and down are found. This has led to a return to the original field control type of rotaries in certain cases where both the primary and secondary voltage variations were within the permissible limits for this method. For instance, it has been found that in certain of the large three-wire city systems, a range up and down of less than 5 per cent may cover not only the daily but the yearly variations. Obviously, such a small range merits the careful consideration of the field control method of regulation, especially as, in modern practise, a considerable amount of reactance is purposely permitted in the supply transformers. The principal merit of the arrangement, however, is in the simplification of the apparatus by the omission of separate regulating appliances. There are minor handicaps in the method, but as long as they are recognized and allowances made for them in the design, they do not concern the operator. Therefore, if this method of regulation of converters is applied within its limitations, there is no reason whatever why it should not prove to be a very satisfactory method.

Here is an illustration of what has happened many times in the history of the electrical business. Methods of construction or of operation, which at first have proven unsatisfactory, due to faults outside themselves, have, after many years, come back into use again, due to new conditions or to modifications of the original limitations through changes in practise or improvements in service. New devices come in which are so old that many of the present generation have never heard of them. For example, voltage regulation in an a-c. system by means of field variation of a synchronous motor or condenser in the system, was proposed some thirty years ago and broadly patented shortly afterwards, but yet there was little or no field for the scheme until long after the patent had expired. This is the basic principle in the earliest voltage control of synchronous converters, which, as mentioned before, went out of use nearly twenty-five years ago and now comes back again when suitable operating conditions develop for it.

Albert A. Nims: One of the many interesting features of this paper is the device for increasing the approximately constant ratio between the alternating-current voltage and the direct-current voltage from the order of unity up to 50 or 60 to 1. This is the dynamotor, where the direct-current and alternating-current windings are separate, but carried on the same core.

There is another device for increasing that ratio to the same extent, to which I was looking for some reference in this paper or possibly in the discussion. That arrangement consists of a rotary transformer mounted upon the rotary shaft with permanent connections between the secondary and the alternating-current side of the rotary itself. The rotating transformer is, of course, an induction motor, and the secondary frequency is correspondingly reduced so that the rotary itself operates at generally half the line frequency. Since the energy is supplied to the shaft through the air gap of the induction motor, no collector rings are required except during the starting period and for bringing out the neutral of the transformer winding for three-wire service. Moreover, with this arrangement, in contrast to the dynamotor, the high-tension winding is stationary, which is a marked advantage.

However, the use of equipment of this kind is, according to my understanding, confined to England and European countries. With all the advantages that, to one who is not familiar in detail with the requirements of this class of apparatus, the motor-converter seems to possess, it is something of a question why it has found greater favor in this country. I would therefore like to ask Mr. Barton if he can explain some of the engineering reasons which render this apparatus inapplicable to conditions here.

Frank D. Newbury: I propose to discuss that part of the paper referring to the comparison between the synchronous booster converter and the simple converter with field control. I do not believe there is any reason for a difference of opinion regarding the fundamental point raised in the paper, that is, that the simple converter with field control has obvious advantages in the case of a limited voltage range, and on the other hand, I do not believe the authors will disagree with me in saying that where the voltage range is of the order of 10 to 15 per cent above and below the mid-voltage the synchronous booster type is the most effective. The real question is one, I think, for the operating engineers to consider—it is the question of choice of each type with respect to the operating conditions existing in any particular system, and it is particularly important that the operating characteristics of the two types be understood in order that this application shall be correctly made in any particular case.

The particular points I wish to discuss in the paper refer to this question of characteristics and I feel that the authors have presented the characteristics in some instances in such a way that misunderstandings may occur. I have two particular things in mind in making this statement. First, in Fig. 1 of the paper it is assumed that the booster reactance is 10 per cent, and it is then stated that this value is a minimum value, and in 60-cycle units this value is apt to be exceeded. Now, 10 per cent reactance, referred to the converter rating, with a 15 per cent range in booster, means a 70 per cent reactance voltage in the booster, referred to the booster rating. The booster is simply an alternator having the same characteristics as any other well designed alternator, and this statement amounts to saying that it is usual to design an alternator with 70 per cent reactance. That is not, of course, necessary, nor is it desirable in a generator used as a booster in the synchronous converter, where low reactance is one of the desirable characteristics.

In converters with which I am familiar, the reactance instead of being 70 per cent, is more apt to be 30 and 40 per cent, even in 60-cycle units, and that is equivalent to four or five per cent reactance referred to converter rating, instead of 10 per cent. This difference between 10 per cent reactance, and 4 or 5 per cent reactance, will modify many of the comparisons made in the paper.

Further on in the same paragraph on page 665, the statement is made that the booster converter armature in some cases must operate at 95 per cent power factor to hold unity power factor at the transformer primary. Is not that a little bit unfair to the synchronous converter? Why burden it with the additional duty of holding unity power factor on the high-tension side of the transformer when we are comparing it with a device that must of necessity operate at much larger wattless currents in the transmission circuit than does the booster converter even when the latter operates at 100 per cent power factor at low-tension side of the transformer. It is an advantage possessed by the booster converter, it can be operated at variable power factor, independently of its direct-current voltage, but that virtue should not be used against it in comparing it with a device that necessarily operates at a fixed power factor for a certain condition of load and reactance.

In the second place, most of the comparisons that have been emphasized in the text have been made between the synchronous converter operating with a 15 per cent range and the field control converter operating at a 5 per cent range. This, of course, is all right if the distinction is kept in mind that one type of apparatus is limited to low range applications and the other type can be used for wide-range applications.

If the performance of the synchronous converter had been based on a reasonably low reactance of four or five per cent, and if the range in application for the synchronous converter had been assumed at values now more commonly used than 15 per cent, that is, from ten to twelve per cent, the various comparisons would look differently and would be much more in favor of the synchronous types; but let me repeat: these statements are in no sense to be taken as a disparagement of one type against the other, because each has its field, and each has advantages in its own field, and these comparisons are important only in sizing up the situation in a particular case for a particular operating system.

There is, however, one point mentioned in the paper that is, I think, of fundamental importance; the question of efficiency. It is stated in the paper that the synchronous booster type has a considerably lower efficiency than the field-control type. I question, however, whether this statement can be made generally, based on the evidence we now have.

We have recently made input-output efficiency tests, using a 60-cycle converter of 6000 amperes normal rating. We used a 60-cycle booster converter, because it would have the greatest load losses, and presumably the greatest differences in performance under different voltage conditions. Except for the load losses, the efficiencies of the two types of converter can be accurately compared by comparing the separate measurable losses. I am not claiming any extreme accuracy for these input-output tests. I have said so much, on former occasions, about the difficulty of making such tests, and these difficulties are still with us, that I cannot take any other position now; but I will show we have been as careful as possible in making these tests to get accurate and reliable results, and that the results of the various tests are quite consistent. The machine used was a 6000-ampere, 60-cycle, 260-volt, booster converter having a voltage range of 230 to 290 volts. The unit is large enough to be typical of those used in Edison service without being too large for careful factory testing. The input-output test methods used, while not new, comprised all of the details and refinements in equipment, methods, and personnel that have been found by experience to be essential in tests of this character. The a-c. power was measured by three single-phase wattmeters and also by one polyphase wattmeter while the d-c. power was measured by two sets of d-c. voltmeters and ammeters with independent shunts. A specially trained force of meter readers was used; all meters were thoroughly shielded; four groups of 15 readings each were taken for each load, each group with different meter positions, and special precautions were taken to avoid including any readings during which the slightest change of load occurred. Tests of this character are strictly laboratory tests, costing from one to two dollars per machine kw. in addition to tying up a great part of a manufacturers test equipment. Although not feasible on commercial circuits, the use of laboratory input-output tests is justified on the manufacturers part when it represents the only method whereby comparative data can be obtained on certain operating conditions in machines.

The curve (Fig. 1) shows the difference between the calculated separate-loss efficiency and the input-output efficiency for the condition of no buck and no boost, that is, with the booster unexcited, and with a normal voltage of the converter of 260 volts. At full load the separate loss efficiency is 95.75. The observed input-output efficiency at full load is 94.95 giving a load loss of 0.8 of one per cent. You will notice that the separate loss efficiency continues to increase slightly at 1.25

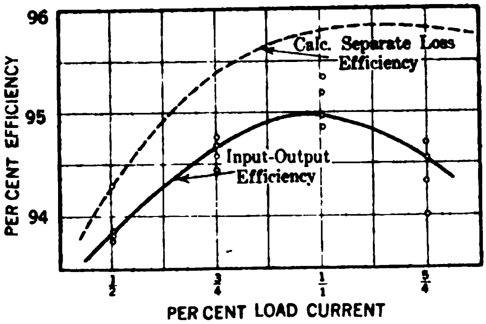


FIG. 1—INPUT-OUTPUT EFFICIENCY TESTS
6000-Ampere, 290-260-230-Volt Booster Converter. Tests at 260 Volts.

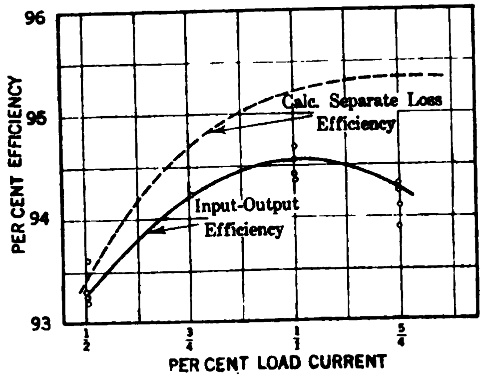


FIG. 2—INPUT-OUTPUT EFFICIENCY TESTS
Same machine as Fig. 1. Bucking to 230 volts.

load, but the input-output efficiency falls off perceptibly being 94.55 at the overload. This point is of considerable importance in considering the change from nominal and overload ratings to single load ratings. Current densities cannot be materially increased without increasing the load losses in much greater ratio.

The curve (Fig. 2) shows the bucking condition, with 230 volts; that is, bucking 30 volts or roughly 12 per cent below the mid-voltage. Here the difference in efficiency at full load is 95.25 to 94.55 or 0.70 per cent load loss which is practically the same as at full load.

The curve (Fig. 3) shows the contrary condition of 30 volts boosting, or 290 volts. Under this condition, the separate loss efficiency is 95.55 and the input-output efficiency is 94.6, giving a load loss of 0.95.

You will notice under the three voltage conditions and at full load, the load loss is substantially the same in per cent, 0.8, 0.70 and 0.95. It is slightly less at the bucking condition and slightly more at the boosting condition than at the mid voltage.

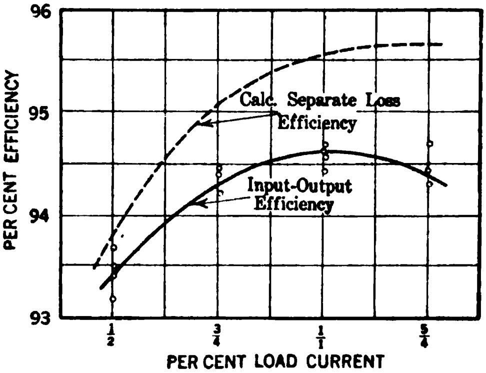


FIG. 3—INPUT-OUTPUT EFFICIENCY TESTS

Same machine as Fig. 1. Boosting to 290 volts.

This small variation in load loss with wide variations in voltage disposes of the supposition that the efficiency of the booster converter is several per cent lower than the efficiency of the field controlled converter because of load losses. If load losses are eliminated as a cause of low efficiency there remain only losses that can be directly measured and about which there is no uncertainty. These other losses account for about one half per cent efficiency in favor of the simple converter due to the absence of the booster losses. To offset this there will be increased losses in transformers and lines due to the lower power factor of the field controlled converter.

This same booster converter was used to obtain an approximation of the load losses at a power factor corresponding to the minimum power factor of the field controlled converter. The converter was operated at mid voltage, 260 volts, with the booster unexcited, but with the converter field adjusted to give 30 per cent wattless current, leading. This does not give the same condition as when the booster is entirely absent but the results approximate this condition since the booster armature reactance is low. Fig. 4 shows the separate loss and input-output efficiency under this condition of low power factor. The efficiency, at full load, is 95.6 per cent by separate losses and 94.3 per cent by input-output, resulting in load losses of 1.3 per cent. This value would be reduced somewhat if the booster armature were absent but it is reasonable to assume that the load losses would still be several tenths of a per cent above the load losses of the simple converter operating at unity power factor and, in fact, above the load losses of the booster converter at mid voltage and unity power factor. This test shows that operation at 95 per cent power factor (30 per cent wattless current) corresponding with a 5 per cent increase in voltage results in a greater increase in load losses than does the addition of the booster for a 12 per cent increase in voltage.

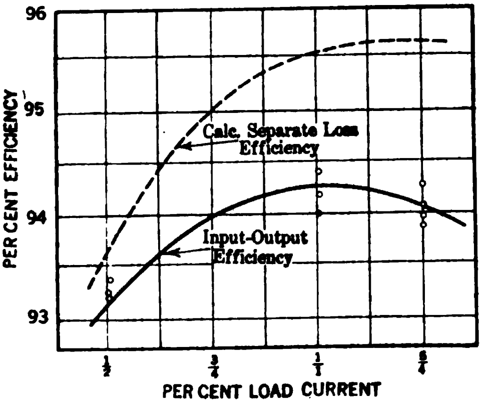


Fig. 4—Input-output Efficiency Tests
Same machine as Fig. 1. Mid-voltage 30 Per cent Wattless Leading.

I think the conclusions that one can safely draw from these tests are as follows:

First, that the efficiency of the booster converter is not necessarily or inherently lower than the efficiency of the simple converter operated at low power factor.

Of course, individual comparisons could show that result, but I do not think that we can draw a general conclusion that lower efficiency is an inherent characteristic of the booster type. There is nothing in the size or the losses or the different losses existing in the two types, to account for any important difference, and this test made on a large modern machine bears this out.

Second, in the particular machine tested, the efficiency of the booster converter throughout a 60-volt range is, on the average, as high as the simple converter when operated through a range of half this voltage. Compared on the basis of the same voltage range, the synchronous booster converter would have a higher average efficiency and with the increased loss in the high-tension distributing circuit, due to the greater wattless current in the case of the field control converter, this comparison would be still more favorable to the booster synchronous converter.

Third, the percentage load losses is fairly constant throughout the entire voltage range and is of the order of one per cent.

This is interesting, because we have very little available data from actual tests on load losses in converters;—some years ago when the subject of load losses was quite thoroughly discussed in the Institute, considerable data were presented concerning alternating-current generators and direct-current generators, but practically nothing was available concerning converters of any type.

A. M. Garrett: With reference to the field-controlled converter from an operating standpoint, can this type of unit be applied to a transmission system having in some of its lines a power factor of relatively low value. That is, for example, we may have a group of parallel lines working at 70 per cent power factor or lower, and the converter may further reduce the capacity of these lines and necessitate investment of additional lines, unless some means can be devised whereby the performance would always compensate and improve the power factor conditions.

If this type of unit can operate successfully with the present type now in service, and parallel with them on the alternating and direct-current side, I can see no reason why the field-control converter cannot be used on an Edison network having high load density and narrow pressure range. The efficiency then, it would seem, would be the main determining factor.

With reference to the automatic substation, the creation of new load centers is based solely on existing distribution losses. The saving of these losses is in the same amount, regardless of whether the substation is manual or automatic. A saving in current losses can be made, however, with automatic operation in case of a special customer that otherwise would require long feeders from the existing system.

In the case of the automatic control, the wages of operators are eliminated, but the cost of inspection must be considered. Building maintenance charge per unit are the same in either type. The maintenance charges for the major apparatus in the substation are likewise the same for either class. We have an additional maintenance charge for the automatic features and fixed charges on additional investment to cover the cost of automatic apparatus, which at present practise will be equal, approximately, to one-third of the total cost of plant installation.

I might say that automatic apparatus at present costs somewhere between $35,000 and $40,000, say, $35,000. It would seem that from these figures there is not the saving in automatic operation as shown in the paper. If we have a number of automatic substations properly placed, it would be a very valuable feature in the restoration of service if these converters could be controlled from some central point, and bring them up at the same rate, rather than having the present type of multiple acceleration and starting.

Raymond Bailey: The authors' reference to alternating-current starting is of particular interest to all of us. They refer both to low-tension and high-tension starting and of the different methods of high-tension starting have named three; series-multiple, extended primary, and Y-delta.

It would seem that the series-multiple connection would not be of general application because it is of particular value only where the source of energy supply is two phase, and there are not many instances of this.

The extended primary winding method of starting involves extra cost for the transformers and is adaptable when provided with reactors for switching under load, but up to the present time there has not been a real demand for switching converters under load conditions

In Philadelphia about four months ago a 3315-kw. synchronous booster converter was put in operation, making use of Y-delta starting which we believe is the first use of this method of starting converters. The results obtained have been very satisfactory.

The use of high-tension starting greatly simplifies the low-tension copper work, and makes the interleaving of these conductors possible without any great complication. The low-tension conductors can be of short length and when inter-leaved properly, give very little reactive voltage drop.

In the particular instance referred to above, the starting and running switches are electrically and mechanically interlocked, so that the operator cannot close the running switch unless the starting switch has been closed first, and when closing the running switch the starting switch is tripped automatically just before the running switch closes. This arrangement fixes the time between opening ot the starting switch and the closing of the running switch, and it cannot be changed either intentionally or unintentionally by the operator. This arrangement simplifies the starting process and consequently does much to prevent trouble.

The cost of the installation for high-tension starting is considerably less than for low-tension starting and in this particular case, it is estimated that the saving is about 50 per cent.

It is a good plan to have provision for readily re-energizing any part or all of the Edison network, should an interruption to service occur. One possible way of accomplishing this is by bringing the network voltage up to a certain point by means of a number of converters operating on the starting tap, and then raising the voltage from that point to normal by means of converters operating on the running tap. High-tension starting links in very well with an arrangement of this sort both on account of simplicity of operation and because the transformer neutrals used to obtain three-wire d-c. service can be of connected before the converter is first thrown on the line on the starting tap, and remain closed during the entire process of rè-energizing, thus preventing possible serious effects from unbalance.

I have a question in connection with the commutation of the field-control type converter which I would like to ask Mr. Barton. The statement is made in the paper presented this evening that the commutation control is obtained from the main field rheostat as the amount of correction to the commutating-pole field strength is proportional to the strength of the main field. I would like to ask what commutation conditions would be expected with this type of converter carrying an overload when the voltage of the a-c. supply is somewhat below normal which it may be required to do under abnormal conditions or when carrying rated load, operating on the starting connection?

Philip Torchio: Speaking from the standpoint of the operating man, as Mr. Lamme pointed out, the first time we started to operate rotary converters was by means of field control. We had purchased induction regulators but there was some question of patent rights involved, or perhaps the manufacturer did not know how to design them, so that we did not get the induction regulators, and the manufacturers sent us instead some external reactors to put in series with the circuit. They operated in a satisfactory way. We liked them because they offered a simple method of operation of rotary converters.

Then came the induction regulator. That was also satisfactory to the operators, but it gave a lot of trouble to the engineers, due to mechanical weakness of the quadrants in withstanding sudden overloads.

Then one day a salesman of one of the manufacturers came around and said they had a new idea—that they had designed a synchronous booster-converter, so we took it up and bought the new thing, and incidentally, a couple of weeks afterwards, I received a pamphlet from abroad, giving an illustration of an installation of four synchronous rotary converters that had been in service for a year or two; I turned it over with the contract to the salesman and said, "You make them at least as good as these." We never tried the split-pole field control, as we were entirely satisfied with the synchronous booster-converter, and to a very large extent our installations in the last fifteen years have been of that type, but some time later came along another salesman who wanted to sell us a dynamotor. We made many tests on a trial machine and finally we came to the conclusion that it was about as efficient as the synchronous booster-converter and required less total floor space.

Then came back our old type field-control converter and in large systems I think it fits in because with 5 per cent regulation up and down, we can meet all the conditions of operations on certain buses. This type of converter, as Mr. Barton has said, is more economical in first cost, occupies less space, and is quite desirable for installation.

We have now submitted for consideration the synchronous motor-generator. I looked over this diagram last night, and after carefully smoking my pipe, I said, "It is all right. It looks more formidable than it really is." Many of the elements in the diagram are small things than can somewhere be taken care of in the station and I came to the conclusion that the whole thing seems very promising and desirable. It is the most valuable contribution I have seen lately for installations in Edison systems.

I heard of this synchronous motor-generator before, but I am very glad to have Mr. Barton's contribution in such a complete form, so that we can study it more in detail; undoubtedly it will be of great value to many Edison Companies.

I want to take issue with Mr. Barton with regard to one statement which he makes, and which may have an unfavorable influence on young engineers. On page 689 he states: "The motor-generator with such characteristics will give continuity of service on an Edison system equal to that of the generating system supplying the power. The motor-generator, therefore, supplements the storage battery and can be used to reduce the amount of battery capacity required to give a system protection against a momentary interruption of the a-c. supply."

The authors start off from the legitimate premises that the a-c. supply may be interrupted, but they also imply that there may be an interruption of d-c. supply and, therefore, if they take that liberty in allowing such an interruption, then they conclude that the motor-generator replaces the storage battery.

Now that is not a fact. It may be that we place our standard of service too high, but we still stick to that standard that we have been educated in, in the past, and we want to live up to today, never to discontinue the service—there must not ever be any momentary interruptions to the customers' supply. We do not say we will never fail, but we will attempt to keep that aim as a standard. We cannot, therefore, admit that there is going to be an interruption of service in the d-c. customers' supply, if the a-c. supply momentarily fails. We think that our customers, particularly in the large Metropolitan district, are willing to pay the additional small extra charge for having the insurance that they may receive absolute continuity of service. Their important requirements will not allow any other treatment of the matter. We may not even consider failure of service permissible if at all preventable, within reasonable limits of cost.

Our practise in laying out our plants is to supply every substation with a-c. power from at least two independent generating stations, so that with the failure of one generating station, no substation will be totally deprived of primary power. In addition, in every substation, we aim to install storage battery capacity sufficient to carry the maximum load for a period of approximately eight or ten minutes.

With such a plan of at least two independent power sources, supplied through independent routes of high-tension cables and with standby storage batteries able to carry approximately the total maximum load for a period of eight or ten minutes, we aim to insure continuity of operation of the substation and of service to all of our customers.

We have had, in my recollection, at least five total interruptions of one or another generating station, and in no case were the rotary converters, which were operated on the other system, affected, and all continued to render service which, in conjunction with the storage batteries, created such a condition that it was hardly noticeable to customers that we had one main generating station shut down.

Also it is our experience that in no case, in these five plant shutdowns, did we fail inside of five minutes—usually I should say inside of one minute—to have the voltage on the buses or part of the buses of the affected station available to deliver service; so that the system operator could signal to connect to the unaffected portion of the generating station rotary converters to pick up loads and relieve the storage batteries.

By these means we have been successful on all occasions in keeping the substations in operation under all conditions. So I am a little disturbed to see that possibly young engineers who probably have not lived with the old Edison standards of service should adopt this view of lowering the standard of continuity of service which I do not think the industry, as far as I know, is ready to accept. It may be that this lower standard may apply to small Edison systems, but certainly it does not apply to any large Edison systems in this country.

Selby Haar: The question that Mr. Nims asked a short time ago recalled to my mind an experience I had—nearly fifteen years ago—with a cascade converter or motor converter. It was a 60-cycle machine, because, as I recall it now, it was intended to overcome the objection at that time to the 60-cycle rotary converter; the development of a satisfactory 60-cycle rotary converter destroyed the need for the more expensive machine. In addition to the fact that the field of this machine disappeared, there was also difficulty in operating it, due to the fact that, as Mr. Nims said, the transformer is an induction motor operating considerably below synchronism, and the difficulty was in preventing the motor from approaching synchronism, or viewing it with the operating speed as a basis, we might say, running away.

H. C. Albrecht: In the two largest Edison systems in this country, New York and Chicago, the energy for practically all of the converting apparatus is supplied at 25 cycles. I will discuss the question of measurement and control of power factor of booster converters, particularly from the standpoint of the operator of the Edison system supplied with energy at 60 cycles, as in Philadelphia.

It has been the general practise throughout the country to measure power factor of both 25 and 60-

cycle converters from a power factor meter connected to the high-tension side of the transformer supplying the converter. The general practise has also been to operate converters with power factor, measured in the manner described, maintained at or very near to unity.

The measurement and control of power factor of booster converters, because of inherent characteristics, is of very great importance, and this is particularly so with 60-cycle apparatus for reasons to be outlined.

Power factor has usually been measured on the high-tension side of supply transformer, because of the difficulty of doing it in any other way, especially with units of very large capacity. The installation of current transformers in the low-tension leads between supply transformers and converter collector rings presents construction difficulties, particularly with 60-cycle equipment, where increased spacings necessary between the conductors would materially increase the reactance, which is undesirable.

I desire to strongly recommend the operation of booster converters so as to maintain approximately unity power factor in the converter armature itself, rather than in the high-tension supply circuit, particularly with 60-cycle equipment, where reactance of transformers, leads and boosters are usually higher than with 25-cycle equipment. Mr. Barton, for instance, has brought out in his paper that particularly at 60 cycles the total reactance is so great that the converter armature itself may have to operate at as low as 95 per cent power factor leading if unity is to be held on the high-tension side of the transformer.

The slight gain in maintaining unity power factor in the supply circuit, from a transmission standpoint, is much overbalanced by the increased loss and greatly increased heating in some parts of the converter armature. I know of one instance in which a slight error in the "leading" direction in the power factor meter, (connected to the high-tension supply circuit) coupled with unfamiliarity with the conditions of high reactance, where a large 60-cycle converter armature was burned out through excessive heating in tap coils, due to leading currents.

In Philadelphia we have decided to operate booster converters at as near unity power factor in the actual converter armature as is possible and to obtain a more accurate method of measuring power factor. In our installations, it is the practise to split up and interleave the copper bars comprising the leads of each phase, so as to keep their reactance to a minimum. This has made the installation of current transformers in these leads practically impossible. Power factor is, therefore, being measured by using current from series transformers in the high-tension supply circuit, and potential from the converter collector rings. This eliminates the effect of transformer and lead reactance. The effects of booster reactance and transformer exciting currents are calculated and largely compensated for by a shifting of the meter scale.

Means of measuring power factor more accurately than with the ordinary power factor meter were carefully looked into and a wattless kv-a. meter operating on the watt meter principle has now been adopted, because of its greater accuracy and is in use on practically all of our booster-converters.

I do not care to enter into the question of design as to whether the 60-cycle booster-converter characteristics, mentioned by Mr. Barton in his paper, are most desirable. It is certainly true, however, that the necessity for careful operation and accurate measurement to maintain armature power factor close to unity is not as great in a design involving reactances and exciting currents lower than the figures stated in the paper.

D. W. Roper: The comparisons of the several types of rotaries set forth by the authors are particularly interesting but it is noted that no mention is made of their relative synchronizing power. This is one of the most important items in the behavior of a rotary converter under operating conditions.

Some years ago when the Commonwealth Edison Company was making some tests on switches and reactors, an opportunity was afforded to make some tests on the relative synchronizing power of different types of rotaries under identical conditions. Three rotaries were used in this test, one each of the split-pole, the induction-regulator and the synchronous-booster types, all of 1000-kw. capacity and with identical overload relay settings. They were connected to a 12,000-kw. generator operating at normal voltage and then artificial short circuits were made on the bus at the generating station. These tests show that the split-pole type of rotary was the most sensitive, the induction-regulator type next, and the synchronous-booster type third, that is, the latter type had the greatest synchronising power. It will be very interesting if the authors of the paper could locate the new type of rotary on this scale of sensitivity.

The question of the behavior of rotaries at times of a complete interruption has been raised, and the authors have inquired the desirable qualifications of a rotary to meet these conditions. The requirements will probably vary for different systems according to their design and their methods of operation. Some differences in the statement of the requirements will also be found among the engineers of the same company due to their different points of view and the differing weight which they ascribe to various factors. In Chicago during the course of twenty-five years there has been no complete interruption of the Edison 3-wire system of distribution, but there have been two or three cases where a portion of the downtown district was cut off from the remainder and was dead for several minutes, but in each of these cases the surrounding substations remained in service and continued to supply current at approximately normal voltage to the remainder of the system. In each case the system was restored to normal operation by starting up a number of rotaries in each of the substations and simultaneously connecting them to the load. In some cases this has been done by disconnecting the battery from the system after it had been about discharged, and using the battery for starting the rotary. Owing to the comparatively small amount of current required for starting the rotary, the battery would be available for this purpose even when it exerted no perceptible influence in carrying the load. In some of the substations there is one rotary arranged to start from the a-c. side, and in such instances this rotary is started first and supplies the direct current for starting the remainder. By having at least one rotary in each substation arranged for a-c. starting it is always feasible to resume service very promptly following an interruption if there is an interrupted supply of primary alternating current, and this is one of the points to which the larger Edison companies are paying the most attention. If the transmission system is laid out so that each substation has a supply from more than one generating station or from more than one section of the bus in a large generating station, then the chances for an entire interruption of the Edison 3-wire system are rather remote.

T. T. Hambleton: Mr. Nims has questioned why the motor converter is not used on the American Continent. The action of this machine is a mixture of d-c. generator and synchronous converter action, and as might be expected, it falls between these two types, both on the score of efficiency and cost. It has the disadvantage that the induction motor reactance and exciting current are both large as compared to that of the synchronous converter and its transformers.

Since the induction motor at a fixed rotor speed is a transformer having one definite ratio the d-c. voltage of the motor converter is fixed, except in so far as it can be changed by the action of reactive current on the induction motor reactance. It, therefore, has the same voltage range limits as the simple field controlled converter. Since it has no marked advantages over the types in general use, it has never displaced them.

Mr. Newbury has expressed the opinion that there may occur misunderstandings of the comparison of characteristics of the field controlled and synchronous booster converter, as presented in the original paper. He has himself misunderstood the term "booster reactance voltage" as used in this paper. The total quadrature or reactance voltage set up in any alternator is often called the "synchronous reactance" voltage. This "synchronous reactance" includes the pure "slot and tooth tip leakage" which varies in different designs from 15 per cent to 30 per cent referred to the rated-voltage and includes also additional flux set up in the poles by the m. m. f. of the armature current. This total "synchronous reactance" as determined from the "synchronous impedance", or sustained short-circuit current of the average alternator is approximately 100 per cent. The m. m. f. is due to reactive current and acts along the axis of the poles.

In this respect the average design of booster is a normal alternator. The conditions are somewhat different when the booster is carrying full energy at the neutral voltage. The m. m. f. of the armature acts between the poles. This reduces the synchronous reactance to 65 per cent or 70 per cent of the booster voltage, or 10 per cent of the converter voltage, as stated in the original paper. This quantity has been measured directly on several different sizes of booster converters, which were provided with an auxiliary collector ring connected to a point between the booster and converter armature windings.

In so far as the knowledge of the writers extend, it may be stated that synchronous boosters made by the various manufacturers in this country are of similar design using either 9 or 12 slots per pole with one coil per slot in the armature. Therefore, the characteristics described in the original paper apply with fair accuracy to all booster converters now in operation. Exception must be taken to the opinion that modification be made in characteristics based on the booster "quadrature" voltage being 10 per cent of the converter voltage.

A question has been raised as to the fairness of comparing the booster converter adjusted for unity power factor at the primary with the field controlled converter which must of necessity depart from unity into both lead and lag at the primary.

It is a fact that some operating companies do hold unity power factor at the primary of transformer of their booster converters. It would seem to be perfectly fair to show what this condition means, particularly in view of the fact that Fig. 6, shows also the performance of the booster converter with unity power factor at the collector rings and in the converter armature itself.

Again, there is questioned the propriety of comparing the 5 per cent field controlled converter with the 15 per cent booster type, whereas the average range is about 12 per cent. A 15 per cent range (230/310) is not an uncommon requirement, so it would seem proper to show this extreme. It should be noted that Figs. 3, 4 and 6 compare the armature copper losses in the two types of converters, and further, that this loss depends only on the actual range at which the booster is operating and not on its potential range. These curves may, therefore, be interpreted for a booster of any range less than 15 per cent. It should be further noted that Fig. 10 compares the efficiency performance (by actual input-output) of an eleven per cent (240/300-volt) booster converter with a 5 per cent (260/285) field control converter.

These two converters are almost identical in design and afford an excellent comparison of the two types. The pure ohmic loss in the booster armature approximate ½ per cent. The actual copper loss due to eddy currents will be approximately 1 per cent. The magnetic field set up by the armature at the neutral voltage contains a large third harmonic and causes considerable core loss which may amount to ½ per cent. This accounts for a difference in efficiency of 1 ½ per cent at the neutral voltage.

Mr. Newbury in comparing the efficiency of these two types has attempted to use a booster machine for field control. The booster in this case is still a booster which has its fields excited by means of reactive current in its armature instead of current in its field coils. The machine is then burdened with all the losses incident to the action of the booster as such and in addition—all the losses associated with field control. It seems evident, therefore, that such a test does not show the relation of losses in the two types of converters and that any general conclusion based on such tests does not hold.

Mr. Garret has raised a question as to the advisability of using the field control converter on low power factor lines. If voltage variations are small enough to permit, a transformer tap could be selected to permit this type of converter to operate at unity or slightly leading power factor.

Mr. Bailey questions the effect of low voltage on the commutation of the field control converter. If it were not for saturation a change of voltage would reduce both the reactive current and auxiliary field current in the same proportion and have no effect on commutation. The saturation effect will not be sufficiently serious to affect commutation for the duration of such low voltage emergencies. This type of machine should commutate its maximum load successfully at 95 per cent power factor without any auxiliary commutating field compensation. Its behavior at low voltage will at the very least be as good as that of the booster-type.

Mr. Roper mentions the synchronizing power of different types of converters. This is a term which in general is rather loosely used. A more accurate expression is —"synchronizing constant" which may be defined as the ratio of synchronizing torque per degree of armature displacement to the moment of inertia of the armature. This constant is a measure of the ability of any synchronous machine to hold in step with its supply voltage. Since the supply voltage is affected by the line reactance and resistance, stability is determined by all these factors. The total effective reactance between the converter armature and the primary is approximately the same for either the field control or synchronous converter; they will have equal synchronizing ability, if the armatures have the same design proportions.

T. F. Barton: Answering Mr. Nims on the merits of the motor converter I would say that such a machine has been used abroad considerably, and has been built for use in this country, but the need of such a machine has never existed with the 60-cycle converter developed to give as successful operation as it does today.

There may come a time when the motor-converter will have a place, but at present, it cannot be justified on the score of cost, efficiency and other considerations, which usually come in to determine the type of machine selected.

Mr. Newbury brings out some very interesting points. It may be that we have been misunderstood in our reference to the values of booster reactance. The reactance drop in 25 and 60-cycle boosters with which I am dealing is about the same. The drop referred to totals the leakage reactance and the armature reaction. Removing the field structure of the booster will reduce the voltage drop across the booster armature for a given current to approximately one-half value.

The efficiencies presented by Mr. Newbury apply to the modified booster converter described in the paper, and the efficiencies are what might be expected for such a combination.

Data given by the curves in the paper comparing the two types of machines are simply to show, as nearly as we can, the relations of the several factors in each type of unit, and are arranged to show plus and minus 5 per cent selected for one type and plus and minus 15 per cent for the other. These values are about right for each type, and since complete data are given a comparison can be made at any desired voltage range requirement. No specific mention is made of comparisons at 15 per cent as against five per cent.

Mr Garrett brings up the question of power factor on the high-tension line. It is a very important consideration, and to best meet this requirement the transformer high-voltage winding is provided with taps to give 95 per cent leading at the converter collector rings at full load, and maximum voltage (about unity power factor on high-voltage line). The inherent relations are such that for any other load or voltage within the designed range of the machine the current in the high-voltage line will not exceed the unity power factor current at maximum output of converter.

Mr. Bailey spoke of changing transformer connections with the converter loaded on d-c. end. One of the possible limitations of the field control converter is its more limited voltage range for restoring service. However, if the transformer is arranged with an extended high-voltage winding and suitable switch gear for changing connections under load, the field control type is more suitable than the booster type for switching under load.

A converter will operate successfully over a wide range in voltage and the determining factor in switching from one transformer connection to another is parallel operation on the d-c. end. If a substation contains a single unit the voltage steps can be large, provided the resistance of the tie to the neighboring stations is not too low. For more than one unit connecting to a common bus the voltage steps must be small to prevent abnormal shifting of load among the machines.

In regard to overload commutation at times of low a-c. voltage, I think there would be no bad effects unless unstable operation resulted, which would be at a very low point.

With self-excitation the power factor of the converter will not vary greatly as the a-c. voltage varies, so that the relation of auxiliary commutating field and reactive current will not be changed enough to seriously effect commutation.

I certainly appreciate what Mr. Torchio had to say on the operation of d-c. systems. It helps a lot in studying the situation to be met. It lays down certain requirements that determine, to some extent, at least, the operating characteristics of the machines.

The storage battery is the logical standby service for an Edison system. If there is complete interruption of power the storage battery alone is available to carry the system. The situation I wish to call attention to is (on 60-cycle systems, at least,) that the great majority of disturbances that finally get into the d-c. system are caused by disturbances on the a-c. distribution. One operating company will report very little difference between the performance of the synchronous converter and the motor-generator set. Another will report that the motor-generator set is very much better. The next one will report that the converter is better; and the fact that I want to get before the Institute is that in the motor-generator set the motor can be designed to withstand sudden changes in frequency and voltage, and the voltage can be entirely removed for a very short time, due to switch operation, etc., and then restored to the machine, which will immediately come back into step, and give such output as it is capable of delivering, whereas in the case of the converter it would be thrown off the line, and considerable time would be required in resynchronizing.

I think it is more important to get the alternating-current end of the motor generator right for system operation than it is the direct current, and the principal effect in load limiting, on the d-c. end, is during times of trouble when other types of machines trip off. Such a generator remains connected to maintain such substation voltage as conditions allow, until the effected generators can be rearranged, and normal conditions more or less restored.

On systems where one generating station supplies all the power, and where there may be an outage beyond eight or ten minutes, there is the problem of restoring the Edison system, and in this connection I want consideration given to the actual requirements of machines. We have thought at times that all machines should be required to meet this situation. In some systems the a-c. supply is only the Edison system, so that the a-c. voltage can be controlled and that is a desirable feature. In most systems, however, other load is supplied so that the a-c. voltage must be made normal as soon as possible, leaving it up to the conversion apparatus, to meet the voltage requirements.

Mr. Albrecht brings up the point of 60-cycle converters, and some of the things I have said in answer to Mr. Newbury will apply to transformer reactance, etc. The converter should be operated within the power limits for which it is designed, and when exceeded the chance of trouble increases very fast.

There is one advantage in operating synchronous booster converters at unity power factor at the armature, and that is under certain conditions of load and voltage, the d-c. excitation of the booster is working against a reactive current, which would exist if holding unity at the high tension of the transformer. For instance, if bucking the voltage, and unity power factor is held at the high tension, there results leading current on the converter, tending to raise the voltage.

With regard to Mr. Roper's remarks concerning synchronizing torque, I think this will vary among machines, depending on the individual designs, and we have not yet tested and placed the field control converter on the list, but I am inclined to believe it would be as stable or more stable than the others, and I do not see why it should be less so. During disturbance the machine least apt to go off is the machine which has the broader regulation. The field control converter has a broader regulation than any of the other conventional types, and therefore, for any disturbance, there is the least amount of load change, and therefore, the least disturbing factor.

Presented at the 369th Meeting of the American Institute of Electrical Engineers, Pittsburgh, Pa., April 16, 1921.

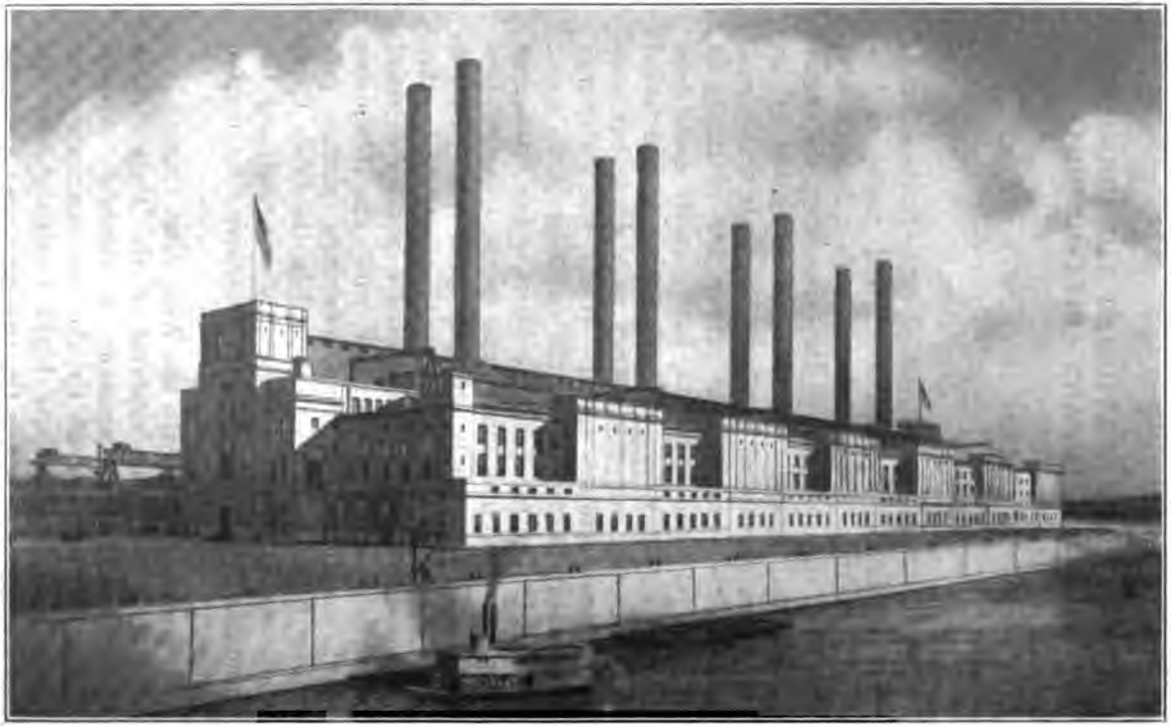
COLFAX POWER STATION OF THE DUQUESNE LIGHT COMPANY PITTSBURGH

BY D. L. GALUSHA AND C. W. E. CLARKE
of Dwight P. Robinson & Company, Inc.

THE PITTSBURGH district is the foremost steel-producing and manufacturing centre in this country. Steel plants with their furnaces and mills line the river banks for miles from the center of the city. Associated industries, attracted by an abundance of natural resources, adequate transportation facilities, ample labor supply, and proximity to markets for their products, have rapidly come into the adjacent territory. Growth during the war period was extensive, and the district as a whole has been busy since hostilities ended. Today, the Pittsburgh district may be fairly called the workshop of the world.

By 1912, central station facilities in the Pittsburgh district had become inadequate to meet the requirements of the rapidly growing industrial demand. The Allegheny County Light Company and other companies, owning and operating a number of small properties, were consolidated with the Duquesne Light Company. A steam-generating station previously built on Brunot's Island in the Ohio River below the city was considerably enlarged and the foundation laid for a comprehensive distribution system.

By an agreement with the West Penn Power Company and with the approval of the Pennsylvania Public Service Commission, a definite division of the territory served by the two companies was effected. The Duquesne Light Company, through this arrangement, serves the two counties—Allegheny and Beaver—with an area of 1154 square miles and a population of about one million and a quarter.



COLFAX POWER STATION—THE ULTIMATE DEVELOPMENT

A power station which will utilize, for condensing purposes, the entire minimum flow of the Allegheny River in 300,000 kw. of turbo-generators housed in a building 830 feet long.

In 1913, the first year after the formation of the new company, the energy output was 283,000,000 kw-hr. In recent years, the output has shown an average annual growth of about 15 per cent. Last year, the peak, which was somewhat affected by the curtailment of business, was 162,500 kw.; the energy output 805,000,000, kw-hr. giving a yearly load factor of 57 per cent.

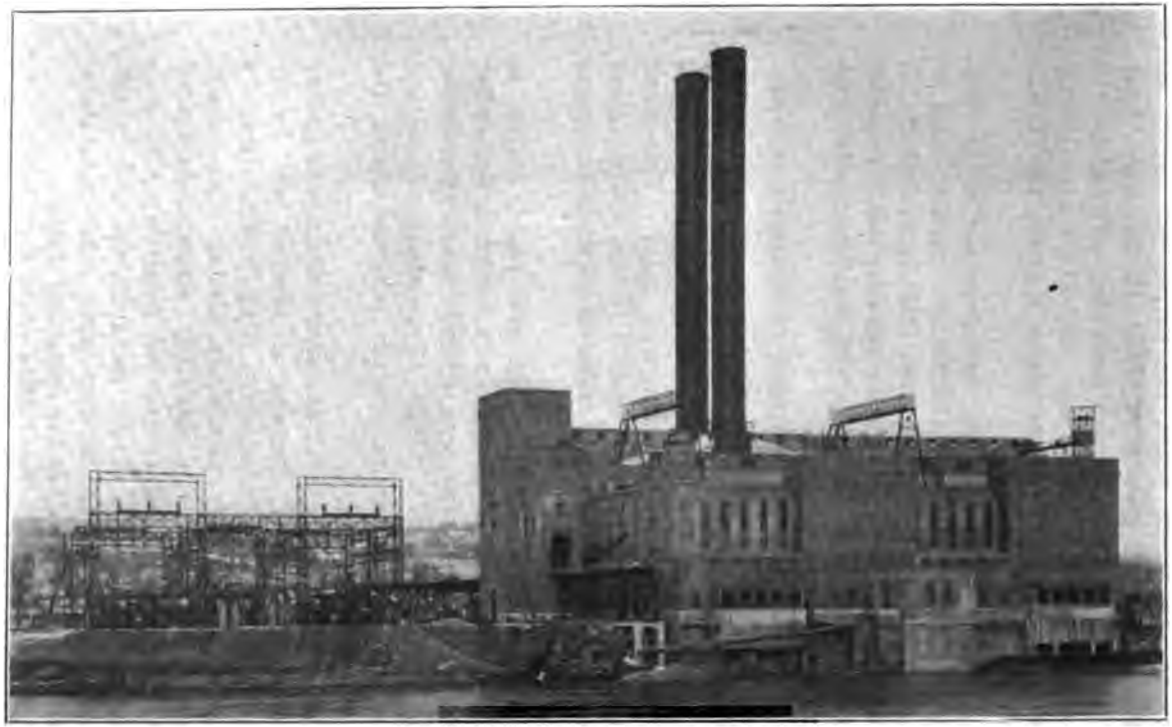
Previous to 1921, power was generated at the Brunot's Island station of 120,000 kw. capacity and at six other plants, varying from 2000 to 17,000 kw. in rating. The total generating capacity safely available from all of these sources under maximum conditions is 160,000 kw.

In anticipation of the need of increased capacity, a site for a new power plant had been purchased. The location selected is on the Allegheny River about 15 miles from the center of Pittsburgh and only a mile distant from the Harwick mine. This mine and the private railroad from it to the power station are owned by interests affiliated with the Duquesne Light Company.

Actual construction of the new plant, known as the Colfax Power Station, was begun in September 1919, and the station was officially opened for service on December 18th, 1920. Transmission line and substation construction was in progress during the same period.

Duplicate 66,000-volt transmission circuits completely surround the city, forming an electric belt locally known as "The Duquesne Ring." The Brunot's Island and Colfax plants are almost diametrically opposite each other in this ring. Substations located at intermediate points and fed from either or both generating stations supply radial 22,000- and 11,000-volt feeders, which, in turn serve other substations and consumers within the industrial district.

In the design of the Colfax plant four major considerations have been kept in view; first, to plan for the largest development which is economical at the site chosen; second, to produce a plant which will generate power at the lowest unit cost, including

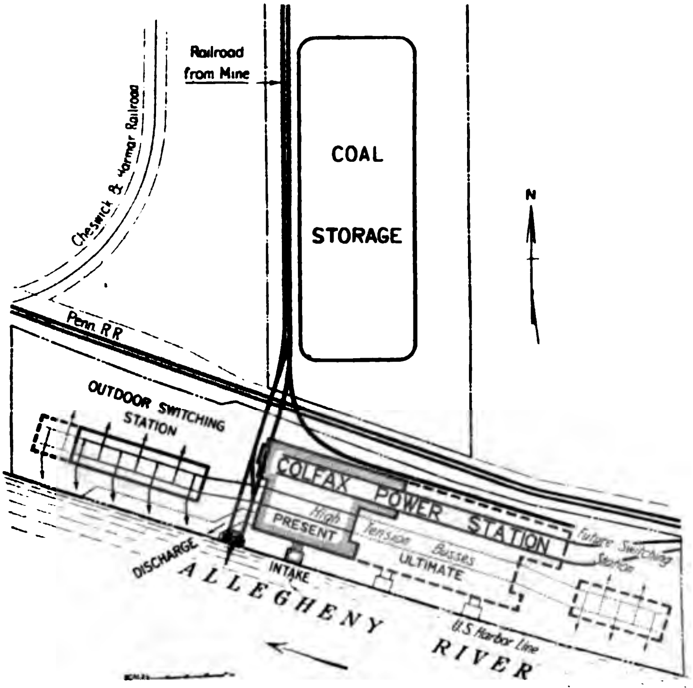


Colfax Power Station—The First Step

A building for two 60,000-kw. units. The standard gage railroad entering the northwest corner of the building brings in the coal, and 66,000-volt cables descending from the roof to the steel structure at the west end of the building take the electric energy away.

fixed charges, permitted by the state of the art; third, to obtain the maximum reliability practicable, and fourth, to adopt simplicity of design as a fundamental policy.

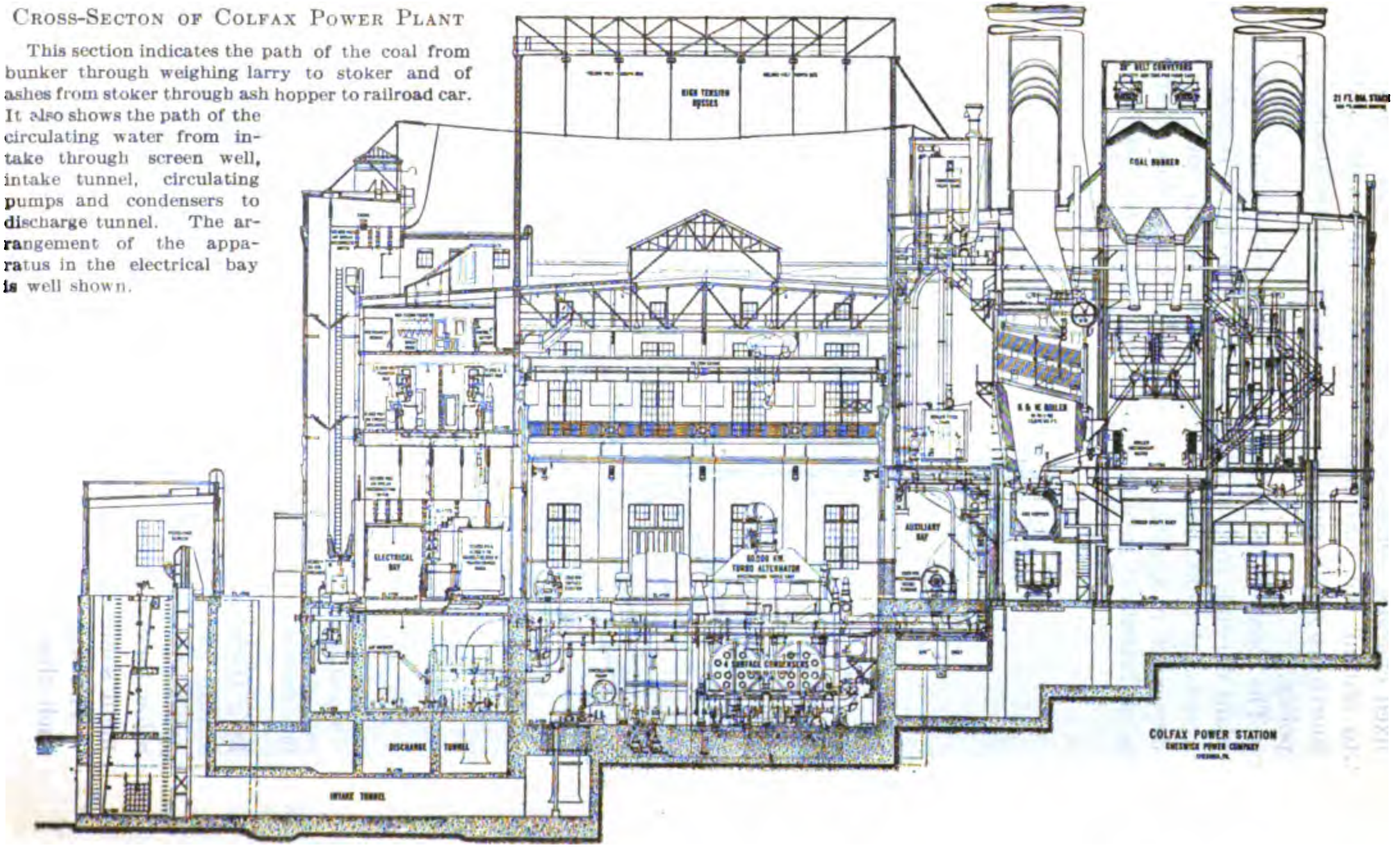
The flow of the Allegheny River, upon which the plant depends for condensing water, is found to furnish a natural limitation to the capacity which may be developed at Colfax. The minimum flow of this river is sufficient to furnish condensing water for 300,000 kw., therefore the design is made so that the power station can be extended on a uniform plan until all available condensing water has been utilized. To allow for contingencies and spare equipment a development somewhat beyond the minimum is provided for.



POWER STATION LOT PLAN

This plan shows the relative locations of coal storage, power house and switching station. It also shows the simple and direct paths along which fuel, water and electric current progress on their way through the works.

The size of the unit chosen, 60,000 kw. nominal, is such that the ultimate development may be divided



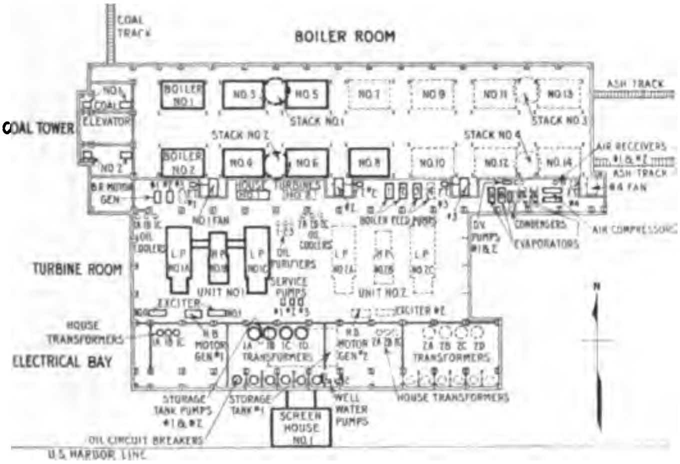
CROSS-SECTON OF COLFAX POWER PLANT

This section indicates the path of the coal from bunker through weighing larry to stoker and of ashes from stoker through ash hopper to railroad car. It also shows the path of the circulating water from intake through screen well, intake tunnel, circulating pumps and condensers to discharge tunnel. The arrangement of the apparatus in the electrical bay is well shown.

into five or six steps and when the plant is completed it will not be complicated with a large number of small units.

The first step of the development which is now completed includes one 60,000-kw. turbine and seven boilers. The power station building is, however, large enough for two units.

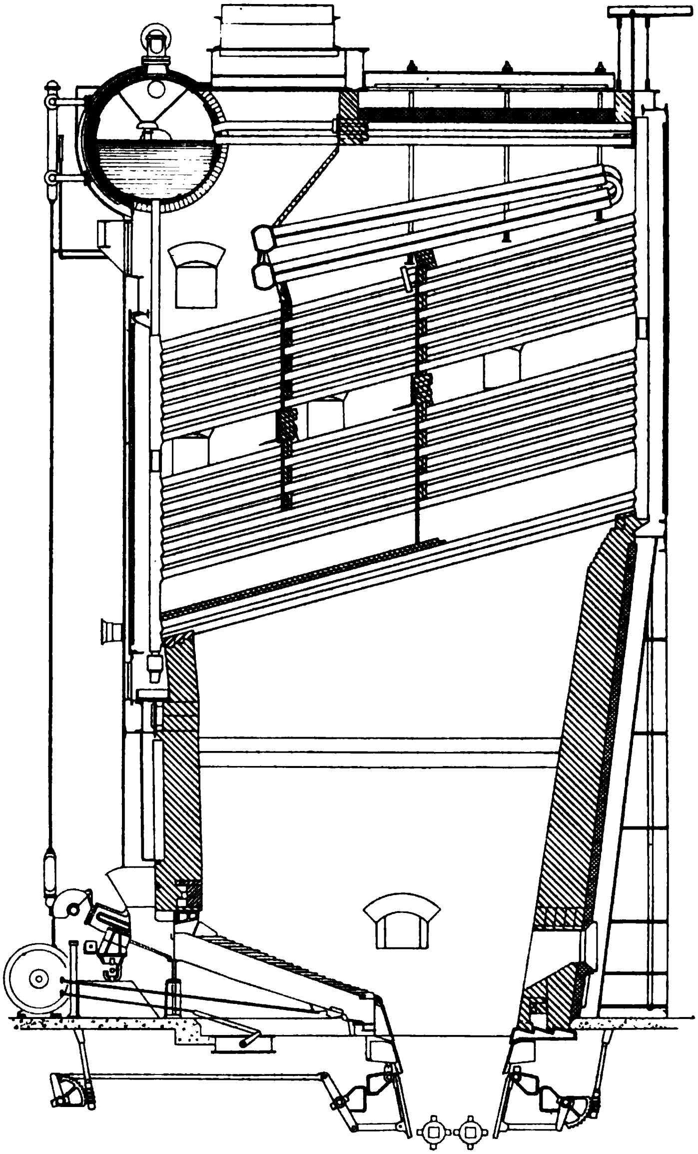
The relative floor spaces occupied by the turbines and the boilers are important factors in the general arrangement of the power station. In this case the turbine room has a width of 84 ft. and the boiler room of 108 ft. which, together with the electrical bay, give a station 240 ft. wide over-all. The boiler room is 350 ft. long and the turbine room is 278 ft. long, giving an approximate balance in length between turbine and boiler room.



POWER STATION FLOOR PLAN

Relative location of boilers, stacks, draft fans, feed pumps, main turbines, house turbines, exciters, heat balance motor-generator, main transformers, house transformers and various auxiliaries.

A Westinghouse three-cylinder compound turbine has been used. In this machine the expansion of the steam is divided into two steps and the low-pressure steam of the second step is divided into two parts. This division of the work of the steam gives three distinct mechanical elements, one being high-pressure



SECTION THROUGH BOILERS

The boilers are 18 tubes high with the two lower rows dropped below the tube bank and exposed to the direct heat of the furnace throughout their whole length. The boilers are set exceptionally high to give a large furnace volume.

and two low-pressure. These three elements are logically grouped side by side with parallel shafts with the high-pressure element in the middle and one low-pressure element on each side. With this arrangement each unit occupies a space 50 ft. 10½ in. in the direction of the shafts and 79 ft. 2 in. at right angles to the shafts.

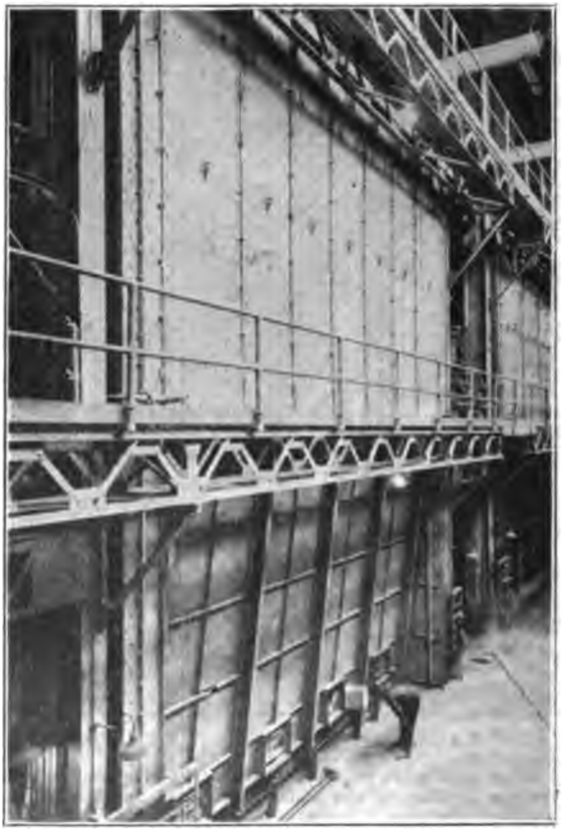
Babcock and Wilcox boilers of the greatest practicable width were selected, each boiler occupying a floor space about 34 ft. wide and 22 ft. from front to back.

COMPLETED BOILER

Illustrates the arrangement of the soot blower piping and its controlling valves, the location of the boiler gage board and the clinker-grinder drive.

With these boilers it has been practicable to use a boiler room with a single firing aisle between a double row of singly fired boilers, an arrangement which is highly desirable where the relative space occupied by turbines and boilers permits.

The illustrations herewith show the arrangement of the power house in much detail and the capacity and ratings of the important pieces of apparatus are listed in an appendix. A further detailed description is dispensed with in order to permit a discussion of some of the more important considerations which governed the design.



REAR OF BOILERS

This view shows rear of south battery of boilers showing walkways on two levels and comparative size of boiler to man in foreground.

ECONOMY

An important factor in insuring the economical generation of power in this particular plant is its location near a coal mine. A mine mouth location, however, is not adapted to efficient generation unless combined with an ample supply of condensing water. The Colfax plant has therefore been located a short distance from the mine on the Allegheny River which gives a water supply of unusual magnitude for a mining region.

Great care has been taken that the coal should move forward in a simple manner from the mine to the furnaces with a minimum number of handlings and that it should be handled by gravity wherever possible.

A private railroad gives a cheap one-mile haul from the mine to the plant. At the plant the cars arrive on an elevated trestle and the coal is dumped directly into the power station hoppers from which it passes by gravity to two crushers. The crushed coal is elevated by a bucket carrier to the top of the boiler room and is then distributed to the bunker by two belts with automatic traveling trippers.

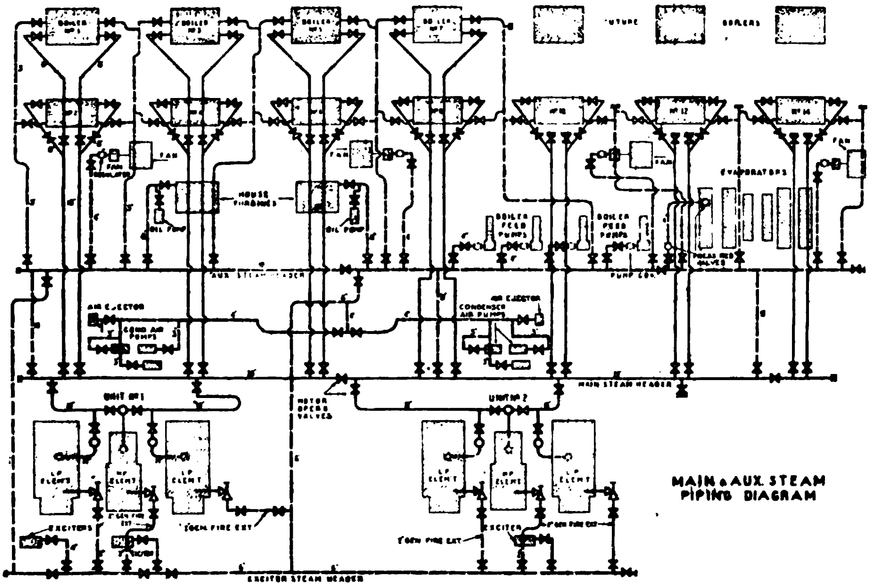


DIAGRAM OF STEAM PIPING

The high-pressure steam pipe which normally supplies only the high-pressure element, branches to give an emergency supply to each low-pressure element. Each generator is piped to receive steam from the exciter steam header for use in extinguishing fire in the generator windings. This diagram covers the present unit and a future second unit.

The mine furnishes a semi-bituminous coal having a heating value of approximately 13,500 B. t. u. per lb. as received. Provision has been made for systematically testing the quality of the coal by taking a continuous sample of the coal as it goes to the belts which distribute it to the bunker.

The quantity of coal used is determined by passing it through weighing larries with recording registers on its way from the bunker to the stokers.

The ashes pass from the furnaces through clinker grinders to large hoppers for temporary storage. Air-operated ash gates discharge the ashes by gravity into standard railway cars in which they are removed without further handling.

From the furnace to the turbine every detail has been carefully considered so that the heat of the coal may be converted to electrical energy with the highest thermal efficiency.

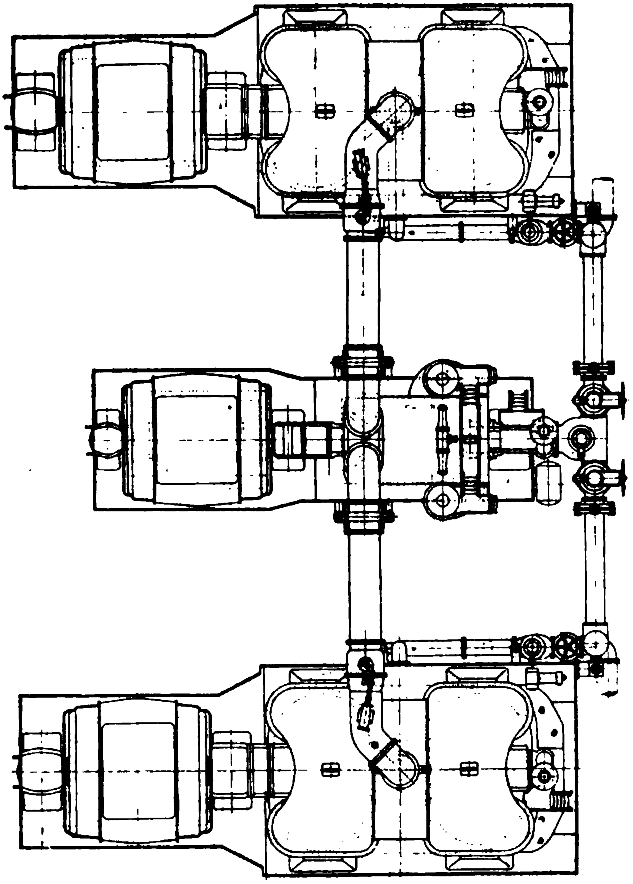
The stokers are extra long and will burn coal at such a rate that the boilers will develop 300 per cent of rating for peaks. However, so long as the load factor on the station is high a lower annual cost will be obtained by operating the boilers at from 200 per cent to 225 per cent of rating.

The boilers are set exceptionally high so that a furnace volume of approximately 3.45 cu. ft. per rated horse power is obtained. This liberal volume permits of the complete combustion of the coal even at high rates of evaporation in the boilers.

The boilers are 18 tubes high, which was the greatest height developed at the date of purchase. This gives the maximum amount of heating surface per foot of furnace width which is favorable for abstracting the greatest proportion of the heat from the gases on their way through.

The usual losses caused by air leaking through the brick boiler settings are much reduced in this plant by using steel casings.

A total steam temperature of about 600 deg. fahr. was chosen as giving the highest thermal efficiency consistent with thorough reliability. It was further decided that approximately 200 deg. fahr. of this steam temperature could best be used in the form of superheat. A gage pressure of 275 lb. per sq. in. was chosen in conformity with these considerations. To provide this superheat the superheating surface is 6700 sq. ft. as compared to 20,876 sq. ft. of heating surface in each boiler.



PLAN OF 60,000-KW. UNIT

The plan shows the three elements of one generator. Each element is of 20,000-kw. capacity. The speed of the central element is 1800 rev. per min. and the frequency 60 cycles; the speed of each outside element is 1200 rev. per min. and the frequency 60 cycles. The outer elements are spaced 30 feet on centers from the central element to give ample space around each element for convenient operation and also around the condensers in the basement below.

The instruments which are provided to permit of economical boiler operation include feed water regulators, water flow meters, draft gages, pyrometers and CO_2 recorders.

Excellent efficiency of the turbo-generators themselves is an essential element in insuring unusually high plant efficiency. The use of the multiple element type of machine has permitted the total temperature drop to be divided into two approximately equal steps which are utilized in separate machines. The high and low-pressure elements therefore can be designed with different speeds and blading to best suit the steam conditions.

The high-pressure element is designed for a speed of 1800 rev. per min. for taking steam at 265 lb. gage pressure and 175 deg. fahr. of superheat while the low-pressure elements are designed for a speed of 1200 rev. per min. for expanding the steam from an intermediate pressure of 55 lb. gage to a condenser pressure of one in. of mercury.

The division of the low-pressure machine into two elements removes an undue disproportion in size and speed between high- and low-pressure elements with this division of temperature and pressures.

When operating at its most efficient point, the unit is guaranteed to generate a kilowatt hour with a consumption of steam of 10.58 lb.

The efficiency of the turbo-generator is dependent in a large measure on the condenser, and in this plant each unit is provided with 100,000 sq. ft. of condenser surface which insures a vacuum of 29 in. at full load.

While a plant should have a high thermodynamic efficiency if each of the major elements, furnace, boilers, turbines and condensers is highly efficient, there is an opportunity for material losses to occur in the numerous auxiliaries, which, with the best of design, may consume 12 per cent as much steam as the main turbines. In this plant great care has been taken in the design of each auxiliary system to stop all preventable losses.

The feed-water system may be taken for example as the most important of the auxiliary systems.

Under normal full-load conditions approximately 87 per cent of the water evaporated in the boilers is used in the main turbines, is condensed in their condensers and, then reused for boiler feed water. Another 10 per cent is used in operating auxiliaries and may also be condensed and used for boiler feed water. The remaining 3 per cent is accounted for in steam used in soot blowers, boiler blow-downs, drips, drains, vents and so forth where the water cannot be recovered.

GENERAL VIEW OF 60,000-KW. UNIT

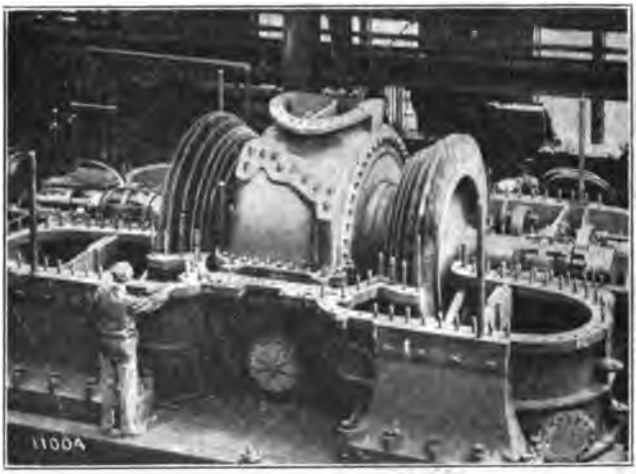
The central or high-pressure element receives steam from the boilers at 265-lb. pressure and exhausts it into the branched overhead pipe through which it passes at about 55 lb. to the two outside low-pressure elements. A butterfly valve in each branch of this pipe permits of this steam passage being closed.

This loss of water is made up by evaporating river or well water to purify it before allowing it to enter the boilers.

The condensate from the main turbines which is the principal source of feed water is removed from the condensers by the hot well pumps at a temperature of 75 deg. fahr. It is desirable to raise the temperature of this water to about 200 deg. fahr. and to add to it the water used by the auxiliaries and the make-up water from the evaporator before pumping it into the boilers. It is furthermore desirable that all heat transferred in the process should be most efficiently utilized.

In this plant the process is therefore divided into several steps.

1. The auxiliary live steam is used to produce as much mechanical power as possible before its heat is used for other purposes. The auxiliaries which are steam-driven are the feed pumps, the forced draft fans and the house turbo-generator. The amount of exhaust steam from the feed pumps and draft fans is always less than the minimum necessary and the additional steam from the house turbine may be controlled at will by transferring load electrically between the generators of the house turbine and the main turbine.



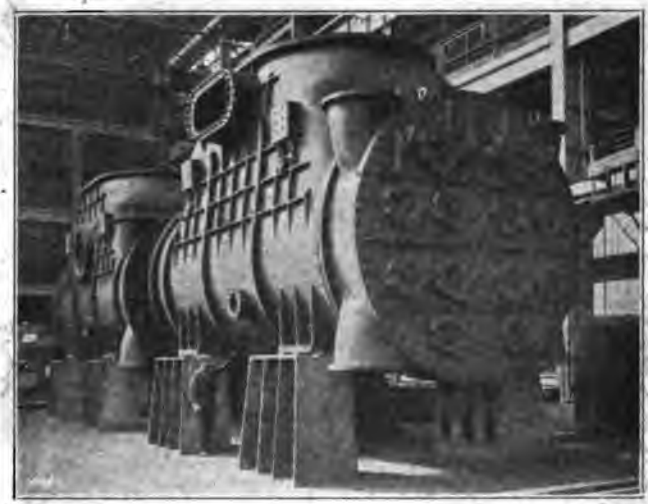
A LOW-PRESSURE ELEMENT

This 20,000-kw. 1200 rev. per min. turbine is of the semi-double flow construction. The steam entering through the opening shown at the top first passes through a section of single flow blading concealed beneath the central casing which is shown in place. The steam then divides and flows toward each end through the double flow blading which is exposed in the view by the removal of the outer casing. At each end the exhaust steam is discharged from the turbine through a separate opening below the floor. These two openings connect with separate condenser shells.

2. Part of the exhaust steam from the auxiliaries is first used in the evaporator for evaporating make-up water.

3. The heat used in the evaporator is again recovered and adds some 20 deg. to 30 deg. to the temperature of the main condensate which passes as circulating water through the condenser of the evaporator to condense the make-up water.

4. The steam from the auxiliaries, which is not needed in the evaporator, is condensed in a barometric condenser, which uses as condensing water the condensate from the main condensers that has already been raised in temperature 20 deg. or 30 deg. as above mentioned.



CONDENSER

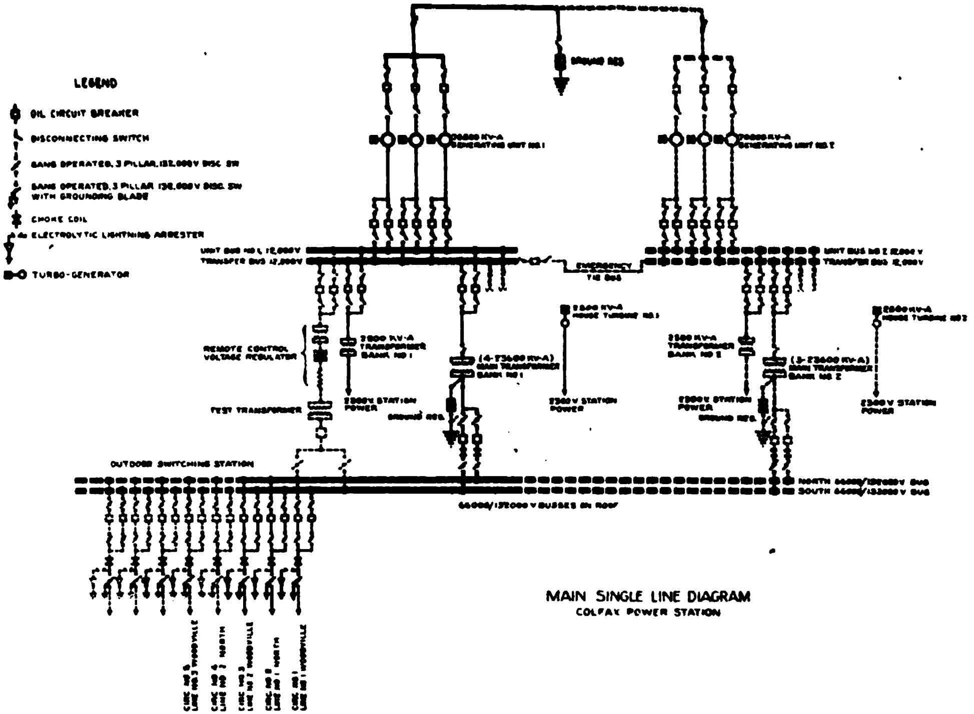
Each unit has 100,000 sq. ft. of condenser surface divided between four shells. This view taken in the shop shows two shells, that is, one-half of the condenser for one unit. Exhaust steam enters the top of each shell through an elliptical opening 14 feet long and 9 feet wide. The smaller elliptical side outlet is for an equalizing pipe between the two shells of the same element. The divided water box construction which permits of separate cleaning of the halves of each shell is indicated by the duplicate flange on each side for circulating piping. The shell is shown standing on feet which are provided for convenience in erection. When in service it is suspended from a steel framework by straps which attach to the pads just below the equalizing opening.

This combination is designed to maintain the feed water at a normal temperature of about 200 deg. fahr. without waste of either water or heat.

The electrical method of transferring the load between the house turbine and main turbine is particularly interesting. Practically all the station auxiliaries are electrically operated by induction motors which are normally supplied from the house turbine circuit. The house turbine circuit has, however, a second source of supply from a generator driven by an induction motor receiving its supply from the main generators. When the house turbine is run at the same frequency as the main generators the motor-generator will furnish no power and the house turbine will carry all of the electrical station auxiliaries alone. The speed of the house turbine is adjustable by the usual governor control, and as its speed is reduced the motor-generator will pick up load on the house circuit. The whole load or any part of it may be transferred from the house generator to the main generator.

General View of Turbine Room

The units are spaced 125 feet on centers with a pit between for dismantling generators and transformers. The auxiliary bay which opens into the turbine room contains the feed pumps, draft fans and house turbines, thus bringing all steam driven auxiliaries to the turbine room floor and under the care of the turbine room operators.



Main Electrical Connections

The main circuit consists simply of a lead from each element to an isolated 12,000-volt bus which unites the three currents into one, a lead from this bus to a transformer bank which steps the voltage up to 66,000 volts, a lead from the transformer bank to a high-tension bus which carries the current from the power house to a switching station where it divides among three outgoing feeders. To facilitate maintenance and repairs both the low-tension and the high-tension busses are in duplicate with oil selector switches throughout.

The electrical losses inside of generating stations are so small that large savings are not possible, but in this plant there has been some improvement in transformer efficiencies. These transformers which are larger than any other single-phase units yet constructed have the high full-load efficiency of 99 per cent.

Records are not yet available to show the normal performance of the plant in actual service, but calculated figures indicate that at a load of 50,000 kilowatts, its coal consumption should be about 1.39 lb. per kw-hr.

THE FOUR 23,600-KV-A. TRANSFORMERS

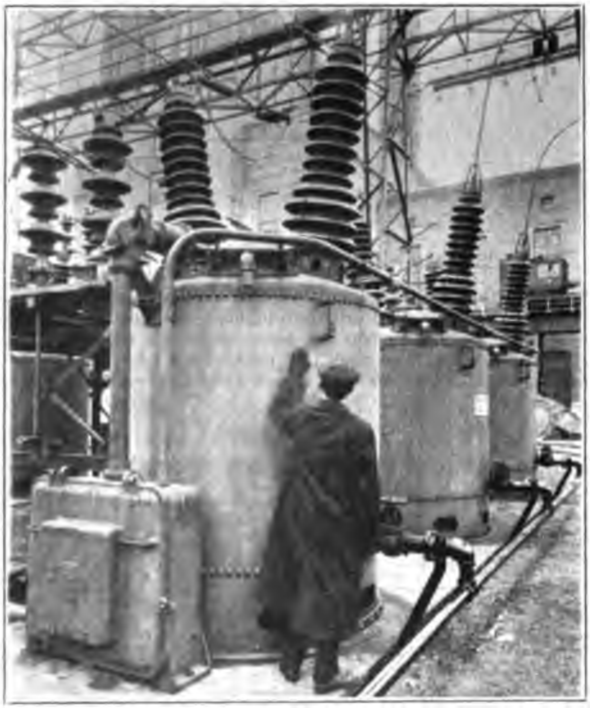
These are the largest single-phase transformers that have ever been constructed. Each is approximately 10 feet in diameter and 22 feet high over the terminals. Three of these units form one transformer bank and the fourth is a spare. The low-tension windings are connected delta for 12,000 volts and the high-tension windings are connected star for either 66,000 or 132,000 volts.

RELIABILITY

Reliability without sacrifice of economy has been the next major consideration in the plant design.

The coal supply is the first point requiring safe-guarding. The natural coal supply of the Colfax plant is direct from the Harwick mine. Two alternative methods of supply are however provided, either by barge on the river or by car over the Pennsylvania Railroad. Finally a coal storage of 150,000 tons within a few feet of the power station makes interruption of fuel supply a remote contingency.

Inside the power house the coal hoppers, coal crushers, coal elevators and conveyors are all in duplicate and each half has a capacity of 200 tons per hour. Furthermore, the coal bunker provides a storage of 240 tons immediately over each boiler.



A 132,000-Volt, 400-Ampere Circuit Breaker

The three tanks shown form a single three-pole oil circuit breaker. There are two of these breakers in the power station to control the high-tension circuit from the transformer bank and six in the outdoor switching station to control the three outgoing lines. Each switch is electrically operated by mechanism enclosed in the iron box shown at the end of the row of tanks. The electrical operation is by remote control from the switchboard.

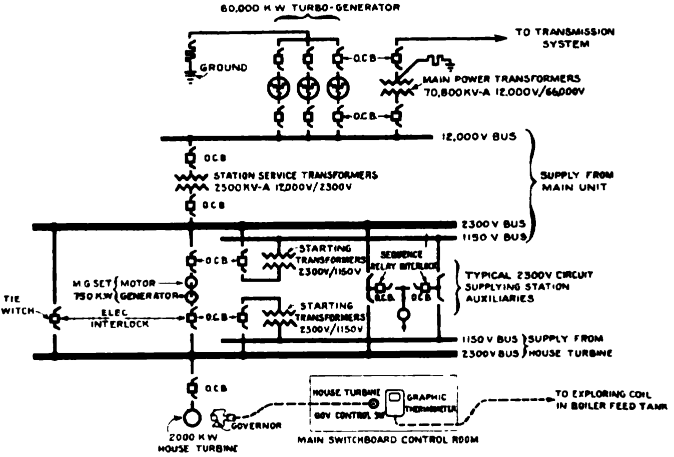
The number and capacity of the boilers is such that it is always possible to take a boiler out of service when it is desirable for cleaning or proper maintenance.

The furnaces are designed to permit high furnace temperature with a minimum of brickwork upkeep.

2300-Volt Bus Structure

The 2300-volt circuits are used exclusively for supplying station auxiliaries. The 2300 system is supplied from duplicate sources, a separate 2000-kw. house turbine and a 2500-kw. bank of station transformers. As absolute dependence has been placed on electric drive for a majority of the essential auxiliaries the 2300-volt busses have been carefully safeguarded in cell work.

In the high-pressure steam piping, special care has been used to insure reliability. Thus in the flanged



CIRCUIT DIAGRAM AUXILIARIES & HEAT BALANCE CONTROL

Diagram of Auxiliary Circuits

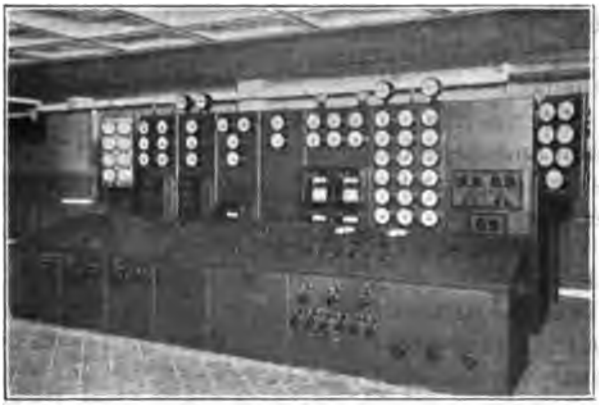
The essential auxiliary connections showing method of heat balance control from switchboard room.

joints double threaded bolts with two nuts of special high-grade, oil-treated steel are used. This avoids upsetting the material to form a head and results in a more reliable bolt.

Control Room

This shows the room 48 ft. long by 30 ft. wide from which the plant is controlled.

The division of the main unit into three mechanically distinct elements minimizes the loss of capacity from an accident to the machine, as any two of the elements



Main Bench Board

This is the board from which all the main circuits are controlled. On top of the desk apron there are mimic busbars representing the actual circuits in diagrammatic form. Circuits of different potential are distinguished by the use of different finishes for these busbars.

may be operated with the other out of service or any one may be operated with the other two out.

Normally, all the steam supplied to the unit is under the control of the governor on the high-pressure element, but each low-pressure element is also equipped with a governor.

The closing of a butterfly valve in one branch of the steam pipe between the high and low-pressure cylinders cuts off the low-pressure steam supply to that low-pressure element. Then the opening of a direct steam connection to the boilers permits of that low-pressure element being operated as an independent condensing turbine on its own governor. Either or both of the low-pressure elements may be so operated.

With the butterfly valves closed in both branches of the pipe between the high and low-pressure cylinders and with the atmospheric relief valve open, the high-pressure element may be operated as an independent non-condensing turbine.

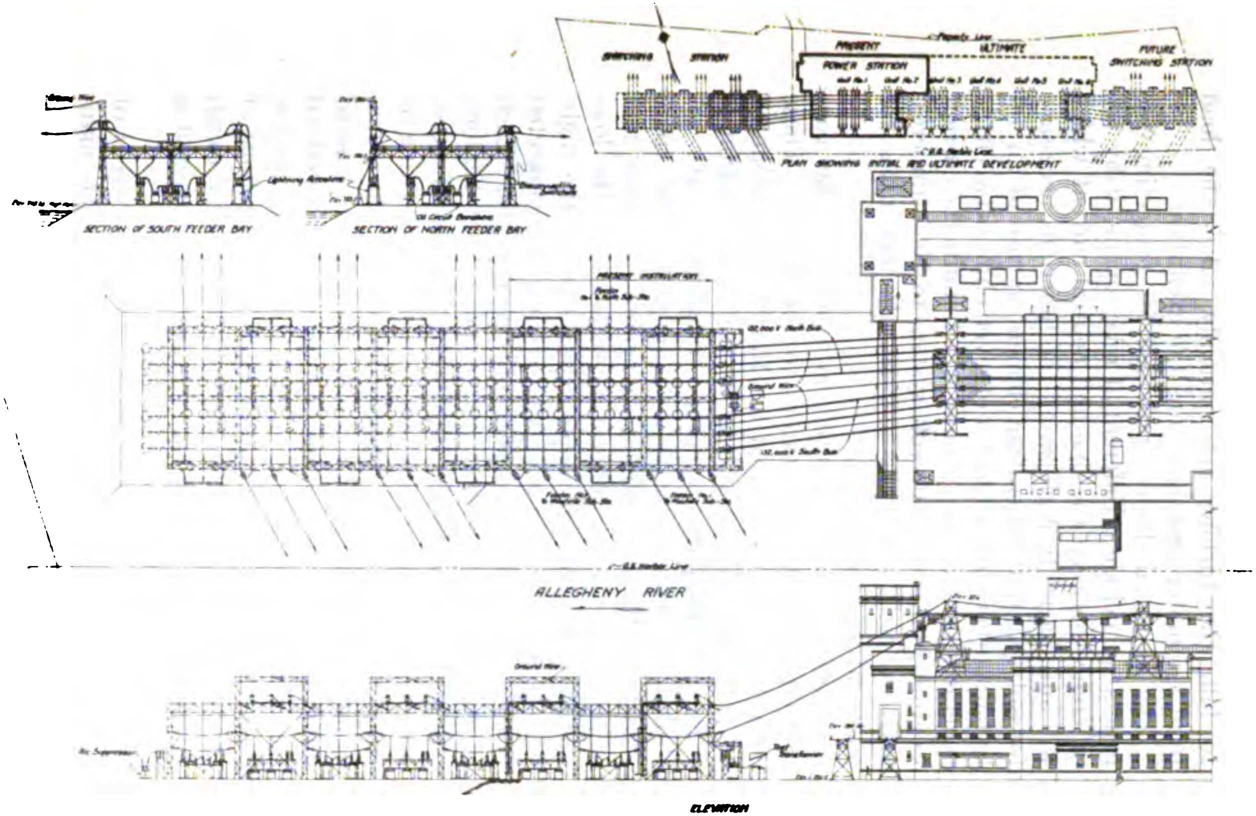
The opening and closing of the proper valves for shifting to separate operation in case of an emergency is automatically controlled by the governors.

Overspeeding of a low-pressure element closes the butterfly valve and cuts off its low-pressure steam supply while a drop in speed admits live steam from the boilers.

Overspeeding of the unit cuts off all steam from the unit and closes both butterfly valves, but a subsequent slowing down will admit live steam to the low-pressure elements.

Each of the low-pressure elements is of the semi-double flow type with two exhausts from each cylinder. This has naturally resulted in dividing the condenser surface between four shells. Each shell is so divided that one-half of it may be isolated for cleaning, permitting one-eighth of the total surface to be cleaned at a time without interruption to service.

The excitation system is especially well protected against interruptions. The exciters are in duplicate, one being a spare machine. The exciters are normally motor-driven, but each is also connected to a steam turbine. When the exciter is being driven by the



OUTDOOR SWITCHING STATION

The high-tension busses extend in a continuous line the length of the turbine room roof, thence across an intervening space to the switching station and then the length of the switching station. The switching station is divided at right angles to the busses into bays, each bay being used to control a separate line.

motor, a small amount of live steam is admitted to the turbine casing and if the motor permits the speed to fall, the turbine automatically takes the load from the motor and maintains the excitation.

The electrical devices provided for protecting the generator include a differential relay operated by the difference between the line and neutral current which will automatically perform all the functions necessary for isolating that generating element in case of an internal short circuit; a resistor of seven ohms between the generator neutrals and ground which limits the current to ground on the 12,000-volt system to 1000 amperes; and six resistance coils and six thermocouples for temperature measurement.

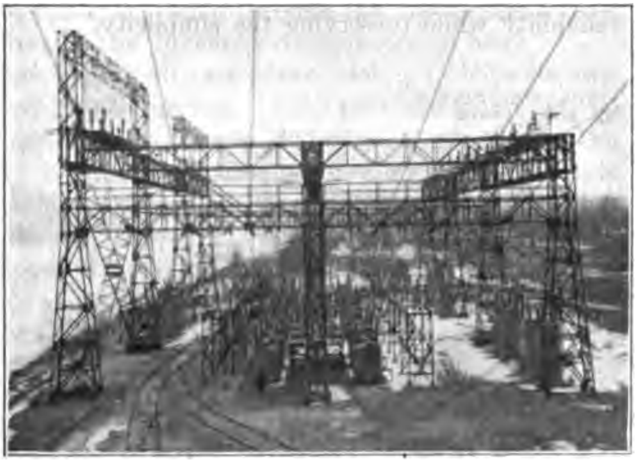
Great care has been used in insulating the connections from the generators to the busses. These consist of cables insulated for 13,000 volts, mounted on porcelain insulators as an additional precaution.

Four single-phase step-up transformers are installed, of which one is a spare unit. The spare transformer has all piping connections in place and is provided with disconnecting switches on the low-voltage side and removable pipe links on the high-voltage side, by means of which it can be connected in place of any of the others in a few minutes. Each transformer has two hot-spot temperature indicators, one at the switchboard and one at the transformer, designed to show the highest temperature existing at the hottest spot in the transformer coils. The transformers are protected by differential relays in case of internal short circuits and by heavily set overload relays in case of a short circuit on the high-tension busses. The neutral of the high-voltage windings of the transformer bank is connected to ground through a resistance, which will limit the current in case of a ground on the high-tension circuit.

All electrical auxiliaries have duplicate sources of supply and may be operated from either the main generators or the house turbine.

The motor-generator which normally interconnects the main and the house turbine has reverse power relays which will disconnect it in case the frequency of the main turbine falls to a point where it would materially interfere with the operation of the house turbine or station auxiliaries.

In order that disconnecting switches may be opened and closed only when the corresponding oil switch is open, each set of switches is provided with a protective device, including as the indicating element, three lamps. A red light indicates a closed circuit breaker, a green light that the breaker is open and a white light that the control wires to the breaker are open.



Outdoor Switching Station

The station consists of an iron framework supporting the insulators, horn gaps, conductors and disconnecting switches which are required. Oil circuit breakers and lightning arresters which stand on the ground.

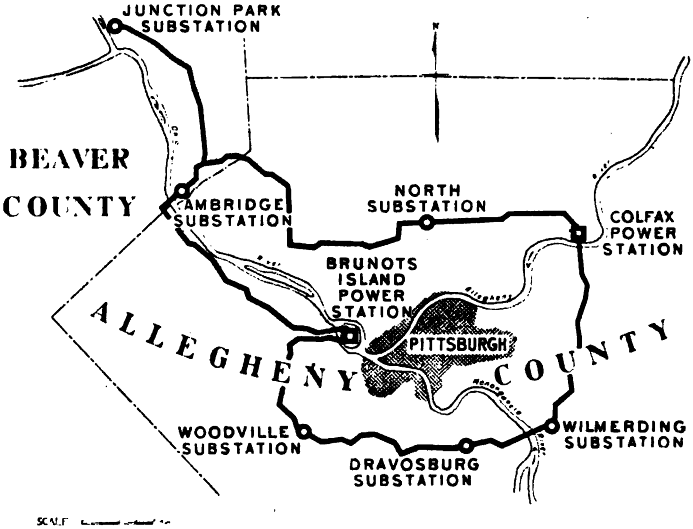
Electric control is used for so many operations that a dependable supply is essential. Duplicate batteries, charging sets and busses are provided. Each circuit is equipped with a double throw switch for connecting to either bus.

A complete emergency lighting system provides sufficient light at every important point to permit of the operation of the station without hazard. When the normal alternating-current supply of the emergency lighting circuits is interrupted, connection is automatically made to a storage battery.

The various precautions to insure reliability above described may be summarized as including, first, careful design and a high factor of safety to prevent accidents, second, a complete duplication of all important but inexpensive elements so that complete service may be maintained in spite of any failure, and third, a subdivision of the large and expensive elements so that a failure merely causes a diminution of capacity without an interruption to service.

Simplicity

Simplicity of design has been favored by the large size of the units, but great care has been necessary to attain reliability while preserving the simplicity.



The Duquesne Ring

A 66,000-volt loop 89 miles in circumference surrounding Pittsburgh. It supplies radial distribution circuits at 11,000 and 22,000 volts through six step-down substations.

The low steam consumption of the turbine and the large capacity of the individual boilers have simplified the boiler room by permitting a single firing aisle.

Each turbo-generator is regarded as a single unit taking steam through a single governor and delivering high-tension current through a single transformer bank.

The division of the unit into three mechanical elements and the resulting division of the generated current into three low-tension circuits are regarded as internal structural peculiarities which can be taken advantage of in case of an emergency but which should not be made an excuse for complicating the design.

The three 12,000-volt generating elements of each main unit are operated as one machine, being switched together on a common bus and given field excitation while stationary, then brought up to normal frequency and voltage as one generator by the admission of steam to the high-pressure turbine and synchronized with the 66,000-volt system through the low-tension circuit breakers of the 70,000-kv-a. transformer bank.

When other units are added each is to have its own isolated 12,000-volt bus. Each generating unit may be considered as a single 66,000-volt machine. The station bus on which the machines operate in multiple is the high-tension bus from which the transmission circuits are supplied. This simple plan has been developed by taking advantage of the location of Colfax at a point where the local loads are not heavy and recognizing that there would be an undue expense and complication if a common low-tension bus were established in order to supply a small local load.

The use of a single transformer bank for each three-element unit simplifies the transformer house while the use of single-phase transformers provides a subdivision of the capacity which gives added reliability without complication or expense.

Another simplification in the power house is obtained by separating the distribution of power from its generation. With this plan the only switches in the power house are those of the generators and auxiliaries. The only high-tension switches which must be provided for in the power house design are two selector switches for each generator. After passing through these switches the generator circuits go out doors to the duplicate station busses which are suspended above the roof. The current thus leaves the power station proper at one end over two busses.

The distribution of power from a separate point permits the use of a simpler design and less expensive construction for this purpose than would be necessary in the power station building.

These simplifications in design have been important factors in keeping down the cost of the station. In spite of the fact that the station was constructed just at the time when the prices of material and labor were at their maximum the cost of that part of the plant which should be allocated to the first unit was about $105 per kilowatt.

APPENDIX

CAPACITY AND RATING OF APPARATUS

Coal Handling Apparatus. Duplicate concrete receiving track hoppers, each 150 tons capacity.

Duplicate crushers, each 200 tons per hour capacity.

Duplicate bucket elevators with overlapping, pivoted buckets, each 200 tons per hour capacity.

Duplicate 30-in. belt conveyers, each 200 tons per hour capacity.

Reinforced concrete bunker, capacity 10 tons, per lin. ft., or 240 tons per boiler.

Duplicate weighing larries, each 20 tons capacity.

Stokers. 17-retort, extra long underfeed with double roll clinker grinders.

Ash Handling Apparatus. Ash hoppers of reinforced concrete, brick-lined, 1900-cu. ft. capacity per boiler, fitted with air-operated ash gates, discharging direct into standard gage railroad cars.

Boilers. Seven Babcock & Wilcox steel-cased cross-drum boilers. Each contains 20,876 sq. ft. of heating surface, is 51 tubes wide and 18 tubes high. Tubes 20 ft. long; diameter of cross-drum 60 in.; steam pressure 275 lb.; furnace volume 3.45 cu. ft. per rated h. p.

Superheaters: Foster type, located above tubes between first and second pass. Each contains 6700 sq. ft. of heating surface giving from 140 deg. to 200 deg. superheat.

Forced Draft System. Three 250,000-cu. ft. per min. fans driven by 420-h. p. geared steam turbines. Air supply taken from generator discharge and boiler room basement.

Stacks. Two brick lined self-supporting steel stacks, each 21-ft. diameter with top 325 ft. above firing floor. Flues are above roof and covered with magnesia with sheet metal protection.

Main Turbo-Generator. One Westinghouse 60,000-kw. three-cylinder, two-stage parallel flow, compound steam turbine generator unit consisting of one 1800-rev. per min., single-flow high pressure element, and two 1200-rev. per min. semi-double-flow low-pressure elements; each element driving one 23,600-kv-a., 85 per cent power factor, 60-cycle, 12,000-volt, three-phase generator. Generators are star-connected with three neutral connections brought out; seven-ohm external resistance in ground circuit.

Main Unit Auxiliaries. Condensing equipment has 100,000 sq. ft. of surface in 4 two-pass shells of 25,000 sq. ft. each, connected to turbines by means of rubber expansion joints. Each condenser shell contains 5070 one-in. Muntz metal No. 16 gage tubes of 18 ft.-10 in. active length.

Three circulating pumps, each 44,000 gal. per min., motor-driven.

Four condensate pumps, each 1000 gal. per min., two-stage, motor-driven.

Three Leblanc air pumps, each 30 cu. ft. per min., motor-driven.

Two submerged removal pumps, each 900 gal. per min., motor-driven.

Two air washers, each 115,000 cu. ft. per min.

Station Auxiliaries. "House" turbo-generator: One 2000 kw., 2300-volt, three-phase, 60-cycle unit, the turbine operating at boiler pressure and exhausting into barometric condenser.

Heat balance set: One 1100-h. p., 2300-volt, three-phase, 60-cycle motor driving 750-kw., three-phase, 60-cycle, 900-rev. per min., 2300-volt synchronous generator. This set connected between the house turbine bus and the auxiliary bus fed from main turbo-generator.

Duplex exciters: Two sets, each consisting of a steam turbine on common shaft with 350-kw., 250-volt, d-c. generator and 530-h. p., 2300-volt motor.

Motor-generator sets for stoker and clinker grinder supply: Two, each consisting of 325-h. p., three-phase, 60-cycle, 2300-volt motor driving 200-kw., 250-volt, d.c. generator.

Battery charging sets: Two, each consisting of 25-h. p., three-phase, 60-cycle, 440-volt motor driving 15-kw., 125-volt, d-c. generator.

Elevator: Combination passenger and freight, automatic, two-ton capacity; to all floors on electrical bay side.

Evaporator, double effect, "dry-tube" type: Capacity 15 tons per hour. The two effects reversible.

Three boiler feed pumps: Each 1500 gal. per min. four-stage centrifugal, turbine-driven.

Main distilled water storage tank: Capacity 200,000 gallons.

Traveling crane: One four-motor, 75-ton main hoist, 25-ton auxiliary hoist.

Transformers. Main Transformers: Four 23,600-kv-a., 11,500/38,100/76,200-volt, single-phase, 60-cycle, oil-insulated, water-cooled, low-tension delta, high-tension star. One transformer in reserve as spare.

Station Transformers: Three 833-1/3-kv-a., 11,500/2,300-

volt, single-phase, 60-cycle, oil-insulated, water-cooled, connected delta-delta.

Duplicate Storage Batteries. For circuit breaker control and emergency lighting. Each 125-volt, 160-ampere-hour.

Main Switchboard. Desk type for controls, vertical panels in rear for instruments on main board of seven sections. All other boards of vertical type. Panels of slate. Mimic busses of all circuits with different finish for each voltage.

Circuit Breakers. Remote control, solenoid-operated, type O-2 and CO-2 on 12,000-volt circuits; type G-2 on high-tension circuits.

Emergency Lighting. Emergency lights throughout plant automatically transferred from normal supply to storage batteries in case of station trouble; restored when trouble is removed.

Telephone, Etc. Duplicate private branch exchange boards. Telephones installed in all parts of building and important points outside of station. Loud speaker on main instrument board permits operator to talk without head set.

Master clock in control room with auxiliary clocks in various parts of building.

Load indicator in center of boiler room firing aisle with double-faced illuminated dial electric clock and steam gage.

Signal System. Induction regulator type sending and reeiving indicators and transmitters between control room and gage boards.

DISCUSSION ON "COLFAX POWER STATION OF THE DUQUESNE LIGHT COMPANY, PITTSBURGH," (GALUSHA AND CLARKE), PITTSBURGH, PA., APRIL 16, 1921.

C. S. Cook: When the Duquesne Light Company started to build the Colfax station it had in mind a high demand for central station power, which has been a rapidly growing one, and meeting it in a way which would enable it to furnish both reliable and economical power.

Until just about the beginning of the war, Pittsburgh as a community was favored with very cheap fuel. Coal could be purchased at something in the ratio of a dollar a ton. That low price of fuel has gone, left us, at the present time, and probably never will return in anything like it was before the war. With dollar coal it was manifestly not good business for any utility company or any mill to put into their power development more than such measure of economy apparatus as would be justified in bringing their total cost both of operation and carrying charges above that minimum.

With three dollar coal, which is probably what we have to face in the future, a great deal more can be done, and as the paper has said, careful consideration was given both to the cost of operation and the interest carrying charges of the plant. If it had been only a matter of higher thermal efficiency, and no consideration of investment charges, we could build a plant tor a little higher economy than we have.

But there are two things to be considered in building this plant. One is operating economy and the other is the reliability of the plant. Operating economy could be obtained by very large individual units. Perhaps we could have used one 60,000-kw. single-cylinder turbine of some form that the engineers could approve, and have built a machine which would have given a few hundredths per cent better water economy and steam economy and general economy in operation than we have, but that would have been one 60,000 unit, and anything that would disable that would put the whole plant out of service.

With the combination of machines which we have, which is practically a new one,—there are only one or two others in the country in operation—we have nearly the same economy when we run as a whole that would be obtained by one 60,000-kw. unit, and by automatic arrangements on the machine, any one of those units may go out, either through accident or be pulled out intentionally, and the other two units carry the load right straight along to the extent of their capacity.

This gives the dependability feature which we could not have with one single unit. I haven't seen one thing about the plant that I would like to change.

G. F. Brown: One of the things that struck me particularly is one point that has been emphasized in Mr. Galusha's paper, and that is simplicity of the unit system of layout. That I think is undoubtedly the trend of most of the larger engineering and operating conpanies, but even so, there are a great many stations being laid out today that include an extensive low-tension switching arrangement, which is no more justified than it was justified here at Colfax. I don't think that it is always realized what a large saving can be made in the separation of the units on the low-tension bars.

We recently made quite a large study, and I remember distinctly that the saving made by eliminating the low-tension switching amounted to almost one-third of the cost of the switchboard and the switching equipment.

In Colfax, as in several recent important stations, the transformers and transformer switches are placed indoors. Have we been tending to go too far with out-door construction in the past; or were there special considerations in this case?

The paralleling on the high-tension bus has another big advantage in that it simplifies the problem of handling short circuits, which are bound to become a very serious problem in systems as large as the Duquesne Light Company's system.

The heat balance set is a very unusual innovation. It might also, beyond the point of controlling heat balance, have a use in improving regulation of the house generator set if necessary.

F. C. Hanker: Mr. Clark has called attention to the mechanical power being the measure of the productivity of civilization. I think in this case we can go one step farther, and call attention to the advantage of electrical power, particularly in its ease of distribution, after we have had experience with the difficulty of securing adequate supplies of coal.

The Pittsburgh district is peculiarly fortunate in having a layout that comprises the so-called Duquesne Ring giving very economical transmission to the very centers of industry. Estimates have been made to show that the amount of power in the district as a whole will probably be on the order of a million and a half kilowatts at the end of 15-year period. The amount of power of that order will involve several stations of the type you have seen today at Colfax. That station at the present day probably represents a type that is as suitable for the bulk generation and distribution of power as any that had been recently developed.

The simplicity has been referred to by Mr. Galusha and the other speakers, and also in the paper, and on the question of reliability one of the factors referred to by another speaker, the heat balance set, was installed to improve the dependability of the source of power to the auxiliaries. When you recognize that the auxiliaries and the continuity of supply to the auxiliaries is just as important as the main units, you will appreciate some of the care in the design of the low-tension layout, that is, the 2300-volt as compared with the 12,000-volt.

The heat balance set, so-called, is essentially a flexible coupling between the circuits of the main unit and the auxiliary bus. In other words you can get disturbance on the outside system that would affect the voltage or frequency of the main system, but have no effect on the auxiliaries. You have in effect, an induction motor that operates at about five per cent below the normal frequency of the system. That means that the main system must drop in frequency to about 57 cycles before there is any transfer from the auxiliary bus or the house turbine to the main load. That would not be the case if they were directly paralleled. In that case the house turbine would attempt to carry its share of the output and probably lose some of the circulating pumps which are essential to the operation. It may represent somewhat of a refinement, but when you take into account the necessity of continuity of service it well justifies the expense of the slight losses involved.

The Pittsburgh district, referring back to the possible load it may have, is the one case that you will find, with the exception of those districts which have an adequate supply of hydroelectric power, where you have a combination of fuel and water that are required for the so-called mouth-of-mine plants. There has been a good deal of discussion in recent years on that type of plant, and the popular conception has usually neglected taking into account the amount of water necessary for condensing purposes. In the present case that limit has been placed around 300,000 kw. A review of the bituminous field in Eastern Pennsylvania will show that there are very few streams that would be adequate for the plants of that order of output. A recent survey was made in that connection, excluding the rivers in the Pittsburgh district. There are only one or two sites that are really suitable for plants in excess of one or two hundred thousand kilowatts, unless you go to the Potomac river and to some points on the Susquehanna. Taking that viewpoint you can realize the advantage of the development of the Pittsburgh district electrically, with its numerous sites on the three rivers where you can get an adequate and dependable supply.

G. G. Bell: The Colfax station is one of five stations in the Pittsburgh district that are either in operation or under construction and are built at the mine mouth. Two of these stations will have 100,000 kw. ultimate capacity, whereas the three remaining stations will have ultimate capacities of 250,000 to 300,000 kw.

The available sites for building large power houses, in which there are sufficient condensing water and land to accommodate a station of large size, are limited. Coal land along the river is in demand on account of its proximity in most cases to railway facilities and the saving which can be effected in transportation costs by delivering the coal by barges. The Duquesne Light Company was fortunate in securing such a site together with the necessary amount of coal required by a large plant, in close proximity to towns which under normal housing conditions should be able to supply the necessary labor, thus eliminating the considerable expense of providing houses, with the necessary streets, water, sewers and lighting, which not only involve a large initial expense but are usually operated at a loss.

The advantages of the ring system have been discussed by former speakers; and it is needless to emphasize further the advantages of continuity of service and opportunity for repairs, which, together with the present and proposed tie-ins with neighboring utilities, should enable the lighting company to transmit and distribute power to their customers with the minimum of transmission line interruptions.

The use of high-voltage transmission increases the reliability of transmission lines. Two 132,000-volt lines operated in the Ohio River district have had records of about one interruption per year.

In addition to the direct supply of coal from the mine, the Duquesne Light Company is also arranging for large storage of coal in close proximity to the power plant to take care of interruption of the mine supply on account of breakage of equipment or labor troubles. The scheme does not at present contemplate the receipt of coal from the river, but plans could be modified at a comparatively slight expense to provide this additional source of supply.

An exceptionally good-looking turbine room has been secured at a comparatively small additional expenditure of money.

All condenser auxiliaries are motor-driven. This necessitates a duplicate source of power in order to insure freedom from interruptions. The use of a heat balancer set to tie together the main units and the house generator is novel. At the Springdale plant the power for the auxiliaries is obtained from a house generator or from the house transformers. Under normal conditions the house generator is operated in parallel with the main units, but on the appearance of a storm on any part of the system the switch paralleling the house generator and the main unit is opened. In case of a short on the line, relays are installed which will open the circuit in case of the house generator feeding any large amount of current into the main units. This arrangement so far has given very good satisfaction. If it is not desired to operate the house generator in parallel with the main units, additional non-condensing turbines of similar size to the house generator might be installed which would supply the additional amount of steam to heat the feed water to 210 degrees and would be operated in parallel with the main units. However, the most economical way of getting the additional amount of steam over that supplied by the house generator, which furnishes the power for only such units as it is absolutely necessary shall have a separate source of supply, as for instance one circulating pump, one condensate pump, motor-driven boiler feed pump, and motor-generator-exciter set, is to bleed this steam from the large units.

Provision for keeping clean condensers is a necessity where rivers supplying the condensing water are subject to such sudden fluctuations and carry the amount of suspended matter that the rivers in the Pittsburgh district carry. The arrangement installed at Cheswick is the result of the Duquesne Light Company's previous experience with a 45,000-kw. unit at Brunots Island, which has given very good satisfaction. It would be interesting to know whether a quarter of the condensing equipment can be cut off for cleaning and reduction of the water leakage without materially increasing the air leakage and consequent lowering of the vacuum.

The installation of twin circulating pumps, especially if the pumps have separate water supplies, permits of more readily cleaning the condensers while in operation, by the shutting down of one pump and making a four-pass condenser of a two-pass condenser, thereby flushing the leaves that have collected on the inlet tube plate back into the tunnels.

The operation of auxiliaries such as circulating pumps and fans in parallel have certain advantages in the way of flexibility and efficiency at part loads, provided that the auxiliaries can be operated at the same speed. However, in the case of forced-draft fans if turbine drive is selected, there must be a certain definite relation between steam pressure, turbine speed, quantity of air discharged and air pressure; and the characteristics of the fans must be such that they are in stable equilibrium, that is, that they tend to carry the same output. Forced-draft fans have this general characteristic, whereas with the type of fan ordinarily installed for induced draft there would be a tendency for one fan to hog the load at the expense of the other, thus causing a very decided loss of efficiency. A thorough investigation of this has been made by the Naval officials and published in a recent issue of the *Bulletin* of the American Society of Naval Engineers. I believe at Colfax that some arrangement has been made for keeping practically constant steam pressure on all fans; that while each fan has its own regulator, there is an equalizing pipe between the turbines on the various fan units and in this way the disadvantage of parallel operation of fan units is greatly overcome.

The amount of flexibility in the soot blower piping is exceptional, but not more than warranted by the amount of trouble that has lately been experienced with more rigid connections between the soot blower elements.

The separation of air from boiler feed water has lately received a great deal of attention. In order to get anything like complete separation it is necessary to raise the water to a boiling temperature and allow the water to stand, preferably in a slight vacuum, with little or no movement. After the air is separated, it is very important that the water should not be exposed to air, which it will very readily absorb. A large surge tank is necessary to take up the fluctuations in the boiler requirements. Where this surge tank is placed between the heater and the boiler feed pump, the surface of the water is usually exposed to air. At Colfax the surface of this tank has been covered with cork, thus reducing the amount of exposed surface. Another arrangement is to have the condensate by-pass the surge tank. This prevents the condensate from being exposed to air, but has the disadvantage of keeping the surge tank at a lower temperature. This arrangement has been adopted at Springdale, and we find that the surge tank temperature is kept about 20 to 30 degrees lower than the boiler feed water temperature. Analysis of the boiler feed water at Springdale shows that with the house generator in service and the average feed water temperature about 210 degrees the amount of air in the boiler feed water can be reduced to one quarter cu. cm. per litre instead of four to five cu. cm. per litre that is contained in the river water.

The use of the generator air in the boilers is an additional economy, but it provides only about one-half the amount of air required by the boiler. It is permissible to introduce the remaining air through the ash pit basement approximately two-thirds of the year, but during the winter months this practise is likely to cause the air in the basement to be foggy and the basement itself to freeze up, especially where large amounts of water are used for cooling the clinker grinder or wetting ashes. This requires that the additional air be secured from the outside, either through ducts under the basement floor or through the boiler room. In some marine installations and foreign plants the air is taken from the top of the boiler room and conducted down the sides of the boiler between the steel casing and the brick work, thereby absorbing and returning to the boiler some of the heat lost in radiation.

C. S. Hershfeld: The authors have been very careful to explain that they struck what one might call an economic balance. I think if the means used in striking that economic balance in the case of the boiler equipment could be elaborated upon for the benefit of other engineers, it would be highly desirable. As I recall the stoker, the boiler heating ratio, the price of coal, and the ratings at which the boilers are to be operated, they have such relations that I believe it would be wise to explain for the benefit of the public why these particular combinations happen to be chosen.

Conditions a few years hence with respect to the relation between cost of coal and capital and other factors will probably be very different from what they are now. On the other hand the choice in this particular case will undoubtedly be used as an argument for a similar choice in other cases.

Also I think it might be wise to include some of the argument which lead to the decision with respect to economizers.

F. Hodgkinson: I think I can add most to the discussion of this paper by telling you the reasons which led to the designing of steam turbines of the type that has come to be known as the "cross-compound" principle, such as you have seen at Colfax. In this particular instance, all of the steam to the system passes first through a high-pressure element, then divides into two low-pressure elements, which in turn exhaust to the condenser, each of these three turbine elements driving a separate generator.

Twenty years ago, designers of steam turbines recognized the advantage of carrying out the steam expansion in two separate cylinders, and a number of turbines as small as 1500 kw. were built tandem fashion at that time, the receiver pressure between the two turbine elements being approximately at atmospheric pressure. The advantage was that there was a lesser temperature range in each of the elements, reducing the difficulties on account of distortion, and any elaborateness of the steam path might be attained without the need of compromising on account of mechanical design, such as distance between bearings, etc.

It was also thought at that time that the advantages of intermediate re-heating would have been worth while. This thought, with the increased cost of fuel, is likely to be reconsidered in the near future in large turbine installations.

The first important cross-compound turbine installation was made in 1913, when the Westinghouse Co. was called upon to build some turbines of 30,000 kw. capacity. This was in those days regarded as of unprecedented size, and it was thought, naturally, that such large machines would set a new era in steam economy. The purchaser and the builder were both desirous that with this step in economy, there should also be a corresponding advance in reliability, and with this in view, the cross-compound principle was evolved for these machines. With this, another advantage over those cited above was secured, namely, operating the respective turbine elements at the synchronous speed most adaptable to the volumes of steam to be dealt with by the high and low-pressure elements, respectively. In this instance, 1500 and 750 rev. per min. were selected. A further advantage of these two rates of speed is that no high blade speed need be resorted to in order to avoid congestion in the low-pressure blading, and therefore a design could be employed involving no high stresses, so that ordinary commercial materials could be used. The experience with these machines since about 1914 has thoroughly justified their design.

These turbines, while they each comprise two entirely independent turbine elements, were always regarded as one single machine. Of course, it is obvious that either element might be operated alone and in subsequent installations, arrangements were made for doing this more or less automatically. With a two-cylinder machine, with one element shut down, the other could operate and deliver its full load on approximately the flow of steam for the two units. In other words, operating one of the elements alone, the steam consumption would be nearly doubled. It then developed that if the turbine were constructed in three cylinders and the three generators of equal capacity, that there would be twice the heat drop through the low pressure elements, when they could be designed to operate alone with very respectable economy. For instance, at the economical load and the complete machine operating, the steam consumption of the machine you have seen approximates 10.4 lb. per kw-hr. With one low pressure shut down, half load may be carried with a steam consumption of 12½ lb. per kw-hr., and similarly, with the high pressure shut down, the two low pressures may carry two-thirds of the total load with a steam consumption of 13.7 lb. per kw-hr.

Naturally, it came to be demanded with a machine such as this, that automatic means be provided that in the event of accident to any one turbine element, the remaining ones will continue in operation without interruption. These features you have seen installed on the machines at Colfax.

W. T. Snyder: It appears in the design that the circulating pumps are above low water level. Are there other reasons than the cost of excavation, for not putting the pumps lower?

I have understood that combustion could be better controlled with forced and induced draft fans. What are the engineering reasons for omitting induced draft fans at Colfax?

With no external reactance what would be the maximum short-circuit current with a short circuit near the plant?

I would like to know the principal reason for motor drive on the stoker, particularly when no direct current was available except through motor-generators?

With such an extensive system extra precautions must be taken against a complete shut down. In case of a complete shut-down what methods or preconceived plans are used to get the system back in operation in the shortest possible time?

Why are transformer substations located in remote places, away from the railroads, and improved highways?

When making comparisons between the central station and the isolated plant: We must keep in mind that in the industrial power plant, of the two factors, continuity of operation is the more important, efficiency next. We can always afford to sacrifice efficiency for reliability.

R. H. Keil: As an engineer of one of the steel companies there were two thoughts uppermost in my mind while visiting the Colfax Plant this morning. These were first, continuity or reliability of service and second, cost of power. Now in the steel plants, as Mr. Snyder has pointed out, continuity of service is the important thing, much more so than in the average industrial plant, because interruption to the power supply means not only an interruption for the time that the power may actually be off, but for the very much longer period which may be required to get mills and furnaces back into operation. This involves both the loss due to the spoiled material and, what is usually the greater loss, that due to curtailed production.

The ordinary steel plant, which has blast furnaces connected with it, can, and usually does generate power very cheaply and therefore in order that the central station may furnish such a plant with power, it too must be equipped to produce power at a very low cost.

With these two thoughts in mind, I made the inspection this morning. Several features of the plant layout struck me forcibly. The extreme simplicity and straight-forwardness of the scheme in general has been emphasized in the paper. Everything about the plant, from coal pile to point of delivery of the power at the outdoor substation, seems to be arranged as simply and logically as possible and is so installed and safeguarded as to give very reasonable assurance of an uninterrupted supply of power. My attention was also attracted to the small number of attendants required to operate this plant, to the uniformity of the load carried, which hung around 52,000 kw., and to the low vacuum maintained by the condensers. All these things tend toward economy of operation and it seems to me that this low cost of operation, coupled with the low fixed charges, which should apply to this station, should enable the Duquesne Light Company to offer a rate for power, which should be attractive even to a steel plant.

E. C. Stone: Mr. Galusha showed you a map giving the routes of the transmission line and locations of substations, and also showed you one or two of the pictures of the design. Just as much attention was given to reliability and the very nearest possible approach to continuous service in the transmission system as in the power plant. There are one or two points that are perhaps of special interest from the operating standpoint.

In the first place we have the two main plants, Brunots Island and Colfax, and it is vitally necessary to operate both of these plants in parallel to assure continuity of service.

Furthermore it is essential for this same purpose that they stay in parallel, and our operating scheme contemplates this solid transmission ring around the city as virtually an extension of the power plant bus. That of course carries with it the necessity of isolating a defective section promptly and effectively. To accomplish this, very high capacity oil circuit breakers have been installed at the power plant and all the substations in order to interrupt even dead short circuits, if they occur. The manufacturer's rating of the oil switches at the power plant gives them, roughly, a rupturing capacity of 1,500,000 kv-a., and it is quite possible that they will have to perform that service before they get through.

To operate these oil switches a system of relays is installed which will automatically cut out a defective section of the transmission system. By defective section I mean one section of line between station and station or one section of substation between the line switches and the transformers, or the transformers themselves.

We already have had very forcibly brought to our attention the point which some of these steel manufacturers have talked about today, the necessity of continuous service, and we fully realize that a one minute or two minute interruption may be just as bad as two or three hours interruption. It is unfortunate that electric motors, if they are subject to serious voltage disturbance will drop off the line. For this reason we have given particular attention to stabilizing the high-tension system, and one important feature is the resistance in the neutral ground lead. This has many advantages, but I want to speak from the point of view of reliability of service. This ground resistance will limit the current flowing into a ground fault to a value comparable to the rated capacity of one of the generators in the power house. You will therefore realize that in the case of a grounded line section the flow of current into that section is limited to something that the power plant can very nicely handle and that will not cause an excessive voltage disturbance. Probably 95 per cent of the failures of high-tension systems are grounds. I therefore believe—sorry we can't speak from experience yet—that even a dead break-down of an insulator will not pull enough power to disturb the operation of the system or to inconvenience in any way the satisfactory performances of the motors attached to the system. The arrangement which we are installing should cut out the defective section promptly, leaving the rest of the system intact.

I believe this is a very important point, for high-tension systems are more subject to grounds than to short circuits, so that by eliminating interruptions to service from grounds we have taken a very important step toward insuring continuity. One gentleman spoke of reactance, and I want to say that the reactance of a 60,000-volt system is very high. A dead short circuit fifteen or twenty miles from the power house will only take five times the rated power plant capacity. On an 11,000-volt system you can easily get twenty-five times power plant capacity. The step-up and step-down transformers have such high reactance that additional reactance in separate reactors is not necessary.

W. E. Clarke: It is interesting to note that the Springdale Plant of the West Penn Power Company has experienced trouble in eliminating the oxygen content of the water. The operation at Cheswick is extremely satisfactory along these lines, with water temperature varying from 180 to 210 degrees.

As to the controlling of fans to operate as one unit, I would state that this is really a matter of fan design. Each fan has the same characteristics, this characteristic being such that pressure, volume and power conditions interact and prevent hunting. Any lack of uniformity would be evident by blowing back, a condition which is readily ascertained and corrected.

Prof. Hirschfield's question in regard to the considerations which led to the decision that economizers should not be installed would lead to an involved story. As to the question of bids submitted by manufacturers, those that seemed to be the most satisfactory, were in general accepted. A study of the economics of the situation at Cheswick developed that only when coal reached $7.00 per ton, all the factors being taken into account, (first cost, maintenance cost, fixed charges, etc.) would the installation of economizers pay. That is no doubt due to the high cost of construction at that period.

As to Mr. Snyder's question as to pumps above the water level, it would be physically impossible to locate the circulating pumps where they would be near the water level at all times and not subject to a suction lift. There is no difficulty in operating pumps as we have located them nor in lifting water 15 to 20 feet. It is usual, and not otherwise. I am not sure that I understood his question as to the operating of fans on both ends of the system. The installation of induced draft fans is simply a question of the maximum rate or limit at which boiler and furnace are to operate. This has been set at 300 per cent, both by the stokers and by the draft.

The difficulties to be encountered in the design of steam engines that will operate successfully with a steam pressure of 275-lb. gage and with a total steam temperature of about 600 deg. fahr. led directly to the adoption of motor-driven stokers.

On account of the variable speeds required for different ratings and because of the fact that fine gradations of control are most desirable, d-c. motors were adopted.

As to the name of the station, Colfax is the name of the Borough, stations being usually named by their geographical location.

D. L. Galusha: Replying to Mr. Brown's question as to why transformers were placed in-doors. It is of course perfectly proper these days to place transformers out of doors where conditions warrant that procedure as we have done in the substation design. The two principal criteria on which to base the conclusion are reliability and cost. Although at first sight it may appear that it would cost more to put the transformers inside, I can assure you that it did not. An outdoor installation for the ultimate station would have cost $500,000 more than an indoor installation.

For an outdoor location at this site it would be necessary to go up or down stream, beyond the power station building, and to carry current to that point at 12,000 volts. The cost of this 12,000-volt transmission accounts for the large difference just indicated.

As to the matter of reliability, the same fundamental results have been obtained indoors as would have been the case outdoors, by the use of equivalent spacing of parts. Ease of inspection and repair, it seems to me are all on the side of the indoor location.

I think that Mr. Snyder's questions have been very largely answered by Mr. Stone. In answer to his question as to how you could get going in a central plant in case of shut-down, I would say that the processes would be practically the same as those for an isolated plant.

He asked why the substations were located in the woods. The locations of the substations are not so far away as he assumes. The substation he mentions is only three miles from the Rankine power station.

I think Mr. Snyder properly took exception to my remark that continuity of power in isolated plants is of secondary importance in certain cases. I have no doubt that in Mr. Snyder's plant that is not true. I was thinking of the average isolated plant. The importance of continuity in the steel business is so great that I have not the slightest doubt that in his plant continuity of service does come first, but I claim that in the average plant my statement is correct, that continuity of power is secondary to output of the product manufactured. Those who are in a position to check me will bear me out that continuity of service does not take the place of importance in the average isolated plant that it does in the central station.

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PERSONAL OBSERVATIONS IN THE INDUSTRY
President's Address

BY ARTHUR W. BERRESFORD

IF, in the selection of a subject upon which to address you, I have gone further afield than the profession of electrical engineering, or, indeed, have seemed to go even beyond the domain of the engineer, I trust that you will not lose sight of the fact that whatever benefits industry as a whole, benefits the engineer; and again, if I seem to doubt the possibility of the engineer being competent in himself to solve all of the problems of our complicated civilization, I trust you will not consider me as holding him to be without function.

It is true that I am not in entire sympathy with what appears to be a growing feeling that the engineer may, with advantage, invade all fields of effort, and I think I perceive a growing resentment toward this conception of the engineer's function. I am not at all certain that the engineer should presume to advise in the relation between employer and employe, nor that he should consider himself competent to adjust the many problems which arise in commerce and industry. Is it not possible that the qualifications of the engineer have been confused with the methods of the engineer, and may it not be possible that what is desired is the application of engineering methods rather than the engineer in person?

However, this divergence in viewpoint might be reconciled—if there be not too much of heresy in the suggestion—by assigning the title of "engineer" (although of a class not yet provided with a distinguishing descriptive adjective) to those who are doing creative work in industry and commerce based on the application of these same engineering methods. If this lack of heresy be conceded, then is what I have to say proper for your consideration.

The outstanding characteristic of the present-day civilization is organization—the almost involuntary gathering together in groups of those possessed of interests in common; usually, in the beginning, that there may be facilities for the interchange of views on matters which engage the daily thought. This is the stated object of our own organization. Sooner or later, however, the possibility of other activities becomes evident and inevitably the initial purpose of the association is broadened and work is undertaken which results in common good. In the measure in which the purpose is altruistic and the element of self-interest is lacking, or enlightened, the accomplishment benefits not only the actual members, but industry as a whole, the community and the nation, and ultimately the world in which we live.

From the instinctive nature of their conception, these associations, however well-conceived for their specific purpose, will not be formed in accordance with some well-considered and throughly-planned scheme, resulting in a properly rounded and carefully calculated whole, but, on the contrary, will present to a broad view the impression of a series of unrelated bodies, each going forward in its own way, and, to an extent, ignoring the interests they have in common, until consideration is forced by some duplication of effort or conflicting action.

This condition has long been recognized and was under discussion when I became connected with the Institute as an associate member some twenty-five years ago. The thought then was that the Institute should be the dominant body in the industry, embracing all branches of activity and permitting the concentration of all available knowledge and experience on any given problem. The possibility of such an organization, or at least of a council, in which all might be represented, is still under discussion. Progress, however, has been along other lines, and today the probabilities are that such an organization would fall because of its very breadth and its consequent inability to deal with other than the broadest problems susceptible only of the most general of solutions. There would not be the concentration of interest necessary to the accomplishment of tangible results.

The major problem of the present day is the education of the mass of the people to the perception of true values. Most of our difficulties result from the honest misunderstandings of honest men—misunderstanding of speech, act or motive—with consequent growth of suspicion and inability to evaluate the opposing viewpoint. This is true of the employer-employe relation. It is equally true of the competitive relation. It is no less true of the relation of industry and government. If the condition is to be removed and the interest of our whole people advanced, the only certain procedure is through adequate education. In the employer-employe relation this can be carried on most effectively in the ultimate unit, namely, in the individual plant, and by those directly interested. In the industry it can be accomplished only through the understanding that comes from contact and interchange—as between industry and government only by the presentation of mass view of the industry, setting forth adequately, accurately and honestly the general need of all.

In other than matters of direct interest, such as the employer-employe relation, the association, for whatever purpose originally devised, forms the natural and obvious means of carrying forward this process of education so vital to our future. Men meet and weigh each other. Trust is born of knowledge and there follows the death of mistrust born of ignorance. Views are interchanged and opinions crystallize. Intelligent analysis determines the underlying fundamentals and does not mistake the symptom for the disease. The diagnosis properly completed, the remedy becomes apparent, and the policies based on the fundamental principles may be followed in the certainty that their consistent and persistent observation will ultimately produce the desired result, however long the interval.

But no single association can do this for an industry.

It becomes necessary that all be represented. Particularly is this true in relation with government and governmental functions. No single group—whether corporate or associate—may assume to present the interest of the whole without arousing the suspicion that self-interest is present, as at least a considerable motive. Nor can it hope to be continually successful in this procedure, however much it may appear to accomplish initially.

These statements are so obvious as to appear trite, but how frequently one hears it said that the association operates mainly to the advantage of the minor interests; that the large corporation, complete in itself is self-sufficing; that it could and does perform for itself all that may be possible through association, and that in consequence it contributes to association by far more than it receives. The essential lack of soundness in this view is immediately apparent, however, when one considers the entire industry and the relation thereto of the large corporation.

For the proper development and economical operation of any industry, the major interests in that industry must have the understanding, support and good-will of those less important. This is true in direct ratio as the policies of these major interests are enlightened, broad and far-sighted. The human instinct of caution, emanating from centuries of need for self-protection, breeds both suspicion and jealousy of power. The policies of a minor manufacturer may be directly contrary to the interests of an industry as a whole, not by intent, but by reason of a limited point of view. He would be entirely willing to reverse these if there were clearly set before him the certainty of ultimate unfortunate result to himself as well as to others, but without this understanding any instance of interfering procedure by a major interest is certain to be interpreted as an assault upon his business for competitive reasons. He will, moreover, ascribe the success of such procedures to a wrongly held and unfairly exerted power by the large corporation rather than to its true cause, and he will be sincere in this attitude. The result must be an increase of suspicion, based on misunderstanding; of jealousy and resentment, based on a sense of personal injury; of mistrust, based on fear of future repetition. All of these breed waste and destructive competition, increase the ultimate cost and reduce distribution, with consequent injury to the industry as a whole and to the individual units which compose it—whether large or small.

If, on the contrary, the major interest, by contact and consideration, secures the trust and understanding of the smaller man, and if it proceeds still further and puts before him the facts and conditions which determine its policies, which data he has neither the facilities nor the opportunity to acquire for himself, thereby increasing his understanding and broadening his viewpoint, much that is otherwise impossible becomes practicable. It may be unfair that the larger interest should be called upon for the expenditure of time, money and patience necessary to this process of education and the devotion to it—as will initially be necessary—of their best minds, but their advantage is largely concerned and their ultimate success involved. The association provides the opportunity for this procedure.

From the industry's standpoint, therefore, the problem becomes the correlation of the necessary associations into a representative coordinating body and the direction of the combined effort in such manner as shall insure such advantage to its members as is consistent with the rights of others and the best interest of the public.

It is immediately evident, however, that the securing of this advantage to an industry—to the corresponding advantage of each division thereof including that of engineering—involves the correlation not merely of engineering associations, but of all associations interested—whether commercial, non-commercial, scientific, or serving some special interest.

I sometimes feel that we of the non-commercial class hold ourselves too much aloof from those organizations whose function is apparently the promoting of the material advantage of their membership. There may be, and is, as high an idealism in industry and commerce as in pursuits termed "non-commercial," and more than one operation of magnitude has been instituted and quietly carried through with far less of thought of ultimate profit than of the service to be rendered to humanity. We have every-day instance of something done for the general good and because it is right, that bespeaks a high-mindedness which those who pride themselves on freedom from commercial incentive may well admire.

And let us not forget that in the end the major incentive to result is self-interest and that properly educated and enlightened self-interest may accomplish more than a less practical altruism, and with no sacrifice of ideals.

Our portion of the work may be to increase the percentage of idealism, while at the same time encouraging the proper operation of this major incentive of self-interest which is absent from few or none; to direct it along broad and well-considered lines of principle and policy, with the elimination of opportunism, and to the end that each may strive to profit with the other, rather than at the expense of the other. There is nothing of communism in this. The reward of each will still be a function of his effort and ability, but there will come understanding of the reasons for the disparity in reward instead of revolt against a seeming unfairness; discontent with one's self and consequent increased effort, instead of jealousy and dissatisfaction with conditions; a coordinated working along well-defined lines, rather than individual attack at possible cross purposes, arising from restricted knowledge of the problem in its entirety. That such procedure must make for the maximum of progress in whatever line of activity it may be applied is self-evident.

Our own branch of industry is peculiar in possessing all of the elements present in any other and many in addition—all of the problems of manufacture and construction, together with specific problems demanding knowledge of almost every other branch in order that proper application of our product may be assured; an extended engineering content; a dependence on pure science and mathematics by far greater than any other of which I have knowledge and a more than ordinary interest in government relation—national, state and local—by reason of public service content. What other branch of industry involves so many factors? It would seem, therefore, that could we offer a solution for some of our own major problems, we would be pointing the way for all industry and that we might anticipate its concurrence and support in what we may initiate.

I have said that the major problem of the day is education, the major phenomenon organization, and that within the industry, organization—properly correlated—furnishes the obvious medium for the process of education; the question being to secure such correlation.

I believe this correlation could be attained if the broad fundamental principles underlying the industry could be enunciated, and if there could be developed therefrom the operating policies which the industry should follow. The proper and adequate performance of this task would secure the assent of all elements, and while permitting each organization to preserve its individuality unchanged would direct procedure along parallel lines leading toward the common goal. The points of common interest would be quickly and conspicuously developed and cooperative, harmonious relations thereon instinctively established.

Who is most competent to perform this task? It seems to me that there will be required the best minds of the industry—the men of the broadest viewpoint and experience and of the widest contact with all of the phases of our work. Where shall we look for such men? It is my opinion that they will be found in the executive personnel of our great corporations. The constructive ability, knowledge and grasp of affairs, keen perception of values and idealism which have put these men in these positions, and without which there could have been no such accomplishment, must result in their becoming the leaders, and, in the main, the doers of this work. That they could in no way more surely serve their own interests is beside the point.

If they undertake it, they will do so from the broader viewpoint of rendering that service to their fellows for which they are the best qualified. That they will undertake it, I believe.

Assuming such a correlation, let us develop one or two of the problems which confront our own industry, and, in varying degree, other industries, and apply the factors which we have been considering. The appreciation of the ultimate dependence of industry on science and the consequent vital importance of research is of too recent birth to have attained general realization. The statement is accepted as a matter of course, but it has not come to be an actual, living, daily reality in the minds and life of most of us. That it will ultimately be so recognized is certain, and possibly in the near future. This being the case, how are we providing for it? The larger corporations are maintaining research laboratories—have been forced to do so by the demands of the industry—in which the bulk of this work has been directed toward the solution of specific problems, the results of which are generally conceived to be for the benefit of the corporation individually, and in part may be so initially.

The universities are carrying on research work in their laboratories to an extent determined by their financial resources and the initiative of their personnel; mostly of abstract nature, directed to the solution of general problems, chosen largely, and sometimes I think mistakenly, for the absence of applicational content.

The Bureau of Standards, under government auspices, and in the interest of the country's industry, is performing work of both types.

There are certain privately operated laboratories whose services may be employed by the industry in general for the solution of specific problems.

To determine how the work as a whole should be correlated to secure the maximum progress requires an understanding of the conditions.

The first conception which it seems necessary to establish is that all research is in the public interest—whether applied or abstract, and irrespective of whether its immediate object is the specific advantage of the concern or person undertaking it, or simply the increasing of the sum of human knowledge.

No one will question that abstract research, forming, as it frequently does, the foundation of important industrial advance, and given to the world without restriction, is definitely in the public interest. There may be those who question the content of what may be termed "practical applications" and who would limit investigation to the more promising possibilities, but the past gives ample warrant for future expectation, and no man can say in advance where value may be found. Much that today seems of no practical value may simply be awaiting the key discovery which will be found by no process other than that of this constant search for fundamental truth.

The misunderstanding seems to lie in the so-called "applied or applicational research," usually directed toward a specific problem, the solution of which becomes, under our patent system, the exclusive property of the instigator and a consequent source of gain. Is not this as it should be? Without this incentive no corporation could justify to its stockholders the necessary expenditure, and but few individuals would possess the necessary resources; for not every problem is solved and many months are spent in work that brings no fruition. Moreover, the period of exclusive use is limited and but short compared with the time during which the solution may ultimately be freely used by all. Again, the public as a whole usually reaps the benefit of the solution during this period of exclusive use and is advantaged in such degree as to make the reward to the owner small in comparison. A corporation laboratory produces ductile tungsten. During the life of its monopoly its profits may be great, but they are insignificant compared to the millions that are saved to the many who employ it in the incandescent lamp during this period, which savings will continue in effect long after the period of exclusive use is past. An improvement in the art of speech transmission may result in increased gain to the corporation controlling it, but it decreases the cost of the telephone to the user (or increases his possibilities at a given cost) even while the patent monopoly continues, and thereafter for all time. This is true in some degree of every successful applicational research.

It becomes clear, therefore, that *all* research is in the public interest, and that from the public viewpoint the sole difference in desirability between abstract and applied research is one of degree and not of fact; that the important point is increased research activity irrespective of where or by what means it is carried on.

There are two prime incentives—direct gain and the search for truth—the first more immediately productive of usable results, but aiming at what may be termed the details—the second laying the broad foundation for the future. There is no middle ground. No one can say at what instant an abstract research may develop an important practical application, and *vice versa*. The division between the two fields is a sharply defined line, not a neutral territory. It is fixed purely by the motive which animates the work. It is all of equal importance to the public and to the industry. It is comparatively unimportant how it is carried on and whether for a brief space someone shall be peculiarly advantaged.

In feeling that industry must supply the driving force, I am not setting the hope of gain as a greater impulse than the search for truth, but means must be supplied and to industry, the producer, we naturally turn. The hope of gain will impel the continuance of applied research where it is already established, and, where the individual concern cannot support its own adequate facilities, will widen the field by the institution of laboratories for the common use of groups possessing similar interests, once its value is appreciated. We may confidently expect, therefore, that this division of the field will show increased intensity of cultivation in direct ratio to the realization of its possibilities.

Fundamental research, however, must be provided for. The search for truth will supply the incentive, but not the means. Universities will do what their poverty permits, but it is not sufficient. Industry must increase the possibilities. An incentive must be offered to induce temperamentally fitted men to undertake this career and to become largely qualified, else industry will go begging for the men it will need in increasing quantity for its applied research. It may fairly be said that this condition is with us today, and that with the increasing demand there is danger that the universities will lose in practical totality those who must be depended upon to keep alive the spirit and train the men who are up-coming. Men now exist, in reasonable number, whose devotion and achievement in this field are an inspiration and an example for emulation among their co-workers which is of far-reaching effect. Given even a minimum of encouragement the future will continue to evolve them, and once in a generation or so a genius.

In the general consideration of such men in relation to organization, may I divert for the moment and offer a word of caution? Genius works not too well in harness and are there not already, both here and elsewhere, indications of a feeling that too much centralization and coordination may hamper or even cripple rather than facilitate?

I know of but one instance (there may be others) in which industry has begun formal consideration of its relation to research in the universities. In February, 1919, the Michigan Manufacturers Association brought to the attention of the regents of the University of Michigan the desirability of establishing closer relations between the university and the industries of the state, realizing that in so doing an appreciable degree of cooperation would be through channels of research. The Regents' Committee considered the matter and favorable action was taken in January, 1920. The first meeting of a combined committee was held on May 27, 1920, and that committee is busied with the many questions involved. Where state universities exist no action could be instituted which promises more of ultimate value to the community.

If, then, industry must take the initiative, if only in its own interest (although I believe the action will be on broader grounds once the condition is appreciated) can it again do better than to secure the concentration upon the problem of the best minds that it possesses and to determine what is to be the relation and what course to pursue? I conceive that those most competent to form such an opinion are those who have the broadest knowledge of our industry and the largest experience with the problems and advantage of research, and again I conceive these men to be the best minds in our major corporations, irrespective of position—whether commercial, engineering, or purely scientific.

Consider the governmental relation as existing between the industry and the Bureau of Standards, in whose operations, by reason of our diversification, we have more than ordinary interest. During the last few years, I have heard many expressions of dissatisfaction with certain Bureau actions and activities, and have heard various causes assigned, among which were the belief of an existing total misconception on the part of the Bureau of its proper relation to the public; a feeling that the Bureau construes its function to be that of protecting the public against some possible unfair act or aggression of the so-called corporate interests, and that in consequence there is being bred in its people an unjustifiable suspicion of, and antagonism to, those who are engaged in operations for profit, and a lack of recognition of the fact that they also are part—and a useful part—of that same public; that this misconception, together with a seeming need for the initiation of activities which should directly appeal to the popular mind in order that appropriation committees might be impressed, are carrying the Bureau beyond its proper scope and into fields of work for which it is ill-fitted—which fields could be covered to far greater advantage by other agencies and methods—and that in consequence distinct damage is being done. Doubt is even expressed of the actual desirability of the Bureau.

These are formidable allegations and must have their foundation in some measure of truth or in misunderstanding. In any event, they are serious and if either the conditions or the misunderstandings are not eliminated, definite harm will result.

The conception of the elimination of the Bureau is surely exaggerated. It requires but little consideration to determine that the maintenance by the government, and under conditions beyond suspicion of improper influence, of a central authority, dealing at least with weights and measures, is essential. That the scope of such an activity may well be extended beyond so limited a function seems equally evident. My own conception is that it may helpfully be broadened to the determination and establishment of all matters of physical fact, but that it should stop short of matters of opinion or economics, but I may be too conservative. The obvious condition is that divergence of opinion exists, and that there will be increasing lack of harmony unless this divergence is removed.

The Bureau has undoubtedly devoted much thought to the course it has adopted. How much real consideration has the industry given to the subject? Is not the situation an instance of two groups, each proceeding along its own preconceived line, until the attention of each is concentrated on the other by an apparent conflict of interest? If the scope of the Bureau's work is of direct interest to the industry—and it seems to me to be of vital interest—then is the situation sufficiently serious to demand the most careful consideration of the industry—and sufficiently acute to demand it immediately.

As to the personnel of the Bureau, I know of no more unselfish, self-sacrificing, patriotic body of men. I have yet to meet one who has given his personal interest even the consideration it merits. If these men are not proceeding along the most helpful lines, it is because of a mistaken conception of what is their duty. Whatever they are doing, they are doing honestly, and there is always a complete willingness to discuss freely and fairly any objection which may be urged. If such misconceptions exist, how much has the industry done to correct them? These men are not of commercial type, nor are they in touch with affairs. How is it to be assumed that they will, out of pure instinct, foresee all of the effects on our complicated industrial structure of some activity undertaken by them in all honesty and apparently in the interest of all? To what extent has industry striven to make clear its condition, instruct the Bureau in its problems and convince the Bureau of its good faith? Is there any other method of curing whatever undesirable condition may exist in this respect?

Again, if there actually exist conditions which have induced what industry may consider as an undue expansion of the Bureau's field in order that the importance of the Bureau may be enhanced in the minds of members of Congressional Appropriations Committees, then is not the industry to blame for these conditions? If, in the interest of the farmer, it is deemed necessary and desirable that millions be spent in agricultural research—and not only public opinion, but the results of record affirm the wisdom of this expenditure—is it not incumbent on industry similarly to make clear to the government its needs and demonstrate to it and to the public the importance and necessity of meeting them? The amount required is far less than the expenditure for agricultural research and the value of the products affected is of at least the same order. Is it consonant with the dignity of the Bureau and the men who give their lives to its work that they should be obliged to manoeuvre for the necessary support, and that when given, it is so meagre that the work is hampered and the men themselves so poorly compensated that many, contrary to their own desire, but purely that their families may live in reasonable comfort, have been obliged to terminate their career of public service and take up more gainful occupation? I conceive it to be the prime duty of the industry, first, to agree on what shall be the scope of the Bureau; second, to educate the Bureau in its conditions; and, third, by demanding that its interests be heeded, to secure the adequate support of the Bureau.

Only a united industry—commercial and noncommercial—can do this. The electrical industry, by reason of its greater interests, should initiate it and carry forward, through its associations, the necessary process of education; and, again, I believe that these same leaders of the industry are most competent to determine the fundamentals and the policies by which we should be guided.

My conception, then, is that the immediate need of the industry is the enunciation of what are its fundamental principles, the statement of what should be its working policies and the outlining of what should be its relation to the major problems which confront it; that there is a sufficiency of organization and of interrelation of organization; that there should be added only cooperation for specific objects where progress or legitimate interest directly indicates its desirability; that the matters in which this cooperation may be applied and the agencies between which it is necessary will be made evident only by the broad analysis suggested; that once made evident it will be instinctive, effective and efficient.

There may be disagreement with my feeling that this analysis would best be made by men in the corporate relation and the thought may be that it would better be done by conference of the industry's organizations, since if this procedure were followed any suspicion of an undue degree of self-interest would be eliminated; but I ask consideration of how cumbersome would be the procedure and how small the probability of reasonable expedition in reaching results. The mere fact that numbers of men would be engaged instead of four or five would make for extended deliberation, and time is an essential element, Moreover, it is evident that the prononucement. when made, would be accepted by the industry only in the degree that it embodies the breadth of view and the knowledge which these men possess and the honesty of purpose which I am certain they would bring to the task. My belief is that it would be thoroughly acceptable. It is no small service to ask of them, but again I am confident that it will be rendered willingly if the industry realizes its importance, agrees as to the method and makes the request.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, June 21, 1921.

ANNUAL REPORT OF THE MINES COMMITTEE

To the Board of Directors:

THE Chairman of the Mines Committee of the A. I. E. E. for 1920-21 has had the honor of being also the Chairman of a similar committee, the Mine Equipment Committee, of the A. I. M. E. It has been the endeavor during the past year to have the two Committees work together since the object of these Committees is very much the same.

A meeting of the Committees was held in Chicago in November of 1920 at which time it was decided that one of the best methods to work together would be to foster joint meetings of the local sections of the A. I. E. E. and A. I. M. E. By these meetings, it was hoped that various engineers in the local sections interested in mining subjects could be brought together and not only become better acquainted, but could be greatly benefited by the interchange of ideas and by the discussion of papers presented on mining subjects.

It was also decided that both Committees should encourage the writing of papers on mining subjects to be presented, either at local section meetings or at the National meetings.

It was also decided that these Committees should work in conjunction with the American Mining Congress and the American Engineering Standards Committee in developing standard practises for both coal and metal mines in the United States.

The first combined meeting of the local sections was held in Pittsburgh on January 18, 1921, the meeting being held at the Bureau of Mines. An afternoon technical session was held at which a paper was presented by F. W. C. Bailey on the subject of "Power Rates for Coal Mines." This paper was well received and produced an active discussion. Following the afternoon meeting, a visit was made through the Bureau of Mines Buildings, after which dinner was served at the same place. The evening session was held in the auditorium of the Bureau of Mines and a paper was presented on "Gathering in Coal Mines" by R. Kingsland of the Consolidation Coal Company of Fairmont, W. Va. Both afternoon and evening papers have been submitted to the Publication Committee of the A. I E. E. for publication in the JOURNAL.

A second combined meeting has been arranged to take place in Chicago on April 25th. This meeting will be participated in by the Electrical Section of the Western Society of Engineers, the Mining Section of the Western Society of Engineers, the Iron & Steel Electrical Engineers of Chicago, and the Chicago Section of the A. I. E. E. Two papers will be presented as follows: "Diversity Factor of Coal Mining Loads" by Carl Lee, Electrical Engineer, Peabody Coal Company; and "Power Distribution Systems for Coal Mines," by W. C. Adams, Allen & Garcia Company.

The Philadelphia Section has agreed to have a combined meeting, but wishes to put it off until the Fall of this year as it has recently held two combined meetings with the Engineers Club of Philadelphia and does not wish to have another combined meeting in the near future.

It is hoped during the present year to have additional combined meetings in some of the Western States.

PROGRESS OF ELECTRIFICATION OF MINES

Until recently, the coal mines of the United States have been particularly active and the price of coal has been such that most mining companies have had a fairly profitable season. This has enabled a great many mines to establish improvements in the way of electrifications that they had been looking forward to for some time. A few years ago, the central stations were having a very difficult time to persuade the coal mining companies that they could sell them power cheaper than the coal mining companies could produce it themselves. Recently, the conditions have been somewhat reversed and in many cases the central stations have found it necessary to refuse coal mine loads on account of having no surplus capacity. In the large majority of cases, it is not difficult to show a coal mining company that it can operate its mines more economically from purchased power than from its own power plant.

Isolated power plants are being installed in some cases where central station power is not available, and also where the operator feels that central station power is not as reliable as his own plant would be. This is particularly true where the coal mining plant is throwing away fairly high grade waste coal and where a stand-by steam plant is kept in operation to take care of operating the auxiliary hoist and fan in the case of power failure. The tendency in isolated plants is to install geared turbines up to a capacity of 500 kw., and above this capacity the direct connected turbine. The turbine installation makes a much simpler plant to operate when compared to the old engine-type stations and turbine plants have records of long continued operation with practically no interruptions and a very low cost of operation.

The synchronous converter is becoming more popular each year for mine service. This is due largely to the improvement in converter design which makes this apparatus as strong and simple to operate as the motor-generator set, with the advantage that it takes up less room and is much more efficient.

The most important development during the last year has been that of the automatic substation for mine service. One of these plants has been in successful operation for several months and several more are being built. The automatic substation has the advantage that it performs all of the operations that are necessary in a substation at the proper time and much better than could be accomplished by manual operation. The automatic equipment makes no false moves and in case of trouble of any kind, acts on the safe side and shuts down the station if necessary. It is felt that in the future, the automatic substation will play a very prominent part in mine installations.

The electric hoist is rapidly replacing the steam hoist to such an extent that a steam hoist is rarely installed in a new mine. The large majority of hoists for coal mines is of the alternating-current type using a wound rotor induction motor with the magnetic type of control. Recent improvements in the control and safety devices make the electric hoist practically fool-proof and serious accidents are of very rare occurrence. A few installations have been made using the Ward Leonard system of control and flywheel motor-generator set. The Ward Leonard control is necessary where very fast hoisting cycles are required and the flywheel is necessary where the customer is penalized for momentary peaks.

The past year has seen a continuation of the develoment and application of magnetic control to mine locomotives. The demand for the individual capacity of mine locomotives has been increasing until it becomes very difficult to supply a drum type controller for 250-volt service. The magnetic type of control is a very satisfactory solution for this problem, and a number of such locomotives have been recently installed. The large unwieldy drum controller is replaced by a small master controller which takes away a considerable element of danger from the motorman's position. The main controller, consisting of magnetic contactors and reversers, can be distributed back in the locomotive, preferably suspended from the underside of hinged covers which enables the equipment to be inspected readily and repaired. The use of magnetic control has greatly simplified tandem operation. With drum-type controllers, it is necessary to mount a large four-motor controller on the primary unit, a two-motor controller on the secondary unit, and the two units connected together by a large number of heavy power cables, when tandem operation is required. With magnetic control, the two units are identical and the only connection between the units required is one power cable and a control cable consisting of nine control wires. The advent of magnetic control makes it necessary for the mining companies utilizing it to furnish better voltage regulation for the mine circuits which in turn will save considerable power loss and also keep down repairs on mining equipment, which repairs in the past have been largely due to poor voltage regulation.

A number of improvements and new features have been added to the construction of mine locomotives during the past year. Of these, the most important are the substitution of the leaf type spring for the helical type of spring, the installation of the end-thrust type journal box, the use of equalizers on two-axle locomotives, the application of detachable rims to locomotive wheels and the more general application of dynamic braking on mine locomotives. The value of these various improvements can only be determined after a thorough trying out.

Metal Mining Industry

The metal mining industry has been particularly quiet during the last year due to the low value of practically all metals excepting iron and steel. In the copper mining industry, one of the recent improvements has been the installation of a motor-driven turbo blower to replace a Root type for such service as air for cupolas, converters and flotation cells. These blowers require high-speed synchronous motors which are of the turbo type.

The metal mines have been doing a little work toward revamping their plants and installing new equipment, but this, of course, has been greatly hampered by the poor market conditions.

Shovels and Drag Lines

Electric power is gradually replacing steam on shovels and drag lines where electric power is available. There are at present, two systems being used, one the a-c. in which wound rotor induction motors are used to operate the various parts of the shovels and drag lines. The other system is to use d-c. mill-type motors receiving power from a synchronous motor-generator set. The motors are operated by rheostatic control. A recent development is being watched closely by all engineers interested in the handling of shovels and drag lines. This consists of d-c. motors on the shovels receiving power from the synchronous motor-generator set with a separate generator for each motor. Ward Leonard control is used and the advantage of the system claimed is that all rheostatic losses are eliminated and the momentary peaks are kept off the power system. It is hoped that during the next few months sufficient data will be obtained to determine the feasibility of this system and its economy when compared with the other two systems.

CAR DUMPER

During the past year, some very important installations of car dumpers have been made at the Atlantic ports. These car dumpers are increasing in size from year to year and there has recently been placed in operation at Baltimore the largest car dumper as yet constructed. This car dumper requires four of the largest mill-type d-c. motors built on the cradle hoist, all operated from one master controller. It is felt that if these car dumpers increase further in size, it will be necessary to utilize the Ward Leonard control system.

A very interesting installation of grain car dumpers has been placed in operation during the past year at Baltimore. This car dumper takes care of unloading box cars filled with grain, with practically no manual labor. All motions are interlocked, so that it is practically impossible for the operator to make the wrong move and cause any considerable damage.

ORE AND COAL BRIDGES

There has been little change in the type of equipment for ore bridges during the past year, but in regard to coal bridges, the largest one ever built has been installed and placed in operation by the American Bridge Company at the By-Product Coke Plant of the United States Steel Corporation at Clairton, Pa. This bridge is by far the largest ever constructed and it is expected to take care of a very large tonnage of coal from barges in the river to storage piles, in order to insure a steady supply of coal to the coke ovens at Clairton, which is the largest by-product coke oven plant in the world.

BY-PRODUCT COKE OVEN

During the past year, an advance has been made in the design of locomotives for quenching service in and about by-product coke ovens. The latest type of locomotive is equipped with electropneumatic control having not only automatic acceleration, but also the ability to operate on any notch. These locomotives weigh about 25 tons each and have a number of new features in regard to mechanical arrangement of parts that are quite an improvement over the past type of construction for quenching locomotives.

The coke-loading locomotives at the Clairton plant are of the combination type, using remote control while the coke train is being loaded. These locomotives have been operating very successfully during their second year, and have affected a large saving over the older scheme of using steam locomotives, or the cable haul. It is felt that in the future there will be a considerable call for the remote control of locomotives and cars, not only around coke plants, but also where large amounts of material are to be handled over fairly great distances.

GRAHAM BRIGHT, *Chairman.*

ANNUAL REPORT OF INSTRUMENTS AND MEASUREMENTS COMMITTEE

To the Board of Directors:

The Instruments and Measurements Committee submits the following report containing a brief statement of its own activities, brief mention of significant papers issued during the year and as comprehensive a statement, as can be briefly condensed into a report of this character, of the progress in the electrical field covered by its title.

The committee arranged for a number of papers for presentation at the Midwinter Convention in February and had a session assigned to it. The papers presented at the session are as listed below:

Regulation of Frequency for Measurement Purposes, by B. H. Smith.

Measurement of Relative Eddy Current Losses in Stranded Cables, by J. A. Cook.

An Electromagnetic Device for Rapid Schedule Harmonic Analysis of Complex Waves, by F. S. Dellenbaugh, Jr.

The Limitations of the Stopwatch as a Precision Instrument, by A. L. Ellis.

The paper by Mr. A. L. Ellis, listed above should be considered as related to the paper by Mr. H. B. Brooks which was presented last year under the title of the Accuracy of Commercial Electrical Measurements. This paper by Mr. H. B. Brooks, it was hoped would contain an analysis of the characteristics and limitations of the stopwatch, as well as the purely electrical instruments. This could not be included, however, and it was felt by the committee this year that it would be desirable to have such a paper on record. The paper was, therefore, prepared by Mr. A. L. Ellis and serves very well indeed to supplement or complete the very thorough paper presented the year before by Mr. H. B. Brooks.

In addition to the papers referred to above, other papers or articles are listed below which seem of sufficient significance and value to include in this brief report. It is not intended or even possible to make a complete bibliography of all papers or articles which may have appeared during the past year, relating to the general subject of instruments and measurements, but as stated above the following brief mention seems of value in this report:

The Corona Voltmeter and the Electric Strength of Air, by Whitehead and Isshiki, in the JOURNAL, A. I. E. E. for May 1920. The proposed increase of transmission line voltages, makes the measurement of crest voltage of increasing importance. In this paper Dr. Whitehead describes refinements in the corona voltmeter and a modification of the previously accepted law of corona.

New Current Balance for Calibration Work, by Otto A. Knopp, *Electrical World*, Vol. 75, May, 1920. This apparatus makes it possible to obtain a large number of standard values of current from a single value calibrated by independent means. It is especially suitable for central station use in the calibration of a-c. ammeters.

Portable Oscillograph, by J. W. Legg, JOURNAL, A. I. E. E., July, 1920. The oscillograph in its previous forms is a valuable instrument, but is not well suited to field work. The form described by Mr. Legg replaces the arc lamp with a tungsten lamp operated at very high efficiency, and excites the galvanometer magnets from a storage battery. A number of ingenious features are included in order to control exposures.

A Dynamometrical Comparator, by Edy Velander, JOURNAL, A. I. E. E., July, 1920. The accurate measurement of small alternating currents presents considerable difficulty. This comparator, in connection with a d-c. potentiometer, is stated to give accurate measurements of currents from 5 to 50 milliamperes, at frequencies up to 2000 cycles.

Permanent Magnets in Theory and Practise, by S. Evershed, *Journal*, Inst. Elec. Eng. (London), Sept., 1920. This paper is primarily of value to the designer and maker of electrical instruments and meters.

Magnet Steel, by Honda and Saito, *Electrician*, Dec. 17, 1920. This paper gives the properties of a remarkable steel for permanent magnets, having a very large coercive force and intensity of residual magnetization.

The method of making large ammeter shunts which was mentioned in a paper before the Institute in February, 1920, has been used by A. B. Field in England, who gives particulars in a paper in the *Journal* Inst. Elec. Eng. for August, 1920. This paper and its discussion are particularly valuable in view of the increasing size of totalizing shunts used to measure the direct-current output of synchronous converters or the total direct-current output of substations.

Wattmeters have been made on the electrodynamic, electrostatic, and electrothermal principles. To these may now be added the "vibration wattmeter," announced in a paper by Biermanns in *Archiv fur Elektrotechnik* for August, 1920. This is similar to a permanent-magnet moving-coil vibration galvanometer, but has two windings in the coil, one used as a current coil and the other, with a non-inductive external resistor, as a voltage coil. Two readings are taken, for the second, the relative direction of current in the two windings is reversed. The power is proportional to the difference of the squares of the deflections. It is said that as low as 10^{-13} watt can be measured.

Considering the question of new developments in apparatus, the makers of watthour meters and demand meters advise, in general, that the effort, during the past year, has been mainly expended in restoring the pre-war quality of output, rather than any considerable amount of new development.

Apparatus continues to be developed for making measurements either of kilovolt-amperes or of the inductive component to be used in connection with rates including a power factor charge.

One of the makers of indicating instruments reports the development of a new line of small size portable instruments (ammeters, voltmeters and wattmeters). These instruments would be of particular interest to those desiring small but accurate and serviceable instruments which can be carried in the pocket or the tool kit.

The makers of precision and recording instruments report the continued development and application of electrical measuring methods and instruments to problems and functions not fundamentally electrical. While electrical methods have been used for years in making laboratory measurements of quantities not electrical, the significant fact now is the wider application of electrical measuring devices for recording and for the actual quantitative control of industrial processes.

Automatic Gas Analysis. Apparatus is now available for the automatic recording of gas analysis. The operation of the apparatus depends on the thermal conductivity of the gases being analyzed. The apparatus is arranged so that variations in the thermal conductivity of the gas being analyzed will cause corresponding variations in the temperature of a resistor having a high temperature coefficient of resistance. The variations in this resistance are recorded by an automatic Wheatstone bridge recorder. Such apparatus finds a valuable application in plants manufacturing hydrogen, oxygen and other gases for commercial purposes.

Electrical Temperature Controller. Equipment has been developed for controlling the temperature of any piece of operating equipment, and particular effort has been made to obviate the trouble due to "hunting" occasioned by the lag between the change in the quantity which is causing the heating and the corresponding change in the temperature of the body under control. The device in question is designed to control the input of the quantity causing the heating in accordance, not only with the actual temperature of the body, but also in accordance with the rate of change of the temperature of the body itself. For instance, if 100 deg. cent. is the limit of temperature desired, it is possible to measure the rate at which the temperature is approaching the 100-deg. point so that the load may be cut off at the proper instant to allow the temperature to drift up to a final limit of 100 deg. cent. without exceeding this value.

The definition of power factor in polyphase circuits which was active last year and mentioned in last year's report as being in preparation by a Special Joint Committee, can be considered as now in the hands of the Standards Committee. A session at last summer's convention of the Institute was devoted to the discussion of this subject and as a result of this open discussion, the Special Joint Committee prepared certain definitions which were reported to the Standards Committee.

The question of standardization of the nomenclature of commonly used electrical instruments and measuring devices was discussed at a meeting of this committee during the year and preliminary steps have been taken, which it is hoped will ultimately lead to the standardization of many names and terms. The work which has been done to date has been confined to the members of the committee only, in preparing as complete a list as possible of the names and terms to be discussed and standardized. No further report can be made at this time but a brief mention of this activity, however, seems desirable with a recommendation that the succeeding committee continue the work during the coming year.

F. V. MAGALHAES, *Chairman.*

ANNUAL REPORT OF EDUCATIONAL COMMITTEE

To the Board of Directors:

The Educational Committee has been greatly handicapped by the wide geographical distribution of its members, the work being delayed by tedious long-distance correspondence.

The Committee held a meeting in Chicago on November 12, 1920, Mr. Schuchardt presiding, and while only three members were present a plan for the year's work was outlined which later received the approval of all the members. The Committee wished to determine in what respects the technical graduates failed to meet the expectations of their employers and to obtain definite suggestions as to how the product of our Engineering Colleges could be improved. For this purpose a circular letter was prepared and sent to over a hundred prominent electrical engineers, requesting their opinions and criticism. A summary of the replies and a discussion of the suggestions received will be prepared for publication in the JOURNAL.

The Committee believes that a better correlation than obtains at present in curricula, in methods of giving instruction, and in other factors that pertain to college training of engineers may be secured among the several branches of the engineering profession. To gain this end the Committee recommends that arrangements be made for holding a symposium on Engineering Education in 1922 in which representatives from all the National Engineering Societies should take part.

In a resume of the progress made during the year in the field represented by the Educational Committee much or little may be said. A statistical report on new buildings, improved equipment, enrollment and graduation data, and the numerous changes in courses and curricula, would no doubt be extensive, as much progress has been made in these respects; but this information, even if available, would probably be of little interest. The large increase in enrollment has made it necessary for most engineering schools to bend every effort towards meeting the increased demands for equipment and larger teaching staffs to the exclusion of all other interests.

The excellent record made by engineering graduates in the World War is by many taken as prima facie evidence that the training given these men must have been highly satisfactory and that a return to pre-war conditions would leave little more to be desired. In any event, the methods of giving instruction and the training given to engineering students now do not differ greatly from what obtained before the war.

The most noteworthy movement in technical education during the past year, is the extension of plans to greatly increase investigational work and industrial research in engineering colleges. The quickening power of research, the discovery and the development of new principles and new applications, is of more vital importance to educational institutions than to industrial organizations. Effective cooperation on a comprehensive scale, between the research divisions of manufacturing companies and the faculties of engineering colleges, is a consummation devoutly to be desired.

As forerunners of greater things to come the Technology Plan of the Massachusetts Institute of Technology and the Research Department, recently established at the University of Michigan, are of general interest. A better understanding of the problems involved and the solutions effected seems highly desirable. To this end the Committee has requested Dr. C. L. Norton, Director of Industrial Cooperation and Research to prepare a paper on the development of the "Technology Plan" for publication in the JOURNAL. Plans are under consideration for similar cooperative research departments or extension of engineering experiment stations in a number of Universities and technical schools.

C. EDWARD MAGNUSSON, *Chairman.*

ANNUAL REPORT OF INDUSTRIAL AND DOMESTIC POWER COMMITTEE

To the Board of Directors:

The Industrial and Domestic Power Committee during the present term has actively continued its plan of specific study and report on the application of electric power to industry. In the work it has had the help of eleven subcommittes, each headed by a member of the Industrial and Domestic Power Committee as follows:

No. 1—Subcommittee on Motors with Particular Reference to Speed-Torque Characteristics. A. C. Lanier, Chairman.

No. 2—Subcommittee on Domestic Power Application. H. Weichsel, Chairman.

No. 3—Subcommittee on Applications in Printing Industry. W. C. Kalb, Chairman.

No. 4—Subcommittee on Cranes and Hoists. R. H. McLain, Chairman.

No. 5—Subcommittee on Applications to Machine Tools. H. D. James, Chairman.

No. 6—Subcommittee on Applications to Passenger and Freight Elevators. H. P. Reed, Chairman.

No. 7—Subcommittee on Applications in the Textile Industry. H. W. Cope, Chairman.

No. 8—Subcommittee on Applications in the Cement Industry. Fraser Jeffery, Chairman.

No. 9—Subcommittee on Applications to Pumps, Fans and Blowers. P. H. Adams, Chairman.

No. 10—Subcommittee on Applications of Electrical Energy in Industrial Heating. M. J. McHenry, Chairman.

No. 11—Subcommittee on Rubber Industry. W. E. Date, Chairman.

A complete roster of the several subcommittees will be found in the Year Book. These subcommittees have worked. Give them and their chairmen the full credit for our work of this term.

The Committee has conducted one Institute meeting at Akron and Cleveland on January 14th, 1921, and under the auspices of Subcommittee No. 11, W. E.

Date, Chairman. It was a good practical meeting, with plenty of interest.

We have had one thorough committee meeting, *viz:* on January 14, 1921, at Akron, Ohio, with an attendance of 21.

I recommend that our committee plan and activities be continued another term. I feel that while our apparent results are not large, that nevertheless a constantly widening group in the Institute is becoming familiar with what we are doing and is taking interest in it. With patience and encouragement the plan will continue to grow in interest and value.

As a portion of this report is submitted a report of progress in the Industry prepared by Mr. W. C. Yates of our Committee and also a full report from the Chairman of each Subcommittee. I recommend these several reports for your careful consideration.

As a committee we have tried hard to make our work of value. It is of value. The work that individuals and groups of two or three have put in with resulting monographs are notable contributions to the Institute files and as Chairman of this Committee, I can do no less than direct attention to them.

I also commend to you the help and efficiency constantly accorded us in our work by the Secretary of the Institute, and those associated with him.

A. G. Pierce, *Chairman.*

Industrial and Domestic Power Applications—Progress of the Art During the Year 1920

By W. C. Yates

Despite the fact that industrial activity slumped decisively during the latter part of the year 1920, the first three quarters of the year compensated for this to such a degree that the sum total of the industrial and domestic electrical equipment installed during the year was unquestionably greater than in previous years.

The use of electrically-driven domestic machinery, such as washing machines, vacuum cleaners, etc., showed an unprecedented growth until the business depression set in. An astonishing amount of such machinery was installed for the benefit of thousands of housewives, and this was especially true of washing machines. All this required no special developments in the way of motors, switching devices, etc., because suitable types of such electrical equipment were already available.

Turning to the industrial field in general, it may be said that considerable advance was registered in the incorporation of safety features in both motor and and control appliances, especially to the latter. The use of 50-deg. motors as compared to the old 40-deg. ratings increased and there was evidence of much more accurate study of the power required to drive machinery and a closer selection of the motors to do the work. This necessitated in turn the evolution of more overload protective devices, in which connection considerable improvement was made during the year.

In certain fields of industry no particular advance in the art occurred during the year 1920 to be particularly worthy of mentioning. In other fields definite steps in advance were made of which the following are worthy of note:

Mining. The activity in mining was not quite up to that of former years, but a number of interesting large equipments and an unusually large number of small hoist motors from 100 to 250 h. p. were installed or under construction at the close of the year. The McKinney Steel Company's hoist at Bessemer, Michigan, was put into commission. This is the largest d-c. iron ore hoist in the United States. It is driven by a 1650-h. p., 80-rev. per min., direct-connected motor.

Steel Mill. A record was made in the number of electric main roll drives put into commission. Improvement was shown in the accuracy of the speed control provided.

Considerable improvement was made in the control devices, especially of the magnetic type for steel mill auxiliary machinery, this improvement having to do with the better wearing qualities of the contactors and consequent longer life of the control equipment.

Machine Tools. In this field the development of motors and controllers for high-speed woodworking machinery stands out most prominently. This application required specially designed motors operated at frequencies as high as 300 cycles.

Textile Industry. An interesting development involved the application of individual drive to a series of tentering machines for starching and drying cloth where three independent rolls, each driven by an individual motor, were tied together by an automatic control equipment that insured the same speed of the fabric through the three machines. This same tie-in of two or three machines to run at the same speed was accomplished in the printing of cloth and did away with expensive line shaft equipment very apt to get out of order.

Paper Mill. A new form of sectionalized motor drive for paper machines was developed, each section being driven by an independent motor, the speed of which with relation to the speed of the other sections may be regulated to suit the requirements, and when once adjusted will retain this relationship as positively as though geared together.

A typical installation of this new drive was to a paper machine consisting of nine sections and employed in the manufacture of newsprint. This machine is designed for high-speed operation, producing paper 164 inches wide at the rate of 1000 ft. per minute. Eight sections of the paper machine are each equipped with a 100-h.p.,-136-rev. per min., shunt-wound motor direct coupled, while the reel is driven by a direct-coupled motor of 30 h. p. These nine motors are supplied with power on a Ward Leonard system from a 600 kw., 250-volt turbine generator, and the speed of the machine as a whole is controlled by the voltage of this generator, the fields of the motor being excited from the same excitation source as the generator. The motors have the same speed regulation from no-load to full load.

The novel feature of the installation consists of 20-h. p. synchronous motors, one of which is mounted on the base of each of the d-c. motors, and is connected to the main motor by means of a gear and a pair of cones belted together with an eight-inch double-ply belt. The function of these synchronous motors is to rigidly tie together the various sections of the paper machine and maintain a positive unvarying speed relation between them.

Oil Well. The demand for oil well motors continued to increase in both old and new oil fields. The power companies were unable to supply ample power for this purpose.

In Los Angeles County the deepest electrically drilled oil well in the world was completed in June and its depth was 4650 ft., this being the "Anita A" well of the Shell Company of California.

Another development of the year in Southern California oil fields was the application of motor drive to deep drilling by the rotary method. This has progressed to a stage which gives every indication of its complete success.

Handling of Coal, Ore, etc. Improvements may be noted in the machines developed to handle coal, ore, and other bulk materials, although this involved no new developments in the electrical apparatus. A particularly interesting installation is the coal loading pier of the Baltimore & Ohio Railroad Company at Curtis Bay, Md. This was improved last year by the addition of four trimming machines. It is now possible to load a 10,000-ton boat in eight hours.

Elevators. Mention may be made here of the application of the two-speed a-c. motor to elevator service, the motor having two windings and the lower speed being employed for making landings.

Pumps and Fans. Particularly worthy of note is the increased use of synchronous motors in the operation of pumps and fans.

Logging. A unique installation which will undoubtedly have considerable influence on the future of the lumbering industry consists of a combined outfit of electrically-operated yarder and loader hoists which was placed in service in August, 1920, by the Snoqualmie Falls Lumber Company of Snoqualmie, Washington. The yarder is operated by a 200-h. p., 600-rev. per min., three-phase, 60-cycle, 550-volt motor of special construction designed particularly for the very high torque which is essential in yarder service.

The loader, which lifts the logs brought in by the yarder, is a duplex outfit with two hoists, each gear-driven by a 75-h. p., slip-ring motor. These hoists are not provided with mechanical brakes, but each has two electrical brakes, one being the standard type and the other a solenoid load brake which has inherent graduated braking characteristics. The reason for this double brake equipment is to secure low and fully controlled lowering speeds when placing the heavy logs on the cars.

Electric Shovels. Considerable improvement was made in the application of electric drive to shovels. The chief improvement involved the use of the Ward Leonard system in the individual drive of the several motions of the equipment.

Advance was made in the design and application of equipment for arc welding, electric furnace work and in other fields. A report of this kind cannot possibly cover the ground in any detail as it is only intended to point out the steady advancement of the art in the broad field of industrial and domestic power.

[This report to the Board of Directors was supplemented by a statement from each of the sub-committee chairmen, giving an outline of the plans and the work accomplished to date of each of the sub-committees.]

ANNUAL REPORT OF TELEGRAPHY AND TELEPHONY COMMITTEE

To the Board of Directors:

The following report contains a review of the engineering of telegraphy, telephony and radio communication during the Institute year 1920-1921.

WIRE COMMUNICATION ALONG RAILROADS

Technical developments of the past year have placed the telegraph and telephone departments of railroads in the United States and Canada in a more serviceable condition than they have heretofore been. The work of the technical committees of the Telegraph and Telephone Section of the American Railway Association has been added to by the institution of committees handling the subjects of telephone transmission, radio and wired radio communication, and technical education for employees. A considerable number of new undertakings are now about ready for service trial in the field. Improvements are embodied in recommendations submitted by committees working on the problems of protection against lightning disturbances, inductive interference, electrolysis, wire transpositions and stronger pole line construction.

The Railroad Administration's trunk circuits radiating from Washington, D. C., were promptly discontinued at the termination of Federal control of the railroads, and the wires returned to the control and use of the individual railroads. The general interchange of wire service between the various roads, through connecting railroads not concerned in the purpose of the communication, was at the same time discontinued.

The employment of recent types of telephone repeaters has been arranged for by a number of the large railroads for the purpose of improving long distance telephone service. On the New York, New Haven and Hartford Railroad the installation was completed of an aerial cable between New York and New Haven. Circuits in this cable have telephone repeaters, and on some pairs loading coils are provided.

The subject of stronger pole lines has been given serious attention on many railroads. On some lines the factor-of-safety plan of construction has been extended.

During the year the increase in telephone lines has not been great, due mainly to retrenchment following temporary business depression.

Some progress has been made in replacing older types of calling selectors, and changing the method of operation of others in order to obtain low-resistance simplexes for telegraph service. Also, some tests have been made with wire-guided carrier-current signaling in conjunction with engineers of the United States Signal Corps under the direction of Major General Squier, Chief Signal Officer.

The practise of welding joints in exposed lines has been extended.

PRINTING TELEGRAPH SYSTEMS

The application of automatic printing telegraph systems to commercial requirements is being extended, both in the United States and Canada. A noticeable tendency is the gradual standardization of apparatus and of methods. Development generally is along the line of reducing equipment maintenance costs by simplifying the various printer units and making them more substantial mechanically.

For trunk circuits carrying heavy traffic the multiplex system is being widely applied. A multiplex system provides two or more two-way channels per wire. The ease with which the multiplex system may be made to meet traffic growth—simply by the addition of operating tables and associated equipment—is one reason for its success. Another reason is that it allows taking full advantage of the signaling capacity of a wire. With the multiplex it is possible to handle eight hundred or more messages per hour over a single conductor; correct incidental errors instantly, and have every message so handled ready for delivery to the addressee as soon as it has passed over the wire. An objection to older automatic systems was the time required in preparing the message for delivery after its receipt. There was also delay in correcting incidental errors.

A new field being entered by printing telegraphs is that including private branch offices, and way-office circuits. Developments in this direction center on the problem of producing a tape-printing machine so dependable as to require only occasional attention from mechanics, and so simple in operation as to be handled satisfactorily by an ordinary typist. A promising use for this system is its employment by commercial concerns and industrial establishments for intercommunion purposes and for communication between business offices and telegraph offices.

"START-STOP" PRINTING TELEGRAPH SYSTEMS

In all modern printing telegraph systems the principle of synchronism is employed. Systems employing continuous synchronism require that the apparatus at the transmitting and receiving stations be in phase at all times, and usually consist of distributors having constantly rotating arms operating in unison. Continuous synchronism is generally used when more than one simultaneous transmission over one wire is desired.

Systems not employing continuous synchronism, but providing instead that a signal be transmitted to start from a position of rest the arms of the transmitting and receiving distributors or their equivalents, are called "Start-stop" systems. The arms of the transmitting and receiving distributors are timed to rotate at practically the same speed for one revolution and then come to rest—one rotation for each letter, figure or other character.

The start-stop systems of recent American development use the five-unit signaling code. For circuits where the traffic requirements are such as to call for a speed of sixty words per minute, start-stop systems are satisfactory and their use is being extended. Such circuits are operated duplex over distances of 300 miles without intermediate repeaters. The employment of repeaters permits operation over greater distances.

Start-stop systems may be grouped into two classes. In the first, the distributor, transmitter and printer are separate units. With systems of this class a speed of approximately sixty-five words per minute is possible. In the second class, the distributor, transmitter and printer are self-contained in a single unit, the transmitter being controlled by a typewriter form of keyboard. Systems of the second class are also known as simplex printers and are operated at a speed of about fifty words per minute.

SUBMARINE TELEGRAPH SIGNALING

From the year 1858 until 1871 submarine cables were operated in one direction at a time only. Since the latter year, cables have been operated duplex. From 1871 until 1908, important improvements were made in existing apparatus. In the latter year "magnifiers" were introduced which permit operation of long cables with considerably reduced line current strength, with consequent increase of signaling speed—50 per cent or more above previous speeds.

In recent years a tendency in cable signaling has been to introduce terminal apparatus aiming at reduction in operating costs. Tape perforators of the mallet type have been replaced by perforators having keyboards similar to those of a typewriter, permitting largely increased output per operator in a given time. Automatic transmitters are used which insure continuous transmission of uniform signals. Automatic relays have been installed to connect together sections of cables to permit direct working without the necessity of manual relaying of messages. In some cases instead of direct automatic relaying a re-perforator is introduced which is actuated by signals from one section of cable perforating a tape which feeds into a transmitter sending into an adjoining section of cable.

Considerable progress has been made in applying printing telegraph systems to submarine cables. Experimental installations have been in actual service operation during the past year or two. The application of printing telegraph systems to ocean cables reduces operating costs and, perhaps to some extent, increases operating speeds. Further improvements now being made in ocean cable printing apparatus will result in much simplified equipment with promise of an increased output in unit time.

PROTECTION OF LINES AGAINST LIGHTNING DISTURBANCES

No radical changes have recently been made in the character of protection installed on communication lines for protection against lightning disturbances, but the growing need for continuous operation of lines has renewed interest in developing efficient self-restoring lightning arresters. Some of the more dependable existing types of arresters have been improved with the object of bettering the protection and lessening circuit interruption after static charges have been dissipated. Present types of arresters embody the principles of the airgap, vacuum gap, and choke coil.

REDUCTION OF INDUCTIVE INTERFERENCE

Promising progress has been made during the year toward the solution of the problem of inductive interference control and reduction. The growing difficulties in keeping communication and power circuits in well separated locations—attendant upon the rapidly increasing demands for these services—has brought a real appreciation of the need for thorough and systematic attention to the coordination of the engineering of these facilities.

As a consequence, increasing effort is being directed toward learning sound methods of coordination, and toward the application of these methods in the initial planning of construction. Prominent among these efforts toward more systematic treatment of the problem are facilities inaugurated by the National Electric Light Association for centralized study by a committee and engineering staff specializing in this subject.

It is an indication of sound progress that the problem is now recognized as of mutual concern by the various electric utilities. The trend is clearly toward cooperative study and treatment as in the best interests of these utilities.

Noteworthy in this direction is a step taken by the American Telephone and Telegraph Company and the National Electric Light Association in developing broadly laid plans for cooperative procedure in working out and applying methods for the control and reduction of inductive interference with telephone service.

So far as the committee has learned there has been no outstanding development during the year in the form of specific devices or methods applicable to either the communication or power facilities for inductive interference reduction. It is, however, of interest to note that the engineers of the American Telephone and Telegraph Company have developed and given some preliminary field use to a new type of "noise meter," designed to measure the degree of disturbance indicated in a telephone receiver without bringing in the personal factor of the observer in judging equivalent noise as is the case with the older "noise" standard employed by the telephone companies.

AUTOMATIC TELEPHONY

During the year there was in general a continuation of refinement in the design of automatic telephone apparatus. So far as radically new developments are concerned no epoch-marking inventions have been disclosed.

Further progress has been made in standardization of apparatus and in details of maintenance and operation. The undertaking to standardize nomenclature resulted in the publication of about 100 definitions of current terms.

There have been placed in service three devices the introduction of which may have an important relation to the further development of the art:

1. The call indicator, used in calling from an automatic office to a manual office during the period of mixed working, which displays the call number before the operator and permits automatic subscribers to dial all numbers.
2. A calling device number plate with office names in addition to numbers, to permit retention of office names in small multi-office exchanges converted to automatic.
3. A calling device number plate with the alphabet in addition to the numerals to enable the first few letters of the office name to be used as numerals in a large multi-office exchange.

CARRIER-CURRENT TELEPHONY AND TELEGRAPHY

At the Midwinter Convention of the Institute there was presented a paper on "Carrier-Current Telephony and Telegraphy," by two members of the committee, Messrs. Colpitts and Blackwell, which gives a history of this art; states the fundamental principles which underlie it; discusses the action of open-wire lines and short lengths of cable to the frequencies used in carrier operation, and describes the carrier systems which have been developed and put into commercial use in the Bell Telephone system. The historical part of this paper is interesting, showing the principles underlying carrier-current operation as having been worked out at an early date, but that economical use of such systems was not possible until the introduction of the three-electrode vacuum tube as a modulator, demodulator and amplifier; until the art of transmission over wires, including repeater operation, had been developed to its present state, and until the development of electric filters had been carried to the point permitting effective utilization of comparatively low carrier frequencies.

The commercial telephone installations described give four added telephone circuits over each pair of line wires in addition to the usual telephone and telegraph facilities provided by the wires. Commercial telegraph systems provide as many as ten added duplex telegraph circuits, also in addition to the usual facilities.

As pointed out in the paper, the apparatus involved in such systems is necessarily complex and, therefore, expensive, so that systems of this type are in general economical only for comparatively long circuits.

RADIO TELEGRAPHY

Radio communication during the past year has undergone a reorganization of ownership of the important patent rights which should relieve a very complicated situation and result in placing in use equipment superior to that heretofore employed. The radio companies are now in a position to proceed without imminent fear of infringement of essential patent rights.

The superior serviceability of continuous waves, with beats reception, has been recognized and the principle is being extended in practise.

The ease with which short waves can now be controlled from electron tubes has had much to do with the rapid change in the practise of the art. Spark transmitter systems, for all but ship emergency uses, are no longer planned for commercial operations.

With the more general use of continuous wave systems and the resulting greater possibilities of selectivity there is a strong legislative sentiment in favor of more liberal regulations. The use, with continuous waves, of a large number of working wave-bands, with a reserved emergency and calling band, will do much to eliminate the interference and troublesome delay which now exists at each of the several important ocean harbors. The sentiment that favors greater freedom in wave-band selection also favors the enforcement of more rigid requirements of purity of radiation and the securing of minimum damping at transmitting stations.

Transoceanic service has been further improved with a resulting increase in the volume of traffic handled and in the quality of service rendered. The gradual elimination of minor defects that commercial operation has brought to light has resulted in pronounced improvement in continuous operation over long distances.

The accomplishments in static elimination, permitting the better utilization of means of amplification of signals, have done much to overcome operating variations due to atmospheric disturbances and other causes.

A broadening of the field is noticeable in adapting radio systems and methods to new uses, and several such applications are looked for in the immediate future. The remote control of switches by means of radio is now being considered.

The superheterodyne method of reception, due to E. H. Armstrong, stands out as an important contribution of the past year.

RADIO TELEPHONY

The progress of radio telephony during the past year has been in the direction of the application of the three electrode tube, developed during the past seven years, to a point where it serves as an amplifier delivering comparatively large power, or as a reliable detector or telephone repeater, to the problem of supplying radio service of a commercial character in connection with existing wire lines.

This progress in all its phases is illustrated in a radio telephone toll circuit now in commercial operation in the territory of the Pacific Telephone and Telegraph Company, furnishing telephone service between the Island of Santa Catalina and the wire network of the mainland centering in California.

The Avalon-Los Angeles radio toll circuit is believed to be the first radio telephone installation in the world to be opened for public service. The service was inaugurated on July 16, 1920. The radio circuit is operated according to wire line methods. The operating circuit is from Los Angeles, Cal., to Avalon on Catalina Island. The radio section is between two coastal stations thirty-two miles apart. The circuit is provided with through line ringing of a type which is free from interference, and a superposed telegraph circuit capable of forming a link in a duplex wire telegraph circuit. The transmission and quality over the circuit are of such high standards that it is regularly connected, when required, into the long distance telephone circuits. On several occasions conversations have been carried on between the S. S. *Gloucester* in the Atlantic Ocean, and the Avalon office in the Pacific Ocean, the transcontinental telephone wire line being used as the connecting link overland.

The extensive application of types of electric wave filters in transmitting and receiving circuits has made it possible to obtain a good quality of speech and at the same time to secure greater selectivity than was possible with the prior art. The use of loops for receiving and of shorter wave lengths for short distances had to some extent reduced interference.

STANDARDIZATION OF TERMINOLOGY

A sub-committee of the Standards Committee of the Institute has been engaged in the work of formulating standard definitions of terms most commonly used in telegraphy, telephony and radio signaling. The importance of such work, especially in the case of an art developing as rapidly as is the art of electric communication, is obvious. Not only is it of advantage to eliminate ambiguous and superfluous terms, and terms wrongly used or etymologically incorrect, although these may have come into extensive use, but it is especially important to select the most logical and appropriate terminology called for by the development of the allied arts so as to get a proper start and thus, in a large degree, avoid the necessity for later revision, and perhaps at a time when incorrect terms have been widely adopted in operating practise.

The terms so far chosen and defined have been simply and unequivocally, though broadly, defined in the light of a comprehensive survey of the field to which they are appropriate, thus eliminating the necessity of a multiplicity of terms covering slightly different applications.

Consideration also has been given to bringing about agreement so far as practicable between English speaking countries. In quite a number of instances the same term is given different meanings, or different terms are employed to convey the same meaning. The sub-committee on Telegraphy, Telephony and Radio is, therefore, cooperating with a corresponding committee of the British Engineering Standards Association, with the above mentioned object in view.

The Bell and independent telephone interests have found it mutually advantageous to unify not only operating methods, but also operating phraseology, for the purpose of facilitating the handling of interconnecting traffic involving cooperation between two groups of operators. This supplies an excellent illustration of the value of standardization as applied to terminology which can promptly be translated into dollars and cents.

EDUCATION IN COMMUNICATION ENGINEERING

Considerably greater attention is now given in American universities and technological schools to instruction and research work in communication engineering. Sheffield Scientific School, Yale University, has an organized course in this field as has the Massachusetts Institute of Technology, and Columbia University, New York, has a course in submarine cable engineering. The College of the City of New York has a thoroughly equipped and organized communication laboratory, and at a number of the United States Army Departmental headquarters, or in their vicinities, thoroughly organized and equipped schools are maintained which cover these subjects.

In addition, the programs announced for the rapid introduction of automatic or machine switching in telephony, and the continued development of machine telegraphy will necessitate the instruction of large numbers of present employees of the operating companies, as well as recruits, who will be required to install, supervise and maintain the equipment. In this connection it is recognized that it is especially desirable speedily to perfect the terminology and thus to make available a common language for teaching purposes as well as for field use.

There is a noticeable drawing together of the engineers of the arts of telegraphy, telephony and radio signaling. The communication engineer of the immediate future will have to be well versed in the engineering of the three divisions of the general subject.

There are approximately six hundred communication engineers identified with the Institute, and the number is now increasing at the rate of about forty applications per month.

This report has been made up to include contributions forwarded by the following members of the Telegraphy and Telephony Committee: O. B. Blackwell, R. E. Chetwood, E. H. Colpitts, Charles E. Davies, H.W. Drake, S. M. Kintner, Stanley Rhoads, A. E. Silver, Arthur Bessey Smith and F. A. Wolff.

DONALD MCNICOL, *Chairman.*

ANNUAL REPORT OF POWER STATIONS COMMITTTEE

To the Board of Directors:

The work of the Power Stations Committee during the past year has included the routine work in connection with the analysis of papers bearing on power station subjects, which were referred to the committee for attention. In addition, the committee arranged for the presentation at the March meeting of the Institute of a paper entitled *Developments in Conversion Apparatus for Edison .Systems,* by T. F. Barton and T. T. Hambleton. The committee also considered the suggestions of last year's committee, and gave considerable thought to the preparation of a symposium on auxiliaries in steam and hydroelectric plants. While a certain amount of work has already been done on this subject, because of the limited amount of time available, further action has been postponed,—the recommendation of this committee being that the incoming committee continue the work which has been started with a view to presenting a symposium on this subject during the early part of the coming year.

In accordance with the request of the Board of Directors, your Committee presents in this report a brief outline of the progress of the art and the most important developments in power station work during the past year. There is also included an appendix, which is an abstract of the bibliography of the important articles treating of power station design and operation appearing recently in American and foreign technical journals.

During the past year, there have been several notable power station developments which have recently been placed in service, or are now in course of construction. These plants are of large size and incorporate many new and interesting features of design, particularly in the details of plant layout and the combination and application of auxiliary equipment.

Among the recent installations may be mentioned the Colfax power station in Pittsburgh, the Hell Gate Station in New York City, the Delaware station in Philadelphia, and the Calumet station in Chicago.

The Colfax power station represents the latest development in the so-called "mouth-of-mine" plant. This type of plant is of especial interest at this time, in view of the trend toward interconnection. It is essentially a design of the type most suited to bulk generation and distribution of power.

The Hell Gate, Delaware and Calumet stations are designed particularly for metropolitan service where a relatively large number of feeders at generator voltage are provided for the distribution of power. In the design of these plants, however, particularly the Hell Gate and Calumet stations, certain marked changes have been made in the general arrangement of busses and high-tension switching equipment.

In the use of auxiliaries, there is to be noted a decided trend toward electric drive. Two of the outstanding features in this development are the application of 2300-volt motors in sizes of 100 h. p. and over, and the use of differential relay protection of the various motor circuits. Considerable attention has been given also to the layout and protection of all auxiliary circuits as well as improvements in the motors and control equipment to insure continuity of service. These features are of vital importance in the modern power station. The increase in the use of electric power for auxiliary drive has been relatively large and involves a number of problems which were not considered of prime importance when the size of the electric installation for auxiliaries was comparatively small.

It is further recognized that conditions in power station service are different from the usual industrial plant, and it is to be noted that the development of present control equipment, which heretofore has been based largely on the experience gained in industrial service, is now being given the attention required for power plant service, where the necessity for continuous operation over long periods requires greater liberality in details of design than has heretofore been considered necessary.

TURBINE GENERATOR UNITS

The past year marks a number of improvements in details of design and construction of turbines. A more careful selection of material, closer inspection and improved testing facilities, particularly in connection with static and dynamic balancing of rotating parts, have had an important bearing on increased reliability and economy of operation.

There was also evidenced a definite change in attitude toward the use of larger generating units. The records of the past year show no increase in the size of single-cylinder steam turbine units, the largest unit of this type being of 45,000 kw. capacity. In two of the largest stations under construction in 1920 and 1921, the generating units have been 30,000 and 35,000 kw., respectively. There are, however, now in operation, a number of 40,000- and 60,000-kw. cross-compound units, consisting of two or three 20,000-kw. generators, which show satisfactory performance in point of continuity of operation and overall efficiencies.

In 1920, the two manufacturing companies engaged in building large turbo-generators, took contracts for 23 units of 20,000 kv-a. capacity, and larger. These 23 units aggregated 800,000 kv-a. and 690,000 kw., the average size unit being 35,000 kv-a. and 30,000 kw. It is interesting to note, in this connection, that of the 23 large units purchased in 1920 only five were for 25-cycle operation, and these units were purchased for installation in New York City.

In large hydraulic installations, the 90,000-kw. development at Niagara Falls, placed in operation in 1920, and the 350,000-kw. plant of the Hydro-Electric Power Commission of Ontario are noteworthy for their large capacity and new features of layout and installation. The No. 3 Station extension of the Niagara Falls Power Company is notable in delivering better than 90 per cent of the available energy of the water to the generator terminals. It is also of interest to note that the 45,000 kv-a. generators and turbines now under construction for the Hydroelectric Power Commission, will, when completed, be the largest hydroelectric units thus far placed in operation.

CLOSED AIR VENTILATING SYSTEMS

A comparatively recent development in turbo-generator cooling is the closed air circulating system, in which a definite volume of air is circulated continuously. There is a closed air path consisting of the generator and short connecting ducts to some device for removing the heat from the air. This cooling device may be the familiar spray washer, analogous to a jet condenser; or the hot air may be passed over tubes through which cold water is circulated, analogous to the surface condenser. Some installations of the closed air system with water tube coolers have been completed in England, and several trial installations have been projected in this country. There are a few installations of the closed air system in operation in this country, using the spray cooler.

The principal advantages claimed for the closed air system are effective elimination of dirt from the generator and reduced fire risk. The water-tube cooler has the additional advantage of eliminating all danger of water or ice entering the generator. There have been a few winding failures from this cause in this country, and apparently a considerable number of such failures in England, which, according to information received, accounts for the more active development of the water-tube cooler abroad. Whether these advantages of the closed air system will compensate for the obvious disadvantages of increased complication and congestion in the station layout and the appreciable increase in cost (in the case of the water-tube cooler), only further study and experience can determine.

LARGE POWER TRANSFORMERS FOR STATION USE

Single-phase transformers of a capacity of 23,600 kv-a., 60 cycles—larger than any heretofore constructed—have been supplied during the past year for stepping up from generator voltage to a present transmission voltage of 66,000 volts and an ultimate of 132,000. A bank of three single-phase transformers takes care of the entire output of a 60,000-kw., 11,500-volt, turbo-generator unit. The transformers are connected in delta on the low-voltage side, and star on the high-voltage side. Each transformer weighs 126,000 lb., requires a floor space of 11 ft., 3 in. by

10 ft. 3 in., and measures 23 feet from the rail to the tip of the high-voltage bushing.

The largest single-phase, 25-cycle, transformers ever built are being constructed for the new Queenston-Chippewa project of the Hydroelectric Power Commission of Ontario. These transformers are of the shell type; are rated at 15,000 kv-a., and are arranged to step up in banks of three from a 45,000 kv-a. waterwheel generator to a present transmission voltage of 110,000, and ultimate voltage of 132,000. Transformers are connected in delta on the low-tension side, and star on the high-tension side. Each transformer weighs 186,000 lb., requires a floor space of 11 ft. 6 in. by 10 ft. 6 in., and measures 28 ft. 2 in. from the rail to the tip of the high-voltage bushing.

For a number of years the maximum voltage for commercial transmission remained stationary at about 150,000 volts, but during 1920 this was raised to 165,000 volts, and transformers are under construction for operation on a 220,000-volt, 60-cycle system now being built. Core type transformers of 16,667 kv-a. and 8,333 kv-a. are being built, arranged for 11,000 volts on the low-voltage side, and 127,000 volts on the high-voltage side, so that three transformers may be connected in star for 220,000 volts.

These transformers are designed for grounded *Y* service and are equipped with one high-voltage bushing, the other end of the winding being permanently grounded to the tank to form the grounded neutral.

The windings of the 16,667 kv-a. transformers are so arranged that the 220,000-volt line lead is at the center of the column of coils, hence the potential to ground decreases towards the ends of the column, so that the coils nearest the yokes of the core are at or near ground potential. These transformers weigh 158,000 lb., require a floor space of 14 ft. 5 in. by 11 ft. 8 in., and measure 22 ft. 9 in. from the rail to the tip of the high-voltage bushing.

Among the large air-blast transformers produced were five 4550 kv-a., 10,900 *Y*/210-volt units for use with synchronous converters for the d-c. system of the New York Edison Company. These transformers are of high inherent reactance and are used in conjunction with the synchronous converters without the use of synchronous boosters to obtain the necessary range in continuous voltage, this voltage range being secured through the compounding characteristics of the synchronous converter in conjunction with the transformer reactance.

The operating reports during the year demonstrate the value and the greatly extended use of the oil conservator on large and high-voltage transformers. The utility of this feature is becoming more definitely established by the protection afforded from condensation of water in the transformer oil, the elimination of possible gas explosions due to decomposition of the oil and the gases so produced mixing with air at the top of the tank, and to the practical elimination of sludging of the oil due to oxidation when in contact with air at fairly high temperatures.

SWITCHING EQUIPMENT

In general, it may be said that there is a decided tendency toward simplification in station layouts and details of design. Complicated switching connections to take care of possible contingencies have been replaced by simpler layouts, resulting in reduced costs and marked reduction in operating troubles. Particular care is evidenced in switch-house layouts in the provision for safeguarding against serious trouble in case of switch explosions or oil fires. It has been recognized as advisable to provide as far as possible for greater space and greater accessibility to all parts of the electrical equipment using oil.

The semi-outdoor type of construction which has been adopted by the Niagara Falls Power Company at their Echota substation, is the most recent example of a departure from the standard type of switch-house construction designed for the purpose of preventing as far as possible the danger from oil explosions. The switches in this case are erected in structures in such a way that the operating mechanisms are covered, but there is no enclosure in front of the oil switch pots so that the force of any explosion which might occur is not in any way confined.

BUS CONSTRUCTION

Considerable attention has been given to the recent designs of switch house and equipment. Increased station capacities with the possibility of increased short-circuit stresses, call for a more substantial type of construction than has heretofore been considered necessary. One installation on record incorporates a type of bus support designed to satisfactorily take care of short-circuit stresses of 10,000 lb. applied at right angles to the top of the support. Greater attention is also being given to the layout of conductors, the avoiding of loops in the circuit wherever possible, and the provision for increased space between conductors so as to minimize the effects of magnetic stresses. In the new station of the Hydroelectric Power Commission of Canada, at Queenston, the busses are arranged horizontally instead of the usual vertical arrangement, and are mounted on five-foot centers on the floor with concrete barriers between phases.

A radical departure in the arrangement of busses and switch-house connections is incorporated in the designs of the new Calumet Station of the Commonwealth Edison Company, Chicago, and the Hell Gate Station of the New York Edison Company. The principle adopted in these stations is to separate the phases of each circuit, putting them into what practically amounts to separate rooms, thereby eliminating the possibility of flash-overs, oil switch explosions, or other troubles resulting in short circuits due to the close proximity of all three phases. This layout has involved the design of new switch-operating gear so that the pots of each phase of an oil switch may be operated simultaneously from a single operating mechanism.

OIL CIRCUIT BREAKERS

The most important development in oil circuit breakers has been in the extremely heavy-duty type. The latest designs are for units having a rupturing capacity approximately twice that of any previous breakers constructed, or 58,000 arc-amperes at 15,000 volts. This has necessitated designing the circuit breaker structure of sufficient strength to withstand shock and internal pressures in excess of any previously encountered. It has also required a design of the conducting details that will withstand the heavy magnetic stresses resulting from heavy short-circuit currents encountered only in the largest systems.

For substation and auxiliary power service, there is a trend toward the truck type of circuit breaker. The designs that are being constructed are fully protected by interlocking features to guard the safety of the operators.

Paralleling the high-voltage developments in transformer design, there has been a corresponding advance in oil circuit breakers for 220,000-volt service for heavy interrupting duty. These breakers are physically the largest ever constructed, the tanks being 8 ft. 6 in. inside diameter, and 11 ft. high. The height to the top of the terminal bushing is 20 ft. For a three-pole unit, a floor space of 10 ft. by 30 ft. is required.

REACTORS

Developments are still under way in the design and application of reactors, particularly as affecting certain mechanical features which have not given highly satisfactory results in operation. These changes have been made, and for present service conditions, the performance of this type of equipment can be considered fairly reliable.

A phase of the subject which is being appreciated more today than heretofore is the necessity for guarding against the introduction of too high a reactance in the tie-line connections between stations or large systems. Too low a reactance on large systems, particularly, will result in excessive energy transfer at time of trouble; and, on the other hand, too high a reactance will result in decreased synchronizing power, with the resulting operating complications at times of system disturbance. The subject of synchronizing power between stations as influenced by characteristics of equipment and tie-lines, prime movers and excitation, is one which warrants the most careful consideration.

DISCONNECTING SWITCHES

The design of disconnectors is undergoing the same improvement as has occurred in other bus and switching connections. The danger of the loaded disconnectors being opened is being removed by the very general use of pilot lights connected to the corresponding oil switches and by mechanical interlocking of the disconnectors with the oil switches. In the case of the new Calumet Station in Chicago, the disconnectors will actually be operated simultaneously with the oil switch by mechanical interconnection so arranged that the disconnector opens immediately after the opening of the oil switch and the disconnectors close immediately before the closing of the oil switch. In some stations, the interlocking is arranged on the doors in front of the disconnectors, thus safeguarding against the opening of the switch before the corresponding oil switch has been opened. The rather frequent mistake of operating the wrong set of three disconnectors has been taken care of in some cases by a system of links and levers which operate all three disconnectors, or, in some cases, even six disconnectors, by the manipulation of a single lever which then may be locked in the open position if necessary.

OPERATING INSTRUCTIONS

Several companies have, during the last few years, prepared detailed operating instructions for their operating and maintenance attendants, covering the operation of transmission and station equipment. The value of such instruction lies in replacing the word-of-mouth transmission of operating experience through a constantly changing operating personnel. Carefully-prepared, written instructions make it possible for operating attendants to be transferred to different watches and to work in different groups without the necessity of the men getting used to each other's peculiarities of operating procedure. It facilitates the rapid breaking in of new men and makes the methods of operation more independent of personnel. The preparation of such instructions entails a large amount of painstaking labor, but in the opinion of those who have done so, is entirely justified by the results obtained.

H. P. LIVERSIDGE, *Chairman.*

APPENDIX

Important Articles on Power Station Design and Operation that have Appeared in American and Foreign Technical Journals

A — STATION DESIGN, OPERATION AND COSTS

"Efficient Operation of Central Power Stations," by J. D. Morgan. *Power*, October 7, 1919. This article presents data and curves dealing with the operation of every unit and of the station as a whole and the systematic testing of all units to detect the falling off in efficiency and the exact cost of operation in the various departments of the plant.

"Development of Automatic Hydroelectric Generating Stations," by T. A. E. Belt. *Electrical World*, February 28, 1920. The author deals with the automatic operation and remote control especially applicable to small and medium sized developments and the use of synchronous and induction generators for this service.

"Power House Foundation," by E. M. Lurie. *Power Plant Engineering*, February 1, 1920. Information is given on methods for testing soil, column footings, drainage and other construction problems in securing permanency of foundation.

"Automatic Hydroelectric Stations," by T. A. E. Belt. *Electrical World*, April 10, 1920. Details are given covering the operation of the automatic hydroelectric generating station of the Iowa Railway and Light Company at Cedar Rapids, Iowa and the remotely controlled hydroelectric generating station of the Ontario Power Company of Ontario, California. Details of a proposed automatic system are given which will tie into a tranmission system which is fed by two very large steam driven generators.

"Water Station of the Southern Power Company," by W. S. Lee and Richard Pfaehler. *Electrical World*, May 8, 1920. Details and construction are given for a 90,000 h. p. generating station and outdoor switching station (the largest of company's system) designed to provide for operation under extreme conditions of floods of large magnitude.

"Data on Output and Load Factor of Largest Generating System in America." *Electrical World*, May 8, 1920. For all lighting, power and electric railway companies in the United States and Canada operating generating stations with outputs in excess of 100,000 kw-hr., the following data are tabulated for the years, 1917, 1918, and 1919: Peak load, date of peak load, yearly output, yearly load factor.

"Steam-Electric Generation in Far West," by W. F. Durand and C. H. Delany. *Electrical World*, May 15, 1920. Present tendencies in the design of generating stations on the Pacific Coast are outlined from the standpoint of fuel consumed, operation with hydroelectric systems, and the size of generating station required. Automatic control is also discussed.

"Importance of Control and Signalling Circuits in a Power

Station," by Probst. *Elektrotechniche Zeitschrift*, January 29, 1920. The author emphasizes the importance of clearness and neatness in mounting all auxiliary conductors and shows on photographs and tracings some examples of the *A E G* back of panel wiring system.

"Stabilizing Large Generating Systems". *Electrical World*, July 3, 1920. Abstract of features brought out by Dr. C. P. Steinmetz and R. F. Schuchardt in papers presented before the American Institute of Electrical Engineers. Operating conditions in the three large power houses of the Commonwealth Edison Company are outlined, giving an analysis of cable failures and the use of reactors. Conclusions drawn by Dr. Steinmetz regarding the use of power limiting reactors, and locating them in the system are given.

"Water Power Plant at Gösgen, Switzerland." *Schweizerische Bauzeitung*, January to May, 1920. Details are given of hydraulic construction with numerous illustrations. The development is located on the Aare at Gösgen, Switzerland and has a total rating of 45,000 h. p.

"Hydroelectric Power Station at the Great Lake, Tasmania." London *Engineer*, July 9, 1920. An interesting scheme of speed control of water wheels is described for which it is claimed the advantages of both needle and deflector regulation are secured.

"Pelton Wheel Reconstruction," by Percy Pitman. London *Engineering*, June 25, 1920. Structural changes in Pelton water wheels are described, first, to replace defective and broken buckets which were becoming a source of danger and, second, to economize water by putting on buckets of a more modern and efficient type. It is reported that the efficiency was improved about 5 per cent by these changes.

"Niagara Falls 100,000-H. P. Development," by John L. Harper. *Electrical World*, September 18, 1920. Details of the general engineering problems involved are given, together with comments by N. R. Gibson in hydraulic design and efficiency of units in plant, comments by L. S. Berin Bernstein of effect of loading on construction of substructures and main features of plant operation by George R. Shepard.

"Centralizing Power Plant Maintenance," by W. C. D. Eglin and F. C. Ralston. *Electrical World*, September, 25, 1920. The author points out that by separating maintenance of plant equipment from operation uniform standards of work can be established and a group of repair specialists developed. The plan of handling maintenance work in centralized shops is shown in organization charts listing the personnel of the maintenance sections and showing their relations to the other groups comprising a station operation division. The system outlined is used in maintenance work in the generating stations of the Philadelphia Electric Company.

"Analyzing Maintenance Costs." *Electrical World*, September 25, 1920. This article shows the relationships of the age of equipment to energy output and shows that electrical apparatus is far less expensive to repair than steam equipment. Data are also given showing total repairs to be virtually proportional to plant rating. Maintenance costs of steam plant equipment for 1918 to 1920 in a station having a rating varying from 43,000 kv-a. to 63,000 kv-a. are given.

"High Economy in Small Steam Plants," by E. H. Tenney. *Electrical World*, September 25, 1920. The author gives results of experience in operating 28 plants containing one to three boilers. The causes of low efficiency are reviewed and means suggested for preventing, detecting and correcting operating conditions.

"Springdale Station of West Penn Power Company," by G. G. Bell. *Electrical World*, September 25, 1920. Details are given of the design of a steam plant with an ultimate rating of 300,000 kw. The station is located at a coal mine and coal is delivered to the bunkers direct from a mine tipple. Part 2 of this article describes electrical and operating features.

"Developments in Power Plants and Generating Stations," by Alfred Still. *Electrical Review*, August 21, 1920. The author gives general tendencies in power station design, both hydroelectric and steam electric.

"Electrical Features of Niagara Falls Power Station," by J. Allen Johnson. *Electrical World*, October 23, 1920. The author points out that to insure reliability of service and simplicity of operation each 32,500-kv-a. generator in the Niagara Falls 100,000 h. p. extension has been dealt with as a separate unit. Features of control are outlined.

"Power Station Designs." *Beama*, August, 1920. This subject is discussed under the following division: Drive of auxiliaries, maintenance of efficiency, condensing plant, feed water system, guarantees and testing, and over-all thermal efficiency of power station.

"Dalmarnock Power Station." London *Electrician*, September 20, 1920. This is a new power plant erected on the River Clyde not far from Glasgow. The ultimate capacity is 150,000 h. p. Energy is stepped up and transmitted at 20,000 volts to substations over three-core split conductors and six-core type cables using the Merz-Hunter system of protection.

"Design of the New Canadian Niagara Power Project." *Engineering News-Record*, October 14, 1920. The article gives fundamentals which govern the design of the hydroelectric installation of the Queenston Chippewa hydroelectric plant of the Hydroelectric Power Commission of Ontario.

"Electrical Equipment of the Super-Power Station at Golpa, Germany," by H. Probst, *Elektrotechnische Zeitschrift*, September 2, 1920. The output of this station was intended to be used for nitrogen fixation and to supply large nitric acid plants in the neighborhood with approximately 250,000,000 kw. hr. or one-third of the total output. The plant is located close to a lignite mine and is laid out for 64 steam boilers feeding eight

A. E. G. turbines each coupled to one 6000-volt 50-cycle 22,000-kv-a. generator.

"Electrical Features of Springdale Plant of West Penn Power Company," by George S. Humphrey, *Electrical World*, December 4, 1920. The author describes the considerations in laying out this station to be operated at high power factor and the use of temperature detectors in generators and transformers, flexible scheme of supply for auxiliaries and balanced relay protection. Part 2 of this article (*Electrical World*, December 11, 1920) dealt with physical arrangement of equipment, balanced relays to protect generators and transformers and methods to indicate total station loads.

"Interconnection of Power Systems," by Harold W. Smith, *Electrical Journal*, November, 1920. The author deals with the important considerations in planning for interconnection of power systems and covers the following points: Selection of switching equipment, tie lines having ample synchronizing power to hold the systems in parallel;. relay protection system; voltage conditions with regard to the flow of reactive current.

"Safety-First Methods of a Big Power Plant," *Power*, April 19, 1921. Rules for protecting employes of the United Electric Light & Power Company, New York City. against mechanical and electrieal dangers.

"Coal Handling Methods at New Baltimore Station," *Electrical World*, Jan. 15 and 29, 1921. Details of how coal is received and handled in a 140,000-kw. station and the method of dividing the load with large hydroelectric plant. Generator fire protection and the welding of steam piping.

"Switchgear in Modern Power Station," by R. A. R. Bolton, *English Electric Journal*, October, 1920. Arrangement of circuits and typical connections with comments on the use of current limiting reactors to reduce effects of short-circuit currents.

"Australian Steam Station of 125,000-Kw. Rating," *Electrical World*, Feb. 19, 1921. Design of a plant located in coal field where coal can be secured at cost of 50 cents per ton. All electrical equipment located out of doors.

"Hydroelectric Station of 50,000-Kw. Rating Built in 15 Months," by R. C. Starr, *Electrical World*, Feb. 26 and March 19, 1921. Construction and design for Kerckhoff station of San Joaquin Light and Power Corporation at Fresno, Cal. Considerations that influenced layout of equipment.

"Development of 450,000 Kv-a. on Pit River in California," by A. H. Markwart, *Electrical World*, March 12, 1921. Plans for construction of five stations utilizing 2070 ft. drop in Pit River. Units of 35,000 kv-a. rating to serve 220,000-volt transmission line.

"50,000-H. P. Waterwheels for 500,000-H. P. Plant," by E. T. J. Brandon, *Electrical World*, March 20, 1921. Layout of equipment for Queenston-Chippewa station of Hydroelectric

Power Commission of Ontario employing 50,000-h. p. turbines under a head of 305 ft.

"Colfax Station at Mouth of Coal Mine," *Electrical World*, April 2 and 16, 1921; *Power*, April 5, May 3, and May 24, 1921. Features of Duquesne Light Company's Colfax station design incorporated to attain high economy and reliability of operation. Details of initial installation of 60,000 kw. for a plant of 300,000 ultimate rating. Three-element compound 60,000-kw. turbo generators are installed and provided for. Duplication of circuits and equipment and arrangements to prevent spreading of troubles that may occur.

"New Type of Switch House to Prevent Bus Short Circuits," by B. C. Jamieson, *Electrical World*, April 2, 1921. Arrangement of New Calumet station of Commonwealth Edison Company with details of wide separation of bus phases to preclude interphase short circuits. Use of current limiting reactors to exclude outside disturbances.

"Plants of Chilean Exploration Company," by M. Neustatter, *Elektrotechnische Zeitschrift*, Jan. 6, 13, and 20, 1921. Detailed illustrated article on station layout and equipment built by Siemens-Schuckert in Berlin for producing electrolytic pure copper from ores in Chile. Power station is rated at 40,000 kv-a. Four 12,500-kw. steam turbines drive 9000-kw., 0.9-power factor, 5000-volt, 50-cycle, 1500-rev. per min. generators and receive steam from 16 B & W oil fired boilers. Descriptions of station electrical layout and transformer station are given, with wiring diagrams.

"Output of Systems Exceeding 100,000,000-Kw-hr. in 1920," *Electrical World*, April 23, 1921. Peak load, date of peak and output for years 1920, 1919, 1918 and 1917 of 71 central station systems and 9 electric railway companies. Also tabulation of energy generated and purchased and that used for light, power and railways.

"Delaware Station of Philadelphia Electric Company," *Electrical World*, May 21, 1921. Factors taken into consideration in laying out a 180,000-kw. station on limited space at a time when steel was difficult to procure. Among the mechanical features discussed are the coal and ash handling facilities, unusual furnace design, facilities for converting to oil or powdered coal operation and the selection of auxiliaries.

B — PRIME MOVERS AND GENERATOR DESIGN AND OPERATION

"Designs of Large Vertical Alternating-Current Waterwheel-Driven Generators," by M. C. Olson, *General Electric Review*, November, 1919. The author calls attention to some of the special features that must be considered in the mechanical and electrical design of large hydroelectric generators.

"Spring Thrust Bearing and Cooling Coils on Larger Vertical Generators," by T. W. Gordon, *General Electric Review*, November, 1919. The author states that for many years one of the limiting features of large vertical machines was the need of a simple thrust bearing.

"Features of Design in Large Hydraulic Turbine," by F. H. Rogers, *General Electric Review*, November, 1919. The author analyzes problems encountered in designing wheels of high efficiency for both low and high head applications. He calls attention to conditions under which certain losses become sufficiently important to warrant considerable effort to minimize them.

"Failures of Turbo Generators and Suggestions for Improvement," by J. Shephard, London *Electrician*, January 16 and 23, 1920. In the opinion of the author failures may be roughly classified under (1) mechanical weakness, (2) electrical weakness, (3) heating and fire risks, (4) ventilating difficulties. An analysis of these failures is presented.

"Alternators Rated at 22,000 Kv-a. for Glomfjord," by J. Wennerberg, *Teknisk Tidskrift Elektroteknik*, November, 1919. This article gives drawings and pictures of two large three-phase generators built for the Norwegian Government's plant at Glomfjord, Sweden. These are rated at 20,000 kv-a. with a continuous overload capacity of 22,000 kv-a. and are the largest water turbine driven generators built in Europe.

"Effects of Short Circuits on Power House Equipment," by E. G. Merrick, *General Electric Review*, November, 1919. The author deals particularly with the electromagnetic stresses and abnormal temperatures developed in power house equipment resulting from short circuits.

"Mechanical Design of Large Turbo Generators," by M. A, Savage, *General Electric Review*, February, 1920. The author deals with high speeds and increased stresses in the construction of rotors and the ventilation of the modern turbo generator.

"Optimist's View of Turbine Development," by Richard H. Rice, *Electrical World*, April 17, 1920. Abstract of an address by Mr. Rice before the Boston section of the A. I. E. E. and A. S. M. E. in which he showed that turbine troubles were due chiefly to manufacturing conditions during the war.

"Ventilation of Steam Turbine Generators," by George Monson, London *Electricity*, March 12, 1920. The article reviews the development of forced air ventilation for cooling large generators and describes the modern closed air circuit with humidifying equipment and air dryers under the generator foundation.

"Short-Circuit tests on a 10,000-kw. Turbine Alternator," by E. S. Henningsen, *General Electric Review*, March, 1920. Data are given covering a series of tests on the performance of alternators having smooth-core rotors under short circuit.

"Huge Induction Regulator Installation," by Raymond Bailey, *Electrical World*, June 12, 1920. The author points out that in order to work transmission lines at maximum load the Philadelphia Electric Company has installed out-of-doors two 1750-kv-a., three-phase regulators and gives the conditions under which they operate. He presents a chart which shows how transmission line characteristics were determined.

"Electric Drive for Station Auxiliaries," by E. E. George, *Electrical World*, June 12, 1920. The author takes up the advantages of electric auxiliaries and the economies that accompany those advantages.

"Heating of Alternators and Induction Motors," by M. Baringolz, *L'Industrie Electrique*, November 25, December 10, and 25, 1919. The author presents a set of formulas permitting the calculation of the working temperature of stator copper, rotor iron and rotor copper in alternators and induction motors.

"Increasing Oil Circuit Breaker Capacity," by C. J. Hejja, *Electrical World*, July 10, 1920. The author gives details of a study on a standard oil circuit breaker with a view of determining the extent to which the rupturing capacity at short circuit of switching units in present use may be increased in order to avoid, if possible, the expense of replacing them by units of larger capacity or of a different type. A breaker equipped with pressure vents, hollow contact rods and improved liquid for quenching the arch showed greatly increased rupturing capacity under test.

"Predetermination of the General Dimensions of Electrical Machinery," by H. de Pistoye, *Revue Generale del'Electricite*, January 24, 1920. This article contains a number of general theorems regarding the relations between output and certain general dimensions, such as rotor diameter, iron length, width of air gap, speed, etc. A general formula is derived which shows the most economical relation of diameter to axial length for rotating machinery.

"Grounding of Electric Machinery and Installations," by J. Damien, *Revue Generale del'Electricite*, January 24, 1920. The author cites the French rules regarding grounding of electrical installations and criticizes their vagueness in wording. Advantages and disadvantages of different methods of grounding are discussed and some practical suggestions given.

"Governor Adjustment for Efficient Parallel Operation," by F. Oppenheimer, *Electrical World*, July 31, 1920. The author presents speed load curves of prime movers with various governor adjustments and gives details of the method used in adjusting the governors in the plant of the Pennsylvania Water and Power Company.

"Present Tendencies in Turbo Alternator Design," by J. Shepherd, London *Electrician*, July 2, 1920. The writer deals particularly with the problem of ventilating and water-cooling of turbo alternators. He also takes up the proper insulating of coils and the danger to coils of vibration.

"Selection of Oil Circuit Breakers," by W. A. Coates, London *Electrician*, July 2, 1920. The writer discusses the rating of oil circuit breakers with reference to breaker capacity as defined by the British Engineering Standards Association. He points out the advantage in having graphic methods of determining short-circuit current values in networks and shows a chart devised for such use.

"Temperatures in Large Alternating-Current Generators," by W. J. Foster, *General Electric Review*, July, 1920. The author calls attention to certain advantages that would be derived in taking the air directly from the room and passing it away to some point in the building remote from the machines or out of doors.

"Features of 37,500-H. P. Water Turbine," *Electrical World*, October 2, 1920. In this article comments are presented by W. M. White on water wheel and generator considered as a homogeneous unit in the 100,000-h. p. extension to the plant of the Niagara Falls Power Company. Louis F. Moody discusses the design of waterwheels for generators of different makes.

"Factors Determining Generator Design," *Electrical World*, October 16, 1920. Comments by F. D. Newbury on the design of generators used in the new extension of the Niagara Falls Power Company together with comments by R. B. Williamson and W. J. Foster on designs furnished by the Allis Chalmers Company and the General Electric Company respectively.

"Repair and Inspection of Hydraulic Turbines," by L. W. Wyss, *Electrical World*, November 27, 1920. Practical information is given on taking machines out of service together with points to be observed during inspection.

"Oil Switches for Large Electrical Power Systems," London *Engineer*, September 3, 1920. Short-circuit characteristics of alternators and speed of oil switch opening with units of extremely large size are discussed in this paper.

"Continental Switch Gears," by W. A. Coates, *Beama*, October, 1920. The author deals with circuit breakers and electrical layout common to European practise.

"Recent Development in Turbo Alternators," by F. D. Newbury, *Electrical World*, January 17, 1920. The author comments on the increase in ratings from 1913 to 1917 and the tendency in steam turbine-generator construction and operation.

"Investigation of Water-Air Radiators for Cooling Generators and Motors," by H. G. Reist and E. H. Freiburghouse, *General Electric Review*, February, 1920. The authors point out that in the case of electrically driven ships the usual method of washing the ventilating air for turbo-generator units cannot be applied on account of the space limitations on shipboard. The plan of circulating salt water through a radiator much on the order of the automobile radiator and cooling the hot ventilating air by this means, has been investigated by the authors. A number of data and curves is given to show the advantages of this method where space is limited.

"Present Status of Large Turbo Generators," by Dr. Louis Bell, *Electrical World*, January 17, 1920. The author deals with the size of station and the requirements from the standpoint of economy and simplicity in station design and operation. The speed stresses are touched upon and the advantages and disadvantages of multiple-stage generating units.

"Some Recent Developments in Large Steam Turbine Practise," by K. Baumann, April 7, 1921, *Journal* Institution of Electrical Engineers, London. The author reviews in great detail developments of steam turbine design and construction in Europe and America since 1912 to date and also deals with a new design which embodies a multi-exhaust system where the steam in the last stage passes partly into impulse blading and partly through reaction blading with claim of greater capacity and efficiency with no appreciable increase in over-all dimensions of single barrel turbines of the Curtis type.

"Temperature Limits of Large Alternators," by G. A. Juhlin. *London Electrician*, Jan. 28, 1921. The possibility of increasing temperature limits in alternators using class B insulation is discussed with list data for breakdown voltage of mica wrapped in copper bars after heating for 7000 hours at 190 deg. cent.

"The Modern Hydraulic Turbine," by Frank H. Rogers and Lewis F. Moody, *Journal of Philadelphia Engineers Club*, March, 1921. Two articles on the hydraulic turbine from standpoints of modern requirements; tests of models, special features of designs; and requirements of larger stations. Mr. Moody reviews the turbine's evolution and describes new types of high speed runners.

"Manufacture of High-Voltage Alternating-Current Windings," by W. Zederbohm. *Siemens Zeitschrift.* Illustrated description of high-voltage motor, generator and regular windings developed during last 20 years. Asphalt treatment and inclosing of coils in sleeves of "Mikanite" standardized by Siemens-Schuchert Works.

"The Gas Turbine," London *Engineer*, Feb. 11, 1921. Tests at works of Thyssen & Company on 500-h. p. gas turbine invented by H. Holzwarth and built in 1914.

C — BOILER PLANT DESIGN AND OPERATION

"What the Adoption of Higher Steam Pressure Will Mean," by F. R. Parsons. London *Electrician*, January 2, 1920. The writer considers the effect of higher steam pressures on standard boiler design, on the material used and on reciprocating engines.

"Extension to L Street Station, Boston," by Charles H. Bromley. *Power*, January 27, 1920. Boiler room provided for convenience and economy. 30,000-kw. single-cylinder impulse turbine installed.

"Electrically Heated Boilers and Heat Storage." London *Engineering*, February 6, 1920. Details are given for the heating of water by electricity where water power is inexpensive. Attention is called to tests on two electricity boilers in Switzerland in which it is said that 90 per cent efficiency was obtained. Several makes of boilers equipped for electrical heating (mostly of Swiss origin) are described.

"Sluicing Ashes Shows Low Cost," by A. W. Morgan. *Electrical World*, July 3, 1920. The method used in the new Denver station of the Denver Gas & Electric Light Company is explained, which shows the handling cost of 16.4 cents per ton of ashes or about 2 cents per ton of coal fired.

"Preparing Pittsburgh District Waters for Boilers." *Power Plant Engineering*, August 15, 1920. Reference is made to the water of the Monongahela River where water pumped from mines into the river is highly charged with sulphates and the industrial pickling and by-product coke plants which line the river banks have a contaminating refuse water which is discharged into it. Efficient testing and treating required for this water are described.

"Surface Condenser Maintenance," by R. J. T. Wood, *Electrical World*, September 25, 1920. The author shows by illustrations the composition and structure of tubes. He points out that many steam station troubles are directly traceable to salt-water leakage in condensers where plants are near the seashore and discusses the over-all plant economy when adequate condenser maintenanee is not attended to. Reference is made to maintenance work in the plant of the Southern California Edison Company at Long Beach and Rodondo Beach.

"Steam Plant Metering Practise," by Robert E. Dillon. *Electrical World.*, September 25, 1920. The author points out that the checking of losses in the boiler room and the turbine room of large central stations by the aid of records from instruments is passing through the stage today which was passed by the electrical end of the station years ago. He refers to the types of instruments and records which are essential to efficient steam plant operation.

"Emmet Mercury Boiler." *Power*, August 3, 1920, Details are given for the construction of a mercury boiler and turbine which has been developed by W. L. R. Emmet and makes use of high boiling point of mercury and its condensing points at 28 inches vacuum and 465 deg. fahr. The heat given out by the condensing mercury vapor makes steam of the cooling water and this steam may be used to drive another turbine or for any other purpose for which steam may be required. The experimental equipment has been in operation with over 1000 kw. load on an electric turbine and its operation showed that the economies predicted were fully realized. Mr. Emmet believes that with an increase of 15 per cent in the amount of fuel used the same amount of steam can be supplied to the turbines as under present conditions and a mercury turbine will generate power equal to about 66 per cent of the power generated by steam turbines.

"Factors in the Design of Large Boiler Plants," by J. G. Rollow. *Electrical Review*, August 21, 1920. The author discusses the principal factors affecting equipment of boiler plants of large capacity.

"Selection of Steam Plant Meters," by J. W. Andree. *Electrical World*, November 20, 1920. The author divides metering of apparatus into classes necessary for safe operation, for good operation, and for checking results and gives a list of devices included in each of these groups. He also shows that the proper use of correct meters will greatly improve economy. Reference is made to the results which are being secured in the Long Beach Steam Station of the Southern California Edison Company.

"Economies to be Expected of a Super-Station," by John A. Stevens. *Power*, June 1, 1920. Table giving power costs for 100,000-kw. turbine station with different priced coal.

"Remodelling Stokers and Furnaces," by T. A. Marsh, *Electrical World*, Jan. 22, 1921. How boiler ratings were increased 39 per cent by enlarging grate areas and improving arch designs.

"Redesigned Stirling Boilers," *Electrical World*, April 23, 1921 and *Power*, April 19, 1921. Details of reclassification and standardization to simplify tube lengths, drum locations and other fundamental elements.

D — FUEL AND COMBUSTION STUDIES

"Burning Low-Grade Coals of Montana and Wyoming," by E. H. Bull. *Electrical World*, January 10, 1920. The author gives test data for fuels that have heretofore given operating men much difficulty and shows that proper furnace design will solve the combustion problem associated with the burning of such fuel.

"Pulverized Coal in Central Stations," by John Anderson. *Electrical World*, March 13, 1920. Data given on tests of five 468-h. p. boilers using pulverized coal in the Oneida Street power station of the Milwaukee Electric Railway and Light Company.

"Fusibility of the Coal Ash from Eastern Coal," by Messrs. Selvig, Brown and Fieldner. *Coal Age* January 22-29, 1920. Tables are given showing the fusing temperatures of the ash of coal mined in certain sections of the eastern coal regions, the sections chosen being parts of Ohio, Virginia, Kentucky, Maryland, Tennessee, and Alabama.

"Burning Oil with Mechanical Atomizers," by Robert Sibley and C. H. Delany. *Electrical World*, March 27, 1920. Operating details are given for the mechanical atomizing oil burner or pressure-jet burner with best operating pressure and temperatures outlined.

"Handling Coal by Using Belt Conveyors." *Electrical World*, April 10, 1920. Details are given for handling coal in modern plants with examples from installations in the Middle West and the East.

"How Bituminous Coal Can Be Safely Stored," by H. H. Stoek. *Coal Age*, March 18, 1920. A careful discussion of the best methods of storing various kinds of bituminous coal are given with special reference to fire risk.

"Burning Low Grade Coals of the Southwest," by W. M. Park. *Electrical World*, April 24, 1920. Operating and test results are given with chain-grate settings of different types with recommendations for using the fuel available in the Southwest.

"Pulverized Coal." *Electrical Times*, (London), May 20, 1920. Deals with changes necessary in water tube boilers for the application of powdered fuel indicating that the front of a furnace may be extended and converted into a combustion chamber.

"Storing of Coal for Central Stations," by H. H. Stoek. *Electrical World*, July 31, 1920. The author points out that the experience of recent years has emphasized the necessity for storing of coal and that coal should be of uniform size and free from dust, but with proper care, run of the mine may be stored. Details of various methods used are outlined, with a discussion of spontaneous combustion and the importance of size of coal in storage. Precautions to be taken in storing coal are also given.

"Unusual Efficiencies with Oil Fuel," by Joseph Pope and Frank G. Philo. *Electrical World*, October 9, 1920. The authors give details of the arrangement for using fuel oil with mechanical atomizers in the plants of the Savannah (Georgia) Electric Company and the Blackstone Valley Gas and Electric Company of Pawtucket, R. I. Details of tests on the new installations are also given.

"How the Coal Situation has Affected Central Stations in the last Six Years." *Electrical World*, October 16, 1920. A tabulation is presented which gives the reports from 54 central stations showing the amount of storage, kinds of coal purchased, the prices paid, and the pounds of coal used per kilowatt hour.

"Mechanical Oil Atomizer Efficient at 320 Per Cent Boiler Rating." *Electrical World*, October 16, 1920. Details of tests made by the Babcock and Wilcox Company on a 450-h. p. boiler fired by mechanically atomizing oil burners are given by Darrah Corbet.

"Remodeling Ignition Arches," by T. A. Marsh. *Electrical World*, October 23, 1920. The author deals with the importance of properly proportioning ignition arches to combustion rates and points out that the desired stoker dimensions influence ignition arch design on which capacity, efficiency, responsiveness, and fuel range depend.

"Efficient Handling of Fuel Oil." *Power*, January 11, 1921 to March 8, 1921. Storing, and feeding to furnaces.

"Pulverized Coal Under Central Station Boilers," by John Anderson. *Power*, March 2, 1920. Methods of applying equipment, and facts concerning operation.

"Superpower Plant for Utilization of Peat," by F. Bartel. *Elektrotechnische Zeitschrift*, Nov. 4, 11, 25, 1920. Design of a 120,000 steam-electric station to burn peat bog. The total production is estimated at 400,000,000 kw-hr. with a peat consumption of 920,000 tons per year. Details for storing the fuel are given.

"Ultimate Boiler Capacity Limited by Fuel Conditions," by Joseph Harrington. *Electrical Review*, March 26, 1921. Size and characteristics of fuel and rates of combustion in furnaces. Fusing temperature of ash and its effect on rates of combustion on grates and in fuel beds.

"Powdered-Coal Firing for Power Stations," by Friedrich Munzinger. *Elektrotechnische Zeitschrift*, Feb. 3, 1921. Details of different systems for pulverizing coal, feeding it to boilers, and burner construction for large station units.

ANNUAL REPORT OF ELECTRICAL MACHINERY COMMITTEE

To the Board of Directors:

In its endeavor to assist in advancing the art in the field coming within its scope, and in recording progress made therein, the Committee on Electrical Machinery has cooperated with the Standards Committee, the Meetings and Papers Committee and the Library Board of the A. I. E. E.

For some time it has had under consideration certain proposed changes in the Standardization Rules relating to high-potential testing in order to overcome the failure of the present rules to impose any test between adjacent coils in any circuit of any phase; any test between phase windings where the highest potential difference exists when the machine is operating, and to overcome the unknown stresses imposed at certain points due to the capacity effects in large machines.

The Committee has reviewed for the Papers Committee all the papers submitted for presentation before the A. I. E. E., or for publication in the Journal, that deal in any way with electrical machinery. Through the medium of papers solicited the Committee has aimed to place on record the advances in the art as indicated in design and theory as well as in the construction of the great power plants on sea and on land. It has arranged for the preparation and presentation of a paper by Mr. E. S. Henningson on "The Application of Synchronous Motors to the Propulsion of Cargo Boats"; a paper by Mr. John L. Harper on "Extension to Plant No. 3 at Niagara Falls," and one by Mr. William M. White on "Hydraulic Turbine Development." These three papers will be read at this Convention.

For the purpose of determining in what way the Engineering Societies Library now supplies the wants of the Electrical Machinery Committee, or of persons interested in electrical machinery, a study was made of the conditions in the Library from the point of view, not of librarians, but of persons desiring to obtain information concerning the theory, design, construction and operation of electrical and allied machinery.

This study disclosed an unnecessarily unsatisfactory condition in the facilities placed at the disposal of engineers interested in, and under necessity for, investigating new phenomena and for solving new problems, and these facts have been laid before the Library Board of the A. I. E. E.

In the work undertaken by the Electrical Machinery Committee, the chairman has had the unanimous and enthusiastic support of the members of the Committee.

B. A. BEHREND, *Chairman.*

ANNUAL REPORT OF PROTECTIVE DEVICES COMMITTEE

To the Board of Directors:

Several years ago it appeared that the work of the Protective Devices Committee would be conducted to better advantage if it should assume that the Committee would be largely reappointed from year to year and that it might undertake investigations which could not be completed within any one fiscal year. Since that time it has practically lost all interest in the fiscal year except for the purpose of making its annual report in accordance with the Constitution. The investigations of its sub-committees has continued from year to year and on several occasions the sub-committees have presented their report in the form of a paper before the Institute.

At the present time the work of several sub-committees has not progressed to a stage where they are ready to present any lengthy reports in the form of papers, so that the present reports can be considered as progress reports. Several of the subjects under investigation by the Committee are discussed in the following summary.

Current Limiting Reactors

BY F. E. RICKETTS

In view of the papers presented at the Annual Convention last year on this subject, this sub-committee has been able to collect but little data that would be of interest.

Certain papers presented at last year's Annual Meeting went into much detail in explaining the possibility of high-voltage stresses between turns of reactors during abnormal conditions of operation. Failures that had occurred in certain forms of reactors where bare conductors were supported by concrete were attributed to this cause. Since certain contributors to the discussion of these papers disagreed with this statement and, as it has since been fairly definitely determined that some of the failures were due to mechanical weakness rather than to high voltages, it seems proper to call attention again to this subject. This type of reactor has since been strengthened by adding more concrete supports for the conductors and it appears that the trouble has been thereby overcome.

Certain tests to determine the rupturing capacity of oil circuit breakers have been made that indicated that reactors while reducing the maximum current may subject circuit breakers to additional strains by tending to prevent the circuit from being interrupted at the zero value of current, which is the point at which a circuit-breaker usually interrupts the circuit in the absence of reactance.

System Troubles

By A. A. Meyer

From replies to a request for data on system troubles experienced during the year 1920, information was received from a number of the larger companies.

Some of the replies include numerous cases of improper functioning of relays, but which were not serious in affecting the system. They could hardly be classed in the same category the committee considered for investigation. Moreover, several of such cases were cited without any word of explanation as to the possible cause of improper functioning. It would take considerable time and study to analyze all such cases of false tripping and draw any valuable deductions. I believe the committee should confine its attention first to the cases which seriously affect the system as a whole.

Among the most noteworthy cases, the following performances and factors are of interest as affecting the system as a whole. Relays are reported as functioning too promiscuously on a transmission system. Instead of the relays close to the source of trouble functioning and isolating the trouble at once, these relays fail for various reasons, and as a consequence, relays elsewhere on the system operate and shut down large sections, if not the entire system. The reasons for the relays failing to isolate only the section in trouble are such as, incorrect connections, improper settings and shortcomings in the relays themselves when called upon under abnormal conditions on the system, accompanied usually by low voltage. Several cases were cited where low pressure, delayed reverse power relays from functioning in the time that was intended. Some transmission systems comprise a series of sections with graded settings, the relays in each section being set a trifle above or below the settings on the neighboring sections. Where the series contains many sections the increments in the settings necessarily have to be small to avoid too high a setting on the section close to the source. In some cases the increments are too low and due to slow circuit breaker operation, isolation of a fault is sometimes obtained by cutting out sections in additions to the desired one. In other cases the increments are too large and a fault occurring in a section close to the source is held connected too long to a system, and as a result the initial fault drags so hard on the generators as to throw them out of step, and a real system disturbance follows. Some desire has been expressed for the need of current limiting feeder reactors to avoid such a heavy drag on the generators due to a fault near the station. System troubles have also arisen out of small initial troubles in several cases due to circuit breakers of inadequate interrupting capacity. Duties on circuit breakers not infrequently outgrow their capacity on fast growing systems. It is quite essential that the capacity be checked up occasionally and compared to the duty which might be expected.

Another noteworthy factor responsible for system troubles comes through the practise of providing low-voltage releases on power house auxiliaries. In several cases it was reported that low main bus pressure caused the plant auxiliaries to drop off, thereby making matters much worse. The practise of providing such protection on plant auxiliaries needs careful reconsideration in, no doubt, many cases.

In the above, reference has been made only to some of the short-comings of relay schemes. Outside of these, troubles have also arisen through electrolytic lightning arresters. One company reports several cases of fire, some of which were quite serious, due to the arrester itself failing through some slight mistreatment. The hazard is greater than perhaps realized by many users of electrolytic arresters.

The above are the main items of interest brought out in the replies to the committee's request for a report on system troubles. No doubt there are several other cases of system trouble still unreported. It is hoped that some of these will be reported at a later date.

Lightning Arresters

By F. L. Hunt

The sub-committee on Lightning Arresters has given consideration to the lightning arrester subject, with a view to determining what might be done by the members of the Protective Devices Committee to increase the usefulness of lightning arresters as protective devices.

Many engineers have questioned the necessity for using lightning arresters on all circuits because the results obtained from their use have been more or less unsatisfactory, due in part to inherent defects in the designs of the arresters, and in many cases on account of misapplication of the equipment that is available.

In order to obtain information regarding the present practise of engineers and operating companies in the use of lightning arresters, and to obtain as much information as possible regarding the defects which have developed in the commercial arresters as produced today, and the unsatisfactory experiences which have been had in their use, a short questionnaire was sent to members of the Protective Devices Committee and to a few other operating engineers. A summary of these data is given herein.

Twenty-nine copies of the questionnaire given below were sent out and twenty replies have been received up to the present time. We were also able to arrange a conference with Mr. R. A. Paine, who has collected data on lightning arrester practise to be used by the Overhead Systems Committee of the N. E. L. A., and to make use of those data so far as they applied to the questions under consideration by our committee. The sub-committee has not had an opportunity as a whole to discuss or consider the data which have been collected. It is recommended that such consideration be given, however, either by the sub-committee or by the main Committee, in order that the greatest benefit may be obtained from these data. The questionnaire sent out was as follows:

1. What general type of lightning arrester would you recommend for feeder circuits of 1000-kw. capacity or greater, leading from a generating station or important substation?

(a) 10,000 volts. (c) 66,000 volts.
(b) 33,000 volts. (d) 150,000 volts.

2. Under what circumtances, if any, do you think it advisable to omit lightning arresters entirely from circuits of the above description?

3. How many lightning arresters would you recommend and what general class of arrester for a substation from which power was being distributed by six 22,000-volt overhead circuits? (Consider only 22,000-volt side of substation).

4. On what class of circuits of 10,000 volts and above would you advocate the use of horn gap lightning arresters?

In addition to the points raised above, the committee is especially anxious to get the fullest possible expression of your opinion as to the objectionable features in the principal types of lightning arresters used today on voltages of 10,000 and above.

We believe the work of the Protective Devices Committee in studying the uses and improvements desirable for protective devices can make progress on the lightning arrester problem by obtaining the reasons for the adverse opinions which exist. If you are willing to give us, therefore, the facts or experiences on which you base any objections you may have, it will be of great service to the committee.

The replies to this questionnaire indicate that the general practise is remarkably uniform. A very large majority of the engineers replying to this questionnaire agrees in its recommendations on each of the points raised. There are a few notable exceptions, however, and a few opinions expressed which vary quite widely from the majority of opinions, but which are given by men of such broad experience and in such responsible positions, and are based on such definite cases of experience that we believe it advisable to give especial attention to these statements. Since we are all familiar with the general practise on these points as is evidenced by the majority of opinions expressed in the answers to these questions, we are perhaps warranted in giving especial attention to the exceptions to the rule.

The answers to Question No. 1 were as follows:

(a) 16 — Oxide film
15 — Aluminum cell
1 — Condenser resistance with horn in parallel to the condenser
1 — Compression chamber
1 — Horn gap with water resistance

(b) 16 — Oxide film
14 — Aluminum cell
1 — No arrester
1 — Horn gap with water resistance

(c) 14 — Oxide film
13 — Aluminum cell
1 — Bennett type
2 — Horn gap with water resistance
1 — No arrester

(d) 13 — Oxide film
13 — Aluminum cell
1 — Bennett type
1 — Horn gap with water resistance
1 — No arrester

It should be noted in the above answers that the majority of those recommending oxide film recommend the aluminum cell also.

Answers to Question No. 2 show 12 who believe there are no cases where arresters should be omitted entirely. There are several who are willing that they should be omitted at small substations or on short and unimportant lines, or at points not subject to lightning. One omits arresters for 30,000 volts and over, one for 66,000 volts and over, and two on 150,000 volts and over. One omits arresters where apparatus of modern design is installed.

The answers to Question No. 3 are as follows:

13 — Recommend one arrester for each circuit, of which ten recommend the oxide film.
5 — Recommend one arrester on the bus.
1 — Recommends one arrester for each two circuits.
1 — Recommends one arrester for each transformer bank.

The answers to Question No. 4 are as follows:

11 — Do not recommend in any case the use of horn gap arresters.
4 — Recommend their use on unimportant circuits from small stations.
3 — Recommend their use with resistance in series on circuits of 12,000 volts or over.
1 — Recommends their use on 22-kv. circuits from substations.

1 — Recommends their use on all circuits over 10,000 volts.

1 — Recommends their use on customer's small substations.

Of the comments on the objectionable features of lightning arresters practically all the remarks were applied to aluminum cell arresters. The disfavor toward the horn gap is shown by the small number that recommends its use. Specific objections to this type were mentioned by a few, as follows:

One objection made which applies to nearly all classes of arresters is that the spark gap used in most designs reduces very much the protective qualities of any arrester, provided the arrester could be designed without a spark gap.

Referring to the aluminum cell arrester, six object to the fire hazard of the aluminum cell, eight object to the care and excessive attention required to keep the aluminum cell arrester in operating condition and in a condition to be a protection to the line, and one states that the mechanical features are poorly designed and do not stand up in service.

Extracts from some of the letters are as follows:

Operation erratic and protective qualities questionable.

Disturbances are set up by the discharge of horn gaps when used without resistance.

Do not stand up under service.

As to the objectionable features of the principal types of lightning arresters used on voltages of 10,000 volts and above, I presume by "principal types" you refer to aluminum electrolytic type and the oxide film types. My principal objection to these types of arresters is that they are dependent for their operation on somewhat obscure phenomena depending upon certain characteristics of the materials of which the arrester is constructed, these characteristics involving the action of films of very minute dimensions. In my opinion a multiplicity of elements of so minute a nature cannot be depended upon to provide the strength and reliability necessary for a lightning arrester.

* * * * *

I have witnessed a number of years of successful operation of large power plants with lightning protective equipment substantially as above, and during these years, at different times and places, both electrolytic and oxide film arresters have been tried out with indifferent success. I believe that all of the electrolytic arresters involved in this evolution have now destroyed themselves, while the horn gap-water barrel combination is still successfully performing its functions.

About two years ago I purchased 16 sets of oxide film arresters for 12,000-volt circuits. Only one of these sets, so far as I know, has had a discharge pass through it and this set was practically destroyed on this occasion. There was present at the time, it is true, an abnormal condition of high dynamic voltage, but I am positive that a water barrel horn gap type of arrester, as above suggested, would not have been injured. It is my opinion that better protection at much less cost can be obtained by means of home made apparatus of the type suggested than by spending large sums of money for hair-trigger types of arresters based on fine haired theories and obscure chemical reactions.

* * * * *

Past experience with lightning arresters makes it difficult if not impossible, to justify their expense particularly so at the high voltages. Where companies have made consistent efforts to get definite data in regard to apparatus failures with and without arrester protection, the results occasion distrust as to the effectiveness of the protection afforded by arresters. One of the companies affiliated with the .... Company has maintained a thorough record of this nature and finds that failures have occurred more frequently and have effected larger apparatus at installations protected with arresters than on other installations of lesser importance which have not been so protected. This is true both at 100 kv. and at 66 kv..

* * * * *

While it cannot yet be said that the omission of lightning arresters at the higher operating voltages is to be generally recommended, in view of the evidence at hand serious consideration should be given the subject and the justification for each new installation decided upon its merits.

* * * * *

We have kept careful records of apparatus failures on our high-voltage lines, and when we first began building these lines in 1910 we were of the opinion that it would certainly be necessary to have arresters to protect the apparatus. Our experience with arresters, however, soon demonstrated that it would be a cheaper thing to have spare transformers than it would be to repair the very large and expensive aluminum cell arresters. We finally, in 1912, stopped using them entirely, and our expense of maintenance has been materially reduced. We probably pay some penalty in first cost of rather expensive transformers, but we feel that we are justified in getting the very best and highest type of transformers and dispensing with the lightning arrester, and feel that from the standpoint of service and the standpoint of economy we have made a gain.

From an analysis of some of the reports on lightning arresters, and from a study of their designs, it appears that in order to secure the best protection, one of the paths through the lightning arrester should be a high current capacity path, that is, a path that will allow a large current to flow at the time of lightning discharge. If such a path is provided, the arrester will have a lower maximum voltage across the terminals at time of discharge than will be the case if the discharge capacity or rate of discharge is limited by the insertion of a resistance. It is possible that with a resistance in series, the maximum voltage will be higher than the break-down potential of the apparatus or cables which the arrester is intended to protect.

In general, transformers intended for a normal operating pressure of about 25,000 volts will withstand somewhat higher potentials than underground cables for the same working pressure. This is due to the fact that transformer windings are submerged in oil which has a high dielectric puncture value, and in addition, the end turns of transformers are generally built with extra insulation which will withstand higher voltages than the remaining turns in the transformer, and as the frequency of lightning discharges increases with their potential, it is the end turns in transformer windings which are subjected to the greatest strains at the time of lightning discharges. This means that for the protection of underground cables which are connected to overhead lines, arresters should be used having a high current capacity at time of discharge such as the aluminum cell or the oxide film arrester, while transformer installations, for supplying individual customers, which are connected directly to the overhead lines may be protected by types of arresters which have a lower discharge capacity and therefore a somewhat higher maximum potential across the arrester at time of lightning discharge.

Circuit Breakers and Switches

By H. R. Woodrow

Your sub-committee has analyzed the replies to the questionnaire on oil circuit breakers which was sent out in cooperation with the Apparatus Committee of the N. E. L. A., and Power Switchboard and Oil Circuit Breaker Section of the Electric Power Club. A short abstract of the general conclusions from these replies was published in the March issue of the A. I. E. E. JOURNAL.

The Apparatus Committee of the N. E. L. A. has prepared a detailed summary of these replies which will be presented before the N. E. L. A. at its annual meeting in Chicago on June 1, 1921.

From the discussion following the presentation of the paper on "Present Day Practise Limitations of Oil Circuit Breakers" at the midwinter convention, the following additional comments are made:

Rated Voltages. The present standards of the A. I. E. E. specify that oil circuit breakers shall be given a dielectric dry test consisting of the application of 2¼ times the rated voltage plus 2000 volts between the live parts and ground for 60 seconds. Although the questionnaire did not indicate in any way that such a test would not give adequate insulation it was brought out in discussion that some operating companies are purchasing apparatus of a voltage rating higher than the system voltage on which the apparatus is to be used.

It is recognized that the dielectric test recommended by the Standards of the A. I. E. E. must meet the requirements of average systems. It must also be recognized that systems not protected by adequate lightning arresters and systems of very large capacity may be subjected to voltage rises due to surges or lightning that will exceed the insulation values required by the Standards of the A. I. E. E. Taking those points into consideration, it is not recommended that these Standards for dielectric tests be changed. However, for systems that have characteristics, or inadequate lightning arrester protection, such that higher insulation is required, the present practise of selecting apparatus of the next higher voltage rating is endorsed.

Rated Continuous Current Carrying Capacity. As little trouble has been experienced from overheating of oil circuit breakers when carrying normal rated current, it is evident that if proper precautions are taken for alinement of current-carrying parts and ventilation of compartments, little trouble would be expected from this source.

Rated Momentary Current Carrying Capacity. As a few cases of trouble were reported from this source and as a result of the tests made by the New York Edison Company, it is recommended that oil circuit breakers be given a short-circuit current rating for periods of both one and five seconds.

Rated Interrupting Capacity. It appears from results of the questionnaire that the operating companies may require ratings on duty cycles other than the present recognized standard as given in the paper by Messrs. Hewlett, Burnham and Mahoney. There is considerable difference of opinion regarding the point of ending this duty cycle, the allowable condition of the breaker at that time, and what is considered satisfactory operation of the breaker.

It has been impossible to answer satisfactorily these questions at this time, and it is therefore suggested that this matter be given careful consideration by the next year's subcommittee.

General Comments. The subject of oil circuit breakers as reported by this committee was intended to cover the field of station breakers which would have to rupture large amounts of power rather infrequently, and is not intended to cover the subject of circuit breakers such as used in control equipment where they should be capable of interrupting full-load current a large number of times per hour for long continued periods and not be required to interrupt heavy short-circuit currents.

The activities of this sub-committee have been confined this year entirely to the subject of oil circuit breakers, and it is suggested that next year's subcommittee consider the question of rating and rupturing capacity of fuses, both of the power class and potential transformer class, in addition to following up the study on limitations of oil circuit breakers.

Schemes of Relay Protection

By E. A. HESTER

It is the function of the sub-committee on Schemes of Relay Protection to act as a clearing house for all information on protective relay schemes and to present this information in such a form that it will be an authoritative record of the progress of the art. The results of the first questionnaire, which was presented to the Institute in June, 1919, covered only such schemes as were recognized as standard because of their successful operation.

A second request for information was sent out February 24, 1920, in order to obtain an authentic record of schemes which are being, or have been, tried out and proved successful or abandoned as worthless.

In pursuance of the program outlined in the report of the Committee last year, the members to whom the six Geographic Sections of the United States and Canada were assigned have submitted to the Chairman answers to the request for information from practically all the operating companies to whom these requests were sent. Much interest was manifested by the various companies in the work of the subcommittee and, while some of the replies were delayed because of the pressure of other work, it may be said that, in general, they responded very promptly.

In replying to this request practically every company has given a description of all relay schemes which it has used, both standardized and otherwise. In many instances the information on the standard schemes is much more complete than that which was given in the reply to the first questionnaire, thus adding to the completeness of the sub-committee files and further substantiating the conclusions given in the previous report.

On account of the very large volume of material contained in these reports the subcommittee has not yet been able to coordinate it into the form of a report. A great amount of classification and compilation will be necessary in order to reduce the information to a report of practical value, and the subcommittee is now engaged in this task. It is planned to present this report in a meeting of the Institute some time next winter.

In addition to the various schemes described in the June 1919 Institute PROCEEDINGS several companies have reported the successful use of other schemes and not a few reported certain schemes still on trial or tried out and abandoned. It is not possible to describe these in this brief resume, though casual mention of two or three of those now in successful operation will be of interest and will serve as an indication of the general trend in protective work.

A new pilot wire scheme has been used very successfully over a period of approximately three years by one large company. This company's system has become so complicated that considerable difficulty was experienced in determining relay settings and in securing selective action of relays.

The new pilot wire scheme was therefore developed in order to reduce the number of relays requiring progressive settings and to simplify and reduce the settings on other relays where this could not be used. It is known by its originator as the Balanced Differential Relay System, and depends for its operation upon an unbalance of currents in the differentially wound relay coils. Such unbalance in the case of a fault on the line results from partial or complete opposition of e. m. fs. on the pilot circuit. On a through fault the e. m. fs. are additive and equal currents flow in the relay coils, but in opposite directions, so as to neutralize. Under normal conditions no current flows through the relays or in the pilot circuit.

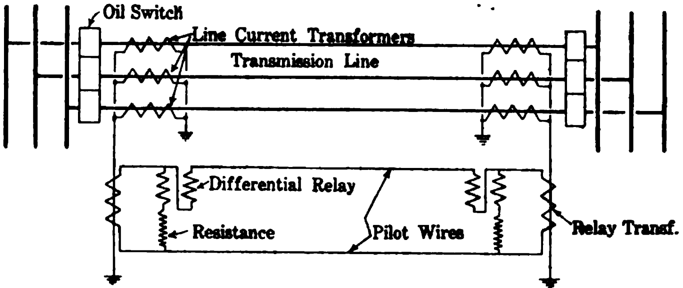

FIG. 1—SCHEMATIC DIAGRAM OF BALANCED DIFFERENTIAL RELAY SYSTEM

This scheme is illustrated in Fig. 1 and as may be seen, only two pilot wires are necessary. It is very simple, and on short lines compares favorably in cost with other standard installations. The cost will increase, however, as the line becomes longer because of the necessity of pilot wires.

In case this scheme is used on ungrounded systems where a ground is not involved in the fault it will be found necessary to use a modification employing three pilot wires. This is not illustrated.

Another company reports the successful use of a modification of the balanced or cross-connected relay scheme in which an additional double-contact differential current relay is used. This scheme is applicable to parallel lines, the lines being paired off and balanced against each other. In the case of three lines the current relays on the third line are given special settings. The differential relays are not used to trip the circuit breakers but to reduce the time settings of the relays on the faulty line to approximately one-half that of the relays on the other line. Thus the faulty line of the pair is selected and the other line is left with adequate relay protection. Advantage for this scheme, over the instantaneous balanced scheme, is claimed in that the circuit breaker is not called upon to interrupt the initial rush of current. If it is desired however, the differential relay can be connected to trip the circuit breaker direct. A diagram of the connections used is shown in Fig. 2.

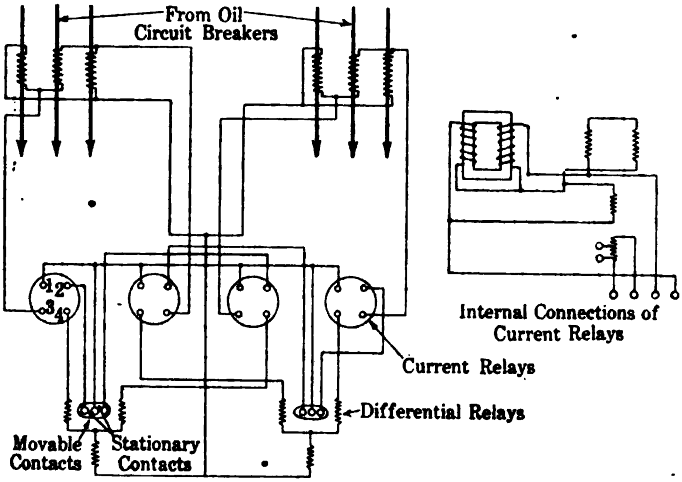

FIG. 2—SCHEMATIC DIAGRAM SHOWING DIFFERENTIAL RELAYS

The cost of this scheme is the same as that of a standard installation except for the additional cost of the differential relay, which is practically the same as that of the standard induction type current relay.

One very interesting installation of selective ground relays is reported. All operations up to the date of the report had been successful but the time of service was not considered sufficient to prove definitely its value. The scheme was installed with the expectation that faults of slow development to ground would be cleared at an earlier stage than is possible with phase relays, thus preventing the trouble from being communicated to nearby lines and preventing the system from being subjected to severe shock.

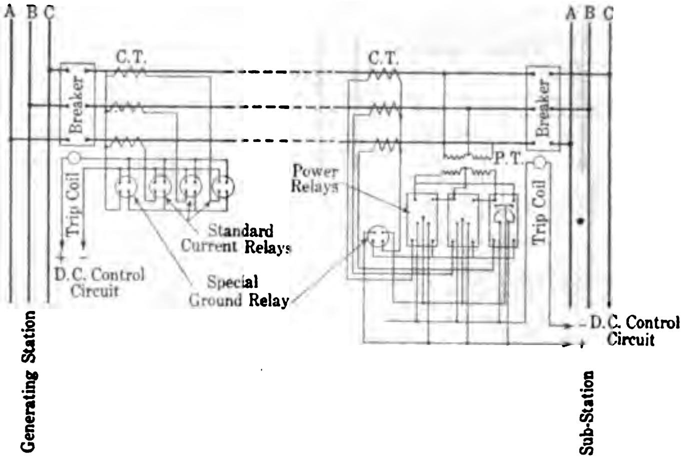

Fig. 3—Schematic Diagram Showing Use of Ground Relay

A special relay wound for low operating current and having low energy requirements is inserted in the current transformer neutral lead on standard current and power relay installations. When used with current relays this ground relay trips the circuit breaker direct, while with power relays at the substation end it is arranged to short-circuit the over-current phase relay contacts, thus leaving the power relay to discriminate as to direction of power flow. The principle of operation is obvious since current will flow in the ground relay only upon the occurrence of a ground. Therefore, in the case of phase to phase short circuits the operation of the phase relays is not interfered with. This may be clearly seen by referring to Fig. 3.

The cost of this scheme exceeds that of the standard installation only by the additional cost of the ground relay which is practically the same as that of the standard type current relay.

The above developments would indicate that the general trend is toward the selection of defective lines by means of the fault or trouble current rather than by relying altogether on the use of progressive time settings and current settings on the basis of the total current. As systems grow larger and more complicated progressive settings necessitate maximum time intervals which are so high as to be impracticable and the need for adequate schemes which do not require progressive settings has become a necessity as well as a convenience. While no scheme has as yet been developed which can be universally applied and which will obviate the necessity of progressive settings, the manufacturing and operating engineers are to be commended for their efforts toward this end. Results which have recently been obtained give promise of a closer approach to the ideal means of protection.

It is the aim of the sub-committee on Schemes of Relay Protection to preserve an accurate record of the developments and operations of the various protective schemes, which records will be available to the operating and manufacturing companies under the Committee rules. It is to be hoped that the service of this subcommittee will play some part in preventing duplication of effort among engineers and foster a gradual tendency toward the standardization of protective relay schemes and devices.

D. W. ROPER, *Chairman.*

ANNUAL REPORT OF IRON AND STEEL INDUSTRY COMMITTEE

To the Board of Directors:

During the past year, the important part played by electricity in the Iron and Steel Industry has in no wise diminished, although the extent of the growth of electrification has been relatively small as compared with recent years, due to the almost complete cessation of expansion in the industry, beginning in the latter part of 1920.

Periods of business depression, with the coincident demand for low production costs, invariably bring into prominence the wasteful and imperfect producing element of each plant, and the present period is no exception. Furthermore, the present necessity for finding ways and means of meeting low-priced competition in foreign markets adds emphasis to the searching out of inefficient units. As heretofore, the more general application of electric power is usually an important factor in the strengthening of the weak links, so that at this time, a large amount of electrical installation, particularly in the line of replacing steam engines in the drive of main rolls, is recognized as essential and is only waiting upon the devising of means of financing.

Much progress has been made in the most recent installations of reversing mill drives and of adjustable-speed equipments for the lighter finishing mills. Control equipment of all kinds shows marked tendencies toward simplification, although at the same time making possible considerable reduction in the human element in the industry.

In common with all industry, the iron and steel plants of many parts of the country will, on resumption, be confronted with the power problem and much attention is being directed toward the development of dependable low cost sources of electrical energy. Again, in steel plants of size, the transportation of the raw and semi-finished materials within the plant limits is responsible for an important percentage of the total production cost and investigations are being directed to the possibilities of the reduction of this item by yard electrification.

Your Committee cooperated in every possible way with the Pittsburgh Section and Meeting and Papers Committee of the Institute in arranging for the Institute Meeting in Pittsburgh on April 16th in joint session with the Association of Iron and Steel Electrical Engineers. One of the papers was prepared by D. M. Petty, a member of the Committee, and other members contributed discussion. The meeting was a very successful one and served to continue the close and harmonious relations so desirable between these two national societies.

WILLIAM F. JAMES, *Chairman.*

ANNUAL REPORT OF TRANSMISSION AND DISTRIBUTION COMMITTEE

To the Board of Directors:

The Cable Research sub-committee appointed jointly by your Committee and the Underground Systems Committee of the National Electric Light Association continued its work during the year.

As the standard specification for paper-insulated lead-covered cables, completed by the sub-committee last year, met with such general favor, it was suggested that the sub-committee prepare similar standard specifications for rubber and varnished cambric insulated cables.

For the reason that considerable work along these lines had already been done by committees of other technical organizations but particularly because the Institute had recently joined the American Engineering Standards Committee it appeared that the entire subject of cable specifications should be brought before that body.

A conference was called in New York on February 2nd, 1921 by the American Engineering Standards Committee and after a thorough discussion of the many considerations involved it was unanimously decided that the unification of cable specifications for wires and cables for other than telephone and telegraph use should be undertaken under one general plan covering substantially all the more important uses. This work is now being carried out under the auspices and in accordance with the rules of procedure of the American Engineering Standards Committee.

In the matter of standardization of cable ratings, some work has been done by the Cable Research subcommittee and further investigations are in progress. Similar work is under way in England under the supervision of the British Electrical and Allied Industries Research Association.

The published report of that Association as well as the investigation so far conducted by the Cable Research subcommittee show very clearly a lack of agreement as to the maximum permissible operating temperature of paper insulated cables.

Until an agreement can be reached on this very important point it will be impossible to arrive at any definite conclusions regarding cable ratings. It may be possible, however, to prepare a tentative rating for cables of various sizes and voltages to show the permissible current for various maximum temperatures and under definite physical conditions, leaving it to each user of cable to determine, for the present, the maximum permissible temperature for his own cables.

At the Midwinter Convention of the Institute, one session under the auspices of the sub-committee on Wires and Cables, was devoted to the discussion of cable ratings and papers were presented by a number of manufacturers and users of paper-insulated, lead-covered cables.

A number of those participating in the discussion expressed the opinion that the maximum limit of 85 deg. cent. is too conservative for low-voltage cables in which the dielectric losses are small and several believed that the limit should be placed at 105 deg. cent. which is the limit for fibrous insulation in electrical apparatus.

It is expected that steps will be taken during the coming year to initiate investigations which will result in a definite determination of this maximum permissible temperature.

TENDENCIES IN OVERHEAD TRANSMISSION AND DISTRIBUTION PRACTISE

Transmission. The present tendency in transmitting electrical energy is decidedly toward the use of increased voltages. This is particularly so in conidering transmission problems, which problems are now involving the transfer of larger blocks of power over longer distances than were formerly considered practical and economical.

The interconnecting of various load centers to take advantage of diversity in demand is receiving the careful attention of transmission engineers. Transmission lines operated at 150 kilovolts have been in service for a number of years and materially higher voltages are now considered. At least one line, that of the Southern California Edison Company, is under construction for

220 kilovolts. This line is being built in connection with the Big Creek No. 8 hydroelectric development and will form part of a system for transmitting over a distance of 240 miles, about 750,000 h. p. at 220 kilovolts.

It would appear that the limit in transmission voltage will be governed by the successful development of conversion and switching apparatus to control the large amount of energy requiring such voltages. Practically all the earlier transmission lines were constructed on steel supports. There is a tendency today, however, particularly in the West, to construct such lines on wood supports, using spans up to six hundred feet in length.

The quality of insulators now available is apparently much better than that obtainable prior to about 1915. This applies particularly to suspension insulators, and while suspension insulator practise since 1915 has shown improvement in performance under operating conditions, a sufficient length of time has not elapsed as yet, to measure this improvement. The design of pin insulators has undergone a decided change in recent years; as now designed they are more substantial, and their performance has been considerably improved. The tendency today apparently acknowledges the greater necessity for a more careful selection, dependent on load characteristics, climatic conditions and also a higher electric factor of safety than was former practise. Every effort is being made to increase the margin of puncture over flashover voltage. Arcing horns and similar devices are coming into use, so designed that no part of the insulator or conductor will be damaged during flashover, by the heat of the arc.

The effect of heat cycles, cement expansion, and similar characteristic changes in insulators is being studied in order to reduce to a minimum the so-called insulator depreciation. The results obtained thus far cannot be said to warrant any radical change in the physical design.

Apparently, overhead ground wires for lightning protection are being discontinued in many locations except where such wires have been installed to provide additional stability to the line structures, dependence being placed entirely upon the successful performance of the lightning arresters connected to the line.

The practise of carrying on maintenance and repair work on live transmission lines seems to be gaining in favor, special tools and equipment having been designed for changing insulators, carrying on new construction work and making repairs to both the line and its accessory equipment.

Aerial cable operated at voltages up to 26,000 has been installed through thickly settled communities for transmission purposes. This field seems to provide a possible solution to many problems involving the transmission of large blocks of power, through thickly settled territories, which heretofore has been considered possible only by the installation of an underground system.

Distribution. It would seem that no great change is to be expected in the 2200-4000 volt distribution system, so generally used at the present time. To provide for the rapidly increasing demand for electric service, additional substations are being installed, fed by aerial or underground transmission lines at relatively high voltage, from which substations the lower voltage primary circuits radiate.

The diverse character of the loads now being connected is resulting in the practise of dividing distribution systems into distinctive lighting and power service. It is common practise to construct power circuits at a higher primary voltage than the lighting circuits, connecting to the power circuit large motor loads, electric furnaces, welders, and similar types of utilization equipment; and as such equipment is usually of low power factor, special attention is being given to the development of power factor corrective apparatus in order that the entire capacity of such feeders will be available for distribution purposes.

The banking of transformers where the loads are congested, is now being generally considered, it having been demonstrated by a number of installations, that not only the power loss is materially reduced but the investment cost in transformers, copper and other similar items is materially lowered.

The greatly increased loads now commonly distributed, together with the large capacity of many of the systems is necessitating the complete redesign of much of the line switching and protective apparatus.

Probably the most recent distribution problem is the connecting of the loads in the more scattered or rural districts. The development of the so-called "farm lines" to reach this class of service has been very rapid. Electric service is a necessity to the modern farming community and its connection is resulting in the development of distribution circuits of 13,000 volts, more or less, constructed in a substantial manner but without the refinements of city construction. Such service is becoming available in practically all sections of the country. Extensions twenty-five to thirty miles in length feeding from fifteen to twenty customers are becoming common.

TENDENCIES IN UNDERGROUND CABLE PRACTISE

Higher-Voltage Cables. Better knowledge of the characteristics of impregnated paper insulation has made it possible to manufacture cables for operation at voltages much in excess of those formerly standard.

Three-conductor paper-insulated cables are now being manufactured to operate at 33,000 volts whereas in the past 25,000 has been the maximum voltage commonly used with this class of cable.

During the year one of the largest central station companies ordered cable to be operated at a voltage higher than any heretofore used in this country. In Chicago there will be installed during the year about thirty miles of three-conductor cable intended for a normal working pressure of 33,000 volts. This cable will have sector shaped conductors each of 350,000 cir. mils, with 19/64 in. insulation around each conductor and 7/64 in. outer belt; the thickness of the lead will be 9/64 in. The over-all diameter will be about 2.95 inches, so that it can be installed in a 3½ inch duct. This cable will be used for two tie lines between a new generating station and one of the older generating stations which is near to the center of distribution.

It is also possible by reverting to single-conductor design to manufacture cable for operation on circuits rated at 60,000 or possibly 100,000 volts. This increase in voltage at which underground cables can be operated is an important advance, as high voltages have long been used on open wire circuits and in many cases the inability to construct cable of corresponding voltages has been a serious disadvantage. There will be many instances where high-voltage cables can be used to advantage in eliminating the necessity of extra transformations.

It is understood that the 60,000-volt single-phase feeders of the St. Gothard line in Switzerland has recently been placed in service, 30,000 volts being impressed on each single-conductor cable.

Larger Cable Sizes. The necessity for using larger sizes of conductors has further increased the demand for sector cables on account of their smaller over-all diameter.

Two-conductor *D*-shape sector cables of 1,000,000-cir. mil and 1,500,000-cir. mil cross section are being used to a large extent on Edison d-c. three-wire circuits. The principal reasons for using this type, instead of the concentric type formerly employed, are the greater ease in splicing and the better balance of the resistance between the two sides of the three-wire system.

Dielectric Losses. The subject of dielectric losses in cables is recognized as being important, but on account of the material reduction in the dielectric losses in cables as at present manufactured, the subject is not so often overstressed as was the case when the matter was first generally discussed. It should also be noted that cable properties are largely interdependent and that undue development of one characteristic may result in the sacrifice of some other equally important feature.

There is now available, cable which will not have more than 0.75 watt dielectric loss per foot of cable when operating at the maximum temperature allowed by the Institute Standards. Cables having dielectric losses within the limits shown in Fig. 1 will be found satisfactory.

Hochstadter Cable. Hochstadter Type *H* triplex cable in which the insulation of each single conductor is covered with an electrically conducting foil (usually of copper) and the three individual conductors assembled without any belt insulation, is in successful operation at high voltage.

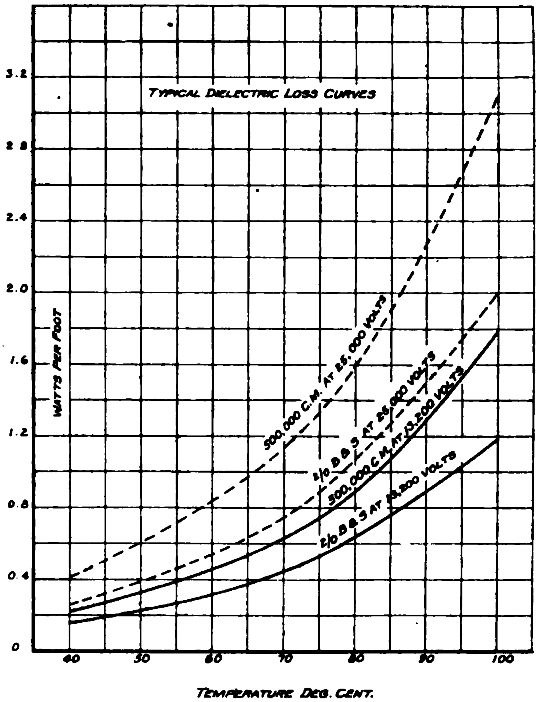

FIG. 1

Two companies have recently ordered three-conductor cable of the Hochstadter type for operation at about 25,000 volts. One of the companies ordered only sufficient cable for a portion of the line and the remaining cable was of the ordinary type with the insulation divided between the conductor and the outer belt. In the other case the entire order was for cable of the Hochstadter type but the manufacturer, at the request of the Cable Research subcommittee, made up a short length of the usual type three-conductor cable for a comparative test, this cable being made of the same materials and manufactured at the same time as the Hochstadter cable.

As a result, the Committee has available the two sizes of Hochstadter cable to compare with the same sizes of cable insulated in the usual manner and has arranged for comparative tests of the merits of the two types of cable. A number of the larger operating companies, and the National Electric Light Association have contributed to the fund necessary for making these special investigations, the result of which should be available during the coming year.

Crystallization of Lead Sheath. Though the method of applying the lead sheath to underground cables has changed but little in many years, there has recently come to notice a number of cases where the lead sheath has crystallized. This is not a new condition but in the past it has been comparatively infrequent. There have been a number of cases where cable shipped for a considerable distance showed signs of defective lead on arrival at its destination while other instances of similar character have been noted in the sheath of cables that were subjected to vibration after installation.

There is evidence of a direct relation between vibration and crystallization of the lead sheath, but it has not been definitely determined whether crystallization is hastened by improper methods in manufacture. It has been suggested that in many cases crystallization has been caused by localized impurities, or by the lead having become too cold in the die.

Power Cable Testing. Power cable testing practise is at present divided into four important branches:

1. Factory research and routine tests.
2. Independent laboratory tests.
3. Factory inspection and acceptance tests.
4. Field or installed tests.

1—*Factory Research and Routine Tests.* Factory research and routine has in recent years been stimulated by the demands of users for cable of higher quality, suitable for operation at increased loads, higher temperatures and higher voltages. Research work by progressive manufacturers has resulted in greatly improved product in all respects. It has also indicated most forcibly the need of improved routine tests in order to check materials and processes so that uniform high quality may be insured at all stages of manufacture. If the routine factory tests are properly planned and carried out during manufacture a consistently uniform product may be turned out, which need be checked only occasionally by special laboratory tests on the finished product. It is obvious therefore that the selection of materials and their handling during manufacture are the most important features of cable manufacture.

2—*Independent Laboratory Tests.* Independent laboratory tests have been carried out, at the request of both consumers and manufacturers. The results have been of great value from the standpoint of all interests for the following reasons:

a. Standard methods of testing have been formulated.

b. Advance information has been secured by consumers and manufacturers alike, which has in some cases resulted in manufacturers realizing the desirability of having their own laboratories equipped for test and research of similar nature.

c. General information which has been given out by such laboratories has shown a great lack of uniformity in the product of some cable manufacturers. This non-uniformity appears to be due to lack of knowledge as to how the component parts of a cable must be handled and tested during manufacturing processes.

3—*Factory Inspection and Acceptance Tests.* It is the practise of many users of power cables to carry out inspection at the factory before cables are accepted for shipment. Some also inspect during the process of manufacture as far as permissible without unfair inquiry into manufacturing secrets. This practise, which appears to be growing rapidly, keeps the manufacturer on the alert because his ultimate profit depends upon the acceptability of his product with a minimum number of rejections.

4—*Field or Installed Tests.* Many power cable users make regular tests after installations to detect injury during installation, and inadequate or faulty jointing. These tests vary from insulation resistance tests only, to complete high potential, insulation resistance, conductor resistance and capacitance tests.

In some cases it appears that unnecessarily severe tests are made which may result in injury to the cable. The test of service is undoubtedly the best of all. Any test which will detect incipient faults due to handling or installation is all that is reasonably required in addition to the factory tests and the test of time.

The safe loading of cables requires a knowledge of the characteristics of the cable location. Test to determine their characteristics are not, strictly speaking, cable tests, but they are of equal if not greater importance. This subject is being studied in this country as well as abroad and some preliminary results have been published in the technical press.

General. The Committee has called attention in previous reports to the reduction in dielectric loss at relatively high temperatures. Routine factory tests inaugurated by some manufacturers have made it possible to predict with accuracy the dielectric losses in the finished cable, which constitutes an important step in the production of cables uniform in this respect. One of the most important results not inconsistent with uniformly low dielectric losses is uniformity of dielectric strength, which has been noted to a considerable extent. The Committee does not think it proper, however, to refer more specifically to routine tests as they are largely the result of factory research.

There appears to be little of importance to report with respect to new methods of testing cables with high voltage, either in the factory or field, with the possible exception of the use of d-c. devices such as the kenotron. This device appears to have possibilities of great importance and, as used experimentally by at least two utility companies, appears to fill a long-felt want for a light and portable apparatus for cable testing, and requires but a very small amount of power or capacity for its operation.

Attention is called to the possibility of paper-insulated cables breaking down under high-voltage tests but followed by immediate rehealing of the puncture. This rehealing is usually temporary but may persist long enough to deceive in a test of stated duration. It is therefore essential that these "spits" be recognized and the test repeated until they have been eliminated.

The practise of testing faulty cables for fault locations has undergone no material change, the devices used being divided into two principal classes, one depending upon the principle of bridging, the other upon the exploring coil with signaling current.

Various mechanical tests are made on cables and cable dielectrics with which most engineers are familiar. One of particular interest is the so-called bending test on paper-insulated power cables. This test is carried out for the purpose of determining the likelihood of a cable being injured by handling during manufacture or installation.

Protection of Cable Systems. The increasing frequency of trouble on low-voltage (less than 550-volt) systems and the consequent danger of communication to other circuits has necessitated a great deal of attention being given to the problem of segregating the circuit on which the trouble originates.

On account of the probable resistance of the fault being sufficiently high to limit the flow of current, at this low voltage, to a value possibly not more than the normal load, it is impossible to get the desired protection by the use of fuses. For this reason some companies have omitted the fuse, while one company fearing an extended burn-out of this class of cables has provided each feeder conductor with a remote-controlled circuit breaker at the service end of the feeder designed to open when the feeder is in trouble.

These circuit breakers do not open from overload but have a trip coil that is connected to a pressure wire in such a way that, if the pressure wire comes in contact with either the lead sheath or the main conductor, the coil will become energized and open the circuit breaker. There is also provision at the station whereby the operator can, by closing a small switch, put current on the pressure wire to trip the switch.

With higher-voltage distribution cables, around 3000 volts for example, there is no difficulty in providing fuses that will carry normal load and blow under short circuit; but in this class of service the problem is to provide a fuse which will successfully open the circuit. For this reason a number of engineers recommend against the use of fuses on underground systems of this voltage.

When we consider still higher voltages of the order of those used for transmission, no attempt is made to use fuses underground. However, the majority of underground troubles originate on this class of cables and it is extremely important that every precaution be taken to prevent trouble starting in one of these cables from communicating to others. For accomplishing this, ducts should be separated by an adequate wall of fire resisting material, such as is obtained by laying fiber tubes in concrete so that the ducts will be separated by a continuous wall of concrete about one inch thick, except near the manholes where the separation should be increased to give a maximum separation at the end of the ducts. This extra separation at the edge of the manholes is advisable on account of the danger of communication of trouble from one cable to another at this point where the protection to the cable is apt to be least. The importance of protecting cables in manholes will be evident when it is considered that more than one-third of the failures in the higher-voltage cables occur in splices alone and a large percentage of the remaining failures also occur in the manholes.

Concrete continues to be the most popular form of protection in the manholes. It is not only a good protector against fire but it is also a better conductor of heat than other forms of protection. Owing to the effect of heat in decreasing the resistance of the insulation of high-voltage cables, it is extremely important, especially with cables constructed a few years ago, to avoid excessive temperatures in the duct line. This applies not only to heat dissipated by the cables themselves, but also to that produced by other sources, such as steam pipes and exhaust steam. There have been many instances during the last few years of serious troubles due to high temperatures produced by steam. Where it has been a case of exhaust steam or a local steam pipe it has been comparatively easy to overcome the trouble by changes in either the duct line or the point of exhaust, but where the heat has been experienced at many points due to an extensive steam heating system, changes that would be necessary to remedy the trouble have been too expensive to undertake.

REVIEW OF PAPERS SUBMITTED DURING THE YEAR

Insulators. In the TRANS., 1920, Vol. II, p 1179, W. D. A. Peaslee contributed an article on *High-Tension Insulator Porcelain.*

This paper reviews the progress made in the ceramic field in the solution of the insulator problem. Procelain used in the manufacture of high-tension insulators must meet certain requirements as to mechanical strength, ability to resist sudden changes in temperature, porosity, homogeneity, and temperature coefficient of resistivity. The author gives a brief discussion on each of these requirements and the progress that has been made in the development of a suitable porcelain. A brief discussion is also given regarding the possibility of the deterioration of seemingly perfect porcelain being intimately connected with the Piezo electric qualities of quartz crystals.

In the A.I.E.E. TRANS., 1920, Vol. II, p. 1645 the same author discusses *Factors Controlling the Design and Selection of Suspension Insulators.*

Attention is called to the factors entering into the design and operating behavior of suspension insulators and the problems to be solved in designing a suspension insulator to overcome the objectionable features shown by experience to affect seriously the operation of the insulators in service. Factors to be taken into consideration in the selection of suspension insulators for a given condition are given and a brief discussion of the general trend of future developments is presented.

F. W. Peek, Jr., presented an article in A.I.E.E. TRANS., 1920, Vol. II, p. 1685 reviewing the duties of the line insulator at voltages above 100 kv. and comparing them with the duties imposed by the lower voltages in order to predict the reliability of future high-voltage lines as compared with those at present in operation and pointing out what changes, if any, are necessary in present practise. While unimportant at the lower voltages, the uneven division of voltage on the different units of a suspension insulator becomes of increasing importance as the voltage is increased. Quite complete data are given on the phase of the investigation dealing with voltage distribution and the successful correction of the uneven voltage distribution by means of an antenna shield from the line. The author believes that with the very high voltages at present being considered, insulator troubles will probably be less frequent than with present voltages.

Operating Performance of Insulators on a 45,000-Volt System by H. B. Vincent in included in the January, 1921, JOURNAL.

This paper presents a method for the recording of insulator performance and shows how such a record enables one to know what service the insulators are giving and what one may expect provided the records have been kept over a sufficient period of time. The data presented refers entirely to pin type insulators and has been gathered from actual records kept by a power company. There is included an analysis of the data obtained from this company's report showing the performance of insulators on the various lines from 1914 to 1919 inclusive.

H. J. Ryan and H. H. Henline contributed an article appearing in the A.I.E.E. TRANS., 1920, Vol. II, p. 1669 dealing with the quantitative relations which exist between the maximum and average voltage unit-duties in line suspension insulators made up of units in common use. The results obtained from a number of tests conducted by the authors to determine these relations on insulators of single and double strings with and without static shields are discussed in detail. From their investigations the authors believe that suspension insulator unit in common use can be satisfactorily employed for the makeup of insulators for 250-kv. lines.

Surface Leakage as a Factor in Insulator Design by T. M. Feder is discussed in the September, 1920, JOURNAL. The author calls attention to the various factors influencing surface resistance and the different methods by which this resistance may be increased. It is shown that the most economical way of decreasing the leakage is the addition of properly proportioned corrugations on the underside of the flange or skirt. Typical computations are given, showing the approximate increase in resistance to be expected when corrugations are added.

Overhead Transmission and Distribution. The 150,000-Volt Transmission Line of the Knoxville Power Company is described by Theodore Varney in the June, 1920, JOURNAL. The author discusses problems encountered in the design and construction of this line and the solution of these problems are described.

The conductor is of aluminum reinforced with steel and the longest span is 5010 feet long, which the author states is the longest single-conductor span in the world at the present time. A detailed description of both the standard and long-span conductors is given together with a summary of the points covered by the specifications drawn for the purchase of the standard suspension and anchor insulator units.

The A.I.E.E. TRANS., 1920, Vol. II, p. 1669 includes an article prepared by D. M. Jones on *Power Factor Correction on Distribution Systems.*

After a review of the causes and disadvantages of low power factor, the writer discusses various methods of eliminating this condition. The methods provide for the use of the unity power factor synchronous motor, the phase modifier, the over-excited synchronous motor, the synchronous condenser, and the static condenser. The advantages, disadvantages and comparative costs of each type of apparatus are discussed.

P. O. Reyneau and Howard P. Seelye prepared an article A.I.E.E. Trans., 1920, Vol. II, p. 1807 on the *Economic Study of Secondary Distribution.*

This paper analyzes and evaluates the factors in the design of the secondary system which lend themselves to such definite analysis and presents the results as aids in the determination of the most economical design for a system. The derivation and application of equations and curves used for the determination of the most economical voltage drop, transformer spacing, transformer size and wire size under theoretical conditions are presented and discussed. Curves for practical conditions are then worked out for use of the designing engineer.

Cables. R. W. Atkinson prepared an article which appeared in the September 1920, issue of the Journal on *The Current Carrying Capacity of Lead Covered Cables.*

After discussing the temperature rise in cables and their surroundings the author describes a method of determining the current-carrying capacity of cables based upon their temperature rise. Data are given whereby the current-carrying capacity of lead-covered cables can be calculated on the basis of thermal limitations. Carrying capacity as limited by voltage drop or economical considerations is not considered. The article shows how further data can be applied as these are determined.

An appendix contains some numerical examples illustrating the use of the data and in addition a chart by which it is possible to determine graphically, for given conditions, the carrying capacity of three-conductor paper and varnished-cloth cables installed in conduits.

C. W. Davis and D. M. Simons presented an article on *Maximum Allowable Working Voltages in Cables* appearing in the January, 1921, issue of the Journal

This paper discusses methods of calculating stresses in triplex cables and gives examples of calculations made. Tables are given for determining maximum voltage stress in single, triplex and type *H* cables. From calculated stresses the authors obtain a solution for the size of conductor which will produce a minimum stress for a given core diameter. The determination of the maximum possible operating voltages for given limits of stress and outside diameter is then described. From the limits worked out in this article it is the conclusions of the authors that for the high-voltage cables of the future the ordinary three-core form cable will be used as heretofore up to

30,000 volts, type *H* cable up to 50,000 volts, and three single-conductor cables having conductors made with a hollow fiber core for 50,000 volts and above.

At the mid-winter convention in February, 1921, James A. Cook presented a paper (See p. 439) dealing with *Measurement of Relative Eddy Current Losses in Stranded Cables* describing a method which will insure accurate measurements of eddy current losses in stranded copper cables on a comparative basis. Results of tests are shown both for the measurements and the reduction of eddy current losses.

CONVENTION PAPERS

The following papers have been submitted and accepted for presentation at the Annual Convention at Salt Lake City:

Long Distance Transmission of Electric Energy by L. E. Imlay. (See page 975.)

Voltage Regulation and Insulation for Large Power, Long-Distance Transmission Systems, by Frank G. Baum. (See page 1017.)

Voltage and Power Factor Control of 66,000-Volt Transmission Lines Connecting Two Generating Stations, by Raymond Bailey. (See page 995.)

A Solution of the Porcelain Insulator Problem, by E. E. F. Creighton and F. L. Hunt. (See page 1173.)

Modern Production of Suspension Insulators, by Edwin H. Fritz and George I. Gilchrest. (See page 1127.)

Voltage and Current Harmonics Caused by Corona, by F. W. Peek, Jr., (See page 1155.)

Transformers For Interconnecting High-Voltage Transmission Systems or For Feeding Synchronous Condensers from A Tertiary Winding, by J. F. Peters and M. E. Skinner. (See page 1181.)

Some Transmission Line Tests, by W. W. Lewis. (See page 1079.)

The Operation of Large Interconnected Systems, by L. L. Elden. (See page 1121.)

E. B. MEYER, *Chairman.*

ANNUAL REPORT OF LIGHTING AND ILLUMINATION COMMITTEE

To the Board of Directors:

The Lighting and Illumination Committee considers that along with the other Technical Committees, it can render a special service to the Institute, by securing papers which relate to subjects within the scope of the Committee and which will be of particular interest to the members of the Institute. The three excellent papers on street lighting distribution presented before the Chicago meeting last year illustrate this point. Following out this general thought, the Committee held a meeting early in the year for the purpose of considering what activities could be undertaken during the current year.

The results of this meeting of the Committee may be summarized as follows:

1. That it would be of value to members of the Institute for the Committee to start the accumulation of data relating to productive intensities in industrial plants, that is, to the question of intensities of illumination in the industries best suited to effective production. This data could well cover the question from the standpoints of the relations of illumination to factory production, to accidents and to reduced spoilage. The Committee felt that it might not be practical to attempt to secure papers on this subject this year because of the incomplete nature of studies which have been and are being made along this line, but it is hoped that in the near future papers may be secured on several particular aspects of the problem such as those relating to opthalmology, psychology, physiology, accident prevention, scientific management and production records.

2. The Committee felt further that it may be possible to secure a paper at some time in the near future dealing with glassware for lighting auxiliaries, such as that used with street and commercial lamps. A paper on this subject did not materialize during the current year but the Committee feels that a general summary of the glassware situation would be of considerable practical value.

Although neither of the foregoing plans of the Committee has taken definite form during the year, it is believed that the formulation of these suggestions has, in itself, been an item of progress and that it may lead ultimately to certain very valuable papers.

In addition to an effort to gather papers, the Committee feels that it may also render a service of value to the Institute by carrying out the intent of the resolution of the Board of Directors of May 11, 1921 through the preparation, as part of the annual report, of a brief summary of progress of the art in the lighting and illumination field. In the present report, reference is made to some of the more important features of the year's progress without any effort to make it complete in detail. Very full notes on the detailed progress and developments in this field are published each year as a Progress Report by the Illuminating Engineering Society. The following notes cover some of the more interesting developments which have been noted by the Committee and by the technical press during the current Institute year:

DEVELOPMENTS IN THE LIGHTING FIELD

Use of Incandescent Lamps. It is interesting to note at the outset that the estimated sale of incandescent lamps in 1915 amounted roughly to about 110,000,000 whereas in 1920 it was estimated that 230,000,000 were sold. These figures indicate that the lamp business has practically doubled in the five year interval from 1915 to 1920. One of the large lamp manufacturers estimates that of the total in 1920 about 215,000,000 or about 92 per cent were tungsten filament lamps and about 16,000,000 were carbon filament lamps. This marked increase in the sale of incandescent electric lamps may be taken in a measure to represent fairly the growing use of electric lighting throughout the United States and it is of considerable interest to note here that the tungsten filament type has now almost entirely superseded the older carbon filament lamp.

The popular idea that the use of arc lamps is decreasing does not seem entirely consistent with the fact that the sale of luminous arc lamps during 1920 indicated an increase of more than 50 per cent over that of 1919.

Lighting in the Industries. The past year has evidenced marked attention on the part of factory managers to the effects of good lighting upon plant production, to the reduction of accidents and to minimizing spoilage. In one large industry an extended study was made to determine whether materially higher intensities of illumination than were formerly used, are warranted on the basis of improved production. These tests have not demonstrated fully just where practical intensity limits should be set for given classes of work nor what relations exist between good lighting and production, but the opinion is quite prevalent that higher intensities promote better workmanship and hence present practise tends towards the design of lighting systems with more liberal intensity levels than formerly.

The relation of poor lighting to accidents has received careful attention. It has been stated that during the 19 months the United States was in the last war, 56,000 American soldiers were killed in Europe, whereas during the same period 236,000 men, women and children were accidentally killed in this country. Of the enormous number of industrial accidents it has been fairly well established that possibly from fifteen to twenty per cent may be chargeable either directly or indirectly to poor lighting. This conclusion has been an item of importance in the work of regulating factory lighting by the State Departments.

The effect of light colored walls and ceilings on the illumination resulting from lighting systems is well known to lighting men but not always appreciated as fully as it should be by plant operators. One of the most helpful efforts looking to a better understanding of wall and ceiling colors and their effects on the resulting illumination, has been Bulletin Number 41 issued by the National Lamp Works of the General Electric Company and prepared by Mr. Earl A. Anderson. This excellent bulletin contains sample colors with the corresponding reflection factors and the method of working these reflection factors into the design of a lighting system is clearly indicated.

Lighting Demonstrations. One of the results of the increased interest in high intensities has been the efforts of the lamp manufacturers to educate the industries up to the apparent advantages of better illumination by using the so called demonstration method of illustrating modern practise and its effectiveness. More or less permanent demonstrations have been installed in ten of the larger cities of the country and several others are in various stages of construction. This activity has been fostered by the National Electric Light Association, with the cooperation of local institutions. Similar travelling demonstrations have been conducted by the lamp manufacturers in about one hundred and twelve other cities.

The Pennsylvania Department of Labor and Industry took advantage of the portable demonstrations presented in that state, to educate manufacturers and others in the application of the Industrial Lighting Code.

The demonstrations have also been utilized for the benefit of engineering students; for example, the Edison Lamp Works of General Electric Company recently conducted demonstrations at the University of Pennsyvlania and at Yale University. These demonstrations have doubtless been generally very successful in making an impression concerning the advantages of adequate illumination.

Miscellaneous Items. It has been stated that the foot-candle meter is now being used much more than formerly for the measurement of illumination by the layman through inexpensive means. Several thousands of these instruments have been sold during the past year or so, and the demand for them by the industries, factory inspectors and others, continues to the extent of several hundred per month. An interesting modification of the earlier instrument has been an increase in its range from an upper limit of 25 foot-candles to one of 40 foot-candles so as to make possible the measurement of higher intensities than formerly.

Highway lighting has received considerable attention and a double reflector unit has been developed so as to reduce the waste of light on either side of the roadway. Among the important installations of street lighting which have been completed and put into operation during the past year or so have been those at Los Angeles, Cal., and Saratoga, N. Y.

It is significant and of special interest to central station operators to know that during 1920 nearly 80 per cent of all incandescent electric lamps sold were used on circuits of 110, 115 or 120 volts, whereas in 1913, by contrast, less than 50 per cent of the incandescent lamps sold were used on circuits of these voltages.

C. E. CLEWELL, *Chairman.*

ANNUAL REPORT OF MARINE COMMITTEE

To the Board of Directors:

In presenting the Annual Report of the Marine Committee only the outstanding features of the Committee's work will be dealt with, the vast amount of detail work involved should not be lost sight of however as it was only through the untiring efforts of the various sub-committees that such splendid progress was made.

On referring to the report of the Marine Committee for the season of 1919-1920, the following items are noted; these items represent subjects to be carried over to the following year or new departures recommended for consideration:

1. Rules for the Recommended Practise for Installations on Ship Board.
2. Work of Historical Committee.
3. Fixtures, Fittings, etc. to meet requirements of new rules.
4. Terminal Facilities at Marine Piers.

Eight meetings of the Committee were held. The first meeting convened on September 30th and October 1st, 1920 at Schenectady, New York and was very well attended. The following subcommittees were appointed:

a. American Standards.
b. Applicances.
c. Editing.
d. Propulsion.
e. Auxiliaries.

The Historical Committee was carried over from the previous year.

The year's work of the above subcommittees may be summarized as follows:

The duty of the American Standards subcommittee consists of the taking up with the American Engineering Standards Committee, the question of having the Recommended Practise for Electrical Installations on Ship Board passed by that Committee as a standard for American Practise. This could not be accomplished however, until these rules and recommendations were placed in printed form and circulated.

The duties of the Appliance subcommittee were to formulate a set of Standards covering electrical appliances which would later be incorporated in the Recommended Practise for Electrical Installation on Ship Board. The following is a partial list of appliances intended to be covered by this work:

Conduits and Fittings.
Junction Boxes.
Deck and Bulkhead Stuffing Tubes.
Receptacles, Watertight and Non-Watertight.
Electric Heating Appliances.
Running Tell Tale Panel.
Gaskets and other Watertight Packing Materials.
Pull Boxes.
Fuses.
Plugs, Watertight and Non-Watertight.
Switches, Watertight and Non-Watertight.
Fans.
Telephones.
Bells, Buzzers and other Electrical Signaling Devices.

The Editing subcommittee this year completed the final editing of the Recommended Practise for Electrical Installations on Ship Board and has been retained to handle all comments and proposed changes in regard to these rules which, from time to time, may arise. These changes to be submitted to the main Committee periodically for its action, and if adopted to be made a permanent part of these rules.

The following is given as a resume of the year's work of the Propulsion subcommittee:

It was first decided that Electric Ship Propulsion had not as yet reached a stage of development and continued use that would justify an attempt to draw up a set of Marine Rules or Recommendations for Propulsion Machinery to the same extent as had already been done for other electrical work. With this in view, the work of the Propulsion subcommittee resolved itself into the following:

a. Preparation of papers for an engineering meeting in New York.

b. The drawing up of a set of Rules or Recommendations for the proper preservation and protection of electric propelling apparatus during the time of installation and after being placed in service.

c. The preparation of a history of electric ship propulsion for use of the Historical subcommittee.

In connection with the preparation of papers for an engineering meeting in New York as mentioned above, the following statement may be made:

A joint meeting of the Metropolitan Section of the American Society of Mechanical Engineering and the Marine Committee of the American Institute of Electrical Engineers was held at the Engineering Societies Building, New York, on January 28, 1921. The following papers by members of the Propulsion subcommittee were presented:

Turbine Reduction Gears vs. *Electric Propulsion for Ships,* by Eskil Berg, of the General Electric Company.

Electric Propulsion of Ships, by W. Thau, of the Westinghouse Electric & Manufacturing Company.

Electrical Terminal Facilities, by C. S. McDowell.

The meeting was very largely attended and the papers read contained much useful information.

Recommendations were made by the Propulsion subcommittee for the preservation and protection of propelling machinery during the time of installation and after the apparatus had been placed in service. These recommendations have been completed and preliminarily passed by the Committee but will be carried over until next year before final reading and publication. The historical side of the work of the Propulsion subcommittee received quite considerable attention by that Committee. An extensive list of references of articles which have appeared in publications from the earliest days of electrical installation until about the year of 1911 have been prepared and turned over to the Historical subcommittee.

It was the intention that the work of the subcommittee on Auxiliaries should go along with that of the subcommittee on Electric Propelling Machinery for Engine Room Auxiliaries only. The Deck Machinery and Terminal Handling Apparatus was to be handled exclusively by this Committee. It is contemplated making the Recommendations of this subcommittee, with regard to the above subjects, part of the Recommended Practise for Electric Installations on Ship Board.

A considerable amount of effort has been expended by the Historical subcommittee upon its work during the past year, but owing to the extent of the task and the vast amount of time required for other activities of the Committee, it was found impracticable to compile its data complete and in detail for publication at this time. It was the original intention of this subcommittee to complete its work up until the year of 1910 but it was later decided to bring the work as far up to date as possible and then have it supplemented from time to time as developments in the field justified. It will no doubt be possible to turn into the Institute, sometime during the coming year, the work which has already been done by this subcommittee.

From the above it will be noted that the Committee has taken upon itself a great volume of work which cannot be accomplished in one year and probably will extend over a period of several years but considerable work has already been done by this year's Committee as follows:

The final revision and passing of the Recommended Practise for Electrical Installation on Ship Board has been completed and published by the Institute. The writing of papers and reading of the same at the joint meeting of the Metropolitan Section of the American Society of Mechanical Engineer and the Marine Committee of the American Institute of Electrical Engineers in New York. The drawing up of recommended practise for the protection and preservation of propelling machinery, also the vast amount of data on the historical side of electric ship propulsion and electrical installations on ship board. A joint meeting has been arranged with the Naval Architects and the Marine Engineers in New York in November at which time two papers will be presented, one on electric propulsion and the other on electric ship auxiliaries.

In concluding this report, I feel that I would be evading my duty as Chairman of the Committee if I did not congratulate every member of the Marine Committee for his interest, attendance at meetings and general attitude with regard to all subjects that have come up for discussion at the various meetings throughout the year. The Committee as a whole has worked conscientiously and consistently and I believe deserves great credit for the amount of work that it has accomplished.

It is this thought in particular that I would leave with the Marine Committee for the ensuing year, that good work can only be accomplished through good will, consistent application and real cooperation.

ARTHUR PARKER, *Chairman.*

ANNUAL REPORT OF ELECTROPHYSICS COMMITTEE

To the Board of Directors:

ADVANCES IN ELECTROPHYSICS 1920-1921

Progress in physics is, as a rule, gradual and it is generally difficult to look back over a space of one year and definitely state what will prove to be the most important advances of that period.

The members of this Committee were canvassed regarding the advances during 1920 and 1921, and it was the general opinion that the most striking and what will prove to be the most far reaching work is that of Rutherford on the atomic nucleus. Rutherford has bombarded the atoms of some of the lighter elements with alpha particles and has apparently succeeded in disintegrating them. Nitrogen was one of the elements thus disintegrated. Hydrogen was apparently found in some of the disintegrated atoms.

Work and speculation on the arrangement of the electrons in atoms and molecules seems to be leading to something, and it is hoped that the results will be of great importance.

Among other important work, that on isotopes might be mentioned. The above list is by no means complete but it touches on some of the work that at present stands out.

LECTURES AND PAPERS

It is regretted by this Committee that the electrophysics lecture was not given a place in the Midwinter Convention this year. This lecture in the past has been better attended than any other meeting. The following list of activities of the Institute in different parts of the country during the year is given as indication that electrophysics subjects are appreciated by our membership:

Philadelphia, October, 1920, *The Epoch Making Discoveries of the Years* 1819-1820, by Elihu Thompson. *Oersted's and Ampere's Discoveries,* by M. I. Pupin.

Pacific Coast Convention, July, 1920, *Centennary of the Discoveries of Oersted, Arago and Ampere,* by C. E. Magnusson.

New York, February, 1921, *Wave Transmission*, by M. I. Pupin.

The Electrophysics Committee during the past year has encouraged electrophysics lectures in the Sections. In this connection we were fortunate in assisting the Pittsfield and Schenectady Sections in securing Dr. R. A. Millikin to lecture on the *Twentieth Century's Contribution to our Knowledge of the Atom.* These lectures were very well attended and the discussions indicated a keen interest in the subject by the members.

The following technical electrophysics papers are to be presented at the Annual Convocation:

Electric Strength of Air under Continuous Potentials and as Influenced by Temperature by J. B. Whitehead and F. W. Lee.

Voltage and Current Harmonics Caused by Corona, by F. W. Peek, Jr.

F. W. PEEK, JR., *Chairman.*

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, June 21, 1921.

HYDROELECTRIC DEVELOPMENT AT NIAGARA FALLS

BY JOHN L. HARPER AND J. A. JOHNSON
Both of The Niagara Falls Power Company

THE PURPOSE of this paper is to trace briefly the progress in the art of power development at Niagara Falls from its beginning to the present time, to describe more particularly the recent developments and those about to be undertaken under the recent license granted to The Niagara Falls Power Company by the Federal Power Commission, and to indicate the present and probable future functioning of Niagara power in the industrial development of the country.

The physical conditions existing at Niagara Falls are not duplicated elsewhere in the world. The immense drainage basin of the Great Lakes contributes an almost uniform outflow of water of such magnitude that the question of adequate supply is not one which need be considered for many years to come. This continuous flow of over 200,000 cu. ft. per second, finds its outlet through the Niagara River which falls through a total height of 336 ft. between the Lakes Erie and Ontario. Of this 336 ft., 165 ft. is concentrated in the cataract itself and another 55 ft. is in the rapids immediately above, so that within a distance of one mile there is available a total head of 220 ft.; or, combining the 94 ft. of drop in the lower Rapids with that above, there exists a head of 314 ft. which may be developed within about five miles, distances being measured on the American side of the river. This flow of water and the natural head available provide a source of power of over 6,000,000 h. p. which, under ordinary conditions, one might expect would be used to the full for industrial purposes.

One factor alone has prevented the perfect working of economic law in this respect, and that factor is the value of the cataract and rapids from the scenic standpoint. That this value is a real one, no thoughtful person will deny. "Man cannot live by bread alone," and who can doubt that God who, in His infinite wisdom, gave us Niagara, intended it to minister to the spirit as well as to the body of mankind.

This division of Niagara's ministration between the material and the spiritual, has always existed since Niagara became known to civilized man, but it is just beginning to be recognized that the division must ultimately be made at that point where the sum total of human benefit shall be a maximum. And when that point is finally determined, the portion of the energy which is found not necessary to maintain the spiritual values will undoubtedly be made available for industrial purposes.

As early as 1725, nearly 200 years ago, a primitive sawmill made first use of Niagara power, and 100 years ago small waterwheels were used in mills located along the upper rapids on the shore and small islands of the American channel; but these early developments have long since disappeared and very little evidence remains to show that they once existed. A short piece of the original headrace is now converted into a scenic pool just upstream from the Goat Island bridge. The size and nature of these mills is indicated by the accompanying illustration (Fig. 1).

The beginning of the existing power developments may be placed as far back as 1852, when the construction of a hydraulic canal was begun, extending from a point at the head of the rapids above the falls, now known as Port Day, to the edge of the gorge a mile below. In spite of the fact that the land for the right of way had been donated by the Porter family who then owned most of the land bordering the Falls, lack of funds caused a suspension of the work in less than two years. However, it was resumed in 1859, and by 1861 there was completed a canal from 20 feet to 36 feet wide and about 8 feet deep, extending from Port Day to the present canal basin at the edge of the gorge in the same location as the present Hydraulic Canal of The Niagara Falls Power Company.

Owing to the industrial depression caused by the Civil War no use was made of this early canal for years although a small stream poured over the cliff unused.

In 1872, however, an installation of 150 h. p. under 25-ft. head was made for driving a grist mill. In 1877 the canal property was purchased by Jacob F. Schoellkopf and others who organized, in 1878, the Niagara Falls Hydraulic Power and Manufacturing Company. Soon afterwards the Schoellkopf-Mathews flour mill was constructed and equipped with 900 h. p. under 50-ft. head. Four years later the head on the mill was increased to 86 ft. which at that time was the highest head used at Niagara. Quite recently some sections of the iron flumes, 9 ft. in diameter, which were the first iron penstocks used at Niagara Falls, have been removed to make room for the works in the latest development.

FIG. 1—VIEW FROM GOAT ISLAND

Looking toward the American shore before the establishment of the Niagara Reservation, July 15, 1885, showing paper mill on Bath, now Green Island

From this time on the Hydraulic Canal was used for supplying water power for manufacturing in important mills. The general method of development was to sink shafts or pits under the mills at the edge of the cliff, taking the water from the canal through flumes and penstocks to turbines at the bottom of the pits and allowing it to discharge from short tailrace tunnels part way down the face of the cliff. The waterwheels were directly connected to vertical shafts which drove the machinery in the mill above.

In the year 1880 the first hydroelectric unit was installed at Niagara Falls, in Prospect Park. This unit, comprising a waterwheel and a d-c. brush dynamo, was used for illuminating fountains in the park by means of two arc lights. Excursions were run from various parts of the country to see the new wonder. This unit has little more than historical interest and diligent search has failed to reveal any photograph of the installation or any technical data concerning it.

Fig. 2—Earliest and Latest Commercial Generators to Operate by Niagara Power

The second hydroelectric development and first commercial installation was made in the year 1885 in the Pettebone Mill on Bath Island. The generator of this unit, which was used for lighting the mill, is shown in the insert in Fig. 2. It was a d-c. machine, having a capacity of 16 amperes at 110 volts. It is interesting to note that the capacity of the latest generator operating at Niagara Falls is about 15,000 times as great as this one. The contrast is shown in the illustration.

As soon as these early installations had demonstrated the possibilities of electrical power, the real hydroelectric development began, and in the year 1891 The Niagara Falls Hydraulic Power and Manufacturing Company began the construction of its Station No. 1, in which dynamos were installed, operated by rope drives from waterwheels and having a total output of 2000 h. p. which was used for supplying electrical power for commercial purposes. This station was abandoned in the year 1904.

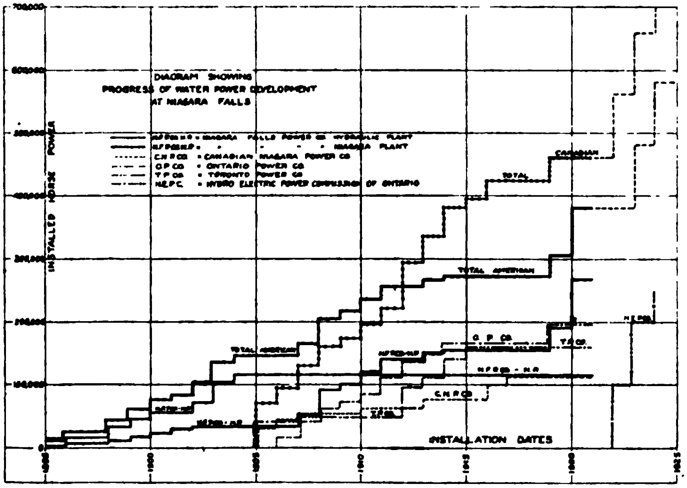

FIG. 3

In 1886, or about the time the second hydroelectric development referred to above was begun, The Niagara Falls Power Company was organized with the intention of developing hydraulic power only, the power to be delivered from the waterwheels direct to the shafting in the mills to be located along a head-race about a mile above the falls, and the tailwater to be collected in a low level tunnel draining into the lower gorge. Negotiations for the construction of the works were not completed until 1889, at which time it became clear that concurrently with the development of hydraulic power, the company could proceed with the development of electrical power and transmission. So successful was the early use of electrical power that a decision was reached in the year 1890 to install three hydroelectric units of large size, each having a capacity of 5000 h. p. A step-up transformer station and 11,000-volt transmission line to Tonawanda and Buffalo were also undertaken. Power from this station was delivered at Niagara Falls in the year 1895, and at Buffalo in 1896.

By this time the hydroelectric power development was fairly under way, and Fig. 3 shows the progress from then on up to the present time. Fig. 4 shows a comparison between the rate of progress in hydroelectric development at Niagara Falls and that in the United States as a whole. From this comparison it will be noted that progress at Niagara has not at all times kept pace with that of the country in general.

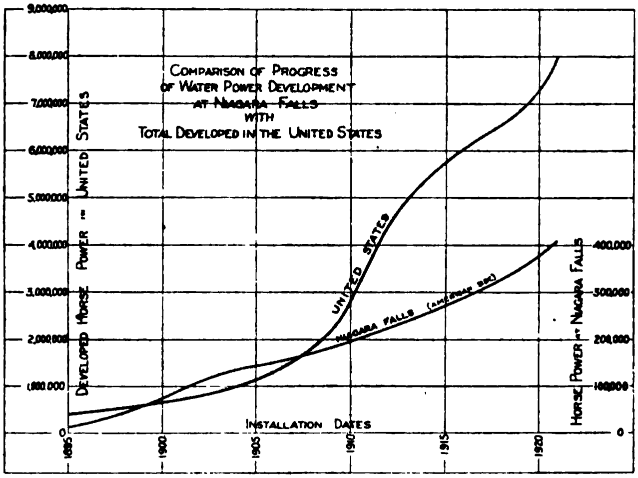

FIG. 4

The period from 1895 to 1905 might be called the "Decade of Progress" in power development at Niagara Falls, when the various companies at work on the American and Canadian sides devoted themselves to overcoming many natural difficulties and to the building of what were then the largest plants in the world.

About 1905 the Niagara Falls Power Company had completed its American plant, marked *B* on Fig. 5. The Hydraulic Power and Manufacturing Company had abandoned its Station No. 1 and completed its Station No. 2, marked *A* and *C* respectively; and in addition other plants were well under way, namely Station No. 3 of the Hydraulic Power Company, marked *D*, and the three plants shown on the Canadian side marked *E*, *F* and *G* belonging respectively to the Canadian Niagara Power Company, the Ontario Power Company and the Toronto Power Company.

These plants have been described so often that no doubt they are quite familiar to all engineers and it will be unnecessary to refer to them in detail. It will be noted, however, that three different types of waterways were employed, *A*, *C* and *D* utilizing a surface canal, *B*, *E* and *G* wheel pits and tailrace tunnels, and *F* pressure pipe lines and open tailraces. The type of waterway determined to some extent the type of machinery; plants *A*, *C*, *D* and *F* being able to use horizontal shaft units with journal type bearings, and plants *B*, *E* and *G* being forced to adopt long vertical shafts with the then less desirable thrust bearings for supporting the weight of the revolving machinery.

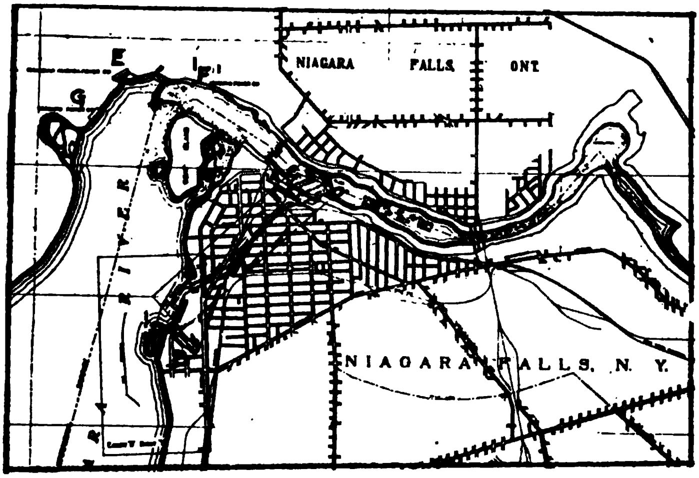

FIG. 5

In the year 1906 the Governments of the United

States and Canada became alarmed at the rapid improvements in the art of power plant building by which the Falls of Niagara were being made to serve the needs of man and the consequent diversion of water from the cataract, and after due deliberation the Burton Bill and the International Waterways Treaty made it unlawful to divert more than a specified quantity of water for power purposes, namely 20,000 cu. ft. per sec. on the American side and 36,000 cu. ft. per sec. on the Canadian side. In this negative way it was hoped to save the great spectacle from destruction.

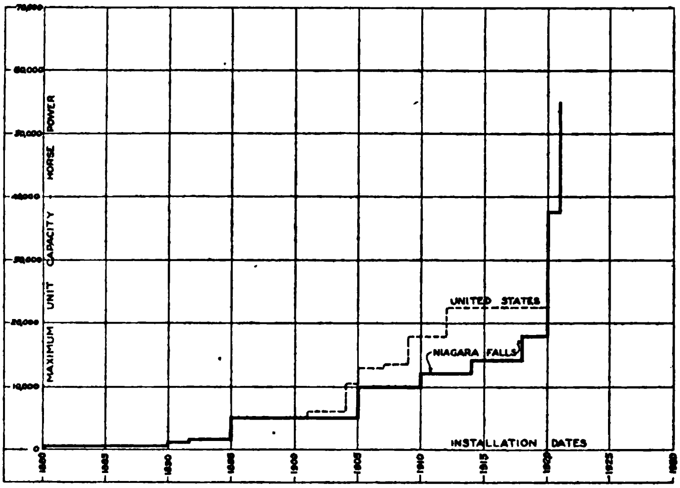

FIG. 6

These laws cast a blight upon the development of the art at Niagara Falls and the period from 1906 to 1916 might properly be called the "Decade of Stagnation." It is quite true that additional units were installed in the existing plants during this interval, but with no future to look forward to there was little incentive to improvement, and little attempt was made to keep pace with the advances being made in other parts of the world. The plants were completed for the most part in very much the same manner as they were begun in 1905.

As an indication of the foregoing, Fig. 6 shows how the development at Niagara Falls lagged behind the progress being made in other parts of the United States in regard to the size of units being constructed, until finally in 1918 Niagara Falls was restored in this respect to its rightful position of first place.

During this time public opinion in regard to Niagara Falls found expression along two diverging lines of thought, one claiming that diversion for power purposes would ruin the scenic grandeur of the falls and therefore should be stopped entirely, the other representing those interested in the work at the falls, who insistently pointed out the folly of attempting to save the falls from destruction by allowing them to destroy themselves. As year after year went by it was apparent that 6 to 8 ft. of yearly erosion at the apex of the Horseshoe, amounting to at least 60 ft. in ten years, was doing more to draw the water from the sides of the Horseshoe and destroy its beauty than all the power plants put together. Once this fact was realized the remedy became self-evident. It is now recognized that by far the greater part of the water in the river not only contributes nothing toward the

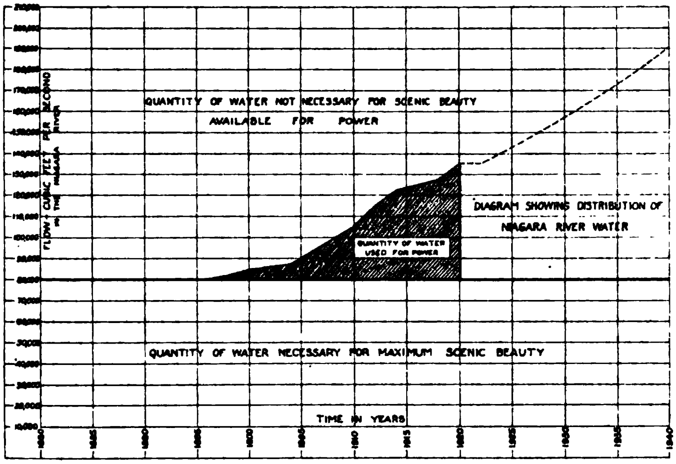

Fig. 7

scenic grandeur but rather tends to detract from it by sending up clouds of spray to obscure the otherwise beautiful sight; and not only that, but is actually destroying the scene by erosion. Instead of arbitrarily restricting the amount of water which may be diverted for power purposes, the sensible thing to do is to adopt some measures that will spread evenly over the crests of the falls so much of the water as is required for scenic beauty and to divert all the rest for power purposes, thereby conserving for all time and to the greatest extent both the spiritual and the commercial values. This division of the flow for scenic and power purposes as recommended by Government engineers is shown in Fig. 7.

During the war emergency and at the suggestion of the representatives of the War Department, the Niagara Falls Power Company, Hydraulic Power Company of Niagara Falls and the Cliff Electrical Distributing Company were merged under the name of The Niagara Falls Power Company, but under the control and management of the owners of Hydraulic Power Comapny, the merged interests owning all the developments on the American side and controlling the Canadian Niagara Power Company on the Canadian side. These plants had a total installed capacity of 350,000 h. p.

Under this unity of control and direction, a plan was quickly evolved not only for immediately placing all developed power at the disposal of the Government agents for distribution to specified customers who were making the materials vital for war work, but also for the rush development of another 100,000 h. p. without sacrifice of permanency of work or efficiency of conversion. These construction plans were being rushed to completion when the signing of the armistice made speed less important; however, the whole 100,000 h. p. was put in operation within 22 months from the time the work was authorized.

Shortly afterward, however, the Government of the United States established the new Federal Power Commission, one of whose first acts was to give approval to the plans being carried out by The Niagara

Falls Power Company and to issue a license to the company for all the water permitted to be diverted from the American side of the falls in accordance with the terms of the existing treaty. At the same time it recommended an increase in the allowable diversion and the construction of remedial works to preserve the beauty and grandeur of both the American and Horseshoe Falls.

This license gave formal federal approval to the plans of development already begun, and authorized their completion. These plans include the placing in reserve of the present Niagara plant marked *B* on Fig. 5, the construction of a new waterway from Port Day to carry the water now being used in the Niagara Plant to the Canal Basin, the maintenance of Station No. 3, marked *D* on Fig. 5 with its 13 efficient 10,000 h. p. units operating under a mean gross head of 217 ft. (see Fig. 8), the extension of this station to the southward and the construction of new units to utilize the 4400 cu. ft. per sec. of water that had not been specifically allotted under the treaty and the water now being used by the Niagara plant. Plans were made so that subsequently the water used by these plants may be re-collected at the most favorable

Fig. 8—Interior of Station No. 3 Generator Room

point and carried by tunnel past the lower rapids to a power house in the lower river where the remaining head may be developed.

The first step of this general plan has already been carried out, namely the construction of what is known as Station No. 3 Extension, marked *H* on Fig. 5, begun in 1918 as a war measure and finished in 1920. This extension contains three units, the combined rating of which is 100,000 h. p., and, together with the other plants of the company, uses all the water allowed by the treaty. The second step has just been authorized, namely the construction of a new tunnel and the installation of the remaining units in an addition to Station No. 3 Extension, marked *K* on Fig. 5.

The third step also has been initiated by the granting of a preliminary permit to The Lower Niagara River Power and Water Supply Company, which allows two years for the presentation of plans for the second or lower river stage of the development. The details of this plan have not yet been worked out and the date of its contruction has not been finally decided upon.

Much has been said about the desirability of using the diverted water under the full head of 314 ft. from the upper river to Lewiston, and when the field is entirely without complication, as in the case of the development of water in excess of the present treaty allowance, a one-stage development will undoubtedly be advisable. The reason for the apparent rejection of this plan for the present diversion may be of interest. As a matter of fact, the scheme of development now being carried out does contemplate the use of the full 314-ft. head, but instead of utilizing this head in one plant with a long new waterway involving the abandonment of the efficient plants already built, it will be utilized in two successive stages, the first stage utilizing a gross head of 220 ft. and the second stage a gross head of 94 ft.

Broadly speaking, the commercial power capacity of the two-stage development is practically the same as that of the single stage, such slight theoretical differences as exist being in a practical sense unimportant. The problem then has been to decide whether the interests of the power consumers, and indirectly of the public, would be best served by an eventual total abandonment of all the plants that had already been built and the construction of a new plant to utilize in a single drop under the full 314 ft. head, the total quantity of water permitted to be diverted under the treaty, or, by conserving as much of the old work as could be conserved without impairing the general efficiency of the use of water and the construction of new works to supplement the old.

It is an axiom that whether a power development is constructed with private or with public funds, the consumer pays the cost. A breach of economic laws, therefore, must be immediately reflected in increased rates. A careful study was accordingly made to determine the most economic development, particular attention being paid to the vital factor of interest on the investment during construction and on the unutilized portion of the new works during the period of business development, items which run into millions of dollars owing to the long time required to build and secure a market for these large developments. The general conclusions of this study are expressed in the plans above outlined.

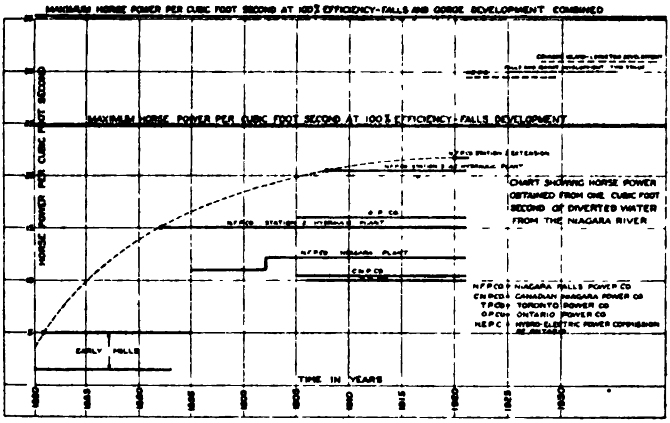

FIG. 9

The gradual advance in the efficiency of the Niagara power developments is shown in Fig. 9. This chart is very interesting. The left-hand end of the horizontal lines shown for each of the developments, indicates the earliest date at which the corresponding efficiency was obtained. The growth of efficiency, particularly as to those plants employing the headrace canal type of development, seems to have worked itself out according to a quite definite law which indicates the inevitableness of the law efficiency of the earlier plants. This law, as expressed by the dotted curve in Fig. 9, provided that it holds for the future as for the past, also indicates the great unlikelihood of any considerable further gain in efficiency, and the probability of a very low rate of obsolescence for Station 3 and Station 3 Extension.

It will have been observed that the rate of obsolescence of the earlier Niagara power developments was fairly high, decreasing however, for the later developments, as the art progressed. The question then as to what rate of obsolescence may be expected for this latest development is a natural one. Obsolescence is undoubtedly a function of efficiency, defining that expression in terms of power and cost, and involves two factors, namely, general operating efficiency, which is promoted by the use of compact stations with large reliable units of similar characteristics; and efficiency in the use of water, which involves first, the development of the maximum available head and second, careful design to get the maximum possible power out of the available water at the head developed.

These curves show very clearly how the development of the art quickly ran through the early stages when only very small units were built, of diverse characteristics, and when only a small part of the available head was utilized, and how such plants rapidly became obsolete on account of the great gain to be obtained by building larger and better designed units under higher heads.

Analyzing this latest development in the light of these considerations we find, first, as to the efficient use of the site, that the entire available 220 ft. has been developed with less than 2½ per cent loss in getting

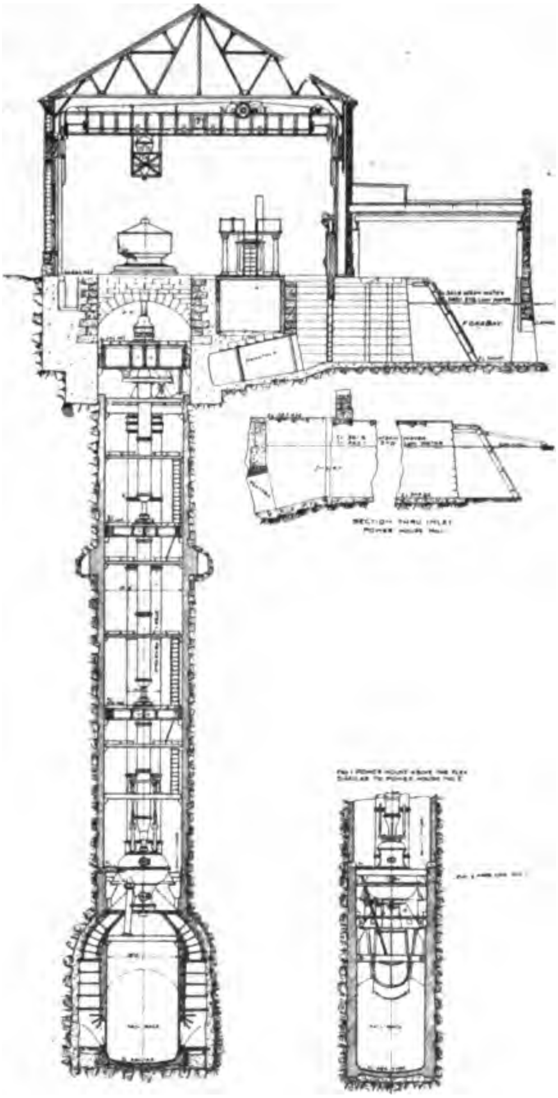

FIG. 10—CROSS-SECTIONS—STATIONS NOS. 1 AND 2
NIAGARA PLANT

the water to the penstocks; second, that of the power available at the penstock entrances, over 91 per cent is delivered in the form of electrical power at the generator terminals; and finally, that although the size of future units may be increased, such increase of size being permissible when the system of which they are a part increases, there is relatively little more to be gained either in lessening cost or cheapened operation, the present 100,000-h. p. three-unit extension requiring but three men per shift to operate it.

These results are so far in advance of previous installations and leave so little room for improvement that is appears justifiable to say that obsolescence of

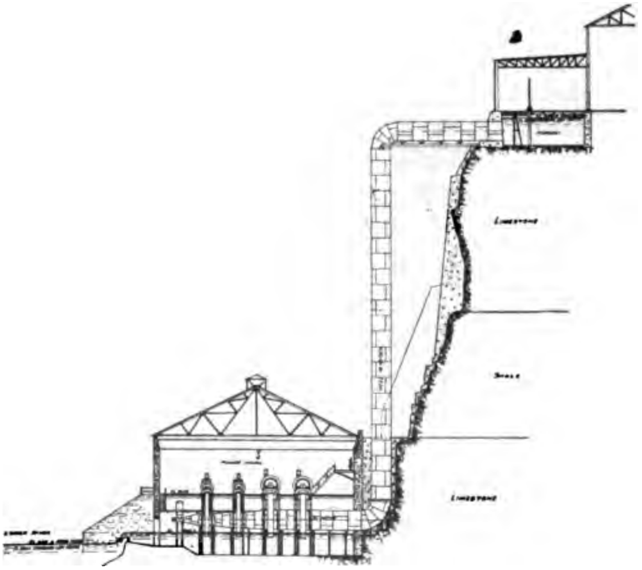

Fig. 11—Cross-Section—Station No. 2
Hydraulic Plant

this plant could be brought about only by some scientific advance in the art of power production of a totally unexpected and revolutionary character.

The recent investigation and report on Niagara conditions by Col. J. G. Warren and its analysis by other federal engineers has supplied a long felt want of authentic data, and has answered with peculiarly disinterested wisdom many of the hitherto perplexing questions in regard to comparison of plans for developments, and also as to the amounts of water necessary for maximum scenic grandeur and the amount that can be released for power purposes. This compilation of data and the well thought out conclusions therefrom, made it possible for the Federal Power Commission to come to a quick determination of the proper form of development to be adopted, which was expressed in its first license which was issued to The Niagara Falls Power Company on March 2, 1921.

The nature of the developments made on the American side at Niagara, prior to 1918, are shown by Figs. 10, 11 and 12. Fig. 10 is a typical cross-section of the Niagara Plant (formerly The Niagara Falls Power Company) shown at *B* in Fig. 5. Fig. 11 is a cross-section of Hydraulic Plant, Station No. 2. Fig. 12 is a section of Hydraulic Plant, Station No. 3.

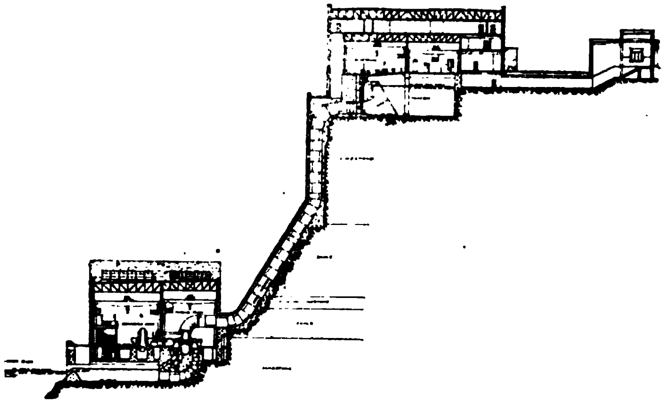

FIG. 12—CROSS-SECTION—STATION NO. 3 HYDRAULIC PLANT

LATEST COMPLETED DEVELOPMENT

The latest development known as "Hydraulic Plant, Station No. 3 Extension," which is the first section of the work authorized by the license from the Federal Power Commission, is shown in similar section in Fig. 13. The three plants shown in Figs. 11 to 13 are all located in the gorge on the bank of the lower river about half a mile below the falls as shown at *C, D* and *H* in Fig. 5. A plan view of Station No. 3 Extension, showing its relation to Station No. 3, is shown in Fig. 14.

This development was designed to utilize the 4400 cu. ft. per sec. of water which was still available under the treaty. It consists of an extension to Station No. 3 containing three units of 37,500 h. p., maximum rating. To distribute this power it was necessary to construct a distributing station three miles away to which the power is transmitted from the generating plant by overhead lines.

In order to get the water out of the river and delivered to these units, it was necessary to make more adequate provision for ice protection at the intake at Port Day, which work is shown in plan in Fig. 15. These improvements comprise a channel dredged in the river bottom extending out into the river a distance of approximately 3000 ft. and a new ice deflecting boom crossing this channel near its outer end. By this means an adequate water passage is always assured even though the surface for many feet deep may be congested with ice floes. Since the completion of this work no trouble with ice has been experienced.

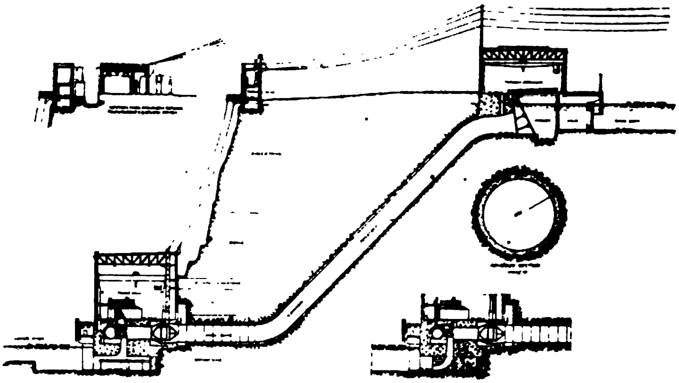

FIG. 13—CROSS-SECTION—STATION NO. 3 EXTENSION, HYDRAULIC PLANT

It was also necessary to deepen the Hydraulic Canal throughout its whole length to a depth of 20 ft., an increase of from 6 to 10 ft. over its former depth. This work was carried out under great difficulties due to the rapid currents through the canal supplying the already existing plants.

Connected to the Canal and its terminal basin there was constructed a new forebay 176 ft. long, 74 ft. wide by 28 ft. deep. The entrances from this forebay to the three penstocks are bell mouths (Fig. 16), 28 ft. wide by 20 ft. high, and gradually taper down to true circles 15.5 ft. in diameter. The penstocks are 350 ft. long, cut in solid rock, and are lined with concretel throughout their entire length. The horizontal section, in addition to having a concrete lining is also lined with boiler plate. The general arrangement is clearly indicated in the sectional view, Fig. 13.

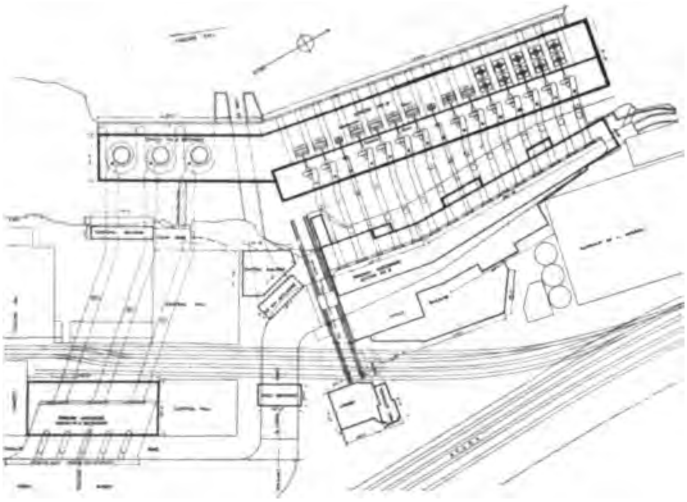

FIG. 14—PLAN—STATION NO. 3 AND STATION NO. 3 EXTENSION HYDRAULIC PLANT

A plate-steel gate is provided for the intake to the penstock. This gate is only used when it is desired to unwater the penstock.

Each of the three turbine casings is connected to its penstock through a valve, (Fig. 17) hydraulically operated and electrically controlled.

The valves are of the balanced needle type, having a movable plunger sliding in an internal cylinder. Operation of the plunger is accomplished entirely by the hydraulic pressure in the penstock, no external force or pressure being required. The valve may be manually controlled locally, or electrically controlled from a switch station on a pedestal near the generating units. The rate of the valve stroke may be regulated to suit the conditions and may be set for any time up to a minimum of 30 seconds for a complete stroke in either direction. The valve is so designed that it will close automatically in case of a serious break in the wheel casing.

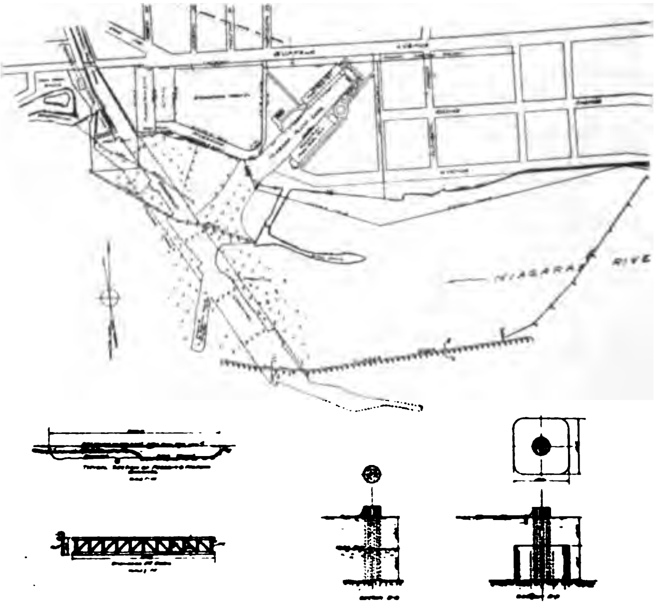

FIG. 15—ICE PROTECTIVE WORKS AT CANAL INTAKE

No provision was necessary to take care of the surges in the penstock, for being hewn through solid rock the penstock itself provides sufficient strength to withstand any force that may be set up, due to suddenly shutting down a machine.

In the design and building of the units four manufacturing companies are represented. Each turbine is of the vertical shaft, single runner, Francis type, operating under a head of 215 ft. at a speed of 150 rev. per min. and is rated at 37,500 h. p., although each has already carried more than 40,000-h. p. load. The three units were designed to develop an average working load of 100,000 h. p. Taking all frictional and other losses, from forebay to switchboard, into consideration, these units are securing over 91 per cent of the potential energy in the water used.

Fig. 16—Bell Mouth at Penstock Entrance

Fig. 17—Upstream End of Johnson Valve Inside of Penstock

Each complete unit—generator, turbine and casing—weighs approximately 1000 tons and is set on a reinforced concrete slab, 11 ft. thick, 53 ft. wide and 55 ft. long, resting on reinforced concrete piers, (Fig. 18); 46 tons of reinforcing steel was used in each slab.

Fig. 18—Tailrace Discharge Openings through Power House Foundations Showing Concrete Supporting Piers

Fig. 19—One of the Cast Iron Turbine Cases

The casings of two of the turbines are of cast iron made in six sections and are embedded in the concrete substructure of the power house. As can be seen from Fig. 19 this casing is bolted together by flanges on the outside, consequently the inside is smooth, and is designed for a gradual acceleration of the water as it passes around the volute. The intake is 10 ft. 6 in. in diameter, and the total weight of the casing is about 263,000 lb. The runner is of cast iron, in one piece, having a maximum diameter of 10 ft. 6 in. and a total weight of 27,000 lb. The shaft is 25 inches in diameter and is provided with a lignum-vitae guide bearing. The draft tube is of the Moody spreading type which regains the whirl component as well as the axial component of the velocity of the water leaving the runner. This results in higher efficiency than the old type of curved draft tube, which does not regain the whirl. The spreading tube also eliminates surging and water hammer, which so often occur with curved draft tubes. These draft tubes are shown in section in Fig. 13. A renewable ring is provided in the draft tube just below the runner, and the upper section of the draft tube is furnished with manholes for the inspection of tube and runner discharge. The total weight of each turbine is about 765,000 lb.

Fig. 20—Inside of Plate Steel Turbine Case

The governors are located on the switchboard gallery with the gate-opening indicator and control stand. The regulating valve stand is on the main generator floor and is provided with plunger valves of the Johnson type. By this means the operation of changing the unit from hand to governor control is easily effected, all valves operating simultaneously.

The other turbine casing (Fig. 20) is made up of a number of conical steel plate sections riveted together, the casing being riveted to a cast-steel speed ring. The runner is of cast iron bolted to a cast-iron hub keyed to the tapered end of the shaft. A lignum-vitae guide bearing is mounted directly above the turbine. The turbine discharges into a single draft tube of the White hydraucone regainer type. Reference to Fig. 13 will make the construction clear. By the use of the hydraucone or spreading draft tube about 80 per cent of the velocity head in the discharge is recovered, whereas with the old type of curved draft tube a large proportion of this velocity head is always lost. Tests show that over 91 per cent of the total energy in the water is delivered at the generator terminals and the turbines themselves have an efficiency of 93 per cent.

The fluid used in the governors is about 99 per cent water and 1 per cent oil, supplied from a central pressure system. Pressure of 115 lb. for operating the governors is maintained by static tanks at the top of the cliff. Should for any reason the fluid supply to the governors fail, they may be operated with water taken from the penstocks.

Each of the three generators is designed for a capacity of 32,500 kv-a. and generates 12,000-volt, three-phase, 25-cycle current when operating at 150 rev. per min. Although designed and built by different companies, each machine has about the same external appearance, and to this end the manufacturers cooperated so that the installation presents a uniform appearance. (Fig. 21).

As to the internal construction of the generators the engineers of the manufacturing campanies were left at liberty to follow their own ideas regarding details, the main restriction being that the electrical characteristics of the three machines must be such that they would operate satisfactorily in parallel. A box frame of usual design, 21 ft. 6 in. outside diameter, cast in sections, is used for the stator. Both ends of each phase winding are brought out so that a balance system of relay protection can be used. The windings are connected in star and the neutral grounded through a resistance of approximately 5 ohms, obtained by using a water rheostat.

The shafts are 27 inches in diameter below the rotor and are fitted with a 45-in. forged-on steel flange, for bolting to a corresponding flange of the turbine shaft. On the upper end of the shaft is the Kinsbury thrust bearing, carried on a bridge having eight radial arms. Each bearing is 49 inches outside diameter, and carries a load of approximately 470,000 lb., 100,000 lb. of which is due to the water thrust on the turbine runner. Directly under the thrust bearing is the upper guide bearing, which is 26 inches in diameter and 36 inches in length. The thrust bearing runs in a bath of oil supplied from a central system. No water cooling coils are provided in the thrust-bearings housing, the oil being cooled and filtered in the central system.

FIG. 21—INTERIOR OF STATION NO. 3 EXTENSION AFTER PLACING OF VENTILATING HOUSINGS AROUND GENERATORS

To bring the rotating element to rest after the turbine gates have been closed, and also to prevent the rotor from turning in case of leaks through the gates, brakes are installed on the generators. These brakes are operated by compressed air, from a valve mounted on the hand-control stand located near the governor.

Ventilating air for the generators is taken into the machine from the generator room and also from the pit under the machine. The amount of air required by the different machines to carry off the heat varies from 70,000 to 90,000 cu. ft. per min. Each generator is surrounded with a steel plate housing, as indicated in Fig. 21, which connects to a duct system through a fan. In the summer months the ventilating air can be discharged outside the station. In the winter months part of it will discharge into the station and control room for heating, and the remainder will go to the ice run. The average efficiency of the three generators at normal load and 90 per cent power factor is 98 per cent.

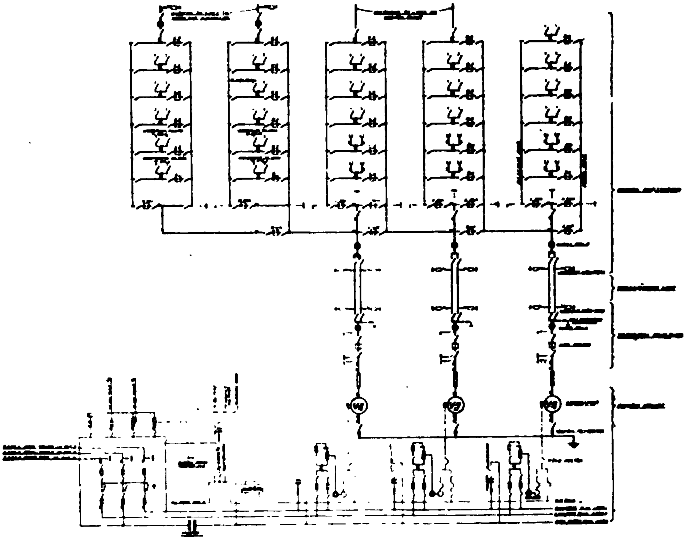

FIG. 22—ONE-LINE DIAGRAM OF CONNECTIONS, STATION NO. 3 EXTENSION DEVELOPMENT

The leads from the generators go to an oil switch located in a terminal building on the top of the cliff above the power house, and then directly to a six-circuit transmission line carried on steel towers, that runs to the Echota substation, three miles away. These generator oil switches are automatically tripped by inverse time-limit relays when short circuits occur outside the generators. In case of trouble within the generators the switches are opened instantaneously and the field circuit is killed by a balanced relay system of protection operated from differentially connected current transformers in the generator leads.

At the top of the cliff above the main generating station is the control building. On account of the simplicity of the switching arrangement, shown by the wiring diagram, Fig. 22, the control is greatly simplified. as is clearly indicated in Fig. 23. When a switch is opened, an annunciator on the control board shows the relay that operates it, thus indicating the source of the trouble. In each of the generators are 18 temperature indicators located at different parts of the stator windings. Six of these in each machine, that show the highest temperatures, are connected up to an indicator in the control room.

FIG. 23—CONTROL ROOM SHOWING PANELS FOR CONTROL OF 100,000 H. P. STATION NO. 3 EXTENSION

Excitation for the alternators is obtained from 2200-volt induction-motor-generator sets. Each exciter is of 225-kw. capacity, shunt-wound with interpoles, and generates 220 volts. The induction motors can be supplied from three separate and distinct sources, any one of which can be connected to a duplicate set of busses, and the 2200-volt induction motors, driving the exciters, connected to these busses through selector oil switches. An emergency source of excitation may be obtained from direct-current busbars in Station No. 3. This circuit is connected through a field rheostat to a busbar, to which the field coils of any one of the alternators may be connected in case of failure of its motor-generator exciter.

In laying out the station, effort was made to divide the electrical and mechanical operating functions. Electrical operation is centered in the control room and the mechanical in the station. How successful have been the efforts to simplify operation is evidenced by the fact that a station of a normal operating capacity of 100,000 kw. is being operated by three men on a shift. The general external appearance of this station and its relation to Station No. 3 are shown in Fig. 24.

TRANSMISSION LINE TO ECHOTA

The transmission line has a length of 16,000 ft. and runs from the terminal building up the canal to the river, thence following the bank past the plant of the old Niagara Falls Power Company (now known as the Niagara Plant) and finally turning away from the river again at Echota to connect with the Echota substation.

The solution of the transmission problem was greatly facilitated by the consolidation of the two power companies, as land for the location of the line for the greater part of its length was already in possession of one or the other of them. For a distance of approximately 4000 ft. through the heart of the city, however, it was necessary to make use of the property already occupied by the hydraulic canal. This was accomplished by means of steel cantilevers anchored into massive concrete foundations on one bank of the canal, upon which were erected the six-circuit transmission towers.

For the greater part of the distance it was found necessary for only the narrow bases of the towers to be placed over the canal right-of-way, easement being obtained from abutting property owners for the overhanging portion of the construction. At the large bridge spanning the canal at the junction of Third and Niagara Streets, however, this was not

FIG. 24—VIEW OF STATION NO. 3 AND EXTENSION FROM CANADIAN SIDE OF NIAGARA RIVER

FIG. 25—TRANSMISSION LINE CROSSING STREET INTERSECTION SHOWING LONG CANTILEVER FOUNDATIONS

possible, and it was necessary to place two towers entirely over the canal. This was accomplished by means of long cantilevers extra heavily braced, as shown in Fig. 25.

The main horizontal members of this structure are composed of two 30-in. I beams, each 60 ft. long, placed side by side. Thirty feet of these beams are buried in the massive concrete foundation, the other 30 ft. projecting out over the canal. In these structures the center line of the towers is 25 ft. from the face of the canal wall. A heavy brace was added to these special structures to give stability and rigidity, although not needed for strength. In the case of the short cantilevers the brace was omitted.

Fig. 26—Portal Anchor Tower

In addition to the special narrow-base towers used on the canal section, the local conditions called for the use of several other types of structure, two of which are shown in Figs. 26 and 27. The portal type of construction was used for the section along the river bank where the line is built over a future street.

The line comprises six three-phase circuits, each consisting of 500,000-cir. mil stranded medium hard-drawn copper. At present two circuits are used for each 32,500-kv-a. unit at 12,000 volts, but clearances are provided for 66,000 volts.

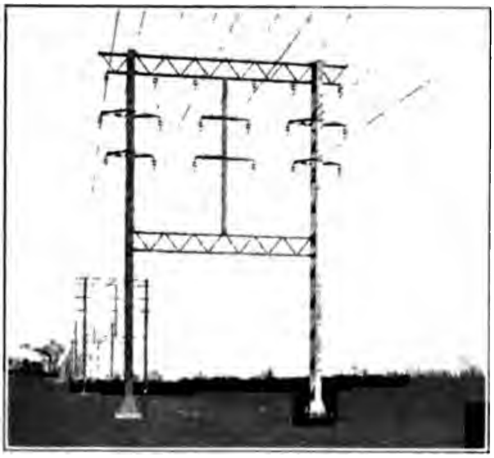

FIG. 27—FLEXIBLE PORTAL TOWER

Owing to the fact that this line passes through the business portion of a busy city, special precautions were taken to guard against failure. Each conductor is strung for a maximum tension under worst conditions of wind and ice of 6000 pounds. At strain

FIG. 28—ECHOTA DISTRIBUTING STATION SHOWING OUTGOING OVERHEAD LINES

Most of the feeders leave the station underground

towers double-strain insulators are used. Short spans, not exceeding 350 ft., were used as a further contribution toward safety and stability.

The line is insulated with substantial spider-type suspension insulators, two units being used in suspension strings and three in strain. On the canal section, because of the peculiarities of the right-of-way, it was impossible to avoid a number of small angles, at which points suspension strings with hold-downs were used. The line is protected against lightning by five overhead ground wires, 3/8-in. copper-clad wire being used for this purpose.

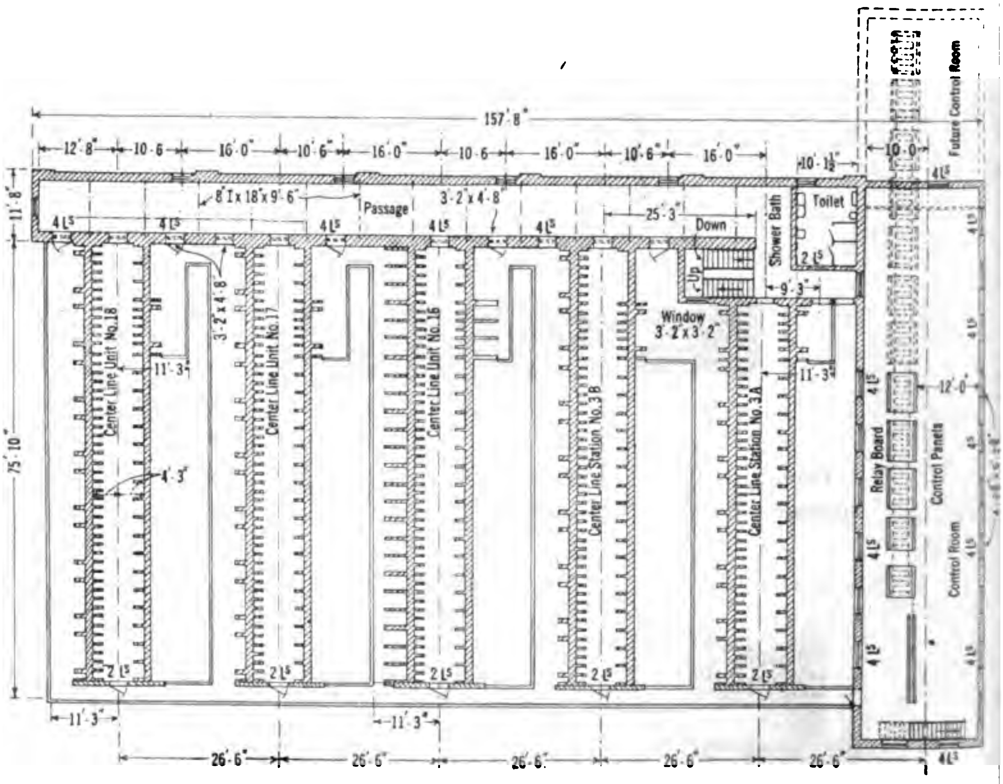

FIG. 29—PLAN OF ECHOTA DISTRIBUTING STATION—SECOND FLOOR

ECHOTA DISTRIBUTING STATION

The Echota substation is intended to serve three functions—(1) to subdivide and distribute the power from the new plant, (2) to serve as a clearing house for the output of the five generating stations, aggregating 400,000 h. p., and (3) to act as a future step-down transformer station.

Inasmuch as the primary function of this station is to distribute the power of the new plant, it was decided to preserve the unit arrangement in its construction. The station was accordingly laid out in units of a nominal capacity of 32,500 kv-a. Five of these units were constructed, three for the new plant and two for interconnection with other generating stations. A control building containing the switchboard apparatus was also erected. The general wiring diagram, Fig. 22, shows the arrangement of the main circuits; the physical layout of the structure is similar to that of the diagram. The general scheme is that of a main tie bus running lengthwise of the building with the unit lateral busses joining it at right angles.

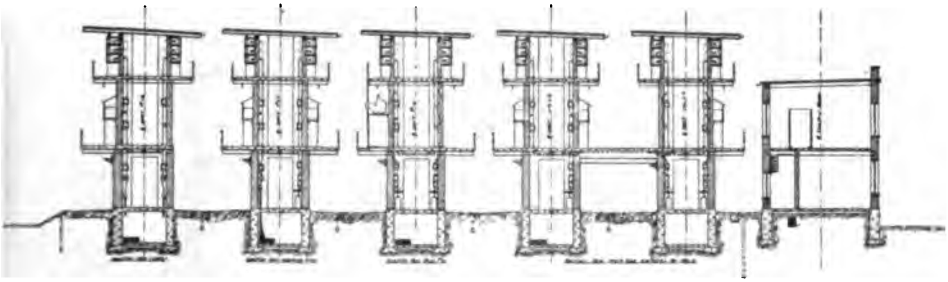

FIG. 30—LONGITUDINAL SECTION OF ECHOTA DISTRIBUTING STATION—SHOWING CROSS-SECTIONS OF BUS AND SWITCH STRUCTURES AND CONTROL ROOM

The five units or bays and the control building are connected at one end by a narrow building or passageway which contains the incoming line protective equipment and serves as a distributor for the control wiring, piping, etc., and as a means of access between the control building and the several unit bays. The main operating portion of the station is concentrated on the second floor which contains the oil switches with their disconnecting apparatus and the control room. Under each of the unit bays is a subway for distribution of cables. This connects at each end with longitudinal subways.

A radical departure from the usual station construction is the placing of all oil circuit breakers on the outside of the building walls; in other words, the main bus and switch structure walls are utilized as the walls of the building, all high-tension connections being upon the inside, where they are thoroughly housed and protected against the elements, and the oil switches upon the outside, where explosions and oil fires can do a minimum of damage. Galleries are provided on the outside for access to the oil switches which are protected from the weather by suitable housings.

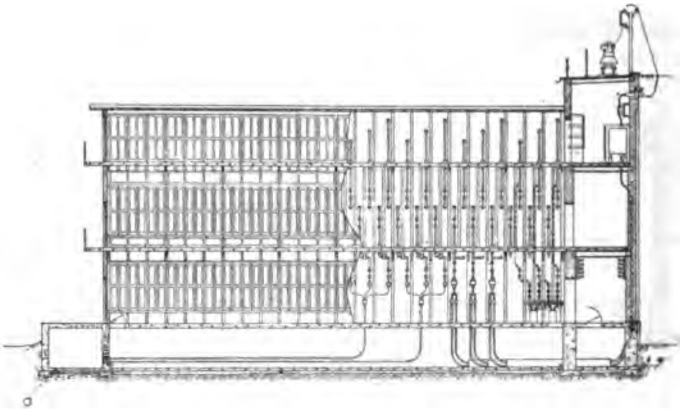

Fig. 31—Cross-Section through One Bay of Distributing Station—Showing Elevation of Bus and Switch Structure

Each incoming line, after passing through a set of choke coils for lightning protection, divides, one side going through an oil circuit breaker to the main bus, the other side through a similar breaker to the unit reserve bus. In each bay provision is made for six outgoing feeders. Each of these connects to the main bus through an oil circuit breaker and to the reserve bus through disconnecting switches. The function of the reserve bus is twofold—(1) It serves as a true reserve bus from which all feeders can be supplied temporarily through the reserve-bus switch. (2) The reserve-bus switch serves as a substitute switch for any individual feeder switch which may be out of service. In this manner duplication of the switching facilities is obtained without duplication of oil switches on each feeder. Provision is made for the installation of reactors between bays, and these will be installed as soon as they are required.

Owing to the great importance of this station in the general scheme of distribution, both present and future, it was determined to insure the greatest possible degree of reliability in the oil switches. Accordingly both of the chief manufacturers were asked for a recommendation on this basis, resulting in the proposal of two radically different types of oil switches, namely type *C O*-2 and type *H*-9. Owing to the absence of operating experience with these switches, it was found impossible to establish definitely the superiority of either one over the other, and it was decided so to construct the station that either one could be used. This was accomplished by slight modifications in the standard assembly of both types, and it was decided to install at the start a number of each type in order that actual operating experience might be had with both.

The doors covering the disconnecting switches of each circuit breaker are all operated together so that it is impossible for an operator to obtain accidental access to a disconnect of an adjacent circuit breaker. These doors are mechanically interlocked with the circuit breaker so that they cannot be opened until the corresponding oil switch is in the open position.

The switchboards consist of vertical panels and are divided into five sections corresponding with the five main bays, in addition to a house-service section. Back to back with the control boards, with a 4-ft. aisle between them, are the relay and terminal boards. Each instrument and relay is provided with a complete set of calibrating link terminals mounted upon small panels on the rear of the main panels.

The vertical wiring on the back of the switchboards is carried in troughs 3½ in. wide, made up of two ¾ in. angle sides with asbestos board back and removable sheet-metal covers. The advantages of this system of wiring are safety, accessibility, neatness, ease of installation and flexibility.

At their point of departure from the board, all control wires pass through terminal links and are then carried in steel pans or troughs mounted one above another on brackets fastened to the wall of the building. By this construction the control wiring is made accessible practically throughout its entire length, and at the same time an enormous amount of conduit work is avoided.

Fig. 32—Switchboard at Echota Substation

For the operation of the control circuits there are provided two 14-kw. motor generator sets and a 120-ampere-hour, 220-volt storage battery.

The incoming lines from the new generating station are each equipped with overload, ground and reverse-power relays. These relays are arranged to trip both the main and reserve-bus circuit breakers. The bus-tie switch is equipped with overload relays. Feeder switches are relayed in two different ways, according to the nature of the feeder supplied. In certain cases where a feeder consists of four parallel cables, split-conductor protection is provided between the two pairs of cables by means of suitably connected current transformers and low-current relays. In other cases ground relays are installed, connected in the current transformer neutrals. Overload relays are also installed on all feeders. All relays are of the induction type, the five-ampere size being used for overload and the one-ampere size for differential and ground protection.

A somewhat unusual feature in connection with the relay system is the installation of annunciators on the switchboard with the drops connected in series with the tripping circuits of the various relays. By this means it is possible to know at once upon the tripping out of a circuit breaker just which relay was responsible. This immediately gives an indication of the nature and in certain cases of the location of the trouble. It also furnishes the means of keeping tabs on the operation of the relays. Although the station has been in operation only a few months, the value of this feature has already been amply demonstrated.

FURTHER DEVELOPMENT AUTHORIZED BY FEDERAL LICENSE

The completion in 1920 of Station No. 3 Extension for three 37,500-h. p. units provides for the utilization of the entire amount of water, 20,000 cu. ft. per sec., which is available under the existing treaty. But there has been, and with the return of normal industrial conditions there will be again, a demand for additional power.

Since by Act of Congress creating the Federal Power Commission the U. S. Government assumed control of the Niagara River situation it became necessary that the Commission's approval be obtained for any further development of power. As no further water is at present available the only source of additional power is the use of some of the present water under increased head. Naturally, the least efficient of the existing plants would be the one first selected for obsolesence, which in this case is the "Niagara" plant, which, operating under an effective head of 140 ft. obtains but 12.1 h. p. per cu. ft. per sec. as compared to 21 h. p. per cu. ft. per sec. in the Station No. 3 Extension.

The economic reasons for the plan adopted for the re-development of this water have been given above and the Company is now proceeding under license from the Federal Power Commission with the construction authorized.

The power will be developed in a further extension to Station No. 3 along similar lines to those followed in the already completed extension.

The water will be brought from Port Day through a 32-ft. horseshoe-shaped tunnel at a depth of about 100 ft. below the surface of the ground. From this tunnel the water will be taken to the penstocks through a forebay similar to that provided for Station No. 3 Extension. The construction of this tunnel was started, with fitting ceremonies, on April 25th of this year, and the work is now proceeding rapidly from both ends and two intermediate shafts. It is expected that the first unit of this development will be started on or before May 1st, 1923.

A portion of the additional power to be obtained from this development will be delivered to the Buffalo General Electric Company. For this purpose a new 66,000-volt transmission line is now under construction from the Echota Station to the vicinity of the steam station of that Company which is located on the Niagara River about a mile below the Buffalo City Line. This new line will consist of two circuits of 500,000-cir. mil copper and will be capable of transmitting upwards of 100,000 h. p. to Buffalo. This line, unlike its predecessors, will take a direct route, first crossing the East arm of the Niagara River from the mainland to Grand Island, thence running straight across the island and recrossing the river to the mainland again between Buffalo and Tonawanda, whence it will extend to its terminus by the shortest available route. At the lower crossing the river is about 4000 ft. wide and the crossing will be made in two long spans of about 1600 ft. and two shorter anchor spans, with channel clearances of 75 ft. At the upper crossing the river is narrower and the crossing will be made in a single long span of about 1800 ft. with 115 ft. channel clearance.

NIAGARA POWER IN AMERICAN INDUSTRY

In a condition of society where each man's livelihood depends upon his own unaided efforts, the state of civilization must necessarily be low and the majority of the population in poverty and misery. Conversely, the state of civilization will be the most advanced and the general well-being the greatest, where the ratio of usefully employed power to population is the highest. It follows therefore, that the ultimate state of civilization will depend upon the efficiency with which the country's *inexhaustible* power resources are made to minister to the needs of man.

It is profitable, therefore, to examine the uses to which our power resources are to be put, and particularly is it profitable to do this in the case of Niagara, the greatest single source of water power in North America. Here is a power stupendous in magnitude, absolutely continuous in character, easily developed, at a construction cost so relatively low that the electric energy cost to customers is the very lowest, and located in the midst of a large industrial population with abundant labor, adequate transportation, and a near-by market immediately available. Compare this with the large western powers, located in almost inaccessible fastnesses of the mountains and far removed from all those other factors necessary to industry, namely, labor, transportation, raw materials and market. The contrast is striking, and should rightly give us pause to consider the corresponding contrasts in the proper utilization of these diverse developments. In general, the western water power must be transmitted great distances and utilized in those applications where the value of the service will warrant the cost of such transmission. Not so, however, Niagara. Here industry can come to the very doors of the power plants and obtain absolutely continuous power with no added expense for transmission.

It would seem, therefore, that Niagara was intended by Nature for application to those primary industries requiring continuous power at low cost, especially electrochemical and electrometallurgical processes, producing essential raw materials for use in secondary industries engaged in the manufacture of finished or semi-finished products. This is the destiny of Niagara. Not primarily in lighting the lamps nor in turning the wheels of industry is to be found the ultimate outlet for Niagara's steady energy, but in the production of the necessary *materials* of industry which can be produced in no other way.

Such has been, in fact, the principal use to which Niagara power has been put, and it is not entirely coincidence that the great industrial growth of America has been contemporaneous with that of the development of Niagara. To what extent, for instance, the development of the automobile industry has been dependent on Niagara power, we do not know exactly, but it has been estimated that the withdrawal from this industry of only three of Niagara's products, namely, ferroalloys, artificial abrasives, and aluminum, would both increase car weights and decrease production by about 80 per cent. What is true of the automobile industry is also true to a very great extent of all of our industries. Niagara might today be rightly named the "Mother of American Industry."

This conception of Niagara's destiny, however, has not always obtained. Before the discovery of these products, or of ways for their manufacture and use, Niagara's energy was thought of entirely in terms of turning wheels and illuminated houses and streets. So some of the earlier developments were predicated upon transmission but with the gradual unfolding of her peculiar genius, it has slowly come to be recognized that, like all good mothers, her most important duty is at home. Immutable economic laws will dictate that at home all her energies must ultimately be expended, "mothering" America's industries. But for some time to come there may not be a sufficient outlet for her energy in this direction.

During the three decades since the birth of hydroelectric development, we have been catching up with the demand and the development has been correspondingly rapid. As the capacity of America to absorb the products of those industries to which Niagara has given birth gradually becomes saturated, the rate of development will naturally become slower and more commensurate with the growth of population of the whole country, unless a new and broader outlet for her energies is developed. That those energies should be developed to the full, and that as soon as may be, is not to be questioned. Once it has been determined, as has now been done by the Federal engineers, as to how much of Niagara's potential power may be put to work, there should be no delay. Every pound of water that can be spared but is permitted to pass without doing work when there is work to be done, means the unnecessary destruction of just so much of our limited coal supplies. Therefore, pending the time when allof Niagara's energy is needed at home for use in primary industries, such part as is not so needed should be employed, elsewhere if necessary, in secondary industries or in ministering to the comfort and convenience of the people in their homes. This is legitimate and feasible, but its consummation should be undertaken with caution.

It must be borne in mind that the attainment of our highest good must ultimately demand the most efficient use of this power. Nor is efficiency here meant in any narrow sense, but in the broadest sense of the greatest good to the greatest number. Within the next few years we shall undoubtedly see great superpower transmission lines reaching out hundreds of miles from Niagara, putting her surplus power to work, but as the years roll on and the growth of our population creates increasing demands for the peculiar products of Niagara's particular genius, we shall see this energy distribution gradually being drawn in. And creeping after it we shall see great steam plants slowly but steadily approaching Niagara, replacing in the homes and secondary industries, that energy which, as times goes on, can less and less be spared from the "mothering" home industries of Niagara.

So we shall finally reach the ultimate condition wherein Niagara shall become the center of a great industrial community. (See Fig. 33.) In an inner ring around the Niagara power nucleus will be the great primary industries producing the peculiar raw materials for which this power is necessary and which are themselves in their turn necessary to others. And surrounding this ring will be another and a wider ring of secondary industries obtaining their specialized raw materials and certain of their tools from the primary industries of Niagara and their power from

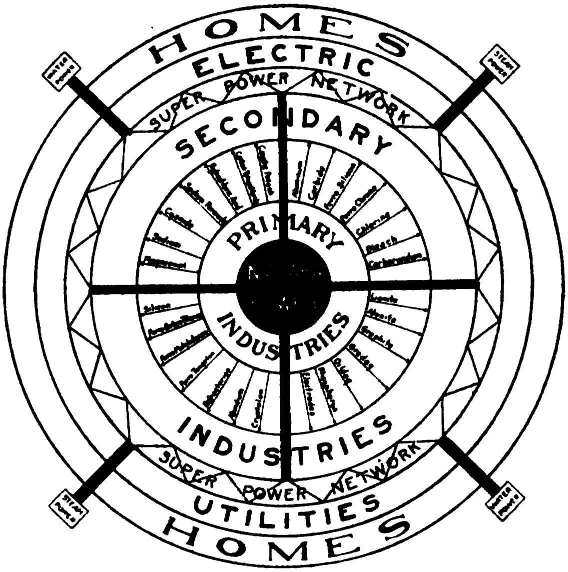

FIG. 33—NIAGARA POWER IN AMERICAN INDUSTRY

a superpower network fed from those inherently variable power sources, both water and coal, such as are adapted to their needs. But connecting this superpower network with Niagara's power will also be transmission lines, and as the tide of industry ebbs and flows so will also ebb and flow the tide of power over these lines. Always, when the need demands, Niagara's power will be drawn back within the inner ring to do its own peculiar work which no other power can do, but when in the swing and surge of industry the home demand is lightened, out will go Niagara's power again over the interconnecting transmission lines to the beneficent work of saving coal by its use in the secondary industries and utilities. In this manner will Niagara's steady flow be kept continuously at work.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 21, 1921.

ADVANCES IN THE ART OF WATERWHEEL DESIGNS AND SETTINGS

BY W. M. WHITE
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THE UTILIZATION of our natural resources for the development of power, its transmission and the employment of that power to relieve man of burdensome toil, has been an outstanding feature in the progress of Western civilization during the past half century.

The advance of communities, states and nations may be read in the record of the percentage of mechanical power utilized per man. An English statesman recently said in open Parliament meeting that the reason why American manufacturers can pay twice the wage paid the English workman and yet compete in the markets of the world, is because each American workman has behind him twice the developed horse power per man that the English workman has behind him.

Of the total power developed in the United States, that furnished by water power forms no inconsiderable part. The amount of power now developed from water is approximately nine million horse power. It has been estimated that fifty million horse power can be developed from the rivers within the borders of the United States. Of the nine million horse power, by far the major portion has been developed in the last thirty years and a curve expressing relation of time and power developed would be parabolic in form with an upward trend.

Power was first developed from water by the Chinese about two thousand years before the birth of Christ. They used paddle wheels and buckets attached to the rim of a large wheel placed in the rapidly flowing stream for the purpose of raising water for irrigation.

The early American types of waterwheels were peculiarly adapted to the locality in which they were made. From the New England States with their meandering streams and low falls came the inward flow, reaction turbine wheels, and out of the mountainous West with its precipitous streams and great falls, came the Pelton or impulse wheel.

The work of J. B. Francis of Lowell, Mass., was a notable contribution to the art, resulting in the development of the inward flow, axial discharge wheel which is essentially the present waterwheel runner of the reaction type. Splendid results were obtained by the early designers by the cut and try method. The determination of the flow of water under given conditions is difficult and is usually computed from empirical formulas founded on experimental data. The problems involved do not lend themselves to easy mathematical treatment. For example, the regulation of a hydroelectric unit with pipe lines involves the varying pressures at the wheel caused by the inertia of the water in the pipe line caused by the varying of the velocities of the water in the pipe line.

Some splendid approximate, mathematical formulas have been developed recently for determining these pressures with given pipe line conditions, but these formulas do not give exact or correct values for all conditions.

It is not difficult to set up differential equations which give proper relative values to the variables involved, but some of these equations are not solvable by the present methods available for simplifying equations.

The electrical quantities involved in the design of electrical apparatus are more readily determined than those quantities entering into hydraulic problems. The loss (friction) in an electric conductor varies directly as the current (velocity). The loss of head or friction in a pipe varies as the nth power of the velocity. The former involves equations of the first degree; the latter, equations of the second degree. The value of n is 2 for the starting of water in motion and the stopping of it; that is, v equals $\sqrt{2gh}$, and the value of n is approximately 1.85 for computing the loss by friction in pipes. $H = K\,V^{1.85}$

It is encouraging to the hydraulic engineer to know, as the writer has recently been assured, that a Professor in one of the Western colleges is now working on a table of functions somewhat similar to the logarithmic functions which will probably enable reductions of certain, now insolvable, differential equations to be made and thus enable us to make use of an exact formula in solving the problems involved in this line of work.

The energy for the production of power from water is the product of the weight of the water and the head or fall utilized. Broadly speaking, the natural configuration of the locality of the power developed, determines the head or fall available, and the drainage area and climatic conditions contributory to that locality are the principal factors in determining the quantity of water. As it seldom occurs that the configuration of the locality and the drainage area and climatic conditions are the same, so it seldom results that one hydraulic power development is an exact duplicate of the other. The hydraulic engineer, therefore, has no one fixed condition to begin with.

From the above it results that each power development requires special study to select that method and type of development suited for the particular location. The problem of finding the proper power house and dam location in the maze of contour lines calls for minute investigations and studies. It requires a great deal of time and the working out of the costs of many preliminary studies of power house design of that particular site in order to find the proper relation of dam, pipe line, power house, tailraces, transmission lines, hydroelectric machinery, and living conditions which will result in the most economical and satisfactory development. The advance of the art must be taken into consideration because what treatment was satisfactory for a given development even five years ago can now be improved by making use of recent advances in the art of waterwheel design and settings.

The modern trend is to develop completely any given power site. The number of units in the given plant is dependent upon the service to be rendered by the given plant. The network of transmission lines is now becoming so extensive that isolated power plants are the exception rather than the rule, as formerly. In an isolated power plant it was necessary to divide the development into several units, usually at least four, so that continuity of service could be maintained by allowance for repairs and renewals. Most of the isolated early developments have now grown to huge dimensions having many plants interconnected with themselves and, in many cases, interconnected with adjacent companies, and now many companies have lines of interconnection reaching into several states. The hydroelectric station in the large systems today is the unit just as the individual waterwheel and generator were the individual unit years ago. The engineer is at liberty, therefore, to handle this unit in any manner which will make for economy in construction, efficiency in operation, and reliability of service. All three of these considerations really demand the same thing—the largest single unit which can be installed in the particular development under consideration, thus doing away with several small units with an additional spare unit.

SPEED

Having determined upon the size of unit for a particular setting, the speed of the unit is practically fixed for that head. A formula which has been used for sometime as fixing the upper limits of speed is as follows:

$$\text{rev. per min.} = \frac{\left(\dfrac{5050}{H + 32} + 19\right) H^{5/4}}{\sqrt{\text{h. p.}}} \qquad (1)$$

Where

H equals head acting on the turbine

h. p. equals the maximum horse power of the turbine.

The formula (1) applies to a single runner and, in the case of multi-runner units, the maximum horse power of the unit is to be divided by the number of runners and the horse power per runner substituted in the formula (1).

The maximum horse power of the turbine is usually from 15 to 25 per cent more than the actual power required to drive the combined unit at its best efficiency. This relation results from the fact that the maximum efficiency of a waterwheel occurs at from 0.8 to 0.9 load, depending upon the type of runner used and the desire to have overload capacity on the turbine. The rev. per min. given by the formula (1) is altered to conform to synchronous speed. The above formula is not rigidly adhered to, although it has been arrived at by incorporating in its factors the experience of all of the waterwheel builders for many years past. Each manufacturer has a line of developed waterwheel runners and is frequently in position to make a selection of speed which will result in considerably lower cost to the customer because of developed apparatus, and in all cases a reliable waterwheel builder should be consulted as to speed. The matter of the selection of speed will be again referred to under the subject of "Specific Speed."

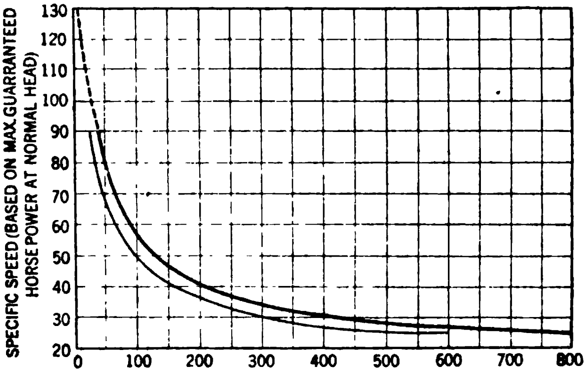

FIG. 1—SPECIFIC SPEED LIMIT CHART

FORMULA

$$N_s = \frac{5050}{H+32} + 19 \text{ in ft.} = \text{ft-lb. lb. units}$$

$$N_{s_m} = \frac{22{,}500}{H+32} + 84 \text{ in metric units} = 4.45\, N_s$$

Insert H in feet in both formulas.

SPECIFIC SPEED

Specific speed is the speed at best efficiency which a given runner will make when reduced homologously to such size that it will produce one horse power under one foot head. The value of the specific speed of a given runner fixes definitely that runner as a type with relation to all other runners. The formula for specific speed is as follows:

$$N_s = \text{rev. per min.} \frac{\sqrt{\text{h.p.}}}{H^{5/4}} \qquad (2)$$

For simplicity of computation in common practise, the horse power of the turbine is reduced to h. p_1. That is, the horse power which that particular unit would give under one foot head. This is obtained by dividing the horse power by the three halves power of the head.

The rev. per min. is reduced to the number of revolutions that particular turbine would give under one foot head, or, namely, rev. per min_1. This is obtained by dividing the rev. per min. of the given turbine by the square root of the head; therefore, formula (2) becomes:

$$N_s = \text{rev. per min.} \sqrt{\text{h. p.}}, \qquad (3)$$

The curve shown in Fig. 1 expressing relation of specific speed and head was determined by plotting the specific speeds of practically all of the noted plants in the United States and some abroad with relation to the head under which they were operating, noting on the point so plotted those plants on which no pitting occurred and those on which pitting of the runner did occur, or noting any other unstable or unsatisfactory performances of plants in operation. A curve was then drawn below the points representing plants on which pitting occurred or which were unsatisfactory on an average, and above the points representing all of the plants on which pitting did not occur and which were satisfactory and efficient in operation. A ceurv

$$Y = \frac{5050}{H + 32} + 19 \qquad (4)$$

plotted with vertical ordinate as specific speed and horizontal ordinate as head gives the specific speed curve referred to above and is the factor used in the derivation in the original equation (1). Steady advances are being made and no doubt speeds higher than those indicated in formula (1) will ultimately be adopted. There is probably no other thing in the design of a hydroelectric plant that received more discussion than the question of the speed of the units. There are several contending forces: The electrical engineer desires usually the higher speeds in order to cheapen the cost and frequently increase the efficiency of the generator. On the other hand, the waterwheel designer prefers his lower speed usually for better efficiency throughout and, certainly, for higher efficiency at lower or part gate loads, and for freedom from troubles in the field such as pitting, erosion and vibration.

It does not always follow that the speed as given by formula (1) does result in a satisfactory waterwheel unit, but the most skilled designers are now enabled to produce those speeds and sometimes higher without dangerous pitting or cutting.

The size of waterwheel units has steadily increased to such a point that now the cost of the generators does not vary as widely with the change in speed, so that it may result that, in the design of larger units now in general contemplation, this troublesome case may settle itself.

SPEED REGULATION

The great inertia of the moving mass of water to and from the waterwheel produces difficulties in the regulation of the speed of the waterwheel unit which can best be controlled by making use of the inertia of the revolving parts of the waterwheel and generator. The greater the inertia of the enclosed supply water, the greater the $W R^2$ necessary to give good regulation. The factors entering into the control of the speed are:

(a) the time (t) in which the water is shut off from or turned on the unit.

(b) the increase or decrease of the effective head on the turbine occasioned by such change.

(c) the inertia of the revolving mass which resists change of speed by acting as a reservoir for the energy unabsorbed otherwise.

The governing apparatus is frequently unfairly charged with poor regulation, when all that apparatus can do is to open or close the turbine gates within a predetermined time (*t*) when actuated by a change in speed. The formula most commonly used for quick computation of speed change, although not exactly correct, gives results well within the limits required.

$$\Delta = \frac{800{,}000 \times \text{h. p.} \times t}{\text{rev. per min.}^2 \times W R^2} \qquad (5)$$

Where

Δ is the ratio of increase or decrease in speed

h. p. is the horse power suddenly thrown on or off

t is the time for the movement of the gates of the turbine

$W R^2$ equals the inertia of the rotating parts of the waterwheel and generator.

Formula (5) is used only for open flume turbines or where the change in pressure or head resulting from the change in flow, is too small to be considered. For cases where load thrown off results in an increase of head at the turbine inlet, the following formula may be used with good results:

$$\Delta = \frac{800{,}000 \times \text{h. p.} \times t}{\text{rev. per min.}^2 + W R^2} \left(1 + \frac{\Delta H}{H}\right)^{3/2} \qquad (6)$$

In case of load suddenly thrown on, the formula becomes:

$$\Delta = \frac{800{,}000 \times \text{h. p.} \times t}{\text{rev. per min.}^2 \times W R^2 \left(1 - \frac{\Delta H}{H}\right)^{3/2}} \qquad (7)$$

Where

H equals effective head, feet

ΔH equals change in head, feet

For a more thorough discussion of speed regulation the reader is referred to Mr. Arnold Pfau's paper, "The Speed and Pressure Regulation of Hydraulic Turbines," copies of which the author will be pleased to furnish.

The resulting change of effective head operating on the turbine caused by the movement of the gates within the time (*t*) is dependent upon the velocity and length of the column of water. Manifestly open flume turbines are easiest of all to regulate. Turbines having long pipe lines with high velocities cause greatest difficulties in regulation. Modern governors are equipped so that they may be readily adjusted for moving the gates open or closed in a predetermined time, usually a different time for closing and opening the gates in order to avoid synchronous waves in the pipe line. An important factor to be taken into consideration is the fact that the horse power to be inserted in formula (5) is the change in horse power which is developed under the changed effective head acting on the turbine, due to the change in pressure occasioned by the quick movement of the gates. Reference was made at the beginning of the paper to the complicated mathematical solution of the problem of regulation, but a fair understanding of pressure changes at the turbines may be had from the following formula.

$$H = \frac{LV}{Gt} \tag{8}$$

H equals the increase or decrease in head
L equals the length of the water column in feet including draft tube
V equals the change in the average velocity of the water in feet per second within the time (t)
G equals the value of force of acceleration of gravity equals 32.2 ft. per sec. per sec.
t equals the time in seconds in which the change in velocity is made.

There are many factors which enter into the exact mathematical solution such as the elasticity of the pipe line, the ratio of change in velocity for any small increment of time during the time (*t*) and the ratio of the increase or decrease of the pressure for any small increment of time during the time (*t*). There are certain peculiar conditions for length of pipe line, velocity in the pipeline and time of movement of the turbine gates which will result in an actual increase of power on the turbine as the gates are closed. In other words, the increment of increase of head is greater than the decrement of the decrease in quantity. The length of the pipe line is fixed by the natural conditions surrounding the development, but the velocities within the pipe line can be controlled and predetermined by the selection of the proper size of pipe line. The cost of the increase in the diameter of the pipe line may be excessive and it frequently results that $W R^2$ may be secured in the generator or in a flywheel at much less cost. If the pipe line conditions are rather rigid and fixed, it becomes necessary to provide proper $W R^2$ to secure the desired regulation as may be computed from formulas (6) and (7). The regulation constant has been determined by observing in power plant operation the $W R^2$ and other conditions necessary for reasonable regulation. The constant is set up by the following equation:

$$K = \frac{(\text{rev. per min.})^2 \times W R^2}{\text{h. p.}} \qquad (9)$$

It will be noted that the constant K includes three of the principal factors of equations (5) (6) and (7).

The value of K should not be less than four million for open flume construction and runs as high as fifteen million on some of the successfully regulated plants having long penstocks with reasonably high velocity.

As waterwheel runners have a very small $W R^2$ compared with that of the generators which they drive, the generator should have a constant for regulation of not less than four million as stated above.

Pressure regulators are used in connection with the governors to reduce the rise of pressure on closing of the gates. They are expensive, however, and where it is possible to obtain substantially equal regulation by increasing the $W R^2$ and omitting the pressure regulators, with consequently slower governor operating time at anything like the same cost, it is preferable.

RUNNER

The most important single piece in the make-up of the water wheel is certainly the runner. The function of all the headworks, supply lines, casings, speed rings, and guide vanes, is to deliver to the runner the maximum amount of energy with proper relation of velocities and pressure, and the function of the proper draft tube or regaining devices beyond the wheel is to return to the runner in the form of added head, as hereafter explained, the maximum amount of energy. The function of the runner, therefore, is to transform the maximum amount of energy delivered to it into mechanical power on the waterwheel shaft.

The diameter of the runner is fixed by the relation

$$\pi D N = \phi \sqrt{2 g H}$$

Where

D = diameter of runner in feet.

N = rev. per min. ÷ 60.

ϕ = coefficient.

H = the effective head on the turbine as measured from the equivalent pressure head at the entrance to the casing plus the distance from the point of measurement to the level of the tailwater in the tailrace.

The value of ϕ varies from, say, 0.6 for very high-head wheels to, say, 0.8 for low-head wheels. The diameter (D) is the diameter of the circle touching the intake edges of the runner vanes along the center plane of the guide casing.

For purpose of explanation let us consider a runner of normal specific speed, say 35, (shown in Fig. 3) where ϕ would equal 0.72, and where the water delivered from the guide vanes to the runner would have its energy about equally divided into velocity and pressure. The runner, therefore, receives the water in a whirling vortex, yet under a pressure of about one-half of the head, and the shapes of the runner vanes are formed so that the water in passing through the runner is directed backward to the rotation of the runner and is discharged from between the runner vanes at a velocity substantially equal to the forward velocity of the runner, so that theoretically and ideally the water should flow parallel to the shaft into the draft tube with a minimum loss, considering the diameter of the discharge of the runner band and the necessary velocity at that point to pass the quantity of water required. This condition of axial discharge is not attained and as a matter of fact is not desired for maximum efficiency. Pitot tube traverses made across the draft tube near the runner band show that usually the water at best efficiency whirls with the runner near the outer band and against the rotation of the runner near the inner band. The amount of energy discharged from the runner, therefore, is greater than that given by

$$\frac{V^2}{2G}$$

where V is the average velocity of the water flowing axially through the upper end of the draft tube where it joins the runner.

The number of vanes or buckets in the runner varies from thirteen to twenty-four depending upon the specific speed of the runner and the head under which it operates. The condition to be satisfied in the selection of the number of vanes is that number which will form passages through the runner sufficiently smooth in shape to avoid eddies and cross currents, and yet not too many vanes as contrasted to the friction which is introduced by the accumulated surface of too many vanes. The diameter of the runner at discharge is contracted until a balance is arrived at between the loss due to the velocity discharged from the runner and the friction loss saved by reduction of vane surface.

Another factor entering into the number of vanes is the question of pitting or erosion. Too few vanes will not give a proper channel between the vanes which results in the water leaving the back side of the vanes near the outer band creating a vacuum and slapping, action causing mechanical erosion, or creating a vacuum in which collects nascent oxygen which eats away the vanes, or a sudden release of air from the water setting up currents causing electrolysis. All or any of the above reasons may be the real one; you may take your choice. The higher the specific speed the greater the ratio of the diameter of discharge of the runner to the nominal diameter D of the runner. If the specific speed is increased the discharge band of the runner is gradually enlarged with respect to the nominal diameter and runners of 100 specific speed have a diameter of the discharge of the runner of 1.3 times the nominal diameter.

As the specific speed is increased the question of friction becomes the controlling element, consequently, this results in a reduction of the number of vanes, and a reduction of the size of the outer band which at maximum specific speed leads to the Nagler runner wherein the outer band is eliminated and the number of vanes reduced to a minimum. Three vanes in this type of runner have been found to give good results.

FIG. 2—55-IN. RUNNER
8000-h. p., 550-ft. head, 720-rev. per min.

The problem of determining mathematically the results of flow in a straight pipe are so difficult, as set forth at the beginning of the paper, that it is apparent that any mathematical formula attempting to predict the results of a given runner under a given condition involving as it does not only friction losses to the 1.85 power but also centrifugal force, shock losses, disk friction losses and reaction losses, certainly has no place in this paper. The reader will be interested, we hope, in a statement of the various types of runners. Probably no single part of any apparatus has been fixed more by cut and try, and experimental methods than the runner of a waterwheel.

Fig. 2 is a runner having a specific speed of 21.5 designed to operate under a head of 415 ft. Fig. 3 is a runner of 34 specific speed designed to operate under a head of 215 ft. Fig. 4 is a runner of 67.7 specific speed designed to operate under a head of 68 ft. Fig. 5 is type No. 13 with a specific speed of 94 designed to operate under heads below 30 ft. Fig. 6 shows a four-bladed Nagler wheel having a specific speed of 137.

Runner Material

The runner being subject to greater stresses and greater wear, due to high velocities, than any other part of the waterwheel should have wearing rings and wearing surfaces wherever possible to facilitate ease of repair.

The ideal runner material is bronze and preferably without any zinc. A composition which has been found eminently satisfactory for this purpose is composed of 90 parts copper, 10 parts tin with a trace of phosphorous. It is economical to use bronze runners on high-head units providing the bronze runner is not too heavy in weight resulting in an excessively expensive runner. Cast steel runners have been used with excellent results on high-head and intermediate-head units. Cast steel is desirable on high-head large runners where the weight of the runner is heavy. Cast iron runners have been used with success on the highest head turbines although they are not as satisfactory as the steel, because at these high heads the velocity of any foreign material flowing through the guide vanes is so great as to break out portions of the cast iron. Cast iron runners are entirely satisfactory for all heads, say from 200 ft. downward.

A type of runner which has been used with considerable success for intermediate and low heads, is one in which the vanes are made of plate steel pressed from forms and then cast integral with cast iron crowns and cast iron outer bands. These runners have the advantage of having very smooth surfaces resulting in less skin friction, and also have the added advantage that the runner vanes may be bent back into position after having once been broken by foreign material entering the runner, which does happen from time to time. Fig. 7 shows a good example of this type of runner in which the vanes are made of plate steel ⅝ in. thick. Their specific speed is 102.5. These turbines are operating under 18.5 ft. head at 136.6 rev. per min., developing over 825 horse power.

FIG. 3—SHOP VIEW OF 125-IN. CAST IRON RUNNER FOR THE LARGEST COMBINED HYDROELECTRIC UNIT IN THE WORLD

32,500-kv-a., 12,000-volt, 37,500-h. p., 215-ft. head, 150-rev. per min. For Niagara Falls Power Co., Niagara Falls, N. Y.

The propeller type of wheel as described in Mr. Nagler's paper, Vol. 41, No. 12, A. S. M. E. *Journal,* entitled, "A New Type of Hydraulic Turbine Runner," has been in use with cast steel vanes cast solid with the hub. Another type in use is cast iron. Another interesting type is that in which the vanes are formed of plate steel and are cast integral with the hub.

DRAFT TUBES

The twofold function of the draft tube is not usually understood. Its function is, first—to enclose and seal a passageway from the runner to a point below the surface of the tailwater so as to produce a suction action at the discharge from the runner, at least equivalent to the difference of elevation between the runner and the level of the surface of the tailwater. Second—to transform the energy in the form of velocity head discharged from the runner into energy in the form of pressure head. This action may be a little more clearly understood by imagining a horizontal flow in which the flow at a given point is at a velocity equal to that being discharged from the runner, and further down stream where the cross-section is increased and the velocity slowed down, the elevation of the water will be found to be higher than at the upper point. The

FIG. 4—CAST IRON RUNNER OF CONCRETE SPIRAL CASED TURBINES

35-ft. head, 90-rev. per min.

amount of this height is dependent upon the efficiency with which the conversion of velocity into pressure takes place. Therefore, the second function of the draft tube is to transform that velocity head into pressure head, thus creating an added suction at the discharge of the runner equal in amount to the velocity head times the efficiency of conversion. This amount added to the difference of elevation between the bottom of the runner and the level of the tailwater gives the total added suction at the runner. By this conversion of velocity back into pressure and by this greater suction action being maintained at the discharge of the runner, the effective head on the waterwheel and runner up to the point of the discharge from the runner is greater than the head as measured from the equivalent level back of the waterwheel to the elevation of the tailwater. Therefore, by the conversion of the velocity head into pressure head by means of some proper form of regainer and maintaining a greater suction at the

FIG. 5—80-IN. TYPE NO. 13 HYDRAULIC TURBINE RUNNER

With steel plate vanes being machined for single vertical open-flume hydraulic turbine. Three units each 600-h. p., 9-ft. head, 60-rev. per min.

runner by means of this discharged energy, the discharged energy is thus used by the waterwheel runner for the production of effective power.

A complete vacuum will cause the water to rise within it to about 34 ft. above the level of the outside water depending upon the air pressure at that particular locality and time. The height, therefore, to which a runner may be located above tailwater level is limited. We turn again to past experience for the factor fixing that height. It has been found that a runner of moderate specific speed may be placed so that the maximum suction at the base of the runner does not exceed 27 ft. theoretically. In determining the theoretical suction there is added to the elevation of the runner above tailwater the total velocity head in the water discharged from the runner, that is, to say, the efficiency of conversion is assumed to be 100 per cent. This is the limit of good practise, and where possible, other things being equal, this should be kept lower. As pointed out previously there is a limit to which the topmost point of the runner at its discharge can be placed. When large

IG. 6—Shop View of 72-in. High-Speed Cast Steel Runner

Assembled on shaft and showing initial stages of assembling for balancing before finally grinding to a surface.

Designed for 600-h. p., 200-rev. per min., 17½-ft. head.

runners are placed with shafts in horizontal position the center line of the shaft is necessarily kept low with relation to the tailwater elevation in order to keep the top of the runner at discharge within the limits as set forth. This elevation of the shaft frequently

FIG. 7—VARIOUS SIZES AND TYPES OF ALLIS-CHALMERS WATERWHEELS

For heads varying from 8 ft. to 2000 ft.

The two large runners in the center have plate steel vanes, as well as the small one just below the impulse wheel.

FIG. 8—GUIDE VANES FOR TWIN HORIZONTAL CYLINDER STEEL PLATE CASING HYDRAULIC TURBINE

Two units, 125-ft. head, 18,600-h. p., 200-rev. per min.

depresses the generator into the foundations below the level of high tailwater and sometimes of even normal or low tailwater. This is a good reason for the adoption of the vertical shaft. An interesting setting is that of the Kerckhoff Station of the San Joaquin Light & Power Corporation where the turbine pit is excavated from granite and draft tubes driven from the bottom of the excavation out to the river channel as illustrated in Fig. 21. This design enabled the avoidance of cofferdams which would have been very expensive at this location.

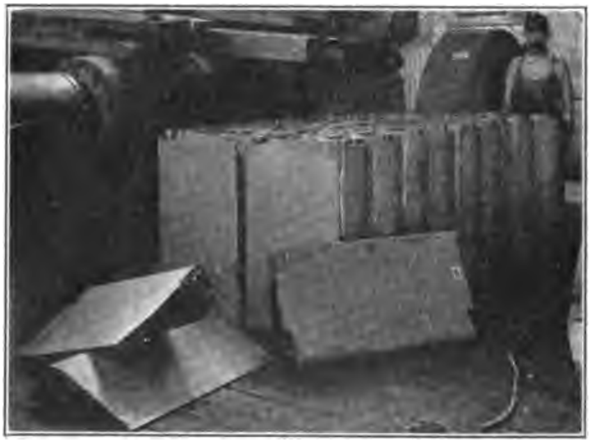

FIG. 9—GUIDE VANES FOR TWIN VERTICAL OPEN-FLUME HYDRAULIC TURBINE

Four units each 4,675-h. p., 30-ft. head, 100-rev. per min.

The regain of energy from the velocity discharged from the runner may be accomplished more or less effectively by—

(a) straight conical tubes.
(b) curved draft tubes.
(c) hydraucone regainers.

Straight conical tubes will regain the energy with high efficiency provided the space available within the power house foundations is sufficiently ample to permit the installation of a long conical tube having a length of preferably more than four times the diameter of the draft tube where it joins the runner. Most of the curved draft tubes are a delusion and a snare. Recent investigations along these lines have shown that curved tubes now in use are so poor in regaining efficiency as to seriously detract from the power plant efficiency.

The Hydraucone Regainer is a new device for regaining pressure from velocity within the limited space available within the power house foundations. It contemplates spreading out the flow of the water on some form of either flat or conical plate and then placing around the surface of the stream an envelope of gradually increasing greater capacity over that required to just enclose the free shape. In the case of the proper conical center a gradually enlarging capacity may be obtained wherein the pressure from velocity is regained. The conical center is not essential as tests have proved

FIG. 10—INSIDE VIEW OF SINGLE VERTICAL TURBINE WITH STEEL PLATE SPIRAL CASING AND CAST IRON SUPPORTING BARREL FOR GENERATOR

8,500-h. p., 53-ft. head, 100-rev. per min.

that substantially the same results have been secured by the omission of the conical center even in regainers having the upper walls especially designed with reference to the cone center. This result, however, may be accomplished only when a conoidal chamber does not vary too widely from the hydraucone which would be formed upon the particular base used. The outwardly extending passages in this form of regainer increase the efficiency of the waterwheel at full and particularly at part loads, since the centrifugal· force of the whirling water may be effectively utilized in these outwardly extending passages.

FIG. 11—FIVE VERTICAL A-C. GENERATORS—THRUST BEARINGS CARRIED ON UPPER HOUSINGS

Direct-connected to 560-h. p.. open-flume turbines with self-contained governors.

A summary of the experiments conducted in perfecting the Hydraucone may be found in the paper, "The Hydraucone Regainer, its Development' and Application in Hydroelectric Plants," which was read by the writer before the Spring 1921 Meeting of the American Society of Mechanical Engineers.

The curved draft tube is illustrated in Fig. 17. The Hydraucone Regainer is illustrated in Fig. 14. The Hydraucone Regainer has an efficiency of conversion of between 70 per cent and 80 per cent depending upon the available width between the walls of the power house foundations.

SHAFT AND BEARINGS

The main shaft is usually tapered and fitted into the hub of the runner. The shaft is sometimes made with a forged sleeve at the runner end to which the runner is secured by means of bolts. The former is the preferred method of fastening the runner when lignum vitae bearings are used on the waterwheel, because by its use a renewable sleeve may be most cheaply and effectively applied to the shaft on which the bearing surfaces are caused to bear. It was formerly the practise to make these renewable sleeves on the shaft of bronze, but later tests have shown that rings forged from alloy steel provide surfaces of greater hardness and longer wear at no greater expense. It may be argued that the steel will rust, but the modern hydroelectric units are so well and strongly designed that they are seldom out of use, therefore, the question of rusting of the shaft is not a factor in arriving at the proper decision. Lignum vitae bearings have been used as illustrated in Fig. 18 for many years with good success. Where the speed is not too high and the

FIG. 12—DIRECT-CONNECTED FLYBALL GOVERNOR
For mounting on the main shaft.

generator is located immediately above the waterwheel, the lower generator bearings may be omitted and the one waterwheel bearing may serve as the lower guide bearing of the generator as well as the guide bearing of the waterwheel. An interesting installation embodying this feature of design is that of the Cheoah Plant of the Aluminum Company of America, equipped with Allis-Chalmers generators and Allis-Chalmers waterwheels, and lignum vitae lower bearing. This plant contains three 27,000-h. p. waterwheels operating under a head of 180 ft. Another interesting plant is that of the Tallassee Power Company at Badin, N. C., where an oil bearing is substituted for the waterwheel guide bearing and this oil bearing serves for the lower generator bearing as well as the waterwheel guide bearing. Wherever it is at all possible the waterwheel and generator shaft should be reamed together in the shops of the makers of one of

FIG. 13—SPECIAL CENTRIFUGAL CONTROL STAND FOR TYPE NO. 4 ALLIS-CHALMERS HYDRAULIC TURBINE OIL PRESSURE GOVERNOR USED IN CONNECTION WITH FLYBALLS MOUNTED ON THE TURBINE MAIN SHAFT BELOW THE GENERATOR

Used for Hydraulic Power Co., Niagara Falls.
Vertical unit 37,500-h. p., 214-ft. head, 150-rev. per min.

the shafts, the bolts fitted to the shaft and the whole shaft turned in a lathe to be sure that the shaft turns true, before shipment. Open-hearth steel forgings of the simplest composition make the best waterwheel shafts because the problem involved is of stiffness rather than strength. It is most interesting to note that recent experiments are proving the superiority of the open-hearth steel shaft as against the specially compounded alloy materials.

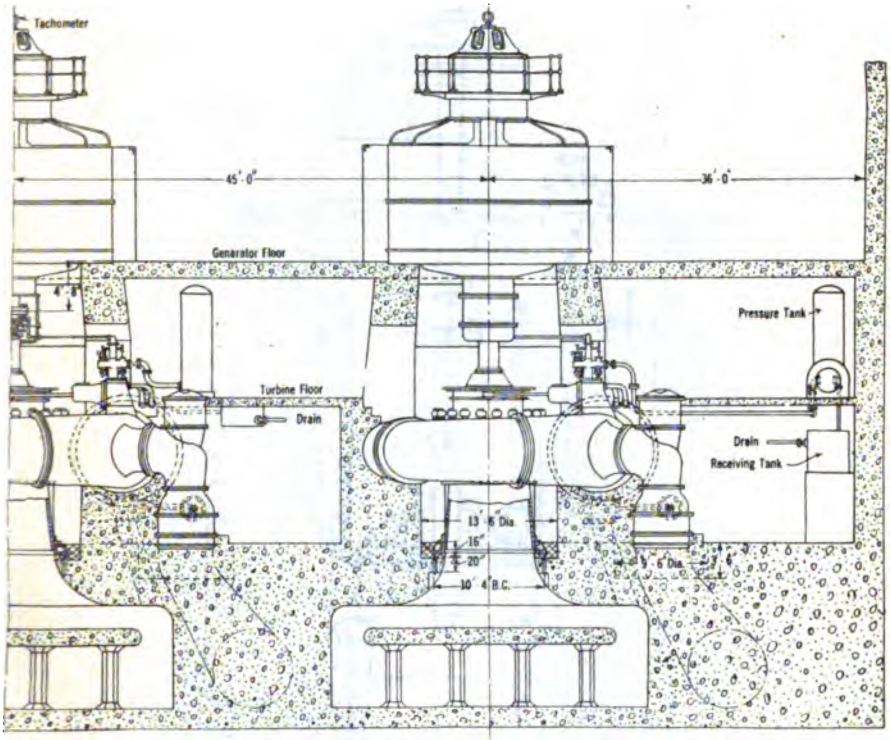

FIG. 14—VIEW OF 40,000-H. P. 421.5-FT. HEAD, 257-REV. PER MIN. TURBINES

With integral governor and direct-connected flyballs and hydraucone regainer.

GUIDE VANES

The trend of modern designs is strongly toward the cast steel guide vane having stems cast integral and controlled by levers and operating mechanism placed outside of the water. Fig. 8 shows some of the guide vanes for the Siskiyou Electric Light & Power Company, 18,000 h. p., 125 ft.

The number of guide vanes is fixed with the same considerations as that fixing the runner vanes, that is, adopting only sufficient guide vanes to form smooth passages so that the water will be delivered to the runner in as nearly one uniform whirling rotation as possible without too many guide vanes so as to avoid the too great accumulated vane surface resulting in

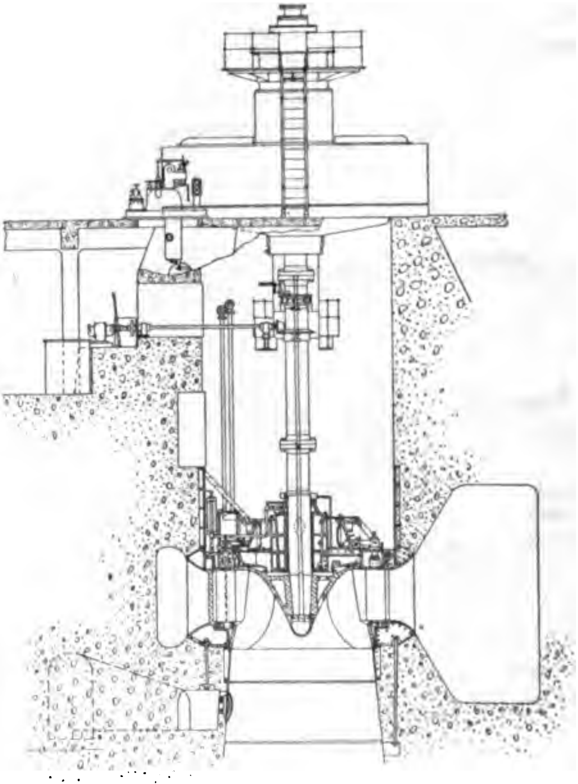

FIG. 15—SHOWING OIL PUMP GEAR-DRIVEN FROM MAIN TURBINE SHAFT

Lignum-vitae bearing.
120-in. diameter cast iron runner.
17,500-h. p.—68-ft. head—100 rev. per min.
Wateree Power Co.

friction losses. The favored number of guide vanes of this type seems to be twenty.. The shape of the guide vane is that left to the individual designer. The writer has used the design of vane illustrated here many years with good success. The guide vanes are

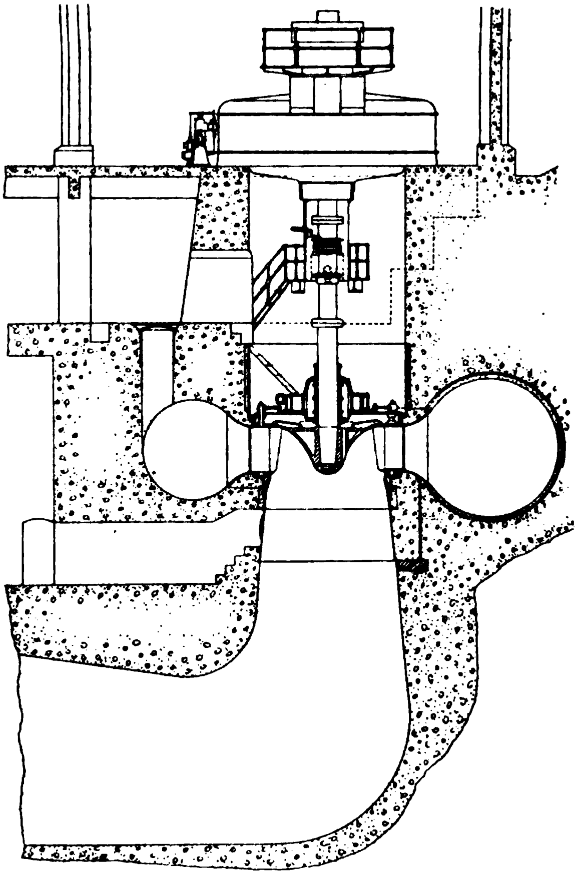

FIG. 16—CROSS-SECTION OF SPIRAL CASING FORMED IN THE CONCRETE WITH REINFORCING BARS ATTACHED TO THE SPEED RING FLANGES

15,000-h. p., 68.5-ft. head, 112.5-rev. per min.

controlled by links and levers to one common shifting ring. It is essential that some adjusting device be interposed between each vane and shifting ring whereby the vanes may be adjusted so as to prevent excessive leakage in the closed position. The adjustable feature is particularly useful when the vanes are sprung due to obstructions lodging between two vanes when closing the unit down. Breaking links interposed between each guide vane and the shifting ring are essential, and that type of link should be used which may be readily replaced without unwatering the turbine.

Cast iron guide vanes, bronze bushed, such as shown in Fig. 9, connected by links to a shifting ring make a very satisfactory arrangement for open flume settings. An adjusting means should be inserted between each guide vane and shifting ring as in the former case.

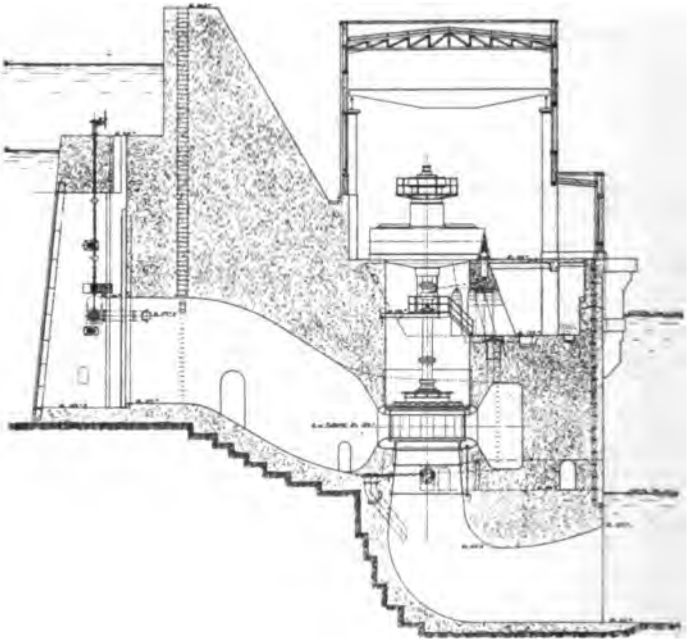

Fig. 17—One of Five Complete Allis-Chalmers Hydro-electric Units

Each 20,000-h. p. under 75-ft. head at 100-rev. per min.

A recent invention of plate steel guide vanes formed from one sheet of metal welded along one edge, has the advantage of having an unusually smooth surface, and of being easily repaired when distorted by foreign substances entering the wheel. It is particularly useful in low-head installations. The ideal control of the guide vanes and operating mechanism

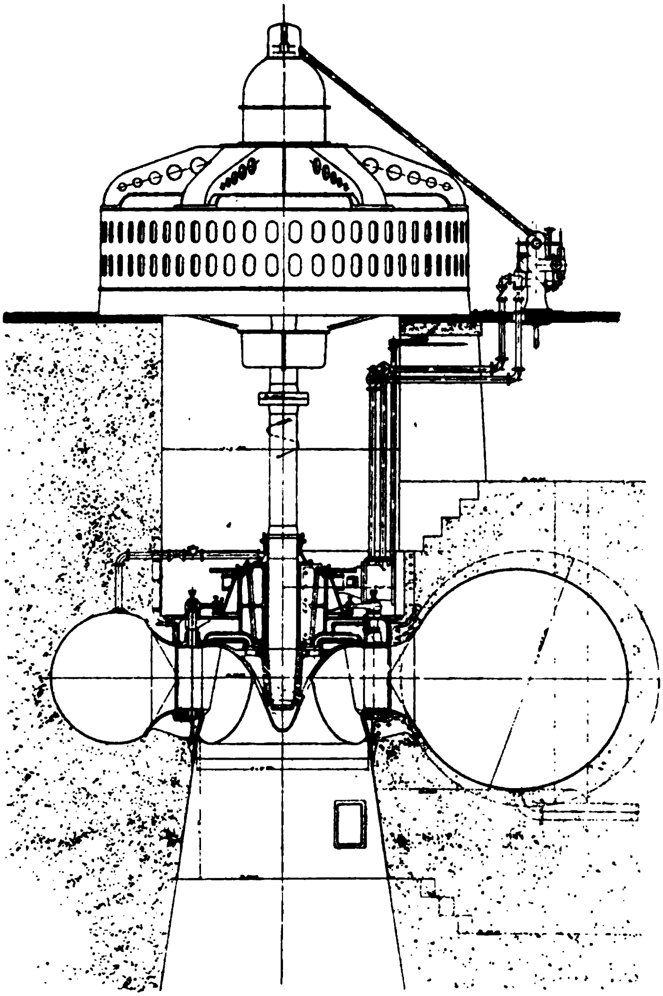

FIG. 18—VERTICAL HYDROELECTRIC UNIT WITH IMBEDDED, CIRCULAR SECTION, PLATE STEEL SPIRAL CASING

Governor flyballs mounted directly on main shaft.

is that illustrated in Fig. 10, wherein the operating cylinders are fixed to the pit ring and operate directly through reach rods to the shifting ring. A very satisfactory arrangement is that wherein the operating cylinder is located on the main generator floor exerting its effort through a vertical shaft to cranks and levers connection to the shifting ring as shown in Fig. 11.

GOVERNORS AND GOVERNING

In the case of poor speed regulation the governor is usually charged with the failure to perform, whereas actually the governor itself is only one of three problems entering into the governing of a waterwheel unit as set forth above. The function of the waterwheel governor in itself is the moving of the guide vanes a proper amount in the proper time, and the readjusting of the guide vanes to the proper conditions of power and speed after the pressure rises produced by the movement of the vanes have been dissipated and conditions have returned to normal for that required power. The waterwheel governor has to perform more functions than any other type of governing apparatus, since it must move the gates to control the rise of pressure in the pipe line and the rise of speed caused by it.

FIG. 19—11,000-H. P. VERTICAL-SHAFT TURBINE

Single-runner, cast iron, spiral-cased type, 360-rev. per min., 258-ft. head. Supporting barrel ready for generator.

A centrifugal flyball imparts motion to the center of a floating lever and the springs of the flyball are usually designed so that the governing mechanism is caused to operate quickly from wide open to closed position and vice versa when the speed has changed in the same time through a range of 20 per cent to 35 per cent of normal, this percentage selected depending upon the $W R^2$ of the revolving parts and the relative inertia of the water to be handled. After this sudden change of speed and motion of gates has taken place then compensation must take place to bring the speed back to normal. This is accomplished through a compensating dash pot introduced between a connection to the shifting ring and the end of the floating lever opposite that to which the regulating valve is connected. This dash-pot arrangement is so devised that for slow changes of load from no-load to full load the drop in speed may be zero or may be 2 per cent for parallel operation as per adjustment of the governor, but for quick changes of speed the gates can be closed or opened only by a change of speed from 20 per cent to 35 per cent as may be adjusted, thus introducing the time element, because the proper $W R^2$ will require time for the absorption of the uncontrolled energy.

Modern hydraulic governors are so sensitive that a change of speed of less than ¼ of 1 per cent will serve to move the gates to cause an adjustment of the guide vanes, and consequently the flow of water to compensate for the speed change. The conditions of inertia and $W R^2$ introduce dangerous factors into the regulation of the plant. These factors are controlled through the time element of motion of the gates. This time element is dependent upon the reliable motion of the flyballs, consequently some means of reliable and effectively fixing the time of the flyballs with reference to the speed of the unit is very desirable in plants having bad conditions for regulation.

Fig. 11 shows a type of self-contained governor which is eminently suited for low-head open-flume plants. The particular governors herein shown are self-contained, having no interconnections; they have now been in operation seven years, and a recent examination of the plant showed that at no time has it been found advisable to have interconnecting piping between the governors.

Fig. 12 shows a directly connected flyball which has been used on a good many of the large plants. This type of flyball avoids the use of belts and the possibility of shut-down from their breakage, and also avoids the gears with the necessary small bearings on the horizontal jack-shaft.

Fig. 13 shows the governor stand for controlling the gates of the 37,500- h. p. unit of the Niagara Falls Power Company. In this particular design the operating fluid is supplied from a central oiling system. The operating fluid is water containing a percentage of oil.

FIG. 20—CAST STEEL SPIRAL CASING

Having a thickness of three inches to withstand a head of 421.5 feet.

INTEGRAL GOVERNORS

The latest advance in the art is that of the integral governor illustrated in Fig. 14, wherein it will be noted that the governor motion is imparted by flyballs mounted directly upon the main shaft and the operating fluid is controlled by operating valves and governor mechanism located immediately on one of the operating cylinders connecting to the shifting ring directly through reach rods. The hand-control mechanism is located on the other operating cylinder. By means of this design we come back to the accepted practise in steam turbines, steam and gas engine design, wherein the governing mechanism is an integral part of the prime mover. The waterwheel governor has so many functions to perform that it is necessarily complicated, and in the early development of the art the governors were made by companies separate from the waterwheel builders; consequently it came to be the accepted practise to consider the governors as a mechanism unto themselves. The present waterwheel governors, however, are so strong in design and reliable in operation that they do not necessarily have to be located on the generator floor immediately under the control of the operator, particularly since the unit may be controlled through a small synchronizing motor from the switchboard. The trend is toward the further simplification of the governor equipment and it is believed by the writer that we will in time come to the self-contained governor with no interconnection between the pressure systems of the several governors as is now frequently the case. Certainly the complicated central system with large sizes of piping required is not receiving the sanction of the buyers as much as formerly. A step in the right direction is the design of the Wateree Power Company, having direct-connected flyballs and the pump which provides the oil pressure for operating the governor driven through gears from the main turbine shaft, as shown in Fig. 15. In the case of the Mount Shasta Power Company the switchboard gallery is located above the main generator floor, and by adopting the integral governor the floor men are automatically placed on the turbine deck.

TURBINE CASING

In low-head open-flume plants the casing is omitted but the walls of the flume are frequently shaped to form more or less of an open spiral so that the water may be directed smoothly to the runner. It is of prime importance that the water flowing to the guide vanes be kept free from eddies and whirls and as nearly an ideal stream flow as possible. It has been found and determined definitely that disturbed flow does increase the efficiency of a waterwheel unit, although the loss of head by that disturbed flow cannot be determined in the stream entering the unit. An analogous condition to that of disturbed water flowing through a runner is that of water flowing over a weir.

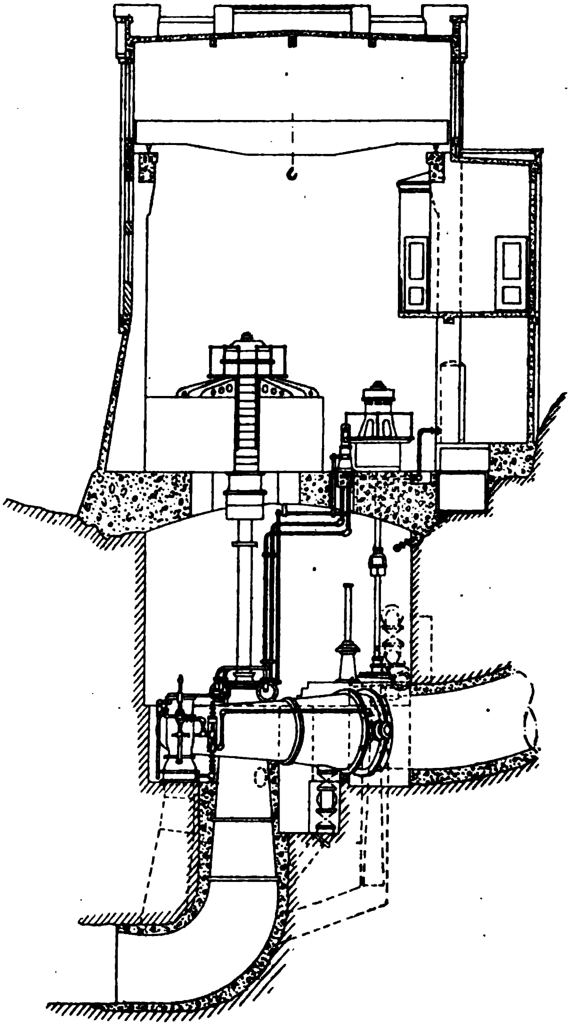

FIG. 21—POWER HOUSE OF KERCKHOFF PLANT OF SAN JOAQUIN LIGHT & POWER CO.

Containing three units, each 15,000-h. p., 315-ft. head, 360-rev. per min. Butterfly valves, pressure regulators, curved draft tubes, and direct-connected flyballs.

Small eddies or cross currents in the stream flow approaching the weir, although so slowly and quietly as to be practically negative, and are certainly not sufficient to break the surface of the water; yet they produce breaks and notches in the weir crest several inches deep, when they flow over the weir. If such disturbances are occasioned in the flow over a weir, which is accompanied by such small surface disturbances, how much greater must be the action within the guide vanes and runner where the velocities are much higher, by disturbed conditions of flow in a pipe where the eddies and whirls may easily be many times that shown on the surface of the water back of the weir. The result of this disturbance has been definitely shown in the decrease of efficiency of the waterwheel.

The spiral casing affords the best means of conveying the water from the pipe line or forebay to the speed ring placed around the guide vanes. The spiral should be proportioned not exactly as per the decrease of the water as it passes through the annular opening through the speed ring to the guide vanes, but the casing should be kept slightly larger toward its smaller end. Water flows around an elbow at greater velocity on the short radius of the elbow than on the long radius of the elbow, and consequently, this higher velocity on the inner radius of flow is very much accentuated since the angle of flow is through 360 deg. in the spiral casing instead of 90 deg. in case of the elbow, consequently, as the velocity is increased on the inner portion of the spiral casing, the area of the spiral should be increased so as to reduce, if possible, the average velocity and consequently maintain the velocity at the inner radius of the spiral as nearly a uniform velocity around the casing as possible.

Concrete spiral casings of rectangular cross-sections have been used in many plants with success, but the present trend in this connection is toward concrete spiral casings having circular cross-sections, with reinforcing rods in the concrete around this circular section, with either end of the reinforcing rod secured to the flanges of the speed ring. A concrete spiral casing of this type is illustrated by Fig. 16. Concrete spiral casings are suitable for heads up to 70 feet or 80 feet only when the superstructure of the power house is imposed on top of the spiral casing to avoid the tension in the reinforcing rods and in the concrete.

A good design of power house, adopting concrete spiral casing reinforced in the manner above mentioned, combined with a section of the dam, is illustrated in Fig. 17. In this design the overturning force of the water against the upstream face of the dam is transmitted through the concrete to the top of the spiral casing and reacts to resist the upward forces produced by the pressure within the spiral casing. Fig. 18 shows a plate steel circular section spiral casing installed at the Lookout Shoals Plant of the Southern Power Company. The head obtained at this plant is 80 feet. This type of casing has been used very extensively during the last eight years on heads varying from 30 feet up to 215 feet. In the latter case the diameter of the inlet to the spiral casing was 11 feet and the thickness of the plate at this diameter was ⅞ inch. Larger casings with heavier plates are being contemplated for similar heads. The advantage of this casing is its cheapness in first cost, its resistance to sudden shocks and its ease of transportation.

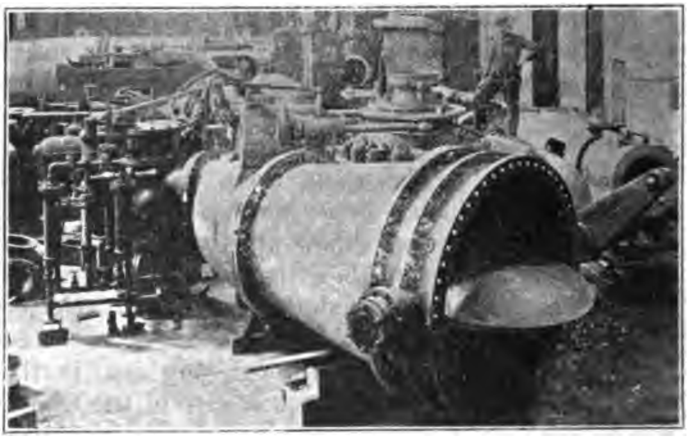

FIG. 22—SHOP ASSEMBLY OF 15,000-H. P. TURBINE UNIT

315-ft. head. 360-rev. per min.
84-in. butterfly valve, pressure regulator, and regulating cylinders.

Cast iron spiral casings are frequently employed, such as are illustrated in Fig. 19. This casing is made in two parts and the unit develops 11,000 horse power under 258 feet head at 360 rev. per min.

The cast steel spiral casing illustrated in Fig. 20, being built for the Mt. Shasta Power Corporation, embodies the latest improvements in high-head spiral casings. The waterwheel is equipped with twenty guide vanes, the casing has ten speed vane ribs, and the casing is divided naturally into five sections each with two speed vane ribs. The ribs are cast integral with the casing. Special provisions were used in preventing casting strains in the making of these castings. Each of the speed vanes are of a definite design decreasing in size around toward the small end of the casing and varying in angular relation to the casing to accommodate each particular speed vane to the flow of the water at that point.

There is no hard and fast line fixing the use of one type or the other of spiral casings but, usually, the configuration of the ground surface at the location of the plant determines the particular type of development best suited for the maximum development of efficiency, taking into consideration economy of construction.

VERTICAL VS. HORIZONTAL UNITS

The trend of modern design is toward larger and larger units and toward designs which will give maximum amount of power from the energy of the water available. This naturally leads to the single-runner, vertical unit because, as pointed out, the larger the waterwheel and generator, the more nearly in accord are the economical speeds of the two. The larger the waterwheel runner, the more difficult it is to place the runner with the shaft in horizontal position. The higher the specific speed of the runner, the greater the energy in the discharged water; consequently, the more important it is to adopt a regaining device which will return the maximum amount of that energy to the runner for effective development of power.

CONTROL VALVES

A recent invention comprising snap rings disposed around the periphery of the disk of butterfly valves provides a means of making this type of valve substantially water-tight. This should bring this type of valve into more general use because of its great simplicity and reliability in operation.

Fig. 22 shows the butterfly valve constructed for the Kerckhoff Plant of the San Joaquin Light & Power Corporation, having a diameter of 84 inches and operating under a head of 315 feet. Note the simplicity of a valve of this type, and the small obstruction which the open wicket causes to the flow of the water through it.

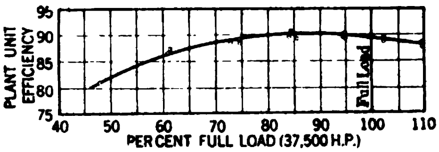

FIG. 23—CURVE SHOWING COMBINED EFFICIENCY OF ALLIS-CHALMERS TURBINE AND GENERATOR

37,500-h. p., 214-ft. head, 150-rev. per min.

POWER HOUSE SETTING

It is really a misnomer to say modern power house setting, because each power development requires a setting peculiar to its location, and that setting is modern only when there is brought to bear in its design experience gained on other power plants. One type of development, if we may call it such, is that exemplified in the Wateree Plant of the Southern Power Company, wherein the power house is made a part of the dam. At this location there was sufficient width in the river to place the power house as a part of the dam and thereby save expense. Another location of apparently similar conditions might necessitate a spillway of the full width from bank to bank which would force the development of possibly a new type of power house or the best of the existing types of power house.

The best power house setting can only be obtained by a careful analysis of all the factors, the aim being, as always, to produce a plant which will after years of operation prove the least expensive, considering not only the original investment, but the operating and depreciation charges.

DISCUSSION ON "HYDROELECTRIC DEVELOPMENTS AT NIAGARA FALLS" (HARPER AND JOHNSON), AND "MODERN DEVELOPMENTS IN WATER WHEELS" (WHITE), SALT LAKE CITY, UTAH, JUNE 21, 1921.

E. A. Pragst: I would like to ask Mr. White if when he plotted these curves between specific speed and head, he found that the specific speeds of modern European built runners were not a little higher than those used in this country, and if so would he attribute it to the excellence of design or simply to commercial reasons, *i. e.*, to a willingness to accept a more rapid deterioration of the runner with a corresponding lowering of efficiency thus necessitating frequent replacements of runners but effecting a saving in first cost instead of using a more expensive unit of lower specific speed which should have a higher maintained efficiency and require less maintenance.

Wm. M. Moody: On page 944 the author has divided draft tubes into three classes, straight conical tubes, curved draft tubes, hydraucone regainers. I might remark that there are other forms. The author also states, "The conical center is not essential as tests have proven that substantially the same results have been secured by the omission of the conical center even in regainers having the upper walls especially designed with reference to the cone center." I suppose this conclusion results from the experiments referred to in the author's paper "The Hydraucone Regainer, etc." These experiments were made on models of the draft tubes alone under conditions of no whirl, whereas tests made in the laboratory on a complete model turbine showed that with a runner of 83 specific speed equipped with a spreading type draft tube, removal of the central cone resulted in a drop in maximum efficiency of 2½ per cent and a drop in maximum power of 9 per cent. The hydraucone involves the principle of a jet impinging against a flat plate and certain of the central stream elements are reduced to approximately zero velocity and then accelerated after impingment, whereas in the spreading tube no such principle is involved and there is at all points a constant and gradual decrease in velocity.

W. J. Foster: This development at Niagara Falls that has been discussed in Messrs. Harper and Johnson's paper was unique in certain particulars, *viz.*: the calling together for a general discussion of hydraulic and electrical engineers before any specifications were put out, and in emphasizing machinery of the highest possible characteristics, initial cost being a secondary consideration. There is, nothing that is more satisfactory to the electrical engineering profession than that attitude on the part of the purchaser.

Mr. White's paper presented arguments with reference to speed in such a way as to cause the impression that this installation at Niagara Falls, consisting of 32,500-kv-a. generators, at 150 revolutions, was both the most efficient and the least costly unit of that size. Now, I am inclined to think that it would not be possible to design or build a generator of higher efficiency than the one at Niagara Falls, *i. e.*, a generator of 32,500-kv-a. and 12,000 volts that would have higher efficiency than the 98 per cent mentioned in Mr. Johnson's paper, but I am very sure that generators at higher speed having practically the same characteristics with exception of efficiency would cost less.

E. M. Breed: On page 903 of the Johnson paper we read, "A renewable ring is provided in the draft tube just below the runner, and the upper section of the draft tube is furnished with manholes for inspection of tube and runner discharge."

A study of the rather small scale drawing of the unit fails to indicate the construction at this point and I would ask Mr. Johnson whether the design includes provision for removing the runner from below when necessary to replace wearing rings or install a new runner; or does the generator and upper turbine ring casing cover have to be dismantled to remove the runner. As there is an unfortunate human tendency to delay such replacement from month to month wherever it requires a considerable expenditure of time and effort to make the change, and as the efficiency of such units decreases rapidly when wear develops at the clearance rings, there is often a considerable loss in power output and revenue unless provision is made to accomplish such change easily.

Also, on page 903 of this paper, it states in reference to the type of draft tube design used; "This results in higher efficiency than the old type of curved draft tube, which does not regain the whirl. The spreading tube also eliminates surging and water hammer, which so often occur with curved draft tubes." "By the use of the hydraucone or spreading draft tube about 80 per cent of the velocity head in the discharge is recovered, whereas with the old type of curved draft tube a large proportion of this velocity head is always lost."

This statement is very general—no limitations or exceptions being given. It was manifestly made in connection with the 37,500-h. p. turbines being described but as the statement that the use of the old type of curved draft tube always involves the loss of a large proportion of the velocity head is applicable only to certain types of turbine runners and certain kinds of turbine settings a brief discussion of this feature will be of interest. The function of the draft tube is to provide a closed passage between the runner and the tailwater of such a shape as to permit of transforming the energy in the form of velocity head discharged from the runner into energy in the form of pressure head. This velocity head existing in the discharge from a high specific speed (low head) type runner is at all gates composed of an axial component and a whirl component and the form of draft tube known as the spreading type or hydraucone has been developed to more efficiently regain the energy of the whirl component. However, the discharge from a properly designed low specific speed reaction runner (high head type) and from a medium specific speed runner at all except the small gate openings does not contain a whirl component of the velocity head and for such installations the straight conical type draft tube with small angle of diffusion and elbow discharge is highly efficient and has given entire satisfaction in a great many installations. I will, in connection with my discussion of Mr. White's paper refer to a plant where this type of draft tube has been installed to handle the discharge from two 25,000-h. p. turbines and on recent tests the draft tubes showed a very high efficiency.

There is also another interesting consideration to be noted in connection with the choice of draft tube type, and that is the economic values. There is a considerable range of hydraulic development involving the use of runners bordering on the low head type or in between the low head and medium head type where the draft head being only a small per cent of the total head it is questionable whether any measurable gain in overall efficiency of the hydraulic prime mover can be obtained by the use of the hydraucone type of draft tube and there is a very considerable probability that the use of the hydraucone type will considerably increase the first cost of the substructure and in fact of the entire power house, not only due to the much more involved and difficult nature of the concrete work in the foundations of the unit, but also in the increased dimensions of the power house due to the shape and horizontal dimensions of the hydraucone.

Mr. L. F. Harza, of Chicago, in discussion of paper by Mr. Forrest Nagler at the December, 1919 meeting of the A. S. M. E. at Chicago, advised that in a power station designed by him, it was found the estimated cost of the substructure and superstructure was increased by nearly 50 per cent in using the hydraucone.

Also, in an article published in the September 23rd, 1920 issue of the *Engineering News Record* by Mr. Louis S. Bernstein, Designing Engineer, Niagara Falls Power Company, it is stated that in the use of the hydraucone type of draft tube, the "Problem of supporting the unit becomes more complicated; in special cases, where the turbine and generator are of extreme size and weight, special provision must be made to take care of the vibration of the machine as well as the superimposed loads." He describes in considerable detail, the extra heavy reinforcing of the concrete foundations considered necessary.

It would, therefore, appear that in these installations where the advantages to be gained by the use of the hydraucone type are questionable, careful consideration should be given to the extra cost involved in the use of the hydraucone.

Mr. White is to be complimented on the comprehensive manner in which he has covered the subject of modern turbine development. The question of low head turbine design and high specific speeds is very much to the front these days, especially in the East where large low head developments predominate. In the West, however, where constant advance in long distance power transmission enables us to get farther and farther back into the mountains, the subject of high head turbine design is of considerable importance.

The interest shown in the 800-ft. head reaction turbines recently designed and manufactured by the company with which the speaker is connected, and the fact that some articles have appeared in the technical press giving a rather imperfect or even incorrect idea of these units may possibly warrant a brief description of some of the features of these turbines.

These turbines, of which two constitute the complete development of the Kern River No. 3 Plant of the Southern California Edison Company, are vertical units having a capacity of 25,000 h. p. each under 800-ft. effective head, and at a speed of either 500 or 600 rev. per min. As this is, by a considerable margin, the highest head under which reaction turbines have ever been designed to operate, a most careful study of the entire problem was made.

The power water, which is taken from Kern River about 12 miles above the plant and conveyed to the forebay by flume and tunnel, is delivered to the turbines by individual lap-welded steel penstocks 2500 ft. long, reducing in diameter from 72 in. at the upper end to 60 in. at the turbine.

No storage is available at this development and at certain seasons of the year the flow is less than is required for both turbines at full load. As it will be frequently necessary at this period to deliver power from one of the units into the 60-cycle system and from the other into the 50-cycle system the governors have been so designed together with certain special interconnecting mechanism that when one turbine is regulating under fluctuating load on the 60-cycle system the other turbine will automatically take on or reject load in inverse proportion, thus maintaining the water level in the forebay within narrow limits and insuring the most efficient utilization of all the water available.

The turbines are designed to permit of the use of interchangeable runners for either 500 or 600 rev. per min. thus permitting of delivering power to either the 50-cycle or 60-cycle system of the company. The lower casing cover and upper part of the draft tube are of a special patented design developed by the manufacturer to permit of easily and quickly removing and replacing the runner from below without disturbing the generator or the gate mechanism on the top or bottom sides of the turbine. It is interesting to note in this connection that a complete change of runners has been made in 20 hours, with a green crew. This covers full time from taking unit off the line until it was ready to put into service again.

The runners are of bronze and provided with rolled steel clearance rings so designed and located as not only to reduce to a minimum the leakage by the runner but to produce a very considerable uplift force thus reducing the load on the supporting thrust bearing mounted on the top of the generator.

The wicket gates are of hydraulic press forged steel with spindles extending through both the upper and lower ring casing covers and provided with independent lubrication from each end. The shop work on these gates was so accurate as to reduce the leakage when closed to an amount such that a back pressure of 150 pounds is built up in the casing through a 4-in. by-pass before opening the Johnson valve.

The governors are designed to easily make a full stroke in 2½ seconds and the speed regulation characteristics of the units are extremely good, showing on test speed fluctuations considerably below those guaranteed. The speed rise with 22,800 h. p. thrown off was 17 per cent.

The governor operated relief valves are of 100 per cent capacity designed for automatic water economizing and during test were adjusted to limit the pressure rise for full load rejection to from 10 per cent to 12 per cent.

Very careful efficiency tests have been made on these turbines, the water quantity being measured by venturi meters in the penstocks. The results obtained are highly satisfactory, particularly when the high head is considered, the efficiency being some 1½ per cent above guarantees and showing a maximum at about 22,000 h. p. The efficiency curve is very flat, being above 90 per cent over a range of 7000 h. p.

A few words in regard to the draft tube will be of interest. The specific speed of the 500 rev. per min. runner is 18.6 and of the 600 rev. per min. runner is 22.3. A straight draft tube with small angle of diffusion and elbow discharge has been used and no evidence of noise or draft disturbance is present. The normal distance between center line of runner and tail water level is 10 ft. and the conversion of velocity head to pressure head is equivalent to about 17 feet, the draft tube having an efficiency of slightly above 80 per cent. Readings of the calibrated vacuum gages checked against known data of runner design indicate the correctness of these figures.

J. A. Johnson: In regard to the question of removing the runner from below. This was very seriously considered in the design and it did not appear from consideration of conditions at Niagara Falls that the provisions would be justified. In the first place the narrow space between the high bank and the river for the facilities which it was necessary to provide, including a channel for the reclaiming of the water for possible future use in the second stage of the development, limited very closely the width of the power house. The necessary passages below the wheel casings would also have been very difficult to provide in view of the type of draft tubes employed. As the wheels were expected to operate at a very efficient point with almost entire absence of pitting, it did not appear that the complicated provisions for removing the runner from below would be justified. It is of course some labor to dismantle the generator but these wheels have overload capacity so that when the plant is completed the other units will be able to absorb the load of any one for a short time without injury so that it would not necessarily mean a reduction in output during the time when the generator would be out temporarily for replacing the runner.

In regard to the economic justification for the spreading type of draft tube; first as to the relative merits of the spreading draft tube and the straight type. It was not our intention in any way to claim that the spreading or hydraucone type draft tube was inherently superior to the straight draft tube if the latter is made sufficiently long but the water passages were so great and the distance between units and other conditions such that the depth of excavation necessary for a straight draft tube was entirely out of the question. The reason for the spreading type as opposed to the curved type was the increased efficiency gained thereby. I do not know if you people in the West have been closely enough in touch with the Niagara situation to realize it but it is a fact that in the East what goes on at N agara is always closely watched by engineers and public alike, and consequently it is always necessary for us to err, if at all, a little bit on the side of safety, on the side of efficiency, rather than on the other side. The use of the more efficient spreading type of draft tube or hydraucone was justified on these grounds if on no others.

W. M. White: I want to say that Mr. Foster is probably right in his statement that it would have cost his company less to make that Niagara generator of a higher speed. In our case our decision was based on consideration of the entire unit, our conclusion being that the lower speed incurred no loss of generator efficiency and little or no extra expense, and at the same time gave considerably better efficiency and greater life of runner. The final combined efficiency result testifies to the correctness of our judgment.

With reference to the specific speed of the runner and the question of pitting brought up by Mr. Pragst, it may be occasionally economical to go to higher speeds and renew the runner when it has pitted, but the saving in first cost has to be balanced against the probable loss due to interruption of service and cost of new parts. Mr. Pragst is correct that European builders go to higher speeds under high heads but their tendency to do so is most decidedly due to commerical reasons and due to catering to an export trade rather than to building apparatus which will have the longest life and that will result in the greatest economy to the owner.

My simple reference to the hydraucone has been used by my competitors as furnishing an opportunity to criticize it. Experiments on the hydraucone began in 1913. These experiments, which were conducted personally and privately for sometime, extended over three years resulting in the hydraucone or spreading draft tube which are one and the same, identical, spreading the water out into a concentric passage and discharging in a radially outward direction.

The Niagara Falls letting brought together at Niagara Falls Mr. Foster of the General Electric Company, Mr. Williamson of our company, the engineers of the I. P. Morris Company, and the writer, other companies not being asked to bid. At that meeting we brought the hydraucone to the attention of the engineers of the Niagara Falls Company and told them we had something new we wanted them to investigate. They stated that they would take it under advisement.

Prior to the next conference on the subject our competitors had advised the Niagara engineers that they could supply the same diffusion efficiency with a curved draft tube, that is, 80 per cent. This is a matter of record in Mr. Shepard's paper. Each of the companies was asked to present a model for securing the maximum possible efficiency. These were tested not by me but by the engineers of the Niagara Falls Power Company. These tests showed at once that the curved tube was just as we had stated it would be and that its efficiency was such that it was not to be considered for the development in question because at Niagara Falls it is important that every possible ounce of power be gotten out of every cubic foot of water. The Moody spreading tube which was developed for the Niagara Falls work after many failures of curved draft tubes is identical to the one which we had over five years ago. Mr. Shepard the hydraulic engineer of the Niagara Falls Power Company, was in charge of all of these tests. His work on the Moody tube showed very thoroughly when they took the cone out of it the efficiency was no less. Mr. Moody has pointed out that these experiments were made on models of draft tubes receiving water under the conditions of no whirl That is true, and the results are all the more striking for that reason, as the contrast between any form of tube and a curved or elbow type of tube is greatly emphasized when such whirl is used in the test. This is due to the fact that any concentric form, even including the straight conical type, handles whirl as efficiently as straight flow whereas a curved draft tube does not. Mr. Moody's further remark that a certain model with a given spreading draft tube having a cone in the center showed lower efficiency after the cone was removed is merely an indication that the form of the outer or enveloping surface was not correct where the particular velocity and whirl conditions existed. The original experiments which resulted in the development of the hydraucone started with a conical center and it was found that as the size of this center was reduced and its angle flattened the efficiency of the water wheel was increased provided the form of the outer envelope was changed to give the proper velocity conditions. This led to a large reduction in the size of the center cone and for the majority of conditions to a complete elimination of it and to the substitution of a surface approximately flat.

The straight draft tube will give just as good efficiency if you can get it long enough, but no power plant owner can afford to go down into the foundations fifty feet or more and secure proportions which will give economical discharge velocities and efficiencies corresponding to those obtainable with a hydraucone or spreading draft tube. It is possible on high head runners which have a low discharge velocity to secure a sufficiently long straight conical draft tube combined with an elbow bend to so reduce the velocities and consequently the energy contained in the discharge as to make curved tubes show high power plant efficiencies under such conditions. This does not indicate that even higher efficiencies could not have been obtained with a concentric tube, and is not at all an indication that efficient diffusion can be obtained with a curved draft tube. It simply indicates that the discharge energy is so far reduced before the elbow comes into action that its detrimental effect is not sufficiently great to prohibitively reduce the efficiency. The lower the specific speed of the runner the more immeasurable is the detrimental effect of a poor draft tube until in the extreme case of the impulse wheel draft tubes are omitted entirely.

This I believe contains the explanation for the result cited by Mr. Breed. One of his statements, however, to the effect that a low or a medium specific speed runner discharges without whirl at all except the small gate openings is not correc . Any runner can have but a single gate opening at which the discharge from it is free from a whirl component. A simple study of velocity diagrams will prove this point conclusively. Mr. Breed's conclusion that an elbow discharge on such runners gives good results because of such elimination of whirl is entirely wrong. I have endeavored to give the real explanation above. If Mr. Breed had made a pitot traverse showing the velocity and direction of the water leaving a low specific speed runner he would not have made such a statement. There are undoubtedly developments involving the use of low head or maximum type of runners where it is uneconomical to make use of the hydraucone for the reason cited by Mr. Breed. It should be remembered, however, that the power house cost is usually but a very small percentage of the total cost of any hydraulic development, and a slight increase or decrease in the cost of the item becomes almost inappreciable when contrasted to the entire cost of the work. Each percentage gain in efficiency, however, means return on the entire investment and there are numerous cases where a gain of 2 to 6 per cent in kilowatt hours output has justified a fraction of 1 per cent increase in the initial cost of the entire project. This is indicated by the fact that to date hydraucones have been installed on water wheels totaling over 265,000 h. p. capacity.

The runners at Niagara Falls cannot be removed without dismantling the generators because it was not considered advisable to make that provision and they decided against it.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 22, 1921.

LONG-DISTANCE TRANSMISSION OF ELECTRIC ENERGY

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ABSTRACT OF PAPER

The paper discusses long-distance transmission of electric energy dealing with (1) the economic conditions which justify it, (2) the plant involved, and (3) the service that may be expected.

The economic conditions which justify long-distance transmission of electric energy are a cheap source of power with an insufficient local demand to absorb it, and a distant market to which the energy can be delivered cheaper than energy can be supplied at that point from any other source.

In dealing with the plant required for long-distance transmission some of the considerations that affect the design are discussed. A graphic method of determining line performance is illustrated by an example, and some essential data on other lines are given. Among the important physical considerations entering into transmission line design, right of way, spacing of towers, line insulators, high-tension switches and lightning arresters are discussed.

Service is considered from the viewpoints of, what people demand, what perfect service will cost, and the service that may be expected from a large interconnected system consisting of steam plants at the mines, hydro plants wherever available and local steam plants.

IT IS PROPOSED in this paper to discuss long-distance transmission of electric energy from three standpoints. First, from the economic point of view, by consideration of the conditions which justify long-distance transmission. Second, from the physical viewpoint, by dealing with the design, construction, and operation of long-distance lines. Third, from the point of view of service, by consideration of the factors, contributing to continuity of service and its value to the people served. This discussion is to some extent based on studies which have recently been made in the development of a superpower system, for the industrial district along the Atlantic seaboard.

THE ECONOMIC JUSTIFICATION FOR LONG-DISTANCE TRANSMISSION

The laws governing the distribution of electric energy under ordinary conditions, losses involved and the various items entering into distribution costs, are fairly well-known. However, when large amounts of electric energy are to be transmitted over long distances the problem is greatly complicated by factors which do not appear, or are negligible in the ordinary distribution of energy. In every power transmission problem the question to be answered is: Can energy be generated and transmitted to the point where it is needed, more cheaply than it can be generated at the point of demand?

The two available sources of power at the present time are expansive force of steam and the energy of water acting from force of gravity. In addition to these we have various forms of chemical energy, energy from internal combustion engines, the mercury vapor engine, energy from the winds and tides and heat energy from the sun, but the application of these as prime movers to the generation of millions of kw-hr. for general distribution appears to be remote.

The point at which energy can be developed by water power is located for us by nature and we must make what we can of it. A power plant located at a waterfall is rarely in an industrial community or where an industrial community may be developed. There are exceptions to this as at Niagara Falls, but in general waterfalls are in out of the way places and their use for power development must either await a local demand, after factories or electrochemical works are built, or the energy must be transmitted to already developed communities where there is demand for it. The problem is whether it will pay to develop it at all, and if this is answered in affirmative whether it will pay better to use the energy nearby or to transmit it to a distant market.

Electric energy by whatever source of power it may be generated should be used in such manner as to supply the economic needs of the country at maximum efficiency. This in general means that hydroelectric energy generated at waterfalls away from centers of industry and steam-electric energy generated at the coal mines must be transmitted to distant centers of demand in order to find a market; but if a demand should exist near the place where the power is generated then that demand must be supplied first, and only the residue, if any, transmitted to the more distant point. This statement should be qualified by the proviso that the local demand for energy be such that the economic needs of the country be supplied by that means more cheaply than in any other way. For example, energy generated by water power at Niagara Falls should be used at that point for the manufacture of chemicals needed by all the people of the country and which can be manufactured and marketed from there more cheaply than anywhere else, rather than sent to New York with the attendant losses and cost of transmission. Niagara Falls energy should not be used locally for heating dwelling houses and factories, even if the producers could furnish it for this purpose, at a profit to themselves, as houses can be heated more economically in some other way. If such use were the only local means of absorbing Niagara energy, then such energy should be sent to a more distant market where it would serve a better purpose. Furthermore, Niagara energy should not be sent to more distant points so long as there is a demand for it in Buffalo, or nearby cities. If, however, hydroelectric energy can be developed at Niagara Falls faster than it can be absorbed in the surrounding territory, it would be in order to build transmission lines to convey the excess energy even as far as New York provided it can be sold at a price which would permit the amortization of the transmission plant while the local demand is being built up. Thus if governmental permission could be obtained to divert water from the Niagara River for generation of 600,000 kw. it is quite within economic possibility that a block of 300,000 kw. could be transmitted to New York and sold at a price which would net a profit to the promoters and provide an adequate sinking fund to retire the investment in transmission equipment. The reason such expenditure can be justified is that energy in bulk is worth about three times as much in New York as it is worth in Niagara Falls.

There are many places where electric energy may be generated from water power where there is locally no present or prospective demand for it. Such locations in the eastern states where large amounts of undeveloped energy may be obtained are the St. Lawrence River, the rivers of the Adirondack Mountains, and the rivers of Maine. The question here is: Can these developments be made and the energy transmitted to any existing, or prospective markets, cheaper than a like amount of energy can be generated at the point where the demand exists, or developed and transmitted to that point from any other source? The competing source of energy will probably be steam-electric energy generated locally or at the mines.

In the case of long-distance transmission of energy from steam plants the same law holds good, that such energy should be used as near the point where it is generated as possible, provided the needs of the country are thereby supplied more cheaply than in any other way. If, for instance, there should be found an economic demand in the anthracite region of Pennsylvania for all the energy that can be generated in that region, due to limitation in supply of condensing water or steam sizes of coal, or to any other cause, then such energy should all be used in the anthracite region. In any case only the residue, after supplying the local needs, should be transmitted to distant centers of demand. The anthracite mines are very deep and require much energy for pumping ventilation and for haulage. In this region it requires 20 kw-hr. of energy to mine and place on the cars one ton of coal. When all the mines are electrified as they probably will be within the next few years, the 80,000,000 tons of coal mined per annum will require 1,600,000,000 kw-hr. of energy at a demand rate of about 400,000 kw. The railroads in the anthracite region will doubtless soon have to be electrified on account of the heavy tonnage and the steep grades. This territory is also developing a large miscellaneous industrial load. It is estimated that approximately 800,000 kw. will be required to supply the total demand for electric energy in this region within the next ten years. All this demand will have to be satisfied, before energy is sent from this region to distant markets.

There are limitations in generating power in the anthracite region due to the amount of condensing water and steam sizes of coal which are available. If, however, highly efficient generating plants are built to supply the 800,000 kw. needed for the local demand, considerable off peak power will be available for transmission to such load centers as New York and Philadelphia. There is also considerable diversity of load between these centers as the peak of the load in the Metropolitan District does not come on until a large part of the load in the anthracite region has gone off.

In the bituminous fields of the Appalachian region the conditions are very different from the conditions in the anthracite field. Very little shaft mining is done and consequently very little energy is needed for pumping water or hoisting. This condition will exist for some years until deep level mining becomes necessary. Eighty per cent of the bituminous mines are already electrified—the principal use of energy being for mine haulage. Therefore, almost all the energy which can be generated at the bituminous mines is available for distant markets.

Unfortunately there are few locations near the mines within reasonable transmission distances of load centers along the Atlantic seaboard where steam plants can be located convenient to coal supply and where there is ample condensing water. Investigation shows that there is no location within 300 miles of New York City where both coal and water can be found for a 100,000-kw. high-efficiency steam plant without the necessity of transporting coal from 10 to 50 miles by railroad. Therefore, quite an appreciable freight charge is involved even for such plants.

The cost of gathering coal from the mines and delivering it to the power plant which must be located where condensing water is available, has a very important bearing on the general problem of transmission of electrical energy from the coal mines. In order to justify the transmission it is necessary to show that the value of the energy lost plus the fixed charges on the cost of the transmission plant is less than the net cost of freight on coal required to generate the same amount of energy at the point of use.

In view of what has been said the economic justification for long-distance transmission of energy may be stated as follows: In the case of all energy generated, either steam-electric or hydroelectric, after the local demand has been satisfied, the residue may be transmitted to distant centers of demand when it can be delivered more cheaply than the energy can be supplied at that point from any other source.

LONG-DISTANCE TRANSMISSION LINES

It is not the purpose of this paper to show how to design high-tension transmission lines, nor how to calculate the performance of these lines, but to point out some of the considerations that must be taken into account and to give some typical examples of design and line performance that have been worked out.

A transmission line should be capable of transmitting the amount of energy for which it is designed at minimum cost. Kelvin's law may be used in the design of high-tension lines by including in the investment the cost of other apparatus which varies for the different sizes of conductors compared, as for example, towers, insulators, transformers, synchronous condensers, switch equipment, etc., the interest and depreciation on which shall equal the value of the energy lost. The law, however, must be applied with the reservation that corona must not be the limiting factor. The design of long-distance lines differs from the design of ordinary circuits for carrying electric energy in that certain factors must be taken into account that may usually be neglected. Corona, reactance and capacitance are each factors that have to be carefully reckoned with. Each of these characteristics present definite limitations which are susceptible of accurate determination in advance. These same limiting characteristics are useful in the operation of the line and may be regarded as making long-distance transmission of electricity possible.

Corona becomes a serious limitation to long-distance transmission at high voltage. There is a critical disruptive voltage for each size of cable, depending on the spacing and arrangement of conductors, the elevation above sea level and the meteorological condition of the atmosphere. Rain, fog, and particularly falling snow increase the tendency for energy to discharge from the conductors and lowers the critical voltage.

Thus for a particular voltage, elevation and climatic condition, there is a definite lower limit to the size of conductor that can be used irrespective of whether this is the most economical section so far as cost balanced against losses is concerned. It may easily happen in a particular instance that diameter in transmission conductor is more important than conductivity and this may determine the material of which the cable is composed or the manner in which it is made. Increase in diameter may be obtained by using aluminum or copper cable with steel core. Corona, however, has at least one redeeming quality in that it doubtless assists materially in dissipating induced high-frequency charges on the line that otherwise would be destructive to insulation of line, transformers and switches.

Reactance limits the amount of energy that can be transmitted over a given line. It varies with the size, arrangement and spacing of the conductors and the reactance volts vary with the current to be transmitted. With a particular line and a definite amount of energy to be transmitted the reactance voltage drop to be dealt with is decreased by increasing the voltage. Where reactance is the factor limiting the amount of energy that can be transmitted over a given line the only way to increase the amount of energy that can be transmitted is to increase the voltage. This in turn may be limited by corona unless the diameter of the cable is increased. Increase in size and consequent cost of conductors for a particular transmission has a definite limit depending on the cost of producing energy in some other way at the point of destination. Reactance is useful, in that it limits the current that can flow in case of short circuit. It thus prevents destruction of the windings of transformers from excessive mechanical strains and makes it possible for switches to open the circuit during short circuits by limiting the flow of current to an amount that can be successfully broken.

It may be mentioned here that by an arrangement of divided conductors, two cables being suspended from one insulator a few inches apart and used as a single conductor—the reactance of the line may be greatly reduced and its capacity proportionally increased. This will enable the line to transmit a much greater amount of energy without increasing the synchronous condenser capacity necessary to regulate it, or conversely if the amount of energy is not increased less synchronous condenser capacity will be required. This advantage is obtained without increase in weight of copper and change in resistance of conductors. The following illustrates the effect of thus dividing the conductors:

	Single Conductors	Divided Conductors
Length of line	350 miles	350 miles
Size of conductor..........	(1)—605,000 cir. mils	(2)—302,500 cir. mils
Energy transmitted per circuit....................	150,000 kw.	150,000 kw.
Voltage of transmission....	220 kv.	220 kv.
Losses....................	14,900 kw.	18,180 kw.
Synchronous condenser capacity required at full load.	76,000 kv-a.	40,350 kv-a.

Capacitance determines the charging current of a line, and depends on spacing, diameter and arrangement of the conductors, frequency and length of the circuit. If full voltage is impressed on a transmission line at the generating end and the receiving end of the line is left open the voltage of the receiving end may rise to such a value as to cause serious damage. At the same time the charging current flowing into the line which must be supplied by the generators may be equal to or even greater than the energy current on the line when fully loaded. This may be much in excess of the capacity of one of the largest generators in the generating station. In case of the 350-mile 220-kv. line just mentioned with single conductors the charging current which must be furnished at the generating station with 220 kv. impressed on the line at 60 cycles is nearly 100,000 kv-a. for each three-phase circuit (200,000 for the two circuits in parallel). This is about equal to the current carrying capacity of four 50,000-kw. (59,000-kv-a. at 85 per cent power factor) generators operating in parallel. In other words, it will require generator capacity necessary to provide 200,000 kv-a. leading current to energize such a two-circuit line designed to transmit 150,000 kw. The charging current being leading in the armature of the generator tends to increase its excitation thus making it self-exciting, possibly to such an extent that it becomes beyond control of the separate field excitation usually provided. In the case cited above, if the frequency were 25 cycles, the charging kv-a. would be about 40,000.

Synchronous condenser or synchronous reactor capacity may be so adjusted to a transmission line as to neutralize lagging or leading current at any point in the line. Capacitance in a line serves much the same purpose as synchronous condenser capacity, the difference being that the former is distributed along the line and cannot be controlled, while condensers are generally located at the receiving end only and can be adjusted to compensate for change in power factor and load. In gradually loading up a line there is a point at which the charging current resulting from capacitance just balances the reactance thus giving unity power factor at the generating end of the line. On a long transmission line it may be found advisable at normal loading to operate with a leading power factor at the generating end of the line which results in unity power factor near the middle of the line and a lagging power factor at the receiving end.

Many factors enter into the choice of voltage for a transmission line. Other conditions being equal, that voltage should be chosen which will permit the energy to be transmitted at minimum cost. The writer knows of one instance where 100,000 kw. was transmitted 2½ miles at 12,000 volts as the price of copper was such that the interest on the investment in copper plus the value of the energy lost in the 12,000-volt circuits was less than the interest on the cost of step-up and step-down transformers, and the other items of cost that the higher voltage would have involved. The economic voltage is dependent upon the amount of energy involved. In the case of very long lines and large amounts of energy the economic voltage is the highest that the state of the art will permit. This at the present time is about 220,000 volts. On shorter lines it may be desirable to adopt a voltage that corresponds to that of other lines in the vicinity in order that the circuits may run in parallel without the introduction of transformers. Determination of the proper voltage for a project requires careful analysis of all the factors bearing on the problem after full knowledge of the value of these factors has been ascertained.

Frequency will generally be determined by the prevailing frequency of the district to be supplied. Up to 350 miles it is practicable to design operative transmission lines for either 60 or 25 cycles, the prevailing frequencies in this country. Beyond this distance it may be found advisable to use the lower frequency in order to keep the reactance and capacitance susceptance within practical limits. There is very good reason to believe that 60 cycles will eventually prevail in this country and all new projects except those involving very long transmission lines should be at this frequency. Even in those communities where 25 cycles now prevail it is usually practicable to take on new business at the higher frequency so that eventually the lower frequency may be retired. In the beginning there was very good reason for the adoption of 25 cycles on account of it being impracticable to build 60-cycle synchronous converters for changing to direct current. Sixty-cycle synchronous converters have now been developed which answer all requirements, and the reason for the lower frequency more expensive apparatus no longer exists.

It is particularly unfortunate that the two prevailing frequencies in this country are such that frequency-changers are necessarily very expensive. There is only one practicable speed, namely 300 rev. per min., which results in a ratio of 25 to 60 cycles. Such machines must have 10 poles for the 25 cycle end and 24 poles for the 60-cycle end, thus necessitating a very expensive machine even for small installations. If 30 cycles had been chosen instead of 25 the matter of changing frequency would have been greatly simplified as the lower frequency machine would then have a pole ratio to the higher of 1 to 2, and in general could be built at much lower cost. This would have been of considerable advantage in the transition of 25-cycle systems in this country to a 60-cycle standard. Or if 50 cycles had been chosen which is the voltage generally used in foreign countries a ratio of 1 to 2 would also have resulted.

The performance of a transmission line may be completely determined graphically with the degree of accuracy necessary for preliminary studies by the use of vector diagrams indicating currents and voltages at the two ends of the circuit and applying the auxiliary constants of the circuit which account for the distribution effect. These constants may be read direct from the Wilkinson Charts. The following illustrations of this graphic method are given as applied to a 225-mile 220-kv., 60-cycle transmission, designed to transmit 300,000 kw. and supply an industrial distributing system at 85 per cent power factor. The transmission will consist of two tower lines, each supporting two circuits. Additional line characteristics and load data are given on the diagrams which apply to one 605,000-cir. mil aluminum steel reinforced three-conductor circuit. Under normal conditions each circuit will transmit 75,000 kw. and under emergency conditions will transmit 150,000 kw. The voltage will be held constant at the high-voltage side of the raising transformers and at the low-voltage side of the lowering transformers. This somewhat simplifies the calculations as it eliminates the impedance of the raising transformers from consideration. In each of these solutions the impedance of the lowering transformers is added to the line impedance and regarded as if it were distributed line impedance. The percentage of error due to this assumption is shown in the lower right-hand corner of each diagram. For an exact determination of the performance of a very long line the complete method of solution would be demanded. In this complete method the localized impedance of the raising and lowering transformers is not considered as distributed line impedance but treated as localized impedance. The illustrations show, in addition to a complete graphical method of solution, the mathematical solution which exactly parallels it. The quantities given on the illustration have been carried out to an extreme degree of refinement so that the error in results as determined by this simplified approximate method compared with the more complicated complete method (not shown here) could be accurately obtained. It may be noted that the approximate solution shown by illustration takes into account the effect of the condenser and lowering transformer losses flowing over the circuit and the effect of the magnetizing current of the lowering transformers in reducing the amount of condenser capacity required under load.

Fig. 1 shows the conditions existing at no-load with normal load connections and with line and lowering transformers energized. With 220 kv. equivalent at low-voltage side of lowering transformers, synchronous reactor capacity of about 30,000 kv-a. will be required to hold the voltage at sending end at 230 kv. The illustration indicates that this capacity of synchronous reactor will hold the sending end voltage at about 227 kv. but the table of percentage error for this method indicates that the voltage at sending end as determined by this method is about 2.13 per cent low. The complete method would give the sending voltage as 230 under this condition. To maintain the same voltage (220 kv.) at both receiving and sending ends of the line about 20,000 kv-a. synchronous reactor capacity will be required as shown in Fig. 4.

Fig. 2 shows the performance of the system at normal load of 75,000 kw. per circuit and 220 kv. at th load. Under these conditions about 42,000-kv-a synchronous condenser capacity will be required t hold receiving voltage at 220 kv. with an 85 per ce power factor load. If the voltage at sending end the line is also held at 220 kv. with load conditio

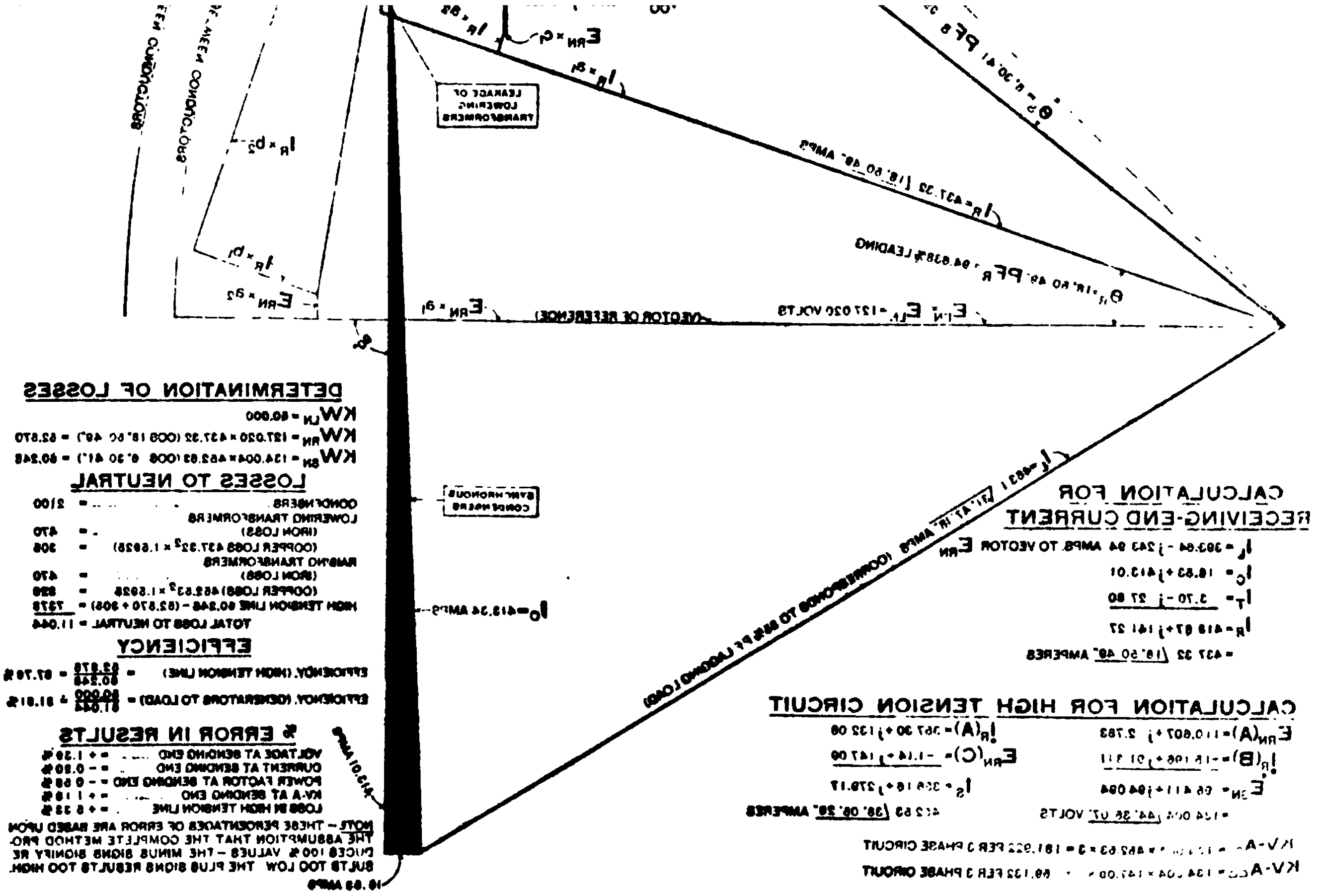

DETERMINATION OF LOSSES
KW_{LN} = 50.000
KW_{RN} = 127.020 × 437.32 (COS 18° 50' 48") = 52.870
KW_{SN} = 134.004 × 452.63 (COS 6° 30' 41") = 60.248
LOSSES TO NEUTRAL
CONDENSERS = 2100
LOWERING TRANSFORMERS (IRON LOSS) = 470
(COPPER LOSS 437.32² × 1.5925) = 305
RAISING TRANSFORMERS (IRON LOSS) = 470
(COPPER LOSS) 452.63² × 1.5925 = 626
HIGH TENSION LINE 60.248 − (52.870 + 305) = 7073
TOTAL LOSS TO NEUTRAL = 11.044
EFFICIENCY
EFFICIENCY. (HIGH TENSION LINE) = 52.870 / 60.248 = 87.75%
EFFICIENCY. (GENERATORS TO LOAD) = 50.000 / 61.044 = 81.91%
% ERROR IN RESULTS
VOLTAGE AT SENDING END = + 1.30%
CURRENT AT SENDING END = − 0.20%
POWER FACTOR AT SENDING END = − 0.56%
KV-A AT SENDING END = + 1.16%
LOSS IN HIGH TENSION LINE = + 5.35%
NOTE – THESE PERCENTAGES OF ERROR ARE BASED UPON THE ASSUMPTION THAT THE COMPLETE METHOD PRODUCES 100% VALUES – THE MINUS SIGNS SIGNIFY RESULTS TOO LOW. THE PLUS SIGNS RESULTS TOO HIGH.
16.63 AMPS
413.01 AMPS
I_O = 413.34 AMPS
SYNCHRONOUS CONDENSERS
LEAKAGE OF LOWERING TRANSFORMERS
$E_{RN} \times a_1$
$E_{RN} \times a_2$
$I_R \times b_1$
$I_R \times b_2$
$I_R \times b_1$
$E_{RN} \times c_1$
$I_R \times a_1$
BETWEEN CONDUCTORS
BETWEEN CONDUCTORS
VECTOR OF REFERENCE
$E_{RN} = E_{LN}$ = 127.020 VOLTS
θ_R = 18° 50' 48" PF_R = 94.638% LEADING
I_R = 437.32 /18° 50' 48" AMPS
θ_S = 6° 30' 41" PF_S
I_L = 463.1 /31° 47' 18" AMPS (CORRESPONDS TO 85% PF LAGGING LOAD)
CALCULATION FOR RECEIVING-END CURRENT
I_L = 393.64 − j 243.94 AMPS. TO VECTOR E_{RN}
I_C = 16.63 + j 413.01
I_T = 3.70 − j 27.80
I_R = 413.97 + j 141.27
= 437.32 /18° 50' 48" AMPERES
CALCULATION FOR HIGH TENSION CIRCUIT
$E_{RN}(A)$ = 110.607 + j 2.783
$I_R(A)$ = 367.30 + j 132.06
$I_R(B)$ = −15.196 + j 01.311
$E_{RN}(C)$ = −1.14 + j 147.06
E_{SN} = 95.411 + j 94.094
I_S = 356.16 + j 279.17
= 134.004 /44° 36' 07" VOLTS
452.63 /38° 06' 29" AMPERES
KV-A = 134.004 × 452.63 × 3 = 181.922 PER 3 PHASE CIRCUIT
KV-A = 134.004 × 147.06 × 3 = 59.132 PER 3 PHASE CIRCUIT

Fig. 3

220 KV PROBLEM – EMERGENCY LOAD

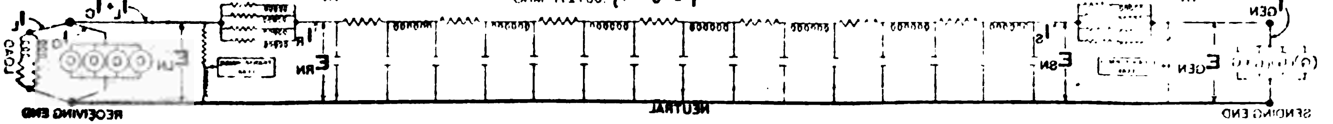
(APPROXIMATE SOLUTION)

THIS APPROXIMATE SOLUTION ASSUMES THAT THE IMPEDANCE OF THE LOWERING TRANSFORMERS MAY BE ADDED TO THE LINE IMPEDANCE AND TREATED AS THOUGH IT WERE DISTRIBUTED LINE IMPEDANCE. THIS ASSUMPTION SIMPLIFIES THE SOLUTION AT THE EXPENSE OF ACCURACY (SEE LOWER RIGHT HAND CORNER OF PAGE, ALSO TEXT)--THE SOLUTION BELOW IS BASED UPON THE VOLTAGE BEING HELD CONSTANT AT THE LOAD SIDE OF THE LOWERING TRANSFORMERS AND AT THE HIGH TENSION SIDE OF THE RAISING TRANSFORMERS.--IF THE VOLTAGE IS TO BE HELD CONSTANT AT THE GENERATOR BUS, THE IMPEDANCE OF THE RAISING TRANSFORMERS MUST ALSO BE ADDED TO THAT OF THE LINE--ALL LOW TENSION VALUES ARE REFERRED TO THE HIGH TENSION CIRCUIT.

RAISING TRANSFORMERS $Z_{TN} = 1.6926 + j\,19.91$ OHMS

HIGH TENSION LINE $Z = 34.66 + j\,178.2$ OHMS, $Y = 0 + j\,.001211$ MHO

LOWERING TRANSFORMERS $Z_{TN} = 1.6926 + j\,19.91$ OHMS



EMERGENCY LOAD

PER 3 PHASE CIRCUIT	PER PHASE TO NEUTRAL
$KV\text{-}A_L = 176.470$	$KV\text{-}A_{LN} = 58.824$
$KW_L = 150.000$	$KW_{LN} = 50.000$
$PF_L = 85\%$ LAG.	$PF_{LN} = 85\%$ LAG.
$E_L = 220.000$	$E_{LN} = 127.020$
$I_L = 463.1$	$I_{LN} = 463.1$

60 CYCLES

CONDENSERS

FOUR 45.000 KV-A SYNCHRONOUS CONDENSERS PER 3 PHASE CIRCUIT WHEN OPERATING AT FULL LOAD PROVIDE MORE COMPENSATION THAN REQUIRED FOR MEETING THE EMERGENCY CONDITIONS - SINCE BOTH 3 PHASE CIRCUITS ON THE SAME TOWERS WILL BE OPERATED IN PARALLEL 7 CONDENSERS MAY BE USED FOR THE TWO CIRCUITS. THE 8TH CONDENSER BEING AVAILABLE AS A SPARE. UPON THIS BASIS THE CONDENSER DATA PER CIRCUIT IS AS FOLLOWS.

3 PHASE	TO NEUTRAL
$KV\text{-}A_C = 157.500$	$KV\text{-}A_{CN} = 52.500$
$E_C = 220.000$	$E_{CN} = 127.020$
$I_C = 413.34$	$I_{CN} = 413.34$
$KW_{C\text{-}LOSS} = 6300$	$KW_{C\text{-}LOSS\text{-}N} = 2100$
$I_{C\text{-}LOSS} = 16.53$	$I_{C\text{-}LOSS\text{-}N} = 16.53$

LINEAR CONSTANTS

$Z = 37.836 + j\,218.02$ OHMS ★

$Y = 0 + j\,.001211$ MHO

★ THIS INCLUDES IMPEDANCE OF LOWERING TRANSFORMERS

AUXILIARY CONSTANTS

$(A) = (a_1 + j\,a_2) = \cosh\theta = .870783 + j\,.021911$

$(B) = (b_1 + j\,b_2) = Z\,\frac{\sinh\theta}{\theta} = \sqrt{\frac{Z}{Y}}\,\sinh\theta = 34.6653 + j\,208.93$ OHMS

$(C) = (c_1 + j\,c_2) = Y\,\frac{\sinh\theta}{\theta} = \frac{1}{\sqrt{\frac{Z}{Y}}}\,\sinh\theta = -.000.009 + j\,.001188$ MHO.

WHERE $\theta = \sqrt{ZY}$

TRANSFORMERS

(FOUR BANKS IN PARALLEL AT EACH END OF THE LINE)

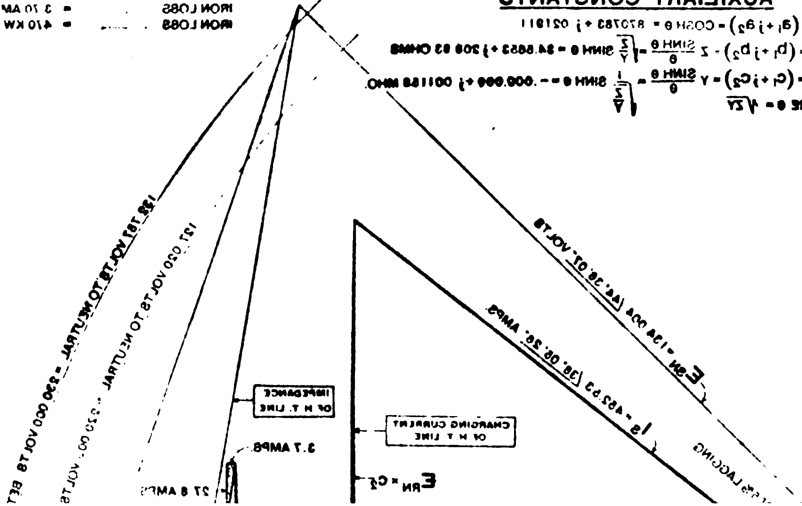
$R_{TN} = 1.6926$ OHMS RESISTANCE

$X_{TN} = 19.91$ OHMS REACTANCE

MAGNETIZING CURRENT = 27.8 AMPS AT 127.020 VOLTS

IRON LOSS = 3.70 AMPS. AT 127.020 VOLTS

IRON LOSS = 410 KW TO NEUTRAL



remaining the same, the synchronous condenser capacity required will be about 53,000 kv-a. as shown in Fig. 4.

Fig. 3 shows the performance of the system when emergency load of 150,000 kw. is carried by each circuit. This condition may exist for short intervals while one tower line is out of service for repairs. With 230 kv. at sending end of line there will be required about 157,000 kv-a. synchronous condenser capacity to hold receiving voltage at 220 kv. with an 85 per cent power factor load. If voltage at sending end is also held at 220 kv. about 173,000-kv-a. condenser capacity will be required, as shown in Fig. 4.

Fig. 4 indicates, under various conditions of sending end voltage, the amount of energy which may be delivered to an 85 per cent lagging power factor load with 220 kv. at receiving end over this 225-mile, 60-cycle circuit consisting of three 605,000-cir. mil aluminum conductors. The synchronous condenser capacities corresponding to different sending end voltages are shown for various loads. It may be noted that with 230 kv. at sending end the maximum amount of power which can be transmitted over this circuit is about 200,000 kw. which will require synchronous condenser capacity at receiving end of about 300,000 kv-a.

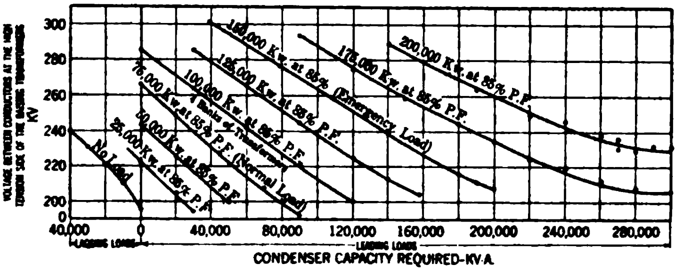


Fig. 4

The curve also shows that 25,000 kw. can be transmitted with about 222 kv. at sending end of line without any synchronous condenser capacity. It also shows that 75,000 kw. (normal load) could be transmitted with 266 kv. at sending end of line without any synchronous condenser capacity.

The following are the essential data on performance of some lines proposed for supply of energy to the superpower zone:

Power to be transmitted	300,000 kw.	300,000 kw.	300,000 kw.
Voltage at receiving end	220 kv.	220 kv.	220 kv.
Cycles	60	25	60
Length of line	350 mi.	350 mi.	115 mi.
No. of tower lines	2	2	2
No. of circuits per tower line	2	2	1
Size of conductors Aluminum	605,000 cir. mils	605,000 cir. mils	920,000 cir. mils
Steel	78,000 cir. mils	78,000 cir. mils	211,000 cir. mils
Normal load per circuit	75,000 kw.	75,000 kw.	150,000 kw.
Emergency load per circuit	150,000	150,000	300,000
Power factor of load	85 per cent	85 per cent	85 per cent
Power factor gen. end (normal load)	0.893 ld	0.884 ld	0.93 lg
Power factor rec. end (normal load)	0.983 lg	0.934 ld	0.97 lg.
Power factor gen. end (emergency load)	0.983 lg.	0.983 lg.	0.91 lg.
Power factor rec. end (emergency load)	0.879 ld.	0.894 ld.	0.98 ld.
Synchronous condenser capacity required (normal load)	152,000 kv-a.	90,000	141,000 kv-a.
Line losses (normal load)	29,800 kw.	36,360 kw.	13,800 kw.
Transformer core losses (normal load)	4,500 kw.	6,000 kw.	4,500 kw.
Synchronous condenser losses (normal load)	6,100 kw.	3,600 kw.	5,640 kw.
Total losses (normal load)	40,000 kw.	45,960 kw.	23,940 kw.
Efficiency of transmissions (normal load)	88.1 per cent	86.7 per cent	92.6 per cent

It may be of interest to note that in the 60-cycle, 350-mile line, with voltage held the same at both ends, the voltage in the middle of the line is approximately 6 per cent higher than at either end. In the 25-cycle line under similar conditions the "bulge" is only about 1 per cent.

The proper design of a transmission system requires special and thorough knowledge of the physical conditions to be met both in construction and operation of the line. The following points are applicable to all long-distance transmission systems:

(1) The right of way must be of ample width, in order that the conductors may be adequately spaced and so that there may be no danger of the conductors of adjacent lines coming in contact with each other. The right of way must be kept cleared so that growing trees cannot possibly come in contact

with the conductors. Standing trees must be left so far away that when felled they do not reach the lines. Transmission lines have often been greatly hampered by inadequate rights of way; owners have had to be content with grants for use of public highways, or to make such terms as they could with private owners. In many cases easements could be obtained only on the basis that trees should not be trimmed except by special consent of the owners. This has resulted in many crooked lines, every bend involving a hazard. A transmission line of the magnitude we are considering is often a more important carrier than a railroad, and there should be laws granting the right of expropriation so that a right of way may be obtained commensurate with the importance of the service which it must render to the public. The lines should change direction as infrequently as possible, even slight curves should be avoided wherever possible. On account of the expense and hazard involved in dead end angle towers tangents must be as long as the character of the country will permit. Wherever possible the right of way should be located away from cultivated areas, as the lines will then be less subject to interference from the activities of the people and the cost of the land will not be so great. Lines should not parallel railroads or communication circuits of any kind if this can be avoided.

(2) The transmission line should consist of steel towers with maximum spacing consistent with strength of conductors and most economical cost. For conductors of moderate size and under the usual assumptions as to limiting conditions of loading, tower spacing will be as follows: For hard drawn copper about 800 feet, for steel reinforced copper about 1000 feet; for steel reinforced aluminum cables this may be increased to about 1500 feet. The configuration of the ground will probably call for many shorter or longer spans but these should be avoided when possible. Few towers mean few insulators, each of which is necessarily a danger point. The conductors for the 220,000 volt lines should be spaced at least 18-ft. delta, or its equivalent, but 21-ft. spacing is better.

If vertical spacing is adopted the conductors should be staggered so that ice falling from one conductor may not cause a short circuit with the conductor below it. In areas where sleet prevails this matter must be given careful attention. Authentic records exist of sleet forming over 1½ inches in radial thickness on line conductors. In case the transmission line lies wholly within a sleet area the cost of construction to withstand this extreme loading may be prohibitive. In this case provision should be made so that during a sleet storm one or more of the circuits may be loaded until they are warm enough that ice will not form on them. The remaining line, or lines should be short-circuited and separate generators used to send enough current through them to keep them warm. This method has been used by one large transmission company, for several years with entire success. In this way the lines may be preserved through a severe sleet storm and kept ready for service although it may be somewhat hampered while the storm lasts. With proper patrol organization the stations at the ends of the line should be kept informed of climatic conditions along the line at all times.

Clearance between conductors and towers should be such that with maximum wind deflection there will be no flash-over to ground. In the past this has been one of the most frequent causes of interruption to service.

(3) The strings of strain insulators should be graded or other means provided so that excessive voltage strains do not come on the units nearest the conductors, when lines are operated at 220,000 volts or higher. The writer sees no great objection to grading the disks, and a fairly even distribution of potential among the insulator units can be obtained in this way. It has been objected that linemen will not pay attention to orders and will install the first unit that comes to hand when it is necessary to make a replacement. After twenty years' experience in operating and maintaining transmission lines the writer believes that this is not a valid objection and that effective organization will prevent such happenings.

(4) Switching must be reduced to its lowest terms. There should be no taps from the transmission line between the step-up transformers at the generating station and the step-down transformers at the point of delivery. Where possible, switching should be done on the low-tension side of the transformers but a certain amount of switching to shift the load from one circuit to another on high-tension lines will be unavoidable. Manufacturers have successfully provided oil switches for 150,000-volt circuits involving comparatively large amounts of power, and switches for 220-kv. circuits will have no heavier duty as the currents are smaller. High reactance inherent in transformers and lines contribute to limiting the currents at time of short circuit to comparatively small amount, thus minimizing the duty imposed on oil switches.

(5) Neither overhead ground wires nor lightning arresters should be provided on circuits of 220,000 volts or higher as it is believed they will cause more trouble than they will prevent. Induced high-frequency charges will be absorbed by the large capacity of the lines and dissipated by corona.

While it is essential that the transmission system be properly designed and constructed, and that the physical conditions surrounding the line be under control of the operating company, the operating organization is of even greater importance. Years are required in which to build up an operating personnel which will get the best service from a transmission system. Eternal vigilance is the price of service, and this can be obtained only with an intelligent, loyal, well trained and well paid operating staff.

THE SERVICE THAT CAN BE EXPECTED FROM LONG-DISTANCE TRANSMISSION

Continuity of service cannot be readily evaluated. In a densely settled community where many thousands of people are entirely dependent on the public utility systems for light, power and transportation, it is customary to set a high value on continuity of service. Public utility companies have gone on the principle that absolute continuity of service, so far as humanly possible, is necessary, and they have provided large excess of generating capacity and duplicate feeder systems at great expense to accomplish this result. The utility manager has in mind the multitude of complaints that arise whenever an interruption to service, however slight, occurs and however small this inconvenience to the company's patrons may have been. Human nature, in this age of rushing effort to accomplish work in its frantic pursuit of pleasure, is impatient at delay. An insignificant interruption to traffic in New York caused by failure of power supply furnishes opportunity for much complaint and publicity in the newspapers all of which is very embarrassing to the utility companies. It must be admitted that much of this frenzy for haste is infectious and is contracted from seeing others so impelled and not from any necessity in the case. Subway and elevated trains must be on time. The commuter hastens to his suburb only to sit down and read the paper for an hour before dinner. Broadway must be brilliantly lighted with thousands of lights every minute of every evening or the crowds are disappointed. In short the service must be perfect.

In some parts of our country large amounts of energy for transportation, power and lighting are brought from power plants located at waterfalls in the mountains. The people understand this and know of the various climatic and other elements beyond human control that may effect this service. A few times in a year there may be interruptions to the service. They do not like it but it is expected, no one is perceptibly the worse for it, and life goes on as usual. Now if these communities were to have the service demanded by New York City, there would have to be large reserves in generating plants, possibly steam plants in the cities would be required, the transmission lines would have to be duplicated and perhaps built along different routes and many other safeguards taken at very great expense. The people would have to pay the cost which might easily be double the price they are now paying for energy. Can they afford it?

New York demands perfect service and, generally speaking, gets it. New York also pays for it. Can she afford it? Like many other things in New York the people pay for this superservice whether they can afford it or not.

The standard of service now given by many of our long-distance plants is not the best that can be attained for there is not one of these, if it were to be rebuilt at the present time, that could not improve its service, although the present standard is high and is being steadily improved. New long-distance lines now building are taking advantage of past experience and increased knowledge of the causes of trouble and means of preventing it. One of the reasons for trouble experienced in the past is that the developing companies were hampered by financial limitations. They could not build as well as they knew how for lack of money and had to do the best they could with the means available. When a plant is once built and in operation it is very difficult to raise additional money solely for the purpose of improving the service, and without expectation of increased revenue. Material improvement in service would generally mean entire reconstruction of the transmission lines and the earning power of very few plants would stand the additional cost.

In order to secure the opinion of those most favorably situated to judge as to whether energy transmitted over long lines can be delivered with the continuity necessary to satisfy the requirements of users of energy in the Superpower Zone, a series of questions were propounded to them premised by the assumption that the energy should be transmitted from either steam or hydroelectric stations ranging from 100,000 to 300,000 kw. in capacity over transmission lines of the highest grade of construction distances ranging from 100 to 300 miles.

Sixteen answers were received from prominent men holding responsible positions either as consulting or operating engineers of companies operating long-distance transmission lines in this country. These men, as well as the history of the transmission systems they are identified with, are well-known to engineers.

The answers received naturally reflected the experiences of the companies which these engineers represent. However, leaving out of account the psychology of the matter as affecting their answers there was practical unanimity of opinion that two tower lines, each supporting two circuits, each tower line with its circuits being capable in emergency of transmitting the entire load, would reasonably insure continuity of service of the character required by the metropolitan district of New York.

Long-distance transmission plants are not the only ones subject to interruptions. Local steam-electric plants are also subject to interruptions from storms, strikes, freight blockades, and from other causes. The remedy for this is numerous and varied sources of supply and interconnection of plants. This is now being carried out locally in various parts of the country particularly in New England, the south Atlantic states and in California, and is the method being proposed on a large scale by the Superpower Survey in the Washington-Boston district. When the whole country is connected with a large network of interconnecting lines between load centers, and these load centers are arranged for supply from local steam stations, large steam stations in neighboring cities, steam stations at the mines, and hydroelectric stations from sites both far and near, continuity of service will be assured far beyond what can be obtained from any single or local source of supply, however well safeguarded. The communities will then be practically independent of strikes or storms or meteorological conditions and will have better and more reliable service than can be obtained in any other way.

The author wishes to acknowledge the assistance of Messrs. William Nesbit, P. H. Thomas, and P. M. Lincoln, in preparing the diagrams and in the calculations, the results of which are given in this paper.

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VOLTAGE AND POWER FACTOR CONTROL OF 66,000-VOLT TRANSMISSION LINES CONNECTING TWO GENERATING STATIONS

BY RAYMOND BAILEY

The Philadelphia Electric Company

ABSTRACT OF PAPER

The problem which confronted The Philadelphia Electric Company of providing for the control of voltage and power factor of the two 66,000-volt transmission lines connecting its Schuylkill and Chester generating stations is presented in this paper.

It is required that the control of voltage and power factor of the transmission lines referred to permit of the transfer of energy in either direction, at suitable power factor, up to the rated kv-a. capacity of the lines, with the generating stations operating at approximately equal bus voltages. The situation is considerably complicated by the necessity for supplying energy to several industrial substations, connected to these lines near the midpoint, which under certain operating conditions are supplied from one of the two lines.

Another important factor in the selection of regulating equipment is the severe short-circuit effects possible in a system of which the ultimate capacity of the present three generating stations will be approximately 500,000 kv-a.

The comparison made to determine upon the most satisfactory type of regulating equipment and the reasons for the selection of three-phase induction regulators are given. Data on the performance characteristics of the lines, with the induction regulators are included.

In the discussion of this problem of voltage and power factor control, certain conclusions of a more or less fundamental character are brought out.

THIS paper deals with a particular installation for control of voltage and power factor, made necessary by the interconnection of a large system, rather than a discussion of this question in a general way. An outline of this specific problem with its requirements, a discussion of the factors determining the selection of equipment, and a presentation and discussion of data on operating characteristics are included. This plan is adopted because it is thought that a paper of this sort will be of more value than one touching upon the subject in a more general way.

This interconnection is made by means of very short transmission lines and, therefore, does not involve any of the problems which go hand in hand with the use of long transmission lines, but is of particular interest on account of the exacting requirements for voltage and power factor control under various distributions of load, and the severe short-circuit effects encountered.

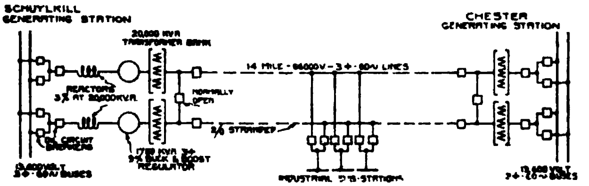

Fig. 1—Single-line Diagram of Schuylkill-Chester Transmission Lines

Disconnecting switches, instrument transformers, lightning arresters, etc. are omitted

The Philadelphia Electric Company supplies Philadelphia, Pa., and surrounding territory with electrical energy mainly through three large steam generating tations, known as the Schuylkill, Delaware and Chester Stations, the present total capacity of which is approximately 275,000 kv-a. and the ultimate 500,000 kv-a. The growth of the demands for power in the district

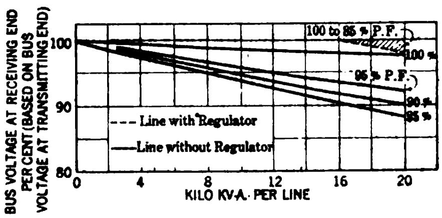

Fig. 2—Curves Showing Variation, for Several Different Power Factors, of Voltage at Receiving End of Line with the Kv-a. Transmitted

of which Chester, Pa., is a center necessitated the building of the Chester Station. With the completion about three years ago of this station came the need for transmission lines connecting it with the Schuylkill Station in Philadelphia to permit of the most economical loading of these stations and make possible the use of minimum reserve generating capacity.

Two 66,000-volt lines, 14 miles long, of approximately 20,000 kv-a. capacity each, with step-up and step-down transformers arranged as shown in Fig. 1, are provided.

The transmission of 40,000 kv-a. for a distance of 14 miles would not in itself call for a line potential of 66,000 volts, but the possibility of future extension and interconnection with other systems made the use of a voltage as high as this desirable.

The Delaware Station has direct cable ties with the Schuylkill Station, but has no tie lines connecting with the Chester Station.

THE NECESSITY FOR VOLTAGE AND POWER FACTOR CONTROL

The need for voltage and power factor regulating equipment on the Schuylkill-Chester lines is clearly brought out by the curves of Fig. 2, which show the inherent regulation of the lines, as shown by Fig. 1, except that the regulators are not included. It is obviously impossible to obtain satisfactory operation with the generating station bus voltage differing by 11.5 per cent, which is the figure for the transmission of 20,000 kv-a. per line at 85 per cent power factor. The curve for transmission at unity power factor indicates that 20,000 kv-a. can be transmitted over each line at that power factor with a voltage difference of only 2 per cent, which is entirely satisfactory. If this is done, however, there will be a certain amount of excess reactive kv-a. to be carried by the generating station to which the lines are supplying energy, as the power factor of the load is about 85 per cent; and this is, in some cases, impracticable to carry out, and uneconomical. This question of relative power factors of the various generating units will be discussed in detail in another part of this paper.

REGULATION REQUIREMENTS

An analysis of the problem brought out the following requirements for voltage and power factor control, which were important factors in determining the selection of equipment for this service.

The demand for large blocks of power, totaling about 15,000 kv-a. at about 90 per cent power factor, by three industrial consumers located adjacent to these lines necessitated their connection thereto. In order to meet all operating conditions, it was decided that regulating equipment must make possible the loading of both lines to rated capacity at either end, depending upon the direction of energy transfer, regardless of the size of the industrial load and whether it is split up between the two lines or all supplied from one line.

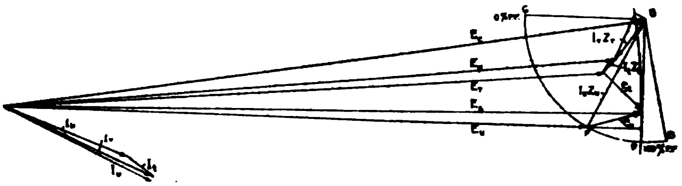

FIG. 3—VECTOR DIAGRAM OF CURRENT AND VOLTAGE RELATIONS OF THE TWO 66,000-VOLT TRANSMISSION LINES FOR CERTAIN ASSUMED LOADS

E_c —Chester Station bus voltage
E_H —Industrial consumer's voltage
E_s —Schuylkill Station bus voltage
E_u —Line voltage at regulator (untapped line)
E_T —Line voltage at regulator (tapped line)
e_u —Regulator voltage (untapped line)
e_t —Regulator voltage (tapped line)
I_u —Current in untapped line
I_T —Current in tapped line at Chester Station
I_H —Current taken by industrial consumers
I_t —Current in tapped line at Schuylkill Station
Z_u —Impedance of untapped line
Z_T —Impedance of tapped line—Chester Station to consumer
Z_t —Impedance of tapped line—consumer to Schuylkill Station

The vector diagram shown in Fig. 3 gives the voltage and current relations of these two lines under the assumed maximum load conditions given for point No. 2 of Fig. 9. Reference to this diagram will give an idea of the relative values of the impedance drops in the line supplying the industrial load and the line which runs straight through with no industrial load on it. To make such load conditions possible, it is evident that the two voltages e_t and e_u must be in series with the two lines in order to meet the bus voltage E_s, and the turbine governors adjusted for the desired kilowatt value. Further consideration of this question will show that as the industrial load diminishes or increases, or is split up between the two lines, the angle and magnitude of the two voltages e_t and e_u should change to keep the same power factor and voltage conditions. This would indicate that regulating equipment selected for this service would have to be of such character as to give a voltage of variable magnitude and phase angle.

The large ultimate generating capacity of the stations at each end of the lines will in the event of a short circuit at the bus deliver a maximum of 700,000 kv-a. The very high short-circuit effects encountered, combined with the necessity for the utmost reliability, led to a decision to install no regulating equipment but that of the most substantial and sturdy construction.

COMPARISON OF VARIOUS FORMS OF REGULATING APPARATUS

Types of equipment considered for the installation in question include the synchronous condenser, the step-type regulator, the synchronous booster, and the three-phase induction regulator.

Synchronous condensers are not practicable for use in this instance because of the necessity for maintaining approximately equal bus voltages in both generating stations and for transmitting energy in both directions. The curves of Fig. 4 show clearly that at line power factors which give a voltage drop of permissible magnitude, the capacity of condensers required is excessive, resulting in a large investment and space requirement. As an example, if we assume the voltages at the ends of the lines differing by 2 per cent, it is found by referring to Fig. 4 that approximately 10,000 kv-a. condenser capacity is required at the ends of the line, thus necessitating a total capacity of 40,000 kv-a. The value of these condensers in reducing the amount of reactive kilovolt-amperes carried by the generators should not be overlooked, but in this instance it was not great enough to warrant their installation.

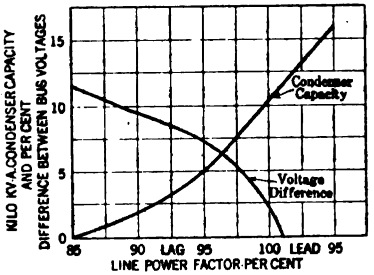

Fig. 4—Curves Showing Difference Between the Two Generating Station Bus Voltages When 20,000 Kv-a. is Transmitted Over the Lines at Various Power Factors, and the Condenser Capacity Required to Give These Power Factors When the Load Power Factor is 85 Per Cent

The step-type regulator which has been developed primarily for electric furnace and electrolytic work, consists essentially of a series transformer connected in the line and energized with voltages of various

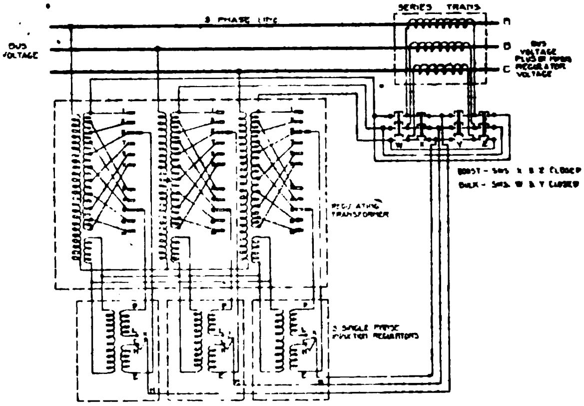

Fig. 5—Diagram of Electrical Connections of "Step-type" Regulator

magnitudes from a special transformer supplied with taps and arranged with single-phase induction regulators, so that a gradual change in voltage is possible. Fig. 5 shows the elemental electrical connections of an equipment of this type for transmission lines regulation. The manner in which this apparatus functions is outlined in detail in Appendix A.

Among the advantages of this type of regulating equipment are that it can be built to withstand severe short circuits because the only apparatus in series in the lines are transformers, and it is slightly cheaper than other types of apparatus for the same service. The principal disadvantages are in the high-voltage sliding contacts which may give trouble and would be difficult to keep in condition, and the complication made necessary to secure the variable phase angle required to permit of loading the lines under different operating conditions.

The synchronous booster ordinarily does not give a variation of phase angle of its voltage; but it can be arranged so that the stator frame can be shifted at will through a certain angle, thus varying the phase angle of its voltage. When so equipped with a frame-shifting device, the synchronous booster gives more flexibility than the three-phase induction regulator because its voltage can be varied in both magnitude and phase angle, while that of the regulator can be varied in phase angle only.

In respect to this application, the induction regulator has many desirable features as compared with the synchronous condenser and the step-type regulator, and appeared to be superior to the synchronous booster. The problem, therefore, resolved itself to a great extent into an exact comparison of the induction regulator with the synchronous booster, equipped with a frame-shifting device. An analysis was therefore made of the operating characteristics of the transmission system which indicated that induction regulators giving a constant voltage of 9 per cent with a variable phase angle would permit of the desired conditions of load, and they were selected for this service in consideration of their advantages as compared with synchronous boosters, listed below:

1. More sturdy construction.
2. Ability to withstand greater short-circuit stresses.
3. Greater simplicity of operation.
4. Higher efficiency.
5. Smaller first cost.
6. Suitability for outdoor installation which greatly facilitated the arrangement of equipment.
7. Is not a "rotating" machine.
8. Less inspection and maintenance required.

FIG. 6—GENERAL VIEW OF THE OUTDOOR SUBSTATION IN WHICH THE REGULATORS ARE INSTALLED

It is true that the synchronous booster with a frame-shifting device permits of more exact control of the lines but the resulting gain is slight and is not comparable with the advantages of the induction regulator set forth above.

DESCRIPTION OF THE INDUCTION REGULATOR

Two 1750-kv-a., three-phase, 60-cycle, oil-insulated, water-cooled, motor-operated induction regulators of

Westinghouse manufacture, designed to give 9 per cent buck and boost on a 13,600-volt circuit, were installed in the Philadelphia outdoor substation, a general view of which is included in Fig. 6.

Fig. 7 is a close-up view of one of the regulators, showing breather and temperature indicating equipment. Arrangement for hand operation is provided but is not shown in the illustration. The height of the regulator is 14 ft. 10 in.; the diameter 6 ft. 3 in., and the weight 56,000 lb. when filled with oil.

FIG. 7—CLOSE-UP VIEW OF ONE OF THE 1750 KV-A. INDUCTION REGULATORS

The regulators can easily be disconnected from the lines if desired when they are not "working" by unbolting the cable connection of each phase at the point *A* and reclamping at the point *B*, from which the cable for normal operation has been removed. This change in connection can be carried out in a very short length of time.

When operating at rated load, the losses of each regulator are 40 kw. and 20 gallons of cooling water per minute are required.

The stator and rotor coils are braced and insulated with A. I. E. E. class B insulation, in accordance with the standard turbo-generator practise.

The regulators are guaranteed to withstand successfully short-circuit currents as great as fifteen times the rated load value. Special stretch bolts are provided in the operating mechanism of the regulator so that in the event of an unusually severe short circuit, they will give way, thus preventing serious damage to the regulator.

Reactors giving 3 per cent drop at rated circuit kilovolt-amperes are installed on the Schuylkill Station end of the line to limit short-circuit currents to a safe value in order to amply protect the equipment installed thereon.

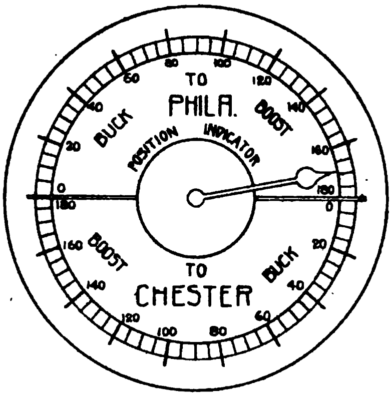

FIG. 8—DIAGRAM SHOWING MARKING OF POSITION INDICATOR DIAL

The switches controlling the regulator operating motors are located on the generating station control panels for these lines, to facilitate operation.

To give further ease of operation, each regulator is provided with a position indicator located on the instrument panel of the line to indicate the angular position of the regulator voltage. This indicator consists essentially of a special 360 deg. power factor indicator; one set of potential coils is connected to the line potential transformers, and the other coil to a potential transformer connected across a secondary winding of the regulator. The regulator has four poles and the pointer of the indicator consequently makes two revolutions to one revolution of the regulator rotor. The markings of the dial of the instrument are shown by Fig. 8 and are arranged so that the operator can readily secure the desired load conditions. The pointer is usually in the half of the scale which has the words *to Chester* printed on it when transmitting energy to Chester, and is in the part of the scale marked *to Philadelphia* when transmitting in that direction.

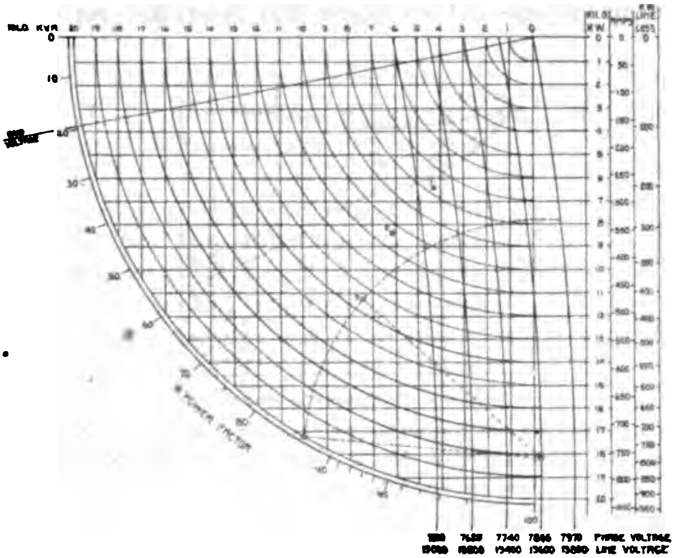

FIG. 9—CIRCLE DIAGRAM OF PERFORMANCE CHARACTERISTICS OF THE TRANSMISSION LINES

DISCUSSION OF TRANSMISSION CHARACTERISTICS

The analysis of the operating performance of the transmission system was made by means of a circle diagram similar to the one shown in Fig. 9, developed to meet the need for some means for readily determining upon the load conditions which should be obtained on these lines under various operating conditions. The principles involved in the construction of this diagram and the method of using it are outlined in Appendix B.

The curves given in Fig. 10 are plotted with readings taken from this diagram and show the transmission of energy from Chester to Philadelphia over the untapped line (no industrial consumers connected), for different amounts of kilovolt-amperes at 90 per cent power factor, furnished to the consumers from the tapped line which is supplied with 20,000 kv-a. at 85 per cent power factor at the Chester Station. Curves *A*, *B*, *C* and *D* show the kilovolt-amperes which can be transmitted at 85 per cent power factor (based on Chester bus voltage) over the untapped line with respectively, zero, one, two and three per cent, difference between the bus voltages of the Chester and Schuylkill generating stations, when the regulators are in one of two possible combinations of positions. Curves *A* and *B* do not extend to the 20,000 kv-a. point as do the others because it is impossible to obtain the load conditions necessary for this with zero and one per cent difference between bus voltages.

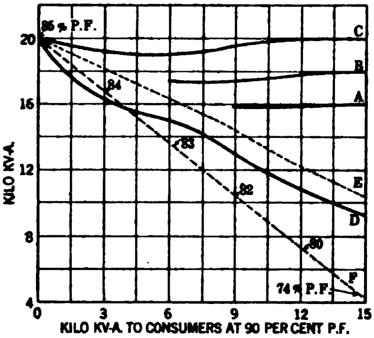

FIG. 10—CURVES SHOWING THE AMOUNT OF KV-A. WHICH CAN BE TRANSMITTED FROM CHESTER TO PHILADELPHIA UNDER VARIOUS CONDITIONS

Curve *F* (Fig. 10) shows the kilovolt-amperes transmitted over the tapped line through to the Schuylkill station and has marked along it at different points, the power factor at that particular load condition.

If the regulators are operated in the other possible combination of positions so that the line will receive kilovolt-amperes from the Chester Station at 85 per cent power factor, the kilovolt-amperes which can be transmitted with bus voltages equal or differing by as much as three per cent are shown by Curve E.

The second combination of regulator positions does not in most cases permit of as high kilovolt-ampere loads being carried as does the first and is, therefore, in general not desirable.

The two possible regulator positions referred to above are shown in Fig. 11 for an assumed load, of current I_l causing an impedance drop e_3. The regulator voltage can take either the position e_1 or e_2 to meet the receiving bus voltage E_1 provided the stations are not tied together through other lines. Figs. 10 and 12 indicate the desirability of one of these regulator positions as compared with the other.

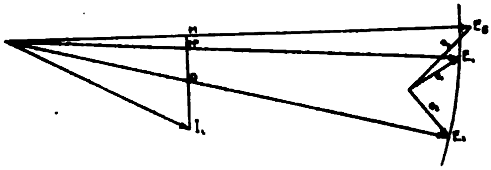

FIG. 11—VECTOR DIAGRAM SHOWING THE TWO POSSIBLE REGULATOR VOLTAGE POSITIONS FOR AN ASSUMED LOAD

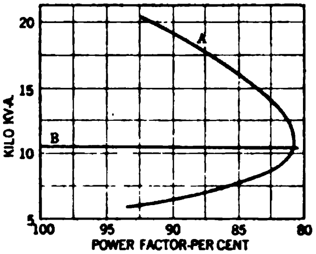

FIG. 12—CURVES SHOWING THE VARIOUS LOAD CONDITIONS POSSIBLE ON THE UNTAPPED LINE WHEN TRANSMITTING FROM CHESTER TO PHILADELPHIA WITH EQUAL GENERATING STATION BUS VOLTAGES

It would appear as though regulator position e_1 is the better of the two, insofar as line power factor is concerned, because it apparently counteracts to a great extent the effect of the line reactance in producing reactive kilovolt-amperes which the generators must carry. This is not true, however, as the ratio current of the regulator when combined with the load current gives a total line current having an angle between it and the load current equal to the angular displacement of the line voltage caused by the regulator voltage, with the result that there is no change in line power factor made thereby. There is, of course, a small change of angle brought about by the exciting current and impedance of the regulator.

Fig. 12 shows the various kilovolt-ampere values that can be carried on the untapped line with the regulators in all the possible positions when the tapped line is carrying 20,000 kv-a. at 85 per cent power factor at the Chester Station and is supplying the industrial consumers with 15,000 kv-a. at 90 per cent power factor. Inspection of these curves will reveal the fact that with the one combination (Curve *B*) of regulator positions it is practically impossible to vary the kilovolt-amperes, but the power factor can be varied. The other combination (Curve *A*) permits of considerable variation of both power factor and kilovolt-amperes and is the more desirable one.

Fig. 2 includes curves showing the transmission of kilovolt-amperes over the lines using the regulators, when there is no industrial load supplied from the mid-point of the line.

One of the limitations of the control of voltage and power factor is in the maximum voltage which can safely be impressed on the transformers at each end of the lines. Owing to the position of the regulators relative to the transformers, this limitation is of consequence only when transmitting energy to Chester from Philadelphia.

Operating experience with these regulators for control of voltage and power factor has been very satisfactory and verifies the results of the analysis made to determine upon the capacity and characteristics of the regulating equipment. There are no rapid fluctuations of load on these lines under normal conditions and, therefore, no difficulty is experienced in maintaining the desired power factors. Some apprehension was felt at first as to the form of instructions which would enable the operators to readily load the lines as desired, but it was found that the position indicators used with the other instruments on the lines made satisfactory operation possible.

The lines connecting generating stations may be used under many conditions to increase the combined economy of these stations. The exact increase in economy made possible by securing more efficient loading of the generating units under various operating conditions is rather difficult to determine, as there are many factors involved. An instance where higher efficiency may be obtained is the case where the units of one station are lightly loaded and those of a second station heavily loaded, and by the use of the tie lines the load may be equalized so that all of the generators will operate at or near the most economical point, which in most cases is in the neighborhood of 75 per cent of the rated capacity. Or, again, we may have two stations in which the units are lightly loaded, in which case the proper transfer of load over the tie lines may make possible the shutting down of one machine and the operation of the remaining units in both stations at a higher efficiency. If, on the other hand, the generators in both stations are heavily loaded, an available spare machine could be started and the load equalized over the tie lines so that all of the machines would operate at a more efficient point.

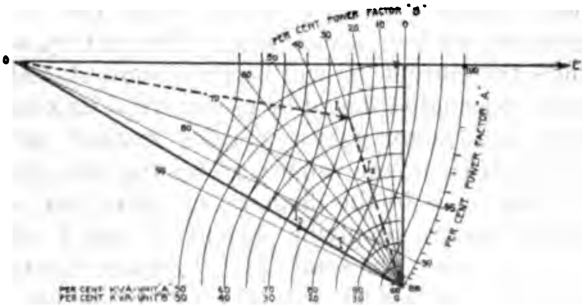

Fig. 13—Graphical Representation of the Increase of Generating Capacity Required by Operation of Units at Unequal Power Factors

In cases where there are generating units or stations differing by a considerable margin in economy, it is often found desirable to operate the efficient units at or near unity power factor, and carry the lagging reactive kilovolt-ampere on the less efficient machines. Where there is a large modern generating station with units of higher efficiency in it than in the older stations, it is customary to keep the most efficient station as near fully loaded as possible, at or near unity power factor. This arrangement requires, however, that the combined kilovolt-ampere generating capacity in use be greater than that of the load, the amount depending upon the difference in the power factors of the generators involved. This will be evident by referring to Fig. 13. To illustrate the point in mind, let us assume that an efficient station which will carry 75 per cent of the kilovolt-ampere load, is available. This station, which supplies the current I_3, will be called unit *A* and the scales so designated should be used to read its kilovolt-ampere and power factor. Scales marked unit *B* should be used in the same way for the less efficient unit. Reference to the diagram will show that when both stations are supplying current (I_3 and I) at the load power factor, the total kilovolt-ampere generating capacity is a minimum and is equal to 75 per cent (scale *A*) plus 25 per cent (scale *B*) or one hundred per cent of the load kilovolt-ampere.

If, however, unit *A* supplies the current I at approximately 99 per cent power factor, it will supply 75 per cent of the load kilovolt-amperes and unit *B* which supplies the current I_2 is operating at power factor of about 30 per cent and supplies kilovolt-amperes equal to 40 per cent of the load; the total kilovolt-ampere generating capacity under this condition is 115 per cent of the load kilovolt-amperes.

The excess kilovolt-amperes required increases as the power factor of unit *A* approaches unity, and that of the unit *B* approaches zero or vice versa, and reaches a maximum of 37 per cent at unity and zero power factor, respectively, with a load power factor of 85 per cent. When the load power factor is higher, this additional generating capacity required to operate at unequal generator power factors becomes smaller.

The discussion given above relative to operation of units to obtain maximum economy applies either to individual units in a station or to several stations of groups of generating units. It is obviously only directly concerned with the operation of tie lines when two or more stations are involved.

CONCLUSIONS

Interconnection of any particular system presents problems which must be solved individually by making a thorough analysis, including consideration of all pertinent features. The use of induction regulators for the control of voltage and power factor in the instance discussed in this paper does not indicate in general that this is the best method of handling the problem.

Summarizing, it could be said that equipment selected for the control of transmission lines should meet the following conditions which are more or less fundamental:

The equipment must permit of the desired transmission of energy at suitable power factor under all operating conditions.

Apparatus of sturdy construction which will give the greatest degree of reliability is absolutely essential, considering the great importance of this service. There is always a possibility that the breakdown of any equipment of generating station tie lines may cause disturbances throughout the system, which may lead to serious consequences. An installation which will require considerable inspection and maintenance is to be avoided.

Regulating equipment which does not permit of ease and simplicity of operation is, as a rule, undesirable. If the operation is complicated, errors are more likely to occur which sometimes lead to serious trouble.

The initial cost of regulating equipment and the cost of operation, including maintenance, are important factors and must be given due consideration.

It is hoped that this paper, although it is a discussion of a specific problem, brings out information of a general character which will be of value to those facing the problem of voltage and power factor control of interconnected systems.

The author wishes to express his appreciation of the helpful assistance of Mr. Frank R. Ford in the preparation of this paper.

APPENDIX A

The Step-Type Regulator

The manner in which the "step-type" regulator functions to give a gradual change of voltage can be most readily understood by following it through one step of the operation.

The voltage induced in each of the regulator coils *N-E* and *L-D* (Fig. 5) is equal to one-half of that between adjacent taps of the regulating transformer. If we assume switch *K* (Fig. 5) closed on contact *N* and the lead *E* of the regulator secondary coil connected to contact 5, then the voltage of the regulating transformer between leads 1 and 5 is impressed on the series transformer when the regulator is in the neutral position. As the regulator is turned in the direction so that the voltage of the coil *N-E* adds to the voltage between taps 1 and 5, the point is reached when the voltage impressed on the series transformer has been increased by the maximum regulator voltage, and the lead *M* is half-way between taps 5 and 6 in potential. As the voltages of coils *N-E* and *L-D* are exactly equal and opposite, the lead *L* is at the same potential as lead *M* and switch *K* is swung from contact *N* to *L*, the brush of lead *D* having just moved on to contact 6. This impresses the voltage from taps 1 and 6, minus that of the regulator winding *D-L*, on the series transformer, thus giving a voltage midway between taps 5 and 6. As the rotation of the regulator is continued, the voltage of the winding *D-L* decreases until the voltage of the regulator is zero and the impressed voltage is equal to that between taps 1 and 6. Further rotation increases the voltage of the induction regulator until the potential of lead *M* is half-way between taps 6 and 7, when the change is made to the regulator coil *N-E*, the selector switch having moved from tap 5 to tap 7 while the rotation of the regulator has taken place. The continuation of this process gives the desired change in voltage up to and including the capacity of the equipment.

The various switches and inductance regulators referred to above are mechanically interlocked so that they function in synchronism as desired. To change from buck to boost or vice versa it is necessary to operate the switches provided for that purpose and so designated on the diagram. It is possible to provide an equipment of this sort with switches so that the series tranformers can be short-circuited when they are neither bucking or boosting, so that they can be disconnected from the line even when it is carrying load.

APPENDIX B

Circle Diagram of the Transmission Lines

The construction of this circle diagram can be readily understood by referring to the vector diagram of Fig. 3, which shows voltage and current relations on the two 66,000-volt lines under certain assumed load conditions. The industrial load is assumed for the sake of simplicity to be grouped at the mid-point of the line. The following considerations refer to whichever line has no industrial load on it or, of course, to both lines if we assume no industrial load.

The length of the vector (Fig. 3) representing the impedance drop bears a definite relation at fixed bus voltage to the kilovolt-amperes transmitted over the line, and a scale placed on the diagram which will read the length of this vector *O-F* in any position can be marked to read kilovolt-amperes transmitted over the line.

A scale placed on the diagram so as to read the projection of the impedance vector on the line *O-D* can be marked to read kilowatts transmitted, and if desired, the reactive kilovolt-amperes can be read on the scale which indicates length of the projection of this same vector on a line 90 deg. from the one reading the kilowatts.

There is also a definite angular position of the impedance drop vector for each line power factor. At unity power factor it will take the position *O-D*; *O-B* is perpendicular to E_c and the ratio of *D-B* to *O-B* is equal to the ratio of the resistance of the line to its reactance. At zero power factor, the vector will swing around 90 deg. to the position *O-G*. The arc *D-F-G* can obviously be marked to read power factor of the line.

The circle diagram of Fig. 9 is based on the principles outlined above, omitting most of the vectors of Fig. 3 for the sake of simplicity and adding the necessary scales each with a series of guide lines to facilitate reading the different values. In addition to the scales referred to above, there have been added, one for reading the amperes at 13,600 volts (as this was of more practical value than the amperes at 66,000 volts) and another for reading kilowatts lost in the transmission system. The kilowatt loss includes in addition to the copper loss in all parts of the circuit, the core losses of the regulator and transformers. These scales are based on a bus voltage of 13,800 volts and apply only to the line which is not carrying an industrial load.

It will be found that a circle, drawn on a piece of celluloid, representing the voltage of the regulator to scale, will be of material assistance in taking readings from the circle diagram. To take a set of readings, the celluloid is placed on the diagram so that some part of the circle coincides with the point which defines the end of the impedance drop vector on one line and the center of this same circle on the arc representing the bus voltage, which it is desired to have at the receiving end of the lines. The load conditions which it is impossible to obtain on the other line can be read at any point on the regulator circle, as desired.

In order to illustrate the method of using this diagram, two sets of readings of load on the untapped line will be taken for the load conditions shown by point No. 3 for the tapped line. If it is decided that the Schuylkill bus voltage should be 13,600 volts, then the regulator in the tapped line should be in the position indicated by the dotted line connecting with point 3.

The point of intersection of this regulator voltage with the bus voltage line is the center of the regulator circle for the untapped line, and its position has been indicated on the diagram. The intersection of the regulator arc with the 20,000 kv-a. arc is the point for which readings will be taken to determine the conditions under which 20,000 kv-a. can be transmitted. The readings are: 17,200 kw., 87 per cent power factor, 10,000 reactive kv-a., 840 amperes, and 925 kw. loss. If it is desired to transmit energy from the Chester Station at 85 per cent power factor, the intersection of the regulator arc with a line from the center of the diagram to the 85 per cent power factor mark, is the point determining the readings, which are as follows: 18,000 kv-a., 15,200 kw., 9600 reactive kv-a., 750 amperes and 775 kw. loss. All readings obtained are based on a voltage of 13,800 volts at Chester, and if it is desired to operate this station at any other voltage the proper corrections must be made.

If it is desired to transmit energy over these lines from the Schuylkill Station to Chester, different points will have to be calculated and plotted on the diagram, as the impedance from the Schuylkill Station to the consumers is not the same as from the Chester Station to the consumers. If there is no load supplied to the consumers, the analysis of performance characteristics is somewhat simplified as the load condition which can be obtained on any line can be read without plotting points, by simply making use of the proper scales and the regulator circle.

It must be kept in mind that the values read from this diagram are approximate but are satisfactory for the purpose of making studies of line performance.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 22, 1921.

VOLTAGE REGULATION AND INSULATION FOR LARGE-POWER LONG DISTANCE TRANSMISSION SYSTEMS

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Abstract of Paper

Heretofore the distance to which power could be transmitted has been limited. This limitation is now removed by a simple method of loading the line with synchronous condensers, so that the current and voltage may be kept practically in phase. High power factor and hence high efficiency result, and the voltage rises of the system are very much reduced, thus reducing insulation strains.

A standard frequency of 60 cycles is advocated for the national system, and 220,000 volts is proposed as standard for extra large-power, long-distance transmission. The system of regulation proposed will result in practically constant voltage at all points of the line at all loads. And power may be taken from or supplied to the line at any point, and the power over sections of the line or over the entire line may be reversed and the constant voltage system maintained.

A simple diagram is given, and this shows that for a 60-cycle, 220,000-volt line, the line-charging current supplies the capacity current required for about 0.8 load or 320 amperes load current, and that for larger loads the synchronous condensers supply leading and for smaller loads lagging current. Thus it is seen that the transmission line has largely inherently the currents required for self-regulation, if we correct initially the power factor of the loads to near unity. Every induction motor added to the power system calls for a certain capacity current for correction of power factor to reduce the losses from motor through to the power station. Every synchronous motor added, instead of an induction motor, helps in the economy all along the line, improves the service and reduces the menace resulting from large lagging currents. Every synchronous motor added becomes an asset to the entire system. Power factor correction should be done largely at load centers, the final correction and regulation being accomplished by the transmission line capacity current and the synchronous condensers.

The advantages of such a system are: Simpler and cheaper generators, transformers standardized for one voltage, insulation strains reduced and a safer

system results, and with constant voltage the flow of power has the greatest possible flexibility. (So far as known the proposal and method of presenting are new).

This will give a system power transmission comparable to railway transportation, with a flexibility not possible in the ordinary system which does not have the constant voltage feature.

The problems of the line insulation are discussed, and especial attention is called to the necessity for low air and leakage resistance stresses. The leakage resistance stresses are most important. For best results these should be distributed as uniformly as possible over the insulator surfaces, under the worst conditions. Results of a large number of tests are given.

A new diagram is given which results from analysis of experimental data, from which the characteristics of long insulator strings may be calculated, knowing the constants of the units relatively.

The wet and dry arc-over may be controlled if desired, as shown by the illustrations, but it is believed best to strive for the elimination of arcs, except for cases of accident.

While the present insulators with some form of shielding or grading (and with a system of regulation as given in Part I) will no doubt give more satisfactory results for 220,000 volts than is now obtained on lower voltage lines, it is desirable that further work be done with a view to crystallizing the best method of handling the line insulation. There is here an opportunity for some pioneer work, which will give us all that is desired, resulting in a high factor of safety for the line insulation.

I. VOLTAGE REGULATION OF TRANSMISSION LINES

INTRODUCTION

WHEN a power man is asked how far electric power may be transmitted, he often qualifies his answer by restricting the frequency, or the per cent power loss, or by saying one mile for each 500 or 1000 volts between wires, etc., etc. The only real qualification should be that we can transmit power as far as economy dictates. That is, we are now, as herein shown, able to transmit power as a commodity from its points of production to the places of its use without restriction as to distance, etc.—*so long as it pays to transmit the power.*

Engineers are prone to pay too much attention to the losses or percentage losses in transmission. But the real answer to the transmission problem—assuming it now possible to give constant service—is the value of the product at the end of the transmission. A man may start out with a truck load of gasoline and transport it so far that only one-half, say, remains, but the remainder—not diminished in quality—may be very profitably used. In many operations only a small fraction of the energy measured in kw-hr. is used at the end of the cycle and yet the operation may be very profitable.

In the electrically driven trains, machine tools—in the incandescent lamp, etc., only a small part of the energy is finally utilized. In wireless transmission of messages only an extremely small fraction of the transmitted energy is received, and yet it is successful. (Wireless transmission of large power is not possible and wire transmission is a refinement over wireless transmission.) The electric transmission of power may be at high efficiency, even for long lines as shown here, and give good service.

Let us suppose we have a cheap source of water power and that the losses in transmission are 10 per cent average for each 200 miles. Then the efficiency of transmission for each 200 miles—giving practically perfect service as will be shown—will be approximately as follows (conductor area remaining constant):

Section	Average Loss	Efficiency & Power
0 to 200 miles....	10 per cent	90
200 to 400 "	9 " "	81.9
400 to 600 "	8 " "	75.35
600 to 800 "	7 " "	70.08
800 to 1000 "	6 " "	65.78

For 1000-mile transmission this shows about two-thirds of the power delivered or one-third lost. The above assumes all the power carried the full 1000 miles. If power is supplied at 200 miles, the efficiency would be 90 per cent, etc. At 600 miles we have an efficiency of transmission of about 75 per cent. For distributed loads the efficiency would be higher.

The cost will not be prohibitive if we have a cheap source of power going to good markets as will be shown by the following:

The capital cost of power at the generating station we may take, say, at $150 per kw., and the transmission cost, including synchronous condensers and their transformers, may be $15 per kw. per 100 miles, or 10 per cent increase in the power cost for each 100 miles, or $300 per kw. (per kw. generated) for 1000 miles. But since the power delivered at 1000 miles will be about two-thirds, then the capital cost per kw. delivered will be $450. The above assumes 100,000 to 200,000 kw. (or more) transmitted per three-phase circuit, which may be successfully done (using aluminum for the smaller and copper for the larger power), as we shall see at 220,000 volts.

There may be a very large market, say five hundred miles from the power source, and the transmission system built for that condition. But another power load may be 50, 100 or 200 miles away and the justification for the added transmission must be that this step must pay the cost of the power at the end of the 500-mile transmission and all of the remainder of the transmission. Such a system may grow to a national power system.

220,000 VOLTS PROPOSED AS STANDARD FOR LARGE POWER AND LONG DISTANCE

Since we can transmit at this voltage so large an amount of power (a thousand miles if economical) over one circuit, and a very large system would want for service insurance at least two tower lines with four circuits, giving a capacity of 400,000 to 800,000 kw. or more, it seems that for this reason it may be best to adopt 220,000 volts as standard for the national transmission system, just as the railroads have adopted a standard gage. It will be shown that so far as other restrictions are concerned we may go to higher voltages, but the economic limitations may be reached by 220,000 volts, when we consider the value of standardization, the service insurance of multiple circuits, the amounts of power available at certain places, or the demand of a given market.

Heretofore I have always said that we would go to higher voltages, but I now believe, for the above reasons, that 220,000 should be standard for extra high-voltage systems. And it would be advantageous if 220,000-110,000-55,000 could be generally adopted, in order that auto-transformation may be used economically.

A STANDARD NATIONAL ELECTRIC POWER SYSTEM

STANDARD FREQUENCY

To have a national electric power system requires first, standardization of frequency. Since 60 cycles is generally advantageous for generators, transformers and distribution, I will assume that this is the frequency of the very long-distance transmission. It is generally assumed that this frequency is disadvantageous for long transmission lines on account of voltage regulation, but it will be seen that all regulation requirements can be very successfully met with 60 cycles. I therefore believe it will be best to standardize on 60 cycles.

CONSTANT VOLTAGE AT ALL POINTS OF LINES

It will be necessary for the successful long transmission line to have practically a uniform voltage for all points of the line—not only for one load but for all loads. This voltage can be controlled within 3 per cent from no-load to full load and with no greater variation for any points on the line. The standard transmission system must provide for power being supplied to the line and for loads to be taken off at certain points, just as does a railway system. The system must be such that the power loads supplied to the line or taken from the line may vary and that the flow of power over sections may be actually reversed, or the flow of power over the entire line may even be reversed—without disturbing the voltage regulation necessary to give good service at all points. There is nothing experimental about the proposal as synchronous condensers for voltage regulation for fairly long lines were used as early as 1904 on what is now the system of the Pacific Gas and Electric Company, to regulate voltage in an emergency for transmission of power over 300 miles of line at 44,000 volts. The present plan differs from the ordinary plan in that synchronous condensers are located, say every 100 miles, and with these condensers the current and voltage would be maintained practically in phase.

It will be seen that the maintenance of constant voltage at all points is not a difficult matter and in doing this we get rid of a lot of other troubles and expense,—such as voltage rise due to dropping loads, transformer variable ratios, voltage regulators, etc., *and reduce the insulation strain.* The successful very long lines must provide for keeping the current and voltage practically in phase at all points of line.

If engineers and operating men can standardize the frequency and the voltage so as to give constant service, and the insulation of the transmission lines is made so that the line is as successful as the transformers, then we may see the real era of very long, high-power transmission systems in the near future. The 220,000-volt lines now being built are therefore extremely important; and extreme care is being given to all the questions, not only in view of the importance of the lines being built, but also because of the effect on the service of these lines on the transmission industry as a whole.

VOLTAGE REGULATION OF TRANSMISSION LINES*

It is necessary to decide on the voltage regulation of the system before we can know what ordinary and extraordinary strains may come on the insulation of the transmission line; hence this subject is treated first.

In Fig. 1 is shown the regulating diagram for a 200-mile, 220,000-volt line, for 400 amperes current. It is shown there that without synchronous condensers for

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*See: The use of Aluminum Line Wire and Some Constants for Transmission Lines, A. I. E. E., May, 1900, by Dr. F. A. C. Perrine and F. G. Baum.

A Simple Diagram Showing the Regulation of a Transmission System for any Load and any Power Factor, *Electrical World*, May 18, 1901, by F. G. Baum.

High Potential Transmission and Control, *International Elec. Congress*, 1904, by F. G. Baum.

Economic Limitations to Aggregations of Power Systems, by R. A. Philip, A. I. E. E., February, 1911.

Synchronous Motor Calculations, *Electrical World and Engineer*, May 17, 1902, by F. G. Baum.

Alternating-Current Calculating Device, Second Edition, 1903, by F. G. Baum.

a power factor of load of 0.95 the generator voltage would have to be 157 per cent of receiver voltage. At no-load the generator voltage would be about 86 per cent if all charging current is carried by generator. Even for non-inductive load the generator voltage at full load would have to be raised 36 per cent above receiver voltage. Now this extra generator

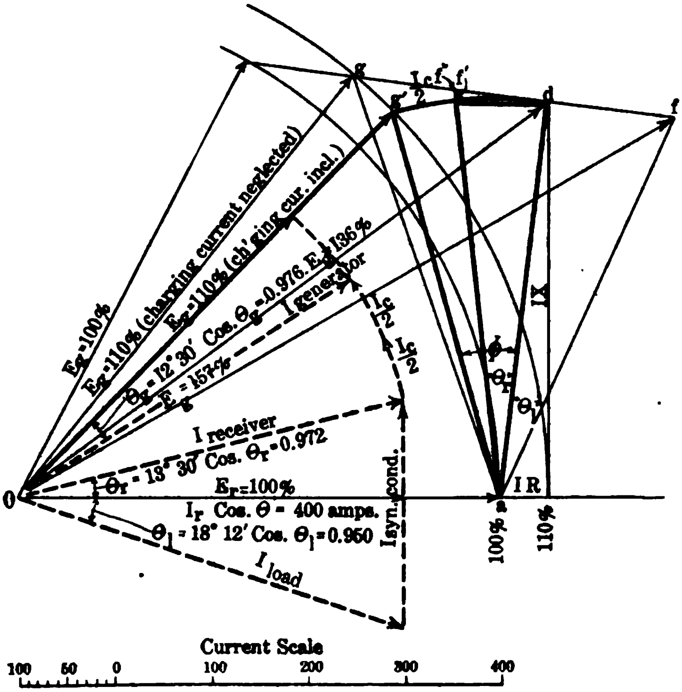

Fig. 1—Regulation of Line with Transformers at Each End

CONDITIONS:

Length of line = 200 miles. Receiver volts E_r constant at 200,000. Charging current 136 amperes.

I Cos θ at receiver = 400 amperes. Power delivered = 138,600 kw.

$I R$ pressure including transformers at each end of line = 10 per cent E_r (approx.)

$I X$ pressure including transformers at each end of line = 80 per cent E_r (approx.)

RESULT:

CASE 1. Charging current neglected. With no synchronous condenser at the receiver and a load power factor of *unity*, the generator voltage E_g = $o\ d$ = 136 per cent E_r = 272,000 volts at full load.

CASE 2. Charging current neglected. With no synchronous condenser at the receiver and a load power factor of 0.95 lagging, the generator voltage $E_g = o\,f = 157$ per cent $E_r = 314{,}000$ volts at full load.

CASE 3. Charging current neglected. With a synchronous condenser at the receiver to maintain a generator voltage $E_g = o\,g = 110$ per cent $E_r = 220{,}000$ volts at full load, the receiver power factor would be 0.89 leading (cos. angle $d\,a\,g$.). The ratio $f\,g/a\,d$ gives the synchronous condenser current necessary to correct the power factor from 0.95 lagging to 0.89 leading (336 amperes approx.).

CASE 4. Considering one-half of charging current as supplied at each end of the line, and a synchronous condenser at the receiver to maintain a generator voltage $E_g = o\,g' = 110$ per cent $E_r = 220{,}000$ volts at full load:

With a as center, draw circular arc $d\,g'$. The length of arc $d\,g'$ is equal to $a\,d \times \Phi$ (in radians).

The angle Φ measures 23 deg. = 0.401 radian. $a\,d = \sqrt{0.10^2 + 0.80^2} \times E_r = 0.806\,E_r$. $d\,g' = 0.806\,E_r \times 0.401 = 32.3$ per cent E_r.

The charging current $I_c\,X/2 = 13.3$ per cent (approx.), hence the correction to be made by the synchronous condenser is $32.3 - 13.3 = 19.0$ per cent.

Lay off $d\,f' = 19.0$ per cent E_r and draw $a\,f'$ and $d\,f'$. Note that the condenser current must be at right angles to $a\,d$, so for practical purposes we may use the point f'' instead of f'.

The power factor of the receiver is 0.972 leading (cos. angle $d\,a\,f''$). The ratio $f\,f''/a\,d$ gives the synchronous condenser current necessary to correct the power factor from 0.95 lagging to 0.972 leading (230 amperes approx.).

· NOTE: Fig. 1 is given mainly to show that very long transmission without synchronous condensers is not practicable. The figure as drawn is not absolutely accurate except when $E_r = E_g$, but the error is not material.

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voltage is part of the capacity of the generator and costs money. Restricting the generator voltage increase to the 10 per cent required to make up the dissipated energy on the line, requires synchronous condensers of about 80,000 kv-a. at full load, but about one-half this amount is required to correct the power factor of the load. In this figure and those following, the explanations are given with each case. Fig. 1 is given largely to show that it is impossible to transmit power over long distances and give satisfactory service without synchronous condensers.

Fig. 2 gives the fundamental basis for regulation for constant voltage by using distributed capacity, of such magnitude that the line current and voltage are always practically in phase. This makes the reactance pressure always tangent to the voltage circle, the reactance voltage being represented by the circular arc connecting the ends of the line pressures.

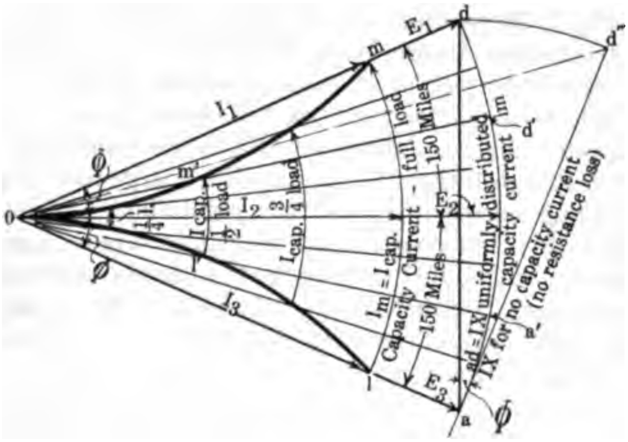

Fig. 2—Regulation of Line Alone

Uniformly Distributed Capacity Current to Correct Voltage at all Loads

CONDITIONS:

Length of line, 300 miles. Voltage at all points constant at 200,000. Charging current 200 amperes.

Energy current delivered to line, 400 amperes. Power delivered to line, 138,600 kw.

No resistance loss and no energy dissipated along the line.

***I X* pressure equal to approximately 80 per cent E_2 and measured by arc *a d*.**

RESULT:

If no power is lost along the line, then current $I_1 = I_2 = I_3$ and they are in phase with voltages E_1, E_2 and E_3, the power factor being unity. If reactance pressure is 80 per cent of E_2, then arc $a\,d = 0.80\ o\,a$ and angle $2\,\Phi = 0.80$ radian = 46 deg. (approx.). The uniformly distributed capacity current is everywhere at right angles to the voltage and the summation is shown by the arc *l m*. If *o l* represents 400 amperes or the energy current, then $l\,m = 2\,\Phi \times o\,l = 0.80 \times o\,l = 0.80 \times 400 = 320$ amperes, the uniformly distributed capacity current necessary to maintain conditions as set down above.

At one-half load the reactance pressure, which corresponds to one-half load, *a d* is reduced one-half to *a' d'*. This reduces the angle between E_1 and E_3 by one-half. Since the current is reduced by one-half *o l* is reduced to *o l'* and the arc *l' m'* becomes one-quarter the length of *l m*. Thus it is seen that the capacity current required varies as the square of the load current.

If there were no capacity current on the line at full load, then the reactance pressure would be $I\,X = a\,d''$ at right angles to E_2. The arc $d\,d''$ shows the voltage correction due to the summation of capacity currents flowing over the line reactance.

Note that the angle between *a d* and *a d''* is always equal to one-half the angle between E_1 and E_3.

CONCLUSION:

To have constant voltage at all points on the line requires that the capacity current uniformly distributed over the line be varied along the curves *o l' l* and *o m' m* from no-load to full load, this variation being as the square of the load current. This maintains the voltage and current practically in phase at all points of the line, and this condition is necessary for successful long-distance transmission of power.

Fig. 3 shows that, for 60 cycles, 200,000 volts and 400 amperes transmitted, the line charging current gives full correction at about 0.8 load, and that the synchronous condensers at full load must supply capacity current of about one-half the charging current. Thus it is seen that the line supplies a large part of the charging current required for regulation. At loads below 0.8 the synchronous regulators supply lagging current. It would be preferable to call the synchronous condensers "synchronous regulators." (This proposal for regulation and the method of presenting it are new, so far as known.)

Thus it is seen that the transmission line has largely inherently the currents required for self-regulation, if we correct initially the power factor of the loads to near unity. Every induction motor added to the system calls for a certain capacity current for correction of power factor to reduce the losses from motor through the power station. Every synchronous motor added, instead of an induction motor, helps in the economy all along the line, improves the service and reduces the menace of large lagging currents. Every synchronous motor added becomes an asset to the entire system. Power factor correction should be done largely at load centers, the final correction and regulation being accomplished by the transmission line capacity current and the synchronous condensers.

There are many places where synchronous motors could replace induction to great advantage. The electrical manufacturers and the power companies should cooperate in developing simplified types of synchronous motors for constant speed work.

The advantages of such a system are: Simpler and cheaper generators, transformers standardized for one voltage, insulation strains reduced and a safer system results, and with constant voltage the flow of power has the greatest possible flexibility.

Figs. 2 and 3 show that it is necessary for constant voltage at all points of the line that the voltage and current be maintained practically in phase. Fig. 4 applies these conditions practically to a 300-mile line and Fig. 5 to a line 800 miles long. The diagram is very simple and may be extended for any line length.

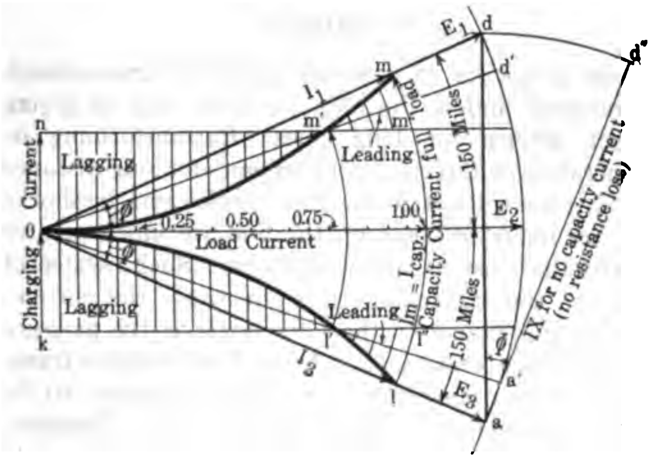

FIG. 3—REGULATION OF LINE ALONE

Line-Charging Current Supplemented by Uniformly Distributed Capacity or Uniformly Distributed Inductance.

CONDITIONS:

Length of line, 300 miles. Voltage at all points constant at 200,000. Charging current, 200 amperes.

Energy current delivered to line, 400 amperes. Power delivered to line, 138,600 kw.

No resistance loss and no energy dissipated along the line.

I X pressure equal to approximately 80 per cent E_3 and measured by arc *a d*.

RESULT:

If no power is lost along the line, then load current $I_1 = I_2 = I_3$. The line-charging current is shown by the line *k n* and is uniformly distributed along the line. At a point of approximately 80 per cent load, the line-charging current *l′ m′* furnishes a uniformly distributed capacity current, which makes the voltage equal at all points along the line. (See conclusion, Fig. 2).

From 80 per cent to full load uniformly distributed capacity current must be added to the charging current, as shown by the lines between *m′ m″* and the curved line *m′ m* and also between the line *l′ l″* and the curved line *l′ l*. The power factor would be unity.

To correct accurately the voltage from no-load to 80 per cent load we would have to have distributed inductance, as shown by the lines drawn between *n m′* and the curved line *o m′* and also between the line *k l′* and the curved line *o l′*. The power factor would again be unity.

CONCLUSION:

The above would give accurately the regulation desired, but we have no method of adding distributed capacity or inductance. The best we can do is to approach the desired result by adding synchronous condensers which may operate as capacity or inductance at the will of the operator.

NOTE:

Thus far we have not considered resistance losses, but they are easily taken into account as will be shown.

This adjustable "loading" of the line to maintain the current practically in phase with the voltage is comparable to the "loading" of telephone lines for long-distance circuits.

CONCLUSION

Such a system of constant potential transmission is practical, and is the only practical way of giving perfect service for long lines. Retransforming or regeneration or direct-current schemes for long-distance transmission will not give as good service and the shocks that are likely to come on the line are much greater than for the constant potential system. Such a system of 'loading" the transmission line to rotate the current through approximately the same angle as the pressure is rotated is necessary for all very long distance transmission, thus causing the reactance pressure to be always tangent to voltage circle. This "loading" to maintain the current and voltage approximately in phase eliminates the question of the natural periodicity of the line, and hence the frequency may be selected independently of this point.

The voltage being constant there is a gradual decrease of current to make up the dissipated energy of the line. The angle between the generator and receiver voltages of a 150-mile section will be about 23 deg. at full load, 60-cycle, and the angle decreases per 150-mile section as the current decreases.

The power factor of line is good, being 0.99 or better from about 80 per cent to full load, and hence efficiency of line is 90 per cent for 200 miles, and 90 per cent for each section of 200 miles, with the result that power may be transmitted 600 miles with an efficiency of about 75 per cent and 1000 miles at an efficiency of about 65 per cent. For distributed loads the efficiency would be higher.

Such a system, with say three or four circuits, and synchronous condenser and switching stations about every 100 miles, may have automatic disconnection for any 100-mile section of each line without disturbing the service. Short circuits should be easily handled.

The synchronous condensers "tie down" the points of the system. Any tendency to raise or lower the line voltage is instantaneously counteracted by the condenser—in this respect acting like an "electric gyroscope."

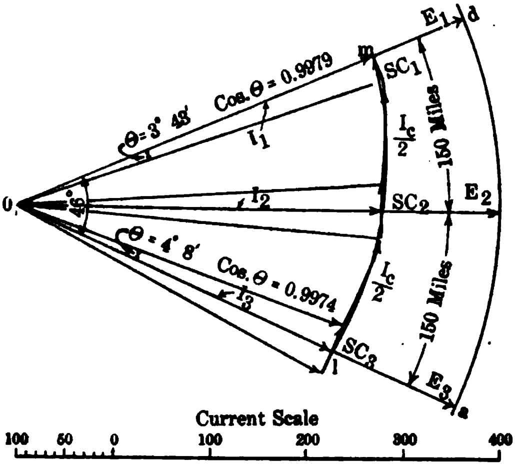

FIG. 4—REGULATION OF LINE ALONE

Leading or Lagging Current Added at Middle and Each End of Line

CONDITIONS:

Length of line, 300 miles. Voltage at middle and each end constant at 200,000. Charging current, 200 amperes.

Energy delivered to line, 400 amperes. Power delivered to line, 138,600 kw. Total energy loss including $I\ R$ = 10 per cent.

$I\ X$ pressure equal to approximately 80 per cent E_1 and measured by arc *a d*.

RESULT:

Since the arc *a d* is 80 per cent of the radius *o a*, the angle *d o a* is 0.8 radian = 46 deg. (approx.).

Since the voltage at each end of the line is constant, the energy loss will appear as a reduction in load current, diminishing in direct ratio to line length, hence if I_1 = 400, I_2 = 0.95 × 400 = 380, I_3 = 0.90 × 400 = 360.

The curve *l m* represents a uniformly distributed capacity current which will give equal voltage at all points on the line at full load. The length of *l m* is approximately equal to 380 × 0.8 = 304 amperes. The charging current supplies 200 amperes of capacity current, leaving 104 amperes to be supplied by synchronous condensers. One-half of this is to be supplied by a synchronous condenser in the middle of the section, one-quarter by the generator, if this is the first section of the line; and if not, by the synchronous condenser at the end of the section toward the power house. The remaining quarter is to be supplied by a synchronous condenser at the far end of the section. This synchronous condenser, however, will be the same capacity as the one at the middle of the section, the excess capacity to care for load power factor correction if it be the terminus of the line or to furnish the initial capacity current required in the next 300-mile section of line. This makes the condensers 18,000-kv-a. (52 × 200,000 × $\sqrt{3}$) capacity, or say 20,000-kv-a. to afford a safe margin, for each 150-mile section of line where there are no transformers or other apparatus to change the $I\ R$ and $I\ X$ pressures as set down above. If transformer resistance and reactance are included, the diagram will have to be modified to fit a section of line enough shorter than 300 miles, so that $I X$ and $I R$ including transformers are 80 per cent and 10 per cent respectively. This lowers the charging current and increases the size of synchronous condensers required for the section. In considering the 300-mile section, the transformers for the synchronous condensers are small and the magnetizing current will be supplied by the condenser. The section is considered as if no transformers were present.

The voltage on a 300-mile section at no-load varies less than 1 per cent, if the charging current is supplied one-half at the middle and one-quarter at each end of the line. The power factor at each end of the 300-mile section will be practically 0.99 and the entire section will have a power factor between 0.99 and unity, from 80 per cent to full load. (See Fig. 3).

Since transformers can be designed so that increase of line voltage gives a very rapid increase of magnetizing current, we have here, as well as in the synchronous condensers, automatic magnetic brakes acting against increases in voltage.

Corona losses increasing with voltage, if size of wire is chosen near the corona point, will also automatically act against increases of speed and voltage.

The voltage strains on insulators, switches and transformers of such a system will be much less than where the constant potential control does not exist, and hence we very largely solve the insulator problem by the voltage control.

The "loading" of the line with transformers designed for a rapid rise in magnetization with increases in voltage, the transformers having secondary or tertiary windings connected delta, connected to synchronous condensers at proper distances, will reduce the insulation rises so that 220,000-volt lines will have less insulation overstrains than present high-voltage lines. Adding to this the improvement to be obtained by decreasing the duty on the line wire insulator units, assures the success of very long transmission lines—practically removing the distance limitation to electric transmission. This method of transmission also eliminates the necessity for further consideration of d-c. transmission as the a-c. system has the advantage of the constant-voltage feature, for any conditions of loads and power supply, and has other advantages over the d-c. system.

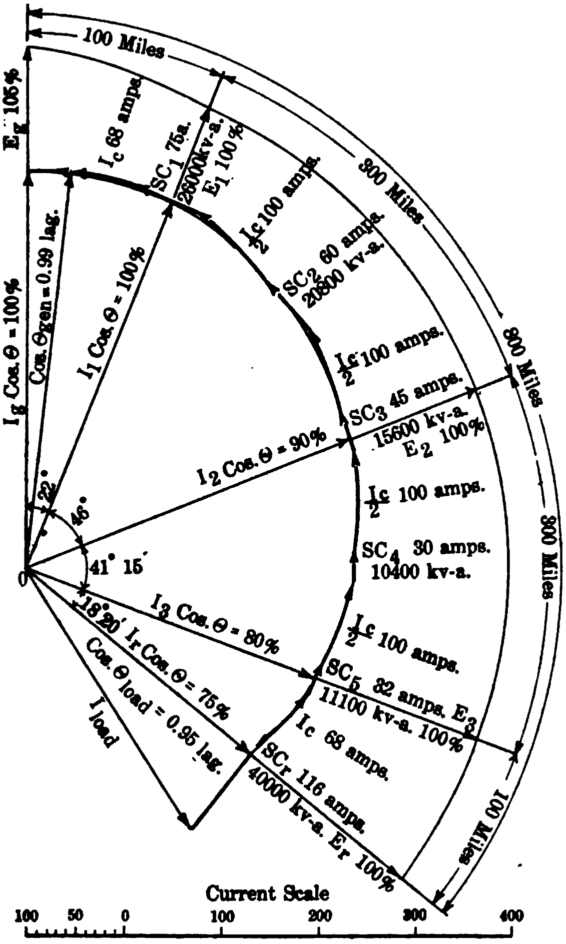

FIG. 5—REGULATION OF COMPLETE TRANSMISSION SYSTEM

CONDITIONS:

End sections of line each 100 miles long. *I X* pressure including transformers, 40 per cent. *I R* pressure including transformers, 5 per cent. Charging current, 68 amperes.

Intermediate sections of 300 miles length. *I X* pressure, 80 per cent. *I R* pressure, 10 per cent. Charging current 200 amperes.

Full-load generator volts, 105 per cent E_r. Voltage constant after first synchronous condenser station.

I cos *θ* at generator is 100 per cent. *I* cos *θ* at first synchronous condenser station is 100 per cent and then decreases uniformly along the line to care for energy losses. (Note that cos *θ* varies only slightly from unity, and that the current tapers from 100 to lower values to make up resistance losses as shown.)

RESULT:

Generator Section: See Fig. 1 which shows a 200-mile section with generator and transformers at one end and condenser and transformers at other end. Apply the generator end one-half of Fig. 1 to this case, modifying it as to generator voltage and consider that the generator carries only one-quarter of the capacity current instead of one-half as shown, the other one-quarter to be supplied by the first condenser in the adjoining section.

Second Section: Conditions exactly as in Fig. 4.

Third Section: Current is now 90 per cent I, hence the $I\ X$ pressure is 90 per cent of its value in section two $= 0.90 \times 0.80\ E_r = 0.72\ E_r$. The arc length representing this pressure is therefore reduced and the angle becomes 0.72 radian = 41 deg. 15 min. The capacity current required is $360 \times 0.72 = 260$ amperes (approx.). The charging current is 200 amperes, leaving 60 amperes to be supplied by the condensers as in section two.

Receiver Section: Current is now 80 per cent I, hence the $I\ X$ pressure is 80 per cent of its value in the generator section $= 0.80 \times 0.40\ E_r = 0.32\ E_r$. The angle now becomes 0.32 radian = 18 deg. 20 min. The capacity current required is $320 \times 0.32 = 102$ amperes (approx.). The charging current is 68 amperes, leaving 34 amperes total to be supplied by the condensers at the ends of the section.

If the load power factor is 95 per cent lagging, then the terminal condenser current will have to be increased by 99 amperes to rectify this load, and the kv-a. capacity would be $(17 + 99) \times 200{,}000 \times \sqrt{3} = 40{,}000$ kv-a. approximately.

NOTE: Power may be delivered to or from the line at any point. The load currents and synchronous condensers may be readjusted to care for the new conditions so that the voltage may remain practically constant. The power flow of the entire line may even be reversed and the constant voltage conditions retained.

II. INSULATION OF TRANSMISSION LINES

The early transmission systems used the pin type of insulator, and lines up to 80,000 volts successfully used this type. Then the demand for higher voltages brought out the disk suspension insulator. Mechanically the disk insulator at first view seems an impossibility. But the insulator men have solved the difficulties and deserve a great deal of credit for the result. Suspension types can now be made with ultimate strength of 7000 to 20,000 lb.

The insulator men have carried a large burden during the development period of the insulator. Sometimes this burden is made greater by the engineer or operator asking for some particular design which may not be as good as standards already made. The desire of the individual to write his name on something is at the bottom of many failures in engineering as well as along other lines of human endeavor. On the other hand pioneer work is required when conditions change and designs must follow fundamental laws.

When the type of insulator for the high voltages changed to the disk type, it was assumed that the addition of more voltage merely required more units.

But it was soon found that the results were not at all in proportion to the number of units in the string. Investigating the cause it was found that the voltage tended to "pile up" on the line unit.

A very large number of tests has been made on voltage distribution, with various arrangements of controlling gradient, and also to determine the arc-over characteristics, both dry and wet, for various control arrangements. These tests were made in the following places and under the supervision of the following men:

Stanford University, Cal. Prof. Harris J. Ryan.
General Electric Co., Pittsfield, Mass. F. W. Peek, Jr.
Ohio Insulator Co., Barberton, Ohio. A. O. Austin.
Thomas & Sons, Lisbon, Ohio. R. H. Marvin.
Locke Insulator Co., Victor, N. Y. K. A. Hawley.
Westinghouse Elec. & Mfg. Co., Pittsburgh, Pa. C. Fortescue.

I very greatly appreciate the interest shown by these men and acknowledge with thanks their hearty cooperation.

In the following pages the insulation problem is discussed in some detail, and the discussion is followed by an appendix giving the results of a large number of tests, the conditions for which are stated. Only a few of the tests made are given.

Insulation of Transmission Line

In the insulation for transmission lines we must consider the following:

1. The air insulation strength.
2. The porcelain insulation and mechanical strength.
3. The voltage distribution.
4. The leakage resistance gradient over the surface of the insulators.
5. Insulation of switches, transformers, etc.
6. Wet and dry arc-over of line insulation.

1. THE AIR INSULATION

Engineers and operators have been prone to blame the insulation difficulties on the air. But as a matter of fact, air is, except where we have salt spray, etc., a very good insulator. Peek (whose work on Dielectric Phenomena is a classic in engineering) has shown in his book that it requires only about three inches of air between 10-inch spheres to prevent break-down for 130,000 volts to ground, which is about the voltage to ground for a 220,000-volt line. Two 20-inch spheres, spaced two feet, give a factor of safety of about four. We are using over six feet from wire to ground at the towers (15 feet between wires in the span), but we do not get a factor of safety commensurate with the distance.

With wires about 1 inch in diameter we need never fear break-down of the air between the wires a few feet away from the insulators, and if it were not for the reduction in the equivalent spacing at the tower, due to the insulator breaking the distance into a number of parts, with unequal stress on the separate units, we could reduce our spacing in the span and thereby reduce the height of the towers.

Fig. 6 shows the voltage air gradient for a wire 0.91 in. in diameter at 220,000 volts, and also the gradient for a wire 0.47 in. in diameter for 110,000 volts. It is seen that the gradient is very high near the surface of the wire, and very nearly the same in the two cases. The break-down value of air is about 20 kv. (effective) per cm. (The size of line wire is purposely chosen so that increases of voltage much above normal will increase materially the corona losses, as this is a safeguard in case of rise in voltage due to speed rise or otherwise). At a distance four cm. from the surface of the 220,000-volt wire the gradient is only about 4 kv. per cm. In the span, away from the insulators, any tendency to produce visual corona has the effect of enlarging the effective diameter of wire so far as surface gradient and break-down are concerned, hence the air in the span does not break down for any voltages that may be reached in operation.

Coming now to the line clamp fittings and insulator pin of the first unit, we see that we have here very high air gradient, due to small diameters, angles of bolts, fittings, and also due to the small pin of the bottom insulator. When excess voltages come on the line they pile up most of it at the insulator units near the line wire. This breaks down the air where it is highly stressed at the line fittings, and the air breaks down serially from one unit to another, by transferring the high electric stress from one unit to another in the string. (Corona also forms acids which attack the metal fittings.) It is necessary to prevent incipient corona pluming or arcs at the insulators, if the transmission line is to be fully successful—by which I mean the insulation of the line must be such that the line should give as good operating results as the transformers or other transmission apparatus. Of course, the line is subject to damage maliciously, or due to accident, but neglecting these, the line should be made as reliable as the remainder of the system.

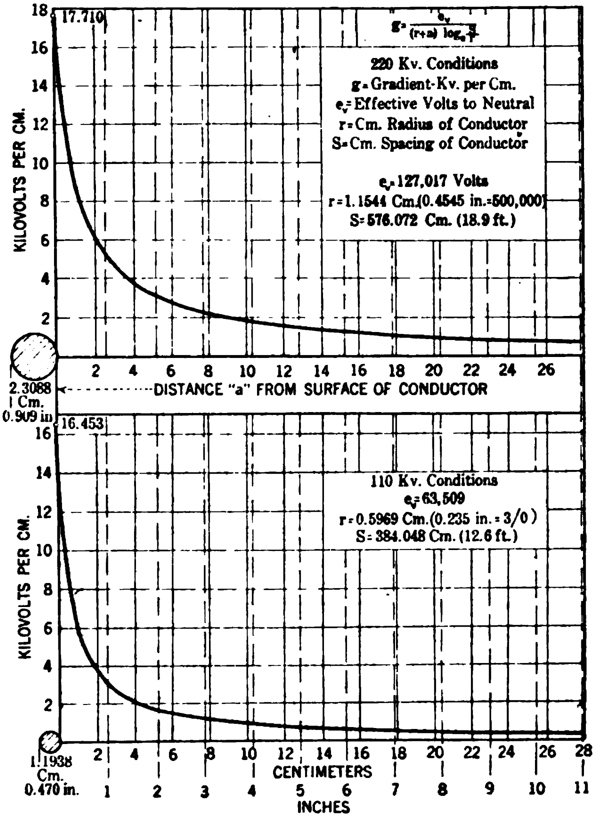

Fig. 6—Air Gradient for 220,000- and 110,000-Volt Conditions

Attempts made to reduce the air grading at the pin and fittings by the use of "shields" (these will be explained later) have led to fairly satisfactory results. And it seems necessary to shield the line wire and fittings by enlarging the conductor diameter by some such cylindrical (or double cone or plane) shield as shown in Figs. 7 and 8. With such a shield the visual corona near the insulator may be raised far above the operating voltage. The fittings of the insulators of the string should also be designed to prevent high air stress.

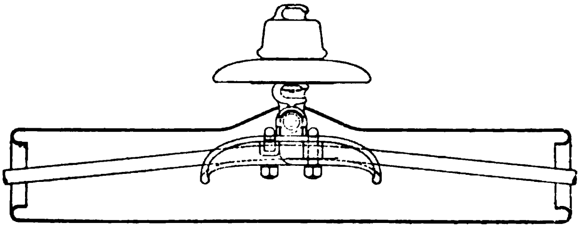

Fig. 7—Line Shield

2. The Porcelain Insulation

Porcelain when well made is a good insulator, and will not puncture under the stress conditions placed on it, if the other elements in the insulation are cared for. The metal fastenings to the "cap and pin" disk types of insulators add a mechanical depreciation factor because expansion and contraction are not the same for the porcelain and the metal parts, and the cement used to fasten the parts together. By careful manufacture, a very tough porcelain can be made, in which depreciation from expansion and contraction can be very much reduced. Careful selection and working of the clay, and sufficient time in firing, give a very high-class insulator product.

Impregnating the cement, to prevent absorption of moisture, has given good results, according to Mr. E. E. F. Creighton. Some means of keeping the moisture out of the cement, and careful mixing and setting of the cement initially, will no doubt reduce the mechanical failure due to these causes to very low values. I have always contended that we should finally obtain insulators that do not depreciate.

In the link type of fastening the mechanical depreciation from expansion and contraction is very largely reduced, but in the types now made we are restricted to small diameter of metal parts, and it is necessary on high-voltage lines to shield the links—at least those in the lower part of the string. (Fortunately this also improves the grading of the string as will be seen later).

The depreciation, due to expansion and contraction, is largely one of cost, and as it is a slow process and we have a factor of safety in the number of units in the string, we may dismiss the mechanical failure from the above causes as not affecting good service with good inspection.

The mechanical strength of all the standard insulators is from 7500 to 10,000 lb. and over, and these can be increased 50 or 100 per cent, where necessary, so that we have ample factor of safety for the mechanical suspension of the line wires.

3. The Voltage Distribution from Line to Ground

Figs. 12 and 13, and plates, D1, D2, D3 and D4 in the appendix, show the voltage gradients for cap and pin insulators and also for the link type. It is seen that, for the voltage corresponding to that between line wire and ground, the total pressure is divided very unevenly among the units. In the cap and pin string of 14 units the volts on the line unit are about 25,000, or about 2.5 times the average, but about six times the volts on the units near the ground end. In the link type as shown, we have even a worse case of distribution of pressure, the maximum being about 37,000 or four times the average, and about ten times the stress on the units nearer the ground end of the string. This unequal stress on the units also causes unequal stress on the air, *but most important it does not distribute the leakage resistance along the string uniformly*. The maximum air and leakage stresses are from six to ten times the average. Reduction of the maximum stresses is therefore very important, and the result desired is that there will be more nearly average resistance stresses over the entire string, for the worst practical conditions.

Discussion of Cause of Poor Gradient and Method of Cure. Before we can say we fully understand a subject we must be able to express the facts in words mathematically or by diagram. Before we can rationally analyze an insulator we must know the factors which will limit the maximum stresses, which are:

1. The air stresses,
2. The leakage resistance stresses,
3. The insulator unit stresses.

The air stresses we know, as shown by Fig. 6, and to control this factor we must enlarge the conductor at the insulator, as shown in Figs. 7 and 8. The first controlling factor for satisfactory insulator characteristics then is that we must have metal parts designed to give low air stresses at the line wire, and also along the string of insulators, at least near the line wire end.

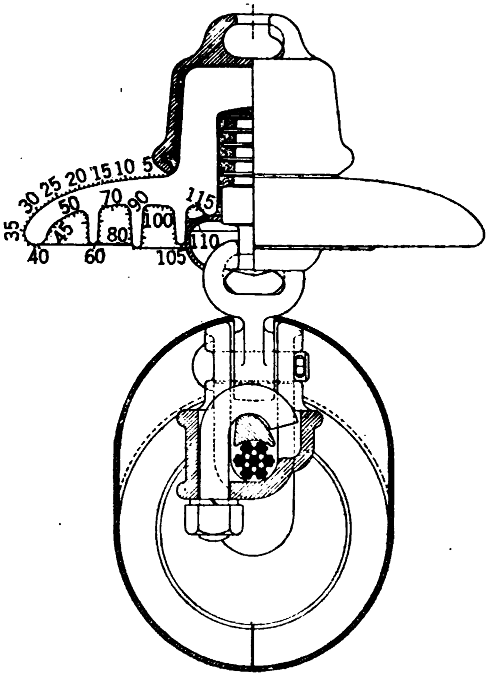

FIG. 8—LINE SHIELD AND PIN SHIELD

Numbers on edge of porcelain are for measuring leakage paths. (See Fig. 14.)

The unit stress affects the leakage stress and therefore it is very important also from this standpoint to reduce the maximum unit duties. The maximum leakage stress can be reduced (1) by reducing the unit voltage and (2) by enlarging the pin as shown in Fig. 8, and by the design of the resistance path from metal to metal as shown in Figs. 14 and 15. The enlargement of the pin and the shield over the line wire also reduces the maximum voltage on units near the line. The importance of reducing the maximum value of the leakage gradient is shown by the fact that in the pin type of insulator with the close fitting inner shell, better operating results are obtained by breaking off the inner shell. Here is one way of reducing the maximum leakage gradient, but the design should take this into account. This will be further discussed under (4): The Leakage Resistance Gradient over the Surface of the Insulator.

Hence, we have these two factors, (1) the enlargement of line wire and metal parts, and (2) the enlargement of pin, to start with to give us a satisfactory insulator. As will be seen, taking care of these two points helps the grading of the units fairly well.

The third factor, the grading of the units, requires that we be able to understand the reasons for the string gradient.

An attempt to explain this is here given in such a way that the drawing of a few lines may show the characteristic of any insulator string, knowing certain factors relatively only. It is not contended that we have all the facts necessary to explain every condition, but the method does give a simple and practical way of explaining many of the observed results, and it is hoped that the method given will lead to a further study of the subject, so that we may design or analyze the design of insulators in the same way as any other engineering problem.

Figs. 9A, 9B, 9C and Table 9D give the explanation which results from a study of the distribution curves shown in Figs. 10 and 11.

(The individual insulator string may be regarded as a short section of transmission line with the *Y* voltage between ends, and with load currents, *B*, taken off at the different sections (or units) and load currents, *C*, being supplied to the sections. The load currents, *B*, depend on the voltage at the particular section.)

Referring to Fig. 10, which is a voltage distribution test curve of 14 cap and pin units, as shown by Curve I, this curve represents the voltage across the units, but as the voltage is proportional to the currents through the units the curve also represents, on some scale, the currents. Now the difference between the current through No. 14 and No. 13 units, for example, is the *net* current from the metal connecting parts to tower or ground. Taking the differences of the voltages and plotting them from the line *a a′* we get the Curve II, which represents the net currents flowing from or to the string. It will be noted that below the fifth unit the currents flow from the string and above that point the currents flow from the air to the string.

In trying to find a physical explanation for this condition we draw the insulator string gradient and the air potential gradient on the left hand of Fig. 10, and from the knowledge gained from Curve II we see that where the net current from the metal part is zero the string potential and the air potential must be the same. Also we see that the summation of currents above the line where distribution Curve I cuts the average voltage, must be zero and that the current *c′ a′* at the top cap must be due to the current flowing to the cap only, as this cap is at zero potential. From this and from calculation of the potential drop through the air near the line wire (which we know follows a logarithmic curve) and from the fact that the air potential reaches zero at some distance above the crossarm in the span, we draw the approximate air potential. The difference between the air and string potential causes the currents to flow to or from the string as in Curve II.

We know that the currents from the metal parts to tower or ground would be approximately proportional to the voltage and hence a line *a′ b* may represent this current. Replacing the curved line II by the straight line III for simplicity of treatment and now calculating the gradient, we get Curve IV which approximates Curve I fairly closely. At the lower unit, due to the high electric stress, there is added potential to the lower unit. The difference between the line *a′ b* and *c′ c* represents approximately the currents from line wire to metal parts. This is the experimental basis for the discussion given in Fig. 9, in which 9B is supposed to represent the physical conditions, 9A the electrical and 9C the diagrammatic conditions. Fig. 11 gives the experimental results for the link type of units.

While not considered exact, the analysis does help us to understand the insulator problem.

Satisfactory voltage distribution may be obtained, as shown by Figs. 9, 10 and 11 and also by Figs. 12 and 13 and the distribution curves in the appendix:

1. By use of ring shield,
2. By use of insulated horn shield,
3. By grading the lower one-third of the units,
4. By combining pin-type insulators at line end with disk-type for the upper end of string.

Methods 1 and 2 are very similar and accomplish the result by control of the field, by reducing the *B*

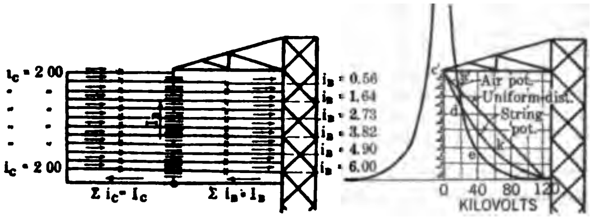

FIG. 9A FIG. 9B

ANALYSIS OF DISTRIBUTION CURVES

Fig. 9a shows an approximation of the different current paths with relation to the insulator string. Fig. 9b shows the potential. The curve of air potential shows the difference of potential between the surface of the conductor and the air at any given distance from the conductor. The straight line marked "uniform distribution" is the potential curve we would get for the insulator string if the voltage drop were uniform along the string. The curve marked "string potential" shows the actual voltage along the string from tower to conductor. Below the point *d* the air potential is lower than the string potential, causing a flow of current *from* the string, while above the point *d* the reverse is true and current flows *into* the string. This gives the line *c′ c* of Fig. 9c showing the difference between the *B* and *C* currents.

Inspecting the several currents shown in Fig. 9a, we have:

First: I_A which is the series current flowing through the string. This current varies as the voltage across the string and inversely as the number of units in the string. For convenience, we will assign a value of 10 to this current in a string of 12 cap and pin-type units with a duty of 10 kv. per unit or 120 kv. for the string.

Second: I_B which is the capacity current from cap to tower or ground, varying directly as the voltage between cap and ground. In a string of 12 cap and pin-type units where I_A is taken as 10, i_B, the current per unit, will vary from zero on the cap attached to the tower to approximately 6 on the cap of the unit next to the wire. I_B flowing in the string at any point is the summation of the currents from all caps between the point considered and the grounded end of the string.

Third: I_C which is the capacity current from the wire to each cap. Since the impedance path consists principally of the impedance of the air between the line and unit, and then in series through the insulator string, it is practically constant. In a string of 12 cap and pin-type units where I_A is taken as 10, i_C, the current per unit, will be approximately constant at 2. I_C flowing in the string at any point is the summation of the current to all caps between the point considered and the grounded end of the string, and may be considered as of the opposite sign to current I_B, because of the fact that the current is arriving *on* the insulator cap from the wire, and not flowing *off* the cap to tower or ground. (Note: Currents from cap to cap practically balance.)

TABLE 9D

		Capacity Current Cap to Tower		Capacity Current Wire to Cap		
		I_B		I_C		
Unit	Series Current in String I_A	In unit	In string	In unit	In string	$I_A + I_B - I_C$ In string
1	10	0	0	2.00	2.00	8.00
2	10	0.55	0.55	2.00	4.00	6.55
3	10	1.09	1.64	2.00	6.00	5.64
4	10	1.64	3.28	2.00	8.00	5.28
5	10	2.18	5.46	2.00	10.00	5.46
6	10	2.73	8.19	2.00	12.00	6.19
7	10	3.27	11.46	2.00	14.00	7.46
8	10	3.82	15.28	2.00	16.00	9.28
9	10	4.36	19.64	2.00	18.00	11.64
10	10	4.90	24.54	2.00	20.00	14.54
11	10	5.46	30.00	2.00	22.00	18.00
12	10	6.00	36.00	2.00	24.00	22.00

Table 9d shows the result obtained by using the values given above for I_A, i_B and i_C, that is 10, zero to 6 and 2, and applying to a string of 12 cap and pin-type units. The voltage duty is assumed as 10,000 volts per unit or a total of 120,000 volts for the string, and since the potential difference is proportional to the current flowing, we have a measure of the unit voltage duty when we know the current flowing. By taking the values of 10, 6 and 2 instead of some other set of numbers bearing the same ratio, the summation curve when plotted as in Fig. 9c, may be read directly in kilovolts duty per unit.

The relative values of the *A*, *B* and *C* currents as taken above hold good for cap and pin-type units when the unit voltage duty averages 10,000. For the Hewlett type insulators the *B* and *C* currents are approximately the same as in the cap and pin-type units, but the series capacity of the Hewlett is approximately only two-thirds that of the cap and pin type, hence keeping I_A at the same value of 10, the *B* and *C* values will be relatively larger and the ratio becomes $A : B : C = 10 : 0$ to $9 : 3$. From this relationship a curve for a string of Hewlett-type insulators similar to the curve in Fig. 9c may be plotted.

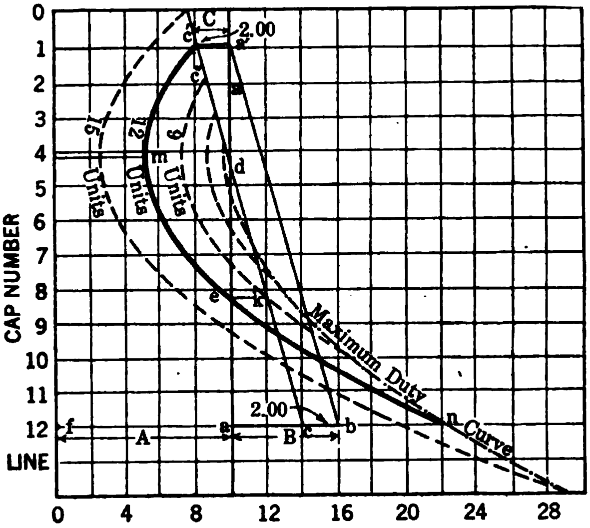

Fig. 9c

Analysis of Distribution Curves

To plot the voltage distribution curve lay off $a\,a' = I_A = 10$, a constant value for each unit. Next lay off $a'\,b$ such that $a\,b = i_B = 6.0$, thus making i_B vary from zero to 6.00. Next lay off $c'\,c$ to the same slope as $a'\,b$ so that $c'\,a' = c\,b = 2.0$. The distribution curve is now found by adding the values represented by $a'\,a$, a constant, and the values of $c'\,c$ as a *summation*, and is shown by the heavy line marked 12 *units*.

NOTE: In all discussions the B and C currents have been considered as varying along a straight line law. This, however, is not strictly true. In plotting the curve in Fig. 9c, it is seen that the line $c'\,c$ represents the *difference* between the B and C currents, and experiments have demonstrated that this *difference* follows closely along a straight line law. For the sake of simplicity, therefore, all have been considered as straight lines.

The point of minimum duty occurs at approximately one-third the distance from tower to conductor, and the voltage duty curve crosses the average duty line $a'\,a$ at a point e such that area $c'\,a'\,d$ is equal to area $k\,e\,d$. This means that above the point e, the voltages are balanced and therefore the only part of the string requiring grading is the unbalanced lower one-third.

Having given the curve for 12 units, the curves for other length of string where the duty remains the same average value of 10,000 volts per unit, may be drawn in for comparison. Since the minimum duty point is always about one-third the distance from tower to conductor, we may consider one-third of the change in length as applied at the tower end of the string and two-thirds at the line end.

The A current will remain at 10 as before since the total voltage across the string bears the same ratio to the number of units. The slope of $a'\,b$ will remain 6/11 as before because the rate of voltage change will not be altered. If we shorten the string by three units, taking one unit from the top and two from the bottom in order to keep the minimum point still one-third of the distance from tower to line, the value of the B current in the bottom unit will be $i_B/(11-3) = 6/11$ making $i_B = 4.36$. The ratio of the B current in the line unit to the C current is three to one, hence i_C becomes 1.45 and the first point on the curve for a nine-unit string is $c'' = 10 - 1.45$. Similarly we may plot a six or three-unit curve, or increasing the string length, a 15-unit curve.

Improving Distribution by Grading: As shown by 9c and by Figs. 10 and 11, the summation of the currents (B-C) from or to the string are balanced above e, the point where the curve cuts the average line. If therefore we grade the units below e to bring the voltage of these units to near the average, then the upper part of curve will rotate to the right around e as center, or the curve above e will move horizontally to the right, due to stress taken from the lower units being added to the upper units, thus improving the entire string distribution. It is found this can be done very well by making the four lower units larger as so to give larger pins and adding to capacity by fixed shields around pins. This also reduces the leakage resistance stress on lower units.

Improving Distribution by Shielding: By raising the air potential opposite the lower units, the C currents may be increased and the B currents decreased. This improves distribution, but it also has effect of adding to air potential higher up and this increases the currents to the upper part of string, and the dry arcs tend to go to ground through the upper third of the insulator string. Note Figs. 28 and 29. Raising the line wire potential above the lower units is also objectionable for several practical reasons.

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currents and increasing the C currents. (The B current refers to the current from metal parts of units to tower or ground and the C currents to the currents from line wire to metal parts of units, as shown in Figs. 9, 10 and 11). The disadvantage of raising the air potential above the units is that this also increases the C or line currents to the upper part of the string. And the dry arcs tend to break into the upper third of the string. (See Figs. 17 and 18.) By the use of the pin shields and line shield, the height of the ring or horn shield may be reduced and part of the objection to the shields removed.

By method 3 we keep the potential of the string as high as possible above the air potential, and hence tend to prevent the arcs from breaking into the string. By using four large diameter units, with larger pins to increase the electrostatic capacity at the line wire end, and by using the line shield, we get a very simple string. It is possible to use the four large units and a low ring or short insulated horn shield to further grade the lower two units, if desired. By this method the size and height of the shield as used in method 1 and 2 would be reduced, thereby making the shield less objectionable. The air potential gradient from line wire to tower should be made as flat as possible, as a steep gradient invites arcs. This means a long string; and the air potential due to the line wire should be as low as possible.

By method 4 the string potential is brought close to the air potential. This method is merely given here as a possible method, as it has not been worked out practically. No doubt other methods combining the present disk insulators with larger units at the line or with bushings or other types at the line end will be worked out.

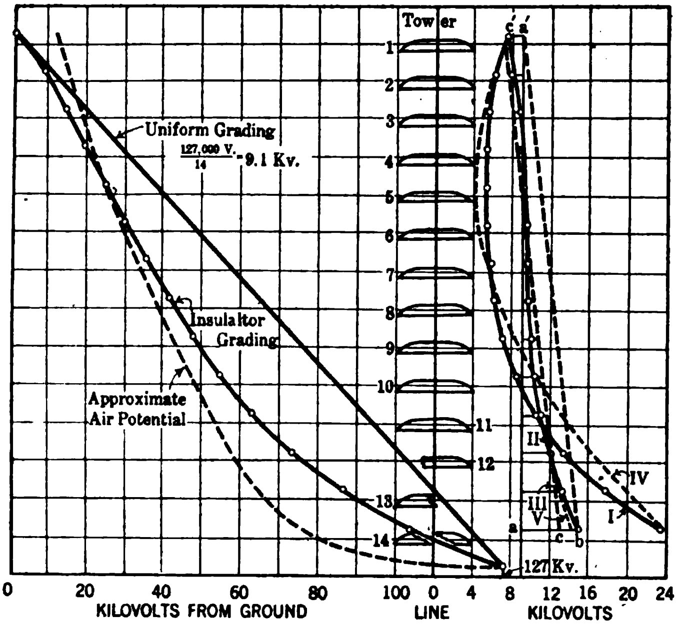


FIG. 10—ACTUAL AND CALCULATED GRADIENTS—CAP AND PIN INSULATORS—14-UNIT STRING—127 KV.

Curve I. Actual gradient by test.

Curve II. $A + (B - C)$ from test.

Curve III. (Straight line). $A + (B - C)$ calculated by assuming $B = 6$, $C = 2$.

Curve IV. Gradient in kv. calculated from Curve III. $[A + \Sigma (B - C)]$.

Curve V. Extension of Curve II as it would be were there no disturbance of field due to lower pin and line wire.

Under wet conditions the potential distribution of the string improves materially. But the most important condition is the leakage distribution with dirty insulators as they become wet or dry.

Because of the large leakage surface and the low cost, and the conditions of the electric field in the upper two-thirds of the string, the present disk type of insulator meets the problem of the upper two-thirds of the string very well indeed.

I have no doubt the insulator men will work out a satisfactory solution for the insulators near the line wire, and *reduce the leakage resistance stresses* and *the air stresses* to less than one-half of those now prevailing on 110,000 to 175,000-volt lines. This is necessary in order to give a satisfactory operating string, in my opinion. Let all work to that end.

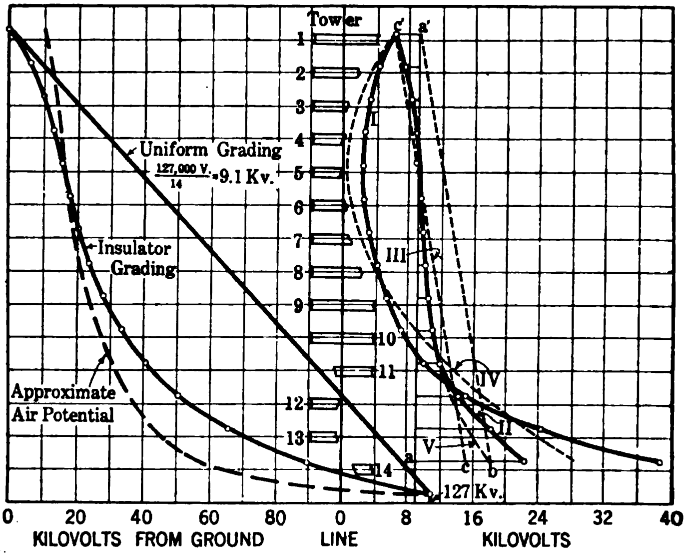


FIG. 11—ACTUAL AND CALCULATED GRADIENTS—HEWLETT INSULATORS—14-UNIT STRING—127 KILOVOLTS

Curve I. Actual gradient by test.

Curve II. $A + (B - C)$ from test.

Curve III. (Straight line). $A + (B - C)$ calculated by assuming $B = 9$, $C = 3$.

Curve IV. Gradient in kv. calculated from Curve III. $[A + \Sigma\, (B - C)]$.

Curve V. Extension of Curve II as it would be were there no disturbance of field due to lower pin and line wire.

With the ungraded string the factor of safety is at the tower end instead of at the line wire end of the string. We should treat each insulator string as we have the end windings of transformers, not add more turns (or add more units), but increase the insulation or decrease the voltage stress on the units near the line wire, so that these can absorb the excess voltages due to switching etc., without undue stress. This can be accomplished by making the lower one-third of the units larger, with internal electrostatic capacity added to reduce the voltage, and by the use of a low external shield, which latter may be combined with a pin and line shield to reduce the stresses on the lower unit to satisfactory values.

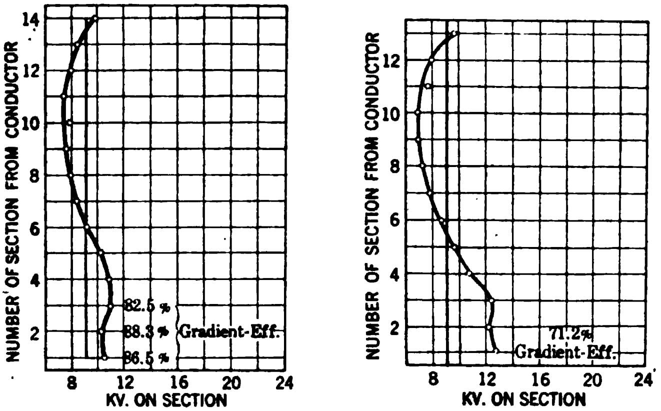


FIG. 12A—VOLTAGE DISTRIBUTION WITH INSULATED HORN SHIELDS AND LINE SHIELD

For 220-kv. line.
No. of sections in string—14.
No. of controls—4.
Size of controls—1 1/4 in. pipe.
Height of controls—9 in.
Spread of controls—23 in.
Angle with plane of conductor—45 deg.
Insulator on controls—No. 11623 spec.
Conductor shield—5—1-in. pipes spaced 60 deg. apart on 12-in. circle.

For 220-kv. line.
No. of sections in string—14.
No. of controls—2.
Size of controls—2 in.
Height of controls—8 1/2 in.
Spread of controls—23 in.
Angle with plane of conductor—90 deg.
Insulator on controls—No. 11623 spec.
Conductor shield—5—1-in. pipes spaced 60 deg. apart on 12-in. circle.

Tests by A. O. Austin

4. THE LEAKAGE RESISTANCE GRADIENT OVER THE SURFACE OF THE INSULATOR

In Fig. 14 is shown the theoretical resistance gradient for the standard insulator shown in Fig. 10, for the standard pin, and for 23,000 volts between cap and pin. It will be noticed that the resistance near the pin is very high and drops very rapidly in the first inch, due to the increase in the area of the leakage path. By enlarging the pin diameter we may reduce the maximum gradient near the pin very materially and increase the voltage gradient of the remainder of the insulator only a small amount as shown. The shaded area *R* 10 is equal to the sum of shaded areas $r_1 + r_2 + r_3$, etc. This result should

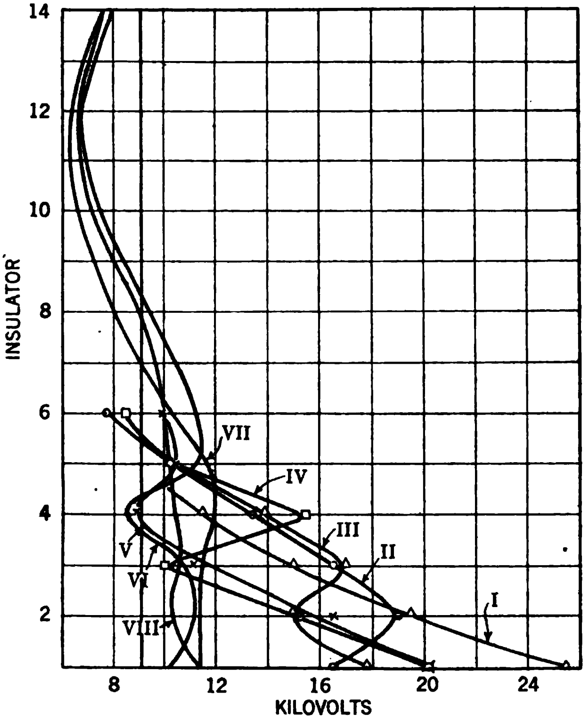


Fig. 12b—Cap and Pin-Type Units Graded for Voltage Distribution—Locke Insulators

Curve I. 14—No. 5800—10-in. cap and pin type. Ungraded.

Curve II. 1—12-in. special; 13—No. 5800. Ungraded. Corona shields on under side of 12-in. unit.

Curve III. 2—12-in. special; 12—No. 5800. Ungraded. Corona shields on 12-in.

Curve IV. 3—12-in. special; 11—No. 5800. Ungraded. Corona shields on 12-in.

Curve V. 4—12-in. special; 10—No. 5800. Ungraded. Corona shields on 12-in.

Curve VI. 4—12-in. special; 10—No. 5800. Graded by two 4-in. by 24-in. parallel tubes at third unit.

Curve VII. 14—No. 5800—10-in. cap and pin type. Graded by four loops of 3/4-in. pipe.

Curve VIII. 14—No. 5800—10-in. cap and pin type. Graded by 1 1/2-in. by 30-in. ring at center of third unit.

Tests by K. A. Hawley.

be approximately realized if we short-circuit the part of the leakage resistance path near the pin as proposed by the use of the sleeve shield around the pin, as shown in Fig. 8.

Fig. 15 (data from tests by Prof. H. J. Ryan) is very interesting, showing that for the ungraded or unshielded unit we get actually a higher voltage at the edge of the disk than we do at the cap. This is no doubt due to the flux density near the line wire. We actually get 19,000 volts on the first inch of the leakage surface.

By short-circuiting to the first petticoat and putting a shield over the line wire, the voltage gradient is reduced one-half. By short-circuiting two petticoats we get a much better curve as shown by V and VI. Further study along this line is advisable.

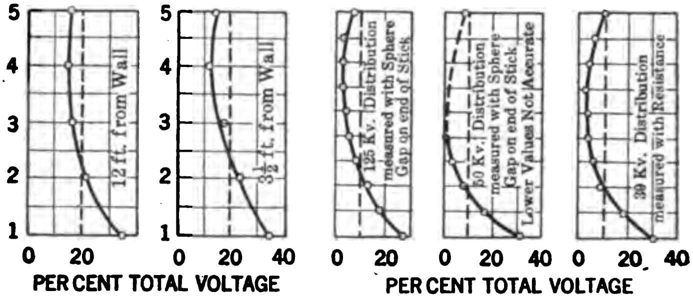
The distribution of the resistance leakage stresses over the string and over each unit as uniformly as possible is, of course, the thing finally desired, and this is the main reason for striving for good string distribution of voltage. It is desired that the distribution remain as uniform as possible *for all conditions occuring in operation.*

5. INSULATION OF SWITCHES, TRANSFORMERS, ETC.

In the early days of electric power transmission the transformers, switches, etc., were housed to protect them from the elements. As the number of substations increased it was found often that the expense of housing the apparatus cost more than the apparatus. Hence there was developed outdoor apparatus.

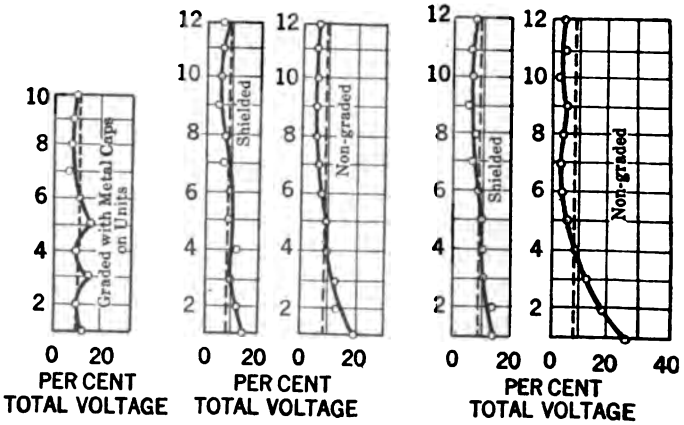
The very large amount of space required for the 220,000-volt substation switches, etc., of course, makes it advisable to use outdoor apparatus so long as the total cost is less than where it is protected from the elements. Probably transformers and disconnecting switches can be more economically placed outdoors than in a building. But the oil switch may give a different conclusion on account of the fact that the enlargement of the bushings for the outdoor use also enlarges the tanks more than otherwise necessary, so that due to the increase in the bushing, the cost of the switches for a given kv-a. capacity may vary somewhat as the square of the voltage, if all the elements of design are carried out consistently. That is, a switch for 220,000 volts may cost nearly double the cost of a switch for 150,000 volts due to the increase of the tank and oil, etc., as a result of the increase of the size of the bushing.

Now the size of the bushing is largely determined by the *wet* arc-over condition. A bushing for a 165,000-volt switch has a dry arc-over of about 480,000 to 520,000 volts. The wet arc-over of a 220,000-volt bushing



The effect of proximity to walls—voltage distribution on string of five insulators.

The effect of applied voltage on the distribution of a string of ten.



Voltage distribution on string of ten insulators.

Voltage distribution on string of twelve insulators.

Voltage distribution on two parallel strings of twelve insulators.

FIG. 13A—DISTRIBUTION CURVES FOR HEWLETT UNITS
As per tests by F. W. Peek, Jr.

will be around 400,000 to 450,000. (The wet arc-over for a 165,000-volt bushing is about 350,000 volts.)

That is, by keeping the 165,000-volt switch, when used on the 220,000 lines, dry and clean, we have a greater factor of safety than we have for the 220,000-volt switch when used outdoors. And since the 165,000-kv-a. switch will give all the rupturing capacity required, it will pay to use this type enclosed, if the cost of protecting it from the weather is less than the extra cost of the higher voltage switches. Of course all the above assumes that ample clearances are provided.

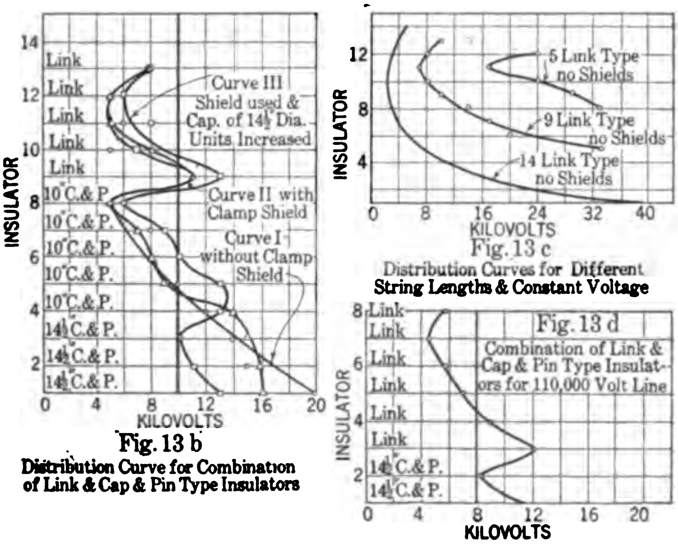


Fig. 13 b
Distribution Curve for Combination of Link & Cap & Pin Type Insulators

Fig. 13 c
Distribution Curves for Different String Lengths & Constant Voltage

FIG. 13B-C-D
Tests by R. H. Marvin

This point does not come up in the case of transformers because the tanks are so large that the larger bushing cost is the only extra item to consider for the higher voltage. If the wet arc-over were increased by increasing the length and not the diameter, it would reduce the size of tanks, etc.

Especially in view of the present development of the art of high-tension switches, we should not expend more for switches than necessary at this time.

Hence, the protection of the oil switches from the weather should be given careful consideration. In this connection it may be noted that the wet 60-cycle arc-over for a 14-unit clean string of disk insulators will be about 450,000 to 550,000 volts, but of course, under outdoor conditions, due to dirt, etc., the arc-over voltage will be lower. We want the switches, of course, to have a higher factor of safety than the line units. Roof protection only may be sufficient.

6. WET AND DRY ARC-OVER OF LINE INSULATION

High-Frequency Arc. The control of the high-frequency arc can be effected as shown in Figs. 16 to 29. These tell their own story. The metal ring

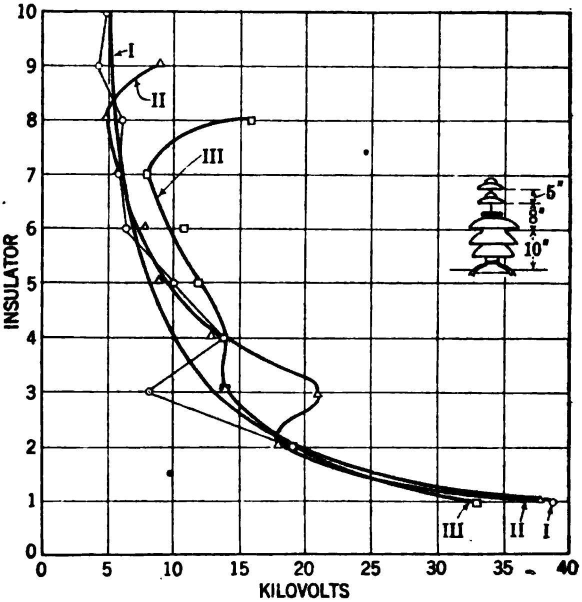


Fig. 13e—Distribution Curves for Link and Cap and Pin Type Combined with Pin Type to Make Insulator String Gradient Approximate Air Gradient

Curve I. One 14-in. special three-part Lapp pin-type insulator next to line and nine 10-in. Ohio Brass Co. cap and pin-type insulators between these and the tower. No shields.

Curve II. Two Thomas pin-type No. 13012 insulators next to line and seven link-type insulators between these and the tower. 6-in. by 3-ft. 0-in. cylindrical clamp shield.

Curve III. Thomas pin-type No. 13012 insulators at top and bottom with six Thomas cap and pin-type No. 1149 between. 6-in. by 3-ft. 0-in. cylindrical clamp shield.

127,000 volts duty on all three strings.

Tests by H. J. Ryan.

shield also gives satisfactory high-frequency arc control. That we need not worry about high-frequency arcs is shown by these illustrations, Figs. 18-21.

60-Cycle Dry and Wet Arc-over. The dry arc-over voltage for a 14-unit string of insulators, shielded with ring or insulated horn shields, is about 700,000 volts, or 50,000 volts per unit. The arc clears the insulators fairly well, but sometimes breaks into the upper third of the string.

Under wet test the arc tends to follow along the string of insulators and the wet arc-over voltage is about 60 per cent of the dry arc-over value, or about 450,000 to 550,000 volts for 14 units, with precipitation of 0.2 in. per minute. The wet arc-over as well as the dry arc-over is affected by the string impedance and especially by the impedance of the upper two-thirds of the string.

The control of the wet arc, to keep it away from the string of insulators, is important. The following tests were made to show that the arc can be controlled in direction and kept away from the string. Fig. 24 shows the arc-over controlled so as to go

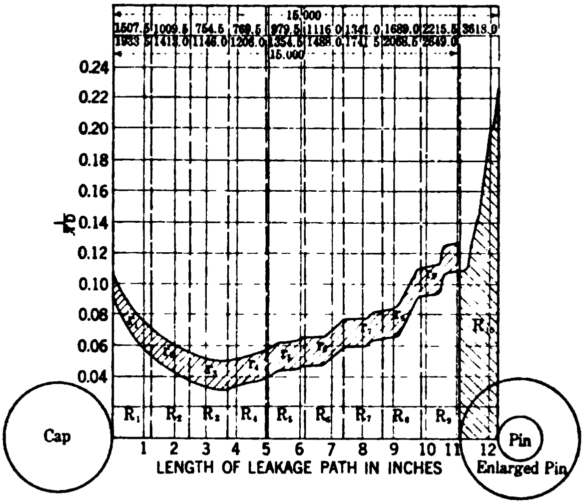


FIG. 14—CALCULATED RESISTANCE GRADIENT AND METHOD OF REDUCING MAXIMUM GRADIENT

Surface resistance integral curves for Ohio Brass Co. Insulator No. 25620.
Area R_{10} = Area $r_1 + r_2 + r_3 \ldots\ldots + r_9$.
See Fig. 8 for leakage path measurements.

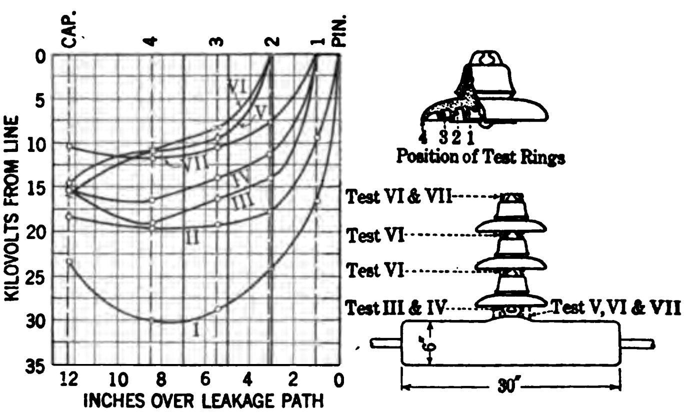


FIG. 15—VOLTAGE DISTRIBUTION OVER INSULATOR SURFACE

Ohio Brass Co. Insulator No. 25620.

CONDITIONS:

Voltage duty over insulator string, 127 kv. to ground. 3/4-in. iron pipe used as line conductor. Standard clamp and hardware.

TEST I:

String of 14 units of O. B. insulators. Test on bottom unit. Rings of No. 14 B. & S. copper fastened with wax in positions shown. No control shields on string.

TEST II:

String of 14 units of O. B. insulators. Test on bottom unit.

Rings of No. 14 B. & S. copper as above.

6-in. diameter iron cylinder, 30 in. long, placed over conductor and extending along conductor 15 in. each side of insulator. Ends of cylinder rounded in.

TEST III:

String of 14 units of O. B. insulators. Test on bottom unit.

Rings each replaced by two arcs of 1/4 circumference. Bisecting radius of arcs at right angles to line. 6-in. diameter cylinder as in II. Sheet iron cylinder around insulator pin between 6-in. cylinder and insulator to increase pin diameter out to position 1.

TEST IV:

Same as III, except bisecting radius of wire arcs parallel to line.

TEST V:

String of 15 units of O. B. insulators. Test on bottom unit.

Rings of No. 14 B. & S. copper fastened in positions shown. 6-in. diameter cylinder as in II. Sheet iron cylinder around insulator pin between 6-in. cylinder and insulator to increase pin diameter out to position 2.

TEST VI:

Four Hewlett insulators at top of string. Five O. B. insulators next. Four O. B. insulators with cylinder surrounding pin and in contact with cap below to give pin diameter out to position No. 1. Bottom unit as in Test V. Pin diameter to position 2 and 6-in. by 30-in. long cylinder around conductor.

TEST VII:

String of 14 O. B. insulators. Test on fourth unit from bottom. Bottom unit as in III except arcs replaced with rings of No. 14 B. & S. copper. Sheet iron cylinder surrounding pin of fourth unit and in contact with cap of third unit to give pin diameter out to position 1.

Tests by H. J. Ryan.

to the lower crossarm. This is done by hanging two insulator units properly spaced below the line wire and then adjusting a pointer on the lower arm to direct the arc. The theory is that the units below the line will become dirty and wet and the insulation depreciate as do the line units. The adjustment for the wet and dry arc to travel to the lower arm can be very close to the arc-over for the string. Instead of hanging the extra units from the line wire, we may hang them from the lower arm, about two feet towards the tower from the line insulators. The wet and dry arc can by proper adjustment be made to clear the string. Instead of the insulators hung from the arm, we may hang a porcelain tube to direct the arc. The result here is even more satisfactory than for the other two cases above. Test Sheets 1 to 4 in the appendix show the result of tests of various methods of arc control.

While the wet and dry arcs may be controlled as above, it is believed this control should be used only as a final protection in certain places. *The effort should be to eliminate the arcs entirely* and it is believed this can be accomplished, except for cases of accident.

Suppression of Incipient Corona or Arcs. I am confident from all my observations and studies that the final complete success of power transmission, at voltages higher than can be handled by pin-type insulators, must come from the design of the metal fixtures (including the line wire) in contact with the air and porcelain, so that the air gradient and leakage gradient will be reduced to low values, in order that there be no tendency for arcs to start, and the maximum unit and leakage resistance will also be reduced to low values. Corona should also be prevented on account of the formation of acids.

Only a small part of the tests made have been included in this paper, in order to keep it within reasonable length. The manufacturers and engineers have heartily cooperated in the tests, and I hope to see cooperation in manufacture to bring about confidence in the transmission industry as a whole.

FIG. 16—HIGH-FREQUENCY ARCS WITH 4-IN. BY 24-IN. HORIZONTAL SHIELDS

FIG. 17—HIGH-FREQUENCY ARCS WITH 4-IN. BY 12-IN. VERTICAL SHIELDS

FIG. 18—HIGH-FREQUENCY ARCS WITH 2-IN. BY 12-IN. VERTICAL SHIELDS WITH INSULATOR OVER SHIELD ON TOWER SIDE

All tests made at Stanford University, Feb. 3, 1921.

CONCLUSION

The insulator problem of the transmission line must be attacked as any other engineering problem. The attempt here made to give the results of work along this line will, it is hoped, encourage further study by engineers and manufacturers.

The insulation problem, as does every engineering problem, reduces itself to working to certain unit stresses—mechanical and electrical—and to the maintenance of certain factors of safety throughout the entire line structure, which includes insulators, towers, switches, transformers, etc. This factor of safety should be as permanent as possible, which means that the depreciation of the insulator should be practically nil in service. This goal is being rapidly reached.

FIG. 19—HIGH-FREQUENCY ARCS WITH 2-IN. BY 12-IN. VERTICAL SHIELDS WITH INSULATORS OVER BOTH SHIELDS

All tests made at Stanford University, Feb. 3, 1921.

It is shown that satisfactory voltage distribution at normal voltage may be obtained by different methods of shielding or by different methods of grading. Further work along this line is desirable in order to crystal-

FIG. 20—TEST WITH 500,000-CIR. MIL, P. G. & E. CONDUCTOR. 14-UNIT STRING, No. 25620

Approximately 545 kv., 35,000 cycles.

FIG. 21—INSULATOR No. 11622 ON CONTROLS AT 45 DEG.

Approximately 545 kv., 35,000 cycles. Compare with Fig. 20.

lize the best methods into practical forms, so that the insulator manufacturers will be able to furnish the complete line insulation equipment.

It is believed that 220,000-volt transmission is no more difficult than 110,000 or 175,000, if due consideration is given to the unit air and leakage resistance stresses, and the insulation of the line is carried out

Fig. 22—Wet Arc-Over—City Water—Three-Line Units with Internal Shields to Increase Electrostatic Capacity

Wet 60 ~ arc-over at 505 kv. on a string of 13 cap and pin units, graded. Ten Locke No. 5800 units at tower end; three 12-in. disk units at line end.

5-in. diam. tube, 4 1/2 ft. long, around the line conductor.

Precipitation—0.2 in. per min.

Tests at Pittsfield, Mass., April 15, 1921.

consistently, as is, for example, the track system of our best railways. But this means, of course, that we must not have on a main-line track 120-lb. rail and 60-lb. rail over which high-speed trains run. The factor of safety in the insulated string should be at the line wire end so that shocks may be absorbed without undue stress on these units.

FIG. 23—WET ARC-OVER—CITY WATER—THREE-LINE UNITS WITH INTERNAL SHIELDS TO INCREASE ELECTROSTATIC CAPACITY

Wet 60 ~ arc-over at 546 kv. on a string of 14 cap and pin units, graded. Eleven Locke No. 5800 units at tower end; three 12-in. disks at line end 5-in. diam. tube, 4 1/2 ft. long, around the line conductor.

Precipitation—0.2 in. per min.

Tests at Pittsfield, Mass., April 15, 1921.

Double-string and dead-end insulator strings should be avoided wherever possible, and in place of these, extra strength units should be used, to allow insulators to swing clear at angles as far as possible.

Higher voltages than 220,000 are possible, but for practical reasons, as given in Part I, it is believed 220,000 should be standard for extra large-power, long-distance transmission. Heretofore I have always said we would go to higher voltages, because we had not reached the voltage required for extra large blocks of power and long distances. I believe 220,000 volts is high enough to meet any situation in this country today.

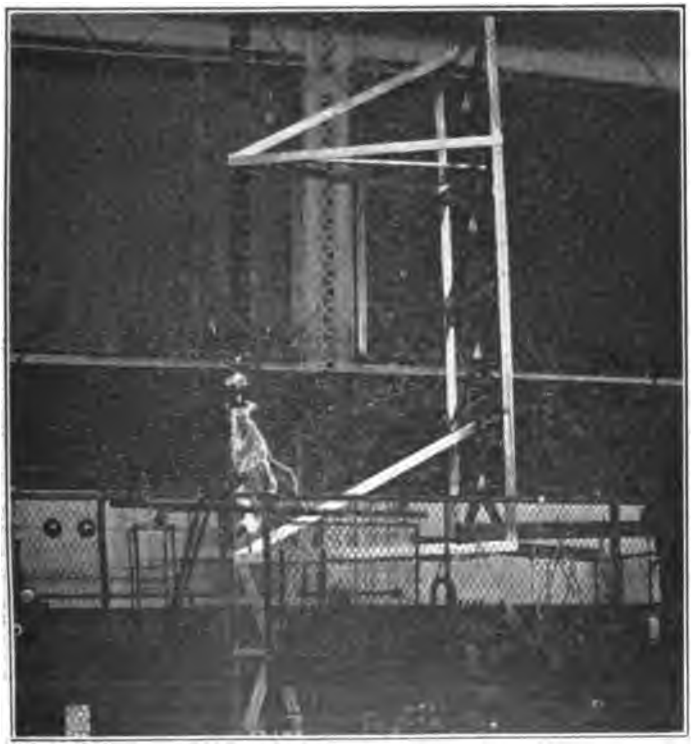


FIG. 24—WET ARC-OVER, 467 KV.—14 HEWLET UNITS—PRECIPITATION 0.2 IN. PER MINUTE—USING TWO INSULATORS BELOW LINE WIRE TO DIRECT ARC

Tests at Pittsfield, Mass.

It is the peculiar characteristic of nearly all electrical apparatus that it depreciates less when used in normal service than when taken out of service for part of each day. This is because the depreciation depends largely on the maximum range of temperature changes and the number of such changes or cycles in a given period. All electrical apparatus, including transmission lines, should be in constant service under conditions that will as nearly as possible cause the apparatus to remain in one condition. It is believed transmission lines will give better service when voltage is maintained on them at all times.

FIG. 25—WET ARC-OVER FOR ARRANGEMENT SHOWN, 508 KV. DRY ARC-OVER, 728 KV.

Tests at Pittsfield, Mass.

A system of transmission controlled as to voltage as given in Part I, and insulated consistently by one of the methods given in Part II, to give low air and

FIG. 26—TESTS ON NO. 1054 INSULATOR—WITHOUT TINFOIL CAPS

Wet flash-over, 331 kv.
Spacing, 5 1/2 in.
Dry flash-over for same 8 units, 380 kv.
Tests, R. Thomas & Sons.

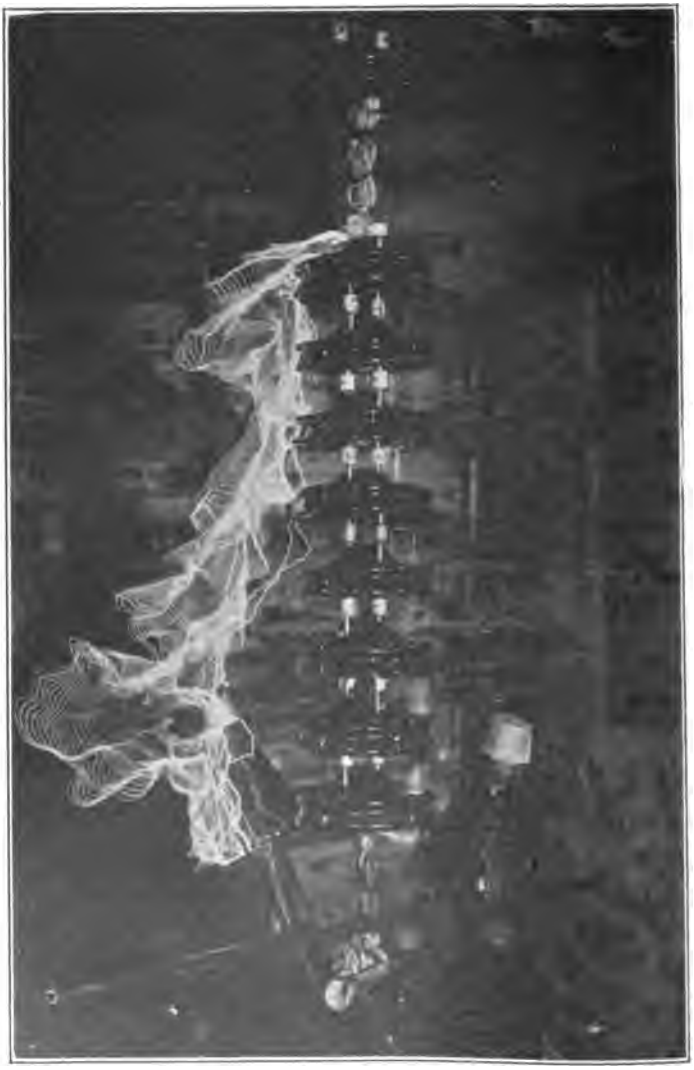


FIG. 27—TESTS ON NO. 1054 INSULATOR—TINFOIL CAPS ON HORN INSULATORS

Wet flash-over, 331 kv.
Spacing, 5 1/2 in.
Dry flash-over for same 8 units, 380 kv.
Tests, R. Thomas & Sons.

Fig. 28—Nine Units—30 Flash-Overs—10 Clear and 20 Cascade

Note bowing out of flux lines at lower end and break-down to upper part of string where string potential is low.

This figure and Fig. 29 illustrate that we must increase string potential in the upper third and decrease the air potential due to the line wire.

Figs. 28 and 29 by Prof. H. J. Ryan.

resistance leakage stresses at all voltages and under all conditions, will give service not possible on lines where these conditions are not carried out. I hope to see a real era of 220,000-volt transmission construction in the next few years, and the engineers and manufacturers can help matters along by proper cooperation.

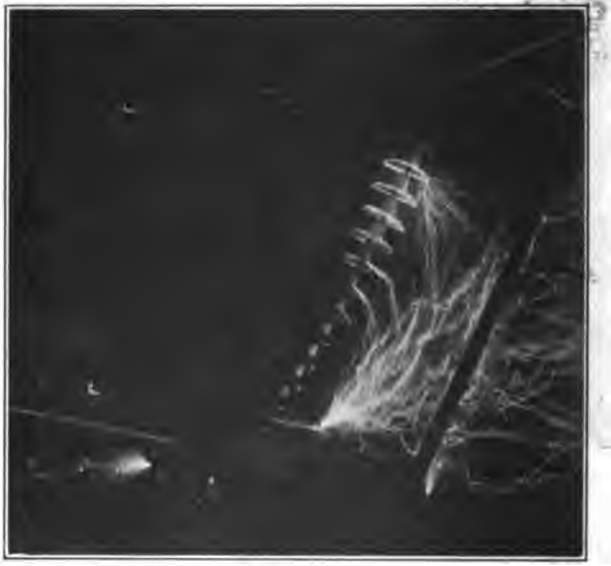


FIG. 29—TWELVE UNITS—30 FLASH-OVERS

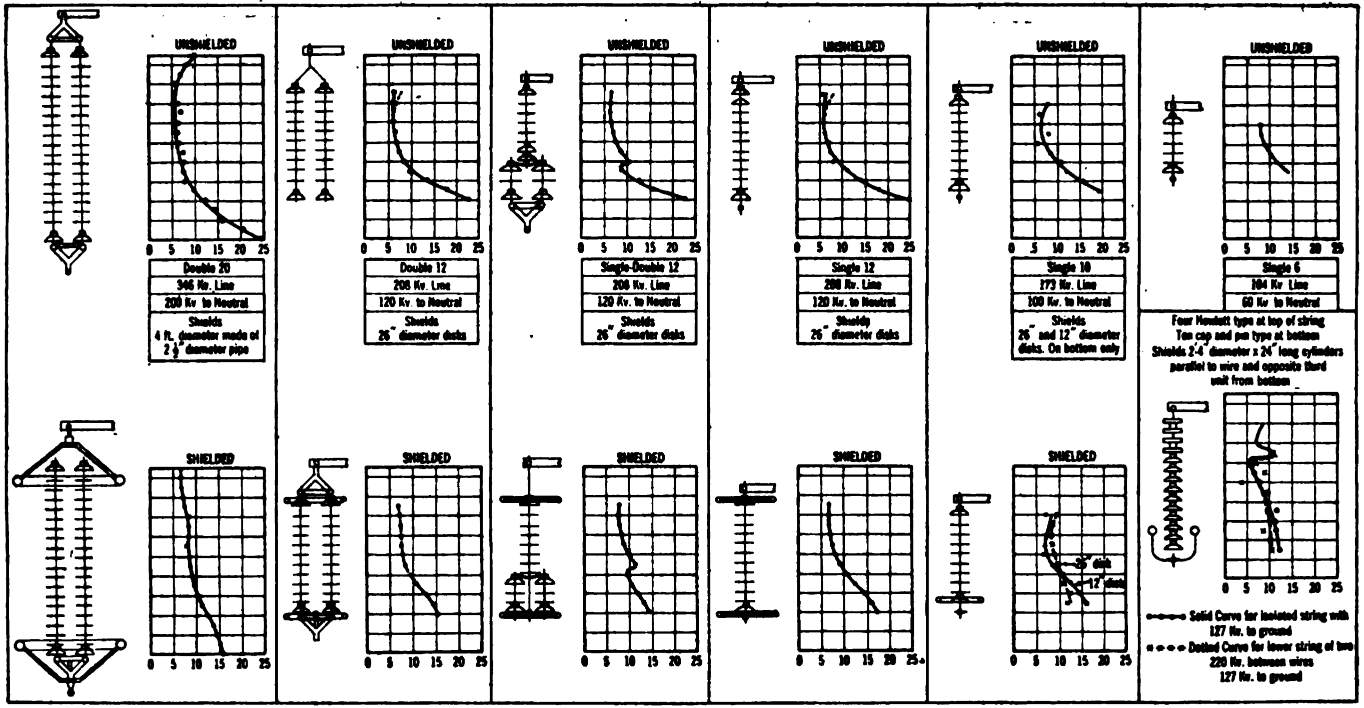
Note bowing out of flux lines at line end due to high string potential and break-down to upper units due to high air potential and low string potential.

This figure and Fig. 28 illustrate that we must increase string potential in the upper third and decrease the air potential due to the line wire.

Figs. 28 and 29 by Prof. H. J. Ryan.

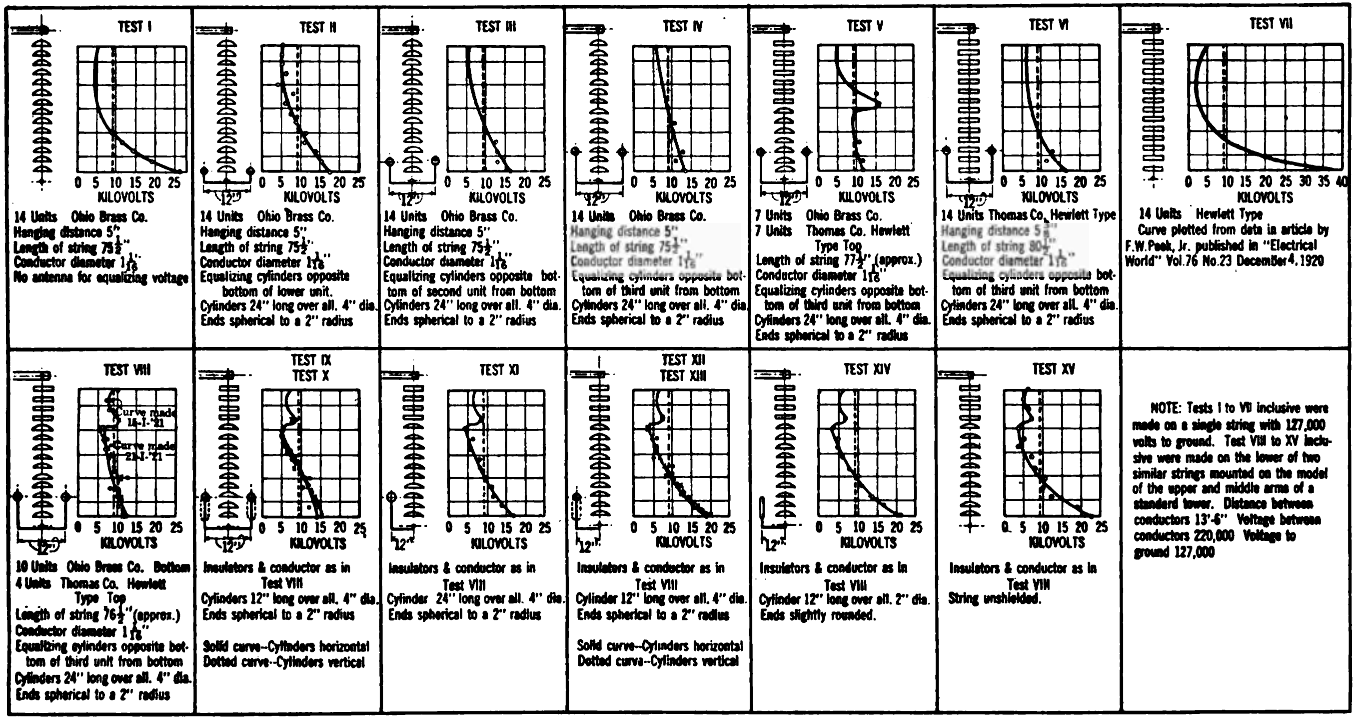
APPENDIX

Tests of Voltage Distribution , Tests of Arc-Over Voltage, etc.



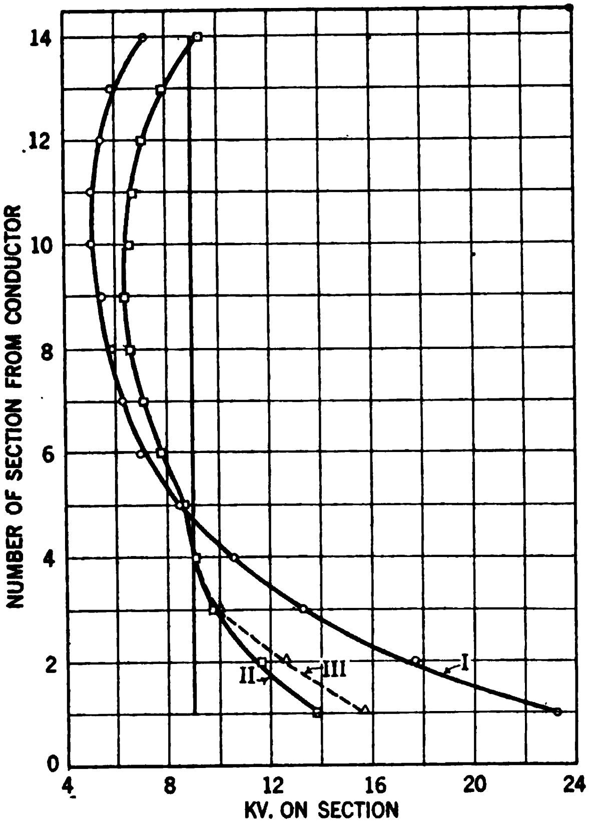
Distribution Sheet D1—Voltage Distribution for Cap and Pin-Type Insulators, Single and Double Strings With and Without Shields

From data as determined by Harris J. Ryan and Henry H. Henline, JOURNAL of A. I. E. E. July, 1920.



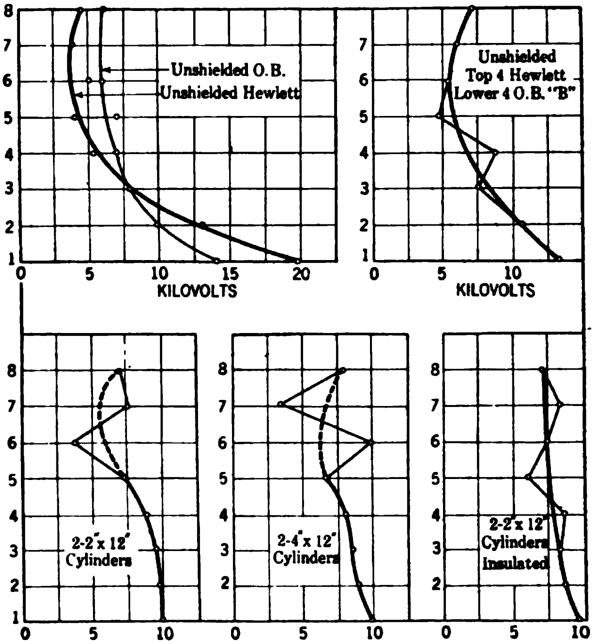
DISTRIBUTION SHEET D2—IMPROVING DISTRIBUTION BY CYLINDRICAL OR HORIZONTAL SHIELDS OR BY COMBINATION OF INSULATORS

14-Unit insulator strings, 220-kv. transmission line. **Tests by H. J. Ryan.**

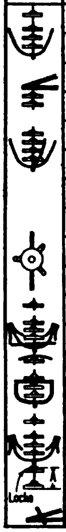


Distribution Sheet D3—Showing Effect of Size and Placing of Shields on Voltage Distribution

Potential Gradient for Ohio Brass Co. Insulator No. 25620.
14 Units in string for 220-kv. line.
Curve I. Unshielded string.
Curve II. Number of controls—2.
Size of controls—2-in. pipe.
Spread of controls—30 in.
Height of controls from conductor—20 in.
Angle with plane of conductor—90 deg.
Insulator on controls—special 125523.
Curve III. Same as Curve II except angle of controls with plane of conductor changed to 30 deg.
Date of tests—March 3, 1921.



DISTRIBUTION SHEET D4—DISTRIBUTION CURVES FOR EIGHT UNITS

Diagram	Type Insulator	No. Units	Type Shield	Arc-Over Dry	Arc-Over Wet	Max. V. Dist. %	Character of Arc
	Hewlett 10"	14	None	Kv. 750	Kv.		Arcing to Top Cascade
	Hewlett 10"	14	2 Horns Uninsulated	595			Arcing to Top with tendency to strike in
	Hewlett 10"	14	2 Horns Insulated	705 698			All Arcing clear to Top Arc to Horn 7" below Line
	Hewlett 10"	14	3 Horns Uninsulated	698			Arc from Horns to Top Arc strikes in
	Hewlett 10"	14	3 Horns Insulated	780 684			Cascade to Top
	Locke 12"	14	3 Horns Uninsulated	557			Cascade to Top
	Locke 12"	14	3 Horns Insulated	612			One Arc to Tower Four Cascade to Top
	Locke 10"	14	3 Horns Uninsulated	581			All Arcs clear to Top
	Locke 10"	14	3 Horns Insulated	640			Arcs tend to Cascade
	Locke 10"	14	3 Horns Uninsulated	567 574			Arcs strike in
	Locke 10"	14	3 Horns Insulated	631			All Arcs clear to Top
	Hewlett 10"	14	2 Insulated Horns with Arcing Tips	698			Arcing from outside Horn clear to Top
	Hewlett 10"	14	2 Insulated Horns with Arcing Tips	674			Arc to Tower Tower 6" closer than above
	Hewlett 10"	14	Circular Shield Arcing Horn on Top Unit	663			Arc clear to Horns
	Hewlett 10"	14	Circular Shield no Arcing Horn	697	455		Arcs clear to Top
	Hewlett 10"	14	2 Insulated Horns 2 Units below A = 12"		431		All Arcs to Horn Horn distance to Line 69" to Lower Insulator 39"
	Hewlett 10"	14	2 Insulated Horns 4 Units below Line		463		All Arcs clear to Top Horn distance to Line 69" to Lower Insul. 39"
	Hewlett 10"	14	2 Insulated Horns 3 Units below Line		458 454		Arcs Clear to Top Horn distance to Insul. 33" Arcs Clear to Top Horn distance to Insul. - 72"
	Hewlett 10"	14	2 Insulated Horns 6 Units below Center 1 Shorted	497	437		All Arcs to Horn Horn distance to Line 81" to Lower Insulator 39"

TEST SHEET 1

Tests made at Pittsfield, Mass.

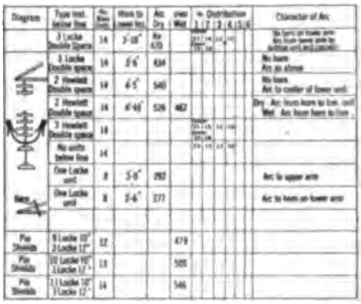


Diagram	Type Insl. below line	No. Main Units	Horn to lower Insl.	Arc-over Dry	Arc-over Wet	% Distribution 1	2	3	4	5	6	Character of Arc
	3 Locke Double Space	14	3'-10"	[illegible] 470		[illegible]	[illegible]	[illegible]	[illegible]			[illegible]
	3 Locke Double space	14	5'-6"	434								No horn Arc as above
	2 Hewlett Double space	14	4'-5"	540								No horn Arc to center of lower unit
	2 Hewlett Double space	14	4'-4½"	526	467							Dry. Arc from horn to line, unit Wet. Arc from horn to line
	3 Hewlett Double space	18				[illegible]	[illegible]	[illegible]	[illegible]			
	No units below line	14				[illegible]	[illegible]	[illegible]	[illegible]			
	One Locke unit	8	5'-0"	292								Arc to upper arm
	One Locke unit	8	2'-6"	277								Arc to horn on lower arm
Pin Shields	9 Locke 10" 3 Locke 12"	12			479							
Pin Shields	10 Locke 10" 3 Locke 12"	13			505							
Pin Shields	11 Locke 10" 3 Locke 12"	14			546							

TEST SHEET 2

Horn shielding.
Arc-over on Hewlett Strings.
Horizontal distance from tower:
14 units—9 ft.
8 units—5 ft.
Tower No. 2 (Multi-member).
Tests made at Pittsfield, Mass.

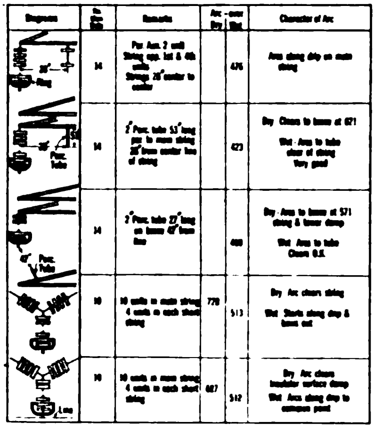
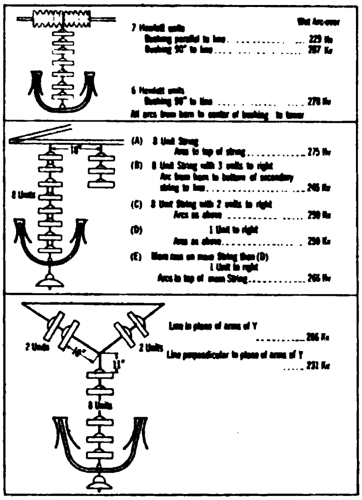


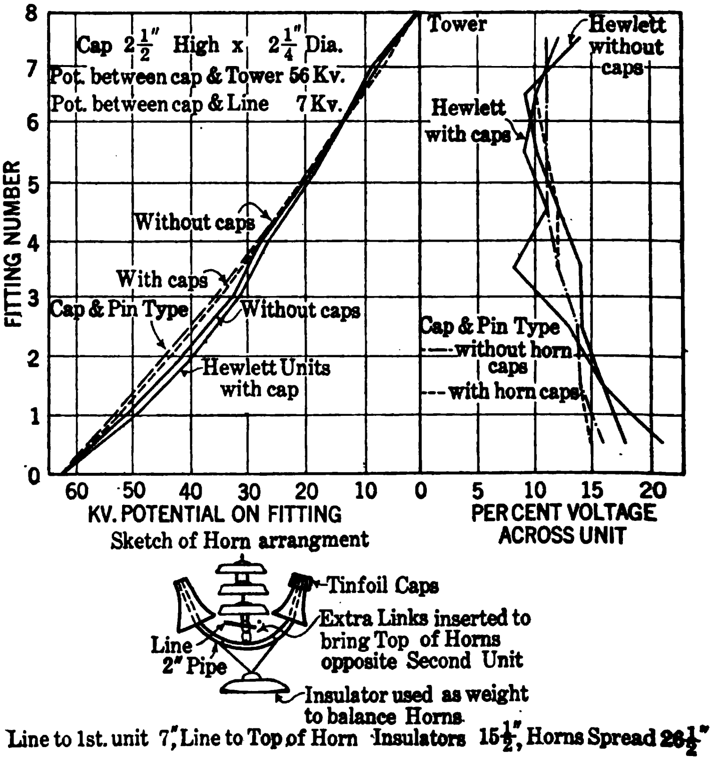
Diagram	No. Main Units	Remarks	Arc-over Dry	Arc-over Wet	Character of Arc
	14	Por. Arm 2 units String opp. 1st & 4th units Strings 28" center to center		476	Arcs along dip on main string
	14	2" Porc. tube 53" long par. to main string 28" from center line of string		423	Dry Clears to beam at 671 Wet Arcs to tube clear of string Very good
	14	2" Porc. tube 27" long on beam 47" from line		488	Dry Arcs to beam at 571 along & lower clamp Wet Arcs to tube Clears O.K.
	10	10 units in main string 4 units in each short string	778	513	Dry Arc clears string Wet Starts along dip & burns out
	10	10 units in main string 4 units in each short string	627	512	Dry Arc clears insulator surface damp Wet Arcs along dip to common point

TEST SHEET 3

Ring shielding.
Arc-over on Hewlett strings.
Horizontal distance from tower, 9 ft.
Tower No. 2 (Multi-member).
Tests made at Pittsfield, Mass.



Test Sheet 4
Tests made at Lisbon, Ohio.



Test Sheet 4b—Comparison of Insulated Horn Shields With and Without Tinfoil Caps

8 HEWLETT UNITS

1. Dry arc-over without caps on horn insulators.............401 kv.
373 "
401 "
(All arcs from horn to top clear of string.)

2. Dry arc-over with tinfoil caps
378 "
380 "
(Arced clear of string from horn to top)

7. Wet arc-over without tinfoil caps
329 kv.
331 "
(Arced from horn to top of string.)

8. Wet arc-over with tinfoil caps
331 kv.
327 "
(Arced from horn to cap to top of string.)

CAP AND PIN-TYPE INSULATOR

Line to first unit......... 6½ in.
Line to top of horn.....15½

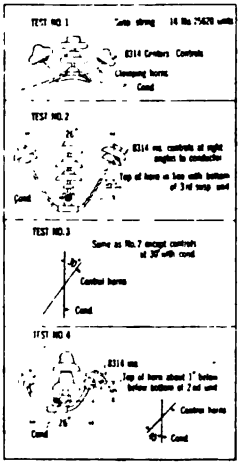
4. Dry arc-over without tinfoil caps
1st trial..............406 kv.
2nd trial..Did not arc over at 429 kv. (limit)

3. Dry arc-over with tinfoil caps
408 kv.
397 "
(Arced from horn to cap to top of string.)

6. Wet arc-over without tinfoil caps
289 kv.
289 "
(Arced along string.)

5. Wet arc-over with tinfoil caps
331 kv.
313 "
(Arced from horn to cap to 5th unit to top.)

Tests at Lisbon, Ohio



TEST SHEET 5 —OSCILLATOR TEST DATA
Ohio Insulator Company.

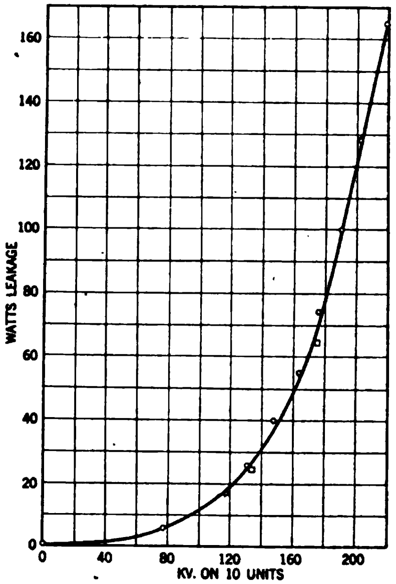
TEST SHEET 6. (OHIO INSULATOR CO.)
FLASH-OVER TESTS

March 8, 1921

Time	V. M. Read.	Multi.	Volts Prim.	Kv.			Water	lb.
					8 units 25620, with 11622 as control on 1-in. pipe horns.			
2:58	113 (?)	4			flash-over	Photo No. 11	Tap	38
3:00	104.5	4	418	245	" "		"	"
3:01	102.	4	408	239	" "		"	"
					Horns changed to 22 in. spread.			
3:45	105.5	4	422	247	flash-over	Photo No. 12	"	"
3:48	105	4	420	246	" "	" No. 14	"	"
					No horns—No controls.			
3:56	110.5	4	442	259	flash-over	Photo No. 17	"	"
					12552 center as control 22 in. spread.			
4:15	70	4	280		No flash-over		"	"

—Ratio used on Leakage Test—

No. 3 Trans. ratio = 585
No. 4 Trans. used as C. T. ratio = 0.000903
C. T. No. 369 (48 turns) Ratio = 5
Total C. T. ratio = 0.000903 × 5 = 0.004515
Wattmeter Ratio = 0.004515 × 585 × Instru. Multi.
= 2.64 × Instrument Multi.
Wattmeter Fields in series, 150-v. circuit. Both sides × ½.



TEST SHEET No. 7—LEAKAGE WET TEST

Precipitation, 0.2 in. per min.
10 units, No. 25620, with No. 12252 shells as controls.
Ohio Insulator Co.

TEST SHEET 8—(OHIO INSULATOR CO.)
OSCILLATOR TEST DATA

Date March 2, 1921

Time	Gen. volts	Gen. amps.	Primary turns number	Primary turns spacing	Primary capacity mfd.	No. of secondary turns	Sphere gap setting	Size of spheres	Kv.	Secondary current milli-amp.	Wave-meter setting	Coil no.	Freq.	Water and lb. pressure	Remarks: Photo no.	Remarks: Time	Remarks: Exp.
						See test sheet No. 5 for description of set up.											
Test No. 1																	
10:31	520	155	10	2¼"	0.3813	16200	20"	50 cm.	545					Dry	13	1 min	32
Test No. 2																	
12:0	520	160	"	"	0.3813	"	20"	"	545					"	1	1 min.	32
12:06	520	160	"	"	"	"	20"	"	545					"	2	30 sec.	32
Test No. 3																	
12:10	520	150	"	"	"	"	20"	Gap	did not arc.					"	5	1 min.	32
12:14	520	150	"	"	"	"	"	50 cm.	545					"	6	7 sec.	32
Test No. 4																	
1:29	500	145	"	"	"	"	20"	No arc.		1.70 to 1.75				"	7	15 sec.	32
1:31	500	145	"	"	"	"	"	"	"	1.70				"	8	1 min.	32
1:45	500	145	"	"	"	"	"	"	"	—No lights on—				"	9	10 sec.	32
Test No. 5		(Like No. 4 except 10 deg.)															
1:52	..	..	10	2¼	0.3813	16200	20"	No arc.		1.72	145	2	35,000		Freq. Reading		
1:56	500	155	"	"	"	"	"	"	"	1.8				"	10	..	32
Test No. 6		(Like No. 4 except no horns or controls)															
2:04	520	150	10	"	"	"	20	No arc.		1.73				"	11	45 sec.	32
2:10	390	92	10	"	"	"	5½	50 cm.	250	1.2				"			
							4½	"	211	considerable corona on cond.							
2:20	..	..	"	"	"	"	4	"	190	0.9 little corona on cond.							
..	..	..	"	"	"	"	3½	"	167	.. corona starting							

TEST SHEET 9. (OHIO INSULATOR CO.)
LEAKAGE TESTS

March 3, 1921

Time	V. M. read.	Multi.	Volts prim.	Kv.	Amp. meter	Act. amp.	W. M. conn.	W. M. multi.	W. M. ratio	W. M. read.	Act. watts.		Water lb.
				10 units.	No. 25620 .	With 12252 shell as control.							
12:45	76	2	152	78	0.12	0.00055	S–150	¼	0.66	8	5.3	Std.	38
	100	2	200	117	0.16	0.00073	"	"	"	26	17.	Water	"
	112	2	224	131	0.19	0.00086	"	"	"	40	26	"	"
	126	2	252	148	0.215	0.00098	"	"	"	60	40	"	"
	138.5	2	277	162	0.245	0.00110	"	"	"	84	55	"	"
	75	4	300	176	0.276	0.00125	"	"	"	112	74	"	"
12:50	81	4	324	190	0.31	0.00140	"	"	"	151	100	"	"
12:50 +	86.3	4	345	202	0.338	0.00153	"	"	"	194	128	"	"
12:51	93.5	4	374	219	0.383	0.00172	"	"	"	250	165	"	"
1:38	114.5	2	229	134	....				0.64	38	25	Tap	"
1:38 +	147.5	2	295	173	0.26				"	98	65	Water	"
1:40	125	4	500	292	10 units would not flash							"	"
1:50	107	4	428	250	8 units flash-over one control punct.								
1:54	110½	4	442	258	8 units flash-over.							"	"
1:55	110½	4	442	258	" " "							"	"
			8 units with 25978 Post ins. as controls										
2:05	73	4	292	171	flash-over							"	"
2:06	69	4	276	162	" "							"	"
			8 units, with 12252 shell & center as control with 1 ' pipe horns.										
2:37	116	4	464	272	flash-over							"	"
2:39	123.5	4	495	290	" "							"	"
2:42	114	4	456	267	" "							"	"
			Same as above, with 12252 shell as control.										
2:49	108.5	4	434	254	flash-over							"	"
2:51	109	4	436	255	" "							"	"

TEST SHEET 10—(OHIO INSULATOR CO.)
OSCILLATOR TEST DATA

Date March 2, 1921

Time	Gen. volts	Gen. amps.	Primary turns number	Primary turns spacing	Primary capacity mfd.	No. of secondary turns	Sphere gap setting	Size of spheres	Kv.	Secondary current milliamp.	Wave-meter setting	Coil no.	Freq.	Water and lb. pressure	Remarks Photo No.	Time	Exp.
Test 2:50	No. 7 525	150	10	2¼"	0.3813	1620.0	20"	No arc		1.8				Dry	12	..	32
Test 3:05	No. 8 520	150	"	"	"	"	20"	No Arc		1.75				"	1	1 min.	32
Test 3:14	No. 9 525	150	10	"	"	"	20	No. Arc		1.8, 1.82					2	1 min. volts; 2 min.	32
Test 4:18	No. 10 525	150	10	"	"	"	20	No. Arc		1.8					5	1¼ min. 2 min.	volt. 32
4:20	525	150	"	"	"	"	20	50 cm.	545	1.82					6	7 sec.	32
4:28	..	..	"	"	"	"	4¼	"	211	0.6	No corona						
4:30	..	..	"	"	"	"	5¼	"	250	0.95	No corona						
4:32	..	..	"	"	"	"	6¼	"	282	1.1	corona showing						

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 22, 1921.

SOME TRANSMISSION LINE TESTS

BY. W. W. LEWIS
General Electric Company, Schenectady, N. Y.

IN THE MONTH of October, 1919, Mr. J. H. Foote of the Consumers Power Co., and the writer made a series of tests on the 30-cycle 140,000-volt system of that company in western Michigan. A summary of the tests for corona loss has been published.[1] There are some interesting features of these tests which were not mentioned in the previous paper, as their explanation was not clear at that time. The questions in regard to these features have now been pretty well cleared up and they will be discussed briefly in this paper.

Corona loss tests were made on a transmission line 101.5 miles long extending from Junction Dam to Grand Rapids, and some tests with an additional 47.3 miles extending from Grand Rapids to Kalamazoo. Fig. 1 shows a diagram of the system. Power for the tests was supplied by the three 6,250-kv-a., 18-pole, 100-rev. per min., 7,500-volt, 30-cycle waterwheel-driven generators at Junction Dam. The generators at Grand Rapids and the frequency-changer set at Kalamazoo were not in circuit, switches marked *A* and *E* being open throughout the test.

The line from Junction to Grand Rapids consists of three conductors, each of seven strands medium hard-drawn copper, total cross-section 110,000 cir. mils. The conductors are spaced practically in a vertical plane 12 ft. apart, and supported by 10-disk insulator units in suspension and 12 in strain. The height of lowest conductor at the tower is about 40 ft. and at

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[1] *General Electric Review*, May, 1920.

the middle of the span about 26 ft. The tower spacing averages about 530 ft. The average elevation of the line is about 750 ft. above sea level. The direction of the line is nearly straight north and south with Junction generating station at the north end. There is one transposition tower about every 15 miles giving a complete barrel in about 45 miles. The line had been in service about one and one-half years at the time of the tests.

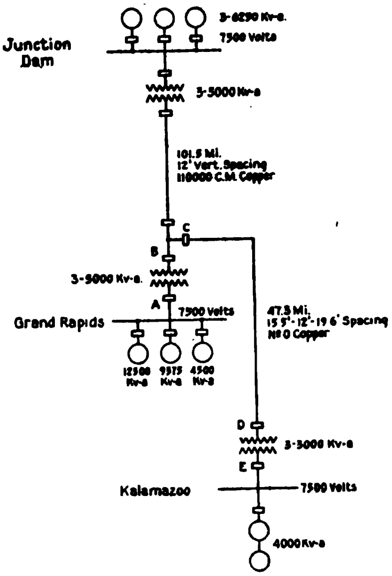

FIG. 1—DIAGRAM OF CONSUMERS POWER CO., 140,000-VOLT 30-CYCLE SYSTEM

The line from Grand Rapids to Kalamazoo consists of No. 0 stranded copper conductor spaced 15.5, 12 and 19.6 ft. respectively, with two conductors supported on the top crossarm on opposite sides of the towers and one conductor on the middle arm of a two-circuit tower. The conductors are supported by 10-disk insulator units.

The most important tests were made on the Junction—Grand Rapids Line. The constants of this line are as follows:

Geometrical mean spacing, 181.5 inches.

Radius conductor, 0.19 inch.

Measured resistance per mile at 47.4 deg. fahr., 0.485 ohms.

Measured reactance per mile at 30 cycles, 0.409 ohms.

Measured impedance per mile at 30 cycles, 0.6345 ohms.

Calculated capacitance per mile, 0.01303×10^{-6} farad.

Calculated susceptance per mile at 30 cycles, 2.457×10^{-6} mho.

For the 101.5 miles from Junction Dam to Grand Rapids these constants become as follows:

Resistance, 49.2 ohms.
Reactance, 41.5 ohms.
Impedance, 64.4 ohms.
Capacitance, 1.322×10^{-6} farad.
Susceptance, 249.2×10^{-6} mho.

The step-up transformers at Junction and step-down transformers at Grand Rapids are similarly rated as follows: Three single-phase, water-cooled, 30-cycle, 5000-kv-a., 140,000/135,000/130,000/125,000/120,000-volt high-tension, 7500-volt low-tension, normally connected delta-delta. The tested impedance of the three transformers at Grand Rapids, based on 5000 kv-a., 7500 volts, 30 cycles and measured by applying voltage to the low-tension winding and short-circuiting the high-tension winding, averaged as follows:

7.13 per cent for the 140,000-volt winding
7.22 per cent " " 135,000 " "
7.25 per cent " " 130,000 " "
7.42 per cent " " 125,000 " "
7.55 per cent " " 120,000 " "
Average temperature 25 deg. cent.

The resistance at 25 deg. cent by shop tests was 17.42 ohms for the 140-kv. winding and 0.0516 ohms for the 7500-volt winding. Excitation curves were taken on the transformers at Junction connected three-phase, with the results shown in Table I and in Fig. 2. Fig. 3 is an oscillogram of the current and potential waves during the excitation test.

The instruments used in most of the tests were calibrated portable voltmeters, ammeters and watt-

TABLE I

TEST NO. 6. EXCITATION OF TRANSFORMER BANK AT JUNCTION CONNECTED 7500 VOLTS DELTA TO 135,000 VOLTS DELTA

Reading No.	Freq.	Volts L. V.	Amp. L. V.	Kw.	Kv-a.	Percent P. F.
1	30	3165	4.0	20	22	90.9
2	30	3640	5.0	24	31	77.4
3	30	4600	6.0	39	48	80.3
4	30	5310	7.5	50	69	72.5
5	30	5920	10.3	62	106	58.5
6	30	6200	12.6	69	135	51.1
7	30	6470	14.8	77	166	46.4
8	30	6950	20.6	89	248	35.9
9	30	7520	31.3	109	408	26.7
10	30	8000	49.4	138	684	20.2
11	30	8280	63.5	158	911	17.4
12	30	8480	79.7	178	1156	15.4

See Fig. 2.

meters and calibrated potential transformers and current transformers from the Schenectady Laboratory. In some of the tests the 400:5 ampere calibrated current transformers were not of sufficient capacity so that it was necessary to use the 2000:5 ampere station current transformers. In these cases the station potential transformers were also used for convenience. Fig. 4 shows the connections of the instruments for the tests, the power transformers being connected at times delta-delta, and at times delta-Y as shown in the figure.

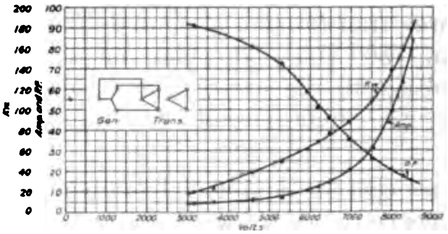

FIG. 2—EXCITATION TEST ON BANK OF THREE 5000-KV-A. 7500 TO 140,000-VOLT TRANSFORMERS AT JUNCTION—TEST 6

DELTA CONNECTION OF TRANSFORMERS

A portion of these tests was made with the line connected from Junction to Kalamazoo, and the remainder with the line from Junction to Grand Rapids (see Fig. 1). The calibrated current and potential transformers and instruments were used throughout and connected as shown in Fig. 4. In these tests, of course, the high-tension side of the power transformers was connected in delta.

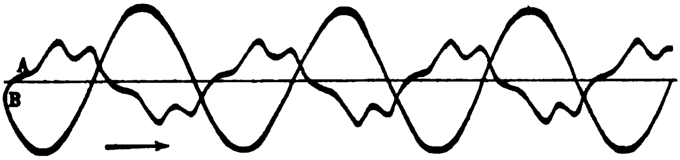

FIG. 3—LOW-VOLTAGE CURRENT AND POTENTIAL WAVES DURING EXCITATION TEST ON TRANSFORMER BANK—TEST 6

Transmission line tests at Junction Dam, Mich.
Consumers Power Company, 140-kv., 30 ~ system. Oct. 14-15, 1919.
Excitation of three 5000-kv-a. transformers at Junction.
Transmission line disconnected.
Curve A—Line current, low-voltage side.
Curve B—Potential, low-voltage side.

The tests may be described as follows:

October 14-15, 1919:

Test No. 7. Line Junction to Kalamazoo. No transformers at Grand Rapids or Kalamazoo.

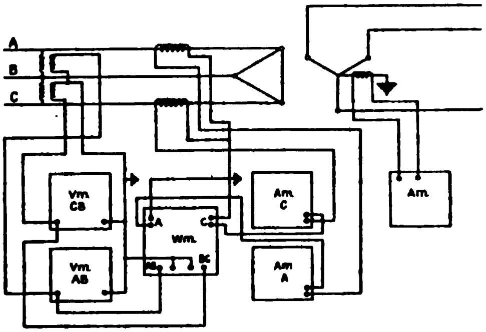

FIG. 4—DIAGRAM SHOWING CONNECTION OF INSTRUMENTS FOR CORONA TESTS

Test No. 8. Line Junction to Kalamazoo. Transformers on at Grand Rapids and Kalamazoo.

Test No. 9. Line Junction to Grand Rapids. Grand Rapids transformers on.

TABLE II

TEST NO. 10. CORONA LOSS TEST. LINE FROM JUNCTION TO GRAND RAPIDS. NO TRANSFORMERS AT GRAND RAPIDS

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
44	30	4140	74.6	205	11.4	56	1470	3.78
45	30	5205	93.8	254	14.1	91	2300	3.96
46	30	5700	102.7	275	15.3	109	2720	3.98
47	30	6100	109.8	292	16.2	142	3090	4.57
48	30	6600	118.8	313	17.4	184	3580	5.15
49	30	7120	128.1	328	18.2	346	4045	8.54
50	30	7555	136.0	340	18.9	514	4450	11.55
51	30	8115	146.0	344	19.1	1051	4835	21.73
52	30	8610	155.0	364	20.2	1700	5425	31.32
53	30	8920	160.5	357	19.8	2165	5520	39.21

Transformer Ratio 135000 : 7500 = 18 : 1
Date.........................Oct. 15, 1919
Barometer....................29.34 in.
Temperature..................44.7 deg. fahr.
Humidity.....................91.4 per cent.
Weather......................Clear
See Fig. 5.

TABLE III

TEST NO. 15. CORONA LOSS TEST. LINE FROM JUNCTION TO GRAND RAPIDS. NO TRANSFORMERS AT GRAND RAPIDS

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
37	30	4700	84.6	227	12.6	66	1850	3.6
38	30	5220	94.0	253	14.1	87	2290	3.8
39	30¼	5605	101.0	270	15.0	114	2620	4.4
40	30	6130	110.4	293	16.3	250	3110	8.0
41	30	6680	120.2	315	17.5	538	3670	14.7
42	30	7210	129.8	338	18.8	866	4220	20.5
44	30	7990	143.8	372	20.7	1558	5150	30.3
45	30	8500	153.0	382	21.2	2030	5620	36.1
46	30	9010	162.1	382	21.2	2690	5960	45.1

Transformer Ratio 135000 : 7500 = 18 : 1
Date.........................Oct. 16, 1919
Barometer....................29.38 in.
Temperature..................43.9 deg. fahr.
Humidity.....................94.4 per cent.
Weather......................Rainy.
See Fig. 5.

TABLE IV

TEST NO. 18. CORONA LOSS TEST. LINE FROM JUNCTION TO GRAND RAPIDS. NO TRANSFORMERS AT GRAND RAPIDS

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
13	30	4320	77.8	209	11.6	53	1565	3.4
14	30	5060	91.1	242	13.4	70	2120	3.3
15	30	5775	103.9	274	15.2	88	2740	3.2
16	30	6340	114.1	297	16.5	105	3260	3.2
18	30	6980	125.6	318	17.7	157	3840	4.1
19	30	7560	136.0	334	18.6	270	4430	6.1
20	30	8160	146.9	340	18.9	805	4805	16.8
21	30	8500	153.0	338	18.8	1230	4980	24.7
22	30	8800	158.4	333	18.5	1600	5080	31.5

Transformer Ratio 135000 : 7500 = 18 : 1

Date..........................Oct. 17, 1919

Barometer.....................29.40 in.

Temperature...................34.7 deg. fahr.

Humidity......................91.0 per cent.

Weather.......................Clear

See Fig. 5.

TABLE V

TEST NO. 9. CORONA LOSS TEST. LINE FROM JUNCTION TO GRAND RAPIDS. TRANSFORMERS ON AT GRAND RAPIDS

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
33	30	4140	74.6	194	10.8	84	1392	6.0
34	30	4480	80.7	211	11.7	101	1638	6.2
35	30	5250	94.6	243	13.5	142	2210	6.4
36	30	5665	102.0	257	14.3	162	2522	6.4
37	30	6170	111.0	274	15.2	188	2928	6.4
38	30	7000	126.0	279	15.5	336	3383	9.4
39	30	7640	137.5	258	14.3	605	3416	17.7
40	30	8080	145.4	218	12.1	964	3052	31.6
41	30	8555	154.0	188	10.4	1548	2786	55.6
42	30	8655	155.8	169	9.4	1730	2533	68.3
43	30	8950	161.1	157	8.7	2090	2433	85.9

Transformer Ratio = 18 : 1

Junction Transformer Ratio 135000 : 7500

Grand Rapids Transformer Ratio 125000 : 7500

Date..........................Oct. 15, 1919

Barometer.....................29.34 in.

Temperature...................46.7 deg. fahr.

Weather.......................Clear

See Fig. 6.

TABLE VI

TEST NO. 13. CORONA LOSS TEST. LINE FROM JUNCTION TO GRAND RAPIDS. TRANSFORMERS ON AT GRAND RAPIDS

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
20	30	4550	82.0	213	11.8	125	1679	7.5
21	30	5130	92.4	238	13.2	151	2114	7.1
22	30	5540	99.8	253	14.1	168	2428	6.9
23	30	6095	109.6	270	15.0	247	2850	8.7
24	30	6795	122.3	282	15.7	594	3320	17.9
25	30	7580	136.5	278	15.4	1225	3650	33.6
26	30	8070	145.3	273	15.2	1610	3818	42.2
27	30	8480	152.6	228	12.7	2082	3350	62.2

Transformer Ratio = 18 :
Junction Transformer Ratio 135000 : 7500
Grand Rapids Transformer Ratio 125000 : 7500
Date........................Oct. 16, 1919
Barometer....................29.38 in.
Temperature...................46.2 deg. fahr.
Humidity......................93.6 per cent.
Weather......................Rainy
See Fig. 6.

TABLE VII

TEST NO. 17. CORONA LOSS TEST. LINE FROM JUNCTION TO GRAND RAPIDS. TRANSFORMERS ON AT GRAND RAPIDS

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
3	30	4530	81.6	212	11.8	87	1665	5.2
4	30	4680	84.3	220	12.2	87	1785	4.9
5	30	5625	101.3	263	14.6	131	2560	5.1
6	30	6090	109.6	280	15.6	166	2950	5.6
7	30	6620	119.2	297	16.5	192	3410	5.6
8	30	7000	126.0	303	16.8	235	3670	6.4
9	30	7620	137.2	308	17.1	384	4070	9.4
10	30¼	8070	145.3	296	16.4	736	4140	17.8
11	30	8600	154.8	253	14.1	1358	3770	36.0
12	30	8900	160.2	229	12.7	1806	3530	51.2

Transformer Ratio = 18 : 1
Junction Transformer Ratio 135000 : 7500
Grand Rapids Transformer Ratio 140000 : 7500
Date.........................Oct. 17, 1919
Barometer....................29.4 in.
Temperature..................33.5 deg. fahr.
Humidity.....................89.0 per cent.
Weather......................Clear
See Fig. 6.

TABLE VIII

TEST NO. 7. CORONA LOSS TEST.
LINE FROM JUNCTION TO KALAMAZOO
NO TRANSFORMERS AT GRAND RAPIDS OR KALAMAZOO

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
13	29.5	4080	73.4	289	16.0	85	2040	4.17
14	30	4400	79.2	313	17.4	89	2388	3.73
15	29.5	5170	93.1	373	20.7	155	3340	4.64
16	30	5470	98.5	389	21.6	168	3680	4.57
17	30	5880	105.8	423	23.5	189	4310	4.39
18	30	6440	116.0	457	25.4	274	5100	5.38
19	30	6900	124.2	493	27.4	418	5890	7.10
20	30	7280	131.0	524	29.1	656	6610	9.93
21	30	7840	141.1	570	31.7	1510	7740	19.51
21A		7930	142.7	578	32.1	1672	7940	21.08
22		8110	146.0	588	32.7	1880	8260	22.78
23	30	8450	152.1	618	34.3	2615	9050	28.90

Transformer Ratio = 135000 : 7500 = 18 : 1
Date.........................Oct. 15, 1919
Barometer....................29.32 in.
Temperature..................51.0 deg. fahr.
Humidity.....................83.9 per cent.
Weather......................Clear
See. Fig. 7.

TABLE IX

TEST NO. 11. CORONA LOSS TEST.
LINE FROM JUNCTION TO KALAMAZOO
NO TRANSFORMERS AT GRAND RAPIDS OR KALAMAZOO

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
1	30	4450	80.2	315	17.5	86	2428	3.46
2	30¼	5310	95.6	380	21.1	157	3498	4.49
3	30	5755	103.6	415	23.1	248	4140	5.99
4	30	6380	114.8	455	25.3	470	5030	9.35
5	30¼	6980	125.6	494	27.5	863	5975	14.45
6	30	7480	134.6	546	30.3	1345	7080	19.00
7	30	8060	145.0	586	32.6	2275	8180	27.80
8	30	8480	152.6	609	33.8	3030	8950	33.88
9	30	8780	158.0	622	34.6	3590	9460	37.96

Transformer Ratio 135000 : 7500 = 18 : 1
Date.........................Oct. 16, 1919
Barometer....................29.38 in.
Temperature..................46.0 deg. fahr.
Humidity.....................96.8 per cent.
Weather......................Rainy
See Fig. 7.

TABLE X

TEST NO. 8. CORONA LOSS TEST.
LINE FROM JUNCTION TO KALAMAZOO
TRANSFORMERS ON AT GRAND RAPIDS AND KALAMAZOO

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
24	30.3	4100	73.8	291	16.2	139	2067	6.73
25	30.5	4530	81.6	319	17.7	171	2502	6.83
26	30	5220	94.0	351	19.5	245	3174	7.72
27	30	5720	103.0	368	20.4	270	3647	7.41
28	30	6260	112.6	385	21.4	400	4175	9.58
29	30	6775	121.9	382	21.2	512	4480	11.43
30	30	7160	128.9	362	20.1	658	4490	14.65
31	30	7500	135.0	327	18.2	874	4250	20.57
32	30	7860	141.5	274	15.2	1195	3730	32.04

Transformer Ratio = 18 : 1
Junction Transformer Ratio 135000 : 7500
Grand Rapids Transformer Ratio 125000 : 7500
Kalamazoo Transformer Ratio 120000 : 7500
Date........................Oct. 15, 1919
Barometer....................29.32 in.
Temperature..................47.9 deg. fahr.
Humidity.....................90.2 per cent.
Weather......................Clear
See. Fig. 8.

TABLE XI

TEST NO. 12. CORONA LOSS TEST.
LINE FROM JUNCTION TO KALAMAZOO
TRANSFORMERS ON AT GRAND RAPIDS AND KALAMAZOO

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
10	30	4540	81.8	316	17.6	164	2487	6.6
11	30	5135	92.4	349	19.4	227	3103	7.3
12	30	5530	99.6	370	20.6	267	3544	7.5
13	30	6220	112.0	392	21.8	477	4222	11.3
14	30	6700	120.6	397	22.0	796	4610	17.3
15	30	7060	127.1	395	21.9	1058	4830	21.9
16	30	7520	135.4	381	21.2	1516	4960	30.6
17	30	8070	145.2	343	19.1	2280	4798	47.5
18	30	8480	152.6	301	16.7	2970	4420	67.2
19	30	8660	156.0	287	15.9	3430	4310	79.6

Transformer Ratio = 18 : 1
Junction Transformer Ratio 135000 : 7500
Grand Rapids Transformer Ratio 125000 : 7500
Kalamazoo Transformer Ratio 130000 : 7500
Date........................Oct. 16, 1919
Barometer....................29.38 in.
Temperature..................46.7 deg. fahr.
Humidity.....................94.2 per cent.
Weather......................Rainy
See Fig. 8.

TABLE XII

TEST NO. 14. CORONA LOSS TEST. LINE FROM JUNCTION TO KALAMAZOO KALAMAZOO TRANSFORMERS ON, GRAND RAPIDS TRANSFORMERS OFF.

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.
28	30	4440	80.0	313	17.4	115	2410	4.8
29	30	5180	93.3	361	20.1	177	3240	5.5
30	30	5600	100.8	385	21.4	233	3740	6.2
31	30	6080	109.4	411	22.8	329	4330	7.6
32	30	6640	119.5	438	24.3	705	5040	14.0
33	30	7160	128.9	457	25.4	1160	5670	20.5
34	30	7480	134.6	464	25.8	1495	6010	24.9
35	30	8010	144.2	476	26.5	2200	6600	33.3
36	30	8500	153.0	486	27.0	3110	7160	43.4

Transformer Ratio = 18 : 1
Junction Transformer Ratio 135000 : 7500
Kalamazoo Transformer Ratio 130000 : 7500
Date..........................Oct. 16, 1919
Barometer....................29.38 in.
Temperature..................46.2 deg. fahr.
Humidity.....................93.6 per cent.
Weather......................Rainy
See. Fig. 8.

Test No. 10. Line Junction to Grand Rapids. No transformers at Grand Rapids.

October 15-16, 1919:

Test No. 11. Line Junction to Kalamazoo. No transformers at Grand Rapids or Kalamazoo.

Test No. 12. Line Junction to Kalamazoo. Kalamazoo and Grand Rapids transformers on.

Test No. 13. Line Junction to Grand Rapids. Grand Rapids transformers on.

Test No. 14. Line Junction to Kalamazoo. Kalamazoo transformers on, Grand Rapids transformers off.

Test No. 15. Line Junction to Grand Rapids. No transformers at Grand Rapids.

October 16-17, 1919:

Test No. 17. Line Junction to Grand Rapids. Grand Rapids transformers on.

Test No. 19. Line Junction to Grand Rapids. No transformers at Grand Rapids.

The data are tabulated in Tables II to XII inclusive, and plotted in Figs. 5 to 8 inclusive.

The readings were corrected as follows: Based on the laboratory calibration curves, made in September and October before the tests and in November after the tests, average voltmeter, ammeter and wattmeter constants, combining both the instrument and instrument transformer corrections, were evolved. The wattmeter readings were corrected for phase angle in the following manner: The phase angles for the current transformers and potential transformers were obtained from the calibration curves, and a constant phase angle of three minutes assumed for the wattmeter. The apparent power factor was found from the kw. and kv-a. as given by the corrected instrument readings, and the angle θ_2 was found from this power factor. The total phase angle for the instrument transformers and wattmeters was added to θ_2 to give the true angle θ. The cosine of θ gives the true power factor. The ratio $\cos\theta/\cos\theta_2$ is the correction factor by which

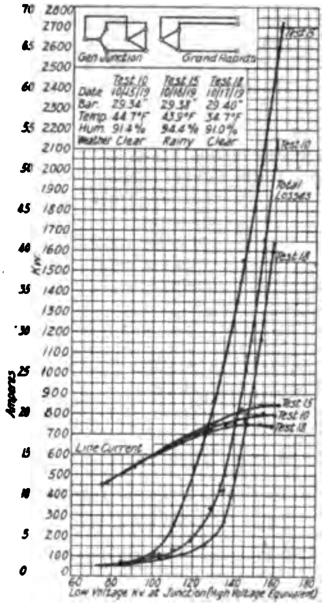

Fig. 5—Corona Loss, Tests 10, 15 and 18—Line from Junction to Grand Rapids—No Transformers at Grand Rapids

the apparent kilowatts are multiplied to give the true kilowatts. This correction factor is greater than one for leading currents and less than one for lagging currents. The correction factor varies from 5 to 13 per cent at the lower values and from 0.2 to 2 per cent at the higher values. It must be understood that in any event the corrections are approximate. The values of kilowatts and power factor given in the tables are corrected values found by this method.

Discussion of Results. Fig. 6 gives a comparison of the losses on the line from Junction to Grand Rapids,

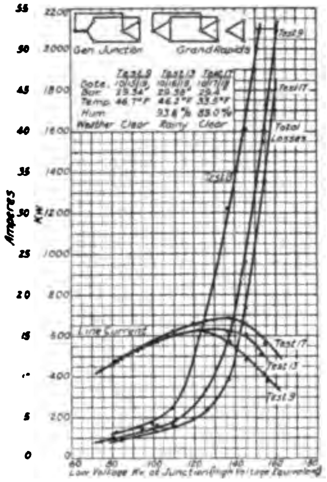

FIG. 6—CORONA LOSS, TESTS 9, 13 AND 17—LINE FROM JUNCTION TO GRAND RAPIDS—TRANSFORMERS ON AT GRAND RAPIDS

with transformers connected at Grand Rapids, under clear and rainy conditions and under clear conditions with two degrees of temperature. The effect of increase of temperature and of rain in increasing the losses is well illustrated. The curves also show the effect of exciting current of the transformers at Grand Rapids, at the higher densities, in decreasing the line current at Junction.

Fig. 5 shows similar curves on the Junction-Grand Rapids line with the transformers at Grand Rapids not connected to the line. The loss curves, it will be noted, practically coincide with those of Fig. 6 except at the lower end, where the loss is nearly all due to the transformers. The line current does not have the marked tendency to droop apparent in Fig. 6, owing to the absence of the Grand Rapids transformer bank.

Figs. 7 and 8 show curves of losses of the line from Junction to Kalamazoo, the former with no transformers on at the end and the latter with transformers connected. The loss curves of Tests Nos. 12 and 14 are practically identical, except at the lower portion, where the additional loss of the transformers at Grand Rapids in Test No. 12 raises the curve above that of Test No. 14.

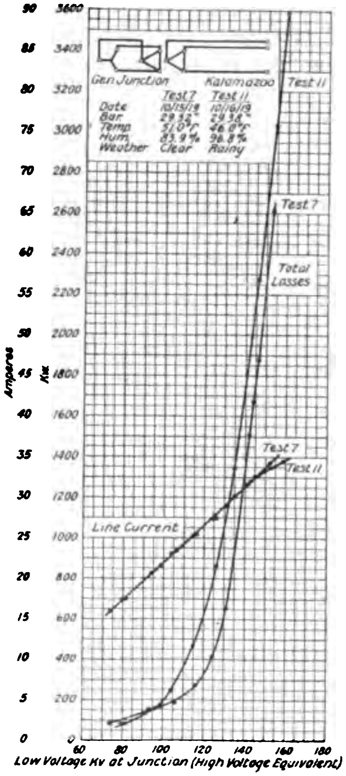

FIG. 7—CORONA LOSS, TESTS 7 AND 11—LINE FROM JUNCTION TO KALAMAZOO—NO TRANSFORMERS ON AT GRAND RAPIDS OR KALAMAZOO

The effect of the transformers is also seen in the line current curves.

An oscillogram of typical low-tension waves taken during these tests is reproduced in Fig. 9.

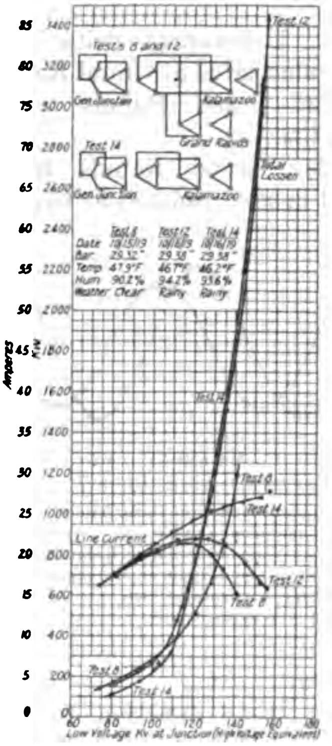

FIG. 8—CORONA LOSS, TESTS 8, 12 AND 14—LINE FROM JUNCTION TO KALAMAZOO—TESTS 8 AND 12, TRANSFORMERS ON AT GRAND RAPIDS AND KALAMAZOO—TEST 14, TRANSFORMERS ON AT KALAMAZOO ONLY

Y-CONNECTION OF TRANSFORMERS

The Y-connected tests were made with the Junction-Grand Rapids line only. In some tests the transformer bank at Grand Rapids was connected to the circuit and in some cases omitted. In all cases the neutral either at Junction or Grand Rapids, and sometimes both, was grounded.

The following tests were made:

October 19, 1919:

Test No. 20. Line Junction to Grand Rapids. Grand Rapids transformers on. Neutrals grounded at Junction and Grand Rapids.

Test No. 21. Low-voltage delta open at Grand Rapids.

Test No. 22. Low-voltage delta closed at Grand Rapids. Neutral isolated at Grand Rapids.

Test No. 23. Grand Rapids transformers disconnected from line.

Test No. 24. Grand Rapids transformers on. Delta open and neutral isolated at Grand Rapids.

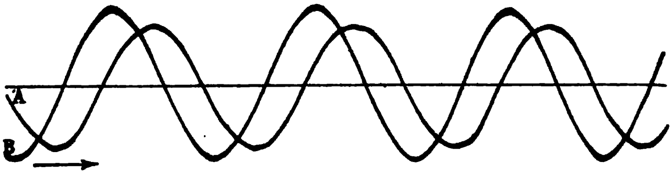

FIG. 9—LOW-VOLTAGE CURRENT AND POTENTIAL WAVES TAKEN DURING TEST 7

Transmission line tests at Junction Dam, Mich.
Consumers Power Company, 140-kv., 30 ~ system. Oct. 14-15, 1919.
Corona test at 135 kv., line, Junction to Kalamazoo.
No transformer on at Grand Rapids or Kalamazoo.
Curve A—Line current, low-voltage side.
Curve B—Potential, low-voltage side.

October 26, 1919:

Test No. 42. Line Junction to Grand Rapids. Grand Rapids transformers on. Neutrals grounded at Junction and Grand Rapids.

Test No. 43. Grand Rapids transformers disconnected from line.

Test No. 44. Grand Rapids transformers on. Neutral grounded at Grand Rapids. Neutral isolated at Junction.

Test No. 45. Grand Rapids transformers on. Neutral grounded at Junction. Neutral isolated at Grand Rapids.

The various connections are illustrated in Fig. 10, and the results of the tests are given in Tables XIII to XXI inclusive.

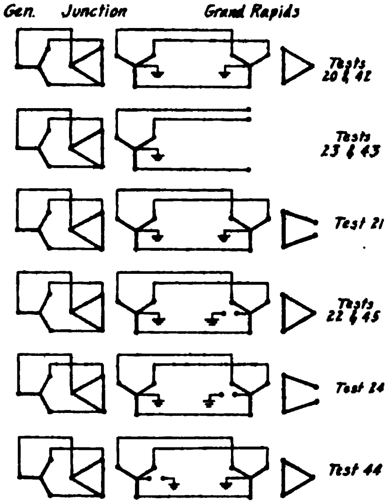

FIG. 10—DIAGRAM OF CONNECTIONS OF POWER TRANSFORMERS DURING CORONA TESTS WITH HIGH-TENSION SIDE OF TRANSFORMERS Y-CONNECTED

TABLE XIII

TEST NO. 23. CORONA LOSS TEST.
LINE FROM JUNCTION TO GRAND RAPIDS.
NO TRANSFORMERS AT GRAND RAPIDS.
NEUTRAL GROUNDED AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Amp. Neut.
24	30	3930	109.0	476	17.2	48	3240	1.48	0
25	30	4550	126.2	548	19.8	72	4320	1.67	0
26	30	5060	140.4	616	22.2	480	5400	8.89	1.25
27	30	5680	157.6	752	27.1	2230	7400	30.13	7.50
28	30	6280	174.2	924	33.3	4030	10050	40.1	13.3
29	30	6710	186.1	1048	37.8	5380	12180	44.2	16.5
30	30	7150	198.4	1200	43.2	6960	14860	46.8	19.0

Amp. Neutral begin at 138500 volts
Transformer Ratio = 120000/208000 Y : 7500 = 27.73 : 1
Date........................Oct. 19, 1919
Barometer....................29.62 in.
Temperature..................48.8 deg. fahr.
Humidity.....................61.4 per cent.
Weather......................Clear
See Fig. 11.

TABLE XIV

TEST NO. 43. CORONA LOSS TEST.
LINE JUNCTION TO GRAND RAPIDS.
NO TRANSFORMERS AT GRAND RAPIDS.
NEUTRAL GROUNDED AT JUNCTION.

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Amp. Neut.
15	30	3350	93.0	420	15.1	48	2440	1.97	0
16	30	4040	112.0	508	18.3	48	3350	1.35	0
17	30	4600	127.6	576	20.8	72	4590	1.57	0
18	30	5020	139.2	632	22.8	648	5580	11.71	2.8
19	30	5680	157.5	772	27.8	2330	7600	30.65	8.8
20	30	5900	163.6	820	29.6	2880	8380	34.4	10.5
21	30	6690	185.5	1032	37.2	5305	11960	44.3	15.9
22	30	7160	198.5	1176	42.4	6840	14590	46.9	18.8

Amp. Neutral begin at 127500 volts
Amp. Neutral 1 amp. at 133600 volts
Transformer Ratio = 120000/208000Y : 7500 = 27.73 : 1
Date..........................Oct. 26, 1919
Barometer.....................29.38 in.
Temperature...................42.5 deg. fahr.
Humidity......................81.0 per cent.
Weather.......................Cloudy
See Fig. 11.

TABLE XV

TEST NO. 20. CORONA LOSS TEST.
LINE FROM JUNCTION TO GRAND RAPIDS
TRANSFORMERS ON AT GRAND RAPIDS
NEUTRALS GROUNDED AT JUNCTION AND GRAND RAPIDS
READINGS AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Amp. Neut.
1	30	3840	106.5	452	16.3	72	3010	2.39	0
2	30	4420	122.6	528	19.0	120	4040	2.97	0
3	30	5060	140.4	592	21.3	480	5180	9.27	0
4	30	5580	154.8	720	25.9	1945	6960	27.94	2.0
5	30	5900	163.6	816	29.4	2930	8340	35.14	4.5
6	30	6740	187.0	1072	38.6	5545	12520	44.29	6.5
7	30	7300	202.5	1220	44.0	7440	15430	48.20	7.5
8	30	7500	208.0	1272	45.9	8160	16530	49.38	8.25

Transformer Ratio = 120000/208000 Y : 7500 = 27.73 : 1

TABLE XV—*Continued*

READINGS AT GRAND RAPIDS

Reading No.	Volts L. V.	Kv. H. V. by ratio	Amp. neut.
1	3600	116.4	0
2	4120	133.2	0
3	4720	152.6	0
4	5160	166.9	3.0
5	5480	177.2	4.5
6	6240	201.8	6.0
7	6780	219.2	6.9
8	6940	224.3	7.3

Transformer Ratio = 140000/242500 Y : 7500 = 32.33 : 1

Date............................Oct. 19, 1919
Barometer......................29.64 in.
Temperature....................51.1 deg. fahr.
Humidity.......................53.1 per cent.
Weather........................Clear, sunshiny.
See Fig. 12.

TABLE XVI

TEST NO. 42. CORONA LOSS TEST.
LINE FROM JUNCTION TO GRAND RAPIDS
TRANSFORMERS ON AT GRAND RAPIDS
NEUTRALS GROUNDED AT JUNCTION AND GRAND RAPIDS

READINGS AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Amp. Neut.
5	30	3950	109.5	460	16.6	72	3150	2.29	0
6	30	4950	127.4	520	18.8	168	4135	4.06	0.15
7	30	4975	138.0	560	20.2	528	4830	10.93	0.88
9	30	5480	152.0	680	24.5	1775	6460	27.5	2.90
10	30	6160	170.9	896	32.3	3650	9560	38.2	4.90
12	30	6520	181.0	1000	36.1	4750	11290	42.1	5.72
13	30	7100	197.0	1152	41.5	6645	14170	46.9	7.11
14	30	7510	208.2	1252	45.1	7970	16290	48.9	8.00

Transformer Ratio = 120000/208000 Y : 7500 = 27.73 : 1

READINGS AT GRAND RAPIDS

Reading No.	Volts L. V.	Kv. H. V. by ratio	Amp. neut.
5	3780	109.1	0
6	4500	129.9	0
7	4800	138.5	0.6
9	5520	159.4	2.4
10	6180	178.4	4.5
12	6540	188.7	5.4
13	7140	206.0	6.72
14	7560	218.2	7.5

Transformer Ratio = 125000/216500 Y : 7500 = 28.87 : 1

Date............................Oct. 26, 1919
Barometer......................29.32 in.
Temperature....................41 deg. fahr.
Humidity.......................93.6 per cent.
Weather........................Cloudy
See Fig. 12.

TABLE XVII

TEST NO. 21. CORONA LOSS TEST.
LINE FROM JUNCTION TO GRAND RAPIDS.
TRANSFORMERS ON AT GRAND RAPIDS
NEUTRALS GROUNDED AT JUNCTION AND GRAND RAPIDS
DELTA OPEN AT GRAND RAPIDS

READINGS AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Amp. Neut.
18	30	4385	121.6	524	18.9	72	3980	1.8	0
19	30	6070	168.4	884	31.9	3580	9300	38.5	13.5
20	30	7300	202.6	1216	43.9	7680	15390	49.9	22.0

Neutral Current Begins at 133200 volts.
Transformer Ratio 120000/208000Y : 7500 = 27.73 : 1

READINGS AT GRAND RAPIDS

Reading No.	Volts L. V.	Kv. H. V. by ratio	Volts open delta
18	4080	132.0	0
19	5640	182.4	0
20	6780	219.2	600

Transformer Ratio 140000/242500 : 7500 = 32.33 : 1
Date........................Oct. 19, 1919
Barometer........................29.62 in.
Temperature........................54 deg. fahr.
Humidity........................53.8 per cent.
Weather........................Clear, sunshiny

TABLE XVIII

TEST NO. 22. CORONA LOSS TEST.
LINE FROM JUNCTION TO GRAND RAPIDS
TRANSFORMERS ON AT GRAND RAPIDS.
NEUTRAL GROUNDED AT JUNCTION.
NEUTRAL ISOLATED AT GRAND RAPIDS

READINGS AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Amp. Neut.
21	30	4672	129.6	572	20.6	192	4630	4.15	0.5
22	30	6006	166.6	896	32.3	3360	9320	36.04	12.0
23	30	7390	205.0	1244	44.8	7970	15920	50.05	20.5

Neutral Current Begins at 126,500 volts
Transformer Ratio = 120000/208000Y : 7500 = 27.73 : 1

TABLE XVIII—*Continued*

READINGS AT GRAND RAPIDS

Reading No.	Volts neutral
21	4440
22	5640
23	6900

Transformer Ratio Grand Rapids 140000/242500Y = 32.33 : 1
Date............................Oct. 19, 1919
Weather........................Clear, sunshiny

TABLE XIX

TEST NO. 45. CORONA LOSS TEST. LINE FROM JUNCTION TO GRAND RAPIDS TRANSFORMERS ON AT GRAND RAPIDS. NEUTRAL GROUNDED AT JUNCTION NEUTRAL ISOLATED AT GRAND RAPIDS

READINGS AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Percent P. F.	Amp. Neut.
1	30	4470	124.0	544	19.6	96	4210	2.3	0
2	30	5040	139.8	620	22.4	528	5410	9.8	2.25
3	30	5575	154.5						7.50
4	30	5640	156.4	732	26.4	2136	7150	29.9	8.15
5	30	6030	167.2	832	30.0	3360	8690	38.7	11.50

Neutral Current Begins at 136,000 volts
Transformer Ratio 120000/208000 : 7500 = 27.73 : 1

READINGS AT GRAND RAPIDS

Reading No.	Volts neutral to ground
1	0
2	0
3	0
4	1800
5	3000

Transformer Ratio 125000/216500Y : 7500 = 28.87 : 1

TABLE XX

TEST NO. 24. CORONA LOSS TEST.
LINE FROM JUNCTION TO GRAND RAPIDS
TRANSFORMERS ON AT GRAND RAPIDS
NEUTRAL GROUNDED AT JUNCTION
DELTA OPEN AND NEUTRAL ISOLATED AT GRAND RAPIDS

READINGS AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Amp. Neut.
39	30	4360	120.9	520	18.8	72	3980	1.83	0
40	30	5080	140.9	612	22.1	552	5385	10.25	1.25
41	30	5470	151.7	680	24.5	1584	6440	24.6	6.0
42	30	5980	165.9	820	29.6	3070	8500	36.1	10.5

Transformer Ratio = 120000/20800 Y = 27.73 : 1

READINGS AT GRAND RAPIDS

Reading No.	Volts L. V.	Kv. H. V. by ratio	Volts open delta	3rd Harm. per leg L. V.	3rd Harm. per leg H. V. by ratio	Fund per leg L. V.	Fund per leg H. V. by ratio
39	5160	136.8	6120	2040	34000	4740	79000
40	5880	147.0	8820	2940	49000	5095	84900
41	6300	157.0	9540	3180	53000	5435	90600
42	6960	172.7	10680	3560	59400	5980	99700
....	7980	194.5	12845	4282	71400	6730	112200
....	8520	209.0	13500	4500	75000	7235	120600

Transformer Ratio = 125000/216500 Y : 7500 = 28.87 : 1
Date..........................Oct. 19, 1919
Barometer.....................29.62 in.
Temperature...................42.1 deg. fahr.
Humidity......................73.2 per cent.
Weather.......................Clear, sunshiny.

TABLE XXI

TEST NO. 44. CORONA LOSS TEST.
LINE FROM JUNCTION TO GRAND RAPIDS.
TRANSFORMERS ON AT GRAND RAPIDS.
NEUTRAL GROUNDED AT GRAND RAPIDS.
NEUTRAL ISOLATED AT JUNCTION

READINGS AT JUNCTION

Reading No.	Freq.	Volts L. V.	Kv. H. V. by ratio	Amp. L. V.	Amp. H. V. by ratio	Kw.	Kv-a.	Per-cent P. F.	Volts Neut. to ground
1	30	5160	143.0	580	20.9	840	5185	16.2	500
2	30	5650	156.7	728	26.2	2208	7120	31.0	2700
3	30	6180	171.4	864	31.1	3720	9250	40.2	3850

Transformer Ratio 120000/208000Y : 7500 = 27.73 : 1

TABLE XXI—*Continued*

READINGS AT GRAND RAPIDS

Reading No.	Volts L. V.	Kv. H. V. by ratio	Amp. neut.
1	5160	149.0	1.8
2	5760	166.4	8.7
3	6600	190.5	11.7
	7800	225.0	12.9

Transformer Ratio 125000/216500Y : 7500 = 28.87 : 1
Date..........................Oct. 26, 1919.
Barometer......................29.38 in.
Temperature....................42.5 deg. fahr.
Humidity.......................81 per cent.
Weather........................Cloudy

Although we have calibration curves for the various instruments we do not have such curves for the station potential and current transformers. It was thought best, therefore, to give the readings uncorrected rather than to correct for the instruments only. In general the instrument corrections and instrument

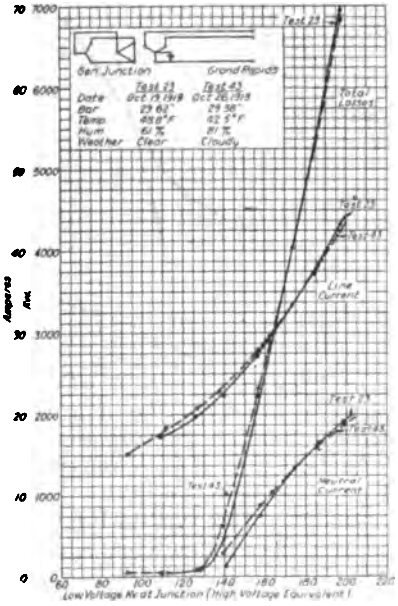

FIG. 11—CORONA LOSS, TESTS 23 AND 43—LINE FROM JUNCTION TO GRAND RAPIDS—NO TRANSFORMERS AT GRAND RAPIDS—NEUTRAL GROUNDED AT JUNCTION

transformer ratios tend to reduce the readings while the phase angle corrections of the instrument transformers tend to increase them. In respect to current and potential therefore the results may be somewhat high while in respect to watts they are probably somewhat low. The corrections are not large, except at the lower readings where they are sometimes appreciable.

Corona loss, amperes line and amperes neutral for Tests 23 and 43 are plotted in Fig. 11 and for Tests 20 and 42 in Fig. 12. The results for the other tests are not plotted, but they follow very closely the plotted curves. In Fig. 13 is plotted the power factor for Test 20, also a comparison of the potentials at Junction and Grand Rapids.

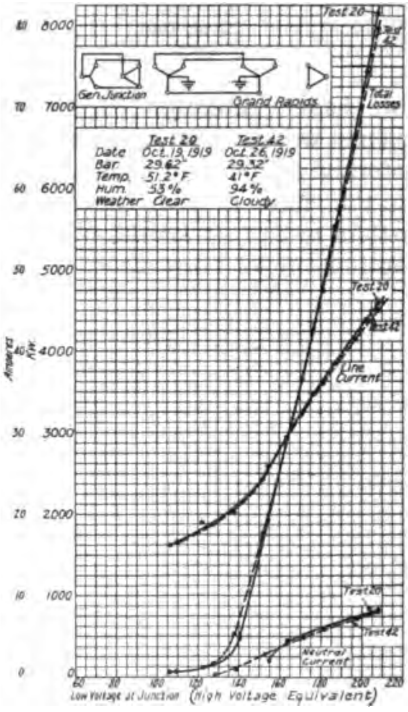

FIG. 12—CORONA LOSS, TESTS 20 AND 42—LINE FROM JUNCTION TO GRAND RAPIDS—TRANSFORMERS ON AT GRAND RAPIDS—NEUTRAL GROUNDED AT GRAND RAPIDS AND JUNCTION

Discussion of Results. In these tests an ammeter was placed in the neutral ground, or if the neutral was open a voltmeter was placed between the neutral and ground. In some cases it was necessary to use a current transformer in the neutral ground and in some cases the current was read directly. In measuring the neutral voltage a potential transformer was used in all cases.

Figs. 14 and 15 show low-voltage waves of potential and current and high-voltage waves of ground current for Tests 23 and 20 respectively. Fig. 16 shows the potential between neutral and ground for Test 44. The oscillograms show that both the neutral voltage and current are of triple frequency. There are two explanations for this, one advanced by the writer and one by Mr. F. W. Peek. The writer's explanation is as follows:

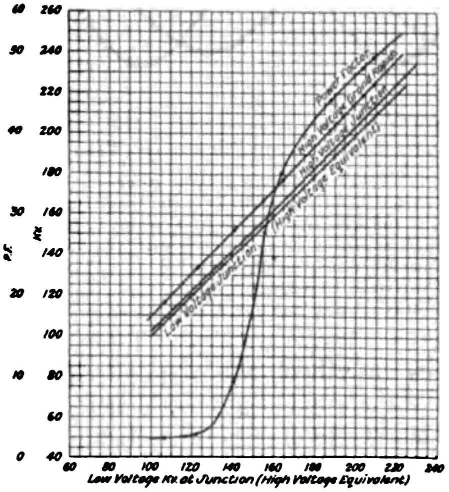

FIG. 13—COMPARISON OF POTENTIALS AT JUNCTION AND GRAND RAPIDS, TEST 20

In the low-tension delta of the transformer bank there is a triple-frequency circulating current which is required by the magnetization of the iron of the transformers. This current is forced through the impedance of the windings by a small voltage which multiplied by the ratio, is reproduced in the high-voltage windings. This voltage impressed between conductors and ground charges the capacitance of the transmission conductors to ground, the charging current of the three conductors in multiple flowing back through the grounded neutral. The action is much the same as for a Y-Y transformer bank with grounded neutral, except that the voltage involved is much smaller.

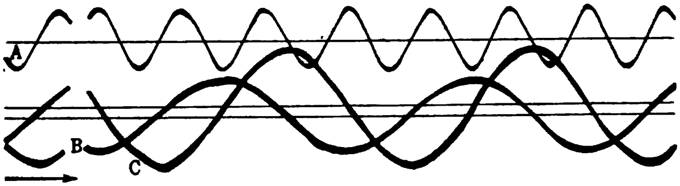

FIG. 14—LOW-VOLTAGE CURRENT AND POTENTIAL AND CURRENT IN GROUNDED NEUTRAL, TEST 23

Transmission line tests at Junction Dam, Mich.
Consumers Power Company, 140-kv., 30 ~ system. Oct. 19, 1919.
Corona test at 198 kv., line, Junction to Grand Rapids.
No transformer at Grand Rapids. Neutral grounded at Junction.
Curve A—Current in neutral ground.
Curve B—Current in transmission line.
Curve C—Voltage across transmission line transformers.

Mr. Peek ascribed this triple-frequency ground current to the corona, the theory being as follows:

The corona starts at a point well up on the ascending part of the voltage wave, and disappears when

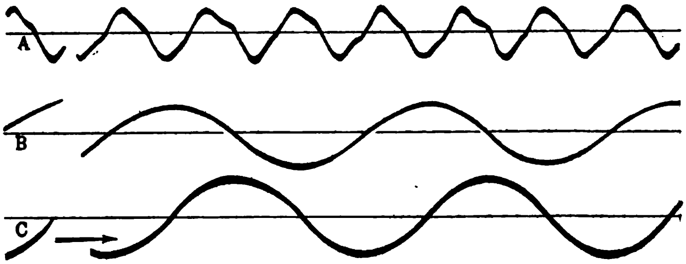

FIG. 15—LOW-VOLTAGE CURRENT AND POTENTIAL AND CURRENT IN GROUNDED NEUTRAL, TEST 20

Transmission line tests at Junction Dam, Mich.
Consumers Power Company, 140-kv., 30 ~ system. Oct. 19, 1919.
Corona test at 208 kv., line, Junction to Grand Rapids.
Grand Rapids transformers on neutral grounded at Junction and Grand Rapids.
Curve A—Current in neutral ground.
Curve B—Current in transmission line.
Curve C—Voltage across transmission line transformers.

the wave has passed through a maximum and reached the same value on the descending portion. This occurs every half-cycle and has the effect of placing a pulsation or harmonic in the voltage wave. The pulsation may be of any odd frequency depending on the point at which the corona starts. Naturally the third harmonic being the first harmonic encountered and being in phase in all three legs, is the most conspicuous. This triple-frequency voltage, acting on the capacitance of the system, which itself is pulsating on account of the increase and decrease of diameter of the conductor due to corona, causes a triple-frequency charging current to flow through the capacitance to ground and back through the grounded neutral.

Mr. Peek has made some laboratory tests, which show conclusively that the greater part of this ground current is due to corona, in accordance with his theory, and that only a small portion of it may be ascribed to the triple-frequency magnetization of the transformers, as suggested by the writer. This greatly relieves the situation as it places the onus for this ground current on the corona, which may be avoided and not on the transformer magnetization which is unavoidable. Mr. Peek will describe his theory and tests in detail in a paper at this meeting.

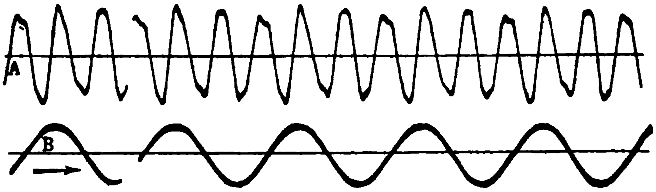

FIG. 16—LOW-VOLTAGE POTENTIAL AND POTENTIAL FROM NEUTRAL TO GROUND, TEST 44

Transmission line tests at Junction Dam, Mich.
Consumers Power Company, 140-kv., 30 ~ system. Oct. 26, 1919.
Corona test at 155 kv., line, Junction to Grand Rapids.
Grand Rapids transformers on neutral open at Junction, neutral grounded at Grand Rapids.
Curve A—Voltage, neutral to ground.
Curve B—Voltage bus side of 7500-volt switch.

The tests show that with open line and one neutral grounded the ground current is from 20 per cent to 40 per cent of the line current at corresponding voltage. With neutral grounded at both ends (and low-tension deltas closed) the neutral current at each end is from 10 per cent to 20 per cent of the line current, the current splitting in this case between the two ends. With transformers at both ends of the line but neutral grounded at one end only (Test 22), or with transformers at both ends of the line and both neutrals grounded, but the delta open at the receiving end (Test 21), the neutral current at the generating station is practically the same as when the line is open at one end.

With transformers at both ends and the neutral at one end only grounded, a voltage exists between the isolated neutral and ground as shown in Fig. 16.

It will be noted that the neutral current begins abruptly in the neighborhood of 140 kv., which means that at lower voltage the current was so small as to give no indication on the ammeter. Thus with the transmission line operating at normal voltage, the ground current will be negligible, and no trouble should be experienced from it.

Rise in Voltage. The power factor in the tests varies from 2 to 50 per cent leading. We would naturally expect a boost in voltage, due to this leading current passing through the reactance of the transformers and transmission line. Fig. 13 shows the voltage rise along the line for Test 20. The rise through the transformers was calculated. The voltage at the Grand Rapids end of the line was measured on the low-tension side, and the high-tension voltage is this measured voltage multiplied by the ratio, as there is no current passing through the transformers and therefore no change in voltage. The calculated rise in voltage along the line is considerably less than the measured rise.

The tests with open line (Grand Rapids transformers connected), Tests Nos. 23 and 43, should give a greater rise than the tests with transformers at the end of the line. The calculated rise with open line, however, is much less than measured with transformers at the end of the line.

These discrepancies may be caused by change in capacitance due to corona, or by harmonics introduced by corona, which will be discussed later.

Open Delta. In Test No. 21 the transformers were on at Grand Rapids, with neutrals grounded at Junction and Grand Rapids. The low-tension delta was open at Grand Rapids. A voltmeter placed across the corner of the open delta read about 600 volts with 203 kv. at Junction.

In Test No. 24, in addition to having the low-tension delta open, the high-voltage neutral was isolated at Grand Rapids. Now a voltage was read across the corner of the open delta which amounted to 13,500 volts with 203 kv. at Junction. One-third of this appears across each leg of the low tension. The triple-frequency leg voltage multiplied by the ratio of transformation gives the triple-frequency voltage across each leg of the high tension, and this voltage (75,000 in this case) appears between the neutral and ground. Such voltages may be expected with Y-Y connection without tertiary winding, and it will be noted that they rise to very high values.

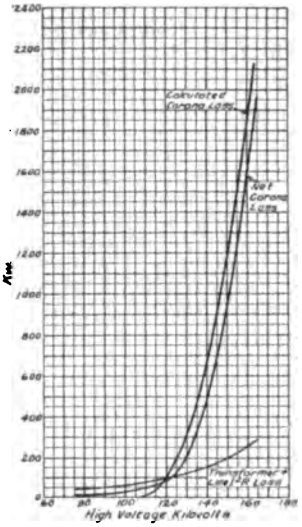

FIG. 17—COMPARISON OF CALCULATED AND MEASURED LOSSES TEST 10

COMPARISON OF CALCULATED AND TEST CORONA LOSSES

It is very difficult to get the true loss, either tested or calculated. The test loss must necessarily be taken on the low-tension side and is subject to correction for the transformer core loss and i^2r loss and the transmission line i^2r loss. Phase-angle corrections of instrument transformers change the results. On account of the rise in voltage over the line, it is doubtful to what voltage the loss should be referred. On the other hand, in calculating the loss, there are certain assumptions to be made as to the irregularity factor, the spacing of conductors, etc. Corona loss starts first on the middle conductor and this is not taken

TABLE XXII

COMPARISON OF MEASURED AND CALCULATED LOSSES
TEST NO. 10

Reading No.	Kv. H. V. by calc.	Amp. L. V. $i + j\,i_1$	Transformer Exc. Cur. $i_2 - j\,i_3$	H. V. Line Cur. (L. V. Equiv.) $i_4 + j\,i_5$	Amp. H. V. by calc.
44	76.2	$7.76 + 205.1j$	$4.24 - 2.65j$	$3.52 + 207.75j$	11.5
45	96.0	$10.07 + 254.0j$	$5.72 - 5.31j$	$4.35 + 259.31j$	14.4
46	105.0	$10.95 + 274.8j$	$6.27 - 7.54j$	$4.68 + 282.34j$	15.7
47	112.3	$13.36 + 292.0j$	$6.38 - 9.92j$	$6.98 + 301.92j$	16.8
48	121.5	$16.11 + 312.7j$	$6.88 - 14.45j$	$9.23 + 327.15j$	18.2
49	131.0	$28.0 + 327.0j$	$7.65 - 21.79j$	$20.35 + 348.79j$	19.4
50	139.0	$39.28 + 337.8j$	$8.38 - 31.09j$	$30.90 + 368.89j$	20.6
51	148.9	$74.8 + 336.0j$	$10.45 - 54.53j$	$64.35 + 390.53j$	22.0
52	158.0	$113.95 + 345.2j$	$12.6 - 89.15j$	$101.35 + 434.35j$	24.8
53	163.8	$140.1 + 328.3j$	$13.22 - 117.2j$	$126.88 + 445.5\,j$	25.7

Reading No.	Total meas. loss	Trans. core loss	L. V. I^2R	H. V. I^2R	Line I^2R	Sum of core & I^2R	Net corona loss	Calc. corona loss
44	56	32	2.18	2.19	6.55	42.92	13	0
45	91	49	3.28	3.42	10.24	65.94	25	0
46	109	59	3.90	4.05	12.11	79.06	30	0
47	142	66.5	4.41	4.47	13.38	88.76	53	12
48	184	78.5	5.06	5.44	16.27	105.27	79	122
49	346	94.0	5.55	6.18	18.50	124.23	222	350
50	514	110.0	5.97	6.94	20.78	143.69	370	644
51	1051	143.0	6.10	7.93	23.73	180.76	870	1118
52	1700	189.9	6.82	10.15	30.39	237.26	1463	1668
53	2165	231.8	6.60	10.89	32.6	281.89	1883	2088

See Fig. 17.

into account in figuring e_0 with the geometrical mean spacing.

Nevertheless the tests here recorded are believed to be fairly accurate and the results representative of the actual corona loss. Also the calculated losses represent the losses accurately within the limitations of the formulas for a line which fulfills the assumed conditions.

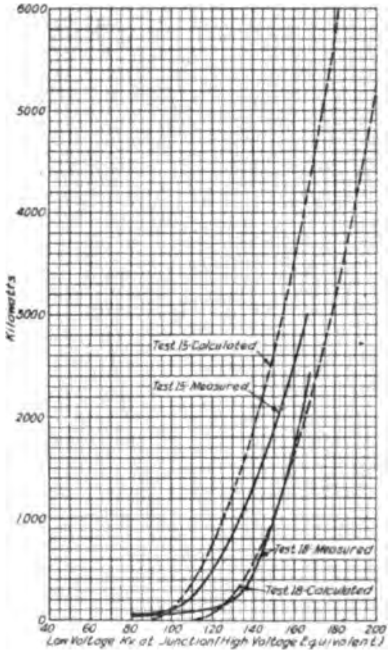

FIG. 18—COMPARISON OF CALCULATED AND MEASURED LOSSES, TESTS 15 AND 18

In Fig. 17 is given a comparison between the tested and calculated corona losses for Test No. 10. In these and the following calculations m_0 is assumed as 0.85 and m_v as 0.82. The test readings were corrected for instrument and instrument transformer errors, and from the total losses thus found are substracted the transformer core and i^2r loss and the line i^2r loss (see Table XXII). The high-tension voltage is calculated from the low-tension voltage and the constants of the transformers, and this voltage is considered uniform throughout the line. The corona losses are calculated and plotted against this high-tension voltage. The calculated losses are higher than the test losses except at the lower part of the curve. Calculated e_0 is 108.1 while the test e_0 is about 120 kv. Calculated e_v is 148.5 kv.

In Fig. 18 are given comparisons of calculated and test losses for Tests 15 and 18. In this case the test losses given are the total losses, including transformer losses and line i^2r. The voltage is the low-tension voltage times the ratio, uncorrected for rise through the transformer. The comparison here is useful mainly in showing the shape of the curves. The calculated e_0 for Test 15 is 86.6 kv. based on storm e_0 = 0.8 fair weather e_0. This is apparently too low a value.

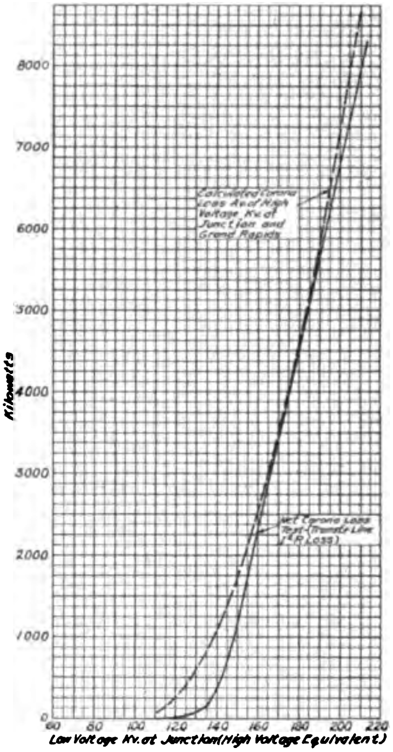

FIG. 19—COMPARISON OF CALCULATED AND MEASURED LOSSES, TEST 20

TABLE XXIII
COMPARISON OF MEASURED AND CALCULATED LOSSES
TEST NO. 20

L. V. Kv. Junction (H. V. Equiv.)	L. V. Amp. Junction (H. V. Equiv.)	$i_1 + j i_2$	Trans. Exc. Cur. Assumed 90° lag	Line Current $i_3 + j i_4$	H. V. line cur. amp.	H. V. Kv. Junction calc.	H. V. Kv. Grand Rapids L. V. × ratio	Avg. H. V. Kv. Jct. & Grand Rapids	Total loss from test	Trans. loss Jct.	Trans. loss G. R.	$I^2 R$ line loss	Total trans. + line loss	Net corona loss	Calc. corona loss Avg. H. V. Kv.
100	16.1	0.370 + 16.09*j*	0.12	0.37 + 16.21*j*	16.22	102.1	109.5	105.8	60	25	30	13	68	0	0
110	16.5	0.397 + 16.49*j*	0.15	0.40 + 16.64*j*	16.65	112.1	120.0	116.1	75	30	35	14	79	0	48
120	17.8	0.490 + 17.79*j*	0.20	0.49 + 18.28*j*	18.30	122.2	130.8	126.5	100	34	41	16	91	9	240
130	19.4	0.815 + 19.39*j*	0.24	0.82 + 20.21*j*	20.22	132.5	141.2	136.9	160	40	47	20	107	53	576
140	21.6	1.945 + 21.51*j*	0.25	1.95 + 21.76*j*	21.82	142.6	152.0	147.3	475	46	53	23	122	353	1058
150	24.5	4.73 + 24.03*j*	0.26	4.73 + 24.29*j*	24.85	153.0	162.5	157.8	1250	52	61	30	143	1107	1698
160	27.9	9.21 + 26.32*j*	0.26	9.21 + 26.58*j*	28.10	163.2	173.2	168.2	2550	58	70	39	167	2383	2488
170	31.8	12.27 + 29.32*j*	0.30	12.27 + 29.62*j*	32.08	173.4	183.9	178.7	3600	66	79	51	196	3404	3412
180	35.8	15.06 + 32.49*j*	0.40	15.06 + 32.89*j*	36.15	183.8	194.5	189.2	4700	75	90	64	229	4471	4495
190	39.3	17.65 + 35.1 *j*	0.60	17.65 + 35.70*j*	39.80	194.1	205.0	199.6	5850	86	104	78	268	5582	5713
200	42.9	20.39 + 37.72*j*	0.80	20.39 + 38.52*j*	43.60	204.2	215.9	210.1	7100	98	123	93	314	6786	7100
210	46.4	23.1 + 40.22*j*	1.25	23.10 + 41.47*j*	47.50	214.8	226.5	220.7	8325	113	150	111	374	7951	8600
220	49.8	25.9 + 42.55*j*	1.75	25.9 + 44.3 *j*	51.30	225.0	237.1	231.1	10000	133	184	130	447	9553	10300

See Fig. 19

It may be that the rain was not sufficient to give such a lowering of e_0, although reports showed that there was a gentle drizzle at the two ends of the line and at Croton, part way along the line. The calculated e_v for Test 15 is 148.8 kv. For Test 18 the calculated e_0 is 110.4 and e_v 151.1 kv.

Fig. 19 gives a comparison of tested and calculated losses for Test 20. The test loss is the total loss less the transformer loss and line i^2r loss, (see Table XXIII). The calculated loss is plotted for the average of the high-tension voltages at Junction and Grand Rapids. Calculated e_0 is 107.5 kv., and e_v 148.6 kv.

In Fig. 20 are plotted the net corona loss (that is total test loss minus transformer loss at both ends of line and line i^2r loss) and the calculated corona loss for Test 42, (see Table XXIV). The losses are plotted against the average of the high-tension voltages at the two ends of the line as found by test. The calculated e_0 in this case is 108.9 and e_v is 149.3 kv.

The test readings of Tests 20 and 42 are subject to correction for instrument and instrument transformer errors, which would probably increase the values of kilowatts at the low points.

It is evident from a comparison of the test and calculated curves shown on Fig. 17 to 20 inclusive that while these curves are in general very much alike in shape and magnitude, still there are some marked discrepancies, and at the lower part of the curve in particular there are noticeable deviations. The test curves in all cases give a lower loss and have a more abrupt bend than the calculated curves. Peek explains this by saying that below e_v the quadratic law does not hold, that the loss here is due to irregularities and that the probability law governs. The probability law is stated:

$$P_1 = q^{-h\,(e_v - e^2)}$$

in which q is a coefficient depending on the number of spots and h is a coefficient depending on the size of the spots. This loss, therefore, depends on two coefficients whose value it is difficult to approximate.

Peek further states that it is of practical importance only to know the limits of the loss on this part of the curve and that e_0 should generally be the limit of the voltage on practical lines, as otherwise storm losses become excessive. This is very well taken and we have no doubt that Peek has stated the case correctly. The desirability of operating below e_0 is more evident than ever in view of the ground current described in this paper.

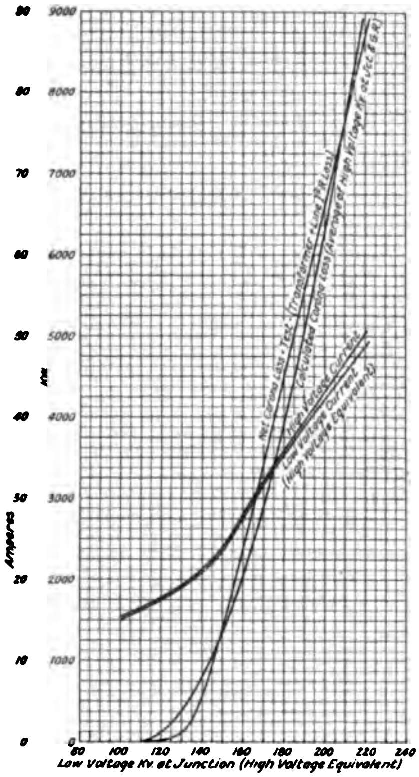

FIG. 20—COMPARISON OF CALCUALTED AND MEASURED LOSSES, TEST 42

Nevertheless a large number of systems are operating between e_0 and e_v and in figuring on new systems or extensions to old systems, it is frequently an economical problem whether to go to a larger size conductor or to stand a limited amount of corona loss. In these cases it is desirable to be able to calculate approximately the losses between e_0 and e_v, and to know whether the actual

TABLE XXIV

COMPARISON OF MEASURED AND CALCULATED LOSSES

TEST NO. 42

L. V. Kv. Junction (H. V. Equiv.)	L. V. Amp. Junction (H. V. Equiv.)	$i_1 + j\,i_2$	Trans. Exc. Cur. Assumed 90° lag	Line Current $i_3 + j\,i_4$	H. V. line cur. amp.	H. V. Kv. Junction calc.	H. V. Kv. Grand Rapids L. V. ratio	Avg. H. V. Kv. Jct. & Grand Rapids	Total loss from test	Trans. loss Jct.	Trans. loss G. R.	I^2R line loss	Total trans. + line loss	Net corona loss	Calc. corona loss Avg. H. V. Kv.
100	15.3	0.268 + 15.29j	0.12	0.27 + 15.41j	15.42	102.0	97.8	99.9	60	26	24	12	62	0	0
110	16.4	0.377 + 16.39j	0.15	0.38 + 16.54j	16.54	112.0	109.8	110.9	75	30	30	13	73	2	3
120	17.6	0.554 + 17.59j	0.20	0.55 + 17.79j	17.80	122.1	121.1	121.6	110	35	36	16	87	23	108
130	19.0	0.874 + 18.98j	0.24	0.87 + 19.22j	19.24	132.5	132.5	132.5	190	40	42	18	100	90	372
140	20.8	2.81 + 20.6 j	0.25	2.81 + 20.85j	21.02	142.5	143.9	143.2	675	46	48	22	116	559	788
150	23.5	5.88 + 22.8 j	0.26	5.88 + 23.06j	23.80	152.7	155.1	153.9	1525	52	56	28	136	1389	1344
160	27.7	9.00 + 26.18j	0.26	9.00 + 26.44j	27.95	163.2	166.2	164.7	2500	59	64	38	161	2339	2079
170	31.7	11.99 + 29.32j	0.30	11.99 + 29.62j	32.00	173.5	177.3	175.4	3560	67	73	50	190	3370	2952
180	35.4	14.86 + 32.12j	0.40	14.86 + 32.52j	35.76	183.8	188.1	186.0	4680	75	83	63	221	4459	3970
190	38.9	17.60 + 34.68j	0.60	17.60 + 35.28j	39.40	194.1	199.0	196.6	5900	85	97	76	258	5642	5120
200	42.3	20.12 + 37.20j	0.80	20.12 + 38.00j	43.00	204.1	209.5	206.8	7000	97	111	91	299	6701	6160
210	45.7	22.50 + 39.80j	1.25	22.50 + 41.05j	46.80	214.8	220.0	217.4	8130	112	133	108	353	7777	7840
220	48.9	24.45 + 42.38j	1.75	24.45 + 44.13j	50.50	225.0	229.8	227.4	9250	133	160	125	418	8832	9380

See Fig. 20

losses will be higher or lower than the calculated losses.

It is doubtful whether the present data are sufficient or of enough accuracy to use in checking the corona law, but it would seem desirable that the law be checked by actual line tests to determine whether or not there is any regularity or uniformity below e_v or whether the deduction of any general law is hopeless, as intimated by Peek.

CHANGE IN CAPACITANCE

Some discrepancies were noted in these tests between the calculated charging current and the tested charging current of the line, between the calculated voltage increase along the line and the measured voltage rise, also between the calculated ground current and the measured ground current. These quantities may be brought closer together by assuming that the corona which breaks down the air surrounding the conductor and makes it conducting has the effect of increasing the diameter of the conductor, thereby increasing the capacitance and decreasing the inductance

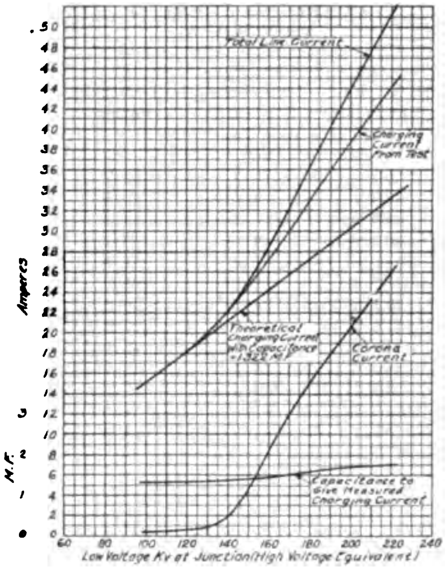

FIG. 21—COMPARISON OF CALCULATED AND MEASURED CHARGING CURRENT, TEST 20

from the calculated values. Also the harmonics placed in the voltage by the corona would naturally increase the charging current and the rise in voltage along the line.

In Fig. 21 (see table XXV) the total high-tension current of Test No. 20 is plotted, also the power and reactive components, the former being due to the corona loss and the latter being the charging current. The theoretical charging current with constant capacitance of 1.322 microfarads to neutral is also plotted. It will be seen that there is a constantly increasing deviation between the calculated and tested charging currents. The values of capacitance which would give the tested charging current are plotted and it will be noted that they begin at 1.322 microfarads and increase with increasing voltage.

TABLE XXV

COMPARISON OF MEASURED AND CALCULATED CHARGING CURRENT

TEST NO. 20

L. V. Kv. Junction (H. V. Equiv.)	Avg. H. V. Kv. Junct. & Gr. Rapids	Calc. chg. current $C = 1.322$ microfarads	Test chg. current	Capacity to give test chg. current microfarads
100	105.8	15.2	16.2	1.406
110	116.1	16.7	16.6	1.313
120	126.5	18.2	18.3	1.33
130	136.9	19.7	20.2	1.356
140	147.3	21.2	21.8	1.36
150	157.8	22.7	24.3	1.415
160	168.2	24.2	26.6	1.452
170	178.7	25.7	29.6	1.522
180	189.2	27.2	32.9	1.598
190	199.6	28.7	35.7	1.642
200	210.1	30.4	38.5	1.685
210	220.7	31.7	41.5	1.728
220	231.1	33.3	44.3	1.76

See Fig. 21.

On Fig. 22 are plotted the neutral ground current measured at Grand Rapids in Test 44, the neutral voltage at Junction and the calculated neutral ground current found from the neutral voltage and the theoretical capacitance of 1.322 microfarads from conductor

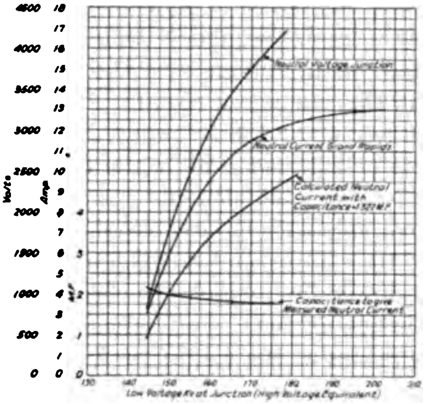

FIG. 22—COMPARISON OF CALCULATED AND MEASURED CURRENT IN GROUNDED NEUTRAL, TEST 44

to neutral, (see Table XXVI). The test values are greater than the calculated and tend to become increasingly greater at the higher voltages. There are also plotted the values of capacitance which would give the measured charging current. These are greater than 1.322 microfarads but appear to decrease with increasing voltage. This is not consistent with the preceding paragraph, in which the capacitance is found to increase with increasing voltage. If we assume that not all the neutral current is capacitance current, but part of it is true power, or corona current, then we can arrive at a reasonable capacitance curve.

TABLE XXVI

COMPARISON OF MEASURED AND CALCULATED NEUTRAL CURRENT
TEST NO. 44

L. V. Kv. Junction (H. V. Equiv.)	Volts Neut. to Ground	Calc. neut. current $C = 1.322$ microfarads	Test neut. current chg.	Capacity to give test neut. current microfarads
145	900	2.02	3.25	2.128
150	1800	4.04	6.0	1.963
155	2475	5.55	8.0	1.903
160	3000	6.73	9.6	1.884
165	3425	7.68	10.75	1.849
170	3750	8.42	11.5	1.806
175	4030	9.04	12.0	1.754

See Fig. 22.

We, however, introduce a new element into corona loss, namely a triple-frequency component.

The actual rise in voltage over the line is apparently greater than the calculated rise, for example the tested rise in Test No. 42 at 180 kv.(equivalent high voltage) is 4300 volts or 2.34 per cent, while the calculated rise is only 600 volts or 0.33 per cent.

The above calculations are based on a capacitance of 1.322×10^{-6} farad and a reactance of 41.5 ohms for the 101.5-mile line, which are the calculated values for the particular size and spacing of conductor. Now if the radius of the conductor is increased to give increased capacitance as shown on Figs. 21 and 22, most of the calculated results show a much closer agreement to the tests. From this it appears that the radius of the conductor increases with the corona, perhaps being a function of the excess of the applied voltage over the critical corona voltage. The rise in voltage along the line is only partly accounted for in this manner, and harmonics may play a controlling part here.

CONCLUSIONS

Corona losses at approximately 210 kv. at the generating end and 225 kv. at the receiving end of a 100-mile line of 110,000-cir. mil conductor have been recorded.

The losses in general follow Peek's law, with some deviation especially at the lower voltages, where the tested loss is as a rule less than the calculated.

A current in the grounded neutral was encountered which at the higher voltages was about 40 per cent of the line current. This current begins at about the normal line voltage. It is apparently due to the corona, which causes a pulsation in the voltage wave and a triple-frequency current to flow through the capacitance to ground and back through the grounded neutral.

The line charging current, the current in grounded neutral and the rise in voltage along the line are all greater than calculated from the geometrical capacitance. This may be accounted for by an increased capacitance due to increased diameter of conductor caused by corona. Harmonics introduced into the voltage wave by the corona may contribute to the effect noticed.

The tests indicate a difference in corona loss with the neutral grounded and isolated, probably due to the flow of triple-frequency current in one case, and the distortion of voltage by triple-frequency component in the other.

The danger of overvoltage across legs and between neutral and ground with Y-Y connection is shown by Test 24.

The tests clearly indicate the desirability of operating a transmission line below the corona voltage, thus avoiding corona loss and its accompanying effects.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 22, 1921.

NOTES ON OPERATION OF LARGE INTERCONNECTED SYSTEMS

BY L. L. ELDEN

Edison Electric Illuminating Co. of Boston

INTERCONNECTIONS have been made between the Boston Edison systems and the systems of the Eastern Massachusetts Electric Company and the New England Power Company, these two companies serving territory adjacent to that served by the Boston Edison Company.

Connection with the former company is effected by a 13,800-volt cable connection between nearby substations of the two companies where transmission facilities were suitable for an interchange of power. The capacity of this connection is limited to 3000 kv-a. by the capacity of the transformers installed in the Eastern Massachusetts Company's substation. The principal generating station of the Eastern Massachusetts Company being located at Salem, Mass., the connection with this station is finally completed via 22,000-volt aerial and underground lines of the E. M. E. Co. Any energy interchanged by the two companies passes through three substations on the Edison system and two substations of the E. M. E. Co., all of which supply local distribution areas.

The connection with the New England Power Company comprises a special transmission line including 25,000-volt underground transmission, 66,000-volt aerial transmission over private right of way, and two banks of step-up transformers each comprising three 5000-kv-a., three-phase, oil-cooled outdoor-type transformers. Switching facilities permit the transformers to be arranged for operation for transmission capacities of 5000 kv-a., 10,000 kv-a., and 15,000 kv-a., respectively as load requirements may dictate.

Connection is made with the N. E. P. Co. at its Clinton substation, from which 66,000-volt lines extend to the several sources of power of that company. These include not only their own hydro and steam stations, but in addition connections with the systems of a number of other public utilities and industrial corporations with which it has reciprocal arrangements for purchase or sale of power.

The physical arrangement of the interconnections with both companies is shown diagrammatically in Fig. 1.

The operation of the connection with the E. M. E. Co. has been uniformly satisfactory, barring some early difficulties initially encountered in adjusting the frequency of the two systems to the required standards and to difficulties encountered in securing suitable relay adjustments on the interconnecting lines. With the elimination of these minor troubles, no other difficulties of moment have been encountered in the daily operation of the two systems other than occasional operation of the relays to disconnect the systems when serious trouble has occurred on either which has resulted in a transfer of energy in excess of the rated capacity of the interconnection. Under normal conditions the E. M. E. Co. is the purchasing company and on several occasions the line has enabled the Boston Company to assist the E. M. E. Co. in emergencies when troubles have occurred at the latter's generating station.

In the operation of the N. E. P. Co. more difficult conditions have been encountered due to the nature and arrangement of the line connections and to the more frequent occurrence of transmission troubles incident to the large amount of 66,000-volt aerial construction exposed to lightning and other line troubles.

Violent fluctuations on both systems have occurred upon the occasion of short circuits on either, the tie line usually opening and separating the systems on such occasions. The extent to which these troubles have affected either system has been entirely dependent upon the generating capacity in service and load on each system at the time of trouble, and in a few cases the results have been rather serious.

Experiments with various relay adjustments have effected some relief, although it now appears that heavy shorts on either system will continue to affect the other in the future as in the past, since there appears no means readily available to eliminate such effects without unfavorably affecting the voltage regulation of the tie line.

In the initial operation of this interconnection certain difficulties developed due to variations in frequency on the N. E. P. Company's system. That company

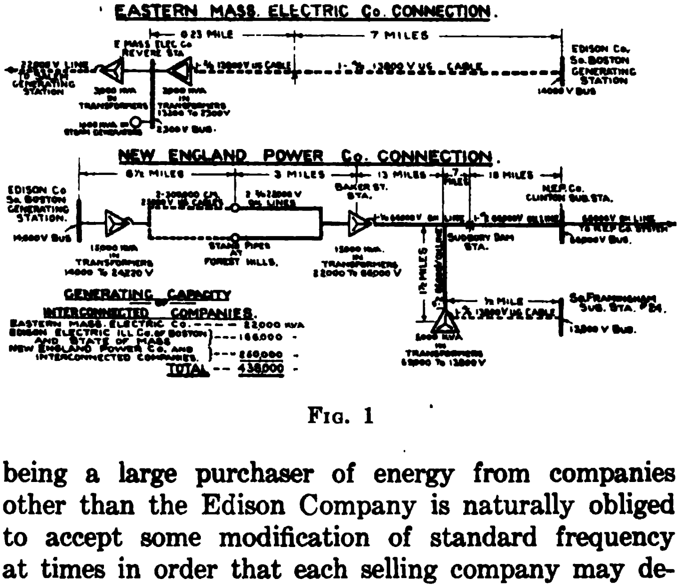

Fig. 1

being a large purchaser of energy from companies other than the Edison Company is naturally obliged to accept some modification of standard frequency at times in order that each selling company may deliver the power required for each day's operating schedule. These variations have caused some difficulty in effecting a proper division of the load between the various systems due to the desire of the Edison Company not to depart from its past practise of maintaining a standard frequency of 60 cycles at all times. This is accomplished through the use of the Warren clock for regulating purposes, and has become an important factor in the operation of the system due to the extensive use of Warren clocks as time keeping devices by the company's customers. The company has, therefore, unintentionally drifted into the undesirable position of operating a "time keeping" system which has been so satisfactory to certain users that it has been employed in some locations in place of Western Union time service.

Operation in connection with the N. E. P. Co. has caused some troubles in this direction, although, in general, time keeping errors are small and are corrected by minor changes in frequency over a given period or until normal time conditions are restored.

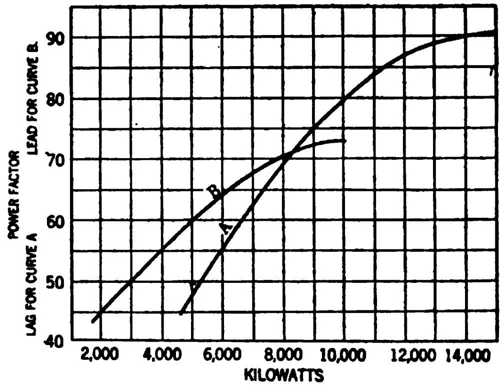

Fig. 2—Power Factor Curves of Interconnecting Transmission Line between the Edison Electric Illuminating Co. of Boston and the New England Power Co.

Curve *A*—Edison Co. supplying power to the N. E. P. Co. at the Edison South Boston Station.

Transformers at Baker St. station connected 22,000 to 66,000 volts.

Curve *B*—Edison Co. receiving power from the N. E. P. Co. at the Edison South Boston station.

Transformers at Baker St. station connected 60,000 to 22,000 volts.

The connection with the N. E. P. Co. as originally conceived was constructed for the delivery of energy to that company, there being no thought of transmitting energy in the reverse direction to the Edison Company beyond substation No. 24 at South Framingham. Variable tap connections were, therefore, provided on the step-up transformers at Baker Street Station to secure proper control of power factor and voltage regulation which have enabled us to secure the results indicated by curve *A* in Fig. 2. It later developed that the Edison Company could purchase so called "freshet power" at times from the N. E. P. Co. under favorable terms, and in accordance therewith a contract was executed for the purchase of such power for delivery during off-peak periods, or when otherwise available.

With the transformers connected for delivery of power to the N. E. P. Co. the conditions for reverse operation were very unfavorable as regards voltage regulation and control of power factor, requiring rearrangement of tap connections to change the ratio from 22,000/66,000 to 22,000/60,000 volts, this arrangement resulting in operating conditions illustrated by curve *B*, when energy is received at L Street Station or at South Framingham, station 24. This condition may be improved by the addition of taps to the high-voltage winding of transformers at L street station or at Baker Street station, the former location for the change being preferable.

To make changes in tap connections rapidly, some special operating mechanism will be required other than what is now available. Such apparatus should preferably be designed for remote control operation. Under present conditions a change in tap connections requires about eight hours and involves a considerable expense. Other methods of accomplishing the same end might include the use of induction regulators or synchronous condensers if the results accomplished would justify their use. It will be obvious that the use of either form of equipment will make it possible to materially improve curves *A* and *B* under any loading conditions, such improvement being of considerable advantage.

Like all transmission companies serving an extended area, the N. E. P. Co. in the past has had to contend with wide variations in voltage in the remote parts of its system, these in part being due to insufficient line capacity and to the effect of loads of low power factor. During the past two or three years these conditions have been materially improved by the reconstruction of certain lines and the installation of a number of synchronous condensers of large capacity at strategic points in the system where control of voltage regulation would be particularly effective. In the operation of the three systems as interconnected, no special provisions have had to be made for voltage regulation other than to provide lines of suitable capacity and suitable tap connections on step-up transformers in the tie lines to secure delivery voltages suited to loading requirements. In the case of the N. E. P. Company's connection, regulation of voltage may be accomplished to a limited extent by increasing or decreasing the number of cables and transformers in service.

The successful operation of interconnected systems appears to require only the complete cooperation of load dispatchers in control of system operation. Modification of existing methods will frequently be found effective in eliminating troubles which occur and in general a careful study of any disturbing factors will usually suggest means for relief in one form or another.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 22, 1921.

MODERN PRODUCTION OF SUSPENSION INSULATORS

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AND
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Westinghouse Electric & Mfg. Co.

ABSTRACT OF PAPER

This paper pictures the progress made during the past few years in the production of electrical porcelain. The information covers: First: The engineering and works organization. Second: The manufacture. Third: Design and test.

THE DEVELOPMENT of transmission line networks has progressed even more rapidly than most of the pioneers in transmission engineering anticipated. No doubt, the development has been materially affected by the increased cost of fuel, which has encouraged the engineers to develop available water power sites. Perhaps, one of the most influential factors has been the necessity of irrigating the fertile lands of the Pacific Coast States. Electricity from water power sources can be generated and transmitted to the farming districts and can be economically employed to pump water, to heat the houses, and to operate the household appliances.

The quality of electrical porcelain, although sufficient to properly insulate low-tension lines, proved entirely unsatisfactory when it became necessary to increase the transmission line voltages. The first thought of the engineer was to emphasize the mechanical strength, but in so doing, he sacrificed other characteristics. He believed the insulators should withstand handling, impact blows from rifle shooting, etc.

He believed suspension insulators must be mechanically strong to prevent dropping the line in service.

There are numerous reasons why the quality of electrical porcelain did not keep pace with the progress in transmission engineering.

First: There were few transmission networks when electrical porcelain was first applied to high voltages.

Second: The demand for electrical porcelain was extremely variable. When a transmission project was under consideration, it was necessary to supply a large number of insulators in a short time. After the material for this project was manufactured and supplied, the manufacturer could not keep a continuous production of high-tension electrical porcelain in his factory. He must again manufacture low-voltage insulators and dry process material such as knobs, tubes, cleats, etc.

Third: The type of labor from which the manufacturer drew his supply had never been trained to appreciate the advantages that can be derived from labor saving devices. They had been very adverse to accepting any new type of machinery, perhaps, more so than the usual workmen.

The most regrettable and fundamental reason of the slow development of electrical porcelain has been the lack of cooperation between the ceramic and electrical engineers. The ceramic engineer was occupied with manufacturing problems only. The electrical engineer, on the other hand, was usually a consulting engineer because the transmission company itself could not afford to assign an electrical engineer to the application of electrical porcelain. The design recommended by him would incorporate his ideas and opinions. He would probably not consult with the ceramic engineer to determine the limitations in manufacture. The varied line of designs which every insulator company carried a few years ago is indicative of this condition.

ENGINEERING ORGANIZATION

The increased demand for electrical porcelain has enabled the manufacturer to command men of greater engineering ability. These men have sufficient training to appreciate the advantages that are gained by close contact between the manufacturer, the engineer, and the consumer. The organization of the modern electrical porcelain manufacturer is built on close cooperation between engineers who have supervision of the works and the application of the finished product.

The ceramic research laboratory operated as a separate department, is of vital importance. Its function is to investigate the present commercial raw materials; new sources of supply; the proportioning of ingredients; the glaze, etc. This laboratory has complete equipment, a portion of which constitutes a miniature clay working plant. This enables the engineer in charge of the laboratory to produce experimental bodies and determine such properties as dielectric strength, mechanical strength, both tensile and impact, resistance to temperature changes, firing range, and shrinkage. Fig. 1 will give a general idea of the completeness of this laboratory.

In connection with this, the proper selection of materials is of extreme importance. For example, we find different grades of clays in the same deposit, some of which will give considerably better results than others which may be only a few feet removed from them in the same strata. The ball clays which are now used contain a considerable amount of lignite and organic matter. This type of clay vitrifies at a much lower temperature than some of the cleaner ball clays and at the same time is a very tough and strong material, such as is necessary to overcome the severe stresses which are encountered in manufacturing the complex insulator shapes. The low vitrification temperature is especially desirable because it assists the feldspar in the vitrification of the product and insures a greater firing range with less danger of underfired or overfired material.

English ball clay has always satisfied these characteristics in the past to the greatest possible extent. Laboratory investigations in recent years have discovered some promising American clays and at the present time experiments are being made on some clays in an undeveloped field in this country which seem to be even superior to the English clays. The laboratory is, therefore, continually investigating new materials and with the continual progress that has been made, it would not be too optimistic to predict that we may at some time find materials which will improve the present product.

The proportioning of feldspar, flint and clay has been given very careful consideration in the research laboratories. The present commercial body is based on the results of this work. It is possible to obtain porcelain bodies from these materials in which certain characteristics predominate. However, since the application of electrical porcelain is very wide, it is necessary to sacrifice high mechanical strength or very high dielectric strength in order to obtain a body which will be satisfactory in all applications.[1]

FIG. 1—CERAMIC RESEARCH LABORATORY—GENERAL VIEW

A second ceramic laboratory is maintained at the works; the function of this department being to properly apply information obtained in the research laboratory to the commercial product and to see that all

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[1] "Experimental Investigation of Porcelain Mixes," G. I. Gilchrest and T. A. Klinefelter, *The Electric Journal*, March 1918, p. 77.

departments of the works function properly, *i. e.*, that the proportioning and mixing of the ingredients is uniformly performed; that the material is properly prepared for the manufacturing processes; that the speed of the machine in forming and trimming the ware is correct; that the firing conditions are uniform, etc. There is very close contact at all times between the two departments and by the continual exchange of ideas each is informed of the other's activities.

One of the most important activities of the works department is the testing of all raw materials as they are received, in order to insure uniformity of the material and the finished product. Feldspar has become so variable in recent years that the old method of assuming that the feldspar will always be uniform in quality is now a hazard. Each shipment must be tested especially in regard to fusibility, for it is this property which has become most variable. A sample is obtained from the car as soon as it is received; the flux value established and if not in accordance with purchasing specifications, it is rejected before coming in contact with any of the material in the bins. The remaining materials are tested in a similar manner. Other routine tests are the determination of the moisture content and non-clay substance in the clays from day to day so that this variable can be adjusted for on the scales and consequent uniform mixture produced.

The electrical engineering department functions in a similar manner. The consulting staff of the company is available when problems arise covering the design and application of the finished product. The Engineerign Department at the works supervise routine testing and the application to the product of suggestions that are made by the consulting staff. It is also a function of the Engineering Department at the works to give careful thought to any suggestions from the field which are based on the inherent design of the product.

MANUFACTURE

The modern electrical porcelain works are the result of the changed conditions and indicate what closer cooperation and a more scientific organization have accomplished. This is most forcibly illustrated in the slip house where the materials are mixed. This department was formerly found in the most dilapidated part of the works and gave an appearance which was repulsive to the intelligent class of workmen. In other words, it was located and operated under conditions which indicated that it was an unimportant department.

Today we find the reverse of these conditions. This department is now considered one of the most important if not the most important, part of the works and the general design and operating conditions are carried out accordingly. It contains the latest type of machinery, with special attention given to labor saving devices in order to make the processes more mechanical and eliminate the human factor wherever possible, with resultant greater uniformity. The department is well lighted and presents a sanitary appearance which is in keeping with the kind of work which is carried on.

FIG. 2—EQUIPMENT TO HANDLE MATERIAL FROM CARS

The raw materials upon arrival after tests have been completed are unloaded in an efficient manner by means of suitable conveying equipment and stored in large bins to prevent contamination with undesirable substances which are carried about in the air in industrial centers. (Figs. 2 and 3.) These bins are directly adjacent to the mixing department and the same conveying equipment can be used to bring the material into a location where it can be conveniently used in the process. (Fig. 4.) The materials are weighed with the minimum amount of manual labor and in such a way that the workmen cannot easily make an error of any consequence. The apparatus is built compactly so that the little transportation which is necessary is performed mechanically. (Figs. 5 and 6.)

The feldspar and flint which were formerly mixed together with the clays in the blungers are now first ground in ball mills in the wet state sufficiently to produce a fineness which has been found to be necessary and which cannot be obtained in the dry state which is the means employed by the producers. (Fig. 7). The cost is large, but the results that are obtained more than repay the manufacturer for this extra operation. The finer structure of the feldspar and flint gives a better mechanical mixture which makes these materials more active in their properties and effects a better performance of the body throughout the manufacturing process, especially in the firing operation. Vitrification begins at a lower temperature and a longer

FIG. 3—MATERIAL STORAGE BIN

firing range is, therefore, obtained, or in other words, greater variation of temperature in the kilns is permissible without detrimental effect on the fired product. It is obvious that the danger of underfired ware is, therefore, materially lessened and on account of the improved methods of kiln firing, an underfired piece of electrical porcelain in the factory is indeed rare.

FIG. 4—MATERIAL BINS FOR DAILY CONSUMPTION

FIG. 5—METHOD OF TRANSPORTING MATERIAL TO MIXERS

Porcelain made from ball milled feldspar and flint is more homogeneous in structure and gives a very smooth fracture. It has a higher dielectric and mechanical strength, although in the case of the latter there is a limit to the fineness which will increase the value of this property. In general it has been very definitely proved that this operation is one of the greatest progressive steps in recent manufacturing developments.

FIG. 6—MATERIAL PROPORTIONING EQUIPMENT

FIG. 7—GENERAL VIEW OF BALL MILLS

While these materials are being milled the clays are mixed in blungers. The design of the blunger has been changed in recent years and machines are now on the market which are much more efficient and rapid in their performance. Complete slaking of the clays is assured in this type of mill, so that lumps of unmixed clay are not found in the blunger when it is discharged, with consequent variation of the mixture. This has been accomplished by means of double rotating mixers which prevent any centrifugal force action and consequent collection of the particles at the edge of the tank which is so commonly found in the old type of blungers. (Fig. 8). The feldspar and flint after being milled are added to this blunged clay slip and the entire mixture is then blunged sufficiently to produce as perfect a mechanical mixture as is possible.

The amount of water which is added to the clay flint and feldspar in the blungers and ball mills is carefully controlled by means of self-regulating water tanks above these machines. The amount of water in each tank is set from day to day in order to make proper adjustment of the water contained in the materials themselves. At the same time the water is heated to the proper temperature and kept constant by means of automatic temperature regulators. In this way the liquid in the ball mills and the blungers is always of the same density and temperature which is essential in pumping uniform filter cakes and in keeping the plastic clay body at the proper temperature. (Fig. 9).

FIG. 8—VIEW OF BLUNGER DETAIL

The clay slip is passed over a double set of lawns, the first lawn being of a coarser mesh than the second. This distributes the amount of residue on each lawn and lessens the danger of breaking the lawn and consequent passing through of coarse materials. After screening, the material accumulates in cisterns, which are now built of considerable size and number. The object in view is to provide storage for the clay slip after it has completely passed through the mixing process where the air which is contained can be eliminated, giving a more homogeneous clay slip.

Fig. 9—General View of Section of Slip House

The pumps which force the material from the cisterns to the filter presses are designed to preserve the uniformity of the clay slip. The pumping action of the piston is now transmitted upon a diaphragm in order to isolate the clay slip from the pumping action. Mixing of air in the slip at this point is, therefore, impossible and at the same time it does not get in contact with the oil in the cylinders. If the air is removed in the cisterns the filter cakes which will be produced at the press will be solid and contain no blebs of any kind. Furthermore, the pumps will not produce a higher pressure than what they are set for, so that the filter cakes are always uniform in water content and working qualities.

With such filter cakes the beneficial effect of aging is largely reduced and it has actually come to a point where equal results can be obtained from the manufacture of insulators from clay directly from the filter presses. Furthermore, ball clays have already passed through considerable natural aging and weathering conditions, and since they compose the major part of the clay content, the body is not noticeably improved by a small amount of artificial aging. For this reason, aging would have to extend over a period of at least one month before any noticeable results would be obtained in the product and this, of course, necessitates a storage capacity which is not commercial in this country.

FIG. 10—FORMING MACHINE

In pugmilling the material in preparation for the moulding process, the more modern and scientific methods of mixing have overcome many of the troubles which formerly were traced to the pugmill. It is now much simpler to produce a satisfactory material from the pugmill and with the improvements in this machine which have been obtained, the ever-present trouble with laminations has been largely overcome. If the material leaves the pugmill free of laminations and with no air contained, the success of the moulding of the insulators is practically assured.

In forming the insulators machine operations are used entirely. This method has proved to be superior to the jiggering process, because of the greater pressure which is obtainable and the elimination of the human factor with the consequent possibility of a non-uniform product. A greater production can be obtained from the machines with an improvement in quality. (Fig. 10.)

FIG. 11—CONDITIONING DRYER

By means of modern conditioning dryers, the insulators can be rapidly and uniformly dried to the stage where they can be removed from the moulds without distortion. (Fig. 11.) They are then ready for trimming which perfects the insulators into their final form. In drying the product to the bone-dry stage the modern tunnel dryer has given the manufacturer a means of drying under carefully controlled conditions as to temperature and humidity. This is of primary importance in drying the material with the minimum amount of strain and at the same time provides a method which is labor saving. A truck carries the insulators through the dryers and they are then taken directly to the glazing department where the glaze and sand coatings are applied.

The color of the glaze has proved of some assistance in indicating the degree of heat treatment received in the kilns. This method, however, has its limitations and is not completely satisfactory.

Recent experimental work in the laboratory has shown that there is a possibility of having the glaze indicate firing treatment by means of its luster. If this glaze can be made satisfactory to the trade, there is no doubt that it will provide a very accurate means of determining the degree of heat the insulator has received in the kiln.

FIG. 12—TYPICAL PHOTOGRAPHIC RECORD OF KILN FIRING

In firing the material, various steps are taken to insure a uniform product such as the location of numerous cone plaques in all parts of the kilns and the use of the electric pyrometer with recording chart which is operated according to a standard firing curve in order to standardize the entire firing cycle. The cone plaques are marked according to their position in the kiln, so that upon removal if any show that insufficient heat has been received, the insulators which are immediately adjacent to such a cone plaque can be segregated and refired. At the same time all of the cone plaques from one kiln are gathered together and assembled in a rack which is photographed together with the pyrometer chart for the kiln. This gives a complete and permanent record of the firing of each kiln and also determines the efficiency of each kiln and of the kiln firemen. (Fig. 12.)

Natural gas, coal and more recently oil are used as fuels. Natural gas is undoubtedly the most desirable fuel because of the ease of control and comparatively low temperatures in the fire boxes. The works are located in the natural gas fields where the supply is abundant. However, protective measures by the gas producers have limited the supply during very severe weather. It, therefore, became necessary to resort to other fuels which has brought about the use of oil. This fuel has proved to be much more satisfactory than coal, because its control can be as easily manipulated as that of gas and the only difficulty encountered is the excessive local heat of the oil flame. This has been overcome by the use of superior refractories so that equal results can be obtained with oil, the only difference being in the cost. Coal is, of course, cheaper than oil as far as cost of fuel itself is concerned, but the ease of control and the more uniform and satisfactory results which are obtained from the oil with consequent better quality of finished product has proved conclusively that the final cost of production with oil is cheaper than coal. Combination oil and gas burners are used so that gas can be used whenever available and the change to oil can be made at any time without loss of heat in the kiln. (Fig. 13.)

Fig. 13—Combination Oil and Gas Burner

ROUTINE TESTING

The porcelain parts are carefully inspected as they are drawn from the kilns. Parts having cracks or other defects that can be detected visually are immediately scrapped. Thereafter the parts are subjected to a 60-cycle flash-over test. The characteristics of the transformer are such as to give a 60-cycle voltage with a superimposed high-frequency voltage. Fig. 14 is indicative of the test.

The insulators having cemented hardware are then assembled with neat Portland cement and placed in a closed chamber where they are subjected to an atmosphere of steam during the initial set of the cement. The insulators are then given a routine mechanical test at a load dependent upon the inherent design of the insulator and its application. After the routine mechanical test the assembled insulators are again subjected to a flash-over test, similar in characteristics to that applied to the porcelain parts. It is not necessary, of course, to give the suspension insulators not assembled with hardware a second electrical test.

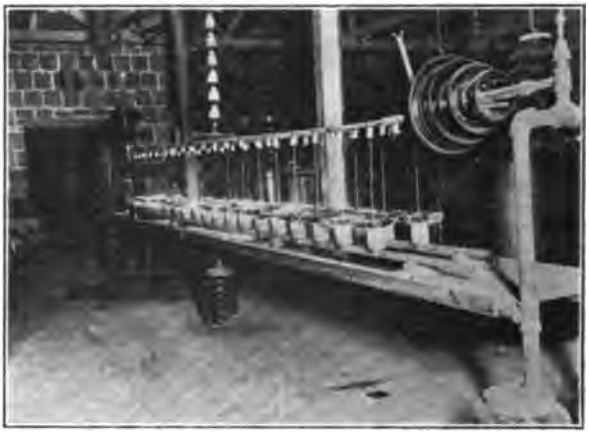

FIG. 14—ROUTINE ELECTRICAL TEST OF PORCELAIN PARTS

DESIGN TESTS

It is very difficult to provide tests which will duplicate service conditions since it is impossible to reproduce in short periods of time in the laboratory the temperature cyclic changes which will occur in line service. Although engineers who are familiar with the testing of electrical porcelain do not feel satisfied with laboratory tests, nevertheless all agree that the design which passes severe laboratory tests has apparent merits.

Many articles have been published in the engineering periodicals during the last few years discussing types and causes of failures of electrical porcelain. These articles have been presented by men in the field and by representatives of the manufacturers. In general, engineers agree that the failure of suspension insulators having cemented hardware is largely due to two causes. First: Porosity. Second: Mechanical stresses.

FIG. 15—DIELECTRIC FIELD OF CAP AND PIN SUSPENSION INSULATOR

No doubt, porosity was one of the vital factors in causing the failure of the suspension insulators manufactured prior to about 1914. It is not necessary to go into a discussion of the causes of porosity. A brief statement that the porous insulator is an insulator that is underfired is perhaps sufficient. Of course, if we consider the problems of the manufacturer it may be that the material is not properly fired, that the ingredients are not properly proportioned or ground, etc. The subject of porosity affords sufficient information for an article. Now that due consideration is given to all of these factors, the more progressive manufacturers have practically eliminated porous ware.

Second: Mechanical stresses have always been instrumental in the failure of suspension insulators having cemented hardware. Although porosity may have been a vital factor prior to about 1914, mechanical stresses have continued to give trouble and are more difficult to eliminate. The subject of mechanical stress has also been very generally discussed in the engineering periodicals and everyone is familiar with the present assembly methods and the very gratifying results obtained. The elimination of the mechanical stresses caused by temperature changes without doubt, depends upon first, the design; second, the assembly of the hardware and porcelain; third, the setting of the cement under temperature and moisture conditions, etc.

It is impossible to give in any detail an analysis of the design tests which our engineers have made during the past few months. In order to give a general picture of the problems involved, the various lines of research are indicated by the following paragraphs.

ELECTROSTATIC FIELD

The cap and pin suspension insulator or the interlinked type insulator do not represent ideal electrical designs from a consideration of the electrostatic field. However, it is necessary in nearly all commercial designs to sacrifice some efficiency of electrical design to produce a commercial unit which will be economical under the average conditions, *i. e.*, a unit which will perform satisfactorily in dry climates, or in humid climates, indoors, outdoors, etc. The design of insulators based on theoretical principles is discussed in considerable detail in a paper presented before the American Institute in June 1918[2]. It is not

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[2] *Application of Theory and Practise to the Design of Transmission Line Insulators*, G. I. Gilchrest, TRANS. A. I. E. E., 1918.

necessary to go into a detailed discussion of the electrostatic design of suspension insulators since everyone is somewhat familiar with the theoretical principles.

For general information and interest, Figs. 15 and 16 are included. Fig. 15 pictures the electrostatic field of the cap and pin suspension insulator; Fig. 16 pictures that of the interlinked insulator. To obtain the most efficient electrical characteristics the lines of of force in the area about the insulator should be either parallel or perpendicular to the surface of the insulating material. It is interesting to note the difference in the field about the two suspension insulators.

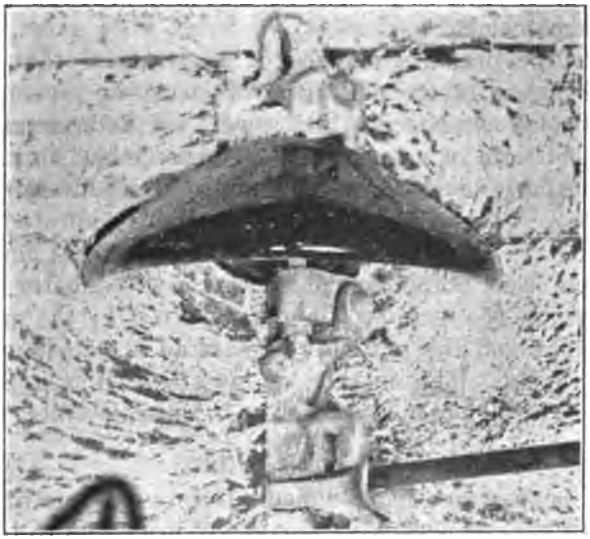

FIG. 16—DIELECTRIC FIELD OF INTERLINKED INSULATOR

As a matter of fact, the distribution of the stress in the air about the interlinked type insulator is materially better than the distribution about the cap and pin type. This perhaps, explains why the interlinked type insulator has a flash-over comparable to that of the cap and pin type, although there is more corona formation around the interlinking hardware of the interlinked insulator below flash-over than about the cap and pin. It is probable, however, that the corona formation does not build up as rapidly over the surface of the insulator sheds as in the case of the cap and pin because of the more favorable electrostatic field.

Several authors have discussed the advisability of obtaining an insulating material having a low dielectric constant or a high dielectric constant. Obviously it is possible to divert further from the theoretical principles in the design of the insulator if the material has a dielectric constant approaching that of air. Electrical porcelain has a dielectric constant of approximately five compared to the dielectric constant of one of air. It is impossible to vary this constant to any great extent by changing the composition of electrical porcelain.

To the practical engineer it may appear that investigations of the field form of insulators are of no particular consequence. However, the determination of field form of a separate unit or assembled units is particularly useful in determining the concentration of stress. Although experimental methods indicated in the figures do not give the distribution of stress, nevertheless when obtaining the results the investigator can determine the sections of high local stress by the manner in which the particles of material act during the experiment. This method of investigation is applicable to strings of units as well as to separate units.

MECHANICAL STRESS

It is, perhaps, more difficult to provide tests to indicate the comparative resistance of insulators to temperature changes. We have followed a number of lines of investigation and will very briefly discuss each line.

SPECIAL DESIGN OF EYEBOLT

A theoretical analysis of the mechanical stress transmitted to the porcelain by the cemented hardware indicates clearly that the expansion of the eyebolt is probably the most serious factor. To definitely determine this in the laboratory, porcelains assembled with caps alone, with eyebolts alone, and without hardware, were tested by alternate immersions in hot and cold water baths. The porcelain parts assembled with eyebolts alone failed under the same severity of tests as the assembled insulators. The porcelain parts without hardware and with caps alone did not fail under any of the temperature change tests.

Several modifications of the solid eyebolt were then considered and two special types were produced and tested. These were assembled with identical porcelain parts and metal caps and under the same conditions. The two modifications consisted of (A) an eyebolt having two drop forgings assembled with a porcelain sleeve. (B) eyebolt having a one-piece drop forging with a metal sleeve into which the eyebolt could be turned.

These two special designs were compared directly with standard design having the solid eyebolt. The insulators were tested by immersing them alternately in water baths maintained at zero and 100 degrees centigrade. The periods of immersion were varied from one minute at the start to ten minutes at the end. The insulators were not under mechanical load during the tests. Briefly the results of this were as in Table I.

TABLE 1

	Number of Failures under Test								Passing all Tests
	1	2	3	4	5	6	7	8	
Solid Eyebolt.........	1			4	5		2	2	2
Eyebolt with porcelain sleeve............						1	2	6	5
Eyebolt with metal sleeve............									14

From an analysis of this table it is very apparent that the insulators having a separable metal sleeve resisted the mechanical stresses from temperature changes more successfully than the insulators having the solid eyebolt or the eyebolt with the porcelain sleeve. Also the insulators having the eyebolt with a porcelain sleeve resisted the mechanical stress better than the insulators with the solid eyebolt.

The inherent design of these insulators is such that the ultimate strength and the combined mechanical and electrical strength are practically identical. Under combined electrical and mechanical test the type with the solid eyebolt gave the highest results averaging between 10,000 and 11,000 pounds. The insulator with the eyebolt having the porcelain sleeve averaged between 9,000 and 10,000 pounds the insulator having the separable metal sleeve averaged between 8000 and 10,000 pounds. The lower strength of the two special types was due largely to the lower strength of the eyebolts. Later, additional samples were made which gave practically the same combined mechanical and electrical test as the solid eyebolt type.

After making these preliminary tests with insulators not subjected to mechanical load, it was thought particularly desirable to have similar tests made with the insulators under tension. The three designs were again tested under a series of temperature changes at 4000 and 5000 pounds load. During the immersions, the insulators were assembled in strings in series with a dynamometer as indicated in Fig. 17.

The load on the insulators shifted somewhat during the transfer from the hot water bath to the cold water. This amount of change varied for the different units and is, perhaps, somewhat indicative of the rigidity of the assembly. It is obvious that the insulator showing the least change of load must have the greatest resilience in its assembly.

	Load Shift under		Per cent Loss	Combined Electrical and Mechanical Strength
	4000 lb.	5000 lb.		
Solid Eyebold (corrugated)	700	625	50	11,350
Solid Eyebolt (sanded)	425	375	40	11,640
Metal Sleeve	750	500	20	11,090
Porcelain Sleeve	825	525	30	10,760

All of the failures occurred during the test under 5000 pounds load. In these tests the insulator having the eyebolt with a metal thimble again proved superior. A portion of the porcelain parts assembled with the solid eyebolt had corrugated gripping surfaces and a portion sanded surfaces. The insulators with the sanded surfaces proved superior in resisting temperature changes and gave less change in load during test, indicating that the sanded surface affords greater resilience than the corrugated surface.

Although the insulators with the special design of eyebolt proved superior to the type with the solid eyebolt, it is not possible to determine in the laboratory whether or not service results will be particularly better. We have, however, sufficient of each type now in transmission line service to determine, we believe, in the next two or three years, whether or not there is any advantage in these modifications. However, the improvements in design and assembly have resulted in insulators of solid eyebolt type, that will undergo these laboratory tests without failure.

FIG. 17—TESTING INSULATORS BY TEMPERATURE CHANGES

SPECIAL CEMENT

A number of investigators have contended that Portland cement may be the cause of some of the line failures. They contend that the cement gradually crystallizes and that it may transmit mechanical stresses to the porcelain. Moreover, the coefficient of expansion of cement is greater than that of porcelain and this may increase the hazard. In an attempt to lower the coefficient of expansion of the cement ground porcelain was mixed with the cement. The materials were ground together in ball mills in the proportion of one part porcelain to three parts cement. Standard tensile briquettes made from this mixture gave an average of 327 pounds after 48 hours.

FIG. 18—60-CYCLE WET FLASH-OVER OF ASSEMBLED STRING

Suspension insulators assembled with this material gave the same ultimate mechanical strength as when assembled with neat Portland cement. The results of these initial tests are so encouraging that the investigation will be continued.

ABRASION TESTS

Probably porcelain that is most resistant to grinding will better resist weathering conditions, the action of acid, moisture, etc. Occasionally, sections from commercial and special insulators are tested to determine their comparative resistance to abrasion.

As an example of the variation, a test of pieces from three commercial insulators of different manufacture is given. The samples were ground under the same pressure and the same area subjected to grinding. The loss in grams per square inch of surface for each minute of grinding was:

No. 1—0.075
No. 2—0.080
No. 3—0.087

It is very apparent that there is a considerable variation in the mechanical structure. Undoubtedly, the individual insulators of any one manufacturer would vary, but the difference is also due to some extent to the materials used and to the factory processes.

FLASH-OVER TESTS

The electrical stress impressed on insulators in line service has been discussed in so many papers that it is entirely unnecessary to go into any detail at this time. The distribution of stress over suspension insulators and the flash-over characteristics of strings of insulators would require a separate paper. Without any special metal fittings to effect a better distribution, the line unit of a string of suspension insulators will assume from 20 to 40 per cent of the total line voltage depending upon the number of insulators in the string, upon the design of the insulator, etc. Many curves of distribution have been published and everyone is familiar with the general shape of these curves which indicate that the line unit or the two units next to the line have much greater than the average stresses impressed upon them.

The installation of transmission lines operating at 150 to 220,000 volts, makes it necessary to give careful thought to the concentration of stress upon individual units. The insulators will be subjected to extremely high stresses whenever a flash-over occurs or whenever surges are impressed upon the line from switching, lightning, etc. Fig. 18 is indicative of the stresses from flash-over. This figure shows wet flash-overs on a combination of the interlinked insulators and cap and pin insulators. The interlinked insulators form the *V* part on the string. It is interesting to note the parallel arcs which occur under wet flash-over. Fig. 19 shows a dry flash-over on a string of interlinked insulators. A study of these flash-overs by means of a high-speed camera is giving good results.

FIG. 19—60-CYCLE FLASH-OVER OF ASSEMBLED STRING

CONCLUSIONS

We should at all times consider that porcelain is an extremely fragile material, and that very careful thought must be given to the assembly of porcelain with metal parts, especially if the assembled unit will be subject to severe temperature changes or to mechanical vibrations.

Rapid strides in electrical procelain manufacture have been made during the past few years. Perhaps the greatest advancement is in the methods of production in the factory.

The manufacturers are very open to suggestions from the field and solicit the constructive criticisms which can, perhaps, be given to better advantage by men from the field than by men in the factory. This attitude will continue to react to the mutual advantage of all.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 23, 1921.

VOLTAGE AND CURRENT HARMONICS CAUSED BY CORONA

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THE FOLLOWING investigation was made to study the effects of corona in producing voltage and current harmonics in transmission systems.

In the early work on corona in 1910 a very complete oscillographic study was made of voltage and current. It was found that the current wave of corona loss very much resembled the excitation current wave of a transformer or iron-core reactor. A typical corona wave is shown in Fig. 1.[1] This wave has a very prominent third harmonic.

In 1919 three-phase corona losses were measured up to about 220 kv. on a line approximately 100 miles long.[2] The corona losses, within the accuracy of such measurements, checked very well with the quadratic law. An interesting part of this investigation was the discovery of very large triple-frequency currents in the neutral of the grounded Δ *Y* transformers. This current was in every respect similar to the triple-frequency excitation current found in *Y Y* grounded neutral transformers. One explanation for its existence would be the amplification of slight residual triple-frequency excitation voltages in Δ *Y* transformers by the high capacity of the line. It seemed, however, as the result of the early work referred to above,

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[1] Peek, "Law of Corona and Dielectric Strength of Air," A. I. E. E., June 1911, "Dielectric Phenomena," pp. 113, 207.

[2] W. W. Lewis "Some Corona Loss Tests," *General Electric Review*. May 1920. "Some Transmission Tests," TRANS. A. I. E. E., 1921, p. 1079.

that the harmonic was caused by corona loss over each half cycle.

When an alternating voltage higher than the critical corona voltage is applied to a conductor the loss starts at a given point during each half cycle as the voltage increases, continues over part of the half cycle, and finally ends at a given point as the voltage decreases.

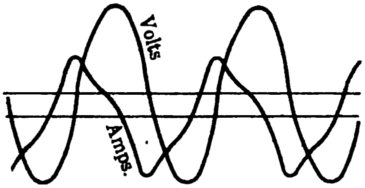


FIG. 1—CORONA CURRENT—SINGLE-PHASE

A varying amount of corona and loss thus occurs during a given part of each voltage wave. The conducting corona, in effect, makes a conductor which periodically varies in diameter. The capacity and loss, therefore, vary during parts of each wave. It follows that if a sine wave voltage high enough to cause corona loss is applied to conductors the current cannot follow a sine wave but must be distorted or contain harmonics. Fig. 1 shows that such a wave contains a prominent third. The phenomenon is, in fact, very similar to that of distortion in the exciting current wave where distortion occurs chiefly due to changing permeability during each half cycle.

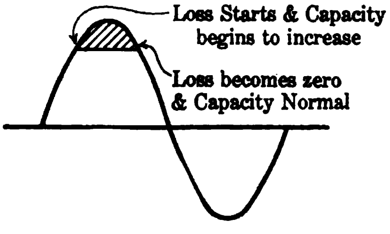


FIG. 2

When corona loss occurs on three-phase lines with grounded neutral, three single-phase paths are afforded for the triple-frequency component of the current through the lines, the capacity to ground, the ground and the neutral ground connection as shown in Fig. 3. If a transformer with a grounded neutral is used at the receiving end part of the current may also be supplied through the transformer. The triple-frequency currents cannot flow in the lines if the neutral is not grounded. This follows because the triple-frequency components are 3 × 120 deg. = 360 deg. apart or in phase. Fundamentally the sum of the currents flowing to the neutral point must be zero. Since the currents are in phase the triple component can satisfy this condition only when it is zero; it can flow over the lines only when single-phase paths are afforded through the grounded neutral. Since with a sine wave voltage the corona current inherently contains

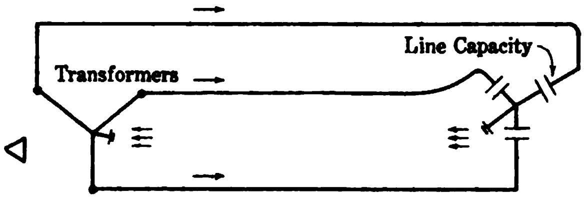


FIG. 3—THREE SINGLE-PHASE PATHS FOR CORONA TRIPLE-FREQUENCY CURRENT

a third harmonic the voltage between line and neutral must be distorted if this component is suppressed. Higher odd harmonics are also caused by corona. With symmetrically arranged conductors, however, only the third and odd multiples of the third can appear on the lines.

Tests were made on short three-phase lines of very fine wire so that the corona loss would be excessive and exaggerate conditions. The transformers were of such a size that the corona loss was an appreciable load. A sine wave voltage was used. There was a large triple-frequency current in the neutral.

After curves were made on the line similar curves were made on *Y*-connected glass plate condensers of approximately the equivalent capacity of the line and of very small corona loss. The neutrals of the condensers and the transformers were connected together.

These tests were made to determine if the capacity of a line free from corona loss could cause high triple-frequency currents by amplification of residual triple-frequency magnetizing voltage harmonics in the Δ *Y* transformers. There were no appreciable neutral currents when the condensers were used.

Fig. 4 gives a set of curves showing the corona characteristics of a three-phase line with Δ *Y*-connected, grounded neutral transformers at the generating end

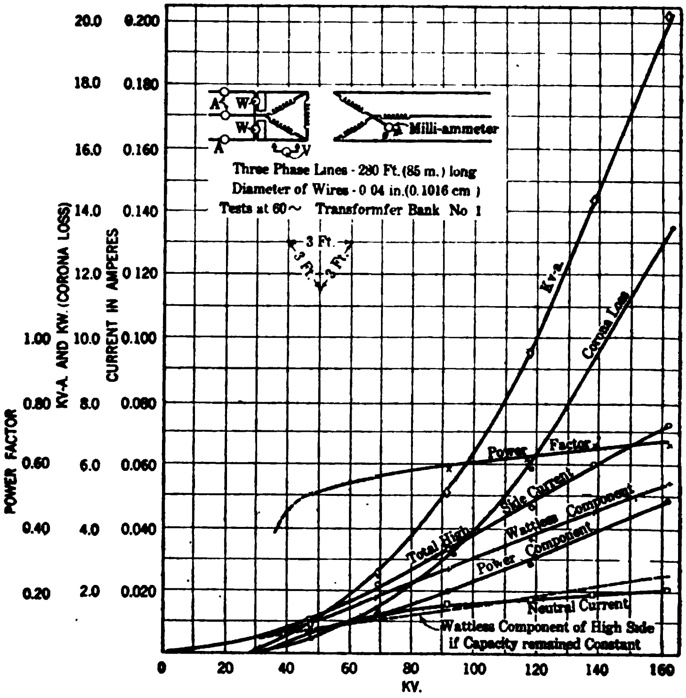
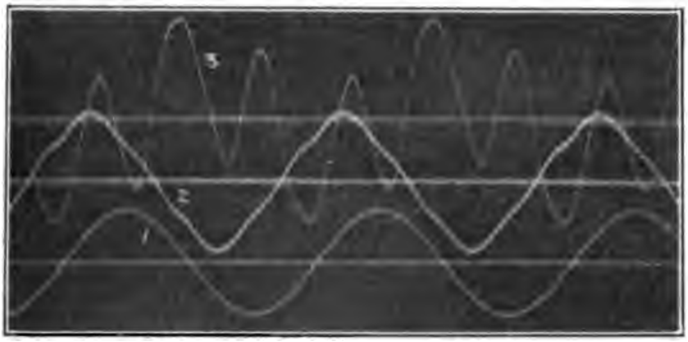
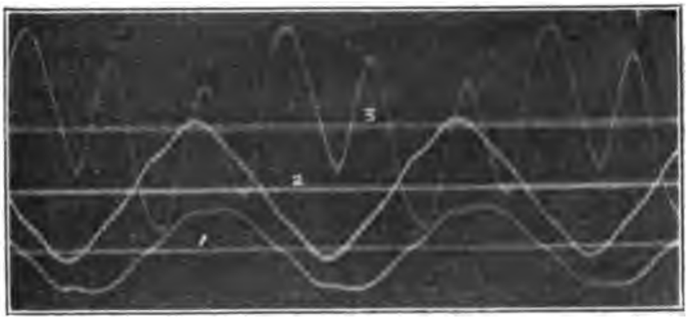


Fig. 4—Corona Characteristics of a Three-Phase Line with Δ *Y* Grounded Neutral Transformers

and open-circuited at the receiving end. All of the measurements, with the exception of the line and neutral currents, were made on the low side but are corrected for losses and referred to the high side. The high side or capacity current starts at zero and increases in a straight line until the corona point is reached. The current then increases much more rapidly than the voltage. This increase in current is caused by a loss component and an added reactive component. The two components are plotted. It is seen that the apparent capacity of the line increases very rapidly with increasing voltage above the corona point. This is seen by referring to the dotted line which would represent the capacity current if there were no apparent increase owing to corona. To account for the reactive component it is necessary to assume that the apparent conductor diameter has increased from 0.102 cm. to 8.0 cm. or about 80 times at 150 kv. The neutral current starts at the beginning of corona loss and soon reaches a value which is comparable to the line current.



A—1. Low side voltage between lines.
2. High side line current.
3. Neutral current.



B—1. Low side line current.
2. High side line current.
3. Neutral current.

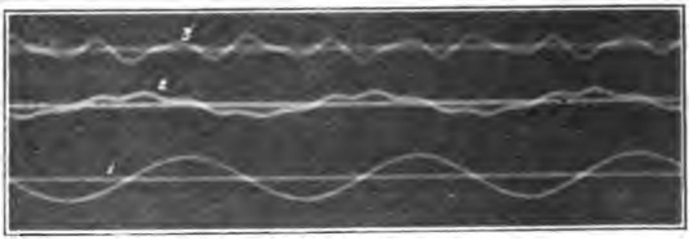
FIG. 5—Δ*Y* TRANSFORMERS AND LINES—NO STEP-DOWN TRANSFORMERS

150 kv., 60 ~ applied to lines—Transformer Bank No. 1
(See Fig. 4)

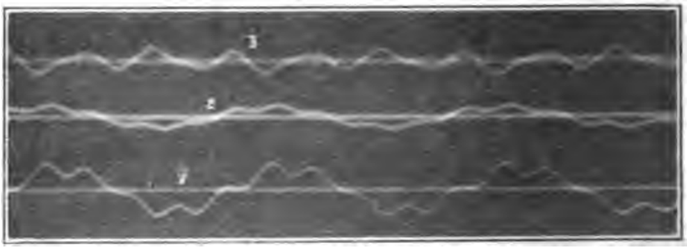
Fig. 5 shows waves of low side voltage and line and neutral currents at 150 kv.

The generator voltage is a very good sine wave. The neutral current contains a very pronounced third harmonic superposed on residual fundamental. The fundamental component in the neutral is caused by lack of exact symmetry in the lines or transformers. Fig. 6 shows a similar set of curves taken at 32.4 kv.

The curves in Fig. 7 were made in the same way as those in Fig. 4 except that three banks of glass plate condensers connected in *Y* were substituted for the line. The condenser neutral was grounded and connected to the transformer neutral. There was a slight corona loss on the condensers and leads. The neutral current is practically negligible. What there is, is probably due to the slight corona loss. Figs. 8 and 9 show the current waves at 110 and 150 kv.



A—1. Low side voltage between lines.
2. High side line current.
3. Neutral current.



B—1. Low side line current.
2. High side line current.
3. Neutral current.

FIG. 6—Δ *Y* TRANSFORMERS AND LINES—NO STEP-DOWN TRANSFORMERS

32.4 kv., 60 ~ applied to lines—Transformer Bank No. 1
(See Fig. 4)

The neutral current wave at 150 kv. is interesting. It appears as a hump at the maximum of the voltage wave due to corona loss on the leads and edges of the plates. This loss does not appreciably change the capacity as in the case of corona on the wires.

Fig. 10 gives corona characteristics of a line with the transformers connected Δ·Δ. The corona loss is not appreciably changed by suppression of the triple-frequency current.

A set of characteristic curves similar to those in Fig. 4 was made with a transformer of lower reactance. See Fig. 11. The general characteristics are very much the same. The neutral current is less, however. The neutral current wave, as shown in Fig. 12, in addition to the third and fundamental contains a decided ninth. There is thus, apparently, a chance of amplification of the corona harmonics by the transformer reactance. The neutral current would, therefore, be expected to vary with the circuit constants.

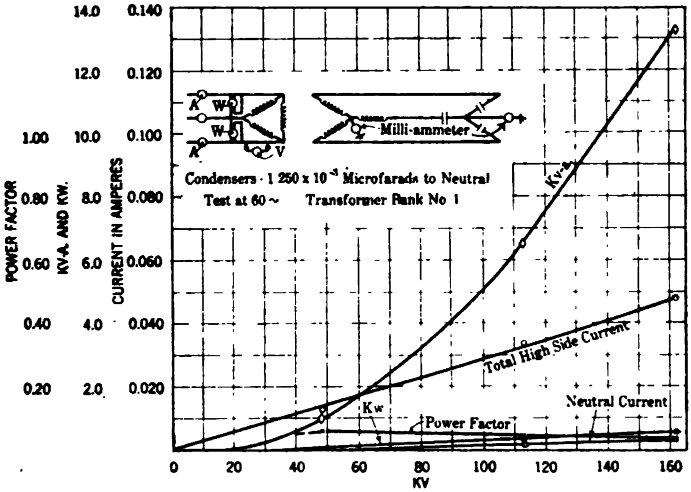
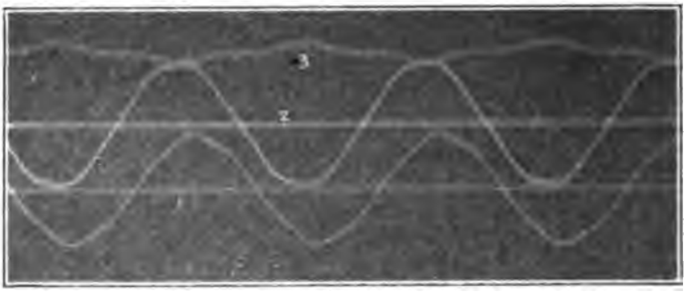


FIG. 7—CAPACITY LOAD ON Δ Y GROUNDED NEUTRAL TRANSFORMERS

With a condenser load the currents were the same as in Fig. 7. The neutral current wave is shown in Fig. 13.

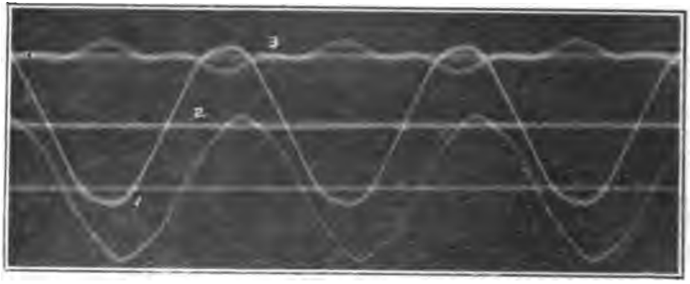
In Fig. 14 Δ Y grounded neutral transformers were placed on the step-down or receiving end. It will be noted that the greater part of the neutral current is supplied from the generator end. The waves are shown in Figs. 15 and 16. The neutral current of the receiving end contains a third and ninth. Fig. 17 gives the same wave with the load disconnected.



1. Low side line current.
2. High side line current.
3. Neutral current.

FIG. 8—Δ*Y* TRANSFORMERS AND CONDENSERS IN *Y*—TRANSFORMER AND CONDENSER NEUTRALS CONNECTED—NO LINES

110 kv., 60 ~ applied to condensers.
Transformer Bank No. 1.
(See Fig. 7.)



1. Low side line current.
2. High side line current.
3. Neutral current.

FIG. 9—Δ *Y* TRANSFORMERS AND CONDENSERS IN *Y*—TRANSFORMER AND CONDENSER NEUTRALS CONNECTED—NO LINES

150 kv., 60 ~ applied to condensers.
Transformer Bank No. 1.
(See Fig. 7.)

The measured and calculated corona loss curves, given in Fig. 18, check very well, especially when the small size of the wire is considered. The quadratic law used in making these calculations is given in the appendix.[3] This reduces to the form ordinarily used when the wires are large. While these measurements were made under conditions favorable for accuracy they emphasized the difficulty in obtaining accurate measurements on long three-phase lines. The deviation from the calculated curve is due to wave shape changes.

CONCLUSIONS

Corona will cause voltage and current harmonics, of which the third is the most prominent.

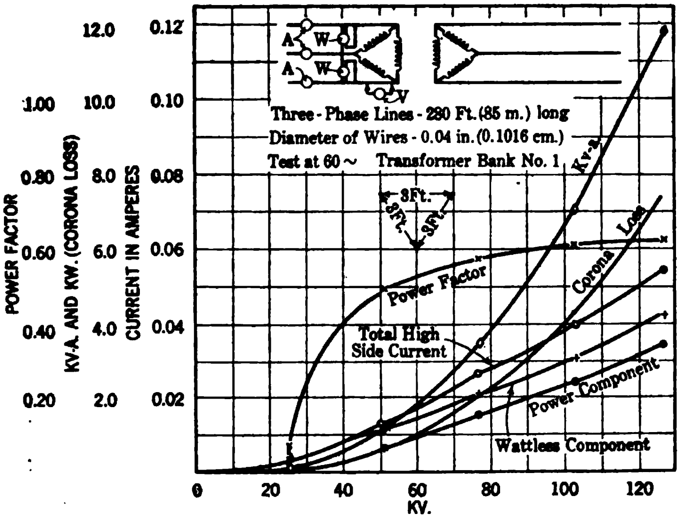


FIG. 10—CORONA CHARACTERISTICS OF A THREE-PHASE LINE WITH ΔΔ TRANSFORMERS

When Δ Y grounded neutral transformers are used, the third and odd multiples of the third harmonic, such as the ninth, may flow in the neutral.

The neutral corona current will not be greater for several grounds than for a single ground.

If the neutral is not grounded, distortion of the voltage may be expected.

The harmonic neutral currents may be of the order

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[3] Peek, "Dielectric Phenomena in High-Voltage Engineering," page 136.

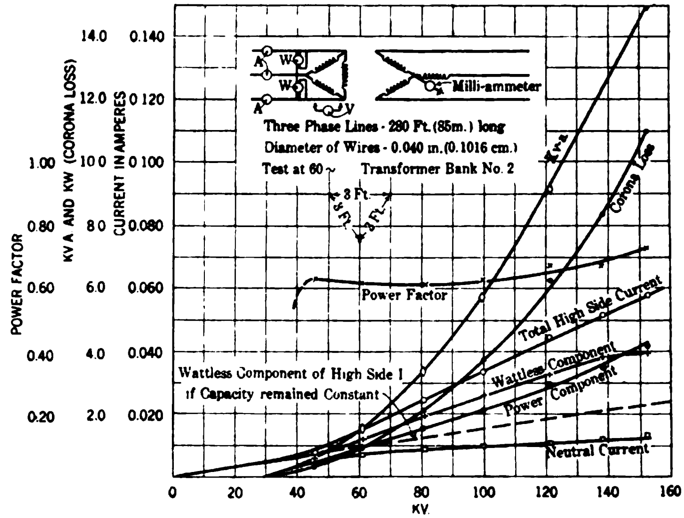
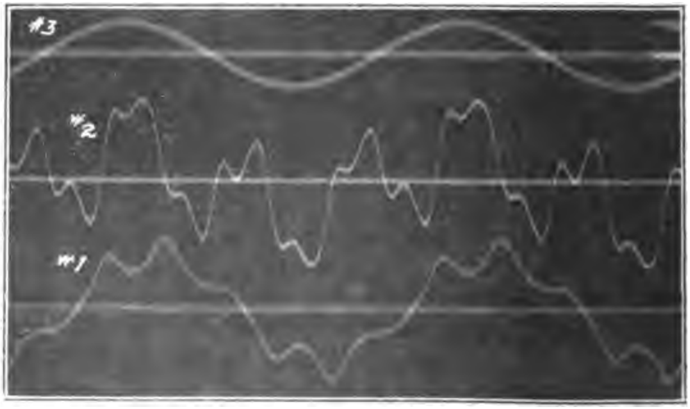


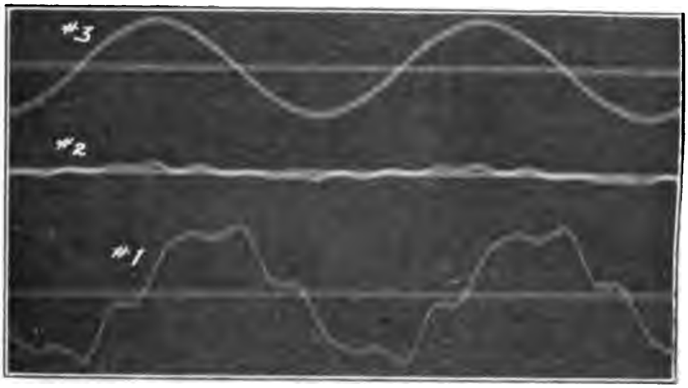
FIG. 11—CORONA CHARACTERISTICS OF A THREE-PHASE LINE WITH Δ Y GROUNDED NEUTRAL TRANSFORMERS



1. Low side line current.
2. Neutral current.
3. Low side voltage.

FIG. 12—Δ Y TRANSFORMERS AND LINES—NO STEP-DOWN TRANSFORMERS

100 kv., 60 ~ applied to lines.
Transformer Bank No. 2.
(See Fig. 11.)



1. Low side line current.
2. Neutral current.
3. Low side voltage.

FIG. 13—Δ *Y* TRANSFORMERS AND CONDENSERS IN *Y*—TRANSFORMERS AND CONDENSER NEUTRALS CONNECTED—NO LINES

100 kv., 60 ~ applied to condensers.
Transformer Bank No. 2.

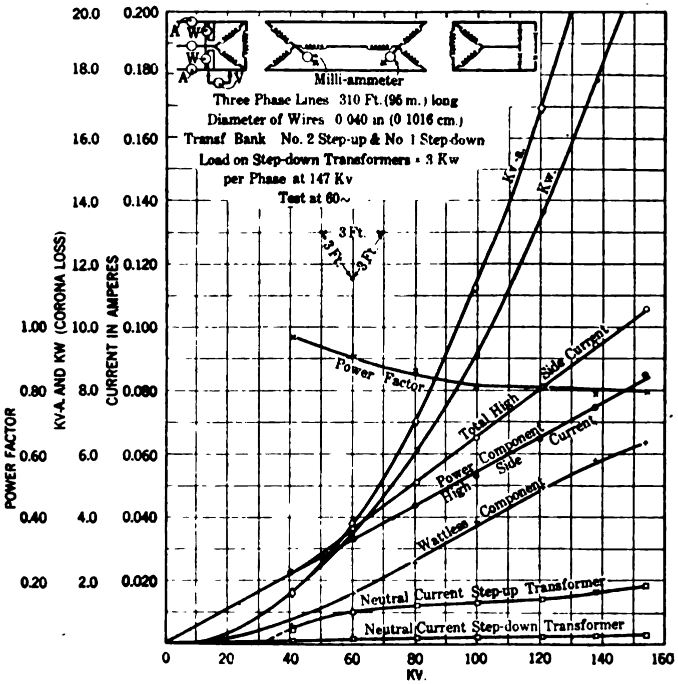
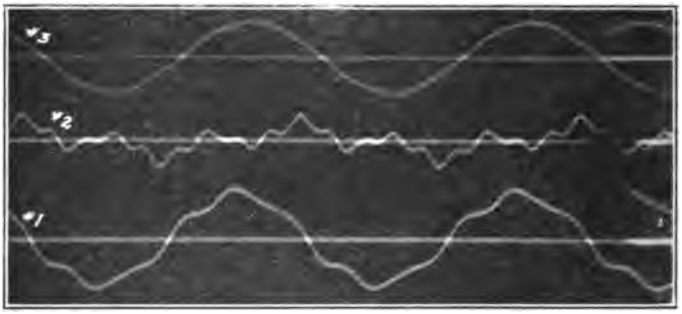


FIG. 14—CORONA CHARACTERISTICS OF A THREE-PHASE LINE WITH Δ*Y* GROUNDED NEUTRAL TRANSFORMERS AT STEP-UP END AND *Y*Δ GROUNDED NEUTRAL TRANSFORMERS WITH LOAD AT STEP-DOWN END

of the capacity current of the line when the corona loss is excessive.

In properly designed practical transmission lines, the harmonic introduced by corona should be inappreciable.

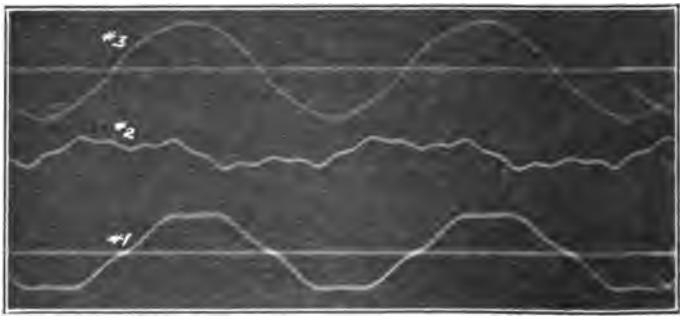
The apparent capacity of the line increases rapidly above the corona point. At 150 kv. the capacity current is equal to that for conductors of 80 times the radius of the one used.



1. Low side current.
2. Neutral current—Step-down transformers.
3. Low side voltage—Step-down.

Fig. 15—Δ *Y* Transformer Bank No. 2, Lines, *Y*Δ Step-Down Transformer Bank No. 1.

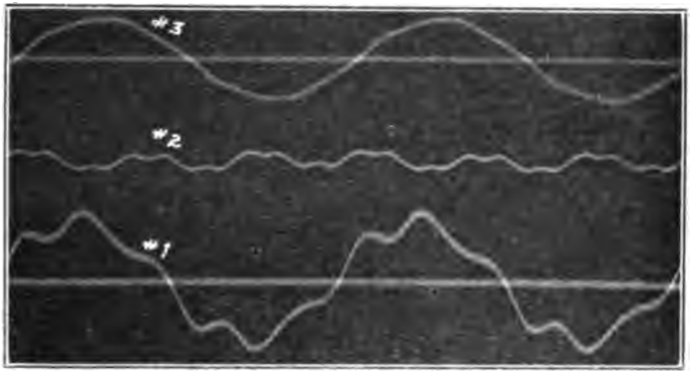
150 kv., 60 ~ applied to lines—with load. Both neutrals grounded. (See Fig. 14.)



1. Low side current.
2. Neutral current—Step-up end.
3. Low side current—Step-down.

Fig. 16—Δ *Y* Transformer Bank No. 2, Lines, *Y* Δ Step-Down Transformer Bank No. 1

32.4 kv., 60 ~ applied to lines—with load. Both neutrals grounded. (See Fig. 14.)



1. **Low side current.**
2. **Neutral current—Step-down end.**
3. **Low side voltage—Step-down end.**

FIG. 17—Δ *Y* TRANSFORMER BANK NO. 2, LINES, *Y* Δ STEP-DOWN TRANSFORMER BANK NO. 1—NO LOAD

150 kv., 60 ~ applied to lines. Both neutrals grounded—no load.

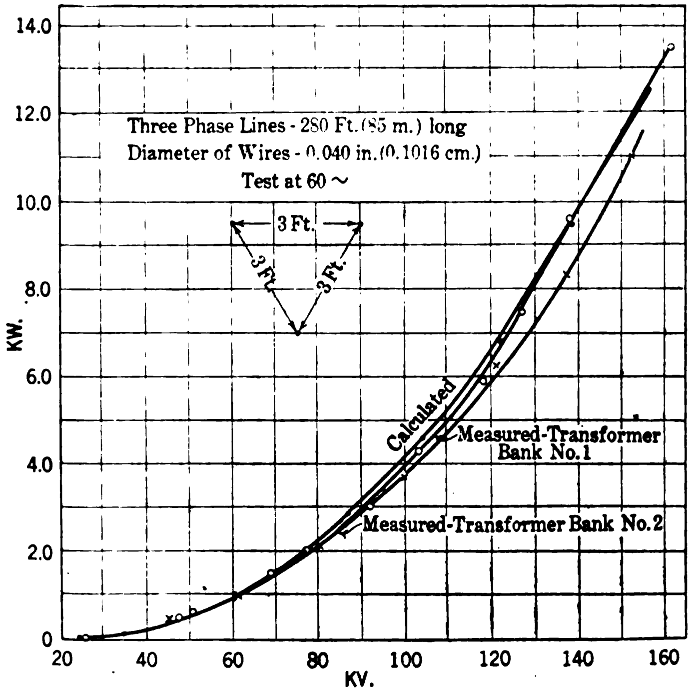


FIG. 18—CALCULATED AND MEASURED CORONA LOSS ON THREE-PHASE LINES

The above tests were purposely made with very small wire and high voltage in order to exaggerate the effects of corona.

The harmonics are affected to some extent by the transformer constants.

Calculated and measured corona losses checked very well.

Thanks are due Mr. W. L. Lloyd, Jr. for assistance in making tests and calculations.

APPENDIX

TRANSFORMERS

Bank No. 1

Each Transformer, 10 kv-a., 400/100,000 volts, 25 ~

Resistance low side, 0.08 ohms. Resistance high side, 15,400 ohms.

Reactance reduced to high side, 116,000 ohms at 60 ~

Bank No. 2.

Each Transformer, 15 kv-a., 440/100,000 volts, 60 ~.

Resistance low side, 0.042 ohms. Resistance high side, 5,760 ohms.

Reactance reduced to high side, 32,000 ohms.

LINE

New copper wire. Diameter 0.040 inches (0.102 cm.). Wires arranged in a triangle at 3 ft. (91 cm.) spacing. Length of each wire 280 ft. (85 m.)

CONDENSERS

Glass plates in air.

Capacity to neutral. 1.25×10^{-3} m.f.

QUADRATIC LAW

$$p = 241\,(f + 25)\sqrt{\frac{r + 6/s + 0.04}{s}}\,(e - e_d)^2$$

10^{-5} kw. per km. per wire

$$g_d = g_0\,\delta\left[\left(1 + \frac{0.30}{\sqrt{\delta\, r}}\right) \times \frac{1}{(1 + 230\, r^2)}\right]$$

$e = m_0\, g_d\, r \log_e s/r$

s = spacing in cm.

r = radius in cm.

$m_0 = 0.95$

$\delta = \dfrac{3.92\, b}{273 + t}$ b = bar. pressure cm.

t = temp. deg. cent.

$p = 0.00217\,(e - 14.)^2$ kw.

TABLE I

Step-up Transformers—No step-down Transformers
Bank No. 1* Δ Y Connection
Temp. = 21. deg. cent. Bar. Press. = 29.237 in. δ = 1.010
No-Load

Low Side						High Side				
Volts†	Amperes†	Kw.	Kv-a.	Power Factor	Kv.	Amperes	Kw.	Kv-a.	Power Factor	Neut. Amperes
				Lead.						0
352	4.69	0.697	2.86	0.24	152.0					0
202	2.55	0.260	0.89	0.29	87.1					0
105	1.15	0.085	0.205	0.41	45.3					
				Bank No. 1	Δ Y	Lines on.		See Fig. 4.		
				Lead.						
352	35.4	14.52	21.6	0.68	161.0	0.0727	13.48	20.3	0.664	0.0208
304	29.5	10.16	15.5	0.66	138.0	0.0602	9.54	14.4	0.662	0.0189
256	23.3	6.40	10.3	0.62	118.0	0.0468	5.85	9.56	0.612	0.0172
201	16.6	3.38	5.76	0.59	91.1	0.0331	3.05	5.22	0.585	0.0151
152	11.1	1.64	2.92	0.56	68.6	0.0216	1.45	2.56	0.567	0.0119
105	5.9	0.55	1.07	0.51	47.0	0.01105	0.457	0.898	0.509	0.0068
				Bank No. 1		Condensers on in Y.	See Fig. 7.			
				Lead.						
354	25.2	1.34	15.5	0.086	162.0	0.0476	0.485	13.35	0.0364	0.0025
247	17.6	0.66	7.52	0.088	113.0	0.0335	0.214	6.56	0.0326	0 †
107	7.3	0.16	1.35	0.118	48.6	0.01225	0.059	1.03	0.0573	0

*Operated at 60 cycles.

†Phase voltage balanced throughout tests. No variation measured.

Phase current slightly unbalanced. No-load ± 1.0 per cent variation in phase current.
With Lines on ± 1.5 per cent " " " "
With Condensers ± 0.5 per cent " " " "

TABLE II

Step-up Transformers—No Step-down Transformers.
Bank No. 1. △ △ Connection
Temp. = 21 deg. cent. Bar. Press. = 29.237 in. δ = 1.010
No-Load

	Low Side					High Side				
Volts	†Amperes	Kw.	Kv-a.	Power Factor	Kv.	Amperes	Kw.	Kv-a.	Power Factor	Neut. Amperes
498	3.92	1.16	3.38	0.34	125.0					
405	3.20	0.80	2.24	0.36	101.0					
305	2.38	0.480	1.26	0.38	76.3					
201	1.49	0.228	0.518	0.44	50.2					
104	0.66	0.073	0.119	0.61	26.0					
Bank No. 1.* △△ Lines on. See Fig. 10										
500	17.2	8.68	14.9	0.58	127.0	0.0540	7.45	11.88	0.627	
403	13.0	5.12	9.08	0.56	103.0	0.0397	4.28	7.08	0.604	
303	8.82	2.50	4.63	0.54	77.1	0.0260	2.00	3.47	0.576	
201	4.76	0.800	1.66	0.48	50.9	0.01309	0.568	1.154	0.493	
102	1.47	0.083	0.26	0.32	25.7	0.00350	0.010	0.1558	0.0642	

† ± 1 per cent variation in line currents of the three phases.
No variation in voltage between lines.
*Operated at 60 cycles.

TABLE III

Step-up Transformers—No Step-down Transformers.
Bank No. 2 Transformers Δ Y
Temp. = 21 deg. cent. Bar. Press. = 28.63 in. δ = 1.030
No-Load

	Low Side					High Side				
Volts	Amperes†	Kw.	Kv-a.	Power Factor	Kv.	Amperes	Kw.	Kv-a.	Power Factor	Neut. Amperes
				Leading						
382	2.89	1.88	1.91	0.985	151.0					0
344	2.76	1.54	1.64	0.97	136.0					0
303	2.56	1.22	1.34	0.91	119.0					0
250	2.22	0.870	0.961	0.90	98.5					0
202	1.87	0.588	0.654	0.90	79.5					0
152	1.50	0.350	0.395	0.95	59.8					0
102	1.03	0.177	0.182	0.97	39.8					0
				Bank No. 2	Lines on.		See Fig. 11			
384	27.6	13.64	18.4	0.74	153.0	0.0639	11.66	16.92	0.689	0.0145
382	25.0	12.92	16.5	0.78	152.0	0.0573	10.96	15.10	0.728	0.0133
344	22.6	9.94	13.5	0.74	138.0	0.0518	8.33	12.4	0.672	0.0120
305	19.8	7.50	10.5	0.71	121.0	0.0442	6.23	9.26	0.673	0.0111
250	15.4	4.54	6.66	0.68	99.6	0.0336	3.64	5.79	0.628	0.0099
203	11.5	2.72	4.03	0.68	80.9	0.0248	2.12	3.47	0.611	0.0087
152	7.3	1.34	1.92	0.70	60.3	0.0152	0.98	1.59	0.617	0.0068
114	4.3	0.60	0.85	0.70	45.2	0.00791	0.39	0.619	0.630	0.0045

†Line current varied in the different phases by ± 5 per cent at the high voltages, ± 2 per cent at low voltages for no-load; ± 2 per cent both high and low voltages with lines on.

No variation in voltage between lines.

TABLE IV
Load on Step-down Transformers.
Temp =21°c Bar. =28.78″ δ =1.026 See Fig. 14.

	Low Side				High Side						
										Neutral Current	
Volts	Amperes†	Kw	Kv-a.	Power Factor	Kv.	Amperes	Kw.	Kv-a.	Power Factor	Step-up	Step-down
386	44.1	24.68	29.5	0.84	154.0	0.1053	22.53	28.1	0.802	0.0175	0.0025
345	39.6	19.56	23.7	0.82	138.0	0.0942	17.80	22.5	0.792	0.0159	0.0025
303	34.5	15.04	18.1	0.83	121.0	0.0812	13.66	17.0	0.803	0.0138	0.0020
251	27.8	10.08	12.1	0.83	100.0	0.0650	9.10	11.26	0.808	0.0126	0.0020
202	21.7	6.92	7.58	0.91	80.8	0.0504	6.09	7.06	0.863	0.0118	0.0020
153	15.9	3.84	4.22	0.91	60.4	0.0366	3.45	3.82	0.903	0.0099	0.0015
103	10.0	1.76	1.78	0.99	41.0	0.0228	1.57	1.62	0.968	0.0045	0.0010

†Line Current in the different phases varied by ± 3 per cent.
No variation in voltage between lines.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 23, 1921.

A SOLUTION OF THE PORCELAIN INSULATOR PROBLEM

BY E. E. F. CREIGHTON
General Electric Co., Schenectady, N. Y.
AND
AND F. L. HUNT
Turner Falls Power and Electric Co.

MANY YEARS ago porcelain insulators on transmission lines began to crack in great numbers. In the earlier cases a few disks in many strings had cracked before the transmission engineers had discovered the condition. Indeed, there was at that time no reason to believe that insulators would deteriorate in any way. As a result of these many unobserved failures which simply reduced the factor of safety in each insulator one accidental failure finally introduced surges which punctured many other insulators just on the point of failure. These failures were tens of miles apart. Thereby the whole system was put out of use.

Today these general failures are avoided by a systematic test of each disk at intervals of time depending upon the conditions of installation and the judgment of the transmission engineers.

The cause of most of the failures of these insulators may possibly be reduced to one condition, namely the presence of the Portland cement. To be sure, the Portland cement at times was only indirectly the cause when it simply supplied the moisture which very slowly distilled into porous porcelain. The most usual cause of failure of the disks, however, was due to a characteristic of Portland cement itself. When Portland cement is dried out it shrinks. When it is again wet it expands not only back to its initial size, but a little more. In each cycle of drying and rewetting the cement increases in volume until it tightly fills the entire space between the metallic hardware and the porcelain. When this condition is reached an unusually warm day will cause an unusual expansion of the metal, and the resulting strain will be transmitted directly through the Portland cement to the porcelain. A crack will result.

Progress in decreasing these failures has been made by the manufacturers of porcelain insulators. For example, instead of resting the cap directly on the porcelain of the usual suspension insulator it is now separated by a slight clearance which prevents the cap from pushing the head off the insulator. This improvement is easily made and has no detrimental factor.

For the expansion of the pin the conditions have been possibly somewhat improved by the use of a layer of soft material next to the porcelain. Unless other conditions are made to conform with this change the insulator is weakened mechanically.

Improvements have been made in the matter of open porosity by greater care in firing. Some manufacturers have also endeavored to overcome this difficulty by glazing all surfaces.

In spite, however, of all of these conditions, the older insulators on transmission lines from all manufacturing companies still fail in sufficient percentages to require the expense of a periodic test and examination. There is an amelioration without a cure. In other words, the life of the insulator has been increased but the tests must still be continued.

The writers attempted to find several solutions of this problem and there is described herewith the satisfactory results of one of these methods. Porcelain disks and hardware were purchased, unassembled, from a reliable manufacturer of insulators. The porcelains were all examined relative to porosity. They were all highly vitrified, in fact there was not the slightest trace of open porosity in a single one of them. A few faults were on the side of overvitrification which manifested itself in a detrimental way by slight checks.

Punctures, where they occurred, took place through these checks. Very severe high-frequency voltages were applied by means of the well-known oscillator. The losses due to these extra severe tests were reasonable.

The solution of the main problem—the prevention of failure of the present type of cemented insulators—lies in arresting the expansion of the cement. The easiest method of accomplishing this is by removal of the moisture from the thoroughly set cement and the prevention of its re-entering the cement. This was thoroughly done by impregnation under vacuum on a large number of the insulators and was less thoroughly done on a portion of the insulators with the idea of determining the difference in life, if any, due to the difference in thoroughness of the impregnation.

In the endeavor to reach 100 per cent results it was necessary to study the characteristics of Portland cement when impregnated by different substances. One of the commonest impregnating substances of an insulating nature is paraffin.[1] It was found, however, that a chunk of Portland cement that had been thoroughly impregnated with paraffin by vacuum and heat treatment and then broken would still absorb moisture through the broken surfaces. A better material was therefore looked for. Some of the pitches were found to give perfect results. Portland cement impregnated with pitch could be broken into small pieces and soaked in water for days without the slightest indication of absorption of the water.

As already stated, different methods of impregnation were applied. This work was done in the laboratory during 1917 and the spring of 1918. The majority of the insulators were given a thorough vacuum treatment under heat and were impregnated under pressure with the intention and hope of getting 100 per cent perfection and a life of indefinite length—much more than twenty years. In order to get a forecast of the future, laboratory processes of aging were developed. A large wheel, twelve feet in diameter, which is known in the laboratory as the Ferris wheel, was made and

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[1] U. S. Pat. 1,360, 896.

operated with the axis in a horizontal plane. Around the rim insulators were secured with bolts and these insulators were passed through a cooling box next to the floor and a heating chamber near the ceiling. The insulators were exposed to the air between these two extremes of heat and an actual blast of moist air was turned on them as they slowly moved around. Here was a device then that gave the extremes of temperature and moisture from 20 deg. cent. below zero to 120 deg. cent. above. The range of temperature and moisture was exaggerated and the rate of change of temperature and moisture was also exaggerated above that found in practise with the idea of hastening any effect that might develop in actual practise. It was estimated that the effect of a single revolution on this wheel would give the insulator more severe strain than would take place in six months in practise—in other words, that two revolutions were equivalent to a year. In this way artificial tests were made extending over more years than any of us will live to enjoy.

In criticism of this method it should be pointed out that it does not give a thorough test of the distillation of moisture into porous porcelain, but it has already been pointed out that these insulators were absolutely without open pores and that consequently that particular feature was not of interest.

Another set of tests was made on these insulators which was more severe in the rate of change of temperature, namely by changing from boiling water to freezing water every half-hour. By these methods we satisfied ourselves that the inpregnation was effective and that the insulators were ready for installation.

THE MOST IMPORTANT CONCLUSIONS TO DATE

Eleven hundred of these insulators, carefully marked, were installed on a 66,000-volt transmission line near the seashore in New England in July and August, 1918, and put into operation in November, 1918. *Up to the present time there has not been a single failure among the lot.*

Thirty-six hundred other insulators of the same design, and built in the same factory, were shipped direct from the factory, having been assembled at the insulator factory, and installed on the same line at the same time as the others.

A test made on the whole line about a year after it was put into operation showed 13½ *per cent of failures among the insulators* which came direct from the insulator factory and *no failure at all on those which had received the above described treatment.* The insulators were then about two years old.

Up to the present time there have been additional failures, amounting to 2 or 3 per cent, among the insulators which came direct from the factory, but no failures whatever in the insulators in which the cement was treated.

Following are some comments relating to (1) the mechanical strength, (2) electrical tests treatment, (3) line testing, (4) aging of porcelain, and (5) open porosity of porcelain—which seem pertinent to the subject in hand.

1. *Mechanical Strength.* In discussing the mechanical strength of insulators as affected by impregnation of the cement, it is desirable to avoid the introduction of other factors which are independent of the treatment of the cement. For example, it is well-known that the geometrical dimensions play a leading part in determining the mechanical strength. A large head and a deep pin-hole give more bearing surface for the cement and thereby increase the ultimate "pull" on the hardware. Therefore a type of disk and hardware will have a fairly definite mechanical strength if the cementing is done in the most favorable way.

If the cement is sufficiently set to transmit the force to give the ultimate strength of porcelain in tension (about 2000 pounds per square inch, 140 kg. per square centimeter) and, furthermore, fills the space between hardware and porcelain surfaces sufficiently snugly to transmit the mechanical force uniformly, what more can be asked of the cement? The type of insulator will then give its maximum mechanical "pull."

To arrive at this desired condition the manufacturing details depend on the application of a few scientifically determined factors. To illustrate briefly: The problem of attaining the proper conditions of the cement was approached by experimenting first with the two extremes. At one extreme the cement was set rapidly in live steam at a pressure of 120 pounds per square inch (8.5 kg. per square centimeter). Most of the disks came out of this treatment with the porcelain cracked due to the expansion of the Portland cement. At the other extreme the cement was set for a few days only under conditions of normal room temperature. As a result, either the pin slipped out of the cement in the "pull" test (as was usual) or the cap slipped over the cement. Sufficient "set" and "snugness" of the cement may be obtained by a manipulation of the factors at either extreme—less time and steam temperature starting from the upper extreme or more time and temperature starting from the lower extreme.

It is impracticable to give details here in this brief account. The treatment must be adjusted to the type of cement. For example, some of the gray cements seems to have common characteristics. It is possible that refinements in the research would show variations in the cement of the same manufacturer at different times of manufacture. We did not go that far. White cement showed the greatest expansion.

The important point in the proposed solution of this problem is that when the cement is given a desirable "set" and "fit" the impregnation excludes moisture which would otherwise change the optimum conditions as the cement grew older. The impregnating material must, of course, be of such a chemical nature as not to attack the cement. If the factors which cause changes in the cement are excluded why will not the cement remain constant forever?

2. *Electrical Tests.* The insulators at the factory and also the specially treated ones in the laboratory were given severe high-frequency tests. Those authorities who have expressed their fear of permanent damage to the porcelain body by the severe electrical tests may feel inclined to explain the loss of over 13 per cent in

only two years of life by attributing it to the severity of the tests. This would seem hardly tenable ground. The insulators with impregnated cement were also given the severe electrical tests and none has failed. Is it not more probable that in the assembly of porcelain and hardware in the factory the particular cement and the particular treatment of it expanded the cement to a snug fit and the alternate dry and moist winds of the New England coast caused a further expansion of the tightly fitting cement, followed by a resulting breakage of the porcelain?

3. *Line Testing.* Again it is desirable to emphasize the fact that 100 per cent perfect insulators are a good investment financially, while the extra money expended in *improving* the insulator is of questionable economy. In one case the expensive and dangerous line tests are not necessary, whereas in the other case the line tests are still necessary although they may be made somewhat less frequently. It takes just as long to test 1000 insulators containing one defective as with a number of defectives. The goal is *no testing.*

4. *Aging of Porcelain.* The aging of porcelain is a question frequently brought up. Distinction should be carefully made between the deterioration of insulators and the deterioration of porcelain. There can be no question regarding the former. There is, however, a grave question whether porcelain in itself deteriorates with age. The series of tests of the application of heat, cold, and moisture to normal porcelain, which may be described at a later date, gave not the slightest indication of any change in the porcelain structure. By normal porcelain is meant the combination of clay, feldspar, and flint in the proportion of about 5, 3 and 2 respectively and fired to a vitrification sufficient to do away with open pores. The time and temperature are of the order of 4 to 6 hours at about 1330 deg. cent. The tests used to discover any possible changes in the porcelain were: puncture tests on 60 cycles and 200,000 cycles, hysteresis tests, and impregnation tests of dyes on broken pieces of the porcelain. While it is tenable that improperly made porcelain, using certain grades of quartz instead of

flint and introducing other foreign chemicals, such as might come in the ball clay or other ingredients, may deteriorate in time, we have not yet found any such results in our researches. Porcelain protected by glaze is naturally free from moisture. It is therefore, in an insulator, subjected only to the range of atmospheric temperature and the mechanical strains due to the suspended transmission lines. While silica assumes a number of molecular conditions at unusually high temperatures there seems little likelihood that molecular changes at atmospheric temperatures could be a source of deterioration. The chance of deterioration is such a slight factor as compared to more evident conditions that we may properly relegate it to a secondary position for the present in analyzing the faults in porcelain insulators. To be sure, if the porcelain is openly porous and moisture is gradually distilled into the pores and is there frozen, the expansion of the moisture in the cells of the porcelain may increase the porosity. This is not an argument proving the deterioration of porcelain with age, but an argument favoring the proper vitrification of the porcelain, and the glazing of the surfaces exposed to moisture to take care of those inevitable cases of slight under-vitrification.

5. *Open Porosity of Porcelain.* In conclusion it should be noted that the use of dry impregnated cement solves also the problem of deterioration of resistance of porcelain due to the absorption of moisture.

As an incidental auxiliary matter, the manufacturer, by request, supplied a few special, underfired insulators for comparison and a method of determining the underfired condition, without destroying the porcelain, was tried. This laboratory test was of the nature of hysteresis loss in the material. A description of it is out of the scope of the present paper. None of these was installed.

Final Comments. Three to four years is not sufficient time to furnish absolute proof of the success of this impregnation method. More reliance is placed on the artificial aging test of the laboratory. There are points for discussion and debate and more work yet to be done. We present the matter as a progressive step.

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TRANSFORMERS FOR INTERCONNECTING HIGH-VOLTAGE TRANSMISSION SYSTEMS

For Feeding Synchronous Condensers from a Tertiary Winding

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ABSTRACT OF PAPER

Owing to the advantages to be realized from the use of the star-star connection in interconnecting high-voltage transmission systems and from the fact that this connection requires the use of an auxiliary winding connected in delta to stabilize the neutral point or to decrease the inductance in the ground connection, a great majority of the transformers designed for interconnecting transmission lines are three-winding transformers. Another type of transformer which would be included in this general class would be that having an auxiliary winding for feeding a synchronous condenser used in controlling the voltage at the receiver end of the line.

Many of the alternatives such as the choice between self-cooling or water-cooling, or between single-phase units and three-phase units, differ in no way from the same questions on transformers for ordinary service. However, there are a number of important features peculiar to three-winding transformers for these classes of service that complicate the design and operation to an extent that justifies special consideration of these problems.

This paper will call attention to these special problems and indicate the way in which the design and performance of transformers for these classes of service are influenced by them.

PHASE DISPLACEMENT BETWEEN INTERCONNECTED SYSTEMS

IF TWO transmission systems are tied in at one point only, the phase displacement between the two systems is fixed by the transformer connection which is used at that point. Future interconnections between the two systems must be consistent with those which have preceded them. A 30-deg. phase displacement would require the use of a delta-star connection. A 0-deg. or 180-deg. phase displacement would require the use of either the delta-delta or the star-star connection. The most common condition is probably 0-deg. phase displacement in which case there is a choice between the use of the delta-delta or the star-star connection. The logical choice between these two alternatives is the star-star connection for the following reasons:

First. It reduces the average insulation stress between the windings and the core of the transformer.

Second. It offers an opportunity to ground either or both the system neutrals at the transformer.

Third. It results in a cheaper and smaller transformer.

Fourth. It offers an opportunity for further reduction in first cost when the neutrals are grounded by the use of graded insulation.

Fifth. It offers an opportunity for further reduction in first cost by the elimination of one high-voltage bushing.

ECONOMY OF STAR-CONNECTED TRANSFORMERS

The average voltage stress between windings and core is 43.3 per cent of the line voltage in a delta-connected winding, but only 28.9 per cent in a star-connected winding, the latter figure being just two-thirds of the former.

A star-connected transformer is cheaper to build than a delta-connected one because of the better space factor resulting from the fewer number of turns of correspondingly larger cross-section. The difference between the costs of the two is a function of the voltage and of the capacity of the transformer, and becomes more marked as the voltage increases and the capacity decreases. The dry weight of a transformer, *i. e.*, the weight of the transformer with its case but exclusive of the oil, is sometimes used as a criterion of the cost of transformers. Fig. 1 shows the relation between the dry weights of star- and delta-connected single-phase, 60-cycle, 66,000-volt transformers, and the kv-a. of the transformer. The dry weight of the star-connected transformer is expressed as a percentage of the dry weight of the delta-connected transformer of the same rating. The saving of the star connection over the delta connection is evident from this curve. For higher voltage classes the differences would be still more marked, while for very low voltages they become negligible. In fact, for extremely low voltages the heavier current may be a handicap and throw the difference in favor of the delta connection. The economies effected through the use of the star connection for high voltages often result in a reduction in the dimensions as well as the cost.

When the neutral of the system is directly grounded at both ends of the line it is often the practise on star-connected transformers to taper the insulation between the windings and the core more or less in proportion to the stress between them and to test them with an induced voltage rather than a disruptive test. The Standardization Rules of the A. I. E. E., Article 6361-e, specify the test for apparatus connected to permanently grounded single-phase circuits of more than 300 volts as 2.73 times the voltage to ground + 1000 volts, but the same rule specifically states that this test shall not apply on three-phase apparatus with grounded star neutral. However, where transformers have been supplied in the past with graded insulation, the practise has been to apply the same rule to three-phase circuits until this practise is now pretty well established. Grading the insulation between winding and core proportionately with the stresses,

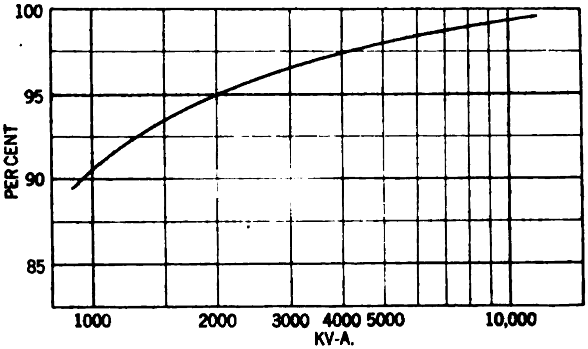

Fig. 1—Dry Weight of One-Phase, 60-Cycle, 66-Kv. Star-Connected Transformers in Per Cent of Equivalent Delta-Connected Transformers

results in a considerable saving and makes it possible to eliminate one of the high-voltage bushings. The cost of high-voltage bushings is quite an item and the increased clearances possible with only one high-voltage bushing through the cover make for greater safety.

STAR-STAR CONNECTION IS ADAPTED TO THE USE OF AUTO-TRANSFORMATION

An auto-transformer offers a decided saving in first cost over an equivalent transformer with separate windings but it can only be applied under certain conditions. These conditions are fulfilled with the star-star connection when the neutral point is directly and permanently grounded. If the neutral of the three-phase star-star connected auto-transformer is not directly and permanently grounded, serious stresses will be put upon the system having the lower line voltage in the event of one of the higher voltage lines grounding accidentally. Assume a three-phase star-star connected auto-transformer stepping down from 150,000 volts and 66,000 volts with the neutral free. In the event of a ground on one of the 150,000-volt lines the potential of the 66,000-volt lines above ground would be increased from 38,100 volts to 48,500 volts on the line in the same phase on which the ground occurs and to 110,800 volts on the other two lines. (Fig. 2.)

The amount of saving effected by the use of auto-transformers as compared with transformers with separate windings depends upon the ratio of transformation. The equivalent size of the auto-transformer to transform a certain kv-a. expressed as a fraction of the kv-a. is $\frac{V_1 - V_2}{V_1}$ where V_1 and V_2 are the higher and lower voltages respectively. It is evident from this expression that the greatest reduction in size and cost occurs when V_1 and V_2 are of nearly the same magnitude. If this were the only consideration, the most likely field of application for an auto-transformer would be where the ratio of transformation is nearly unity. However, the impedance of an auto-transformer is lower than that of an equivalent transformer with separate windings, in the same ratio as the equivalent size is reduced, namely $\frac{V_1 - V_2}{V_1}$ so that as V_2 approaches V_1 the impedance approaches O. The low impedance of the auto-transformers in the range of voltage ratios where they present the greatest economy works against them as it allows very heavy currents to flow through them at times of short circuits. When the transformation ratio falls much below 1 to 1.1 it becomes almost impossible to design an auto-transformer which will be self-protecting, *i. e.*, will withstand the forces incident to a dead short circuit with sustained voltage without mechanical injury. The result of this situation has been to limit the application of auto-transformers to that range of voltage ratios where the stresses due to short circuits are within reasonable limits. A review of the past applications of auto-transformers to power transmission systems indicates that the majority of such applications has been where the ratio of transformation was in the vicinity of two to one.

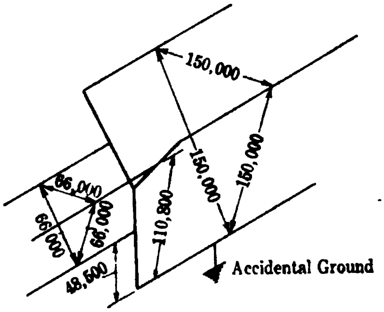

Fig. 2—Voltages to Ground with Star-Star Auto-Transformers and Neutral Free

The economy of the star-star connection, the availability of ground connections, and its adaptability to the use of graded insulation and auto-transformations, gives it a great advantage over the delta-delta connection for use in interconnecting power systems and it has been used almost exclusively in the past where 0-deg. phase displacement is desired.

STAR-STAR CONNECTION REQUIRES THE USE OF AUXILIARY WINDING CONNECTED IN DELTA

When the star-star connection is employed it is necessary to have an auxiliary or tertiary winding connected in delta to obtain satisfactory operation.[1] In all single-phase transformers and in three-phase transformers of the shell type of construction, a tertiary is necessary in order to supply the triple harmonic component of the exciting current which is suppressed by the star-star connection. If the triple harmonic exciting current is not supplied there will be a triple harmonic in the phase voltage which will produce an unstable neutral. This cannot be permitted on account of the insulation stresses imposed on the system. In the three-phase core type of construction the return circuit for the flux in any leg is through the other two legs. The deficiency in third harmonic excitation in any phase at any given instant is supplied from the other two phases which have an excess of third harmonic excitation at that instant. There are other considerations which will be discussed later, under the effect of the tertiary upon the currents which flow when a high-voltage line accidentally grounds, which make advisable the addition of a tertiary winding in the three-phase core-type transformer even though it is not required to stabilize the neutral.

USE OF A TERTIARY WINDING TO FURNISH POWER FOR A SYNCHRONOUS CONDENSER

A tertiary winding is often used to furnish power to a synchronous condenser used for regulating the voltage at the receiver end of a transmission line. It is often possible to effect a considerable saving by having the transformer, which would be required for the synchronous condenser, combined with the main step-down transformer.

When a condenser is supplying leading kv-a. and the main load is at a lagging power factor the two loads combine to reduce the current flowing in the primary so that the addition of the condenser winding will

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[1] See paper on this subject by Mr. J. F. Peters, TRANS. A. I. E. E., 1915, p. 2157.

not increase the size of the primary winding as long as the condenser does not exceed twice the reactive component of the main load. If the condenser load were maintained at all times, it would even be possible to reduce the size of the primary. This is seldom the condition, however, and it is therefore the practise to design the primary so that it will carry full load with the condenser shut down.

The third winding in a transformer, whether it be for stabilizing the neutral point or for reducing the inductance in the connection between neutral and ground in a star-star connected bank or for supplying power to two loads of different power factors, introduces many features which must be recognized in the design and considered in predicting the operating characteristics of such transformers.

LIMITATIONS IMPOSED ON GROUPING OF THE WINDINGS

When transformers tie together three systems where the flow of power may be from any one to the other two or vice versa, one of the first requirements is that the reactance between any two windings be of about the same magnitude. If this is not the case, there will be large differences between the regulation with varying conditions of power flow between the interconnected systems. Moreover, with power supply on all three systems, if the reactance is low between any two of them, the currents flowing under short-circuit conditions will become dangerously large and there will be danger of mechanical injury to the transformer. Thus the problem is one of getting high enough reactance between any two windings without making that between any other two excessive.

In the single-phase concentric-coil core type of construction there are two ways in which the three windings may be arranged with respect to one another.

The first arrangement, Fig. 3a, will result in normal reactance between primary and secondary and between secondary and tertiary, but in very high reactance between the primary and the tertiary due to the greater separation and the resultant heavy leakage across the space occupied by the secondary winding. In the second arrangement, Fig. 3b, by making the disposition of the windings on the two legs different it is possible to equalize the reactances between pairs of the windings. This is a rather dangerous compromise however, because the leakage flux between any pair of windings in one direction on one leg is greater than that returning on the other leg. The excess will have to return through the space surrounding the transformer and would result in an intolerable condition due to the heating caused by the stray flux. If the loads on both secondaries happened to be in phase the condition would be improved as then the sum of the leakage would be the same on both legs. This is a condition which would be difficult if not impossible of accomplishment under operating conditions. With loads of different power factors the leakage flux between one secondary and the primary would be out of phase with that between the other secondary or tertiary and the primary resulting in the condition just described. In a three-phase concentric-coil core-type transformer there is no alternative but to submit to a high reactance between one pair of windings inasmuch as all the winding for one phase is on one leg.

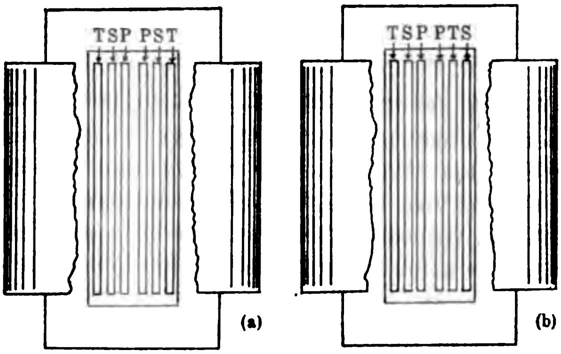

FIG. 3—PARTIAL SECTION THROUGH CORE-TYPE TRANSFORMER SHOWING DISPOSITION OF WINDINGS

In a shell-type transformer it is possible on account of the more extensive interlacing of the windings to equalize the reactance between all pairs of windings without causing heavy stray fields through the unbalancing of the leakage flux.

Refer to Fig. 4 and note that each half of the transformer is balanced in itself, *i e.*, the total leakage between P_1 and S is the same on the left side of P_1 as on the right side. The total leakage between P_2 and S is also the same on either side but its magnitude is different from that about P_1. The location of T with respect to P in one-half of the opening is the same as that of S in the other half so that the reactance between any pair of windings will be substantially the same without creating an unbalance which will result in heavy leakage fields.

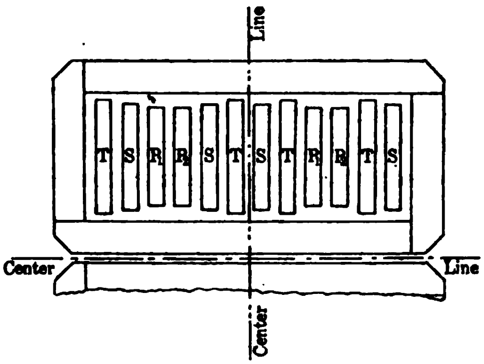

FIG. 4—PARTIAL SECTION THROUGH SHELL-TYPE TRANSFORMER SHOWING DISPOSITION OF WINDINGS

From the foregoing discussion it is quite evident that to design a three-winding transformer to meet certain specified values of reactance between each pair of windings would impose conditions which are extremely difficult and sometimes practically impossible to fulfill. This might be the condition presented to the designer if called upon to design a three-winding transformer to operate in parallel with another unit of different rating.

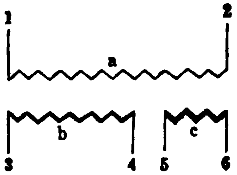

FIG. 5

REGULATION OF THREE-WINDING TRANSFORMERS

A three-winding transformer will usually have different voltage drops from primary to secondary and from primary to tertiary. Moreover, the voltage drop between primary and secondary is usually affected by the load on the tertiary so that if the tertiary is loaded there may be a drop from primary to secondary even though the latter winding is idle.

Let the sub-numbers and sub-letters refer to the windings as indicated in the sketch, Fig. 5.

R = resistance in ohms at reference voltage,
L = self-inductance in henrys,
M = mutual inductance in henrys,
$\underset{\cdot}{E}$ = reference voltage expressed as a complex quantity,
$\underset{\cdot}{I}$ = current in winding at reference voltage expressed as a complex quantity,
X = reactance between windings

$$= w\,(L_p - 2\,M_{ps} + L_s)$$

$$= 2w\,(L - M) \text{ where } L_p = L_s\,.$$

The voltage drop in each winding will be:

$$\underset{\cdot}{E}_{12} = -R_a\,\underset{\cdot}{I}_{12} - j\,w\,(L_a\,\underset{\cdot}{I}_{12} + M_{ab}\,\underset{\cdot}{I}_{34} + M_{ac}\,\underset{\cdot}{I}_{56}) \qquad (1)$$

$$\underset{\cdot}{E}_{34} = -R_b\,\underset{\cdot}{I}_{34} - j\,w\,(L_b\,\underset{\cdot}{I}_{34} + M_{ab}\,\underset{\cdot}{I}_{12} + M_{bc}\,\underset{\cdot}{I}_{56}) \qquad (2)$$

$$\underset{\cdot}{E}_{56} = -R_c\,\underset{\cdot}{I}_{56} - j\,w\,(L_c\,\underset{\cdot}{I}_{56} + M_{ac}\,\underset{\cdot}{I}_{12} + M_{bc}\,\underset{\cdot}{I}_{34}) \qquad (3)$$

$$\underset{\cdot}{I}_{12} = -(\underset{\cdot}{I}_{34} + \underset{\cdot}{I}_{56}) \qquad (4)$$

$$\underset{\cdot}{E}_{12} = +R_a\,(\underset{\cdot}{I}_{34} + \underset{\cdot}{I}_{56}) + j\,w\,[L_a\,(\underset{\cdot}{I}_{34} + \underset{\cdot}{I}_{56}) - M_{ab}\,\underset{\cdot}{I}_{34} - M_{ac}\,\underset{\cdot}{I}_{56}] \qquad (5)$$

$$\underset{\cdot}{E}_{34} = -R_b\,\underset{\cdot}{I}_{34} - j\,w\,[L_b\,\underset{\cdot}{I}_{34} - M_{ab}\,(\underset{\cdot}{I}_{34} + \underset{\cdot}{I}_{56}) + M_{bc}\,\underset{\cdot}{I}_{56}] \qquad (6)$$

$$\underset{\cdot}{E}_{56} = -R_c\,\underset{\cdot}{I}_{56} - j\,w\,[L_c\,\underset{\cdot}{I}_{56} - M_{ac}\,(\underset{\cdot}{I}_{34} + \underset{\cdot}{I}_{56}) + M_{bc}\,\underset{\cdot}{I}_{34}] \qquad (7)$$

The voltage drop from winding *a* through winding *b*:

$$-(\underset{\cdot}{E}_{12} - \underset{\cdot}{E}_{34}) = (R_a + R_b)\,\underset{\cdot}{I}_{34} + j\,w\,(L_a - 2\,M_{ab} + L_b)\,\underset{\cdot}{I}_{34} + R_a\,\underset{\cdot}{I}_{56} + j\,w\,(L_a - M_{ac} - M_{ab} + M_{bc})\,\underset{\cdot}{I}_{56} \qquad (8)$$

Adding $1/2\,j\,w\,(L_b - L_b + L_c - L_c)\,\underset{\cdot}{I}_{56}$ and recombining,

$$= (R_a + R_b)\,\underset{\cdot}{I}_{34} + j\,w\,(L_a - 2\,M_{ab} + L_b)\,\underset{\cdot}{I}_{34} + R_a\,\underset{\cdot}{I}_{56} + 1/2\,j\,w\,[(L_a - 2\,M_{ab} + L_b) + (L_a - 2\,M_{ac} + L_c) - (L_b - 2\,M_{bc} + L_c)]\,\underset{\cdot}{I}_{56} \qquad (9)$$

but, $w\,(L_p - 2\,M_{ps} - L_s)$ is the reactance between primary and secondary, then,

$$-\,(\underset{\cdot}{E}_{12} - \underset{\cdot}{E}_{3}) = [\,(R_a + R_b) + j\,X_{ab}\,]\,\underset{\cdot}{I}_{34} \\ + [R_a + 1/2\,j\,(X_{ab} + X_{ac} - X_{bc})\,]\,\underset{\cdot}{I}_{56} \qquad (10)$$

in the same way

$$-\,(\underset{\cdot}{E}_{12} - \underset{\cdot}{E}_{56}) = [\,(R_a + R_c) + j\,X_{ac}]\,\underset{\cdot}{I}_{56} + [R_a \\ + 1/2\,j\,(X_{ab} + X_{ac} - X_{bc})\,]\,\underset{\cdot}{I}_{34} \qquad (11)$$

These voltage drops will appear as complex quantities and may be reduced to percentage by dividing by the reference voltage $\underset{\cdot}{E}$. They will then be in the form

$$\pm\, a\,\% \pm j\,b\,\%.$$

Then

$$\%\ \text{Regulation} = \pm\, a\,\% + \frac{(\pm\, b\,\%)^2}{200} \qquad (12)$$

The sign of the regulation may be positive or negative, a positive sign indicating a drop and a negative sign a rise in voltage as the load is increased.

It will be noticed that in each voltage drop there is a term which depends upon the current which flows in the winding which is not being considered, for instance, in the voltage drop from winding a to winding b there is a component produced by the flow of the current $\underset{\cdot}{I}_{56}$ in winding c. This indicates that there will be a certain amount of regulation on a winding even at no-load, providing load is being taken from one of the other windings. The condition under which this influence will be a minimum is that $X_{ab} + X_{ac} = X_{bc}$.

The following tables will indicate in a general way how changes in load affect the regulation of a typical three-winding transformer. The transformer chosen is typical of the type under consideration. It is a 35,000-kv-a., single-phase, 60-cycle, star-star connected transformer designed to step down 30,300 kv-a. at 100 per cent power factor, from 220 kv. to 66 kv. and to supply a synchronous condenser of 17,500-kv-a. capacity at 13 kv., the tertiary winding being connected in delta.

TABLE I

Regulation in per cent with varying condenser load. Load on 66-kv. winding constant at 30,300 kv-a. 100 per cent power factor.

Kv-a. at 0% power factor on condenser	Regulation on 66-kv. line	Regulation on 13-kv. line
100 % leading	− 3.12	− 10.75
75 " "	− 2.12	− 7.95
50 " "	− 1.10	− 5.12
25 " "	− 0.095	− 2.31
0 "	+ 0.91	+ 0.48
25 " lagging	+ 1.92	+ 3.29

TABLE II

Regulation in per cent with varying load. Condenser supplying 17,500 kv-a. at 0 per cent power factor leading.

Kv-a. at 100% power factor on 66-kv. line	Regulation on 66-kv. line	Regulation on 13-kv. line
100%	− 3.12	− 10.75
75	− 3.43	− 10.91
50	− 3.69	− 11.06
25	− 3.89	− 11.18
0	− 4.04	− 11.24

TABLE III

Regulation in per cent with varying power factor on 66-kv. winding. Condenser supplying 17,500 kv-a. at 0 per cent power factor leading

30,300 kv-a. on 66-kv. line at power factor	Reg. on 66-kv. line	Reg. on 13-kv. line
100%	− 3.12	− 10.75
95	− 0.26	− 8.59
90	+ 0.83	− 7.75
85	+ 1.60	− 7.15
80	+ 2.25	− 6.67

APPLICATION OF FORMULAS TO AUTO-TRANSFORMERS

It has been pointed out that the star-star connected auto-transformer with a tertiary winding is a special case of three-winding transformers.

Following the same system of notation and referring to Fig. 6, note that there are three conditions of loading.

(A) Winding 13 delivering power to, or receiving power from, windings 23 and 45.

(B) Winding 23 delivering power to, or receiving power from, windings 13 and 45.

(C) Winding 45 delivering power to, or receiving power from, windings 13 and 23.

CASE A. Let $\underset{\cdot}{I}$ with proper subscript = current due to load on auto-transformers.

Let $\underset{\cdot}{I}'$ with proper subscript = current due to load on two-winding transformer.

$$\underset{\cdot}{E}_{13} = -R_a\,\underset{\cdot}{I}_{12} - R_b\,\underset{\cdot}{I}_{23} - (R_a + R_b)\,\underset{\cdot}{I}_{13}' - j\,w\,(L_a\,\underset{\cdot}{I}_{12} + L_b\,\underset{\cdot}{I}_{23} + M_{ab}\,\underset{\cdot}{I}_{12} + M_{ab}\,\underset{\cdot}{I}_{23} + L_{ab}\,\underset{\cdot}{I}_{13}' + M_{ab-c}\,\underset{\cdot}{I}'_{45}) \qquad (13)$$

$$\underset{\cdot}{E}_{23} = -R_b\,(\underset{\cdot}{I}_{23} + \underset{\cdot}{I}_{13}') - j\,w\,[L_b\,(\underset{\cdot}{I}_{23} + \underset{\cdot}{I}_{13}') + M_{ab}\,(\underset{\cdot}{I}_{12} + I_{13}') + M_{bc}\,\underset{\cdot}{I}_{45}'] \qquad (14)$$

$$\underset{\cdot}{E}_{45} = -R_c\,I_{45}' - j\,w\,(L_c\,\underset{\cdot}{I}_{45}' + M_{ac}\,\underset{\cdot}{I}_{12} + M_{bc}\,\underset{\cdot}{I}_{23} + M_{ab-c}\,\underset{\cdot}{I}_{13}') \qquad (15)$$

In order to handle the ratio between windings *a b* and *b* it is necessary to introduce a factor *r*.

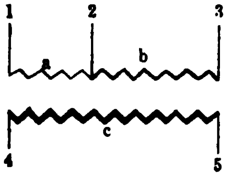

FIG. 6

$$\text{Let} \quad \frac{\underset{\cdot}{E}_{13}}{\underset{\cdot}{E}_{23}} = r = \frac{\underset{\cdot}{E}_{12} + \underset{\cdot}{E}_{23}}{\underset{\cdot}{E}_{23}} = \frac{\underset{\cdot}{E}_{12}}{\underset{\cdot}{E}_{23}} + 1,$$

$$\text{then} \ \frac{\underset{\cdot}{E}_{12}}{\underset{\cdot}{E}_{23}} = (r - 1)$$

$$\text{and} \quad \frac{\underset{\cdot}{I}_{12}}{\underset{\cdot}{I}_{23}} = \frac{1}{r-1} \ \text{or}$$

$$\underset{\cdot}{I}_{23} = -(r-1)\,\underset{\cdot}{I}_{12}; \ \text{also,}\ \underset{\cdot}{I}_{45}' = -\underset{\cdot}{I}_{13}'$$

Then,

$$\underset{\cdot}{E}_{13} = -[R_a - (r-1)\,R_b]\,\underset{\cdot}{I}_{12} - R_{ab}\,\underset{\cdot}{I}_{13}' - j\,w\,[L_a\,\underset{\cdot}{I}_{12} - (r-1)\,L_b\,\underset{\cdot}{I}_{12} + (2-r)\,M_{ab}\,\underset{\cdot}{I}_{12} + L_{ab}\,\underset{\cdot}{I}_{13}' - M_{ab-c}\,\underset{\cdot}{I}_{13}'] \qquad (16)$$

$$\begin{aligned}\underset{\cdot}{E}_{23} = {} & R_b\,[\,(r-1)\,\underset{\cdot}{I}_{12} - I_{13}'] + j\,w\,[L_b\,(r-1)\,\underset{\cdot}{I}_{12} \\ & - L_b\,I_{13}' - M_{ab}\,(\underset{\cdot}{I}_{12} + \underset{\cdot}{I}_{13}') + M_{bc}\,\underset{\cdot}{I}_{13}'] \qquad (17)\end{aligned}$$

$$\begin{aligned}\underset{\cdot}{E}_{45} = {} & R_c\,\underset{\cdot}{I}_{13}' + j\,w\,[L_c\,\underset{\cdot}{I}_{13}' - M_{ac}\,\underset{\cdot}{I}_{12} \\ & + (r-1)\,M_{bc}\,\underset{\cdot}{I}_{12} - M_{ab\text{-}c}\,\underset{\cdot}{I}_{13}') \qquad (18)\end{aligned}$$

The voltage drop from winding *a* through winding *b*:

$$\begin{aligned}-(\underset{\cdot}{E}_{13} - r\,\underset{\cdot}{E}_{23}) = {} & [R_a + (r-1)^2\,R_b]\,\underset{\cdot}{I}_{12} \\ & + j\,w\,[L_a - 2\,(r-1)\,M_{ab} + (r-1)^2\,L_b]\,\underset{\cdot}{I}_{12} \\ & + (R_{ab} + r\,R_b)\,\underset{\cdot}{I}_{13}' + j\,w\,(L_{ab} - M_{ab\text{-}c} - r\,L_b \\ & - r\,M_{ab} + r\,M_{bc})\,\underset{\cdot}{I}_{13}' \qquad (19)\end{aligned}$$

Adding $1/2\,j\,w\,(L_c - L_c + r^2\,L_b - r^2\,L_b)\,I_{13}'$ and recombining and making use of the relation

$$1/2\,L_{ab} = 1/2\,(L_a + 2\,M_{ab} + L_b)$$

$$\begin{aligned}= {} & [R_a + (r-1)^2\,R_b]\,\underset{\cdot}{I}_{12} + j\,w\,[L_a - 2\,(r - 1\,M_{ab} \\ & + (r-1)^2\,L_b]\,\underset{\cdot}{I}_{12} + (R_{ab} + r\,R_b)\,\underset{\cdot}{I}_{13}' \\ & + j\,w\,1/2\,(L_{ab} - 2\,M_{ab\text{-}c} + L_c)\,\underset{\cdot}{I}_{13}' + j\,w\,1/2\,[L_a \\ & - 2\,(r-1)\,M_{ab} + (r-1)^2\,L_b]\,\underset{\cdot}{I}_{13}' - j\,w\,1/2\,(L_c \\ & - 2\,r\,M_{bc} + r^2\,L_b)\,\underset{\cdot}{I}_{13}' \qquad (20)\end{aligned}$$

$$\begin{aligned}= {} & [R_a + (r-1)^2\,R_b]\,\underset{\cdot}{I}_{12} + j\,X_{ab}\,\underset{\cdot}{I}_{12} \\ & + (R_{ab} + r\,R_b)\,\underset{\cdot}{I}_{13}' + j\,1/2\,(X_{ab\text{-}c} + X_{ab} \\ & - X_{bc})\,\underset{\cdot}{I}_{13}' \qquad (21)\end{aligned}$$

Similarly, the voltage drop from winding *a* through winding *c*

$$\begin{aligned}-(\underset{\cdot}{E}_{13} - \underset{\cdot}{E}_{45}) = {} & (R_{ab} + R_c)\,\underset{\cdot}{I}_{13}' + j\,X_{ab\text{-}c}\,\underset{\cdot}{I}_{13}' \\ & + [R_a - (r-1)\,R_b]\,\underset{\cdot}{I}_{12} \\ & + j\,1/2\,(X_{ab\text{-}c} + X_{ab} - X_{bc})\,\underset{\cdot}{I}_{12} \qquad (22)\end{aligned}$$

The regulation may be obtained from these voltage drops in the same way as from equations (11) and (12).

CASE B. Developing this case in exactly the same way results in expressions as follows. The voltage drop from winding *b* through winding *a b*:

$$\begin{aligned}(r\,\underset{\cdot}{E}_{23} - \underset{\cdot}{E}_{13}) = {} & [R_a + (r-1)^2\,R_b]\,\underset{\cdot}{I}_{12} + j\,X_{ab}\,\underset{\cdot}{I}_{12} \\ & + r\,(r-1)\,R_b\,\underset{\cdot}{I}_{45}' + j\,1/2\,(X_{ab} + X_{bc} \\ & - X_{ab\text{-}c})\,\underset{\cdot}{I}_{45}' \qquad (23)\end{aligned}$$

The voltage drop from winding *b* through winding *c*:

$$\begin{aligned}(r\,E_{23} - \underset{\cdot}{E}_{45}) = {} & (R_c + r^2\,R_b)\,\underset{\cdot}{I}_{45}' + j\,X_{bc}\,\underset{\cdot}{I}_{45}' \\ & + r\,(r-1)\,R_b\,\underset{\cdot}{I}_{12} + j\,1/2\,(X_{ab} + X_{bc} \\ & - X_{ab\text{-}c})\,\underset{\cdot}{I}_{12} \qquad (24)\end{aligned}$$

CASE C. In the same manner under this condition the drop from winding c through winding $a\,b$:

$$\begin{aligned} -(\underset{\cdot}{E}_{45}-\underset{\cdot}{E}_{12}) &= (R_c+R_{ab})\,\underset{\cdot}{I}_{45}+j\,X_{ab\text{-}c}\,\underset{\cdot}{I}_{45} \\ &+ (R_c+r\,R_b)\,\underset{\cdot}{I}_{45}{}'+j\,1/2\,(X_{ab\text{-}c}+X_{bc} \\ &\qquad - X_{ab})\,\underset{\cdot}{I}_{45}{}' \qquad (25) \end{aligned}$$

and the drop from winding c through winding b:

$$\begin{aligned} -(\underset{\cdot}{E}_{45}-r\,\underset{\cdot}{E}_{23}) &= (R_c+r^2\,R_b)\,\underset{\cdot}{I}_{45}{}'+j\,X_{bc}\,\underset{\cdot}{I}_{45}{}' \\ &+ (R_c+r\,R_b)\,\underset{\cdot}{I}_{45}+j\,1/2\,(X_{ab\text{-}c}+X_{bc} \\ &\qquad - X_{ab})\,\underset{\cdot}{I}_{45} \qquad (26) \end{aligned}$$

Referring back to Fig. 5, assume a short circuit occurs on winding a. Let $R_b'+j\,X_b'$ and $R_c'+j\,X_c'$ represent the impedance of the lines and generators connected to windings b and c, respectively. Including these impedances in the voltage drops as given by equations (10) and (11) we have:

$$\begin{aligned} -(\underset{\cdot}{E}_{12}-\underset{\cdot}{E}_{34}) &= [\,(R_a+R_b+R_b')+j\,(X_{ab} \\ &+ X_b')\,]\,\underset{\cdot}{I}_{34}+[R_a+1/2\,j\,(X_{ab}+X_{ac} \\ &\qquad - X_{bc})\,]\,\underset{\cdot}{I}_{56} \qquad (27) \end{aligned}$$

$$\begin{aligned} -(\underset{\cdot}{E}_{12}-\underset{\cdot}{E}_{56}) &= [\,(R_a+R_c+R_c')+j\,(X_{ac} \\ &+ X_c')\,]\,\underset{\cdot}{I}_{56}+[R_a+1/2\,j\,(X_{ab}+X_{ac} \\ &\qquad - X_{bc})\,]\,\underset{\cdot}{I}_{34} \qquad (28) \end{aligned}$$

Let

$$Z_1 = R_a+1/2\,j\,(X_{ab}+X_{ac}-X_{bc}) \qquad (29)$$

$$Z_2 = R_b+R_b'+j\,X'_b+1/2\,j\,(X_{bc}+X_{ab}-X_{ac}) \qquad (30)$$

$$Z_3 = R_c+R_c'+j\,X_c'+1/2\,j\,(X_{ac}+X_{bc}-X_{ab}) \qquad (31)$$

Then

$$\underset{\cdot}{I}_{34} = \frac{Z_3}{Z_1Z_2+Z_1Z_3+Z_2Z_3}\,\underset{\cdot}{E} \qquad (32)$$

$$\underset{\cdot}{I}_{56} = \frac{Z_2}{Z_1Z_2+Z_1Z_3+Z_2Z_3}\,\underset{\cdot}{E} \qquad (33)$$

and

$$\underset{\cdot}{I}_{12} = \underset{\cdot}{I}_{34}+\underset{\cdot}{I}_{56} = \frac{Z_2+Z_3}{Z_1Z_2+Z_1Z_3+Z_2Z_3}\,\underset{\cdot}{E} \qquad (34)$$

The most satisfactory method of calculating short-circuit currents in a complicated network is by the use of a calculating board, *i. e.*, by setting up a network of resistances whose values are proportional to the impedances of the various parts of the system, impressing a known voltage, and measuring the currents which flow in the various branches of the network. From these measurements the magnitudes of the actual short-circuit currents are calculated. It is interesting to note from equations (27) and (28) how a three-winding transformer would be set up on such a calculating board. One component of impedance is common to both $-(\underset{\cdot}{E}_{12} - \underset{\cdot}{E}_{34})$ and $-(\underset{\cdot}{E}_{12} - \underset{\cdot}{E}_{56})$ so that the three-winding transformer may be represented by a three-legged star with legs respectively Z_1, Z_2 and Z_3. (Fig. 7).

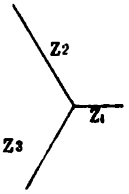

FIG. 7—GRAPHICAL REPRESENTATION OF IMPEDANCES IN A THREE-WINDING TRANSFORMER

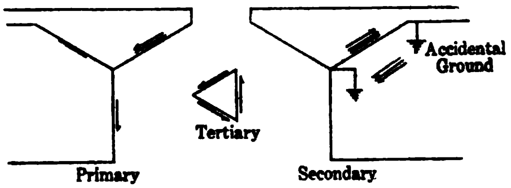

FIG. 8—FLOW OF CURRENT WHEN SECONDARY LINE GROUNDS—STAR-STAR CONNECTION WITH TERTIARY

EFFECT OF A TERTIARY WINDING IN LIMITING CURRENT WHICH FLOWS WHEN ONE LINE ACCIDENTALLY GROUNDS

In a star-star connected transformer with a tertiary winding and with the neutral grounded on either or both of the high and low-voltage sides but with the neutral of the supply not grounded, the magnitude of the current which flows in case of an accidental ground on one of the lines is influenced very largely by the reactance between the main windings and the tertiary. In a transformer with a 1 to 1 turn ratio between all windings the current in the tertiary will always be one-third of the current flowing to ground on the secondary side because this is the only division of current which makes the ampere turns of primary and secondary equal in each phase. Refer to Fig. 8 which shows quantitatively how the currents would divide under the conditions shown.[2] The ampere turns of phase *A* on the grounded side are balanced by those in phase *A* on the primary side and by those in phase *A C* in the tertiary. The conditions which determine the division of current are that the current in each leg of the tertiary be the same since it flows in series through each of them, and that the sum of the currents in phases *B* and *C* on the primary side be equal to the current in phase *A* since the current is a single-phase current. The only way current can divide between phases *B* and *C* and fulfill these conditions is to divide equally. Since the currents in phases *B* and *C* of the grounded side carry no current, that which flows in the same phases of the primary side must be all balanced by the current in the same phase of the tertiary.

The total magnitude of the ground current usually depends partly upon the impedance of the generators supplying the line to the unbalanced currents which flow through them under such conditions. For this reason it is difficult to calculate accurately as these special impedance measurements are seldom at hand. It is quite evident however that with large capacity back of the transformer, the impedance of the generator and supply lines is relatively small, and the magnitude of the current which flows depends largely upon the impedance between various pairs of windings in the transformer, and may be closely approximated

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[2] See Article in the *Elec. Journal*, Nov. 1919, Tertiary Winding in Transformers, Their Effect on Short-Circuit Currents, by J. F. Peters.

by neglecting the generator and supply line impedance and assuming full voltage maintained. Under this assumption the currents flowing under various combinations of grounding will be as given in Table IV.

I_n = normal current in winding at full load.

Z_o = impedance voltage between primary and secondary in per cent at full load.

Z_t = impedance voltage between primary or secondary and tertiary in per cent at a load in the tertiary corresponding to full load, depending upon the winding under consideration.

This means that in any of these connections the ground connection has more or less inductance in it. The amount of inductance can be minimized by keeping these same impedances to low values. This fact shows why it is necessary to supply a tertiary winding for a three-phase core-type transformer, if there is no tertiary. The ampere turns in the winding which is grounded are balanced by the ampere turns on the other two legs, and the leakage flux would be very great. This is equivalent to a tertiary with very high reactance and means that the ground current would be limited to a very low value. However, it is limited by what is equivalent to inserting a large inductance in the neutral cônnection. When a three-phase core-type transformer without a tertiary is under consideration

TABLE IV

Connection of Transformer bank		Supply	Side on which fault occurs	Tertiary	Short-circuit Current	
Primary	Secondary				In tertiary	In main winding
Star Grounded	Star Grounded	Grounded	Secondary	No	0	$\frac{100\ I_n}{Z_o}$
Star Grounded	Star Grounded	Isolated	Primary	Yes	$\frac{100\ I_n}{Z_t}$	$\frac{100\ I_n}{Z_t}$
Star Grounded	Star Grounded	Isolated	Secondary	Yes	$\frac{100\ I_n}{2Z_o + Z_t}$	$\frac{300\ I_n}{2Z_o + Z_t}$
Star	Star Grounded	Grounded or Isolated	Primary	Yes	0	0
Star	Star Grounded	Grounded or Isolated	Secondary	Yes	$\frac{100\ I_n}{2Z_o + Z_t}$	$\frac{300\ I_n}{2Z + Z_t}$

Z_t becomes the impedance voltage between the winding on one leg and the windings on the other two connected in parallel in per cent at full load.

For this reason all transformers for star-star connection should be equipped with tertiary windings and the impedance between main windings and tertiary should be kept fairly low to avoid the conditions which obtain when there is inductance in the neutral connection. When the tertiary is not designed to supply a load its capacity is determined by the heating conditions imposed by short circuits. For this reason the short-circuit conditions should be carefully investigated and full information furnished the designer.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 23, 1921.

THE ELECTRIC STRENGTH OF AIR UNDER CONTINUOUS POTENTIALS AND AS INFLUENCED BY TEMPERATURE

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ABSTRACT OF PAPER

The paper describes a series of experiments on the influence of temperature on corona-forming continuous potentials. The observations have been made on three sizes of wire of diameters 0.0251 cm., 0.0803 cm., and 0.0933 cm., and in each case at several values of temperature within the range 5 deg. cent and 70 deg. cent. At each temperature the pressure has been varied from a value in the neighborhood of that of the atmosphere downwards, reaching in the extreme cases the value 6.03 cm. of mercury. Within the range of values reached, as indicated above, the general form of the law of corona, as developed experimentally by a number of other observers, is found to be fulfilled. There are separate families of curves for positive and negative potentials as obtained by varying the pressure for each constant value of temperature.

The observations show that under constant conditions as to pressure and temperature a higher value of negative potential than positive potential is required to form corona.

As plotted graphically, the results seem to indicate that when larger wires are used corona appears at the same values of both positive and negative potential. The observations, however, have not been extended sufficiently to show this identity of value. This conclusion is at variance with the observations, of a number of other experimenters, in particular those of W. S. Brown, who concludes that with larger values of diameter of wire negative corona may appear at lower values than positive corona.

The experiments substantiate the empirical laws developed by Whitehead and Peek, although the constants of the equations involved are higher than any heretofore observed. There is some indications that at temperatures in the neighborhood of 70 deg. cent. a departure from the empirical laws mentioned may set in.

INTRODUCTION AND HISTORICAL SETTING

THE LAW of corona formation on round wires in air has been devised empirically from the observations of a number of experimenters. It involves the electric intensity at the surface of the wire, the radius of the wire, and the relative density of the air.

The empirical law has been investigated over quite wide ranges of values of radius of wire and air density as dependent on pressure. Comparatively few attempts have been made however to study the influence of temperature on corona formation. This paper describes a series of experiments in which corona voltages have been measured at several temperatures within the range of 5 deg. cent. to 70 deg. cent., the pressure being varied in each case from that of atmosphere downward, in the extreme cases to 6.03 cm. of mercury.

Continuous potential has been used throughout the work. Various investigators have shown that with alternating corona voltages the maximum values of the wave are very closely, if not identically, the same as the continuous voltage values.

The law of corona had its origin in the laws governing the sparking between plates. Townsend[2], upon the experiments formed by J. B. Baille[1], first stated the relation for the sparking voltage in air as given by the formula

$$V = 39\,P\,S + 1700 \qquad (1)$$

Where V = voltage between two parallel plates,
P = pressure of the gas,
S = the distance between the plates.

This formula by dividing through by $P\,S$ gave use to the relation

$$\frac{E}{P} = 39 + \frac{1700}{P\,S} \qquad (2)$$

Since the electric intensity between the plates is uniform and therefore $\frac{V}{S} = E$. The relation concentrated the attention upon the electric intensity and not upon the total voltage. Townsend in his development of secondary ionization first showed that in a corona tube the distance S in the above formula is that of the path which an ion traverses in the greatest field and therefore is next to the wire. Under this consideration the above formula for the corona tube is,

$$\frac{E}{P} = A + \frac{B}{r_w} \cdot \frac{1}{\sqrt{P}} \qquad (3)$$

Where A and B are constants of the phenomena and r_w is the radius of the wire. This equation giving the law of corona formation was first developed experimentally by Whitehead, Peek and others, and Townsend has shown that it may be derived from his experiments on gaseous ionization at low pressures and that it is in accord with the theory of ionization by collision.

Whitehead[8] first determined these constants in a corona tube for air under normal conditions. Peek[11] later showed that the density or the pressure and the temperature together affected the formation of corona and established the density factor δ.

$$\delta = \frac{3.92\, P}{T} \qquad (4)$$

where P = pressure of the gas in centimeters of mercury,
T = absolute temperature in degrees centigrade.

The corona formula then reduced to the form

$$\frac{E}{\delta} = A + \frac{B}{\sqrt{\delta\, r_w}} \qquad (5)$$

which it has at present.

Whitehead[8] and Peek[11] carefully investigated the values of A and B with alternating potential by changing δ, r_w, humidity of the air and the material of the wire. Later Whitehead and Brown[8] also determined the constants A and B with continuous potentials by changing the diameter of the wire. Farwell[6], Watson[4] and Schaffers[5] also worked with direct potentials upon corona. Their method of detecting corona was mostly visual and with the methods and material available at that time they secured qualitative results which later experiments under more favorable conditions to a larger degree confirmed.

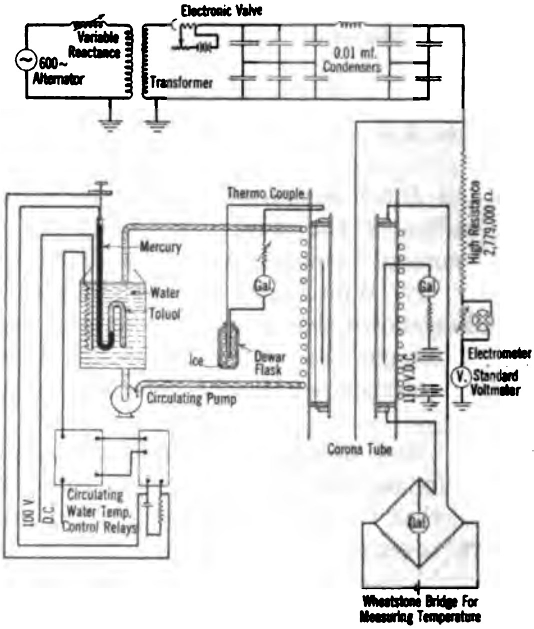

FIG. 1—CONNECTION OF HIGH-POTENTIAL VOLTAGE TO CORONA TUBE AND AUXILIARY APPARATUS

It remained for Whitehead and Pullen[3] to develop a tube which gave more sensitive indications of corona.

This experimental investigation aims to continue the work of Whitehead and Brown[3] with continuous potentials. The immediate purpose was to investigate the constants A and B with positively and negatively charged wires under different temperatures and variable pressures at each temperature.

DESCRIPTION OF APPARATUS

The source of high continuous potential in these tests was secured from a "kenotron"* or rectifying vacuum tube, in connection with a high voltage transformer and condensers. Fig. 1 indicates the manner in which they were connected and how they were controlled.

The alternator was a two-armature generator designed to operate at either 600 cycles or at 3000 cycles and was directly connected to a three-h. p., 220-volt continuous-current shunt motor. The motor power, as well as the field excitation were secured from a 450-ampere-hour, 110-220-volt storage battery to insure steadiness of alternating potential.

The voltage to the transformer was controlled by a variable iron reactance. This reactance consisted of two coils mounted upon the legs of a core type transformer in which the core could be adjusted. The adjustment was accomplished by a screw having a pitch of twenty threads to the inch, and in this way the reluctance of the magnetic circuit was changed; and this in turn changed the ratio of voltage upon the transformer and the reactance coil. The generator voltage remained constant. In this way the high potential voltage could be raised in a continuous manner with an exceptional degree of adjustment.

In the high-tension circuit of the transformer a kenotron was connected in series with a battery of condensers, of which each unit had a capacity of 0.01 microfarad. The kenotron was designed for 40,000 volts and 1/10 ampere. In this experiment the voltage was limited by the condensers to 20,000 volts. The current taken by the exciting coil of the kenotron was six amperes for 100 per cent electronic emission. The resistance of the heating filament, a ten-mil tungsten wire was one ohm. The construction and theory of the kenotron are now quite well understood and thoroughly described by Dushman[7]. A small storage battery of six cells in series with a small carbon compression rheostat was sufficient to properly excite and regulate the filament current. The kenotron together with its exciting apparatus

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*Name given by General Electric Company to a rectifying Fleming valve.

was carefully insulated from the ground by wooden insulators and logical grouping.

The condensers were of the oil-insulated high-potential type and were grouped into two batteries, one of six units, the other of four units each. The combined capacity of the first condenser battery was 0.015 microfarad and the combined capacity of the second condenser battery was 0.01 microfarad. The needle gap of each condenser was adjusted to 10,000 volts, thereby making the voltage across two condensers 20,000 volts. Between these two batteries was connected an inductance of 0.027 henry. According to Hull[8] the voltage fluctuation would be,

$$V = \frac{8\, i\, \pi}{L\, w^3} \left(C + \frac{1}{L\, w^2} \right)^2 \tag{6}$$

$$= 4.62 \times i \times 10^{-10} \text{ volts}$$

where C = total capacity in farads,

$w = 2\,\pi\, f = 2\,\pi \times 600$ angular velocity in radians per sec.

L = coefficient of self-induction in henrys between condenser batteries,

i = current taken from the second condenser battery.

The current i which was used in the voltage measuring circuit never exceeded 0.01 ampere. From the above formula it is seen that the correction factor is negligible. That this coincided with experimental observations was tested by Brown[3].

The voltage was measured with a precision Weston voltmeter in series with a resistance of 1,428,000 ohms of manganin wire and of 1,343,000 ohms of lavite resistances. About 50 watts was the maximum rate of energy dissipation in the form of heat in this circuit. The quadrant electrometer connected as shown was not used for detecting corona voltage, but for other purposes to be described later. The resistance in this circuit did not change within the range of 1 per cent in this experiment as tested by a Wheatstone bridge upon the summation of the individual units composing this resistance. (See Fig. 2.)

The corona tube as constructed for this experiment was similar to the one constructed before by Whitehead[3] and Pullen[3]. The main chamber was constructed from a piece of 6-in. steel piping 19 in. long. This pipe was carefully bored out in a lathe so as to receive the concentric cylinder supports and perforated corona cylinder. (See Fig. 3.) Around the inner 4-in. brass cylinder was another metal cylinder carefully insulated from it. This insulated cylinder received a small fraction of the corona current and, in conjunction with a galvanometer, served to indicate the presence of corona. (See Fig. 1.) The tube was closed at each end by a fiber head which also supported the central wire. Glass, one inch thick, was first

FIG. 2

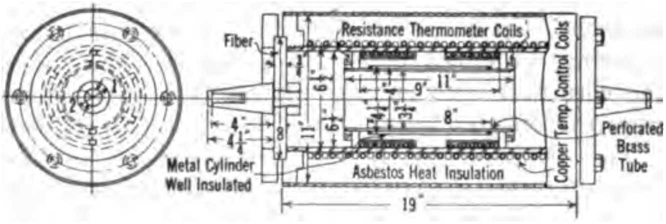

FIG. 3—DIAGRAM SHOWING CONSTRUCTION AND DIMENSIONS OF TUBE

tried for this purpose, but it was found that it was unable to withstand the stress due to internal pressure. The fiber used for this purpose was thoroughly boiled in paraffin to expel all moisture. Glass windows were inserted into this fiber to observe the condition of the wire at all times. Around the outside of this cylinder were wrapped coils of copper tubing to serve as heating or cooling coils to the apparatus. These coils of copper tube were further insulated as to heat on the outside by an asbestos heat insulating compound. Directly above and below the inside brass cylinder, but out of the electric field, were placed two copper wire coils each having a resistance of two ohms. These two coils were connected in series and served as a resistance thermometer. A thermocouple was also placed in the tube well away from the iron walls, to measure the temperature of the gas. The thermocouple was made with a very small heat capacity so as to quickly acquire the surrounding temperature, and thereby give an indication of any quick change of temperature of the gas inside of the tube. All of the joints were carefully packed with string first immersed in a packing compound. Insulated terminals were taken from the tube by the aid of spark plugs. The pipe joints were all well coated with litharge before finally adjusting them. All of the cylinders were machined to align centrally and the adjustment was within one-hundredth of an inch. Upon the outside of the tube was placed a spring, as shown in Fig. 4, which served to keep the wire taut with changes of length of tube arising from the unequal expansion to the tube and its wire.

The temperature of the circulating water used in maintaining the temperature of the tube was controlled by a special thermostatic regulator. This regulator consisted of a glass tube of 3/16-in. bore, sealed at one end, filled with mercury and toluol, as indicated. Since the coefficient of volumetric temperature expansion of mercury is too small for sensitive regulation, toluol was also placed in this tube, as shown in the diagram of connections. The mercury acted as a seal for the very volatile toloul and at the same time served as a conductor in all the control circuits. The circulating water was heated with an immersion iron wire rheostat and was capable of carrying, when submerged, fifty amperes. This current was automatically interrupted by a remotely controlled switch, when the water had risen to its predetermined temperature. The control circuit of this switch was operated through a telegraph relay since it was necessary to interrupt this control circuit at a difference of potential of 110 volts d-c. A six-volt storage battery was used to excite this relay connected in series with a resistance. When the mercury in the tube had risen sufficiently high it short-circuited the battery connection to the relay and thereby opened the remotely controlled switch. As soon as the temperature receded this short circuit was removed and allowed the heating current to reestablish itself. The final temperature of the cirlating water was adjusted by means of a regulating screw. The height of this regulating screw determined the amount of expansion which the mercury and toluol could have before actuating the control circuits.

Fig. 4

This constant temperature water was circulated by a positive rotary pump through the heating coils of the tube. By this method the corona tube reached a final steady temperature after one and one-half hours. The difference in temperature of the circulating water and of the gas in the tube was three degrees when operating in a steady state. Tempera tures lower than room temperatures were secured by using cracked ice in the circulating water supply tank. The temperature of the circulating water in this case was that of melting ice, which was sufficiently constant for the experiment. In a like manner the temperature of one thermal junction was kept constant; only here a Dewar flask or thermos bottle was used to keep the ice from melting too rapidly.

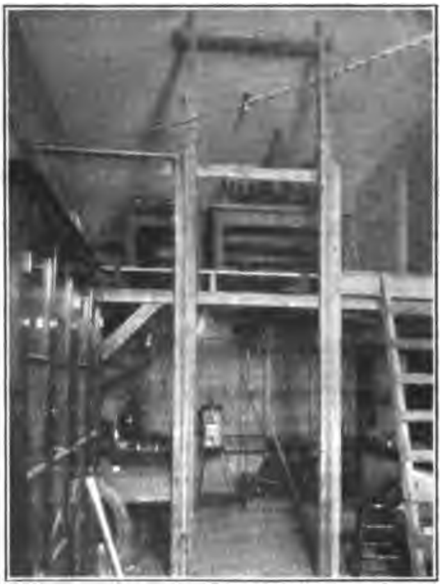

Fig. 5

The vacuum pump used to exhaust the corona tube was a small "Gyrek" model belted to a motor. (See Fig. 4.) The pressure was measured directly with a mercury manometer. Needle valves were used in all of the pressure control tubes to assure positive closing of the air connections.

From Fig. 5 it is seen that with the arrangement employed here it was possible to use but one lamp for illuminating the galvanometer mirrors, and also one scale sufficed to measure their deflection. The scale in this case was constructed from a ten-foot California redwood board bent into the arc of a circle of ten feet radius and mounted ten feet from the temperature measuring galvanometer. For indicating the presence of corona a D'Arsonval galvanometer slightly underdamped was used. This galvanometer ordinarily had a sensitivity of 83 megohms but with the above scale arrangement it was increased to 250 megohms.

It was found expedient, because of the large amount of apparatus used for operating this experiment, to separate the high-potential apparatus from the remainder by a platform. The platform was constructed above the corona tube, as is shown in Fig. 5. In this way it was possible to do all of the manipulating with dispatch and without any danger of coming into contact with high-potential circuits.

PRELIMINARY EXPERIMENTS

The method of securing high-potential direct-current voltage was substantially the same as that used by Brown[3]. However, it was found more convenient to control the alternating-current potential across the transformer with a reactance than with the field circuit of the alternator.

The voltmeter used in these tests was a precision Weston model No. 1064. It was, however, checked with a Weston standard cell and a Leeds and Northrup potentiometer through its entire range and was found accurate within the limits of observation.

The resistances of the voltage measuring circuit were measured with a Leeds and Northrup precision bridge and checked from time to time.

The thermocouple was made from a junction of "Advance" and copper wire and was calibrated with a standard mercury thermometer in a bath of water well agitated and slowly cooling. With the aid of a resistance in the copper portion of this circuit it was possible to adjust the deflection to an exact multiple of the temperature unit. One degree centigrade corresponded to a deflection of two divisions upon the scale. The resistance of the galvanometer was 110 ohms and the extra resistance in the circuit was 1161 ohms, thereby making a total of 1271 ohms in this circuit.

This thermocouple was then used to calibrate the resistance thermometer in the corona tube. According to Dellinger,[10] this resistance should have a linear variation of temperature within the range of temperature from 0 deg. cent. to 70 deg. cent. Its calibration will therefore check the accuracy of both the variation of mercury thermometer and of uniformity of temperature distribution in the tube. The temperature resistance curve upon this basis proved to be a straight line and hence the errors were below that of observation. (See Fig. 6.) The calibrating was done by first bringing the tube to a high steady temperature and then allowing it to cool slowly. It required six hours to secure this calibration curve.

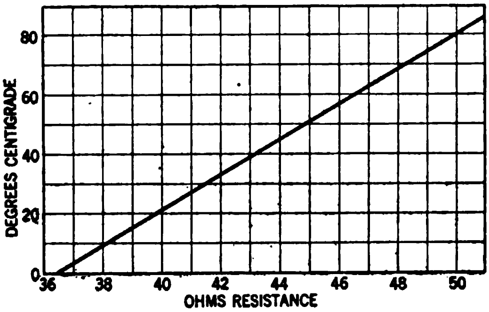

FIG. 6—CALIBRATION OF RESISTANCE THERMOMETER WITH THERMOCOUPLE

The question of insulation was a more difficult one. It was found that the metal electrode cylinder around the perforated brass cylinder had a resistance to ground of 20 megohms through the hard rubber insulation. This was changed by replacing the insulators with new hard rubber.

Since the foundation of generating high direct potential by this method presupposes almost perfect insulation, it was necessary to check all of the leaks to ground in the generating system This was done by charging the high-potential side of the system to a difference of potential of forty volts to ground and observing the decrease of potential upon the quadrant electrometer. The relations which exist by measuring the resistance by the loss of charge method are:

$$V = V_0 \epsilon^{-\frac{1}{CR}t} \tag{7}$$

where V = 34.7 potential at time t = 10 seconds.
V_0 = 39 initial potential,
C = 0.025 capacity in farads,
R = the resistance to ground.

This resistance from the observations as shown by the test was 38×10^9 ohms. It is safe to conclude that even under the highest voltages the leakage current did not modify the potential within limits of observation. (See formula 6). Fig. 7 shows the insluation test with the quadrant electrometer.

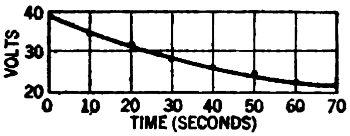

FIG. 7—INSULATION TEST WITH QUADRANT ELECTROMETER

FINAL OBSERVATIONS

The three wires chosen for this experiment had diameters 0.0521 cm., 0.0813 cm., and 0.0993 cm., respectively; the first two were german silver and the latter was steel. Each was carefully polished with crocus cloth and chamois skin before being placed in the tube. The wire was carefully placed in the tube and the tension applied for maintaining it straight. The diameter was measured before and after the test. The tube was now exhausted to 10 cm. of mercury absolute pressure and voltage was applied to the wire. If the corona which appeared around the wire was evenly distributed and gave no indications of beads, the wire was ready for observations. It was found advisable to begin at low pressures and gradually increase the pressure by letting air leak in through a needle valve. At low pressures the corona current from the insulated cylinder to the brass tube was very high as compared with the values at higher pressures.

The voltage which gave the first indication of a deflection in the corona indicating circuit was taken as the corona-forming voltage. The magnitude of this deflection, according to Whitehead and Pullen,[8] depended upon the number of ions per second which passed through the holes of the perforated brass cylinder and gave up their charge to the insulated metal cylinder surrounding the brass one. It was expected and verified experimentally that the current in this indicating circuit was present only if the potential gradient was continued in the same direction as the gradient existing between the inside charged wire and the brass cylinder. A 110-volt storage battery was used to supply this potential gradient, as shown in the diagram of connections. In this battery circuit was connected a D'Arsonval galvanometer of 283-megohm sensitivity to indicate this portion of the corona current.

The polarity of the potential circuit was reversed by reversing the kenotron and the observations were repeated with reversed polarity. When this was done the polarity of the insulated metal cylinder was also reversed.

Each corona indication was repeated three times before a final reading was taken. The pressure, corona voltage, and temperature were observed simultaneously. Curves of voltage and pressure were plotted as the experiment progressed to check any false observation and to insure continuity. The temperature was then changed to another value and the observations repeated. All of the temperature and pressure observations were again repeated for the other wires. No difficulties were encountered with the wire charged positively; however, with the wire charged negatively care was necessary to register the voltage at the beginning of the corona cycle. The general form of the positive and negative corona indicating circuits are shown in Fig. 8.

The difference between these two characteristics was observed by Whitehead[8] and are under further investigation.

RESULTS OF OBSERVATIONS

For the analysis of the results of these experiments it was assumed that the electric intensity at the surface of a wire is given by the following relation:

$$E = \frac{V}{r_w \log_n \frac{D_t}{D_w}} \qquad (8)$$

where V = the potential difference between the wire and the tube,

r_w = radius of wire in centimeters,

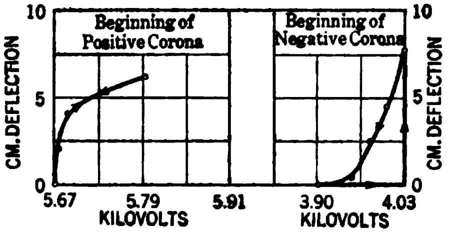

FIG. 8

D_w = diameter of the wire,

D_t = diameter of the tube.

The value for these constants for all of the wires used is given in Table I.

TABLE I
WIRE DATA AND CORONA TUBE CONSTANTS

Diameter of Tube 3.75 in. inside measurement.
" " Wire No. 1 = 0.0205 in. = 0.0521 cm.
" " " No. 2 = 0.0320 in. = 0.0813 cm.
" " " No. 3 = 0.0391 in. = 0.0993 cm.
Radius " " No. 1 = 0.01025 in. = 0.02605 cm.
" " " No. 2 = 0.01600 in. = 0.04065 cm.
" " " No. 3 = 0.01955 in. = 0.04965 cm.

$\text{Log}^n \frac{\text{dia. cylinder}}{\text{dia. wire}}$ No. 1 wire $\text{Log}_n \frac{3.75}{0.0205}$ = Log 183 = 5.2095 numeric

No. 2 " $\text{Log}_n \frac{3.75}{0.0320}$ = Log 1172 = 4.7638 "

No. 3 " $\text{Log}_n \frac{3.75}{0.0391}$ = Log 96 = 4.5643 "

(Radius of wire) $\text{Log}_n \frac{D_c}{D_w}$ No. 1 wire $= 5.2095 \times 0.02605 = 0.1358$ cm.

or No. 2 " $= 4.7638 \times 0.04065 = 0.1936$ cm.

$r_w \text{Log}_n \frac{D_c}{D_w}$ No. 3 " $= 4.5643 \times 0.04965 = 0.2260$ cm.

$\dfrac{1}{r_w \text{Log}_n \frac{D_c}{D_w}}$ No. 1 wire $= \dfrac{1}{0.1358} = 7.375$ 1/cm.

No. 2 " $= \dfrac{1}{0.1936} = 5.170$ 1/cm.

No. 3 " $= \dfrac{1}{0.2260} = 4.430$ 1/cm.

Resistance of voltmeter No. Weston = 441.4 ohms 3-volt scale
No. scale divisions for 3 volts = 150 numeric.

Amperes per unit scale division $= \dfrac{3}{441.4} \times \dfrac{1}{150} = 0.00004536$ amperes.

Resistance of voltage circuit 2,779,000 ohms.
Volts per unit scale division $= 2,779,000 \times 0.00004536 = 126$ volts.

$$E = \frac{\text{Def.}}{r_w \text{Log}_n \frac{D_c}{D_w}} = \frac{\text{Electric Intensity}}{\text{Unit Deflection}} \times \text{Deflection}$$

= No. 1 wire = 126 × 7.375 = 926 volts/cm. /unit deflection.
= No. 2 wire = 126 × 5.170 = 651 volts/cm./unit. deflection.
= No. 3 wire = 126 × 4.43 = 558 volts/cm./unit deflection.

The results were further analyzed in accordance with the relation (9), the work of all other investigators indicating that this relation is correct, and J. T. Townsend having shown that it is in accord with the theory of ionization by collision.

$$E = A\,\delta + B\sqrt{\frac{\delta}{d}} \tag{9}$$

where E = electric intensity,
A = a constant of the phenomena,
B = another constant of the phenomena,
δ = density factor $= \dfrac{3.92\,P}{T}$
P = the absolute pressure in cm. of mercury,
T = the absolute temperature in deg. cent.

TABLE II POSITIVE CORONA

Applied voltage = 126 × deflection								Diameter of wire = 0.0205 in. = 0.0521 cm. E = 926 × deflection					
No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	k_i	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r cm.	$1/\sqrt{\delta r}$	E/δ
1	19.9	2508.0	18380	7.28	19.5°	21°	293°	2525	0.0978	0.3718	0.0259	19.89	188000
2	24.5	3088.0	22600	10.38	"	"	"	2176	0.1392	0.3110	"	16.17	16230
3	27.9	3515.0	25750	13.13	"	"	"	1960	0.1765	0.2761	"	14.80	145800
4	31.6	3980.0	29170	15.98	"	"	"	1825	0.2145	0.2505	"	13.43	135800
5	36.8	4640.0	33950	20.48	"	"	"	1656	0.2755	0.2215	"	11.82	123200
6	41.3	5200.0	38100	24.23	"	"	"	1571	0.3262	0.2034	"	10.89	116800
7	46.0	5800.0	42400	28.48	"	"	"	1490	0.3830	0.1878	"	10.04	110600
8	50.2	6330.0	46300	32.28	"	"	"	1436	0.4340	0.1761	"	9.45	106800
9	54.2	6830.0	50000	35.93	"	"	"	1392	0.4830	0.1670	"	8.94	103400
10	57.8	7280.0	53300	39.28	"	"	"	1357	0.5275	0.1596	"	8.58	101000
11	62.7	7900.0	57800	44.08	"	"	"	1312	0.5920	0.1508	"	8.06	97800
12	67.1	8450.0	61900	48.70	"	"	"	1271	0.6540	0.1432	"	7.68	94800
13	72.7	9160.0	67100	54.48	"	"	"	1223	0.7310	0.1357	"	7.27	91800
14	78.4	9870.0	72300	60.43	"	"	"	1197	0.8100	0.1288	"	6.90	89300
15	85.2	10720	78600	67.83	19.5°	21°	293°	1160	0.9120	0.1216	0.0259	6.51	86200
1	22.2	2798.0	20470	10.11	70°	69°	342°	2050	0.1160	0.3145	0.0259	18.25	176800
2	25.0	3150.0	23050	12.76	"	"	"	1810	0.1462	0.2805	"	16.24	156700
3	33.1	4170.0	30520	19.71	"	"	"	1548	0.2260	0.2255	"	13.08	135100
4	37.4	4710.0	34500	23.76	"	"	"	1453	0.2720	0.2055	"	11.92	126800
5	41.5	5230.0	38300	27.86	"	"	"	1375	0.3198	0.1896	"	11.00	119900
6	45.3	5710.0	41700	31.96	"	"	"	1305	0.3662	0.1771	"	10.28	113900
7	48.9	6160.0	45100	35.91	"	"	"	1255	0.4120	0.1670	"	9.69	109300
8	53.7	6760.0	49500	40.91	"	"	"	1210	0.469	0.1563	"	9.08	105600
9	57.8	7280.0	53300	45.21	"	"	"	1182	0.519	0.1489	"	8.64	102700
10	62.8	7920.0	58000	51.46	"	"	"	1129	0.589	0.1395	"	8.11	98600
11	69.7	8790.0	64300	59.01	"	"	"	1090	0.677	0.1302	"	7.56	95100
12	76.2	9600.0	70300	66.61	"	"	"	1056	0.758	0.1228	"	7.15	92800
13	82.7	10410	76300	74.66	70°	69°	342°	1023	0.856	0.1159	0.0259	6.73	89200
1	20.1	2532.0	18530	8.24	52°	54°	325°	2253	0.993	0.3482	0.0259	19.72	186800
2	25.8	3250.0	23800	12.44	"	"	"	1913	0.150	0.2835	"	16.05	158700

TABLE II—*Continued*. POSITIVE CORONA

Applied voltage = 126 × deflection

Diameter of wire = 0.0205 in. = 0.0521 cm.
E = 926 × deflection

No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r cm.	$1/\sqrt{\delta r}$	E/δ
4	32.3	4070.0	29800	17.99	"	"	"	1660	0.2168	0.2360	"	13.38	137300
5	36.6	4610.0	33750	21.89	"	"	"	1540	0.2640	0.2140	"	12.10	127900
6	40.8	5145.0	37650	25.84	"	"	"	1456	0.3120	0.1970	"	11.13	120600
7	44.8	5650.0	41800	29.74	"	"	"	1391	0.3585	0.1836	"	10.40	115200
8	48.9	6160.0	45100	33.89	"	"	"	1331	0.4080	0.1720	"	9.73	110200
9	52.6	6630.0	48500	37.64	"	"	"	1289	0.4540	0.1631	"	9.23	106900
10	57.3	7220.0	52800	42.59	"	"	"	1242	0.5140	0.1533	"	8.67	102800
11	62.2	7840.0	57400	47.89	"	"	"	1200	0.5760	0.1448	"	8.19	99600
12	66.0	8320.0	60900	52.24	"	"	"	1162	0.630	0.1382	"	7.93	96700
13	73.2	9225.0	67500	58.54	"	"	"	1152	0.706	0.1310	"	7.40	95700
14	77.4	9750.0	71400	64.74	"	"	"	1102	0.780	0.1245	"	7.04	91500
15	82.7	10410	76300	70.94	"	"	"	1078	0.855	0.1190	"	6.73	89300
16	87.8	11050	81000	76.49	52°	54°	325°	1060	0.921	0.1144	0.0259	6.47	88000
NEGATIVE CORONA													
1	22.1	2885.0	20400	7.58	25°	27°	298°	2690	0.0997	0.3640	0.0259	19.70	205000
2	27.6	3479.0	25450	10.88	"	"	"	2342	0.1430	0.3035	"	16.42	178000
3	41.2	5190.0	38000	20.58	"	"	"	1849	0.2704	0.2210	"	11.96	140800
4	46.3	5840.0	42700	24.78	"	"	"	1724	0.3260	0.2010	"	10.89	131000
5	51.2	6450.0	47250	28.98	"	"	"	1632	0.3810	0.1862	"	10.08	123800
6	55.3	6970.0	51000	32.78	"	"	"	1557	0.4310	0.1749	"	9.47	118200
7	58.4	7350.0	53800	36.53	"	"	"	1475	0.4800	0.1656	"	8.97	112100
8	64.1	8080.0	59200	41.33	"	"	"	1432	0.5440	0.1559	"	8.42	108800
9	70.1	8840.0	64700	46.68	"	"	"	1386	0.6130	0.1466	"	7.98	105600
10	82.4	10380	76000	58.93	"	"	"	1290	0.768	0.1307	"	7.10	98900
11	90.0	11440	83800	66.73	"	"	"	1258	0.877	0.1228	"	6.64	95800
12	99.3	12500	91600	75.68	25°	27°	298°	1212	0.996	0.1151	0.0259	6.23	92100
1	18.5	2330.0	17080	6.30	68.5°	69°	342°	2710	0.0722	0.3990	0.0259	23.12	236200
2	24.3	3060.0	22400	10.05	"	"	"	2230	0.1151	0.3158	"	18.32	194500
3	28.3	3565.0	26100	12.75	"	"	"	2045	0.1461	0.2801	"	16.28	178900
4	32.2	4060.0	29700	15.80	"	"	"	1880	0.1812	0.2518	"	14.60	163900
5	37.1	4670.0	34210	19.85	"	"	"	1723	0.2275	0.2245	"	13.02	150600

TABLE II—*Continued*. NEGATIVE CORONA

Applied voltage = 126 × deflection

Diameter of wire = 0.0205 in. = 0.0521 cm.
E = 926 × deflection

No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r cm.	$1\sqrt{\delta r}$	E/δ
6	42.3	5330.0	38100	23.95	"	"	"	1594	0.2745	0.2045	"	11.88	138900
7	46.4	5845.0	42750	27.80	"	"	"	1538	0.3190	0.1895	"	11.00	134100
8	51.1	6445.0	47100	32.10	"	"	"	1468	0.3680	0.1768	"	10.24	127900
9	54.7	6890.0	50450	35.65	"	"	"	1413	0.4090	0.1678	"	9.72	123200
10	59.0	7430.0	54400	40.25	"	"	"	1352	0.4615	0.1578	"	9.16	117800
11	63.4	7990.0	58450	45.65	"	"	"	1282	0.5240	0.1481	"	8.58	111300
12	67.2	8470.0	62000	51.35	"	"	"	1209	0.5880	0.1395	"	8.11	105300
13	71.0	8950.0	65500	57.70	"	"	"	1134	0.6620	0.1320	"	7.63	98900
14	76.3	9610.0	70400	66.95	"	"	"	1052	0.7670	0.1225	"	7.10	91800
15	82.4	10380	76000	74.70	68.5°	69°	342°	1019	0.8560	0.1160	0.0259	6.72	88800
1	22.5	2835.0	20750	8.39	52°	52°	325°	2480	0.1011	0.3456	0.0259	19.54	204500
2	27.3	3440.0	25200	11.69	"	"	"	2158	0.1410	0.2925	"	16.56	178900
3	32.4	4080.0	29900	14.84	"	"	"	2015	0.1790	0.2597	"	14.70	167000
4	38.6	4860.0	35600	19.89	"	"	"	1791	0.2400	0.2242	"	12.69	148200
5	44.2	5570.0	40750	24.59	"	"	"	1658	0.2963	0.2020	"	11.42	137600
6	45.9	5775.0	42300	26.4	"	"	"	1603	0.3182	0.1960	"	11.02	133000
7	48.9	6160.0	45100	28.29	"	"	"	1562	0.3410	0.1882	"	10.62	132200
8	50.0	6300.0	46100	29.69	"	"	"	1553	0.3580	0.1834	"	10.39	128800
9	52.8	6660.0	48700	32.29	"	"	"	1512	0.3903	0.1762	"	9.96	124600
10	54.3	6850.0	50100	33.69	"	"	"	1488	0.406	0.1722	"	9.76	123200
11	59.2	7470.0	54600	37.94	"	"	"	1440	0.457	0.1609	"	9.19	119400
12	64.8	8160.0	59750	43.39	"	"	"	1379	0.523	0.1520	"	8.59	114200
13	69.9	8800.0	64500	47.94	"	"	"	1346	0.578	0.1447	"	8.18	111700
14	75.2	9475.0	69400	53.89	"	"	"	1289	0.650	0.1365	"	7.71	106800
15	80.3	10110	74100	59.59	"	"	"	1243	0.719	0.1298	"	7.34	103000
16	84.3	10610	77700	65.99	"	"	"	1183	0.795	0.1232	"	6.97	97800
17	84.9	10690	78300	66.39	"	"	"	1180	0.800	0.1228	"	6.95	97900
18	88.9	11200	82000	70.34	"	"	"	1167	0.848	0.1192	"	6.76	96700
19	93.5	11780	86300	76.14	"	"	"	1134	0.918	0.1148	"	6.49	94000
20	94.8	11930	87500	76.49	52°	52°	325°	1145	0.921	0.1143	0.0259	6.47	95000

TABLE III
POSITIVE CORONA

Applied voltage = 126 × deflection								Diameter of wire = 0.0205 in. = 0.0521 cm. E = 926 × deflection					
No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r_w cm.	$1/\sqrt{\delta r_w}$	E/δ
1	30.9	3895	20100	11.14	6°	6°	279°	1805	0.1567	0.3000	0.04065	12.45	128500
2	36.1	4550	23420	14.14	"	"	"	1660	0.1988	0.2661	"	11.08	118100
3	40.9	5150	26570	17.00	"	"	"	1565	0.2390	0.2425	"	10.10	113000
4	47.7	6010	30980	21.29	"	"	"	1458	0.2992	0.2168	"	9.03	103900
5	53.7	6770	34900	25.29	"	"	"	1380	0.3558	0.1990	"	8.28	98300
6	64.7	8160	42000	32.84	"	"	"	1280	0.4610	0.1746	"	7.27	91400
7	70.3	8860	45750	36.74	"	"	"	1245	0.5160	0.1650	"	6.87	88700
8	76.7	9670	49900	41.29	"	"	"	1210	0.5800	0.1559	"	6.49	86200
9	84.7	10680	55000	47.64	"	"	"	1158	0.6700	0.1450	"	6.03	82300
10	93.2	11730	60700	53.54	"	"	"	1131	0.7520	0.1368	"	5.66	80600
11	101.8	12820	66200	60.04	"	"	"	1102	0.8450	0.1291	"	5.38	78400
12	113.0	14230	73600	68.24	"	"	"	1078	0.9590	0.1211	"	5.05	76800
13	128.6	15580	80500	76.04	6°	6°	279°	1058	1.0680	0.1149	0.04065	4.78	75300
1	24.3	3060	15800	7.92	20°	20.5°	293°	1997	0.1059	0.3555	0.04065	15.17	149500
2	30.6	3878	19890	11.47	"	"	"	1735	0.1532	0.2956	"	12.60	129600
3	36.9	4650	23950	15.35	"	"	"	1564	0.2052	0.2557	"	10.89	116700
4	42.9	5410	27900	19.10	"	"	"	1456	0.2555	0.2290	"	9.77	109100
5	48.8	6150	31800	23.12	"	"	"	1376	0.3092	0.2080	"	8.87	102100
6	54.9	6900	35750	27.44	"	"	"	1300	0.3672	0.1910	"	8.15	97200
7	61.0	7690	39750	31.87	"	"	"	1247	0.4260	0.1772	"	7.56	93100
8	67.3	8480	43800	36.52	"	"	"	1199	0.4880	0.1658	"	7.07	89600
9	75.2	9480	49000	41.37	"	"	"	1181	0.5530	0.1558	"	6.63	88400
10	82.3	10370	53600	47.67	"	"	"	1124	0.6380	0.1450	"	6.19	83800
11	88.8	11190	57700	53.02	"	"	"	1187	0.7100	0.1375	"	5.86	81300
12	105.2	13270	68600	65.97	"	"	"	1037	0.7810	0.1233	"	5.58	87800
18	112.8	14200	73500	72.07	20°	20.5°	293°	1018	0.9640	0.1179	0.04065	5.03	76300

TABLE III—*Continued*
POSITIVE CORONA

Applied voltage = 126 × deflection								Diameter of wire = 0.0320 in. = 0.0813 cm. E = 651 × deflection					
No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
n	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r_w cm	$1/\sqrt{\delta r_w}$	E/δ
1	27.6	3478	17930	10.53	50°	49.5°	353°	1670	0.1279	0.3082	0.0406	13.82	140500
2	32.6	4110	21180	13.53	"	"	"	1564	0.1642	0.2721	"	12.18	128800
3	37.8	4760	24570	17.08	"	"	"	1439	0.2070	0.2421	"	10.88	118700
4	43.7	5460	28390	21.28	"	"	"	1334	0.2581	0.2170	"	9.86	109800
5	57.3	7220	37230	31.43	"	"	"	1184	0.3815	0.1788	"	7.95	97700
6	63.3	7970	41100	36.03	"	"	"	1140	0.4370	0.1668	"	7.47	94100
7	69.3	8740	45020	41.03	"	"	"	1097	0.4980	0.1561	"	6.99	90600
8	76.1	9590	49490	46.03	"	"	"	1067	0.5620	0.1471	"	6.58	88000
9	84.1	10590	54670	53.08	"	"	"	1028	0.6450	0.1372	"	6.15	84700
10	91.8	11550	59690	59.48	"	"	"	1005	0.7210	0.1298	"	5.81	82800
11	97.5	12280	83400	64.33	50°	49.5°	353°	987	0.7800	0.1248	0.0406	5.59	81400
1	21.6	2710	14030	7.44	67.5°	67°	340°	1887	0.858	0.3670	0.0406	16.90	163700
2	26.9	3390	17480	10.54	"	"	"	1658	0.1217	0.3082	"	14.20	143900
3	36.2	4560	23510	16.89	"	"	"	1394	0.1945	0.2436	"	11.20	120900
4	41.1	5180	26730	20.34	"	"	"	1315	0.2345	0.2221	"	10.30	114000
5	46.2	5820	29990	24.34	"	"	"	1234	0.2805	0.2030	"	9.33	106700
6	51.6	6510	33510	28.44	"	"	"	1176	0.3281	0.1880	"	8.62	102300
7	56.4	7100	36630	32.04	"	"	"	1144	0.3695	0.1768	"	8.13	99200
8	61.4	7730	39890	36.29	"	"	"	1098	0.4180	0.1662	"	7.64	95500
9	68.4	8610	44420	42.19	"	"	"	1054	0.4750	0.1541	"	7.16	93700
10	74.0	9340	48030	47.14	"	"	"	1022	0.5430	0.1458	"	6.70	88400
11	80.3	10120	52150	52.49	"	"	"	995	0.6050	0.1381	"	6.35	86200
12	87.8	11060	57080	59.04	"	"	"	968	0.6810	0.1302	"	7.98	83900
13	93.9	11810	61000	64.29	"	"	"	950	0.7310	0.1248	"	5.77	83400
14	101.5	12790	66000	70.99	"	"	"	932	0.8180	0.1189	"	5.47	80700
15	107.0	13490	69640	76.29	67.5°	67°	340°	913	0.8800	0.1147	0.0406	5.26	79200

TABLE III—*Continued*
NEGATIVE CORONA

Applied voltage = 126 × deflection

Diameter of wire = 0.0320 in. = 0.0813 cm.
E = 651 × deflection

No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r_w cm.	$1/\sqrt{\delta r_w}$	E/δ
1	24.3	3062	15800	6.07	6.5°	7.5°	280°	2600	0.0850	0.4060	0.0406	17.00	185800
2	33.3	4190	21620	10.48	"	"	"	2062	0.1466	0.3090	"	12.88	147500
3	39.7	5000	25800	13.57	"	"	"	1902	0.1898	0.2720	"	11.34	135900
4	48.3	6110	31370	18.47	"	"	"	1701	0.2582	0.2326	"	9.72	121600
5	56.3	7100	36560	23.27	"	"	"	1575	0.3260	0.2075	"	8.64	112300
6	63.2	7960	41000	27.47	"	"	"	1495	0.3845	0.1912	"	7.96	106600
7	68.5	8640	44500	31.07	"	"	"	1432	0.4350	0.1795	"	7.49	102400
8	74.6	9410	48400	35.10	"	"	"	1381	0.4910	0.1690	"	7.04	98800
9	81.9	10310	53200	39.87	"	"	"	1334	0.5580	0.1585	"	6.61	95300
10	89.1	11220	57900	45.02	"	"	"	1285	0.6300	0.1492	"	6.22	92000
11	98.7	12420	64100	51.27	"	"	"	1251	0.7180	0.1398	"	5.83	89300
12	117.2	14780	76200	65.07	"	"	"	1671	0.9100	0.1240	"	5.18	83800
13	129.9	16350	84400	74.22	6.5°	7.5°	280°	1137	1.0390	0.1160	0.0406	4.84	81300
1	27.3	3440	17830	8.38	20°	21°	293°	2115	0.1121	0.3455	0.0406	14.74	158000
2	36.8	4640	23900	13.33	"	"	"	1762	0.1783	0.2742	"	11.69	134100
3	42.2	5320	27440	16.28	"	"	"	1687	0.2175	0.2480	"	10.59	126400
4	48.2	6080	31340	20.23	"	"	"	1546	0.2705	0.2225	"	9.50	115700
5	60.9	7670	39590	28.38	"	"	"	1396	0.3795	0.1880	"	8.01	104400
6	66.5	8380	43200	32.33	"	"	"	1336	0.4320	0.1760	"	7.51	100100
7	72.4	9110	47000	36.38	"	"	"	1295	0.4860	0.1660	"	7.08	96900
8	78.2	9860	50900	40.70	"	"	"	1249	0.5440	0.1570	"	6.68	93800
9	84.6	10660	55000	45.33	"	"	"	1213	0.6060	0.1488	"	6.35	90800
10	93.3	11750	60600	52.08	"	"	"	1164	0.6960	0.1387	"	5.92	87000
11	104.0	13100	67600	59.98	"	"	"	1128	0.8030	0.1292	"	5.50	84200
12	110.7	13920	72000	65.33	"	"	"	1100	0.8740	0.1238	"	5.29	82400
13	118.9	14970	77200	71.43	"	"	"	1080	0.9550	0.1185	"	5.05	80800
14	125.5	15810	81600	76.43	20°	21°	293°	1067	1.0210	0.1144	0.0406	4.89	79800

TABLE III—*Continued*
NEGATIVE CORONA

Applied voltage = 126 × deflection								Diameter of wire = 0.0320 in. = 0.0813 cm. E = 651 × deflection					
No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r_w cm.	$1/\sqrt{\delta r_w}$	E/δ
1	24.1	3038	15670	7.18	50°	50°	323°	2180	0.0871	0.3740	0.0406	16.73	180000
2	28.9	3641	18790	9.53	"	"	"	1969	0.1158	0.3240	"	14.53	162700
3	34.2	4310	22240	12.33	"	"	"	1801	0.1497	0.2855	"	12.78	148700
4	48.8	6150	31750	21.53	"	"	"	1475	0.2615	0.2156	"	9.63	121600
5	54.8	6910	35620	25.53	"	"	"	1397	0.3100	0.1990	"	8.87	114900
6	61.0	7690	39650	29.83	"	"	"	1327	0.3620	0.1832	"	8.20	109400
7	66.7	8410	43300	34.13	"	"	"	1268	0.4140	0.1712	"	7.67	104700
8	72.5	9140	47130	38.18	"	"	"	1236	0.4630	0.1621	"	6.26	101700
9	78.7	9920	51200	43.18	"	"	"	1187	0.4240	0.1522	"	6.81	97800
10	85.7	10790	55700	48.53	"	"	"	1147	0.5890	0.1438	"	6.44	94500
11	95.1	11980	61800	55.68	"	"	"	1111	0.6750	0.1342	"	6.01	91700
12	103.6	13030	67400	62.38	"	"	"	1080	0.7560	0.1268	"	5.69	89300
13	114.6	14420	74600	71.93	"	"	"	1037	0.8720	0.1182	"	5.29	85500
14	121.0	15240	78800	76.43	50°	50°	323°	1031	0.9260	0.1142	0.0406	5.13	85000
1	24.6	3100	15990	7.74	68°	67°	341°	2069	0.0889	0.3600	0.0406	16.56	180000
2	31.8	4010	20660	11.54	"	"	"	1786	0.1328	0.2950	"	13.55	154600
3	39.3	4950	25540	16.08	"	"	"	1590	0.1848	0.2495	"	11.49	138400
4	65.1	8200	42310	33.93	"	"	"	1247	0.3900	0.1720	"	7.90	108400
5	70.2	7850	45600	37.88	"	"	"	1204	0.4350	0.1628	"	7.48	104800
6	75.3	9490	48940	42.38	"	"	"	1156	0.4860	0.1538	"	7.08	100600
7	81.6	10280	53060	47.43	"	"	"	1121	0.5450	0.1455	"	6.68	97400
8	88.5	11130	57530	53.53	"	"	"	1085	0.6160	0.1368	"	6.30	93400
9	100.3	12670	65320	63.79	"	"	"	1025	0.7310	0.1255	"	5.77	89400
10	108.1	13620	70350	70.69	"	"	"	996	0.8130	0.1192	"	5.47	86600
11	114.3	14410	74160	76.29	68°	67°	341°	973	0.8760	0.1146	0.0406	5.28	84700

TABLE IV
POSITIVE CORONA

Applied voltage = 125 × deflection								Diameter of wire = 0.0319 in. = 0.0993 cm. E = 558 × deflection					
No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r cm.	$1/\sqrt{\delta r}$	E/δ
1	22.4	2822	12490	5.75	5°	8.5°	280°	2171	0.0806	0.4170	0.04965	15.82	154900
2	27.5	3465	15350	8.10	"	"	"	1895	0.1138	0.3520	"	13.32	135100
3	34.4	4330	19180	11.45	"	"	"	1676	0.1602	0.2955	"	11.21	119500
4	42.8	5390	23910	15.75	"	"	"	1519	0.2205	0.2524	"	9.55	108200
5	47.6	6000	26580	18.45	"	"	"	1441	0.2582	0.2330	"	8.93	102800
6	56.2	7080	31350	23.35	"	"	"	1345	0.3270	0.2074	"	7.84	95900
7	64.8	8160	36140	28.25	"	"	"	1280	0.3960	0.1882	"	7.12	91400
8	74.0	9330	41170	34.20	"	"	"	1204	0.4790	0.1712	"	6.49	85900
9	83.1	10480	46300	39.80	"	"	"	1162	0.5575	0.1585	"	6.01	83200
10	91.6	11530	51200	45.40	"	"	"	1128	0.6360	0.1487	"	5.63	80500
11	100.0	12600	55800	51.10	"	"	"	1092	0.7160	0.1400	"	5.30	77900
12	111.6	14060	62300	58.50	"	"	"	1064	0.8200	0.1310	"	4.96	76100
13	120.6	15190	67400	64.85	5°	8.5°	280°	1038	0.9080	0.1242	0.04965	4.71	74200
1	28.3	3565	15800	8.73	21.5°	22.5°	295°	1812	0.1162	0.3385	0.04965	13.18	136000
2	35.0	4410	19530	11.98	"	"	"	1633	0.1591	0.2891	"	11.27	122800
3	41.0	5170	23910	15.28	"	"	"	1568	0.2028	0.2560	"	9.97	117900
4	47.4	5970	26450	18.98	"	"	"	1393	0.2520	0.2298	"	8.95	105000
5	54.0	6810	30170	22.78	"	"	"	1325	0.3022	0.2100	"	8.16	99800
6	59.8	7540	33490	26.48	"	"	"	1262	0.3520	0.1946	"	7.56	95200
7	69.0	8700	38550	32.38	"	"	"	1190	0.4300	0.1760	"	6.84	89500
8	75.3	9490	42080	36.58	"	"	"	1151	0.4860	0.1657	"	6.43	86600
9	82.3	10380	46030	40.78	"	"	"	1132	0.5420	0.1570	"	6.09	84900
10	89.2	11230	49760	45.68	"	"	"	1092	0.6070	0.1481	"	5.76	81900
11	97.3	12260	54300	50.81	"	"	"	1067	0.6750	0.1404	"	5.46	80500
12	102.9	12960	57430	54.68	"	"	"	1050	0.7270	0.1355	"	5.27	78900
13	111.4	14050	62200	60.38	"	"	"	1031	0.8020	0.1288	"	5.01	77600
14	125.8	15820	70200	70.66	21.5°	22.5°	295°	993	0.9400	0.1192	0.04965	4.63	75200

TABLE IV —*Continued*
POSITIVE CORONA

Applied voltage = 125 × deflection								Diameter of wire = 0.0391 in. = 0.0993 cm. E = 558 × deflection					
No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r cm.	$1/\sqrt{\delta r}$	E/δ
1	25.4	3200	14450	7.68	45.5°	46°	319°	1882	0.0944	0.3624	0.04965	14.60	153200
2	32.4	4080	18420	11.28	"	"	"	1633	0.1386	0.2980	"	12.05	133000
3	38.6	4860	21950	14.78	"	"	"	1484	0.1816	0.2614	"	10.56	120800
4	53.6	6760	30490	23.98	"	"	"	1272	0.2945	0.2045	"	8.27	103500
5	61.5	7750	34970	29.08	"	"	"	1202	0.3575	0.1858	"	7.50	97800
6	69.4	8750	39460	34.73	"	"	"	1136	0.4270	0.1700	"	6.86	92400
7	77.4	9750	44000	39.63	"	"	"	1110	0.4880	0.1591	"	6.42	90800
8	84.1	10600	47840	44.48	"	"	"	1074	0.5450	0.1500	"	6.07	87700
9	89.2	11220	50670	48.33	"	"	"	1037	0.5940	0.1440	"	5.81	85300
10	97.2	12230	55200	54.18	"	"	"	1019	0.6660	0.1360	"	5.50	82900
11	105.6	13300	59950	59.63	"	"	"	1006	0.7330	0.1297	"	5.24	81900
12	112.1	14120	63800	64.48	"	"	"	987	0.7920	0.1247	"	5.04	80600
13	120.0	15120	68200	70.43	45.5°	45°	319°	969	0.8650	0.1192	0.04965	4.83	78900
1	24.2	3050	13500	7.10	62°	63°	336°	1902	0.0828	0.3855	0.04965	15.60	163000
2	29.1	3670	16250	9.80	"	"	"	1660	0.1142	0.3195	"	13.29	142100
3	34.3	4320	19140	12.85	"	"	"	1489	0.1500	0.2790	"	11.60	127700
4	39.9	5030	22260	16.1	"	"	"	1381	0.1880	0.2495	"	10.37	118400
5	45.4	5720	25390	19.65	"	"	"	1291	0.2292	0.2257	"	9.38	110600
6	51.1	6440	28520	23.35	"	"	"	1222	0.2724	0.2070	"	8.60	104700
7	57.8	7280	32300	27.85	"	"	"	1158	0.3250	0.1895	"	7.87	99400
8	64.1	8080	35780	32.15	"	"	"	1112	0.3750	0.1765	"	7.33	95300
9	75.3	9490	42080	40.40	"	"	"	1041	0.4710	0.1575	"	6.54	89400
10	81.0	10200	45230	44.65	"	"	"	1014	0.5210	0.1498	"	6.20	86800
11	86.8	10930	48450	49.05	"	"	"	987	0.5730	0.1428	"	5.92	84500
12	93.2	11730	51980	54.35	"	"	"	956	0.6340	0.1357	"	5.64	82100
13	99.1	12490	55310	58.30	"	"	"	949	0.6810	0.1310	"	5.44	81300
14	104.6	13180	58350	62.25	62°	63°	336°	937	0.7260	0.1268	"	5.26	80300

TABLE IV—*Continued*
NEGATIVE CORONA

Applied voltage = 125 × deflection

Diameter of wire = 0.0391 in. = 0.0993 cm.
E = 558 × deflection

No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r cm.	$1/\sqrt{\delta r}$	E/δ
1	30.0	3780	16740	7.63	4.5°	5°	278°	2195	0.1076	0.3622	0.04965	13.71	155000
2	39.2	4930	21870	11.48	"	"	"	1907	0.1620	0.2955	"	11.18	135000
3	47.2	5940	26350	15.43	"	"	"	1705	0.2178	0.2542	"	9.61	121000
4	54.8	6910	30630	19.48	"	"	"	1578	0.2745	0.2265	"	8.58	111400
5	63.6	8020	35520	24.24	"	"	"	1464	0.3420	0.2035	"	7.66	103900
6	72.2	9100	40280	29.28	"	"	"	1374	0.4130	0.1850	"	6.99	97700
7	79.3	10000	44200	33.38	"	"	"	1327	0 4700	0.1735	"	6.55	94100
8	85.6	10780	47760	37.28	"	"	"	1279	0.5260	0.1639	"	6.19	90600
9	94.2	11850	52590	42.03	"	"	"	1251	0.5930	0.1543	"	5.82	88800
10	101.4	12790	56630	46.78	"	"	"	1211	0.6600	0.1462	"	5.52	85800
11	108.3	13670	60470	50.88	"	"	"	1188	0.7180	0.1404	"	5.30	84100
12	115.0	14500	64200	55.58	"	"	"	1152	0.7880	0.1343	"	5.07	82000
13	124.9	15720	69600	61.88	4.5°	5°	278°	1126	0.8720	0.1273	0.04965	4.81	79900
1	35.2	3430	19630	10.28	21°	21°	294°	1912	0.1370	0.3121	0.04965	12.12	143500
2	42.8	5400	23900	14.03	"	"	"	1703	0.1871	0.2670	"	10.49	127800
3	48.6	6130	27150	17.23	"	"	"	1574	0.2300	0.2410	"	9.35	117900
4	54.0	6810	30130	20.13	"	"	"	1498	0.2682	0.2230	"	8.66	112100
5	64.9	8180	36200	26.43	"	"	"	1370	0.3525	0.1948	"	7.55	102500
6	70.0	8820	39090	29.58	"	"	"	1322	0.3940	0.1875	"	7.14	99300
7	77.1	9730	43000	34.18	"	"	"	1261	0.4550	0.1714	"	6.65	94600
8	83.6	10520	46600	37.98	"	"	"	1228	0.5060	0.1625	"	6.31	92000
9	89.5	11280	49970	41.98	"	"	"	1189	0.5590	0.1547	"	6.00	89400
10	97.2	12240	54210	46.98	"	"	"	1152	0.6260	0.1461	"	5.67	86600
11	104.0	13110	58000	51.48	"	"	"	1127	0.6850	0.1395	"	5.42	84800
12	111.3	14040	62190	55.83	"	"	"	1112	0.7450	0.1341	"	5.20	83400
13	117.8	14820	65830	60.98	"	"	"	1078	0.8130	0.1282	"	4.97	81000
14	125.7	15820	70170	65.48	21°	21°	294°	1070	0.8720	0.1238	0.04965	4.80	80500

TABLE IV—*Continued*
NEGATIVE CORONA

Applied voltage = 125 × deflection								Diameter of wire = 0.0391 in. = 0.0993 cm. E = 558 × deflection					
No.	Defl.	Volts	Elec. Int.	Abs. Press. cm. H_g	Temperature			Density Factor			Radius Wire		
					Th. Cpl.	Res.	Abs.						
#	D	V	E	P	t_c	t_r	T	E/P	δ	$1/\sqrt{P}$	r cm.	$1/\sqrt{\delta r}$	E/δ
1	27.0	3401	15050	7.78	68°	68°	341°	1937	0.0894	0.3590	0.04965	15.04	168700
2	35.7	4500	19920	12.18	"	"	"	1637	0.1399	0.2874	"	12.02	142500
3	43.4	5470	24230	16.28	"	"	"	1488	0.1870	0.2480	"	10.40	129600
4	49.8	6280	27830	19.88	"	"	"	1401	0.2282	0.2243	"	9.42	122000
5	56.5	7120	31400	24.08	"	"	"	1304	0.2770	0.2040	"	8.54	113200
6	68.6	8650	38250	31.78	"	"	"	1203	0.3650	0.1778	"	7.44	104800
7	74.5	9520	41590	35.28	"	"	"	1179	0.4060	0.1687	"	7.05	102400
8	86.4	10880	48200	43.73	"	"	"	1099	0.5030	0.1514	"	6.34	95800
9	92.2	11610	51490	48.03	"	"	"	1071	0.5500	0.1443	"	6.06	93600
10	107.6	13550	60070	59.38	"	"	"	1012	0.6820	0.1299	"	5.44	88000
11	113.5	14300	63400	64.73	"	"	"	980	0.7440	0.1245	"	5.21	85200
12	128.6	16200	71790	75.78	68°	68°	341°	947	0.8700	0.1151	0.04965	4.82	82600

TABULATED RESULTS

Electric Int., $E = A\,\delta + B\,\frac{\sqrt{\delta}}{\sqrt{a}}$ kilovolts/cm.

Density Factor, $\delta = \frac{3.92 \times \text{pressure}}{\text{absolute temp.}}$

was made variable by changing the pressure and the temperature.

The above formula may be written

$$E/\delta = A + B' \cdot \frac{1}{\sqrt{r\,\delta}}$$

Where A = constant
B = constant
r = radius of wire (cm.)
a = diameter of wire (cm.)
B = constant
$B' = B/\sqrt{2}$

CORONA

Wire Chgd.	Temp. Deg. Cent.	Wire Diam.	Radius	A	A aver. per wire	A aver. all wires	B	B aver. per wire	B aver. all wires	B' aver. per wire	B' aver. all wires
+	6°	0.0993	0.04965	41.6			10.2				
+	20°	"	"	39.1			10.2				
+	50°	"	"	39.2			11.21				
+	68°	"	"	38.3			11.00				
					39.5			10.56		7.46	
+	6°	0.0813	0.407	39.9			9.78				
+	20°	"	"	40.2			9.97				
+	50°	"	"	42.0			10.25				
+	68°	"	"	40.5			10.15				
					40.6			10.03		7.09	
+	21°	0.0521	0.0260	37.9			10.56				
+	52°	"	"	38.75			10.62				
+	70°	"	"	40.3			10.34				
					39.2			10.50		7.42	
						39.8			10.36		7.32

TABULATEL RESULTS. CORONA—*Continued*

–	6°	0.0993	0.04965	37.9			12.4				
–	20°	"	"	37.5			12.28				
–	68°	"	"	44.8			11.60				
					40.1			12.09		8.52	
–	6°	0.0813	0.0407	40.3			11.79				
–	20°	"	"	40.4			11.23				
–	50°	"	"	41.7			11.57				
–	68°	"	"	41.8			11.71				
					41.0			11.57		8.17	
–	25°	0.0521	0.0260	30.7			12.12				
–	52°	"	"	39.0			12.24				
–	69°	"	"	41.0			11.85				
					40.3			12.07		8.52	8.41
						40.3			11.91		

With combined averages

$E = 39.8\,\delta + 10.36\sqrt{\delta/d}$ for + corona.
$E = 40.3\,\delta + 11.91\sqrt{\delta/d}$ for – corona.

or

$E/\delta = 39.8 + 7.32\dfrac{1}{\sqrt{\delta r}}$ for + corona.

$E/\delta = 40.3 + 8.17\dfrac{1}{\sqrt{\delta r}}$ for – corona.

BROWNS' RESULTS

$E = 33.7\,\delta + 11.5\sqrt{\delta/d}$ for + corona.
$E = 31.0\,\delta + 13.5\sqrt{\delta/d}$ for – corona.

FARWELL'S RESULTS

$E = 35.0\,\delta + 11.4\sqrt{\delta/d}$ for + corona.
$E = 31.6\,\delta + 11.9\sqrt{\delta/d}$ for – corona.

Expanding in the above formula

$$E = \frac{3.92\,A\,P}{T} + B\,\frac{\sqrt{\frac{3.92\,P}{T}}}{\sqrt{d}} \qquad (10)$$

Divide both sides of the equation by P

$$\frac{E}{P} = \frac{3.92}{T}\,A + B\,\frac{\sqrt{\frac{3.92}{T}}}{\sqrt{d}} \cdot \frac{1}{\sqrt{P}} \qquad (11)$$

If $\frac{E}{P}$ is plotted as ordinate and $\frac{1}{\sqrt{P}}$ as abscissa, then for a given absolute temperature T, the resultant curve, if A and B are constant, should be a straight line.

The slope of this line is $B\,\frac{\sqrt{\frac{3.92}{T}}}{\sqrt{d}}$.

The intercept is $\frac{3.92}{T}\,A$.

Also, if the formula is rewritten in the form

$$E = A\,\delta + B'\sqrt{\frac{\delta}{r}} \qquad (12)$$

where r = radius of the wire

$$B' = \frac{B}{\sqrt{2}}$$

Then

$$E = A + B' \cdot \frac{1}{\sqrt{\delta\,r}} \qquad (13)$$

With this last formula it is possible to reduce all of the wires at all temperatures to the same law if A and B' are the same for all wires at all temperatures and pressures.

Accordingly, the various quantities have been computed and are given in Tables II, III and IV. Each table gives the electric intensity for corona at the wire, electric intensity divided by pressure

$\left(\frac{E}{P}\right)$, electric intensity divided by the density factor $\frac{E}{\delta}$, the density factor δ and $\frac{1}{\sqrt{\delta\, r_w}}$, where r_w is the radius of wire in cm.

Curves showing the relation of applied voltage and pressure were drawn for the positively and negatively charged wire, as shown in Figs. 9, 10, and 11. For the same pressure and temperature positive corona appeared at a lower voltage than the negative corona. Although the difference in temperature between two adjoining curves was only twenty degrees, less than 10 per cent upon the absolute scale, at no time is there doubt about the points of observation.

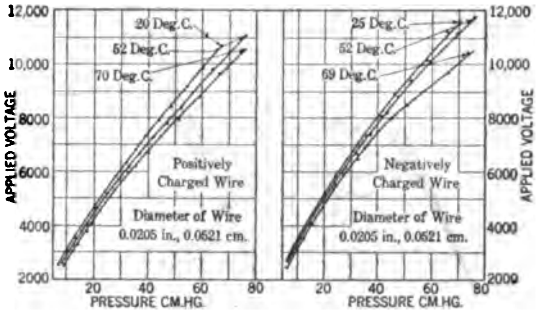

Fig. 9

Curves showing the relation of $\frac{E}{P}$ and $\frac{1}{\sqrt{P}}$ are straight lines within errors of observation. (See Figs. 12, 13, and 14.) The positive and negative corona curves for each wire have a characteristic family. The positive curves show the smallest divergence for the same change in temperature. In the tabulated results the values of A and B are stated for each wire at every constant temperature observation for a variation of pressure from 10 centimeters to 70 centimeters of mercury. It is seen that B is always greater for negative corona.

The curves shown in Figs. 12, 13, and 14 were

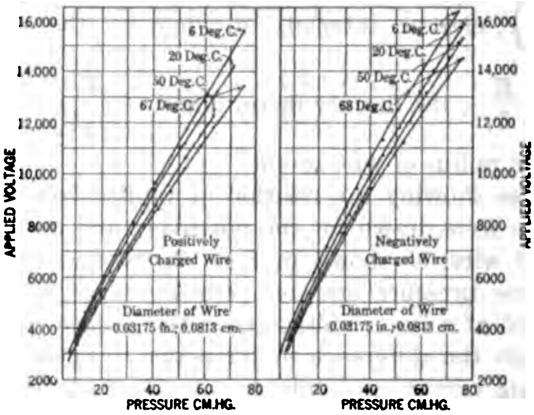

FIG. 10

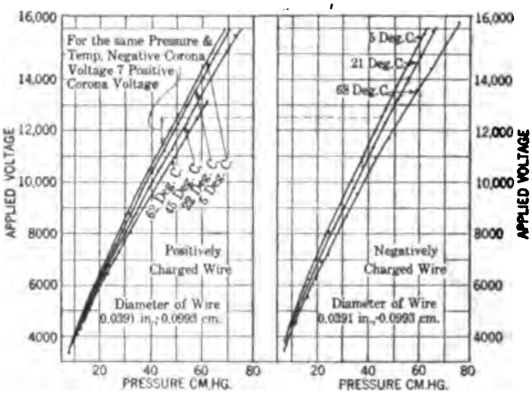

FIG. 11

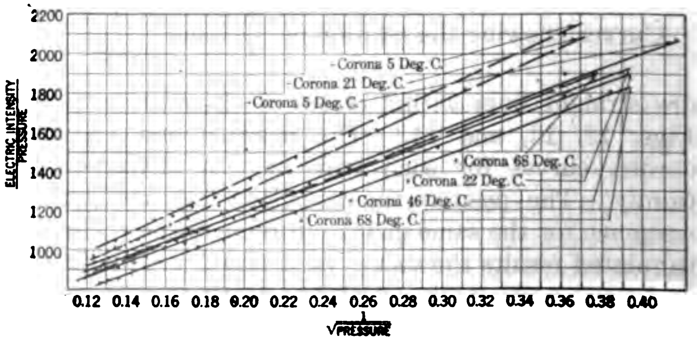

FIG. 12—POSITIVE AND NEGATIVE CORONA

Showing linear relation between

$$\frac{\textbf{Electric intensity}}{\textbf{Pressure}} \text{ and } \frac{1}{\sqrt{\textbf{pressure}}}$$

at different temperatures.
Diameter of wire = 0.0993 cm.

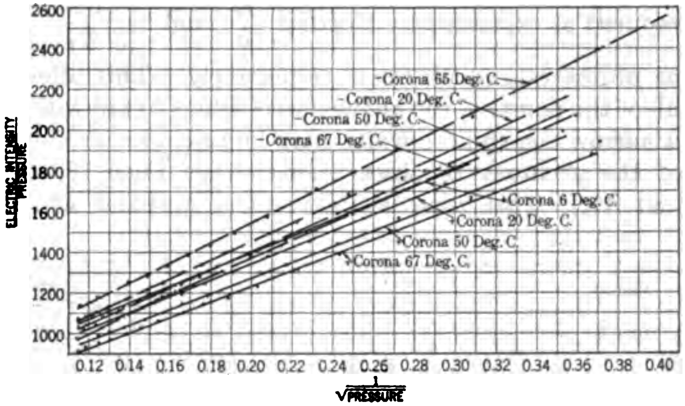

Fig. 13—(Same as Fig. 12, Except Diameter of Wire = 0.0813 cm.)

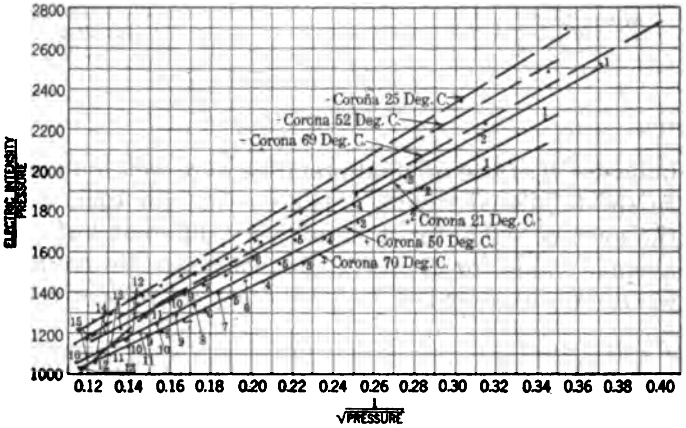

Fig. 14—(Same as Fig. 12, Except Diameter of Wire = 0.0521 cm.)

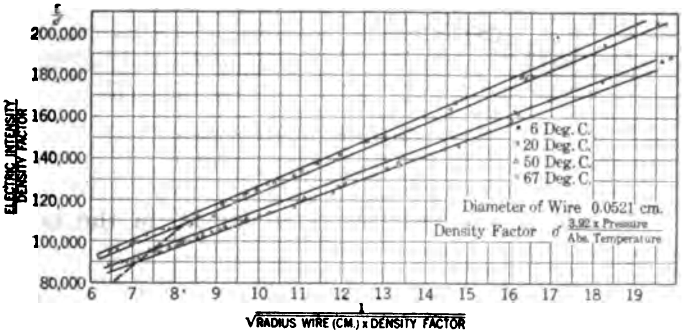

Fig. 15

reduced as explained by plotting $\frac{E}{\delta}$ and $\frac{1}{\sqrt{\delta\, r}}$ as ordinates and abscissas respectively. This allows all of the points of the above observations to fall within a narrow zone whose width may be taken as an index of the accuracy of observations. (See Figs. 15, 16, and 17.) This zone is also a straight band which indicates that the original premises were well founded. In the tabulated results it is seen that for each wire the average value for A is not very different but the average value for B has a distinct separate average for the positive and the negative corona respectively.

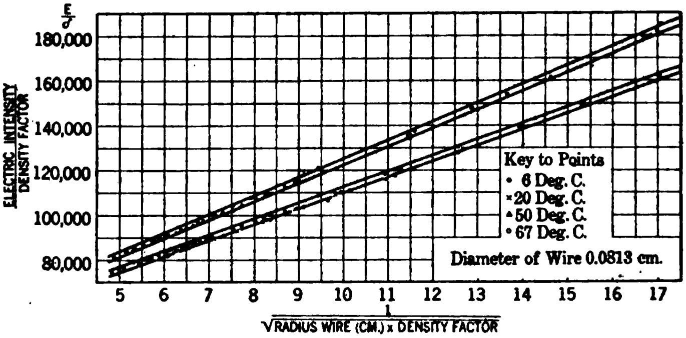

Fig. 16

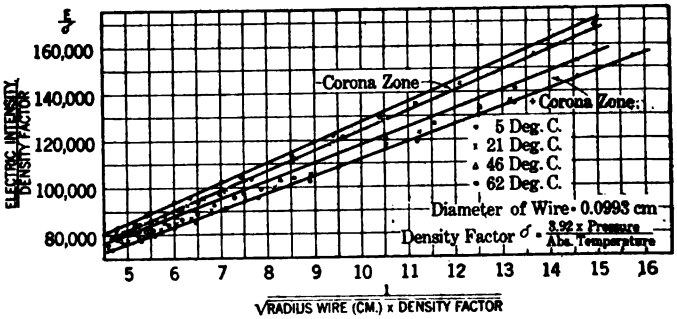

Fig. 17

The table also shows the value for B' in the later adopted form

$$\frac{E}{\delta} = A + B' \frac{1}{\sqrt{\delta\, r}} \tag{13}$$

It should also be noticed that at the highest temperature of 69 deg. cent., especially with the smaller diameter wire, a break in the continuity of the corona curve occurs. (See Fig. 14.)

The observations leading to these apparent departures from the fundamental law of formula (13) were repeated several times, and in each case yielded the results indicated. There is no obvious explanation why these breaks should appear in one set of curves and not in others in their neighborhood. Investigation of this interesting question is being continued.

DISCUSSION

The fact that positive corona starts at a lower value is in accord with the investigations of Farwell, Schaffers, Watson and Brown. It is in accord with the général theory of Townsend that negative ions are the active agents in the starting of corona. If the wire is positively charged they will move into an ever increasing field from a large region and hence will multiply more rapidly than if the reverse were true. According to Brown and Schaffers this principle fails when the value becomes less than a definite value. The results of this investigation indicate that the positive corona is always lower than the negative corona. Brown mentions great difficulty in securing definite negative corona readings. It was noticed in this investigation and discovered earlier by Whitehead[3] that negative corona occurs very abruptly from what seems a kind of supersaturated condition. If the negative corona is once formed the potential may be decreased below this corona-forming value with the corona phenomenon still persisting. The exact cycle of this phenomenon is at present under further investigation.

It is interesting to compare the value of the electric intensity as observed by Brown's relation upon the 0.0993-cm. wire. Brown states his positive corona formula

$$E = 33.7\,\delta + 11.5\sqrt{\frac{\delta}{d}} \text{ kilovolts per cm.}$$

Upon substituting the above value for d and using a density factor of unity

$E = 70.15$ kilovolts per cm.

If Farwell's relations are used

$$E = 35\,\delta + 11.4\sqrt{\frac{\delta}{d}}$$

$E = 71.15$ kilovolts per cm.

The results of this investigation give

$$E = 39.8\,\delta + 10.36\sqrt{\frac{\delta}{d}}$$

$= 72.6$ kilovolts per cm.

At pressures lower than atmosphere, both Brown's and Farwell's results indicate higher corona voltages than those found in these experiments. It should be stated that this is the only observation in which the field of these experiments touches that of Brown and Farwell.

CONCLUSIONS

1. The critical corona-forming electric intensities of these wires, ranging in size from 0.0521 to 0.0993 cm., at several constant temperatures in the range 5 deg. to 70 deg. cent. and at various pressures for each temperature have been investigated under continuous positive and negative potentials.

2. The critical surface intensity at which corona started upon the above wires can be summarized in the relation

$$E = 39.8\,\delta + 10.36\sqrt{\frac{\delta}{d}} \text{ for + corona}$$

$$E = 40.3 \quad + 11.96\sqrt{\frac{\delta}{d}} \text{ for − corona.}$$

3. The constant A in the positive and negative corona relation is the same.

4. Within the range of this experiment negative corona, under the same conditions of pressure and temperature, always occurs at a higher value.

5. The curves of positive and negative corona each form a separate family of curves when observed at

the same temperature with variable pressure upon the same wire.

6. The observations give accordant results with Farwell and Brown when used under pressure and temperature conditions of observation at which their data were taken.

7. The results of the investigation are in accord with Townsend's theory of secondary ionization.

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DISCUSSION ON "LONG DISTANCE TRANSMISSION OF ELECTRIC ENERGY" (IMLAY), "VOLTAGE AND POWER FACTOR CONTROL OF 66,000-VOLT TRANSMISSION LINES CONNECTING TWO GENERATING STATIONS" (BAILEY), "VOLTAGE REGULATION AND INSULATION FOR LARGE POWER, LONG DISTANCE TRANSMISSION SYSTEMS" (BAUM), "SOME TRANSMISSION LINE TESTS," (LEWIS), "NOTES ON THE OPERATION OF LARGE INTERCONNECTED SYSTEMS" (ELDEN), "MODERN PRODUCTION OF SUSPENSION INSULATORS" (FRITZ AND GILCHREST), "VOLTAGE AND CURRENT HARMONICS CAUSED BY CORONA" (PEEK), "A SOLUTION OF THE PORCELAIN INSULATOR PROBLEM" (CREIGHTON AND HUNT), "TRANSFORMERS FOR INTERCONNECTING HIGH-VOLTAGE SYSTEMS OR FOR FEEDING SYNCHRONOUS CONDENSERS FROM A TERTIARY WINDING" (PETERS AND SKINNER) AND "ELECTRIC STRENGTH OF AIR UNDER CONTINUOUS POTENTIALS AND AS INFLUENCED BY TEMPERATURES" (WHITEHEAD AND LEE), SALT LAKE CITY, UTAH, JUNE 22-23, 1921.

W. I. Slichter: Mr. Baum pointed out the different reasons for the variation of the line voltage, the principal one being the line capacity, and he suggested methods for taking care of this variation by placing variable reactance in the form of a synchronous motor in shunt to the line. This leads to the thought that as our country develops and our transmission systems develop we will have a distribution system rather than a transmission system. There will be transmission for say 50 miles, then a step-down substation with transformers and a synchronous motor, then another 50 miles with another substation. Thus as business develops the line will be naturally subdivided and loaded with variable reactance which will take care of voltage variation. That is, it will be another case of proportioning the inductive and capacity reactances properly, as is now done in telephone lines.

The idea of proportioning inductance and capacity in a long line was patented a great many years ago, for this idea we presented the Edison Medal to Dr. Pupin last February. The patent has now expired and is at the service of all.

Livingston P. Ferris: Mr. Lewis and Mr. Peek in his paper give us some very interesting data on a relatively new phenomenon in power transmission, that is, the production of harmonics by the cyclic variation of at least one of what we have hitherto been accustomed to assume as line constants.

A study of Mr. Lewis' data seems to show that they are sufficient to draw the conclusion that the transformers were not the source of the relatively large third harmonic neutral currents which were observed, that is, we may discard the transformer hypothesis even without the support afforded for the corona hypothesis by Mr. Peek's laboratory experiments.

The first evidence of this we may obtain by comparison of Tests 23 and 43 with Test 21. Referring to Figure 10 of Mr. Lewis' paper which illustrates the different test conditions, you will see that for Tests 23 and 43 the line was supplied from Junction with no transformers at the other end. In Test 21, there were transformers at the other end of the line, Grand Rapids, with their neutral grounded and the delta open. Now if the third harmonic arises in the transformers, we should expect the change from condition 23 to condition 21 to affect very materially the neutral current observed at the supply end of the line, Junction, but Mr. Lewis' data show there is very little difference between the two conditions. No reading is given of the neutral current at Grand Rapids for Test 21. It would be interesting to have this.

Now as further evidence that the transformers are not here responsible for the third harmonic, I have had some theoretical estimates made of the neutral current to be expected from the transformers for test conditions 23 and 43 and find that the calculated neutral current due to the transformers is a very small fraction, less than 5 per cent, of that observed, thereby pointing to some cause other than the transformers. This estimate is based on the assumption that the open-circuit third harmonic voltage per transformer acts in a series circuit through the leakage impedance of the transformer and the impedance to ground of one line wire. The third harmonic voltage was estimated from the test exciting current and transformer impedance data given by Mr. Lewis, and an assumed representative wave form (See Appendix for details). Acknowledgment that the estimate is very rough is not likely to account for the large difference between calculated and observed values so it forces us to look for a source outside the transformers.

In view of the prominence of corona and the fact that the neutral current showed a marked increase above the corona voltage, it seems natural to look to corona for an explanation. If the neutral current is due to a periodic change in the line admittance, it may be simulated by a fictitious third harmonic generator placed in series with the line admittance to ground.

From Figure 11 we obtain a neutral current of 19 amperes for 200 kv. at Junction with no transformers at Grand Rapids. The voltage of the fictitious generator, which would also be the neutral voltage if the neutral were isolated, may be calculated from the current of 19 amperes and the line and transformer impedances. It comes out about 11,000 volts. Using this and the proper line and transformer impedances, we may compute the neutral currents for the condition of both neutrals grounded, Test 20. The circuit is as in Fig. 1, showing one wire only of the three:

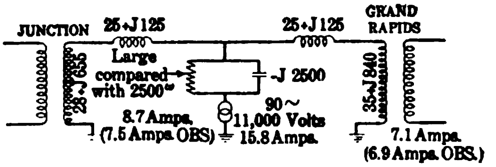

FIG. 1

The calculated currents recorded in the figure have been multiplied by three to give the corresponding neutral currents. Comparison of these and observed neutral currents, Test 20, Table 15, Fig. 12 of paper, shows very good agreement.

Mr. Lewis in presenting his paper mentioned that Figs. 21 and 22 were not entirely consistent and that Fig. 22 could not be satisfactorily explained. Now on the theory that the neutral current is due to a cyclic variation of the admittance of the line to ground and representing this effect by a generator in series with the shunt admittance, we have a circuit like Fig. 2, showing one phase only for Test 44. Under the conditions of Test 44, the neutral voltage observed at Junction is seen to be practically the voltage drop of the Grand Rapids neutral current through that transformer impedance and half of the line series impedance. The 125,000-volt connection was used at Grand Rapids for this test, giving an impedance of 30 + *j* 700, one-half

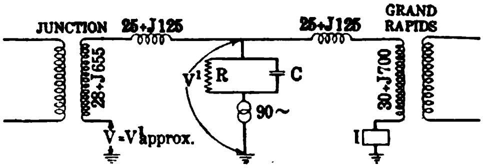

FIG. 2

line series impedance = $25 + j\,125$, sum = $55 + j\,825$. Using this impedance and the values of observed neutral voltages at Junction, the neutral currents at Grand Rapids have been calculated and are shown below:

Junction		Grand Rapids	
L. V. KV.	Volts Neutral to ground	Calculated Neutral Current	Test Neutral Current
145	900	3.28	3.25
150	1800	6.6	6.0
155	2475	9.0	8.0
160	3000	10.9	9.6
165	3425	12.5	10.75
170	3750	13.7	11.5
175	4030	14.7	12.0

Very good agreement is to be noted between calculated and test neutral currents justifying the hypothesis that the line is the source of the harmonics. Now I believe that Mr. Lewis' Table 26 and Fig. 22 show a comparison between measured and calculated neutral currents based on the assumption that the neutral voltage at Junction is the drop of the neutral current at Grand Rapids through the impedance of the line to ground, taken as its lump capacitance. This further assumes that the triple harmonic neutral current is due to the transformers at Grand Rapids rather than the line and that the triple harmonic voltages in the Junction bank are negligible as compared with those in the Grand Rapids bank. This latter is, of course, not the case since the two banks of transformers are similarly rated and operated at approximately the same magnetic density. Mr. Lewis' calculated neutral current under these assumptions would not appear as close as it does to the observed neutral current were not an incorrect capacitance used. The capacitance should be three times the *direct* capacitance to ground of one conductor, which is approximately half of its equivalent capacitance to neutral, the latter being used by Mr. Lewis.

Referring to Fig. 21 and Table 25, before concluding that the capacitance has changed, we should know how much of the increased charging current might be accounted for by the harmonics which Mr. Lewis states are in the voltage. The theoretical charging current curve should not be a straight line but should bend upward to take account of these harmonics.

In the middle of the second column of page 1106 some comparisons are made. First, in reference to the splitting of the neutral current between the two ends of the line with similar banks of transformers at each.

This would also hold true if the transformers were the source of the triple harmonics. Second, in reference to the comparison of neutral currents at one end of the line (a) with the distant end open or neutral non-grounded, and (b) with the distant end neutral grounded but secondary delta open. It has already been pointed out that the neutral currents would differ materially if transformers were the important source of triple harmonics. Of course, the opening of the secondary delta in the one case (Test 21) is the equivalent, so far as triple harmonics are concerned, of having that bank of transformers connected star-star with the neutral grounded on the high-tension side and isolated on the low-tension side.

In this connection it is interesting to contrast the effects of isolating the neutral on the triple harmonics due to transformers and corona. So far as transformers are concerned, isolating the neutral of a three-phase bank practically eliminates that bank as a source of triple harmonic residual current or voltage. The neutral of the bank, however, pulsates at triple harmonic voltage with reference to the ground, while the line is practically at ground potential so far as the triple harmonics are concerned. Now in the case of corona, as the source of the triple harmonics is in the line itself, isolating the neutrals of all connected transformer banks while interrupting the residual current (assuming such banks at the line terminals) will not eliminate the triple harmonic residual voltage, and the line as well as the transformer neutrals will pulsate at a triple harmonic voltage with reference to the ground, this voltage being somewhat greater for the line, with the neutrals isolated than when grounded due to the elimination of the impedance drop of the residual current. If we should have a case where both the transformers and the line, due to corona, contribute harmonics of comparable magnitudes, the problem of estimating their distribution and the effects of different conditions, would be much more complex.

In conclusion, I simply wish to add that telephone engineers are, of course, interested in corona harmonics as a possible new source of difficulties, but I am very glad Mr. Lewis points out the desirability of operating below the corona voltage, thus avoiding these difficulties. This new phenomenon is but another illustration of an old recognized fact that the sources of interference to telephone lines are not the essential and important factors in power transmission but the little excrescenses, such as harmonics, which as in the case shown by Mr. Lewis may be quite undesirable from a power viewpoint.

APPENDIX

The assumed wave form of exciting current for a single transformer is as follows:

Harmonic	Percentage
1	86
3	44
5	22
7	10

The third is of course absent from the 30 amperes observed in the leads to the primary delta which is made up of fundamental fifth and seventh only.

At the bottom of the last column of page 1041 are given some values of leakage impedance of the transformers upon which the following for the third harmonic have been deduced.

Winding	Impedance—Ohms
120,000	$28 + j\,655$
125,000	$30 + j\,700$
140,000	$35 + j\,840$

The real terms in the above impedances are based upon the assumption that the only losses are due to the ohmic resistance. The actual losses are doubtless considerably larger. One-half of this leakage impedance is assumed to exist in the low-voltage winding.

On page 1081 Mr. Lewis gives the value of 1.322 microfarads as the capacitance to neutral of one wire of the Junction Dam—Grand Rapids Line. This corresponds to a value of about 2.1 microfarads for the capacitance of the three wires in multiple to ground, assuming an empirical ratio found to hold in a number of cases. At 90 cycles this gives an impedance of $-j\,1081$ ohms or $-j\,2500$ ohms per wire. The series impedance of the three wires with ground return may be derived in a similar manner from the reactance given on page 1081, being at 90 cycles about $16.4 + j\,83$ ohms or per wire $50 + j\,250$ ohms.

Buckner Speed: Referring to the papers on 220,000-volt power transmission, I would like to say a word. There seems to be a call for a genuinely new, a genuinely pioneer invention, an invention which is as thoroughly a pioneer invention in the art of power transmission as the invention of the vacuum bulb was in telephone engineering. What I mean is a thoroughly fundamental invention, not thought of at the present time, for stepping d-c. power up or down, which would do for power transmission what was imperfectly done by the series of d-c. generators at the generating end and the series of d-c. motors at the receiving end in the

Thury d-c. long-distance power transmission system experimented on with only moderate success a good many years ago. If we are going to net up the entire country, then necessity is calling, and necessity is the mother of invention. Were the fundamental scientific knowledge now available for us to successfully engineer a d-c. power transmission system using a quarter of a million volts direct current, we could put our main interconnecting links underground in the form of a single copper conductor properly supported inside of an oil pipe line with proper insulating oil slowly pumped through it from substation to substation, probably cleaning it and drying it up to the highest insulating point as it passes by each substation. Of course no such scheme can now be engineered because we neither know how to make a quarter of a million volt d-c. power in large quantity, nor how to transform it into lower voltage, either alternating current or direct current, or into mechanical movement, without the above referred to thoroughly fundamental pioneer invention, and this I say is needed.

Further, in one of the papers, I do not recall which, there was a slight error, or else there may have been an error suggested in the minds of some, in the idea that the Fourier analysis of periodic variations gives a correct representation of the current or voltage variations in a circuit exhibiting corona. I think this has been referred to by our friend John B. Taylor. I wish he were here. The fact is, the corona loss begins abruptly, does not occur through the entire cycle and consequently while we can simulate as closely as we like the effects arising from corona by a super-position of sine waves, we must bear clearly in mind that we are merely considering a thing which approximates and does not represent the actual conditions, for the corona has not only *not* a harmonic variation, not even a complex harmonic variation, it is a series of disconnected events. In the matter of the development of high-frequency in the neutral of a high-voltage system, where the peaks of the waves in the three transmission wires reach the point where the corona begins, it is interesting to note that it would be possible to make a high-frequency system of generation through the use of three or six-phase power transformed up to a point where the corona effect is found at the peak of the wave, and by a suitable star connection get either 180 or 360 cycles in the neutral conductor; or if we start with a three-phase generator of very high initial frequency we can very simply get six times this frequency through the same scheme.

F. W. Peek, Jr.: I wish to repeat that I have every confidence in the success of the transmission of energy at 220 kv. There is, in fact, no reason why these proposed systems should not be more reliable than the lower voltage systems.

As Mr. Baum states, the question of regulation and stability becomes of the utmost importance as the lengths of lines increase. This is so, long before the quarter wave length (750 miles at 60 cycles) is reached. Very successful operation has been obtained for years, on lines up to more than 200 miles in length by means of synchronous condensers placed at the ends. Mr. Baum proposes to place synchronous condensers at intermediate points on long lines. The effect is equivalent to stacking up a number of shorter lines. Stability should thus be secured up to great lengths.

There is still an insulator problem. While undoubtedly great improvements have been made in the mechanical design of the cemented type, these insulators still sometimes crack and fail. The Hewlett with its loose fitting hardware has been free from this trouble. This problem applies to high and low-voltage lines alike and must not be lost sight of in the discussion of the problem of grading or shielding which becomes of importance at the higher voltages.

I first became interested in grading or shielding about ten years ago.[1] What was then only an academic problem has now become an important practical problem. There is sometimes a misunderstanding as to the reason for grading. The primary reason is not to increase the arc-over voltage of the string but to make each unit take care of its share of the voltage.

An insulator string consists of a number of equal capacities in series. The voltage would divide evenly if it were not for a disturbing factor. The disturbing factor is the capacity to ground of the caps and fittings.

The capacity to ground causes from 20 to 30 per cent of the voltage to appear across the line unit. Correction may be made by increasing the capacity of the line unit, increasing the next one above the line to a lesser extent and so on up the string. This may be done by units of different size or by adding plates to standard units. It is rather difficult to make this correction without also increasing the capacity to ground, this is called grading.

Correction may also be made by shielding. As the name implies, this method shields the string, or, in

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(1) Peek, *Electrical Characteristics of the Suspension Insulator*. A. I. E. E. TRANSACTIONS 1912, Vol. XXXI, page 907.

Peek, *Electrical Characteristics of the Suspension Insulator—II*, TRANS. A. I. E. E., 1920 Vol. XXXIX, Part II, p. 1685.

effect, eliminates the disturbing element, the capacity to ground. Fortunately this is very easily done on standard insulators. The simple ring shield is hung on the line end of the string.

The relative characteristics of the two methods may be summarized as follows:

Shielding: (a) Reduces the voltage on the line unit from one-third to one-half. (b) Prevents corona on the units. (c) Directs the arc away from the string. (d) Reduces surface voltage stresses from one-fourth to one-third and thus increases the arc-over above that on the unshielded string when part of the units become conducting by dirt. (e) Prevents high local stress due to transients by establishing the proper field through the air and not through the reactance of the links and hardware. (f) Does not require special insulators.

Grading: (a) Reduces stress on line units. (b) Causes corona formation. (c) Causes arc to cascade badly along the string. (d) The addition of capacity plates increases the hazard by adding extra edges for corona formation, and, by covering a larger area requires a larger part of the porcelain to be perfect. (e) Requires several different types of units.

M. E. Skinner: There is one question which the great length of high-voltage systems, such as those considered in Mr. Imlay's paper, present, which it has not been necessary to consider with transmission lines of the length and voltages used up to this time. I refer to the possibility of resonant voltages at triple frequency.

When the length of a transmission line having a grounded neutral approaches 250 miles, this possibility is present and must be considered. Every transformer bank is a potential source of triple-frequency voltage and as Mr. Lewis' paper points out, the corona loss may also result in voltages of triple frequency. If the normal operation is below the corona point the latter source is less important to consider than the triple-frequency voltages produced by the transformer banks.

Third harmonics in the generator voltage, between line terminals will be eliminated by the star connection of the generators and delta connection of the low-voltage side of the step-up transformers.

The triple-frequency voltages in the three phases are in phase with each other and will act as a single-phase system consisting of all three transmission wires in parallel as one side and the earth as a return; the circuit being completed at the generator end through the step-up transformers. The paralleled transmission wires may be replaced by an equivalent conductor.

The constants of the resultant single-phase system will depend upon the effective depth of the earth current which may be anywhere from the depth of the image to several thousand feet. Tests indicate that 500 to 1000 ft. below the surface will represent fairly average conditions. The impedance of the earth return is negligible. The impedance of the transformers is, of course, that of all three phases in parallel or ⅓ normal.

Mr. R. D. Evans has developed fairly simple formulas covering the various conditions such as receiver open or closed, which are shortly to be published. By the aid of these formulas or others similarly developed it is possible to compute the length of line necessary for perfect resonance or the resonant conditions on a given length of line.

In case resonant conditions exist the amount of the triple-frequency current will depend upon the amount of triple-frequency voltage residual in the system and upon the resistance of the circuit. The latter is very low as the three transmission wires and the three legs of the transformer bank are in parallel.

Some of the possible sources of triple-frequency residual voltage on a system will be: (1) Corona, (2) Transformer banks, (3) Unsymmetrical transformer connections.

Corona, of course, can be controlled. The triple-frequency residual voltage from symmetrically connected transformer banks can be minimized by the use of delta-Y connection or by the use of low impedance high capacity delta connected tertiary windings. In fact the low voltage side of the Y-delta connection may be considered as a tertiary winding of very low impedance; in the case of the tests referred to about 7½ per cent at fundamental frequency. Low capacity tertiary windings used primarily for reduction of the third harmonics have sometimes been made with impedance as high as 30 per cent to 50 per cent at fundamental frequency and full kv-a.

Unsymmetrical magnetic circuits in transformers such as are commonly used in 3-phase core form transformers may be sources of trouble even when equipped with tertiary windings as outlined. This is for the reason that the length of the magnetic circuit in the outer legs is greater than that of the mid-leg. Consequently they require a different amount of triple-frequency excitation than the mid-leg. It is obvious that this cannot be supplied by a current which circulates through all three phases of the tertiary winding in series.

Unsymmetrical transformer connections can be avoided.

Certain operating conditions tend to minimize the possibility of triple-frequency resonance.

1. Transformers connected as part of the transmission lines without oil switches. This in effect avoids the possibility of open-circuit resonance by having the circuit closed at all times through the step-down transformers and their ground connection. This is also advantageous in limiting the regulation of the step-down end of the line when load is removed, as any rise in voltage, produces a very heavy low power factor lagging load due to the over-excitation of the step-down transformers. Over voltages of 30 to 40 per cent would increase the exciting current from a few per cent up to a value comparable with the normal full-load current of the transformer.

2. Transformers connected at some intermediate point thus modifying the circuit constants.

The indications are that some of the larger high-voltage transmission lines now contemplated are approaching this resonant condition.

C. L. Fortescue: In Mr. Imlay's paper on page 988 he makes comparison of the performance of a transmission line 350 miles long at 60 cycles and 25 cycles. In going over that table I notice that the conditions do not indicate that he had the best working proposition for 25 cycles.

I think we are coming more and more to see that the transmission system should include transformers and synchronous condensers and the rest of the regulating equipment, as part of the transmission lines and Mr. Baum has pointed out that we probably should consider the length of 100 to 150 miles as standard and keep the voltage at each end of these lengths uniform by means of synchronous condensers. In that way we will be able to get the best operating condition on the line.

Mr. Peek and also Mr. Baum have shown two ways of considering the insulation problem. We can obtain uniform string distribution by grading the insulators, we can also obtain it by shielding. I would like to point out that in 1913 in some papers Mr. Farnsworth read before the Institute I pointed out that the problem of insulation was not a problem of obtaining strength in the porcelain body of the insulator but rather the designing of the insulator and the metal parts so as to obtain the maximum strength in the air path. It was pointed out that one important point in connection with this problem was the proper shaping of the porcelain body itself. Another equally important factor was the proper shaping of the electrodes. The problem is no different for the suspension insulator than for pin type insulators. In the suspension insulator—I prefer to consider a string of insulators as a mechanical support. We have to consider the electrical characteristics of the mechanical support. In the string of insulators of equal units, *i. e.*, equal capacities as Mr. Peek has pointed out, what form of shield shall we put in to get best results. The answer is that the shield should be such as to produce as far as possible a uniform field.

I would like to say that the insulator itself is a disturbing feature in the voltage produced between line and ground. By various devices we can shape the distribution so that the gradient at the end insulator will not be steep. We may do that by means of rings, etc.

I think it important to consider both shielding and grading. Grading will probably reduce the entire arcover because it artificially forces a distribution at the insulator string different from the natural one and in doing so we produce high normal intensities at the hardware on the string. We may in removing the string distribution instead of increasing the arcover, reduce it. It appears therefore that a great deal of further study is needed on this subject.

Professor Ryan: Mr. Baum's paper, I know, to be the product of an enormous amount of work on his part. He develops two problems, indicates for us their solution. To the first he gives one solution, the second several solutions. The first is the problem of indefinitely long distance power transmission and the second supporting of the necessary conductors for the same by effective insulation. I have had the privilege of working with Mr. Baum in person through a few phases of his great undertaking. In so doing, I have become very much interested in routes of discharge when flashovers occur and the causes thereof. The great importance of the primary electric field, especially the field in advance of the development of the flash, which leads to flashover, was analyzed and likewise auxiliary fields that inevitably accompany the development of such flashovers. Studies were begun in this way that I hope will be undertaken by many and carried through because they involve factors of great importance. In regard to the point that was brought up by Mr. Imlay in his paper concerning dependency upon corona for dissipating the renegade energies that develop overvoltages. There is a time element therein that is of very great importance, which should be studied a lot before we make up our minds to depend upon corona for such purpose. The accompanying photograph, Fig. 3 was made when a series of wave trains was impressed upon a conductor that was supported by a *V*-string, the string having 15 suspension insulator units. In the test the end of the conductor was terminated in an 18 sphere-net so as to suppress corona there. The terminal was, 84 in. from the wall, the conductor proper was 51 in. to the tower crossarm, and 49 in. from tower members. Out of 32 wave trains two struck 84 in. to the wall, 27 to the crossarm and 3 to the tower. Now while a flash developed a length of 84 in., corona grew out from the 1 in. conductor. Time is the essence of this sort of thing and while a great deal is known about the breakdown of air columns still little is known beyond the work of certain pioneers, Messrs. Fortescue, Peek, Steinmetz and Hayden.

FIG. 3

J. T. Barron: I wish to elaborate on the statement of Mr. Bailey's on page 1009, relative to interconnection.

In New Jersey, where we have connections between several generating stations totaling about 175,000 kv-a. with an approximate total of 1000 miles of transmission at 13-kv. and 26-kv. and with the main generating stations five to fifteen miles apart, we have made studies as to the best method of operating the system.

A theoretical division of the system load is made, based upon the most economical operation of the various stations under different conditions. These results are plotted as curves and placed in operation, the results being noted with respect to both service and economy. Necessary revisions are then made to the charts and the results obtained with the revision compared with the original and if necessary further revision made and placed in service. In this manner, a series of operating charts covering all operating conditions is finally obtained from which load dispatchers operate the system.

With service the first consideration, and no regulating apparatus employed on transmission lines, the theoretically correct division of load and power factor by means of field and governor control is not always obtainable, but the results obtained by use of charts have shown large savings by comparison with the operating costs prior to the close application of such charts.

The installation at proper locations of corrective apparatus for the improvement of the system power factor will result in further economy and better voltage and operating conditions. It is our policy to install 13,200-volt and 2400-volt synchronous motor-generator sets for this purpose, the generators being used for d-c. railway service.

M. E. Skinner: Referring to Mr. Bailey's and Mr. Elden's papers, there are several types of tap changers available for use with tie-in transformers. They divide themselves into those which may only be operated when the transformers have been killed, and those which may be operated under load.

In the former class is the tap changer consisting of switches mounted in the top of the main transformer with an operating handle extending outside the case. The latest type of such a tap changer employs cam operated contactor switches.

When the load cannot be interrupted there are two cases:

1. Where abrupt changes of a reasonably small amount can be permitted.
2. Where smooth and continuous variation in voltage is necessary.

For the first case, cam operated contactors with a preventive coil have been used. By placing the tap changing switches in the neutral they will be relieved of voltage strains to ground. The West Coast affords at least two good examples of this type.

For the second case, the step-induction regulator, mentioned by Mr. Bailey and described in detail in the appendix to his paper, page 1012, offers an ideal solution. The objection raised by Mr. Bailey of the high-voltage sliding contacts has been met by the use of cam operated contactor switches.

Tap changers should always be placed in the winding of lower voltage unless the current is excessive, because

(1) the ratio of transformation can be changed equally as well.

(2) it is much easier to insulate switches.

(3) it is much easier to bring the leads out of the

transformers. The number of leads should always be limited to the absolute minimum as each extra lead represents a serious complication.

H. W. Smith: In connecting two power systems, the questions of voltage and power factor regulation are extremely important. Possible methods of regulation are as follows:

(1) The use of synchronous condensers without any other regulating equipment; (2) The use of synchronous condensers combined with other voltage regulating equipment; (3) Voltage regulating equipment not involving synchronous condensers.

Voltage regulating equipment other than synchronous condensers may comprise the following:

(1) Induction regulators; (2) Step-induction regulators; (3) Auto-transformers with or without tap changing schemes; (4) Two winding transformers; (5) Three winding transformers, the third winding supplying a synchronous condenser; (6) Synchronous booster.

Mr. Bailey's paper describes very completely an application of the induction regulator. Up to the present time induction regulators have not been built for voltages higher than nominal 13,200-volt systems. For higher voltages, the step-induction regulator presents the advantage of lower first cost.

In some interconnections, auto-transformers giving an additional boost of 10 to 20 per cent may be used in conjunction with synchronous condensers to give good results. Auto-transformers can be provided with one or two taps and these changed under no-load conditions, to allow for changes in load conditions. To change taps under load means the use of a number of switches in conjunction with a small auto transformer and for high voltages will be costly. Two and three-winding transformers can be used to obtain any additional voltage desired, and they have the advantage of isolating the two systems. The third winding can be used to supply synchronous condensers in order to get power factor control. Some of the points to be considered in the use of three-winding transformers are covered in Messrs. Skinners' and Peters' papers.

The synchronous booster can be used, but in most cases its voltage will have to be stepped up through a series transformer for insertion in the line. This is necessary because it is extremely difficult to design a small high-voltage machine which will stand up under the short-circuit conditions obtaining on a large system. Other objections are also the higher losses and the attendance necessary.

A. O. Austin: There is one thing that usually happens: When there is trouble on a transmission system and we can not locate the source, it is generally blamed on the insulator. This is largely due to the fact that evidence coming from the field is often misleading. Owing to the smaller clearances at the tower, a power arc starting from the conductor or clamp will be near the insulator and is likely to involve same. Trouble which may be started by birds is usually at the tower and is also likely to involve the insulator. While these troubles are naturally laid at the door of the insulator, it is however, highly important that we distinguish between troubles starting from the insulator itself and those which may start from some other cause but involve the insulator, making it appear as though the insulator was the real cause of the trouble. If this is not done, unnecessary expense may be incurred without materially improving reliability of the system.

The insulator has often been regarded as the limiting factor as to operating voltage, whereas it would seem that the real factors are the old and important ones of regulation and the breakdown of air along the conductor. During the war the Government came up against a serious situation in connection with the operation of the large radio stations which used a persistent wave. The claim was made that the limitation in operating voltage and the efficiency of the large radio systems was due to the insulator. In return it was claimed that insulators were then available, which if used, would put the limitation up to the breakdown of the air on the aerial. That this latter assumption was correct has been proven by a recent trial run on the Lafayette Station. During the trial run it developed that approximately 200 kv. was the limiting voltage as the conductor or aerial would plume. At high frequency a plume or arc may start from the conductor at a comparatively low voltage, the arc going to ground a distance of some feet if there is sufficient energy.

It would seem that in general we have the same situation on the large transmission system that we have with the radio stations. In the case of the radio systems it is possible to place the limiting factor up to the pluming point of the aerial or conductor and it would seem that by applying the same methods to transmission work, it will be possible to place the weakest electrical point on the system on the conductor some distance from the insulator.

By the use of the insulated control, it is possible to greatly raise the voltage which the conductor will carry in the vicinity of the tower and as this device is effective on any frequency or voltage, it is certain that the upper limit of voltage is not that due to the insulator. By the use of the insulated control and the caging of the conductor, it is possible not only to control the gradient of the string, but what is even more important, the pluming point of the conductor may be greatly raised so that the danger of breakdown in the vicinity of the tower is greatly reduced. The breakdown voltage in some cases may be practically doubled for a given clearance. This is particularly important where it is desired to raise the voltage on an old system having small tower clearances or where it is desired to operate at an exceedingly high voltage.

On any transmission system there are certain agencies tending to set up high-frequency disturbances, which, if not damped out, may cause a breakdown regardless of the line insulation. The damping will increase approximately as the square of the frequency and as the square of the voltage. From this it is evident that if attachments in the vicinity of the tower raise the flash-over or pluming point of the conductor or fittings, even by a small amount, the increased losses possible before a spilling voltage is reached may absorb the energy in the transients and prevent a spill or arc with attendant interruption.

The small damping or absorption of the disturbances on the large projects of today, owing to their low natural period, must be given due consideration. On the system having a low natural period, and consequently a low absorption rate, it is highly advisable to raise the flash-over and prevent the line spilling so that the increased losses will absorb the disturbance before the spilling voltage is reached. Fortunately the losses in the ground and air increase as the square of the voltage. It is then evident that improvements, which will permit an increase in the maximum possible voltage which may be placed on the system before arcing will occur, may be very much more effective in damping out the disturbances than would be generally supposed. A system having considerable trouble from spills may then be benefited materially by raising the spilling point of the conductor or insulator system.

On transmission systems there are many causes tending to set up disturbances. These disturbances need, however, to cause little or no trouble if the spilling point can be raised to a value where the absorption will cause the disturbance to be dampened out or at least held within safe limits.

It has been evident for some time that systems having large conductors apparently have a different class of disturbances and the question of effect of corona in producing harmonics should be given careful attention. In the large conductor there is of course no discharge present up to a point in the wave where the air breaks down. When the air breaks down there is a rush of current in the streamers which will certainly increase the effective diameter of the conductor and its effective electrostatic capacity. There will also be a reduction in the effective capacity of the conductor when a certain point is reached in the wave. This voltage is likely to be lower and will be effected by frequency and size or nature of the conductor to some extent. While I believe it is possible that corona may set up rather serious disturbances, it would seem that we have a remedy at hand, for raising or lowering the voltage will change the point at which discharge tends to take place, and thereby affect the resultant harmonic.

Tests at normal frequency would indicate that it is not possible to place sufficient voltage on the transmission system to cause insulator trouble as the apparatus would not have sufficient kv-a. capacity to charge the line. Where transients are likely to cause the arcing to ground, a small additional expense will place the limitation at the pluming point of the conductor several feet from the insulator. The same scheme which will increase the flash-over of the insulator or conductor in the vicinity of the tower can also be made to produce practically any gradient in the insulator string so that it would seem that there is little or no cause to fear from the insulator for any voltage contemplated. This may be accomplished with the regular suspension insulator as generally used.

The following photographs will show what may be accomplished by the use of insulated controls and conductor guards at comparatively small cost. Fig. 4 shows a suspension string arcing at 355 kv. Fig. 5 shows the same suspension string equipped with very small insulated controls. In Fig. 5 it will be noted that the arc is taking place from the conductor to the tower, the arc starting several feet from the insulator. Fig. 6 shows the same insulator string with insulated controls and a conductor guard or cage for increasing the flashing voltage of the conductor.

The relative difference shown in the several photographs will be very much greater where there is considerable energy available or where the transient approximates conditions of a persistent wave for a fewer cycles. Fig. 6 shows means available for raising the arcing voltage of the system so that damping losses may become effective before a spill will occur. While this treatment may not be necessary or advisable on a given system, the method is very effective in raising the flash-over of the system and, gives a favorable gradient as is shown in Fig. 7.

The real problem in the insulator is an economic problem, which it would seem is on an exceedingly satisfactory basis. The depreciation rate on the best insulators is exceedingly small and insulators of comparatively large size can now be built without having an unduly high rate of depreciation. This permits of a single string in place of multiple strings resulting in a considerable saving. The problem is an exceedingly interesting one but time will not permit of a thorough discussion.

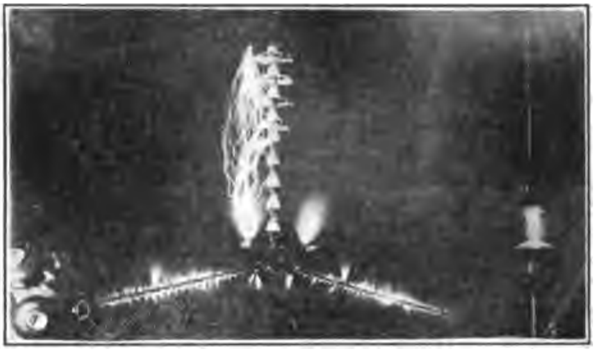

FIG. 4—NINE SECTION INSULATOR WITH B. C. HARDWARE AND CENTER PHASE CLEARANCE—335 KV.—35,000 CYCLES

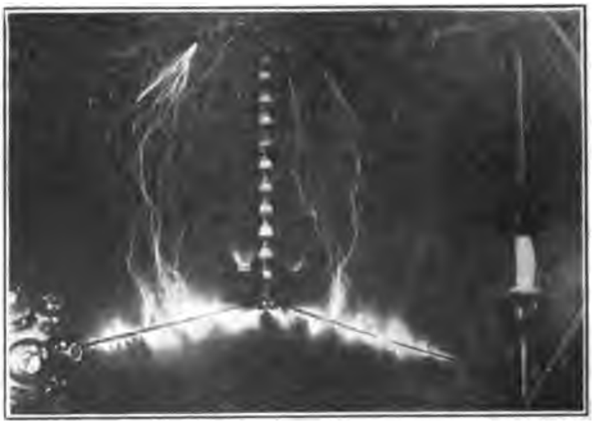

FIG. 5—NINE SECTION AND ONE SPECIAL SECTION INSULATOR. 477 KV.—35,000 CYCLES. B. C. TOWER INS. CONTROL NO. 11623 S. C.

I can bear out Mr. Creighton in what he says regarding the treatment of insulators. I do not believe, however, that he should have obtained the very high losses in the untreated insulators unless the insulators or cementing materials used were very inferior. There are records from the field on thousands of insulators, some of which have no treatment of the cement, and others having partial treatment, where the losses after six or seven years are negligible. The cement in insulators has been treated in different ways in certain types for a number of years, but it is not believed that the treatment of the cement is a cure-all, although it may be a material benefit in some cases.

FIG. 6—SAME INSULATOR STRING. 514 KV.—34,000 CYCLES. INSULATED CONTROLS AND CONDUCTOR GUARD

One of the easiest methods is to impregnate the cement with paraffine and gasoline, which has been shown to be very effective in reclaiming porous insulators, the method being applicable for field work. A number of cases have come to my attention where the porcelain without any metal in connection with same and without any cement, cracks, owing to the stresses set up due to temperature gradient or some other cause. Treatment of cement regardless of its value will evidently not take care of these cases.

There are now operating records on hundreds of thousands of insulators which take care of stresses set up by the cement by resiliency in the joint or by restriction of the bearings area and there are vast quantities of insulators where that portion of the cement which is likely to be affected by time has been impregnated. While it is thought that this treatment has been worth the cost and effort put on same, it must not be over-rated for very severe stresses may be set up owing to the temperature gradient in the case of pin insulators and the difference in expansion between the metal and porcelain in the case of suspension insulators which will exist regardless of the treatment of the cement. Some of the means applied for relieving stresses were discussed in a paper in June, 1917, but time will not permit of a complete discussion of this subject.

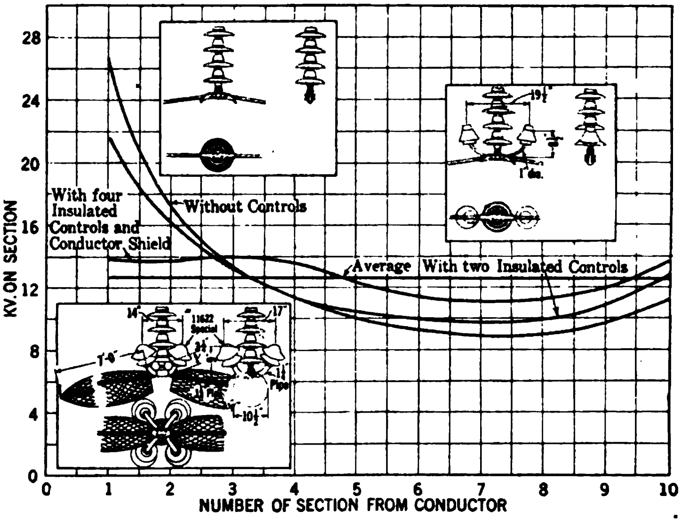

Fig. 7—Potential Gradient Curves for 220-Kv. Line 10-Unit String No. 25621 Insulator

It is gratifying to note that Mr. Creighton is evidently satisfied, that the simple impregnation of the cement will apparently eliminate the theoretical disadvantage in the cap and pin type insulators.

It would seem that the real problem today in high-tension transmission is not the insulator, but, first, line regulation, and second, corona losses and their effect upon the system.

With the advent of exceedingly long lines, it would seem that there is also some question as to the frequency to be adopted unless the magnitude of harmonics which are likely to coincide with the natural period of the line can be kept exceedingly small.

All of these problems can be solved and even should trouble develop, it is possible that simple remedies may be applied which would eliminate serious trouble. It would seem that we can install a transmission line at the present time for the highest voltage contemplated with greater certainty than in the case of a 60-kv. line a few years ago.

K. A. Hawley: Referring to Mr. Baum's paper, all of the earlier transmission lines were carried on insulators of multipart pin type, reaching the practical upper limit at that time at about 66,000 volts. With the development of the suspension type insulator it became possible to place any number of units in series, thereby dividing the voltage between more than four thicknesses of porcelain, the practical limit of pin type. For several years thereafter, the suspension insulator took care of lines quite satisfactorily up to 100,000 volts and even to 150,000.

The records taken from these higher voltage lines show insulator flashovers which, while not making operation unsuccessful, yet have been frequent enough to be a real annoyance. So far, it has not been possible to explain completely why these troubles occur. Aside from lightning which must always be expected to cause insulator flashovers, these failures come from various other causes such as wet dirty insulators, switching surges, etc.

It is now well understood that with a string of standard suspension insulators, the unit next to the line will have to carry from 20 to 30 per cent of the voltage to earth.

It has not been found that this voltage concentration has caused failures of the line units or appreciably increased the mortality of it above the other units in the string. This would indicate a possibility of using fewer units for a given voltage providing the insulators share the work alike, and also providing proper protection is obtained against surface failures or flashovers.

In case of wetting of insulators by fog or light rains, voltage concentration means greater local power loss and more rapid drying at these points. This, in turn, increases the local surface resistance against the leakage currents, thereby increasing still further the voltage concentration. The result is that incipient arcs are started at these points which make more easy complete flashover in case of line surges and, in fact, these small arcs may possibly become the generators of local high-frequency disturbances and surges which would be the cause of complete flashovers.

Just as the breakdown value of air between needle points is much less than between spheres, because of the building up of high-voltage gradients about the points, so the great differences of pressure about the bottom of the insulator string make the beginning of flashover easy with ultimate disasterous results in case of switching surges and other disturbances.

A combined arcing and grading ring about the lower end of the insulator string will have two very decided advantages in correcting the above troubles.

The grading ring will redistribute the voltage over the insulators so that the maximum voltage will not be over 12 per cent as compared with 20 to 30 per cent. as stated above. This, of course, will make the drying of insulators from power current leakage much more nearly uniform and, at the same time, will stop the beginning of corona around the hardware of the insulators, which will reduce the tendency to flash over when dry. As long as lightning is uncontrolled and nature provides arcs a mile long, it will be impossible for us to protect the line so that it will not flash over to the tower, and at the present state of the art, this will usually occur along a wet insulator string. The power arc which follows will immediately form from the arcing ring which will effectively lead the arc away from the insulators so as not to damage them. The arc rising to the ring, as it does on our grading ring, follows a course upwards such that the reactance of the arc, acting as a magnetic blowout aided by the heat or chimney effect, causes it to be blown quickly away from the insulators without damage. This ring must, therefore, be connected directly to the line and not insulated from it. Its function is to protect the insulators from certain arcs which we now do not know how to prevent. The protection against further damage becomes rather a power plant problem in the suppression of the arcs by devices now available.

We have found that with a 14-unit string, we could observe corona on the insulator parts at 100,000 volts to ground without the grading ring, whereas no corona could be seen at 200,000 volts to ground, when the string was protected with the grading ring.

It is our belief that it will be found desirable to use the grading ring with all insulators operating on transmission lines above 100,000 volts. It is possible that this will even permit the use of fewer units in the string, as there appears to be little fear from danger of puncturing of the porcelain itself. The combined arcing and grading ring will afford a double protection, preventing flashovers from causes aside from lightning, and will greatly aid in protecting the insulators in those rare occasions when arcs do occur.

Referring to the Fritz-Gilchrest paper, the manufacture of electrical porcelain has, at times, been clouded with deep mystery as to the wonderful virtues of the materials used, as well as unexplained performances of insulators because of different shapes and sizes. All of this can be, and is now, largely reduced to an exact science, the price of perfect porcelain being largely a matter of eternal vigilance. In this paper just read, the manufacturing processes followed by the Locke Insulator Mfg. Company have been quite satisfactorily described, even to the extent of some of their patented machinery. We are very glad indeed to have electrical engineers visit our factory. We will show them the intimate details of the handling, cleaning and grinding of the ingredients used in first class porcelain. We have also extended the same courtesies to other manufacturers' engineers. We are now very interested to see how completely their processes conform with ours which we have had in quite complete operation for over four years past. We have found that aside from insulator design involving mechanical and electrical features, the biggest and most important problem is the manufacture of perfect porcelain involving, primarily, careful grinding and cleaning of the materials, thereby permitting the manufacture of thoroughly vitrified, homogeneous body without the extremely glassy texture which tends toward brittleness.

In the design of eye bolts, we have, of recent years, found no trouble in operation. The surfaces of the bolt have been carefully laid out so that a load can be delivered to the insulator with a minimum length. On the earlier types, the pin hole was completely filled with cement. Now the pinhole is filled only to the depth necessary to deliver the load, reducing the mass of the head and increasing the radiation. In the larger size, heavy duty, insulator, it has seemed desirable to cover the bolt surfaces with a thin coating of elastic compound, although severe laboratory temperature cycles have not shown it necessary.

In connection with Mr. Creighton's paper, I will say that during the earlier period of the development of electrical transmission lines, the pin type insulators gave fair commercial satisfaction, especially at the lower voltages. At the time that it became necessary to develop the suspension type insulator in order to take care of voltages above 66,000, it was quite generally considered that the porcelain insulator as then developed, was about all that could be desired. I remember having read in an editorial in one of the leading technical magazines early last decade, that the problem of insulation had been solved and that all that remained for the use of extremely high voltages was the development of transformers and switching equipment.

Not long after this, however, the power companies realized that both types of insulators were in serious trouble and that unless remedies could be found, the practical limit of voltage had been reached if not actually passed. The cemented type suspension insulator was turned out in large quantities by all manufacturers without full regard as to the mechanical, ceramic, or electrical problems involved. No expansion joints were provided between the hardware or porcelain; the porcelain was not as carefully made or fired as is now done; or properly shaped for its electrical duty. Little attention was given to the kind of Portland cement used. Certain kinds of cement, especially those giving very quick setting characteristics, are inclined to expand in setting and still further in changing their crystalline structure later on. Cracking of the insulators has undoubtedly resulted from this. The coefficient of expansion of iron or steel is higher than that of porcelain. Consequently, metal parts cemented inside of porcelain will cause it to burst unless there is some cushioning for it, or unless the porcelain is elastic within the limits involved. Such a failure as this would cause longitudinal or vertical cracks in the porcelain parts. In the experience of our oldest men, they have never seen such a crack in the head of a suspension insulator such as we would expect from the expansion of the bolt.

The only conclusion that we can draw from the above is that the cement has furnished this cushioning effect. Instead of causing the failure of these insulators, it has, we believe, been the thing which has prevented 100 per cent failure of the suspended insulators.

An analysis of the failures of suspension insulators shows two types of cracks which may have been due to temperature expansion. One is an annular crack about the head of the porcelain at the top of the cemented pin. This has been corrected by placing a compressible pad on top of the pin where the cement is thin. The other was a similar crack at the lower edge of the cap where it bore upon the horizontal shell. We have corrected this by leaving a clear space between the two parts and at the same time have placed no cement in the pin hole lower than the level of the edge of the cap.

This last change was made in about 1915 when we placed under the lower edge of the cap a rubber gasket. Some of these insulators have failed and have been returned to us for inspection. In almost every case, it was found that this gasket was eccentric and was not properly performing its function. We now use a gasket of different material and remove it with all traces of superfluous cement before the insulator leaves our factory.

It is also obviously unfair to the cement to blame it for holding water for thirsty, porous porcelain to absorb. If the porcelain is properly made, the presence of water which is now always with us, will do no harm.

As far as we know, failure of insulators aside from surface failures, have been entirely mechanical and not electrical. The standard insulator, as now made by the Locke Company, is an entirely different product from that made only a few years ago.

During the early years of suspension insulators, there was a percentage failure altogether too large. Yet in spite of this, there are a very large part of those insulators still in service giving a good account of themselves. While on some of these early lots, failures amounted to several per cent per year during the very first years of operation, insulators sent out during the last four or five years have not yet shown the beginning of failure, even those not having all of the modern insulator attachments. We are, therefore, unable to make any time performance curves to show the life of insulators we are now making, and considering temperature cycle tests, etc., to which we have subjected samples of these insulators, we believe that the practical life will be limited largely by the life of the hardware.

At the present time, this porcelain insulator problem seems to be solved. However, if in the future we find that there is trouble due to cement expansion, as described in Mr. Creighton's paper, which we do not now expect, we can apply his remedy. The only objection to it is the matter of cost, and the weakening of the mechanical strength of the insulators by preventing the complete setting of the cement. Or else it will be necessary to turn to the Hewlett type insulator which uses no cement.

R. H. Marvin: The Company with which I am connected started experiments on impregnating the cement of suspension insulators in 1916. The results obtained may be of interest in this connection.

The tested insulators were prepared by allowing the cement to become well set, then thoroughly drying the cement, and finally soaking the insulator in melted paraffine. In addition a coat of varnish was applied to the outside of the cement as a slight extra precaution.

During December 1916, the following samples were made up and placed out doors near our factory:

41 treated units in strain position under load of about 3000 lb.;

80 untreated units in strain position under load of about 3000 lb.;

80 untreated units in vertical or suspension position without load;

Megger tests were made at intervals but without finding any failure. Thinking that the megger test might not be showing up the deterioration, in July 1919, two and one-half years after erection, we took down all the units and gave them the following test:

50 kv. for one minute to pick out any already broken down, then one minute at flashover voltage to check up the quality of the porcelain.

Of the 41 *treated* samples, there were two failures at 50 kv., but as these had been chipped in handling it is doubtful if these were true failures.

Of the 80 *untreated* samples in strain none failed at 50 kv and would, therefore, have passed a megger test. However six failed during the flashover test, which may indicate some deterioration.

The 80 *untreated* samples in suspension gave no failures on either test, except one unit which had been chipped in handling and failed at 50 kv.

The experiment to date has run about four and one-half years. Recent megger tests show no further losses.

These experiments do not indicate much difference between the treated and untreated units. It is true that climatic differences are an important factor, and it must also be admitted that as the insulators were simply suspended between supports and not subjected to the motion of an actual line that the conditions were not quite so severe. However, they do suggest that further study is desirable in order to form a definite opinion as to the value of impregnating the cement.

G. I. Gilchrest: I am especially interested in Mr. Creighton's paper. He suggests in his paper that the ceramic engineer is largely responsible for the solution of the problem of producing quality porcelain. I agree that the ceramic engineer certainly has plenty of work to do, but I think that the production of commercial pin type or suspension insulators that will withstand service conditions is even more a problem for the mechanical engineer.

The mechanical problems in factory production, such as assembling of porcelain to porcelain or metal parts to porcelain are especially important. If the problem of assembling insulators had been given more careful thought by the mechanical engineer in the early days of transmission engineering, the service results obtained from the insulators, I believe would have been better. The failure to give proper consideration to the temperature stresses developed in service is now a matter of history.

Mr. Creighton suggests that it is probably possible to treat porous insulators with inpregnating material so that these insulators will withstand service conditions. I am very doubtful if such insulators would have anything but a relatively short life in service. Although it is possible to impregnate porcelain sufficiently thoroughly so that it will pass laboratory tests, the temperature changes which develop in line service are of a somewhat different nature.

The cycles through which the insulators pass when installed on transmission lines involve longer periods of time and afford opportunity for the capillary attraction to draw moisture into the pores of the insulators. I believe the majority of engineers who are experimenting with porcelain feel that any porcelain body which is sufficiently porous to allow impregnation, offers a hazard if placed in line service where it is subjected to high voltage.

I wish to express my opinion of specifications. In general, specifications are very useful not only to the customer, but to the manufacturer. The manufacturer must have specifications which he follows in his factory in order to maintain a standard quality. However, specifications will not entirely determine the quality of the insulators which pass the specified tests. The final quality is very dependent upon the quality of the insulator parts as they come from the kiln.

If a proper supervision of raw materials, of mixing and proportioning, manufacturing and firing is not maintained, it is not possible to obtain a uniform quality in the finished product. If the test losses represent a high percentage of the parts, it is very apparent that either the design is not proper or there is some error in the manufacturing process. Moreover, the portion of the test period during which failures occur should be carefully noted.

I am very glad indeed that Mr. Austin has discussed the problem of air insulation, as I think a consideration of the air insulation is of extreme importance in the design of the insulator. Mr. Fortescue discussed in his paper before the Institute in 1913 the desirability of considering the stresses in the air path in the design of an insulator. The field inside of the fabricated material will give no disturbance in the air about the insulator when voltage is applied. Obviously, i is necessary to give a proper design to the inside of the insulator in order to avoid over-stressing any of the material. However, this is a very simple problem.

The external field, *i. e.*, the air about the insulator, must be carefully designed if an efficient insulator is to be obtained. By proper consideration of the electrostatic field according to principles established by Mr. Fortescue in his paper, the most efficient design of insulator between given electrodes can be obtained. The problem can be solved by laboratory experimentation as suggested by Mr. Fortescue.

The distribution of stress over suspension insulator strings is now being given sustained attention by the central stations who expect to raise some of their line voltages to 220,000 volts. Mr. Baum's paper discusses proposed methods to properly distribute stress. The method of grading has not been developed commercially in this country, but has been applied to some extent on transmission lines in Sweden. The Swedish engineers have graded some of their 66,000-volt transmission lines by the installation of units of different capacity. I do not believe it necessary to consider grading 66,000-volt lines, but perhaps their method will be interesting.

Their 66,000-volt line is insulated by a string of six suspension insulators (cap and pin type). Two insulators at the line end have a large capacity obtained by a large area of porcelain of a relatively thin section in the cemented section. The two middle units in the string have a low capacity obtained by a unit having porcelain of relatively thin section and smaller area than those installed on the line end. The two units next to the cross arm have about the same area of section as the middle units, but the section of insulating material is thicker.

The Swedish engineers with whom I have discussed this grading scheme seem to believe it is advantageous to use this method even on voltage of 66,000.

E. E. F. Creighton: I will confine my remarks to Mr. Gilchrest's paper. I think the ceramic side of the problem is one that needs a great deal of attention. The most surprising thing for a scientific man is to go into a porcelain factory and see the crude methods they use in their manufacture. Necessarily the ceramic side is more or less a craft—they have to depend a great deal upon the individual. The materials they use are dirt, dug out of a bank. The particles vary greatly in size and in chemical content. Some of the materials that they use are not in any way refined. Naturally unless they control the mines they are going to get a wide variation in materials that will make a final variation in the product. The particles used in the make-up of the porcelain vary tremendously in size, from the ultra-microscopic fine particles in the ball clay to the ground-up feldspar and flint. The particles of variable size tend to segregate. Mr. Hawley says the way to prevent that is by finer grinding.

The problem of drying is one that has not received enough scientific attention, although today the automatic driers have given an important advance. The difficulties that beset the ceramic engineer, then, are a composition of large and small particles not well blended, drying more or less unequally with the resultant mechanical strains and cracks, the proper proportioning of the ingredients, and on top of all of these only 20 to 40 degrees allowable variation in temperature, at a temperature of about 1350 degrees.

Now to one point brought up by Mr. Gilchrest regarding the porosity—I have investigated insulators that have been out and perfectly satisfactory for ten years and found a very considerable degree of open porosity which, in that case, was protected by well-glazed surfaces. It is not necessary to have the pores entirely closed. Porcelain differs from glass in that porcelain is porous. It is filling the open pores with moisture from the cement that gives most of the trouble. If the pores are not sufficiently open or large to weaken the dielectric strength, simply glazing over the surface will prevent trouble. I do not want to emphasize or recommend, using open pores in the porcelain, but nevertheless one can exaggerate the dangers of pores too much.

Now as to testing. If insulators have the defects of open pores as they come from the furnace, if they are just on the point of puncture when arc-over voltages are applied, naturally a second test or a longer continued electrical test will develop some of these faults. Therefore, I want to emphasize again the prime importance of improving the ceramic side. When an insulator has a puncture voltage considerably above flashover voltage, then it is possible to make successive tests without causing a puncture. Some day the manufacture will reach the state permitting these "over-voltage" tests.

Professor Ryan: First in regard to Mr. Peek's paper, I would like to bring your attention to the accompanying Cady diagram, Fig. 8, that expresses the relation between voltage and corona formation in the breakdown of large air columns.

The relation between the current set up through air (and gases generally) and the correspondingly required voltages is illustrated by the curve *O A B C D F* between the widest limits. For convenience ever changing scales are used for the corresponding values of *I* and *E*. On the application of 100 volts, more or less dependent upon the size of the air column in use, an extremely small current is set up. In all ordinary dimensions such current will be a small fraction of a microampere. It will increase with the voltage until an early limit at *A* is reached. At this

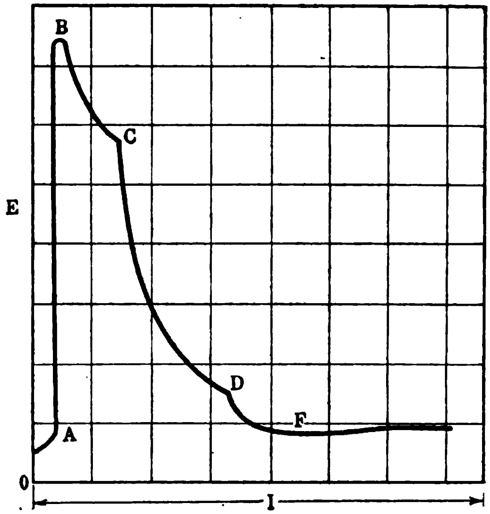

Fig. 8—Unstable States in Arc and Glow Discharge (W. G. Cady, Metallurgical and Chemical Engineering, Nov. 15, 1915 .

stage the free ions are being conveyed to the opposing electrodes as fast as they are formed by nature. No further increase of current through the air can occur without some additional source of ions. This conduction through the air in the *E* : *I* relation at *A* is known as the *saturation current*. When the voltage has been increased greatly (attaining the value of about 30 kilovolts per centimeter in the air about the electrode at sea level) ionization by collision of ions and neutral atoms occurs resulting in a bountiful supply of ions, glow discharge occurs and the *E* : *I* relation at *B* has been developed. This is an unstable state of the conduction of current through the air column. If the voltage is not lowered through some automatic control, as by an ample resistance in circuit, corona formation will develop into long flashes which when they reach the opposing electrode form *flashovers.* Flashovers occur, therefore, at the *B*-state or just beyond it if the flow of current is not limited by some form of ample "ballast," *i. e.,* resistance or reactance and the voltage is high enough to cause the glow or streamer discharge to touch the opposing electrode or to touch a similar glow or streamer discharge from such opposing electrode. If flash-over is not permitted, through current control, the corresponding voltage is lowered as the current is allowed to increase until the stage at *C* in the $E:I$ relation has been attained. At *C* the cathode has been heated by the bombardment of incoming positive ions to the degree whereat it radiates ions in abundance. A further and rapid drop in voltage ensues with increase of current until the $E:I$ relation develops the stage at *D.* At this stage the anode has begun to fail forming thereby the *fourth* and most prolific source of ions. The $E:I$ relation between the *C* and *D* stages is that of the *half-arc*; the Poulsen arc converter used in radio telegraphy is an example of this type of arc. The fully developed *power arc* as we ordinarily know it occurs at and beyond the *F* stage.

All of these unstable forms of conduction through the air have the common physical property of constituting sources of oscillating currents and, therefore, of line trouble to a greater or lesser extent.

The trend of practise is to make the line aperiodic, to make it open only to currents at normal frequency, and to see in every respect as far as we can that it is closed for the circulation of current at any other frequency than the frequency of action for the transmission of power. Accordingly our trend of effort, action and development must be to cut out as far as possible all sporadic sources of alternating current. Everything that we learn in regard thereto is a great help.

Passing on to Mr. Creighton's paper: During the past year a committee of the N. E. L. A. engaged in the conducting of an aging test; cap and pin insulators from prominent makers were selected and put through a temperature cycle test in strings, beginning in the middle of January and completed a few days ago. 3600 temperature cycles, one cycle per hour. The string contained a dozen units each loaded to 2000 pounds. In a climate where the air is dry the air surrounding the insulators in the ovens was heated up by means of resistors. A rather drastic cycle occurred,—130 deg. fahr. variation in temperature in the rims of the insulators and 40 deg. at the centers. After each 150 cycles for a few minutes the action was stopped and high-voltage flashover tests were applied to see if they were all enduring the temperature test and remaining in good condition. All have endured this test. A few more cycles will be added so as to round out the cycles to near the number of daily cycles in a ten year period. The insulators were dried out thoroughly and by sawing right through them on a plane through the center, cracks were found to extend up and down through the cement.

Passing on to Dr. Whitehead's paper: Mr. Fortescue in his discussion yesterday and today Mr. Creighton and Mr. Gilchrest have emphasized the importance of air surrounding the support of the high-voltage transmission line as well as the support of many other things operating at high voltage. It follows therefore that Mr. Whitehead's paper is of particular interest to us all and of great value. It is through his work, in regard to which he has well informed us from time to time, that we are able to go ahead with many experiments in high-voltage research.

F. W. Peek, Jr.: Referring to papers by Baum and Lewis during the discussion there has been quite a bit said about "high frequency" causing trouble on transmission lines. The term may equally well cover a large variety of transient disturbances and I believe engineers should be careful not to speak in too loose a way. If by "high frequency," *undamped* radio frequency is meant, I believe that we can safely say such disturbances practically do not exist on transmission lines.

It was my good fortune some years ago to assist in conducting an investigation of the disturbances occurring on transmission lines due to lightning. A 25-mile idle line in the mountains of Colorado was available for this purpose. The characteristics of lightning induced on transmission lines were studied. Measurements were made of voltage, energy, duration, etc. In general, it was found that the voltages were of steep wave front. Many discharges took place on the lower voltage gaps. The discharges on the higher voltage gaps were less and less until finally there were very few on this line at a needle gap setting for about 200 kv. This would perhaps correspond to about 400 kv. in actual volts.

Other transients that are of importance on transmission lines are those caused by arcing grounds on systems with isolated neutrals, and those caused by switching. Such disturbances that we have been able to measure are either in the nature of a surge or a *highly damped* high-frequency oscillation. Disturbances of this character sometimes reach double voltage but often cause very little rise in voltage across the line. They may, however, build up to high values internally in inductive apparatus.

Fortunately the grounded neutral system is fast replacing the isolated system.

Insulator failures may be caused by excessive voltages, by weakened insulation, or by a combination of the two. Available data indicate that the greater number of insulator failures have not been primarily due to excessive voltages or to "high frequency."

A. W. Copley: For some time in the past it has been customary to frown on star-star connected transformers and especially when these transformers were auto transformers; but with the development of the lines interconnecting systems all over the country, and particularly the development of interconnecting lines on the Pacific Coast, the desirability of making those interconnections in the most economical way has caused the development of the star-star transformer to such a point that it is entirely safe to use it not only from the standpoint of telephone interference, which at one time was considered the big bugbear, but from the standpoint of the power system itself, and so Mr. Skinner's paper is especially interesting at this time. The use of the tertiary delta and the solidly grounded neutral, together with the proper distribution of reactances in the transformer between the various windings has been the solution which has been arrived at of the problems which were present and which a few years ago were worrying engineers who had to make these interconnections. The advantage of using the auto transformer for connection of a 220-kv. system of lines to a 110-kv. system of lines in which case the 220-kv. and the 110-kv. systems may be part of the same system, consists very largely in the reduction in cost of making this interconnection. At the same time at points of interconnection the presence of the tertiary delta makes comparatively simple the application of synchronous condensers for obtaining the regulation of the line. Mr. Baum pointed out in his paper the necessity for the use of synchronous condensers in order to get regulation at the end of the line. He also called attention to the desirability of considering the line as divided up into sections with each section provided with a synchronous condenser so that at the points along the line the voltage is kept within reasonable limits. In applying the synchronous condenser, however, it must be borne in mind that the no-load condition is important as well as the full-load condition, and I think that in Mr. Imlay's paper the schemes which he mentions as having been prepared by Mr. Thomas, of using two conductors or possibly three conductors suspended from one string of insulators, is perhaps open to criticism because of the no-load condition. The charging current of the line is very greatly increased and the amount of leading current to be supplied by condensers is increased. A synchronous condenser as normally designed will take somewhere in the order of 40 or 50 per cent of its zero power factor leading rating at zero power factor lagging, and, therefore, if the synchronous condenser is called upon to *supply* a very large amount of leading current, which means it has to *take* a large amount of lagging current when the line is lightly loaded it may be unnecessarily large when the line is carrying full load. Therefore, the application of the condenser for the regulation of the line, must take this into account. As to the division of the line into sections. I believe it is going to be a necessity, not only because we do not want the middle part of the line to be raised in voltage considerably above the ends of the line, but also because of the effect of reducing or eliminating the tendency toward resonance to third harmonics, which is brought about by such subdivision. I believe that with a line cut up into 150 or 200-mile sections, the possibility of resonance to third harmonic is practically eliminated.

L. H. Burnham: In connection with the Peters-Skinner paper, Fig. 3, in reference to "Limitations imposed on Grouping of Windings" applying to primary secondary, and tertiary, Mr. Skinner has stated that in single-phase concentric-coil core type of transformer construction there are *two ways* in which the three windings, primary, secondary and tertiary may be arranged with respect to one another; and that the first arrangement, Fig. 3A will result in normal reactance between primary and secondary, and between secondary and tertiary, but in *very high reactance* between primary and tertiary due to the greater separation.

Mr. Skinner has also advised that in a three-phase concentric-coil core type transformer, there is no alternative, but to *submit to a high reactance* between *one pair of windings* inasmuch as all the windings for one phase are on one leg.

I would like to state that in addition to the methods shown in Fig. 3, there are *several other coil arrangements*, applicable to the *concentric coil* core type transformer which may be, and in fact are now being used for adjusting the reactance, over a wide range, between the various windings. The particular arrangement used will depend upon the requirements of the individual design.

In a core type design, it is also possible to interlace the three windings, primary, secondary and tertiary, in exactly the same manner as proposed by Mr. Skinner for the shell type transformer, shown in Fig. 4, and obtain any amount of interlacing of windings for adjusting the reactance between the various windings. High or low reactance may be obtained as desired.

Therefore, by using the proper coil arrangement, it is *not necessary* in the core type transformer, either single-phase or three-phase, to submit to high reactance, between one pair of windings, as balanced reactance, if desired can be obtained between all pairs of windings. I will say also, that these results can be gotten without excessive eddy loss in any part of the winding.

In reference to the arrangement shown in Fig. 3b, I do not believe that this should be considered, as it would not be good design practise to follow.

M. E. Skinner: I will accept Mr. Burnham's criticism to the extent that the paper should probably not have referred to there being *only two* methods of coil arrangement *possible* with the concentric core form of construction. The thought behind that statement was that in the core form of construction when used for high voltages there are great difficulties in the way of insulation between windings when it is necessary to get from the inner shell to the outer shell and I presume that the methods to which Mr. Burnham refers to will involve some such interlacing between the inner and outer shell, or, perhaps he refers to the interleaf core type of construction which is really in effect a shell type transformer with the cruciform core and circular coils. I do not believe that this type of transformer is applicable to the extremely high voltages which are being considered for long distance transmission lines today.

J. P. Jollyman: A short time ago the Pacific Gas & Electric Company was faced with the problem of providing for the transmission ultimately of some 500,000 kv-a., most of it to be transmitted a distance of from 200 to 260 miles. As Mr. Baum has stated, the question came up as to the voltage to be employed. Studies were made of the characteristics of circuits of different voltages, of the efficiency of such circuits, and of their probable costs.

If we take a circuit of a certain specified length such as 200 miles and 60 cycles, Fig. 9, the frequency being fixed by the requirements of the community, and study their characteristics the first thing we find is that the capacity of a single circuit increases with the square of the voltage. The reason for that is this,—the amount of current that can be put on the line is determined by the reactive drop in that circuit in per cent of voltage at the generating end or at the receiving end, whichever you make reference to. Therefore, as the voltage goes up the per cent of reactive drop over the line that is permissible remains the same but the actual reactive volts increase. The reactive drop is created by the flow of current, therefore the current that may be transmitted at a higher voltage may be increased with the voltage. If, therefore, the current and voltage both increase with the voltage, the kw. that may be transmitted increases as the square of the voltage. At 110 kv. the power that may be transmitted over one circuit, is 30,000 kw.; at 220 kv. this becomes 120,000 kw. That, is not the absolute maximum but is a convenient point for comparison. Now, let us see what happens if you double that voltage again, assuming it can be done some say, at 440 kv. the capacity goes up to 480,000 kw. and that was all the power we had to transmit. Obviously if it has been deemed feasible it would not have been wise to have entrusted the entire output to one circuit, an amount

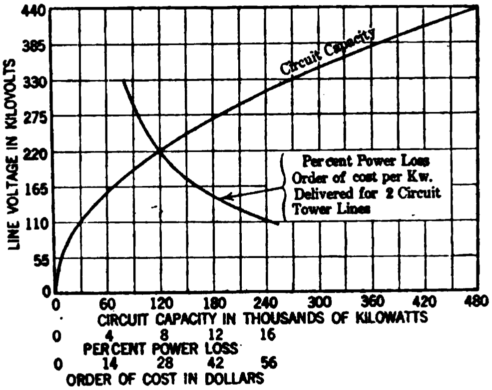

Fig. 9—Characteristics of 200-Mile, 60-Cycle Circuits

of power practically twice the entire load of the present system. The next question considered was relative costs and efficiencies. Now it was found that the cost of this 220-kv. circuit was roughly twice as much per mile as the 110 kv., with a capacity four times as much. The cost per kw. transmitted is only half as much. It was also found that with the conductors chosen in accordance with Kelvin's law, or based on the application of Kelvin's law, that the actual power losses decreased as the voltage went up. The per cent loss in transmission at 110 kv., was about 16 per cent, at 220 kv. it is about 8 per cent, at still higher voltage it would be less in per cent. It was, therefore, seen that somewhere around 220 kv. would be the desirable point if it could be accomplished. One other consideration—the charging kv-a. of a circuit of fixed frequency and length increases with the square of the voltage and is, roughly, for 60 cycles and 200 miles, about a quarter of the capacity of the line. For operating reasons it is very convenient, probably necessary, that the generators of the larger plants should be sufficient to charge one circuit to full voltage at the receiving end. It is probable that it will not always be so operated, but it is a very desirable thing. To do anything else is probably going to be very slow. 220 kv. at 200 miles requires a generator of approximately 35,000 or 40,000 kv-a. to handle the circuit conveniently. If we go on up, consider what would happen if we would double that voltage. The generator capacity would have to be 150,000 kv-a. Such machines have not been developed or even proposed, and even at 330,000 kv. the charging kv-a. becomes so great that no generator ever proposed could handle it for 200 miles. It was deemed that 220 kv. was probably the greatest advance beyond the present 150 kv. that was conservative at this time. It was also found that the construction of such a circuit, its cost and losses, fit in very nicely with the proposed development. The entire load in this project can be carried over three circuits of what will probably be two 2-circuit lines ultimately, thus giving the benefit of a spare circuit. As a matter of fact it will be many years before we need to pass beyond the present construction of a two-circuit line. The 220-kv. line may be considered as comparable with a well equipped double track railway circuit. It can handle a lot of traffic. To attempt to give much more would be equivalent to attempting to increase the gauge of your main railway line, putting on cars of extra large capacity and locomotives of unheard of size. This is beyond the economical requirements of present day traffic and beyond the economic possibilities of present day construction.

If I may take a moment I would like to give an analogy that I have given of the action of synchronous condensers. I put it this way, that a transmission line is something like a shaft supported on a bearing at one end and transmitting power from a pulley at the other end. The amount of power that such a shaft can transmit is largely determined by the bending of the shaft. As the belt pulls against the unsupported end the energy is transmitted by the torsional strength of the shaft but the limit of that energy is the bending of the shaft rather than the twisting. The synchronous condenser is equivalent to an outboard bearing that holds up the shaft and permits it to operate in torsion. This is a homely illustration of the action of synchronous condensers and indicates that they may be desirable in the center as well as at the end of very long lines.

S. Barfoed: In laying out a 220-kv. system it is necessary not alone to consider the electrical features; we must also consider the powerful production end of the scheme. In our particular case we generate power hydraulically, and I will go so far as to say that even the design of the headworks must have reference to the insulator you choose for your transmission line. The hydraulic transmission system has losses and surges each of which will effect the regulation of the line if not carefully handled and will be reflected in choice of insulators and conductors and therefore also the supporting towers and their foundations. The problem then is to coordinate all these various details into one harmonious whole.

We have heard proposed a transmission system whereby you would transmit by direct current through conductors drawn through oil pipe lines. This in order to overcome trouble from inductive interference with communication circuits. Now, as Mr. Baum has told us, the application of the synchronous condenser at intervals along the line and at the receiving end will permit the desirable feature of constant voltage transmission. This is done by automatically controlling the total receiver power factor through synchronous condensers, or the power factor at points along the line where condensers were installed. With d-c. transmission the interconnecting link between transmission line and distributing system is cut off preventing constant potential transmission, leaving the power factor problem of the substation still on your hands.

When it is considered, as Mr. Jollyman stated, that we can transmit 150,000 kw. over one circuit, it is necessary that the engineer make it absolutely clear to himself that he assumes great responsibility because if this flow of power was interrupted even for one day, it would cause loss in prestige, loss in money, inconvenience to the public and thereby indirectly affecting civilization. It goes to show that your civic community, your state, your country is also affected. Some day it may be that through the general transmission of power in this way the very philosophy of life will be influenced.

Mr. Fortescue: I want to emphasize one point brought out in Mr. Gilchrest's paper, *i. e.*, the importance of low factory losses. If the factory losses in insulators are low it is an indication that all the processes are well taken care of, in other words, that the drying is thorough, that the insulator is being carefully made and that the material is uniform. It is a very good criterion of the quality of the manufactured product of porcelain if the factory losses are low. Referring to Mr. Peek's paper. Mr. Peek says that no third harmonics or the multiples can appear on the line due to corona. This would indicate that corona is of symmetrical character. There are some very interesting energy transformations in these corona actions.. We all know, of course, that the energy must come from the generator. It is transformed through the action of corona from the fundamental frequency, and part of it may be actually generated by the production of rotating fields in the armature. Another point we have to think of here is this, that in connection with corona the size of conductor and the voltage are such that the corona is of a negligible quantity, and I want to assure our telephone friends that this corona feature is not to be considered seriously in the matter of inductive interference. There may be some cases in which corona has been a factor in inductive interference. We have cases I know of in which a slight reduction in the voltage has made a very great improvement in the interference and which we have not been able to attribute to any improvement in the magnetizing current of the transmission. Of course some lines are not designed as carefully as they might be, in which case the corona will be a factor.

I want to point out to Mr. Creighton that the impregnating of a body conglomerate like cement takes away its conductive value, it becomes a compound insulator and it may take years before the effect of the high internal stresses and thin layers of impregnated material surrounding the conducting portions of the cement will show any deterioration. It is quite possible that there will be some chemical action with the high internal electric field. In connection with the general problem of transmission of 220 kilovolts, I want to point out that in the actual line problem, the method of working out the amount of power that can be transmitted, etc. is well known. There is one form of diagram which I have found exceedingly useful, the diagram suggested by Mr. Dwight of the Canadian Westinghouse (power circle diagram). With that diagram you can make your sending voltage what you please and the receiving voltage what you please. You can draw up a series of circles which represent various receiving voltages and obtain quickly the limits of power demand which can be transmitted. With each receiving voltage it is shown that there is a very clearly defined zone in which the conditions are unstable.

Now as to the synchronous condenser: I want to point out that the synchronous condenser on a transmission line is not the same as loading. In the condenser regulation of the line you keep your voltage at the condenser constant and you supply either negative reactive power or positive reactive power just as required, and it is an entirely different thing from loading which primarily has to do with maintaining certain fixed ratios between line constants. Another thing about the synchronous condenser is this; it is a condenser and can be regulated for fundamental frequency only; for any other frequency it is purely an inductive impedance. The nature of the design of the synchronous condenser is such that at zero phase sequence current, that is current flowing in the neutral wires, it has very low impedance. Consequently if it is used with a star bank of transformers with its neutral connected to that of the transformer, the latter may be operated with the neutral grounded and the synchronous condenser will insure low impedance to ground currents. It would therefore tend to prevent any resonance of the type pointed out by Mr. Skinner. The synchronous condenser therefore stabilizes not only line voltage but the potential of the transmission line.

I want to point out in connection with the transformer problem, a problem that one might say is very cut and dried, that it gives very little trouble. A few minor things come up from time to time such as mechanical bracing, etc. so as to prevent destruction from short circuit. In considering short-circuit conditions it is necessary to be able to figure out the short-circuit current with a fair degree of accuracy because of the mechanical stress caused by it. Every mechanical support introduced is simply an added expense, so it is a good thing to have a method of calculating short-circuit current at the end of the transmission lines and interconnected systems thoroughly worked out. I want to agree with Mr. Peek in saying that the 220,000-volt system is going to work out all right. We are not going to have very many troubles and the insulator problem will be worked out, and I think the factor of safety will be really higher than on say the present 150,000-volt systems. In 1913 I had some testing transformers made which were designed for the Inawashiro Power Company for testing the transmission lines, they were normally rated at 300 kv-a. One of the conditions of this proposition was that these transformers should operate at their normal rating for two days continuously. We operated these transformers under normal load at 350,000 volts above ground for a week, and after that they were tested again for a half hour at 450,000 volts. Of course that doesn't appear to be a great factor of safety, nevertheless it shows that transformers can be operated at a very high voltage above ground for considerable periods and since the insulation problem of the transmission line is only slightly different in character from that of transformers, we can say confidently that there is no question but that the proper solution will be arrived at.

A. H. Lawton: J. H. Foote, of the Consumers Power Company, who, with Mr. Lewis, conducted the tests on which the latter's paper is based, has prepared a written discussion which will later be printed. The object of his discussion is to urge that further consideration be given to the investigation of corona losses between the limits of the disruptive critical voltage and the visual critical voltage, as there is a large discrepancy between the calculated and the actual losses within that range.

As an illustration, if you will refer to Fig. 17, and Table XXII you will observe that for the delta connection of transformers the actual corona losses are only about 60 per cent of the calculated, and if you will refer to Fig. 20 and Table XXIV which test was made with Y-connected transformers, you will observe that the actual corona losses are only about 30 per cent of the calculated. This discrepancy would seem to be larger than reasonable.

We consider the matter of considerable importance for those companies having moderate amounts of power in the order of 30,000 kw. to be transmitted distances of approximately 100 to 200 miles, and we are not sure but that in the economic consideration of lines of this character a certain amount of corona loss may not be found justifiable.

Livingston P. Ferris: I wish to correct a misapprehension or misunderstanding of some of the speakers who preceded me. I can assure you that I know of no pessimism on the part of telephone engineers in regard to 220,000-volt power transmission, or indeed a higher voltage if such should prove advantageous in power work; no pessimism, of course, as to the success of the system from the power standpoint and no pessimism as to the ability of engineers to solve any interference problems which may arise.

As to the matter of corona, which Mr. Fortescue mentioned, I can assure him that we are not timid as to the effects of corona and I agree with him that corona does not now promise to be an important factor in interference. As I endeavored to point out yesterday, it seems a possible future factor but is not at present serious. So far as the future goes it does not look a probable source of interference because power engineers assure us it is bad practise from the power standpoint to operate a line above the corona voltage, so if that is taken care of, there is no reason to expect any interference to telephone lines from that source. Now I think the only gentleman whom we have heard express an opinion that corona was a factor in the interference situation is Mr. Skinner. I understood him to state, in effect, that corona was the important source of triple harmonics in contrast to transformers which were a negligible source. I think that the actual facts of the case are just the opposite, that is, such trouble as we do get from triple harmonics comes in practically all cases from the transformers and not from the line and I expect such will continue to be the case, but even there I believe that conditions are going to be taken care of.

Mr. Copley stated that *Y Y* transformers were now satisfactory from the interference standpoint. There has been no change, so far as I am aware, to make the use of the straight *Y Y* transformer bank more satisfactory or unsatisfactory from the interference standpoint than it was a number of years ago, but the type of transformer that Mr. Copley and Mr. Skinner are advocating is not the straight *Y Y* transformer but one with tertiary delta and that is quite a different thing. The *Y Y* connection gives the maximum effect in producing triple harmonic residuals. The addition of a tertiary delta reduces these and is, therefore, beneficial, so again we have no real difference of opinion.

M. E. Skinner: I would like to say a word in reply to Mr. Ferris' comment regarding the relative chances for the transformers or the transmission line corona loss being a source of triple frequency. I did not mean to state by any chance that the corona was the most probable source of telephone interference, but if it is assumed that triple frequency or high frequency do cause interference, then it seems to me that the evidence presented in Mr. Lewis' paper is overwhelming, that the corona loss is the more probable source of trouble. I do not think that the evidence can be disputed in spite of the slight inconsistencies represented by the change of capacitance mentioned by Mr. Lewis.

Livingston P. Ferris: The conditions under which Mr. Lewis' tests were made and which gave him these prominent third harmonic neutral currents, were not practical conditions under which transmission lines operate but test conditions chosen to exaggerate the corona. Mr. Lewis recommends very strongly against that condition of operation; so does Mr. Peek, and from cases which have arisen in the past, taking the whole field, the source of interference of triple harmonic frequencies has, in general, been the transformers and I know of no case of interference due to corona. If there is, it is not widespread enough to make it comparable in importance with the transformer as a source of triple harmonics. I would agree with Mr. Skinner if lines were operated in practise as Mr. Lewis did in these tests, for then undoubtedly exposed telephone lines would be subjected to much interference from this source; but in view of past experience and present strong recommendations against that method of operation I don't believe we can say corona is the more important source of interference compared with transformer.

C. L. Fortescue: I understand Mr. Ferris endorses the *Y Y*-connected transformer with tertiary winding. I would like to know whether he also endorses the 3-phase core type *Y Y*-connected transformer.

Livingston P. Ferris: Mr. Fortescue says I endorse the *Y Y* transformer with tertiary delta—I do—in comparison with the *Y Y* transformer without tertiary delta. In preference, however, to the *Y Y* transformer with tertiary delta, the straight delta *Y* connection gives less triple harmonics than the *Y Y* with tertiary delta, for the tertiary delta usually has only a small part of the capacity of the bank and, therefore, will not, in general absorb so much of the triple harmonics as a full capacity lower impedance delta. In reference to the 3-phase core type *Y Y*-connected transformer: it may be said that as regards the production of triple harmonic neutral and residual currents, the 3-phase core type transformer in particular cases may not have any advantage over the shell type or three single-phase units. This is due to the comparatively large m. m. f. of the triple harmonic frequencies which exist in phase in the three legs of the core and produces a leakage flux through the air space and case of the transformer. This flux induces triple harmonic voltages in the windings which, if connected in *Y* with the neutral grounded, gives triple harmonic currents in the line. From this standpoint it is advantageous, therefore, to have a tertiary delta on the transformer, even if it is of the core type.

H. R. Summerhays: In looking over the papers of Mr. Peek and Mr. Lewis with regard to corona loss, the idea naturally arises that if this extra corona loss which appears in a grounded neutral system is due to varying the voltage of the three phases to the neutral, why not do away with it by inserting in the neutral a triple-frequency booster and displace the neutral point at the proper times so as to balance the other effect. With reference to long lines of about 220,000 volts and the transmission of large amounts of power, there are some limitations which have not been touched upon. In some of the long transmissions contemplated, the amount of synchronous condenser capacity is 60 to 75 per cent of the kv-a. transmitted. In attempting to increase the amount of power which can be transmitted over a single circuit at a given voltage, of course, the first most natural thing to do is to increase the size of conductor, but that does not get you any where, because the limitation is in the reactance. The next thing to do is to increase the synchronous condenser capacity and we produce results up to a certain point, but there is a limitation beyond which that can be carried and those limitations have been worked out in the curves presented by Mr. Lewis, which show that beyond a certain point you get unstability of operation. It shows that for a certain voltage and with a given voltage drop between generator and receiver there is a limiting kv-a. or kw. which can be transmitted by any given line, and you cannot increase that no matter how far you increase the synchronous condenser capacity.

Livingston P. Ferris: Delta connected tertiary windings are in some cases called for to reduce the triple harmonic currents and voltages which would otherwise be produced in connected lines and thereby mitigate interference with parallel telephone circuits. It is gratifying therefore to note the increased usefulness and importance of the device from the strictly power standpoint as evidenced by the paper of Messrs. Peters and Skinner. The effectiveness of the tertiary delta as a triple harmonic suppressor is controllable by the designer to a considerable extent, independently of its load capacity, though generally speaking larger capacity may be considered favorable in this respect. The point to be emphasized, however, is that by skillful design the effectiveness of a relatively small winding may be largely increased. I have no doubt this is fully appreciated by the writers.

Mr. Peek's experiments taken in conjunction with Mr. Lewis's tests supply abundant proof that corona can and does under certain conditions, give rise to triple harmonic neutral current in high-voltage transmission lines.

What is meant by "amplification of slight residual triple-frequency excitation voltages of delta-Y transformers by the high capacity of the line," a statement which occurs in the third paragraph of Mr. Peek's paper? On the second page of the paper a similar reference is made to "amplification of residual triple-frequency magnetizing voltage harmonics in delta-Y transformers". Another reference to "amplification of harmonics" is made on the third page of the paper. This time it is corona harmonics amplified by transformer reactance. Are these references to resonance or some other phenomenon?

In Figs. 4 and 11 Mr. Peek shows a line labelled "wattless component of high side current if capacity remained constant." This in both cases is a straight line passing through the origin. Now it would seem proper if there are harmonics in the voltage, which is admitted, that this curve of charging current should bend upward to take account of the increased current which would result from the increased admittance of the line at the harmonic frequencies. The difference between the wattless component shown by this straight line and the total wattless component is ascribed by Mr. Peek to an increase in the capacitance of the line. It would be interesting to know how much of this difference might be accounted for with normal capacitance by the increased current of harmonic frequencies.

From a rough inspection of the oscillograms given in the paper it does not seem possible to account for all of the difference in this way. This is a point I should like to see Mr. Peek cover, including a more complete statement of how the total wattless current was determined.

In the conclusions the statement is made that the third harmonic will be the most prominent of those caused by corona. This will probably be true in much the greater number of cases but conditions of resonance might in some cases so favor the ninth harmonic as to more than overbalance the normal relationship and the ninth might become more prominent in the neutral current than the third. This however could scarcely be termed amplification in its true sense.

In regard to the apparent increase in the capacitance of the line above the corona point it would be particularly interesting to have more complete data and a discussion of the mechanism of the phenomenon. For this purpose the study need not be complicated by a consideration of a three-phase line, which was, of course, necessary for the primary purpose of Mr. Peek's study, but it might be reduced to the simplest single-phase conditions. An exploration of the electric field surrounding a conductor under corona conditions and a comparison with the normal field would be pertinent; and perhaps also experiments over a range of fundamental frequencies. Presumably a change in leakage at least of that portion of the medium immediately adjacent to the conductor, must take place before or simultaneously with any change in capacitance. It would seem that the line leakage could be enormously increased and still have the copper surface of the conductor constitute a boundary at which a large change in radial electric force occurs. In this connection I would ask Mr. Peek how he uses the term "conductor."

James H. Foote (by letter): Referring to Mr. Lewis' paper, in comparing calculated and test corona loss results, it is, of course, easy to find discrepancies which at first thought tend to discredit the test results, since values obtained by the use of a formula, based on thousands of precise measurements, are naturally convincing. It would seem, however, that the fairly consistent tendency of variation of a series of test results away from those obtained by calculation should be of some significance.

The results of these tests indicate that for a line having the physical characteristics of this particular line.

1. The tested corona loss (and even the total tested

loss) between the limits of the critical disruptive voltage e_o and the visual corona voltage e_v is usually less than that calculated by the standard formulas. This is the portion of the corona loss curve which is of interest in designing a transmission line similar to that tested.

2. The shape of the loss curves for the delta tests differs consistently from the shape of the curves obtained from tests when Y connected.

Such consistent deviation from the calculated loss curves causes doubt as to whether provision for all the conditions existing in the case of a line such as that tested is properly made in the usually accepted formulas.

It was such a doubt entertained by the Consumers Power Company based on the indications of various tests and operating data which dated back to tests by the G. E. Company on the Croton-Grand Rapids 110,000-volt line in 1908 that prompted the conducting of the tests which are the subject of the paper. Following up these same consistent deviations, Mr. Lewis has pointed out some absolutely new considerations in the matter of the quantity of corona loss which may be expected on some practical transmission lines.

Thus, as pointed out in the paper, a formula may be correct for sets of conditions similar to those upon which the formula was based and still not apply with accuracy to a line differing greatly from that used in deriving the formula. In fact, the tests with Y connection do not even approximately check the formulas below the visual corona voltage.

In the comparison of calculated and test losses of test No. 10, which may be taken as representative of the tests with delta connection, Mr. Lewis has made a tabulation in Table XXII, showing segregated losses, net tested corona loss and calculated corona loss. An inspection of the comparative corona losses given in the last two columns and plotted in Fig. 17, would lead one to believe that possibly there are yet losses other than those due to corona present in the tabulation of "Net Corona Loss", as indicated by the slowly ascending curve of these losses below the calculated value of e_o.

Even with this adverse indication, the test corona loss over the range of voltage for which the line is designed; namely, 120,000 to 140,000 volts, averages 6.6 kw. per mile against 11.0 kw. per mile calculated, the latter being, therefore over 65 per cent greater than the test values indicate.

In fact, the calculated corona losses for this range in voltage average slightly greater than the total measured losses at the generator.

When comparing calculated and test values for the Y-connection tests, still greater discrepancies are evident.

Referring to Table XXIV and Fig. 20 where are shown details of test 42, it is seen that the calculated and test values of e_o coincide and that for 20,000 to 30,000 volts above this value (using the values for average line voltage given in the table and not the uncorrected voltage shown on the curve) the test corona loss is very noticeably low as compared to that calculated.

For instance, at the average full-load line voltage which is about 132,500 volts, the test loss is less than 1 kw. per mile, while the calculated value is over 3.6 kw. The corona loss at the receiving end of the line with a voltage in the neighborhood of 120,000 to 125,000 volts would average about 0.3 kw. per mile against slightly over 1 kw. per mile calculated, and the loss at the generator end of the line with 140,000 volts potential would actually be in the order of 3.5 kw. per mile instead of the 6.3 kw. or thereabouts as calculated.

The point is simply this: That even though the test results may be inaccurate to a considerable degree, which may or may not be true, it is very evident that differences as great as shown above are not easily brushed aside when the economical design of certain types of transmission lines is being studied.

The paper states that a transmission line should be so designed that under normal conditions no corona is present. This may be economical in many cases, but in the design of such lines as are required on the system of the Consumers Power Company and other similar systems, it can be shown that a moderate amount of corona is economical and can be justified, just as can other kinds of transmission losses.

When studying the economics of corona loss, it should be remembered that:

1. The voltage usually decreases in value from the generator to the receiver, so that there may be corona loss at the generator end and not over the entire line. This is a very pertinent point and should not be overlooked.

2. The load factor of the line has an important bearing just as in the case of transformer core loss.

3. The total quantity of power to be transmitted is also an important consideration.

4. The weather conditions prevailing over the enitre year must be studied since the loss in cold weather is very much less than in warm months of the year.

5. The cost of various construction materials as well as labor must be considered. For instance, in determining the size of conductor required to reduce corona loss, if the conductor size is increased, the tower cost is also increased together with the labor, freight, cartage overhead, etc. Also a point may be reached, and in fact has been reached by the latest Consumers Power Company's lines when an increase in conductor size necessitates either a stronger and more expensive strain insulator or the installation of two of the standard insulator strings in parallel. This may cause a serious increase in cost per mile of line, should there be many angles in the line.

Of course, a composite conductor is often used to increase the conductor diameter, but the saving in corona loss should be balanced against any excess costs which there may be incident to its use.

After a study ot these and other considerations which will present themselves, the total annual kw-hr. loss due to corona, as determined from the best information at hand must be evaluated to determine whether or not conductor sizes or voltage conditions can be economically changed.

Of course, all such studies must be based on assumptions that will average from year to year and may vary for different lines on an interconnected system, so that compromises must be made, but we consider it feasible to make such studies and to decide on a standard voltage, conductor, and spacing to suit average conditions.

To sum up: it is believed to be good engineering to allow some corona loss to exist on at least the higher voltage portion of many transmission lines during at least a portion of the year.

This consideration allows this company to employ 140,000 volts as the initial voltage on a No. 0 30-cycle (or No.00 60-cycle) transmission line, whereas 102,000 volts would be the limit if the summer value of e_o were not to be exceeded. Or, to put the problem another way, greater than a No. 0000 copper conductor would be required if 140,000 volts were to be used and e_o not exceeded. The reduction in voltage to 102,000 volts would reduce the load ability of the line almost 50 per cent, and the increase in conductor size increases the load ability almost 100 per cent; either expedient failing to meet the desired unit size of transmission line (in this case 25,000 kw.) which had been selected as most desirable for this company's condition.

Looking at the corona loss proposition with all these considerations in mind, it is very evident that the accurate determination of power loss values between e_0 and e_v may often be of very great practical importance.

Gordon Cameron (by letter): On page 1122 of the Elden paper a paragraph begins with the words "Violent fluctuations on both systems," etc. I suggest that the most violent or dangerous of such disturbances could be damped out without cutting the two systems apart by the use of a reactance in the tie line arranged to be normally short-circuited by an instantaneous trip overload circuit breaker. The circuit breaker would be specially speeded up so as to operate rapidly enough to prevent system disturbances from spreading to the adjoining system. Upon opening of the circuit breaker it would be held open, until the systems became normal again, by the use of a low-voltage relay connected across the reactance and arranged to close the closing coil circuit of the circuit breaker when proper conditions were reestablished. A low-current relay in series with the reactance would answer the same purpose as a low-voltage relay. It would be necessary to provide an auxiliary switch on the circuit breaker with a delayed action on closing the circuit breaker. See Fig. 10.

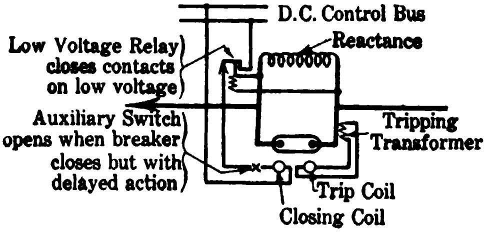

FIG. 10

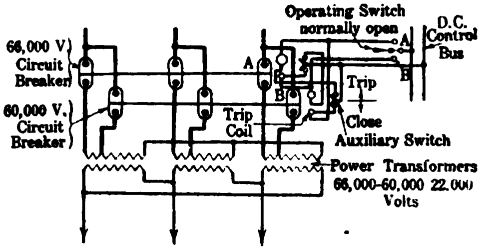

FIG. 11

On page 1125 in the same article mention is made of the difficulty in changing tap connections on the high-tension side of the transformers. I suggest that transformers with 66,000 and 60,000-volt taps be used, each set of taps permanently connected to a three-pole non-automatic circuit breaker. These two circuit breakers would be electrically operated, remote control, with electrical interlock so that only one could be closed at a time and so that practically instantaneous transfer could be made from one connection to the other. See Fig. 11.

H. L. Wallau (by letter): The transmission problem in the larger industrial centers is of a different nature from that usually visualized when high-tension transmission is spoken of.

In these cities the problem resolves itself into finding suitable locations for two or more power plants, which are developed to as large a size as consistent with local conditions and must then be tied together through transmission lines of moderate lengths.

The great size of the units installed in these plants requires tie lines of high capacity in order to transfer energy from one to another in case of breakdown or for reasons of economy and the difficulty and expense of securing right-of-way for high-tension lines makes it advisable to use as high a voltage as is reasonably practicable.

Service requirements demand that the voltage of both generator and incoming line busses be equal and in phase so that the supply may be distributed from a common bus which involves the use of regulative equipment of some kind.

In the short lines dealt with the capacitance is negligible and the synchronous condenser capacity required is, therefore, relatively larger than on long lines.

The solution adopted by the Philadelphia Electric Co. provides a very effective way of meeting the requirements of the case and is worthy of close study by engineers of other companies who may be facing a similar problem.

R. G. McCurdy (by letter): In connection with the paper by Messrs. Peters and Skinner on three-winding transformers, it is of some interest to consider the effect of the disposition of the windings on the division of triple-frequency exciting currents among them. It is highly desirable, when two sets of the windings of a 3-phase bank of such transformers are connected in *Y* with neutrals grounded and with the third windings connected in delta, that as large a proportion as possible of the triple-frequency exciting currents be carried in the delta winding. Since the division of current depends upon the relative impedances of the three windings to triple-frequency currents, this requires that the impedance in the tertiary delta be as low as practicable.

From this standpoint the construction shown in Fig. 3A of the authors' paper is of particular advantage. Since the tertiary winding is next to the core, its impedance to the triple-frequency currents is a minimum, and if the secondary and primary windings are connected in *Y* with neutrals grounded, the triple-frequency currents in their neutral connections will be comparatively small. The construction shown in Fig. 3B will result in a considerable increase in impedance in the tertiary delta and a corresponding increase in the currents in the primary and secondary neutral connections.

As pointed out by the authors, the drawback to the construction shown in Fig. 3-A is the inequality in the leakage impedances between the various pairs of windings, which results in an unsymmetrical regulation. This might be avoided to some extent while preserving the advantages of having the minimum impedance in the tertiary winding to triple-frequency currents, by dividing the secondary or primary winding into two parts with the primary or secondary between, as the case may be. This would result in approximately equal impedances between primary and tertiary and secondary and tertiary but in an impedance between primary and secondary less than either of the other two. This would not be disadvantageous, however, if the tertiary winding were of a lower kv-a. rating than the primary and secondary. An advantage of this form of construction is that the impedance to triple-frequency currents in the tertiary delta is, within limits, independent of the kv-a. capacity of the tertiary winding.

Considering the shell type transformer with the windings of equal kv-a. capacity disposed as shown in Fig. 4 of the authors' paper, the impedance to triple-frequency currents in the three windings are approximately equal. The impedance in the tertiary delta would be very much greater than in the case of the core type transformer discussed above. Considering two banks of equal kv-a. rating and similar magnetic characteristics, one of core type constructed as in Fig. 3A or in accordance with my suggestion above, and the other of shell type as in Fig. 4, the triple-frequency currents in the primary and secondary neutrals would be several times as great in the latter as in the former case.

A form of construction which would avoid this difficulty with the triple-frequency currents and still approximately fulfill the conditions of equal impedances between the three sets of windings, would be one in which the tertiary winding consisted of a cylindrical coil next to the iron, with the primary and secondary windings consisting of a number of pancake coils applied outside of the tertiary winding. By adjusting the space between the tertiary cylinder and the primary and secondary coils, any desirable value for the impedances between the primary and tertiary and secondary and tertiary, depending upon the kv-a. capacity of the tertiary, could be obtained without appreciably affecting the impedance between primary and secondary or the impedance of the tertiary to triple-frequency currents.

D. I. Cone (by letter): The use of star-star transformer or auto-transformer banks with grounded neutrals gives rise to important triple-harmonic residual (earth-return) currents in the connected lines. A matter of great interest is the division of these triple-harmonic currents among the windings, and the effect of the tertiary delta in lessening their amount in the line circuits.

As an example, consider the case cited in the Peters-Skinner paper, of a 35,000-kv-a. bank of 220 to 66 kv., star-star transformers with 17,500-kv-a. in delta-connected tertiary windings at 13 kv. Assuming the exciting current to be 5 per cent of the full-load current and that 40 per cent of this exciting current is of third-harmonic frequency, the third-harmonic magnetizing current, with the delta-connected winding absent (or open) would be about 1.8 amperes per phase, if confined to the 220-kv. side only. Since these currents are in common time-phase, the total third-harmonic residual current would be three times the above or about 5.5 amperes. If the third-harmonic magnetizing current were confined to the 66-kv. windings and line only, this current would amount to about 18 amperes. Under ordinary conditions there would be third-harmonic currents in both 220 and 66-kv. windings, and their sum would lie between the two extremes given, the division of the current between the two windings being dependent upon the self and mutual impedances of the windings, the line impedance to the third harmonic, and the action of any other sources of triple-harmonic residuals in the system. A similar analysis, with much smaller current values, holds for higher triple-harmonic frequencies, such as the ninth.

From the standpoint of the triple-harmonic residuals, the tertiary delta acts as a short-circuited winding in each transformer. In order to determine the action of the delta in redistributing the required triple-harmonic magnetizing currents, the self and mutual impedances of the several windings must be taken into account in a way closely resembling the procedure employed by the authors in considering regulation. Bearing in mind that a definite total third harmonic m. m. f. is required by the iron for a given sinusoidal induced voltage, a small third-harmonic induced voltage serves to drive the required currents in the several windings.

Extending slightly the notation used in the paper, let

Z_{sm} = $R_m + j\,w\,L_m$, the impedance of winding m.
Z_{mn} = $j\,w\,M$, the mutual impedance between windings m and n.
Z_{Lm} = line impedance connected to winding m.
E_m = induced triple-harmonic voltage.
I_m = triple-harmonic current.

Reducing the various quantities to terms of one winding as reference, and using subscripts $a, b, c,$ to designate the windings, the following equations may be written:

$$\begin{aligned} E_a = E_b = E_c &= I_a\,(Z_{sa} + Z_{La}) + I_b\,Z_{ab} + I_c\,Z_{ac} \\ &= I_a\,Z_{ab} + I_b\,(Z_{sb} + Z_{Lb}) + I_c\,Z_{bc} \\ &= I_a\,Z_{ac} + I_b\,Z_{bc} + I_c\,(Z_{sc} + Z_{Lc}) \end{aligned}$$

Letting winding C be the tertiary delta, Z_{Lc} represents impedance inserted in the corner of the delta. Usually $Z_{Lc} = 0$. If, as sometimes happens, one of the star connected windings and associated line has comparatively very high impedance so that the current in it may be neglected, the case becomes the same as a two-winding star-delta bank. Thus, assuming Z_{Lb} large so that $I_b = 0$ the equations become

$$I_a\,(Z_{sa} + Z_{La}) + I_c\,Z_{ac} = I_a\,Z_{ac} + I_c\,Z_{sc}$$

or
$$\frac{I_a}{I_c} = \frac{Z_{sc} - Z_{ac}}{Z_{sa} - Z_{ac} + Z_{La}}$$

Here it has been assumed that $Z_{Lc} = 0$ as discussed above. Thus by making the delta path of low impedance relative to the star paths, including the lines, the current in the line is lessened. The effectiveness of the delta in limiting the triple-harmonic residuals depends on leakage impedance relations within the transformer and on line impedances, and is not at all directly related to the capacity rating of the delta winding.

J. B. Whitehead (by letter): The alternating corona begins at a definite value on the ascending voltage wave. It does not, however, terminate on the descending side of the wave at the same value of voltage, as indicated in Fig. 2 of Mr. Peek's paper. The corona continues down to a slightly lower voltage, doubtless owing to the large number of ions present and possibly to the slight elevation in temperature due to the corona. These statements apply to the visual corona. It is probable that ionization and a substantial conductivity continues even longer and therefore to lower values of voltage. I question therefore whether the loss becomes zero and the capacity becomes normal at so definite a point as indicated by Mr. Peek. In fact, it seems probable that in a 3-phase line the whole region surrounding the three conductors is in a more or less continuous state of conductivity with intervals of ionization and replenishment on the crests of the waves where the voltage gradient rises above the critical corona forming value. In view of these facts it would appear that the line losses would be independent of the method of transformer connection. On the other hand it is easy to see that in a *Y*-connected grounded neutral system the high conductivity on the crest of the voltage wave lends itself im-

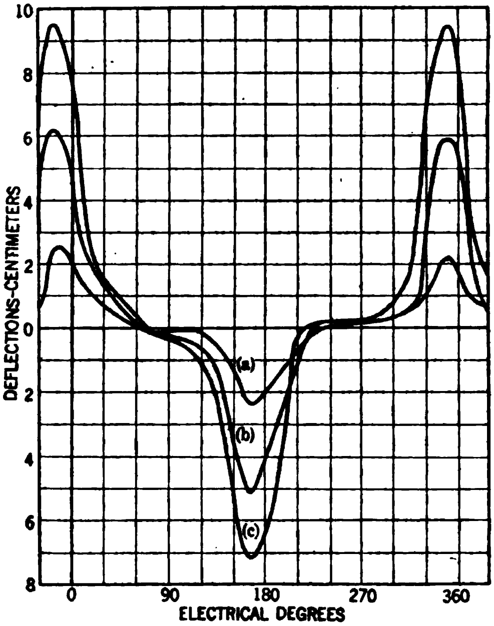

Fig 12—Wave Form of Corona Discharge

Corona Starts	36.7 volts
Curve a	37.0 volts
Curve b	41.0 volts
Curve c	45.0 volts

mediately to the amplification of the third harmonic current or any odd multiple thereof in the neutral.

The sharp rise of current during the continuance of corona may be seen from the accompanying curves, Fig. 12. These curves represent a true conduction current from a corona forming wire located on the axis of a metal cylinder forming the opposite side of the circuit. Wave forms were taken with a point by point method of the total current flowing to ground from the outer cylinder and of the capacity charging current to ground for a value of voltage just below that at which corona starts. The curves as shown are the differences between the two measured curves. All of the curves, and especially curve *a* which corresponds to a corona of very brief duration, show that the conductivity extends over a considerable portion of the entire cycle.

R. J. C. Wood and H. Michener (by letter): There is no need at this period of electrical development to make any apologies for 220-kv. transmission. The quantities of power and distances of transmission involved in the State of California alone lead to the selection of at least such a voltage for economic reasons. There naturally are problems in connection with an advance from the existing highest commercial transmission voltages, the one most prominently under discussion being the insulation of the line.

The first consideration is to have sufficient air space between the conductor and the tower, or other grounded supporting structure, so that abnormal voltages that may occur in the line will not flash over.

This is a matter of both distance and potential gradient in the air, and where clearances are small it may be necessary to enlarge the conductor where it passes by the tower.

The safeguarding of the conductor having been attained, the insulating support must be put in. The consensus of opinion seems to be that the simple string of suspension insulators is unsuitable on account of the greater electrical stress upon the unit next to the line.

In the case of 220-kv. line the voltage across the No. 1 unit will be in the neighborhood of from 25 kv. to 28 kv. when using cap and pin insulators, depending upon the number of units in the string. It has not been proven that operation might not be entirely successful with such unit stresses but it is generally felt that better results would be obtained if a more uniform distribution of voltage were to exist along the insulator string. A great many tests have been carried out at Stanford with the kind cooperation of Prof. Ryan with a view to determine suitable methods of improving this voltage distribution, and further to investigate the path of the discharge when flash-over occurred.

This work done for the Southern California Edison Co. in December, 1920, and January 1921, developed the fact that oscillator discharges at about 55,000 cycles could be controlled so as to be kept away from the string of insulators, and that a shield ring similar to that used in radio work would reduce the voltage across the No. 1 unit from about 26 to about 15 kv. in a 14-unit string.

This work was a continuation along the line of Prof. Ryan's previous work described in his Portland paper.

A further series of tests was made at Stanford in April of this year to confirm the earlier data and more particularly to determine the characteristics of a string of but 9 insulators with different forms of shields.

Practically all the oscillator flash-over tests were photographed and compared with the corresponding voltage distribution curves. In those cases where the voltage across units decreased to a minimum, and then increased again towards the top of the string, there was cascading of the discharge over those units above the minimum point in the string, contrariwise where the unit voltage continually decreased from conductor to support there was not any cascading but the discharge occurred free of the string.

This is understandable when it is considered that the discharge tends to follow the tubes of force and that an increase in unit voltages at any point in the string denotes an entrance of tubes of force into it.

This action is particularly noticeable where a composite string is used having units of low internal capacity placed at the upper end.

The ideal voltage distribution curve appears therefore not to be one of uniform distribution but a slightly sloping straight line denoting a uniform decrease in unit voltage across the insulators in the direction from line to support. There is then a flux outward from all the insulators and a minimum tendency for the discharge to strike inward.

To obtain such a distribution a grounded ring or shield may be put at the upper end of the suspension string where it serves the two purposes of stopping cascading and of keeping a power arc away from the upper insulators.

To obtain a further check upon this condition, an insulated wire ring, of the same diameter as the shield rings, was suspended around the insulator string at different heights above the lower ring and its potential above ground determined in each position by the potentiometer method. The plane of the wire ring was perpendicular to the axis of the string and its center coincided with it. The potential of the air was thus determined along a line joining the upper and lower shield rings, it was found that the string potential was higher than the air potential from the No. 3 unit up.

The No. 1 and No. 2 units were at lower potential than the air, see Fig. 13. the tubes of force are however, so divergent in this region that no striking in of the discharge is possible.

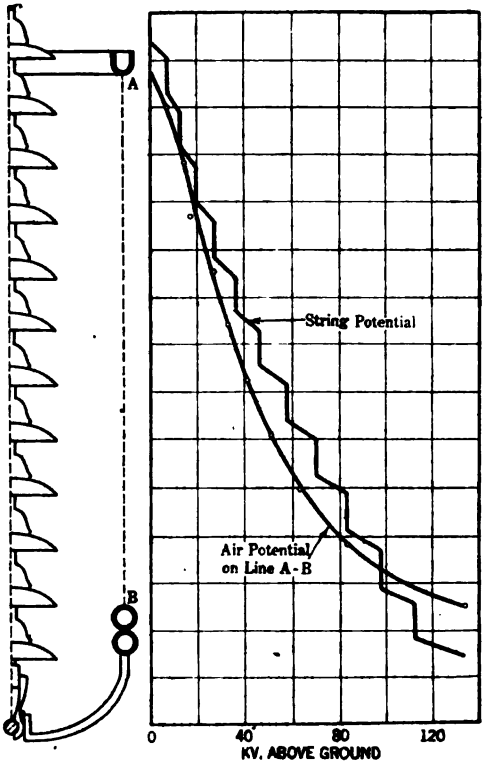

Fig. 13—Potential Gradients in and Around Shielded Suspension Insulator String

The reduction of the distribution curve to a formula is very ingenious but of limited application, the distribution curve of the insulator string finally to be used on actual 220-kv. lines will differ very materially from that of a nearly unshielded string, and its mathematical analysis is liable to become too unwieldly for profitable use.

A great deal of theory has already been developed for the multigap arrester which is applicable to the suspension string of insulators.

Other methods of controlling the distribution of voltage have been proposed falling into two classes; either bodies at line potential are put near the lower units in the string or else insulators of differing internal capacitance are used in different positions in the string.

The latter method of using a graded string is open to the objection that it introduces a complication of parts and perhaps the employment of the wrong part when making repairs. In the practical maintenance of a line the use of but one kind of insulator is of advantage all the way from the insulator factory to the transmission tower.

Among the methods employing conducting shields of all kinds of shapes and sizes there is one which is radically different from the others in that it has the metallic shielding devices covered by insulation.

This enables a higher flash-over voltage for oscillator discharges to be obtained over the whole string than if the shield insulation were absent, at all events in dry tests. Under rain tests the advantages of this method are not so evident and in the event of any of the insulation upon the shielding arms failing, the results are no better than with bare metallic shields.

Another method of keeping the flash-over voltage high is to keep the radius of curvature of the shielding device as large as possible. The advantage of this construction lies in its immunity from accidental destruction of its qualities.

Part of the work done at Stanford comprised voltage distribution when one or more insulators in the string had zero resistance, obtained by connecting cap and pin with a fine copper wire kept close to the surface of the porcelain. Oscillator discharges were also made over such faulty strings.

For the sake of uniformity a standard set of conditions was arrived at, viz.: No. 2 unit (second from conductor) shorted. No. 2 and No. 3 units both shorted. Four top units all shorted. These tests were developed in order to detect and eliminate any system of distribution correction which might depend so entirely upon certain single insulators in the string that their loss might cause successive failures or distress throughout the string.

In February and March of this year experiments were carried out in the Southern California Edison Co.'s laboratory, upon model insulators mounted in a model of the Big Creek transmission line tower. The scale ratio being 1:7. These experiments were made at 50 cycles with a 150-kv. testing set, the object of the investigation being to see whether the behavior of the 50-cycle flash-overs differed radically from oscillator discharges.

The work was done in miniature in order to bring it within the range of the test set.

These tests showed practically a linear relation between the number of insulators in the string and the dry flash-over voltage within the limits of from 6 to 12 units, which latter flashed at 117 kv. It was not expedient to give a regular rain test as the pin of the insulator was fastened to the porcelain with glue. With soaking wet blotting paper on the top surface of the porcelain, but without any drip water, the flash-over voltage still increased linearly up to 11 units but increased more slowly from 11 to 14 units. The dry flash-over voltage of individual insulators averaged 15.4 kv. It was while making these tests that the influence of the upper shield ring was noticed in stopping cascades, it was also found to raise the flash-over value of the string although it reduced the clearance between conductor and ground. It is hoped in the near future to make such tests upon full sized insulation and perhaps determine the electrical scale ratio as a function of the physical one.

Through the hearty cooperation of one of the insulator factories it has been possible to make a further study of oscillator discharges at a frequency of 30,000 cycles, and at the same time determine the flash-over voltage by sphere gap measurement.

The bulk of this work was upon 9-unit strings with a few check tests upon 11-unit strings. Both dry and wet tests were made, tap water of low resistance being used in a fine spray. All wet tests are subject to interpretation according to individual conditions, the results are however, believed to be of relative value. Figs. 14 and 15 show a summary of the results. The Big Creek insulator is of 9 units with arcing horns both at top and bottom of the string having 48-in. clearance between top and bottom horns. The flux control shield consisted of four metal arms surmounted by pin type insulators surrounding the lower end of the string. The conductor cages were tubular enlargements of the conductor and the lower 27-in. ring was made of 2-in. standard pipe having its top surface 5½ in. above the conductor center and the upper ring was of cast iron surrounding the top insulator. In order to get some practical tests upon insulation under actual outdoor conditions, the Southern California Edison Co. will have 26 miles of its Big Creek transmission line energized to from 220 to 260 kv. It is expected to have this experimental line in operation within a few weeks. Means of measuring corona loss are to be provided, 9-string and 12-string insulation will be in service and ring shields are being installed.

This length of line is insufficient to develop everything that may occur on a long line, it is however, hoped that information will be obtained upon the moot question as to the origin of flash-overs in surface leakage, and certain definite information as to corona losses will be obtained. It is of interest to note that the black deposit that forms upon the Big Creek line operated at 160 kv. diminishes corona losses. Experiment upon a length of line, one-half of which had had the black deposit cleaned from it chemically, without damaging the aluminum, showed that the critical visual point was about 15 kv. higher on the uncleaned portion.

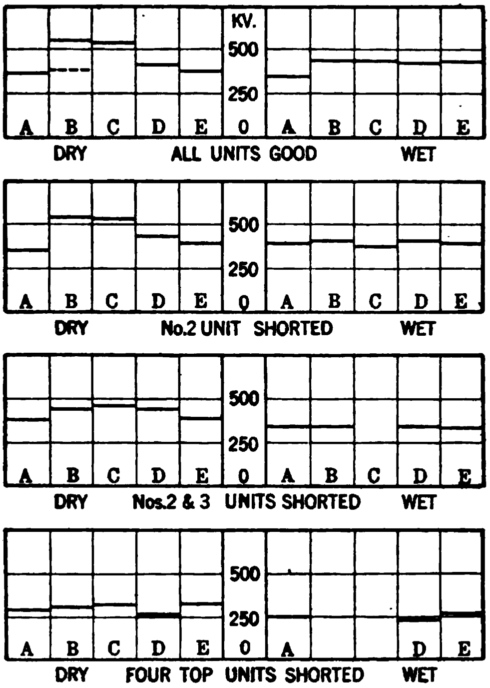

Fig. 14—Flash Over Voltage of Suspension Insulator Strings. Oscillator Discharges at 30,000 Cycles. 9-Unit Suspensions.

A. Big Creek line construction; arcing horns at top and bottom of string.

B. Insulated shielding horns and tubular enlargement of conductor to 15 in. diameter and effect of removing insulator from one horn.

C. Tubular enlargement of conductor only.

D. Shielding rings 27 in. *O. D.* and tubular enlargement of conductor to 15 in. diameter.

E. Shielding rings 27 in. *O. D.* only.

The deposit in question is a macadam of microscopic dimensions. Small mineral particles are cemented together with a black binder, the whole probably being the result of a Cottrell precipitation process. The deposit is firmly adherent and upon rubbing with the hand takes on the appearance of a black enamel.

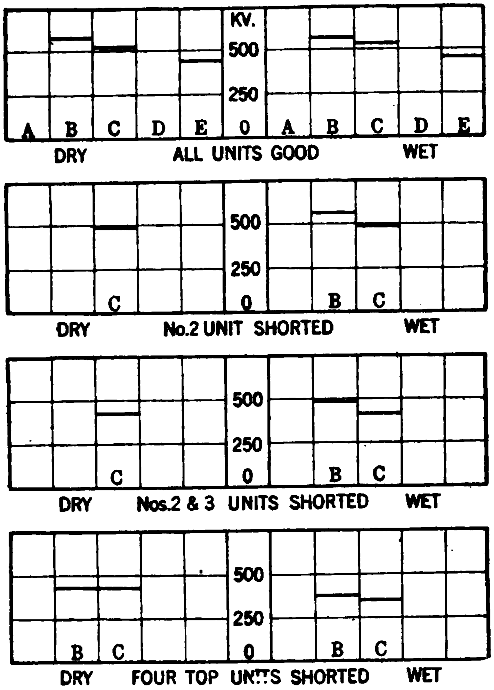

Fig. 15—Flash Over Voltage of Suspension Insulator Strings. Oscillator Discharges at 30,000 Cycles. 11-Unit Suspensions.

B. Insulated shielding horns and tubular enlargement of conductor to 15 in. diameter.

C. Tubular enlargement of conductor only.

E. Shielding rings 27 in. *O. D.* only.

Raymond Bailey: Tap changing switches referred to by Mr. Skinner, which are used with transformers on tie lines, which can only be operated when transformers have been "killed", would appear to be somewhat limited in their application. In many cases the necessity for changing transformer tap connections is brought about by a demand for an increased amount of power, which may make it impossible to take the transformer out of service to change the taps.

Mr. Skinner, in discussing the step-type regulator stated that the objection of having high-voltage sliding contacts has been met by the use of cam-operated contactor switches. While it is possible that the contactors, would be more reliable than sliding contacts, there would unquestionably be a certain hazard introduced into the high-voltage system by the connection thereto of a number of contactor switches. He emphasizes the desirability of having the greatest simplicity when he recommends that the number of leads brought out from a transformer should keep to the absolute minimum as each extra lead brings about more complication with the consequent likelihood of serious failure. The point brought out that tap changing equipment should be connected in the transformer neutrals where practicable on account of limiting the voltage stresses imposed on such equipment, is well worth keeping in mind.

In the industrial centers throughout the East the transmission problems usually have to do with the transmission of large blocks of energy in either direction between power stations, in such a manner as to give the most economical operation of the system, which usually involves the control of voltage and power factor of the tie lines. These requirements for transmission are clearly outlined by Mr. Wallau.

More and more emphasis is being placed by the operating companies on studies made to determine upon the most economical method of operating their systems under the various loading conditions and upon placing the information obtained from these studies in the hands of the men directly in charge of operation. An example of this is given by Mr. Barron who states that his company has developed curves theoretically which are modified by experience, which are used to give the most economical operation of the entire system. He further points out that one of the most important factors which affect the theoretical curve of economy is the precaution taken to insure continuity of service.

F. G. Baum: In the design of a large system, especially one involving new problems such as this 220,000-volt system, we find quite a number of things in the beginning that cause quite a lot of mental exercise. Of the two main points that bothered us originally, one was the voltage control of the entire line and on that we feel quite statisfied now. Synchronous condensers act very much like a gyroscope, so to speak, *i. e.*, the machines refuse to change their position and they tie the voltage down at various points.

Prof. Ryan has touched upon the large aspects of what I have tried to bring out. It is only through the cooperation of a number of people that we are going to really have long distance transmission. I believe we have to do it in that way. The insulator problem of course, must be solved. The telephone men refer to d-c. transmissions. I think we can discuss that entirely as dealing with a past art. The successful long distance transmission system must be a *constant* potential system and this means a-c. transmission.

I prefer to speak of either the internal shield or the external shield, they both are shields, one is the internal and one the external, and I believe the result is finally going to be the combination of those two, as to what purpose I do not know.

Fig. 29 is a very remarkable picture of an arc by Prof. Ryan. It shows an insulator string with its arcs bowed out due to this cross voltage, due to the insulator-string being bowed out and reaching into the upper third of the string. The important thing we have to consider is the surface leakage from the insulator string as a whole under all conditions, under the worst conditions, especially when that insulator string is changed from one form to another, as when dew falls on it. We can get a wet arcover of half a million volts that is entirely satisfactory, I think we may be statisfied and congratulate ourselves that we have been able to get as high as 500,000 volts.

W. W. Lewis: Referring to Mr. Ferris' discussion, especially that portion concerning Fig. 22, Comparison of Calculated and Measured Current in Grounded Neutral, Test 44: The writer admits that his method of calculating this current was incorrect and that Mr. Ferris' method more nearly approximates the true conditions.

In regard to the statement in the conclusions that the tests indicate a difference in corona loss with the neutral grounded and isolated: Figs 16 and 17 illustrate this. In Fig. 16 is a comparison between the corona loss and charging current of Test 10, neutral isolated, and Test 43, neutral grounded at Junction, no transformers at Grand Rapids. These curves are replotted from Figs. 5 and 11 of my paper respectively There is a distinct tendency for the grounded neutral curves of both loss and current to draw away from the isolated neutral curves. The current curve for Test 10 droops at the higher voltages due to transformer magnetizing current, while the current curve for Test 43 bends upward. In Fig. 17 are similar curves for

Tests 9 and 42, replotted from Figs. 6 and 12 of the paper. In these tests transformers are connected at the end of the line. The tendency of the line current of Test 9 to droop is more marked than in Test 10, while the current of Test 42 maintains an upward trend. In order to appreciate the reason for this differ-

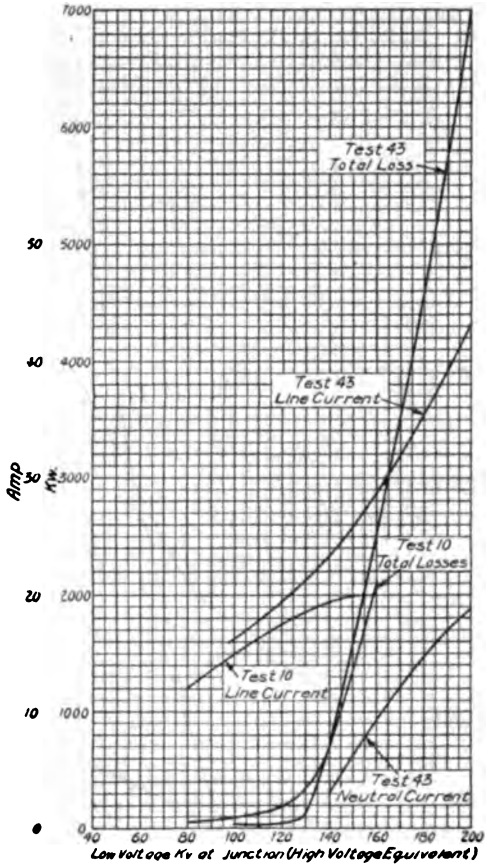

FIG. 16—COMPARISON OF CORONA LOSS, ISOLATED NEUTRAL (TEST 10), AND GROUNDED NEUTRAL (TEST 43)

	Test 10	Test 43
Date	10 15 19	10 20 19
Bar	29.34″	29.38″
Temp	44.7°F	42.5°F.
Hum	91.4%	81%
Weather	Clear	Cloudy
Neutral	Isolated	Grounded

Line Junction to Grand Rapids.
No Transformers at Grand Rapids.

ence in the charging current and loss curves, it will be useful to examine briefly the mechanism of corona formation:

Fig. 18 (a) represents a sine wave of voltage. Corona begins at the point *m* on the ascending part of the wave and ceases at the point *n* on the descending part

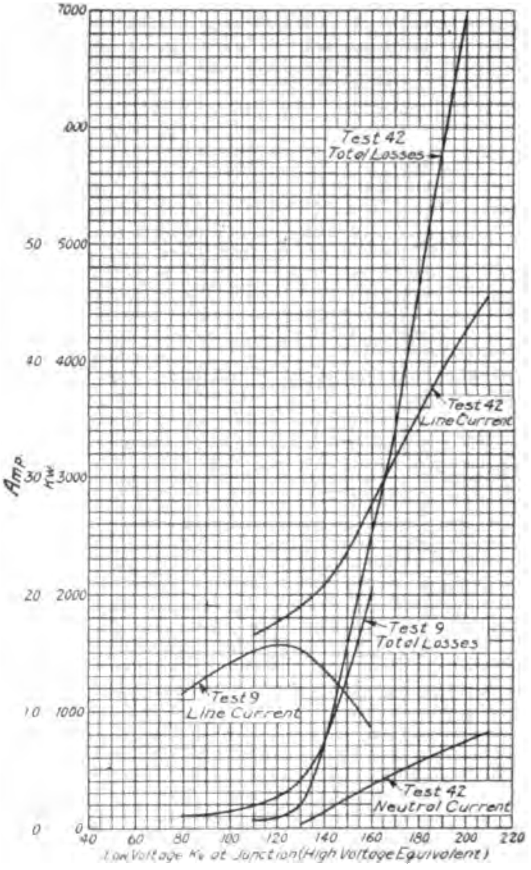

FIG. 17—COMPARISON OF CORONA LOSS, ISOLATED NEUTRAL (TEST 9) AND GROUNDED NEUTRAL (TEST 42)

	Test 9	**Test 42**
Date	**10 15 19**	**10 26 19**
Bar	**29.34″**	**29.32″**
Temp	**46.7°F.**	**41°F.**
Hum		**94%**
Weather	**Clear**	**Cloudy**
Neutral	**Isolated**	**Grounded**

Line Junction to Grand Rapids.
Transformers on at Grand Rapids.

of the wave, similarly for the other half cycles. The shaded parts of the wave represent the portion during which corona is formed, or it may be said they represent the corona voltage. In (b) are replotted the shaded parts of (a). The resulting wave (b) may be analyzed into a fundamental, triple and other harmonics. In this case only the fundamentals and triple harmonics are shown, the other harmonics being small. In (c) are shown the line to neutral voltages of a three-phase system with their shaded corona-forming portions, and in (d) the analysis of the shaded portions of (c) into fundamentals and triple harmonics It will be noticed that the fundamentals have the same relation to each other as the original waves in (c), while the triple harmonics are all in the same phase. If there is a path for current to flow such as would be formed by a Y-connected transformer bank with grounded neutral, the triple-frequency voltage of each phase will cause such a current to flow from conductors to ground and back through the grounded neutral, the currents from the three conductors adding up as represented by the dashed line in (d). This current is represented as in phase with the voltage which produces it, but there is a quadrature current also due to the line capacitance.

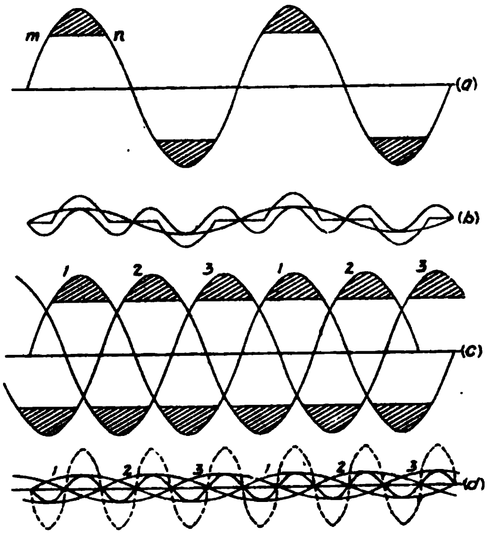

FIG. 18—FORMATION OF TRIPLE-FREQUENCY CURRENT Y-CONNECTION, GROUNDED NEUTRAL

If the neutral is not grounded then the triple-frequency current cannot flow. In order to suppress it, we may consider that there is an equal and opposite current produced by a voltage equal and opposite to the triple-frequency voltage of Fig. 25 (d). In Fig. 19 (a) are represented the three leg voltages with the triple-frequency voltage that is responsible for suppressing the current. This added to the fundamental gives the distorted voltages represented by the dashed-line curve, the shaded portion again representing the corona forming part. It will be noted that this part of the wave is now flat topped.

Fig. 19 (b) shows the vector relation of the leg voltages and illustrates how line voltage 1—2, for example, is the difference between voltages 1 and 2 or the sum of 1 and 2 reversed. In (c) voltage waves 1 and 2 are added as indicated in (b). It will be noted that the triple-frequency components are equal and opposite and cancel, leaving only the fundamentals which add to give the dashed curve of line voltage.

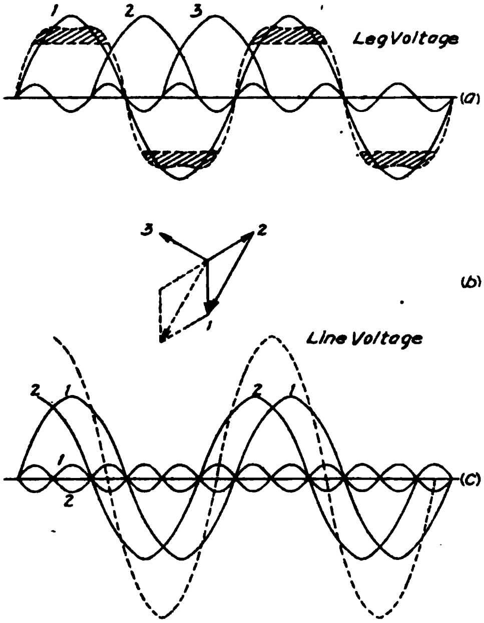

Fig. 19—Distortion of Voltage, Isolated Neutral

The result of the flow of triple-frequency current for the case with grounded neutral (Fig. 18) is an increased charging current and an increased loss due to the in-phase component of current. In the case of Fig. 19, in which the triple-frequency current is suppressed and the voltage wave flattened there is no increased loss or increased charging current. On the other hand, the flat topped voltage wave produces a peaked flux wave in the transformers, causing an increase in transformer magnetizing current. The result on the generator side of the step-up transformers is a dropping off of the current at the higher voltages, because this current is the resultant of the line charging current, which is leading, and the transformer magnetizing current, which is lagging. These conclusions are confirmed by the curves of Fig. 16 and 17 the currents here shown being low-tension generating station currents expressed in high-tension equivalent.

The conclusions reached in this paper are, of course, tentative and may be confirmed or require revision as the result of further tests.

M. E. Skinner: When a delta-connected winding is used solely for suppressing third-harmonic voltages its relative physical location with respect to the core is not as important as might be inferred from Mr. McCurdy's communicated discussion. In case the neutrals of the star-connected windings are not grounded the flow of current in the tertiary is limited only by the resistance and self-inductance of this winding. The self-inductance is almost independent of the physical location of the winding with respect to the core. This is for the reason that the flux enclosed by the winding is practically entirely within the iron core and therefore independent of the air space between the winding and core. The resistance of the winding will be least when the tertiary is located immediately adjacent to the core, but this is such a small factor in the total impedance that it may be neglected.

If the neutrals of the star-connected windings are grounded so that third-harmonic current may flow in all three windings, then the disposition of the windings with respect to each other enters into consideration. However, even under this condition, the mutual inductance between the tertiary and the primary or secondary windings is not the determining factor in the amount of third-harmonic current which flows in the ground connections of the star windings. If the very improbable condition of resonance to the third harmonic between the inductance of one of the main windings and the capacity of one line to ground is eliminated, then in every case the important factor in determining the flow of third-harmonic current in the ground connection is the impedance which is external to the transformer. For these reasons I disagree with the conclusions which Mr. McCurdy reaches as stated in the last two paragraphs of his discussion.

The conclusion may be drawn that it is only when power is to be transferred at fundamental frequency between the various windings of a three-winding transformer that the disposition of these windings with respect to each other becomes of really vital importance.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 24, 1921.

SYNCHRONOUS MOTORS FOR SHIP PROPULSION

BY E. S. HENNINGSEN
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SINCE the inception and development of the idea of electric ship propulsion, the question of the possibility of using synchronous motors for such service has often been raised. Such a motor could be designed for unity power factor with a resulting saving in cost, weight, and efficiency, of both motor and generator. So far as mechanical design was concerned, the answer was, of course, that the same substantial mechanical features could be obtained with a synchronous motor as with an induction motor. In addition, the synchronous motor would have greater clearance between rotor and stator and repairs could be more easily made since it would not be necessary to remove the rotor to replace either field or armature coils. The question, therefore, was whether or not satisfactory electrical characteristics could be obtained with this type of motor. The affirmative answer to this question is attested to by the fact that the S. S. *Cuba*, a fast passenger and express boat belonging to the Miami Steamship Company, and the first vessel of any kind to be propelled by a synchronous motor, has been in successful operation since November 1920, and five more equipments are under construction. Four of these are to drive cutters being built for the U. S. Coast Guard Service and one for a fruit steamer.

The first consideration in the problem was to determine as accurately as possible what the torque requirements were, first under normal operation, and second, during reversal of the propeller. The only point in question under normal operation is the margin in break-out capacity that is required to keep the motor in step during rough weather or when the ship is making a turn. From the limited data available on single-screw ships, it appears that the torque imposed on the propeller, due to the pitching of the ship in rough weather, varies between zero and about 175 per cent of the average. The period of this variation in torque is about seven seconds. However, this requirement is not peculiar to the synchronous motor drive, since it is equally necessary to meet this condition with any form of electric drive. Since the break-out capacity depends upon the ratio of no-load ampere turns to synchronous impedance ampere turns and also upon the amount of field excitation that can be carried on both motor and generator, sufficient break-out torque is simply a question of proper design.

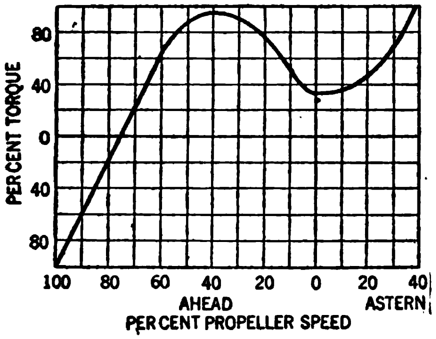

FIG. 1—CURVE OF TORQUE REQUIRED TO REVERSE THE PROPELLERS OF THE U. S. S. *Delaware*

The torque required to reverse the propeller under full speed conditions has been accurately determined for battleships by the Navy Department, and is illustrated in Fig. 1 for the U. S. S. *Delaware*.[1] This curve, which assumes that the ship continues ahead at full speed, shows that when the driving torque

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[1] From an article by Lieut. S. M. Robinson, U. S. N *Journal American Society Naval Engineers*, February 1916.

is reduced to zero, the propeller drops to the no-slip speed which is 76 per cent of its full speed. To bring the propeller to rest against the action of the water requires a constantly increasing torque until at about one-half of the no-slip speed, the maximum braking torque is reached. This value is about 95 per cent of full torque. Below this speed the required torque falls off and at zero propeller speed is about 33 per cent. One hundred per cent of normal torque is required to drive the propeller at 38 per cent speed backwards. These values will, of course, be somewhat lower due to the retardation of the ship during the time required for switching and reversing. No such accurate curve is at present available on a single-screw ship, but tests on several such ships indicate that the torque required to reverse the propeller is materially less than that shown in Fig. 1. It is, therefore, safe to assume that this curve represents the maximum torque requirements that must be met during reversal.

In land practise, motors are usually operated from a constant potential and constant frequency system. For ship drive, since the main power circuit comprises only the generator and the motor, it is neither necessary nor economical to design for either constant potential or constant periodicity during the operation of reversing. In other words, both motor and generator may be overexcited for brief periods and advantage may be taken of the fact that the generator's speed can be reduced until the motor has been synchronized and the two units then brought up to speed together. Based on these facts a number of methods of reversal were suggested and tested out on an equipment consisting of the following machines: A 375-kv-a. generator, driven by a 3600-rev. per min. turbine, was used to supply power to a 36-pole, 275-h. p. synchronous motor. The propeller was represented by a 200-kw. direct-current generator mounted on the same shaft with the motor. By varying the field excitation of the motor-driven exciter to which the d-c. generator was connected, the load on the synchronous motor could be reversed and varied rapidly enough to approximate very closely the propeller torque curve of Fig. 1.

The results of some of the tests made on this equipment may be briefly summarized as follows:

1. The first method to be tried out was to cut off the steam from the turbine, reverse the phase rotation between motor and generator, establish field excitation on both machines, allow the turbine to come to rest with the motor and then start up by admitting steam to the turbine, bringing the motor up in synchronism with the generator from zero speed. Although sufficient braking torque could be developed by this method, it was not found to be feasible because the amount of load that could be started was very small when the number of poles of the generator differed widely from those of the motor. On the particular motor and generator used in these tests, it was found that with normal full load field current on each, the motor could just be started with no-load on the d-c. generator. With 190 per cent of normal full-load field current on each only 22½ per cent of normal load could be started. This method is also objectionable on account of the high tempera-

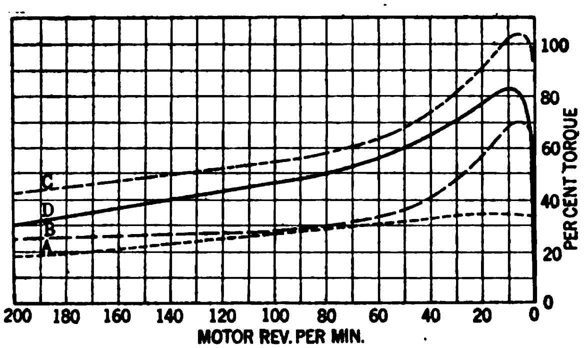

FIG. 2—BRAKING TORQUE TEST—GENERATOR AND SYNCHRONOUS MOTOR CONNECTED TOGETHER WITH OPPOSITE PHASE ROTATION

Test *A*—Field on Generator. Motor field short-circuited.
Test *B*—Field on motor. Generator field short-circuited.
Test *D*—Field on both motor and generator.
Curve *C*—Sum of curves *A* and *B*.

tures that result when steam is admitted to the turbine at standstill.

2. The second suggestion was to reverse the phase rotation and establish both fields as before but allow the generator to drop to only one-fourth speed. The objection to this method was the excessive mechanical vibration that resulted when the motor was at standstill but still excited and the generator running (also excited) at one-quarter speed. In this connection it is interesting to note the test shown in Fig. 2. Curve *A* represents the torque developed by the amortisseur winding of the motor with normal excitation on the generator field and the motor field short-circuited. Curve *B* represents the torque developed by the motor functioning as a generator with normal excitation on the field and the armature leads connected to those of the generator. It was expected that with both fields normally excited, the resulting torque curve would be the sum of curve *A* and curve *B*, or curve *C*. Instead, the resultant curve *D*, obtained from test, shows that due to interference of the two polyphase systems of opposite phase rotation, the resulting torque is only about 86 per cent of the sum of the separate torques.

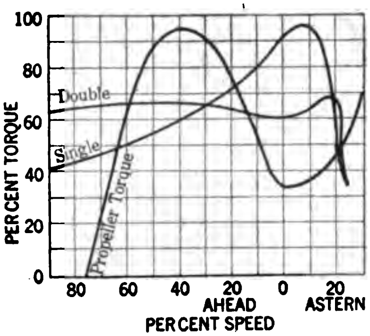

FIG. 3—COMPARISON OF THE TORQUE CURVES OF A SYNCHRONOUS MOTOR WITH SINGLE AND DOUBLE AMORTISSEUR WINDINGS

The generator was held at one quarter normal speed and had the same field excitation for each curve.

3. The motor was then equipped with a double

amortisseur winding to find out whether the advantage so gained would be worth the added mechanical difficulty. Fig. 3 shows the test curves obtained with both the single and double amortisseur windings. The generator was run at one quarter of full speed and with the same field excitation for both curves. It will be noted that the double winding will give a slight gain in the time of stopping the propeller, but an almost equal loss in time to come up to speed in the opposite direction, hence practically no advantage will be obtained with the double winding.

Fig. 4—Coupling End of 46-Pole, 2600-H. P., 50-Cycle, 130-Rev. per Min., Synchronous Motor for Ship Propulsion

4. It was found that with a given field excitation on both generator and motor, a 10 per cent greater maximum load could be carried before the motor would fall out of step when the load was varied between zero and a maximum in a seven-second period, than when the load was gradually applied. Also when the swinging load was increased somewhat and the motor fell out of step on the high swing it would pull back into synchronism on the low swing.

5. The tests showed that the two most satisfac-

tory methods of accomplishing a full speed reversal of the propeller are as follows:

Method No. 1: (a) Throw the turbine speed governing mechanism to the quarter speed position; (b) reverse the phase rotation between motor and generator; (c) excite the motor field only, thus causing the motor to function as a generator and hence brake the propeller to zero speed; (d) energize the generator field and deenergize the motor field, thus causing the motor to come up to approximately one-fourth speed as an induction motor; (e) apply motor field to synchronize, and (f) bring up the turbine speed.

Method No. 2: (a) and (b) same as in Method No. 1, (c) establish field on the generator, thus causing the motor to come to rest and up to approximately one-quarter speed in the opposite direction by means of the amortisseur winding torque only; (d) apply motor field to synchronize, and (e) bring up the turbine speed.

Method No. 1 although requiring one more operation has the advantage that very much higher braking torque can be obtained from the generator characteristic than from the induction motor torque characteristic and also that it affords a means of keeping the propeller from rotating while the ship is still going ahead due to its momentum, a procedure which is not possible without complicated control when only the induction motor torque characteristic is used.

The construction of synchronous motors for ship drive is illustrated by Figs. 4 and 5. They differ in the following particulars from those designed for land practise: The diameter is smaller and the length correspondingly greater; they are of the end shield bearing type; the air gap clearance is somewhat greater; special precautions are taken to make the insulation moisture-proof; the amortisseur winding is so constructed that the poles may be removed without removing the rotor; jacking bolts are provided in the bearing housings for taking the weight of the rotor when it is desired to remove a bearing. In order to facilitate temporary repairs, the armature winding has as large a number of circuits as the number of poles will permit. Then in case of a burn-out it is only necessary to cut out that particular circuit or circuits without having to install jumpers across the damaged section. Since the power to drive the propeller varies approximately as the cube of the speed, cutting out one circuit of a twelve-circuit winding, for instance, would mean a drop in speed of only a little more than 2½ per cent to keep the load on the other circuits as before.

The motor illustrated in Fig. 5 has the ship's main thrust bearing installed in the forward lower bearing bracket, the upper part of which is made in the form of a deep beam. Details of this spring thrust bearing are shown in Fig. 6. Lubrication of the thrust bearing and horizontal bearings is furnished by an oil pump, driven from the main shaft and mounted in an oil tank bolted to the under side of the bearing bracket. This particular design of the motor, thrust bearing, and oil system as a unit, contemplated installing the motor in a separate compartment as

FIG. 5—THRUST BEARING END OF 60-POLE, 3000-H. P., 50-CYCLE, 100-REV. PER MIN., SYNCHRONOUS MOTOR FOR SHIP PROPULSION

far atf as possible and hence doing away with the usual long shaft alley. In such an installation a gravity feed oil system could be installed to be used in case of a failure of the direct-connected oil pump. With such low speeds as are employed, very little lubricating oil is required and a comparatively small gravity tank would supply oil until repairs could be made. With a motor such as shown in Fig. 4, the spring thrust bearing is mounted in a separate housing.

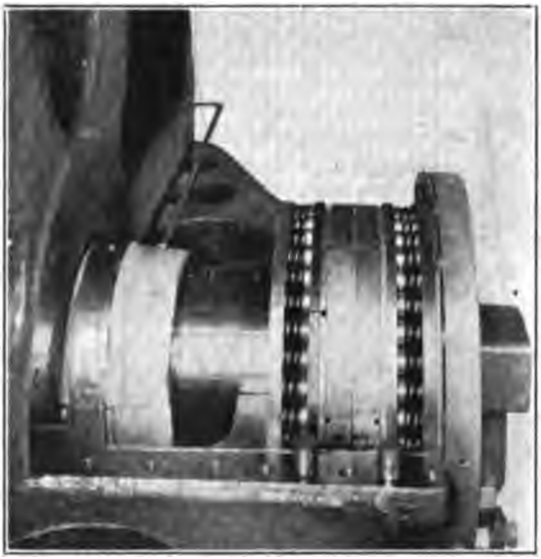

FIG. 6—3000-H. P., 50-CYCLE, 100-REV. PER MIN., SYNCHRONOUS MOTOR FOR SHIP PROPULSION

With bearing caps removed to show one journal bearing and spring thrust bearings assembled in lower bearing bracket.

Fig. 7 shows the torque characteristics of an equipment consisting of a 3000-h. p., 100-rev. per min. synchronous motor and a 3000-h. p., 3000-rev. per min., 50-cycle turbo-generator installed on the S. S. *Cuba.* The curves marked braking torque show the torque developed by the motor functioning as a generator with both 125 volts and 250 volts across the collector rings. The motor is connected to the generator with opposite phase rotation but the field of the generator is not excited. The curve marked induction motor torque is the torque developed by the amortisseur winding of the motor. For this curve the generator is running at one-fourth of normal speed and has twice the normal excitation voltage impressed across the collector rings. This double excitation is obtained by means of a 250-125-volt, three-wire exciter. During normal operation the generator and motor fields are connected across the 125-volt circuits and during reversal across the 250-volt circuit. The propeller torque curve given in Fig. 1 has also been plotted in Fig. 7. As mentioned before this curve is considerably higher than that of a single-screw vessel. Tests made on the S. S. *Cuba* showed that the propeller could be brought to rest from full speed in three and one-half seconds by means of braking with 220-volt excitation; in twenty-seven seconds by braking

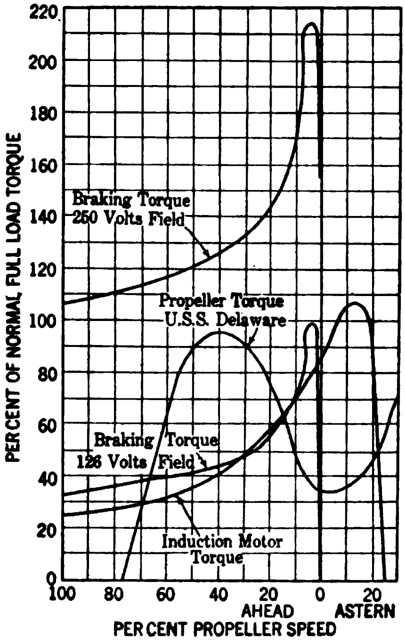

Fig. 7—Torque Characteristics—3000-H. P., 100-Rev. per Min., Synchronous Motor

with 110-volt excitation; and in thirteen seconds with the motor operating as an induction motor.

The load characteristic of this equipment is given in Fig. 8. With 125-volt excitation across the collector rings, the margin in break-out capacity is 161 per cent for a steadily applied load. Somewhat more than this can be safely carried when the load is a variable one such as will result due to the action of the waves and rough weather.

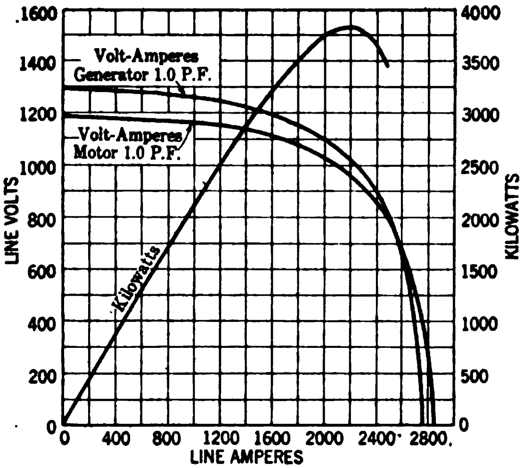

FIG. 8—LOAD CHARACTERISTIC AT FULL EXCITATION—3000-H.P., 3000-REV. PER MIN. GENERATOR AND 3000-H. P., 100-REV. MIN., SYNCHRONOUS MOTOR

The successful application of synchronous motors to ship propulsion, therefore, marks another advance in the ever widening field of activity of this type of motor. It is certainly to be expected that the same high record of substantial and reliable performance that it has established in other lines of industry will be duplicated in the marine field.

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 24, 1921.

MAGNETIC PROPERTIES OF COMPRESSED POWDERED IRON

BY BUCKNER SPEED AND G. W. ELMEN
Research Laboratories of the American Telephone & Telegraph Company and the Western Electric Company, Inc.,

Abstract of Paper

This paper describes a new magnetic material which is peculiarly suited to the construction of cores in small inductance coils and transformers such as are used in a telephone plant. The requirements which were to be met involved a core material which should have a constant permeability, a small hysteresis loss, and a small eddy current loss within the range of magnetizing forces and frequencies which are met in telephonic operation. The material which was developed to meet these requirements is formed by fine grains of powdered iron, insulated and compressed. There is described the circumstances and experiments which led to this development and also the method of commercial production. Tables and curves are given showing the magnetic, electrical, and mechanical properties of the material.

THE DEVELOPMENT of a successful method of compressing insulated grains of iron to produce a material magnetically and electrically suited for use in the telephone plant has had a determining effect upon recent progress in methods of loading and compositing telephone lines as well as upon the introduction of carrier current systems of multiplex telephony. It is the purpose of the present paper to discuss briefly the circumstances and experiments which led to this development and to describe the method of commercial production and the magnetic characteristics of the finished material.

The most important use of this material is in the construction of the cores of the loading coils which are introduced at regular intervals to increase the inductance of a telephone circuit.[1] It is also used in the cores of inductance elements in filters for carrier current systems,[2] and in those of reactance coils and transformers for radio telephone circuits. Coils for use in these circuits have to meet requirements which are in general quite different from those of other circuits, as, for example, power transmission circuits.

In telephone-transmission lines, for example, the inductance of the loading coils must remain constant throughout the entire range of intensities of the currents which are employed in the telephone plant. The amplitude of the currents to which a given coil is subjected may vary as much as one hundredfold.

The first requirement for the magnetic core-material of a loading coil, therefore, is that its permeability shall remain constant over the range of magnetizing force corresponding to the normal range of telephone currents.

The second requirement arises from the simultaneous use of circuits for telephone and telegraph transmission. It is necessary that the variation in the effective resistance of the coil, which is caused by hysteresis[3] and occurs when two currents of different frequencies and amplitudes are superposed, shall be so small that what is known as "flutter" in the transmitted speech shall not be objectionable.

The third requirement concerns the effective resistance which is introduced into the telephone circuit because of hysteresis and eddy-current losses in the core-material of the loading coil. It is required that the effective resistance due to these causes shall be small in order that the total resistance of the coil, including its copper loss, shall be small as compared to the resistance of a length of line conductor equal to the length of the loading section. Since the effects

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[1] B. Gherardi. "Commercial Loading of Telephone Circuits in the Bell System." TRANS. A. I. E. E. 1911, Vol. XXX, p. 1743.

[2] Colpitts and Blackwell. "Carrier Current Telephony and Telegraphy," JOURNAL A. I. E. E., Feb. 1921.

[3] Fondiller and Martin. "Hysteresis Effects with Varying, Superposed Magnetizing Forces." JOURNAL A. I. E. E. Feb. 1921.

of hysteresis and eddy currents will depend upon both the frequency and the amplitude of the telephone currents, it is further evident that the constancy of loading coil operation requires that these losses shall be minimized.

These requirements were met successfully in the early development of loading coils by the use of hard iron either in wire or in sheet form. Cores of hard-drawn wire were developed and adopted by the engineers of the American Telephone & Telegraph Company and were used successfully until the core-material herein described was put on a production basis. Two advantages pertain to the use of hard material in preference to soft. In the hard material the variation in permeability for a large range of magnetizing forces is less than in the soft iron. This is especially true at the initial part of the magnetization curve where, for a very large range of magnetizing force, the permeability of the hard material is constant. The second advantage is due to the fact that over this range in which the permeability is constant the hysteresis loss per unit of volume is less in the hard than it is in the soft material for the same flux density.

In order to take advantage of the constancy in permeability and the low hysteresis loss at small magnetizing forces[4], the coils were designed so that for the range of speech currents the magnetizing force corresponded to that of the initial part of the magnetization curve. In a standard design of coil the magnetizing force corresponding to an average telephone current of one milliampere is of the order of 0.01 gauss.

In addition to the magnetic requirements for the core-material, its electrical resistivity is also of great importance. This is due to the fact that the important frequency of the speech currents as usually assumed, is approximately 800 cycles per second and unless the resistivity of the material is very high or the core material is very finely subdivided, the losses caused by the eddy currents are excessive. In order to reduce the effective resistance caused by these losses it was

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[4] In this paper the term "small magnetizing force" is used to indicate forces below 0.1 gauss.

found necessary to employ iron wire drawn down to a diameter of 0.004 in. and, in addition, to insulate the separate convolutions of the contiguously-wound core. Two types of wire were established as standard for loading coils, classified according to the permeability at low magnetizing forces. For one type the permeability is 95, and for the other, 65. The difference in permeability between the two types is the result of a difference in the process of drawing the wire, that of lower permeability being drawn a greater number of passes without annealing.

Cores constructed in the above manner were used for a number of years. With the introduction of repeaters, and especially on composited and phantomed circuits, the requirements as to stability and constancy in the physical characteristics and operation of loading coils became more severe. To meet these conditions it was found necessary to introduce air gaps[5] at right angles to the flux path in the core of the loading coil. The introduction of such air gaps was conditioned by certain other requirements, specifically for example, by the requirement as to a balanced-winding arrangement in coils designed for phantom circuits where an absence of balance between the several windings would introduce stray magnetic fields. In telephone practise parallel circuits are loaded at a common point and the coils are either adjacent on a loading pole fixture, or are assembled in a common case. Under the latter condition, if stray magnetic fields surround the cores of such coils there would be introduced an interference between parallel telephone circuits which is ordinarily spoken of as "cross-talk." For this reason the air gaps which are introduced into the core of the loading coil have to be spaced symmetrically with respect to the balanced-winding arrangement.

The production of this hard-drawn wire requires the use of diamond dies and these were imported from Europe. Early during the war importation became impossible and our supply of hard-drawn wire was thus seriously curtailed. Fortunately the develop-

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[5] Fondiller and Shaw. U. S. Patent No. 1, 289, 941. 1918.

ment of the powdered-iron cores while not completed had reached the stage where the material could be quickly put into commercial production to meet the demand for core material.

In order to be useful as a substitute for fine iron wire, a magnetic material must have the following general properties: (1) the permeability at low magnetizing forces must be between 20 and 100, (2) the material must be very finely divided in a direction at right angles to the magnetizing force in order to decrease the effective resistance caused by the eddy currents, (3) the hysteresis loss must be low, and (4) the cost of manufacture into core form must compare favorably with that of iron-wire cores.

From a preliminary investigation the most promising possibilities seemed to lie in the direction of using finely-divided iron powder, each particle sufficiently insulated to eliminate eddy currents between contiguous particles. The general idea of using this kind of material for telephone-magnet cores was old. In 1887 Heaviside[6] described cores made from finely divided iron and insulated with wax. Coils with such cores were tested on an inductance bridge at telephone frequencies for the purpose of determining to what extent the effective resistance caused by the eddy currents had been eliminated. The results indicated that the subdivision was very effective in eliminating eddy-current loss.

About the same time others[7], notably Fritts, suggested the use of finely divided iron for pole pieces and armatures in dynamos and motors and for the core of other electromagnets. Interest along this line then subsided, probably because more satisfactory results could be obtained with laminated iron.

About 1900 the interest in the use of finely divided iron for a core material was revived by the introduction of loading coils. For the cores of loading coils Dolezalek[8] suggested the use of finely divided iron in very much the same form as Heaviside had previously employed it for telephone magnets.

A constructive suggestion was made in 1901 by F.

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[6] *The Electrician*, Feb. 11, 1887, p. 302, also Elect. Papers Vol. II, page 398, 1894.

[7] See bibliography at the end of the paper.

[8] U. S. Patent No. 716206, 1902.

A. Pickernell of the Engineering Department of the American Telephone and Telegraph Company. He advocated the use of finely divided magnetic oxide of iron or iron powder as a suitable material for loading-coil cores. The possibility of using iron oxide was investigated by the Telephone Company engineers and actual methods of production [9] were developed and loading coils with cores of this material were constructed. Toroidal cores were made by using iron laminations or irontape. After the cores were formed they were subjected to an oxidizing process which transformed the iron into magnetic oxide of iron (Fe_3O_4). The results obtained on these coils gave enough promise to indicate that it would be possible to produce cores in this way. As hard-drawn iron wire cores were developed about the same time and as the energy losses of these cores were considerably less the development work was discontinued.

The magnetic properties of finely divided iron have also been studied by a number of investigators[10] but all the permeabilities which they record are for values of magnetizing force much larger than those with which we are concerned in telephony. In all of the investigations, with the exception of Benedicks[11], the material was either entirely uncompressed or was very slightly tamped. The permeabilities recorded by these experimenters are less than 10. Benedicks compressed his material by continued tamping, and the permeability of his core, at the magnetizing force of 143 gausses, was 90 as compared with a permeability of 143 for solid iron at the same magnetizing force. Benedicks, however, was interested only in direct-current magnetizations, and the material which he produced was of no value at high frequencies as the particles of iron were not insulated.

There was nothing in the literature to indicate what permeabilities could be obtained at low magnetizing forces. It seemed, however, to one of the authors[12]

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[9] Lee and Colpitts, U. S. Patents No. 705935 and 705936. 1902.

[10] See bibliography at the end of the paper.

[11] *Journal of the Iron and Steel Inst.* Vol. I, p. 407, 1914.

[12] B. Speed, U. S. Patent No. 1274952, 1918.

that the use of powdered iron for core materials had important possibilities. He concluded that if a pure finely divided iron powder could be insulated with a very tenacious insulation and compressed so that the specific gravity was nearly that of solid iron, it should be possible at low flux densities to obtain permeabilities of the order required for loading-coil cores.

Experimental Work

The experimental work, through which powdered-iron cores of commercially valuable properties were first obtained, could not be fairly stated unless we here made acknowledgment of the able assistance rendered by J. T. Butterfield and J. H. White. To W. Fondiller is due the designing and engineering of the loading coils embodying the compressed iron cores.

Early Experiments. Our earliest efforts were directed towards obtaining particles of finely divided iron each with a coating which would retain its insulating properties when a mass of them was compressed to a specific gravity of the order of that of solid iron. The iron powder used in the early experiments was powder reduced from iron oxide in hydrogen. This powder was mixed with a little water and slowly dried by heating it to a temperature between 100 and 150 deg. cent. until the particles had a coating of oxide on them. This oxide was mostly red oxide of iron although under certain conditions both the red and black oxide were present. After the oxide coating was obtained, the powder was mixed with a thin solution of shellac and dried while the mass was stirred to prevent caking. When dried, the insulated powder was put in a mold and pressed into rings from 1/8 to 1/4 in. thick, and with inside and outside diameters of 2 1/8 and 3 7/8 in., respectively.

Pressures. The pressing was first done with a press which developed a pressure of 100,000 pounds per square inch of surface of the rings. As this pressure did not seem high enough to obtain the required permeabilities, a press was obtained which, for the same surface, produced pressures up to 250,000 pounds per square inch. When the material was subjected to 200,000 pounds per square inch of surface cores were formed which had sufficiently high insulation between the particles and also at low magnetizing-forces a permeability[13] between 50 and 60, that is of the order required by a substitute in loading coils for the 95-permeability wire.

Insulation of the Particles. In addition to the method of insulating the particles described above, a number of other methods were attempted before the one now used commercially was adopted. In place of oxidizing and shellacking, some cores were made in which shellac only was used. Others were insulated with asphaltum compound dissolved in carbon tetrachloride, and the mixture stirred until the solvent evaporated. A number of different kinds of varnishes were also tried. In place of oxidizing the surface of the iron particles, there was also tried the method of chemically producing on the surfaces coatings of other compounds of iron. None of these methods gave as satisfactory results as the method used in our early experiments. This was due to the fact that if the insulation were made sufficiently thick to prevent the iron grains from cutting through it under pressure, it introduced too large air gaps in the magnetic circuit.

While investigating these possibilities, J. C. Woodruff[14] discovered that when a quantity of iron powder was rolled in a zinc-lined drum for a few hours and then insulated with a shellac solution the resulting product showed for corresponding permeabilities a higher specific resistance than had been obtained by any of the previous methods. Pursuing this further he found that if before applying the shellac he mixed the iron powder with flaked zinc, rolled the mixture in a drum for a few hours, and then removed the zinc by sieving, a very thin and tough insulation of the grains of iron was obtained which did not break down when the cores

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[13] In determining permeability no correction is made in the flux density for the insulation and the air space. The cross-sectional area is assumed to be the measured cross-sectional area of the ring, and the permeability recorded is the total flux divided by the cross-section of the ring and the magnetizing force.

[14] U. S. Patent No. 1,292,206, 1919.

were compressed. As this is a very convenient method of insulating the material commercially, it was adopted and is being used in commercial production of powdered iron cores.

Production of Iron Powder. Next to the question of the possibility of using iron powder for making cores, the problem of obtaining a source of supply is important. In the early experimental work, as has already been stated, there was used iron reduced from the magnetic oxide by hydrogen. The two main objections to this material were the high cost of production and the fact that the reduced iron was very soft The latter is a serious defect, as has already been pointed out, in case the material is to be used for cores in the highest grade of loading coils. The pressing of the iron powder introduces a considerable amount of mechanical hardness but is insufficient to give the material as good magnetic qualities as the 65-permeability iron wire. The introduction of other means of hardening the material, although possible, would increase the cost of production. When studying the question of obtaining a source of supply, one of the authors[15] concluded that if iron was deposited from a suitable electrolyte it could probably be ground to the required fineness and it would also have the additional quality of being a hard material. This method of producing iron powder would also be relatively inexpensive and the quality of the material could be controlled a great deal more readily than in other methods of production. Work was immediately started to investigate this possibility and the preliminary work was so encouraging that a good-sized experimental plant was installed.

Satisfactory material was obtained by electrolysis of a solution containing ferrous sulphate and chloride and ammonium sulphate using anodes of mild steel and cathodes of polished sheet steel, with current densities of about twelve amperes per square foot. The cathodes were removed when the deposit had reached a thickness of 1/8 to 1/4 in., and washed in hot water to remove the electrolyte.

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[15] G. W. Elmen, U. S. Patents No. 1297126 and 1297127, 1919.

The deposited iron was then stripped from the cathode sheets and broken up into pieces about an inch square. This material was next placed in a ball mill and ground until all of the material would pass through a sieve with 80 meshes to the linear inch. The ground iron then contained particles from the largest size passing through the sieve to the very finest flour. Sieve analysis showed that approximately 35 per cent to 50 per cent of this material would pass through a 200-mesh sieve. Unless the iron powder was to be annealed, it was now ready for the insulating process.

If annealed iron was desired, the powder was packed into cast-iron boxes and heated to about 850 deg. cent. and then allowed to cool slowly with the furnace. The material was then removed from the boxes. Because of a certain amount of sintering it was necessary again to break up the material into the original mesh by putting it through a rock crusher. By this process the iron was very readily reduced to its original fineness. The annealing process also purified the iron to a certain extent since the occluded hydrogen was liberated at a comparatively low temperature and reduced to pure iron the oxide which was present. This made the annealed iron purer than the unannealed.

This method of obtaining the supply of iron powder has been adopted commercially and a description of the commercial plant will be given later in this paper.

Magnet Cores. The present method of producing magnet cores from iron powder is as follows: The iron is deposited electrolytically, ground, sieved, insulated and pressed in dies at a pressure of 200,000 pounds per square inch of surface. The rings are pressed to a thickness of approximately ¼ in., the inside and outside diameters depending on the design of the coil. After pressing, these rings are baked at a temperature of 125 deg. cent. to remove the moisture. The cores are constructed from these rings. Ordinarily several of the rings are stacked together to make a core and covered with insulating tape before the copper winding is put on.

The use of iron powder of the kind described lends itself very readily to the construction of cores having any desired permeability below 60 at low magnetizing forces. At the present time three standard types of core-material are commercially produced. These will be designated, for convenient reference, as grade A, grade B, and grade C. The order of designation does not imply the order of superiority in magnetic properties. The same pressure, 200,000 pounds per square inch, is used for all of these grades. Grade A consists of annealed and insulated iron-powder which has passed through a sieve with 80 meshes to the linear inch.

The permeability of this material at low flux densities is approximately 55. Grade B consists of material of the same mesh as grade A but is a mixture, 90 per cent unannealed and 10 per cent annealed. The permeability for the same magnetizing forces is approximately 35. Annealed iron is added in order to bring the permeability up to the desired value and also to add somewhat to the mechanical strength of the rings. Grade C is a mixture of the same proportions as grade B, but it passes through a sieve of 200 meshes per linear inch. The shellac insulation for grade C is also considerably heavier than for grades A and B. The permeability of grade C is approximately 25.

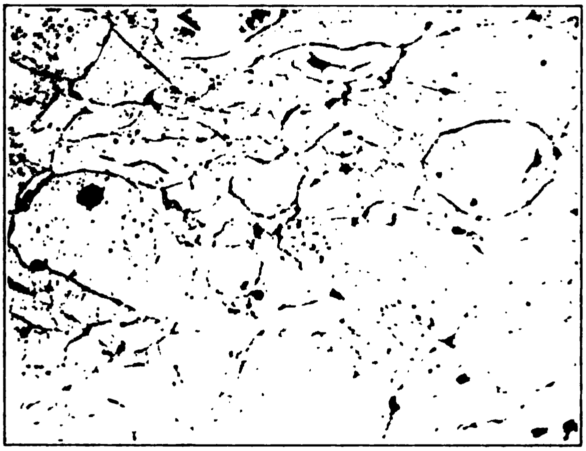

FIG. 1—MICROPHOTOGRAPH OF SURFACE OF GRADE A RING
Magnification 100 diam.

Fig. 1 is reproduced from a microphotograph of the surface of a grade A ring showing the distortion of the iron grains and the thin walls of insulation separating them.

Figs. 2 and 3 show two sizes of rings and a coil in which part of the winding and core has been removed.

ELECTRICAL AND MAGNETIC PROPERTIES

There will now be presented the results of tests under a large number of conditions, from which there may be obtained a very complete idea as to the electrical and magnetic properties of electrolytic iron powder. The tests to be described cover cores pressed from electrolytic iron-powder both annealed and unannealed. The results are also given of tests on uninsulated powder. In this case the powder was of the same fineness as that of grades A and B. There is also shown the effect of different pressures upon the physical constants of both the annealed and the unannealed iron-powder. The tables show also the specific gravity and the tensile strength of some of the materials. It is to be noted that grades A, B and C are standard materials; the other materials for which values are given are recorded only for purposes of comparison.

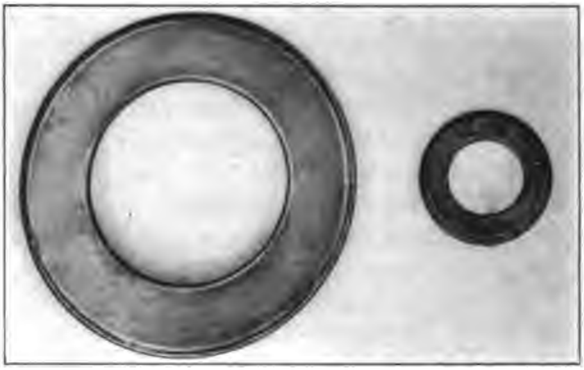

FIG. 2

Specific Gravity. The specific gravity for uninsulated iron powder, compressed with different pressures, is given in Fig. 4. The specific gravities for the grades A, B and C cores are given in Table I.

Tensile Strength. The mechanical strength of the rings is considerable and no difficulty is experienced in handling them in the general process of manufacturing cores. In Table I is recorded the load in pounds per square inch of cross-section necessary to disrupt the pressed rings under tension. The specific gravity of the rings is also given in this table.

FIG. 3

TABLE I.

	Tensile Strength Pounds per sq. in.	Specific Gravity
Grade A rings...............	1375	7.1
Grade B rings...............	925	6.4
Grade C rings...............	375	6.0

Specific Resistance. In the measurement of specific resistance the current was led into core rings of the material by small clamps, placed diammetrically opposite one another, and thus dividing the ring into two equal current paths. The drop of potential was measured in different parts of the surfaces of the two halves of the ring. The clamps were then turned through 90 deg. and measurements were again made. The specific resistance of the compressed rings was calculated from the dimensions of the ring and the distance between the potential points. The specific resistances of the various types of iron powder used in these measurements are recorded in the same tables as the magnetic properties and in Fig. 5 is plotted the specific resistance for uninsulated powder compressed with different pressures.

Magnetic Properties. The magnetization curve and hysteresis loops for direct-current magnetization were measured with the ballistic galvanometer. From these measurements the permeability, the hysteresis loss (W_h), the hysteresis exponents (x), and the hysteresis coefficient (η) were computed. The data on various types of cores are tabulated in the following tables and in some instances are shown by typical graphs.

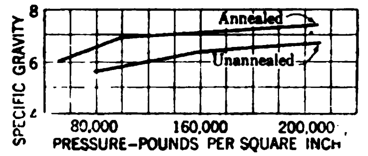

Fig. 4—Specific Gravity of Uninsulated Iron Powder Cores Compressed with Different Pressures

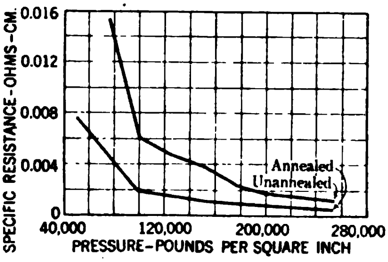

Fig. 5—Specific Resistance of Uninsulated Iron Powder Cores Compressed With Different Pressures

Tables II and III and Figs. 6, 7, 8, 9, 10 and 11 give the data on uninsulated iron powder cores, both annealed and unannealed, for various pressures.

Tables IV, V, VI give data on cores of grades A, B and C. The magnetization curves for these cores are plotted in Fig. 12.

TABLE II
PROPERTIES OF ANNEALED UNINSULATED IRON POWDER CORES

Pressure lb. per sq. in.	Sp. gr.	Sp. Res. ohm-cm.	H max.	B max.	μ	Coercive force	Remanence	W_h Ergs per cm^3 per cycle	x	η
254,000	7.4	0.0007	57.4	13,650	238	5.5	5,780	24,350	1.705	0.002105
			24.7	10,460	425	4.9	5,060	14,300	1.715	0.001892
			16.8	8,490	505	4.5	4,300	10,000	1.730	0.001683
			8.14	4,060	500	2.95	1,960	2,910	1.780	0.001114
			2.57	514	200	0.52	112	57.5	2.005	0.000208
			0.70	105	150	0.09	8	2.0	2.295	0.0000460
203,000	7.3	0.0010	60.6	13,000	214	5.8	5,250	24,180	1.655	0.00370
			26.05	9,760	375	5.2	4,490	14,050	1.675	0.00300
			17.05	7,500	440	4.6	3,650	9,080	1.700	0.00239
			8.87	3,640	410	3.1	1,725	2,720	1.810	0.00953
			2.85	498	175	0.47	96	50.7	2.000	0.000232
			0.816	98	120	0.08	8	2.15	2.155	0.000103
152,000	7.1	0.0012	57.6	10,800	184	7.0	4,200	21,700	1.635	0.00568
			30.2	8,200	272	6.45	3,750	14,050	1.670	0.00402
			20.2	6,250	310	5.45	2,920	8,650	1.720	0.00264
			10.2	2,950	290	3.45	1,270	2,340	1.805	0.001265
			3.07	399	130	0.51	73	45.6	2.075	0.0001815
			0.943	99	105	0.08	7	1.67	2.795	0.00000437
101,600	7.0	0.0019	56.5	9,600	170	5.90	3,330	16,900	1.585	0.00826
			26.8	6,700	250	5.55	2,850	9,800	1.605	0.00687
			17.9	4,990	279	4.75	2,200	5,880	1.635	0.00536
			8.90	2,180	245	2.90	860	1,420	1.855	0.000897
			2.17	325	150	0.41	50	30.8	2.210	0.0000867
			1.10	99	90	0.07	7	1.55	3.005	0.000001555
50,700	6.1	0.0078	62.0	5,890	95	5.75	1,750	10,100	1.745	0.00266
			30.1	4,210	140	5.10	1,400	5,440	1.760	0.00230
			22.4	2,650	163	4.00	960	2,390	1.780	0.00193
			8.66	1,300	150	2.30	425	687	1.830	0.001355
			1.905	200	105	0.42	28	18.5	2.140	0.000218
			0.715	50	70	0.06	4	0.716	2.750	0.0000153

TABLE III
PROPERTIES OF UNANNEALED UNINSULATED IRON POWDER CORES

Pressure lb. per sq. in.	Sp. gr.	Sp. Res. ohm-cm.	H max.	B max.	μ	Coercive force	Remanence	W_h Ergs per cm^3 per cycle	x	η
254,000	6.7	0.0013	61.0	7,200	118	10.60	2,760	18,310	1.590	0.01365
			30.1	4,360	145	8.45	1,750	8,130	1.785	0.00259
			21.65	3,050	141	6.40	1,090	4,110	1.900	0.00100
			10.05	1,000	99.5	1.90	195	414	2.225	0.0000869
			3.03	200	66	0.16	11	8.25	2.430	0.0000247
			1.00	57	57	0.025	1.8	0.458	2.640	0.00000912
228,000	6.65	0.0016	60.1	7,100	118	11.0	2,900	19,590	1.555	0.01995
			30.3	4,300	142	8.5	1,790	8,260	1.775	0.00299
			20.3	2,720	134	6.0	1,000	3,610	1.940	0.000772
			9.8	950	97	1.9	185	389	2.200	0.000108
			3.28	210	64	0.26	18	11.3	2.455	0.00002255
			1.065	57	53.5	0.02	1.2	0.325	2.885	0.00000277
203,000	6.55	0.0019	60.7	6,800	112	11.2	2,675	18,230	1.650	0.00838
			31.0	4,100	132	8.2	1,600	7,350	1.785	0.00273
			20.7	2,650	128	6.0	950	3,385	1.950	0.000569
			10.2	935	92	1.85	175	368	2.295	0.0001432
			3.38	203	60	0.20	13	7.94	2.550	0.00001208
			1.13	59	52	0.04	1.8	0.402	2.675	0.00000662
178,000	6.4	0.0024	60.5	5,870	97	12.0	2,400	17,390	1.700	0.00686
			30.5	3,450	113	8.8	1,460	6,810	1.860	0.001808
			19.9	2,170	109	6.0	760	2,745	2.015	0.000527
			9.76	790	81	1.8	158	318	2.200	0.0001327
			3.10	170	55	0.26	14	9.55	2.430	0.0000362
			1.01	48	47	0.02	1.0	0.276	2.875	0.00000406

TABLE III—*Continued*

PROPERTIES OF UNANNEALED UNINSULATED IRON POWDER CORES

Pressure lb. per sq. in.	Sp. gr.	Sp. Res. ohm-cm.	H max.	B max.	μ	Coercive force	Remanence	W_h Ergs per cm^3 per cycle	x	η
152,000	6.3	0.0030	58.4	5,200	89	10.6	2,050	12,600	1.615	0.01245
			30.1	3,280	109	7.9	1,260	5,870	1.800	0.00271
			20.5	2,150	105	5.4	700	2,380	1.975	0.000681
			10.12	810	80	1.9	159	334	2.215	0.000119
			3.14	163	52	0.18	10	6.69	2.585	0.00001275
			1.03	46	45	0.02	1.0	0.239	2.755	0.00000628
127,000	6.1	0.0047	62.8	5,460	87	13.5	2,150	15,710	1.700	0.00697
			28.2	2,850	101	7.9	1,100	4,870	1.980	0.000681
			18.8	1,800	96	5.0	550	1,815	2.180	0.0001435
			9.32	625	67	1.05	85	124	2.360	0.0000390
			3.11	140	45	0.15	7.5	5.73	2.535	0.00001495
			1.13	44	39	0.02	0.9	0.182	2.680	0.00000780
101,600	5.9	0.0060	61.7	3,950	64	11.4	1,375	9,980	1.620	0.01472
			31.2	2,275	73	7.3	780	3,535	1.835	0.002675
			19.1	1,425	74.5	4.8	450	1,551	2.045	0.000551
			10.0	515	51.5	1.6	75	161	2.350	0.0000673
			3.02	109	36	0.13	4.0	3.8	2.675	0.0000137
			1.00	33	33	0.02	0.9	0.105	2.990	0.000003015
76,100	5.6	0.0155	60.2	3,375	56	11.0	1,140	8,450	1.650	0.01255
			30.45	1,825	60	7.0	560	2,680	1.895	0.00183
			20.2	1,130	56	4.6	285	1,074	2.070	0.000507
			9.77	430	44	1.4	60	132.5	2.235	0.000172
			3.06	95	31	0.16	5.2	3.28	2.635	0.0000202
			0.994	28.3	28.5	0.015	0.6	0.084	3.075	0.00000287

DATA DERIVED FROM MEASUREMENTS OF INDUCTANCE AND EFFECTIVE RESISTANCE

Certain data as to magnetic constants are deducible from the values of inductance and effective resistance of coils especially wound on cores of the various materials. Measurements of inductance and effective resistance were made with an inductance bridge. Measurements were made for frequencies, within the audible range, of values 500, 800, 1200, 1600 and 2000 cycles

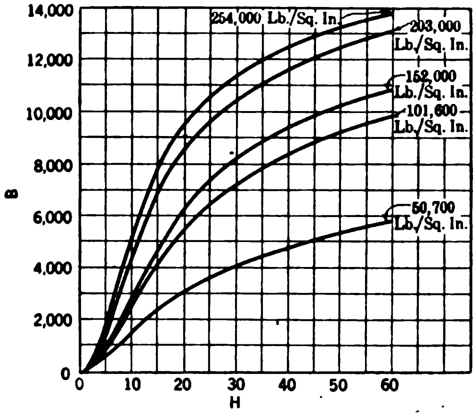

FIG. 6—MAGNETIZATION CURVES FOR ANNEALED UNINSULATED IRON POWDER COMPRESSED WITH DIFFERENT PRESSURES

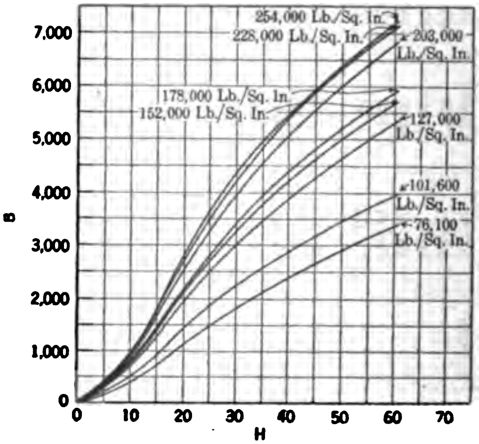

FIG. 7—MAGNETIZATION CURVES FOR UNANNEALED UNINSULATED IRON POWDER COMPRESSED WTIH DIFFERENT PRESSURES

per second. In all these bridge measurements the flux density of the cores was low. The measuring current was obtained from a vacuum tube oscillator which gave a sinusoidal wave. The test coils were so constructed that for the highest frequency of measuring current the energy losses in the copper winding caused by eddy currents, and also the dielectric losses were very small compared to the iron losses. These losses, were therefore, negligible and did not enter into the computation of hysteresis and eddy-current losses in the cores themselves.

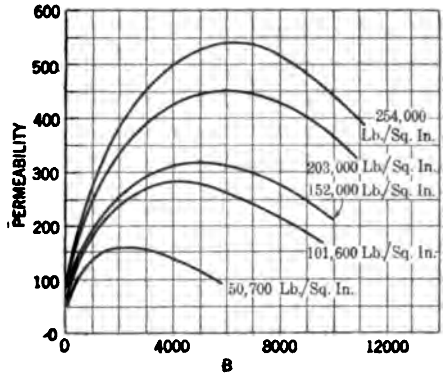

Fig. 8—Permeability Curves for Annealed Uninsulated Iron Powder Compressed With Different Pressures

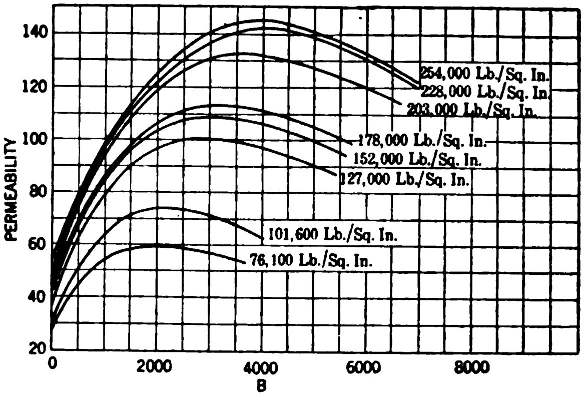

Fig. 9—Permeability Curves for Unannealed Uninsulated Iron Powder Compressed with Different Pressures

From measurements of the effective resistance and inductance of the test coils there was derived the permeability of the core-material, and also the components, due to eddy currents and hysteresis respectively, of the iron losses in the core. The equations whereby these calculations were made are given below. Preceding them there is a statement of the symbols which are employed in the equations.

The permeability of the core material was computed by equation (3). The effective resistance corresponding to the iron losses was separated into its components by equation (7), which is derived from Steinmetz's equation (1). Instead of expressing the power loss in the iron per cubic centimeter, it is more satisfactory for purposes of coil design to express the effective resistance per henry of inductance.

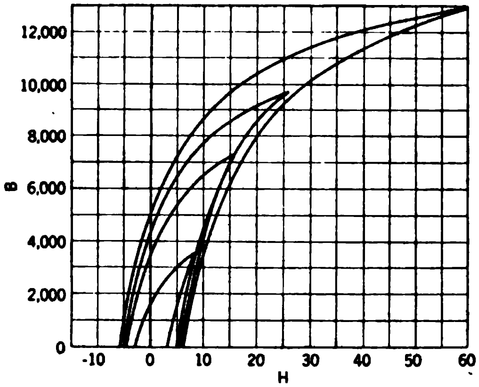

FIG. 10—HYSTERESIS CHARACTERISTICS FOR ANNEALED UNINSULATED IRON POWDER CORES COMPRESSED WITH A PRESSURE OF 203,000 LB. PER SQ. IN.

The transformation of the usual Steinmetz equation to the form which we have found convenient is indicated by equations (1) to (8) inclusive and the accompanying text.

L = inductance in henrys
I = current in amperes (r. m. s.)
W = power expended in ergs in the core
H = magnetizing force in gauss
B = flux density in gauss
μ = permeability

N = total number of turns of winding on the core
A = cross-section of core in cm^2.
v = volume of core in cm^3.
l = mean length of the magnetic circuit in cm.
R_t = effective resistance in ohms caused by the iron losses. This is equal to the measured resistance at a designated frequency minus the direct-current resistance.
R_h = effective resistance caused by hysteresis loss
R_e = effective resistance caused by eddy current loss
x = hysteresis exponent

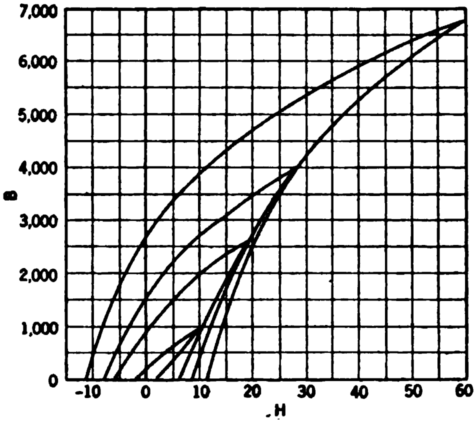

FIG. 11—HYSTERESIS CHARACTERISTICS FOR UNANNEALED INSULATED IRON POWDER CORES COMPRESSED WITH A PRESSURE OF 203,000 LB. PER SQ. IN.

η = hysteresis coefficient
γ = eddy current coefficient
f = frequency in cycles per second

$$W = \eta\, v f B^x + \gamma\, v f^2 B^2 \tag{1}$$

$$W = R_t I^2 \times 10^7 \tag{2}$$

$$L = \frac{4\,\pi\, N^2 A\, \mu}{l \times 10^9} \tag{3}$$

$$H = \frac{4\pi\, N\, I\, \sqrt{2}}{l \times 10} \tag{4}$$

$$v = l A \tag{5}$$

From (1) and (2)

$$R_t I^2 \times 10^7 = \eta f v B^x + \gamma f^2 v B^2 \tag{6}$$

TABLE IV

PROPERTIES OF GRADE A IRON POWDER CORES

Sp. Res. ohm—cm.	H max.	B max.	μ	Coercive force	Remanence	W_h Ergs per cm^3 per cycle	x	η	Method of test
0.6	59.9	8,260	138.0	7.25	1,725	15,550	1.64	0.00638	Ballistic galvanometer
	29.9	4,680	156.5	5.55	1,187	6,165	1.74	0.00283	"
	20.0	3,100	155.0	4.13	760	2,860	1.81	0.001595	"
	10.0	1,210	121.0	1.96	258	531	1.91	0.000750	"
	3.0	232	77.4	0.35	26.6	18.0	2.13	0.0001035	"
	1.00	61.9	61.9	0.04	3.1	0.72	2.59	0.0000184	"
	0.60	35.5	59.1	0.002	1.5	0.190	2.70	0.00001175	"
	0.155	8.78	56.5	0.002	0.1	0.00386	2.785	0.00000911	"
	0.146	8	54.8			0.00294	2.775	0.00000912	Inductance bridge
	0.128	7	54.8			0.00203	2.765	0.00000931	"
	0.1095	6	54.8			0.00132	2.750	0.00000956	"
	0.0913	5	54.8			0.000803	2.735	0.00000983	"
	0.0730	4	54.8			0.000436	2.685	0.00001055	"
	0.0547	3	54.8			0.000204	2.630	0.00001132	"
	0.0365	2	54.8			0.0000710	2.554	0.00001208	"

TABLE V

PROPERTIES OF GRADE B IRON POWDER CORES

Sp. Res. ohm—cm.	H max.	B max.	μ	Coercive force	Remanence	W_h Ergs per cm³ per cycle	x	η	Method of test
0.2	60.0	3,440	57.3	8.60	645	6,023	1.66	0.00875	Ballistic galvanometer
	30.0	1,655	55.2	5.05	312	1,787	2.02	0.000550	"
	20.0	1,000	50.0	2.60	134	561	2.22	0.0001303	"
	10.0	434	43.4	0.85	38.5	84.7	2.50	0.0000216	"
	3.0	103	34.4	0.09	3.2	2.0	2.75	0.00000515	"
	1.0	33.5	33.5	0.01	0.4	0.0852	2.75	0.00000515	"
	0.331	10	30.2			0.00290	2.750	0.00000515	Inductance bridge
	0.298	9	30.2			0.00217	2.750	0.00000515	"
	0.265	8	30.2			0.001568	2.750	0.00000515	"
	0.232	7	30.2			0.001087	2.750	0.00000515	"
	0.199	6	30.2			0.000711	2.750	0.00000515	"
	0.166	5	30.2			0.000433	2.707	0.00000555	"
	0.1325	4	30.2			0.000238	2.675	0.00000584	"
	0.0994	3	30.2			0.0001107	2.623	0.00000620	"
	0.0662	2	30.2			0.0000391	2.509	0.00000688	"
	0.0331	1	30.2			0.00000711	2.405	0.00000711	"

TABLE VI
PROPERTIES OF GRADE C IRON POWDER CORES

Sp. Res. ohm—cm.	H max.	B max.	μ	Coercive force	Remanence	W_h Ergs per cm^3 per cycle	x	η	Method of test
10	60.4	2,900	48.0	9.75	690	6,000	1.84	0.00257	Ballistic galvanometer
	30.2	1,290	42.8	4.70	200	1,260	2.18	0.0002115	"
	20.1	795	39.6	2.50	96	417	2.31	0.0000804	"
	9.96	335	33.6	0.68	22	52.6	2.54	0.00001905	"
	2.99	86.8	29.0	0.07	1.7	1.49	2.72	0.00000750	"
	1.10	30.4	27.6	0.02	0.5	0.0721	2.83	0.00000455	"
	0.380	10	26.3			0.00309	2.832	0.00000455	Inductance bridge
	0.342	9	26.3			0.00228	2.832	0.00000455	"
	0.304	8	26.3			0.00165	2.832	0.00000455	"
	0.266	7	26.3			0.001125	2.810	0.00000474	"
	0.228	6	26.3			0.000729	2.786	0.00000497	"
	0.190	5	26.3			0.000441	2.751	0.00000527	"
	0.152	4	26.3			0.000242	2.719	0.00000555	"
	0.114	3	26.3			0.0001105	2.670	0.00000589	"
	0.0762	2	26.3			0.0000383	2.553	0.00000652	"
	0.0380	1	26.3			0.0000070	2.401	0.00000699	"

Eliminating I^2 and v from this equation by means of (3), (4) and (5), gives

$$\frac{R_t}{L} = 8\pi\,\eta\,f\,\mu\,B^{x-2} + 8\pi\,\mu\,\gamma\,f^2 \qquad (7)$$

Equation (7) gives the effective resistance caused by the energy losses in the core in ohms per henry. The first member on the right-hand side of the equation is the effective resistance caused by the hysteresis loss and the second that caused by the eddy current loss.

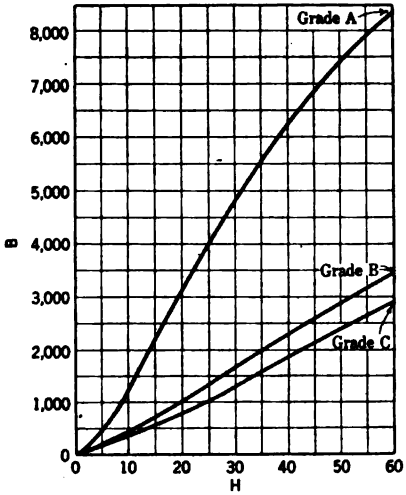

FIG. 12—MAGNETIZATION CURVES FOR GRADES A, B, AND C CORES

In order to separate the two, equation (7) is divided through by the frequency, giving

$$\frac{R_t}{Lf} = 8\pi\,\eta\,\mu\,B^{x-2} + 8\pi\,\gamma\,\mu\,f \qquad (8)$$

This equation represents a straight line when plotted with $\frac{R_t}{Lf}$ as one of the coordinates and the frequency as the other. The intercept of this line with the axis of $\frac{R_t}{Lf}$ gives the effective resistance for a given flux density per henry per cycle, caused by the hysteresis loss. The slope of the line multiplied by the frequency gives the effective resistance, per henry per cycle, caused by the eddy current loss at that frequency.

The permeabilities and the magnetizing forces in the alternating-current measurements were computed by means of equations (3) and (4).

In Fig. 13 are plotted the permeabilities of the uninsulated iron-powder at low magnetizing forces and for different pressures.

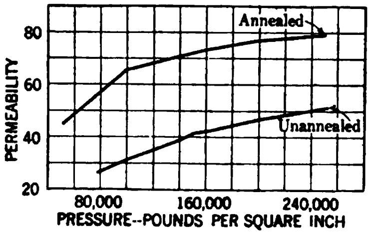

FIG. 13—PERMEABILITY AT LOW MAGNETIZING FORCES FOR UNINSULATED IRON POWDER CORES COMPRESSED WITH DIFFERENT PRESSURES

In Fig. 14 $\frac{R_t}{L}$ is plotted against frequency for several densities for grade A material, and in Fig. 15 $\frac{R_t}{Lf}$ is plotted against the frequency for the same flux densities.

Fig. 16 shows the variation of $\frac{R_t}{L}$ with frequency. The plot is for $B_m = 2$ gauss and permits a comparison of the three grades of material.

Fig. 17 shows, in per cent of the initial "a-c. permeability," the variation in a-c. permeability, which is produced by the superposition of various values of steady magnetizing force. In determining the relations of Fig. 17 the inductance bridge was used, and the a-c. permeability was calculated from the measured inductance of the test coil by the application of equation (3). In addition to the alternating current which was used for the bridge measurements there was superposed upon the windings of the test coil a direct current. The magnetizing forces corresponding to various values of the superposed d-c. are shown by the abscissas of Fig. 17. The figure illustrates the magnetic stability of the core material—a characteristic which will be discussed more fully later. It may be noted, however, that stability to superposed d-c. magnetizing forces is important in coils designed for telephonic purposes, for example, in loading coils which are to be used on composited circuits, where the inductance to the voice frequencies must not be greatly altered by the superposed telegraph currents.

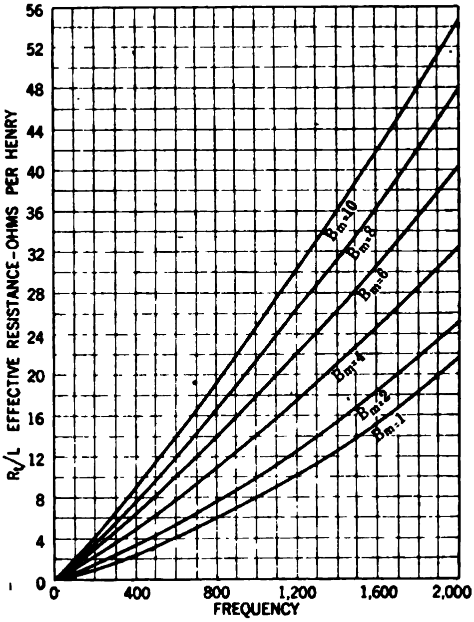

FIG. 14—INCREASE WITH FREQUENCY IN EFFECTIVE RESISTANCE CAUSED BY THE CORE LOSSES, FOR GRADE B CORES

Tables IV, V and VI, to which reference has already been made, give the results of computation based upon bridge measurements in addition to those derived from the ballistic measurements. Bridge measurements permit accurate determinations of the magnetic constants for low values of *H*. The higher values were computed from ballistic measurements as mentioned above. The tables give hysteresis coefficients and hysteresis exponents and also energy losses per cm.^{3} per cycle. The energy loss has been expressed per cm.^{3} per cycle in the case of the bridge measurements to facilitate comparison with the corresponding values derived from ballistic measurements.

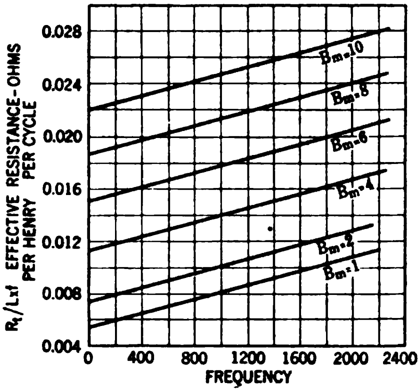

FIG. 15—SEPARATION INTO ITS COMPONENTS OF EFFECTIVE RESISTANCE CAUSED BY THE CORE LOSSES FOR GRADE B CORES

DISCUSSION OF MAGNETIC AND ELECTRICAL PROPERTIES OF POWDERED IRON CORES

The data collected in the tables and curves give a fairly good idea of what can be done with compressed iron-powder for magnetic purposes.

When annealed, uninsulated, powder is compressed to 254,000 pounds per square inch, the specific gravity of the mass is 7.4 as compared to 7.6 for solid cast iron and 7.85 for solid wrought iron. The specific gravity of the unannealed powder at the same pressure is 6.7.

The greatest change in specific gravity occurs below 100,000 pounds pressure per square inch. (*cf.* Fig. 4). With this pressure the annealed uninsulated iron has a specific gravity of 7. For a pressure two and one-half times as large it is increased only to 7.4. Although the additional pressure increases the specific gravity very little, the maximum permeability for the same difference in pressures is more than doubled as is shown by Fig. 8. The additional pressure is, therefore, very effective in closing up the air gaps in the magnetic circuit. It appears also from Table I that high pressure is effective in producing an intermeshing of distorted iron grains which holds the compressed mass together and results in a mechanically strong structure. The microphotograph of Fig. 1 illustrates this intermeshing, as well as the thinness of the gaps between adjacent grains.

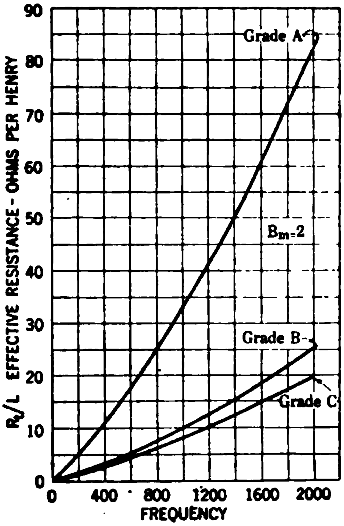

FIG. 16—INCREASE WITH FREQUENCY IN EFFECTIVE RESISTANCE CAUSED BY CORE LOSSES FOR GRADES A, B, AND C, WITH CONSTANT B_m

The measurements of specific resistance for cores pressed from uninsulated powder show the same characteristic variations as the specific gravity (Fig. 4). The specific resistance (Fig. 5) changes very rapidly with the pressure, for pressures below 100,000 pounds per square inch, but for higher pressures the change is more gradual. It is interesting to note that even when the specific gravity is 7.4 the specific resistance of the compressed, uninsulated, powder is 50 to 60 times that of the solid iron.

The magnetic properties of compressed iron-powder are in general similar to those of solid iron rings in which air gaps have been cut. The magnetization curves of Figs. 6 and 7 are sheared to the right as the value of the air gap is increased. This is due to the increase in the reluctance of the magnetic path. The magnetization curve for the highest pressure (Fig. 6) is very similar to one given by Ewing [16] for a wrought-iron bar cut into eight pieces.

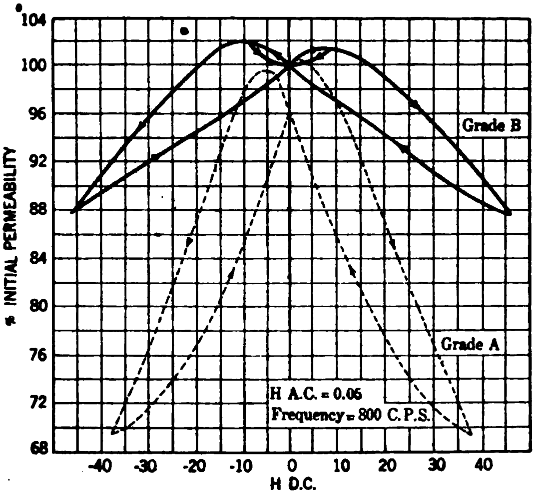

FIG. 17—THE EFFECT OF SUPERPOSED D-C. FIELDS ON THE A-C. PERMEABILITIES OF GRADES A AND B CORES

There is quite marked difference between the permeabilities of the insulated and uninsulated powder. If we compare the uninsulated powder at a pressure of 150,000 pounds per square inch and a specific gravity of 7.1, with the grade A material, the specific gravity of which is the same, we find that the maximum per-

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[16] J. A. Ewing. "Magnetic Induction in Iron and other Metals." 3rd Edition, 1900, page 292.

meability and the retentivity of the former is more than double that of the latter. The permeability at low magnetizing forces shows a similar although smaller difference. This difference is presumably caused by the way the air gaps are distributed in the two types of material. In the grade A cores each grain is insulated with a thin film which remains substantially intact while the grains are being distorted under the high pressure. In the uninsulated material it is probable that in certain parts of the mass the grains are pressed together until the air spaces between adjoining grains disappear but in other parts the air spaces are fairly large; hence the structure is that of a honeycombed mass.

The maximum permeability recorded for compressed iron powder is 545. This is as high a permeability as can be obtained with many grades of solid iron as is evident from Table VII. In this table are given the maximum permeability, and the permeability for $H = 0$, for several kinds of iron and steel as tested

TABLE VII.

	Permeability	
Kind of Material	Maximum	H = O
Electrolytic iron, wrought bar....................	7,800	250
Poor grade of cast steel, annealed...............	710	131.5
Poor grade of cast steel, hardened...............	170	58
Cast iron, annealed........	620	175
Cast iron, unannealed.....	240	69.4
Iron powder, annealed, uninsulated, compressed with 254,000 pounds pressure...................	540	80
Iron powder, unannealed, uninsulated, compressed with 254,000 pounds pressure...................	156	52
Grade A iron-powder cores.	156.5	54.8
" B " " " .	57.2	30.2
" C " " " .	48	26.3

by Gumlich and Rogowski[17], and also for several grades of compressed iron-powder as tested by the writers. For grades B and C the tabulated values of maximum permeability are those obtained with the highest magnetizing forces at which the coils were tested. At the magnetizing force of $H = 60$ the permeabilities were still slowly increasing.

The permeabilities of grades B and C are practically constant for flux densities below $B = 100$. For grade A this is true below $B = 50$. For flux densities below $B = 10$ there is no change in permeability that can be detected by accurate bridge measurements. This constancy is one of the important properties which makes our core-material useful for magnetic purposes.

The change in a-c. permeability when the cores are subjected to high d-c. magnetizing forces (*cf.* Fig. 17) is less for grade B than for grade A material. With a d-c. force of $H = 45$ the a-c. permeability of grade B is 85 per cent of the initial. When the force is removed the permeability returns to its original value. For grade A cores, with a d-c force of $H = 35$, the a-c. permeability is decreased to 70 per cent of its initial value and returns to 96 per cent when the d-c. force is removed.

For purposes of comparison it may be noted that in the case of 65-permeability iron-wire cores, which were mentioned above as standard prior to the development of the powdered iron, the stability is less than that of both grade A and grade B material. In the case of 65-permeability iron-wire cores the a-c. permeability may decrease to as little as 35 per cent of its initial value when a d-c. magnetizing force of $H = 45$ is superposed. When this superposed force is removed the permeability returns to only 62 per cent of its initial value.

From Tables IV, V and VI a comparison may be obtained of the present standardized grades of powdered iron as to the energy losses due to hysteresis. It will be noted that for flux densities below $B = 10$ the

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[17] E. T. Z. February 23, 1911.

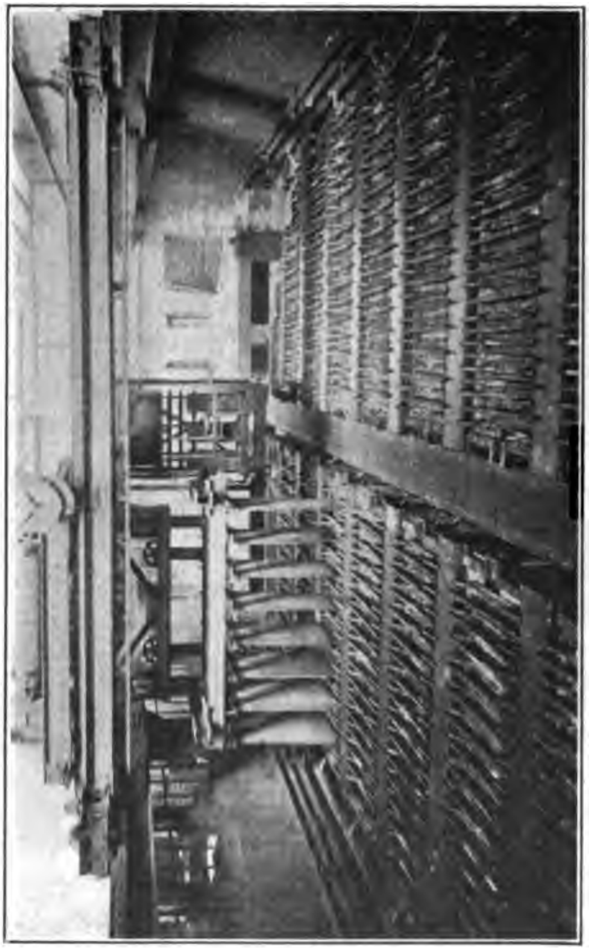

Fig. 18

energy loss in grade A is approximately double that of grade B or grade C.

For the purpose of the design and operation of telephone equipment it is convenient to express energy losses implicitly in terms of an increase in effective resistance rather than explicitly, since the effective resistance is a determing factor in the calculation of attenuations. Table VIII is added to permit a comparison of grades A, B and C in terms of increments in effective resistance. The values, there tabulated, represent differences between the resistance of test coils to currents of 800 cycles, and to direct currents,

Fig. 19

that is represent differences between effective and ohmic resistance at 800 cycles. In this table are indicated the components of the total increment in effective resistance due to hysteresis and eddy currents. The separation into components was effected by means of equations (7) and (8). The methods is illustrated by Figs. 14 and 15, but the actual values used in determining the tabulated values were obtained from the data of Fig. 16, and correspond to the flux density of $B = 2$.

TABLE VIII.

	R_h per henry	R_e per henry	R_t per henry
Grade A cores.......	19.7	5.4	25.1
" B "	5.9	1.7	7.6
" C "	5.1	1.2	6.3

It will be noted that the effective resistance due to eddy currents is approximately 20 per cent of the total increment in effective resistance. The percentage would be less at higher flux densities as is evident from the relations of equation (7).

COMMERCIAL PRODUCTION OF POWDERED-IRON CORES

Powdered iron cores are today manufactured in large quantities by the Western Electric Company at Hawthorne, Illinois. The present equipment has a capacity of 25,000 pounds of iron powder per week.

In Fig. 18 is shown some of the equipment used in producing electrolytic iron.

It shows the electric crane lifting eight cathodes with their electrolytically-deposited iron. In each tank there are sixteen cathodes and a corresponding number of anodes. In removing the cathodes only alternate ones are withdrawn at a time, partly for convenience in washing and handling, and partly so that the operating conditions in the tank will be less violently altered than if all the electrodes must be started fresh at once. The background of the figures shows the back of the switchboard and controllers, and also the stripping floor where the deposited iron is removed from the cathode plates.

A cathode with a full weight of electrolytic iron, ready for stripping is shown in Fig. 19.

After being stripped from the cathode the electrolytic iron is ground in a Hardinge conical-ball mill.

Fig. 20

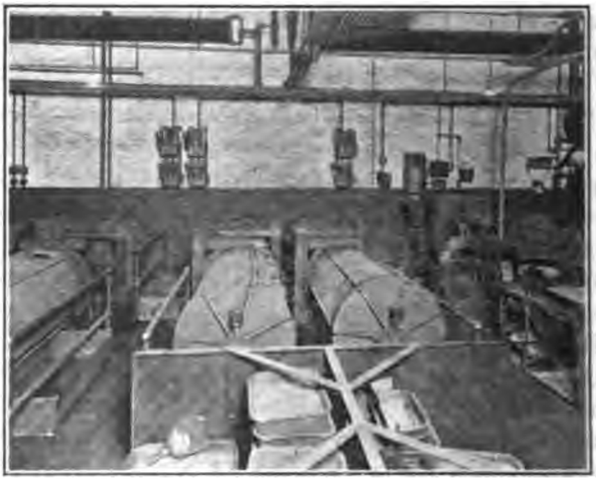

Fig. 21

Two of these mills are shown in Fig. 20. These mills operate with automatic feeders and deliver their output to rotating brass sieves (80 meshes to the linear inch). In the illustration the sieves are not seen because of their rectangularly shaped iron covers.

To the right of this illustration may be seen the annealing ovens.

The portion of the iron which is to be annealed is treated in cast-iron pots which hold about one hundred pounds each. Fig. 21 shows, at the extreme right, how the annealed iron appears as it is just being taken from the annealing pot. During the process of annealing the powdered iron is sintered to a fairly coherent mass. In order to reduce the iron to its original mesh the annealed product is passed through a rotary rock-

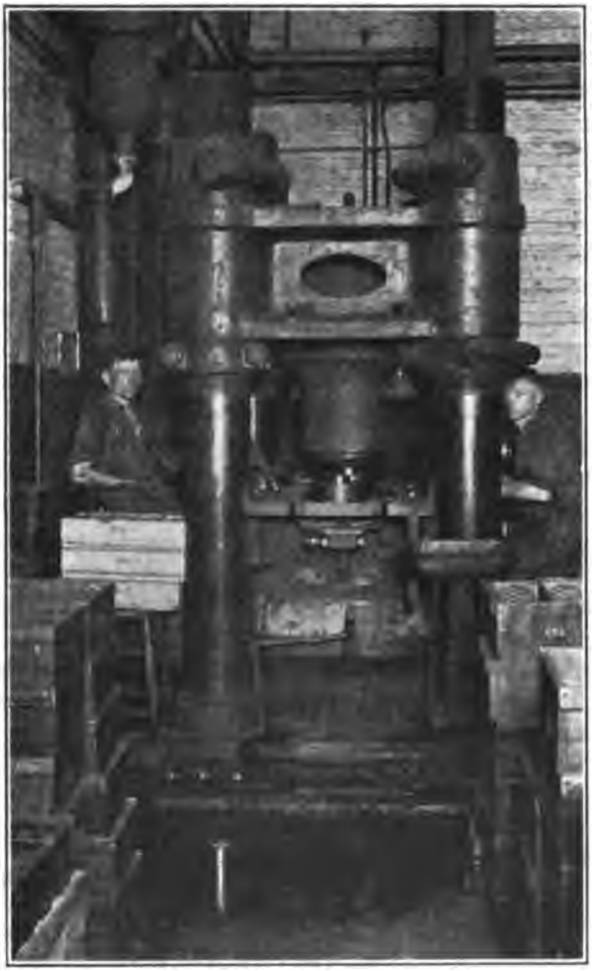

Fig. 22

Presented at the 37th Annual and 10th Pacific Coast Convention of the American Institute of Electrical Engineers, Salt Lake City, Utah, June 24, 1921.

HEAT LOSSES IN THE CONDUCTORS[1] OF ALTERNATING-CURRENT MACHINES

BY WALDO V. LYON
Massachusetts Institute of Technology

ABSTRACT OF PAPER

The principal object of this paper is to show how hyperbolic functions of *complex angles* may be applied to the solution of the problem of heat losses in rectangular conductors that are embedded in open slots. A certain knowledge of the functions themselves is presupposed. Inasmuch, however, as they are handled like trigometric functions of real angles—except in regard to the plus and minus signs—it is a simple matter to acquire the requisite technical skill to use them.

The hyperbolic function of a complex angle, consisting as it does of a real and an imaginary part, may represent a vector—the real part being the component of the vector along the horizontal, and the imaginary part, component along the vertical. Thus, for example, $A \sinh (x + j\,x)$ represents a vector just as $A\,\epsilon\,j\,\theta$, $A\underline{/\theta}$, $A\,(\cos\theta + j\sin\theta)$ represent vectors.

Considerable experience has shown that the vector

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[1] An abstract of this paper was presented before the Research Division of the Electrical Engineering Department at the Massachusetts Institute of Technology, April 13, 1920. The author's attention was first directed to this method of analysis by Dr. A. E. Kennelly to whom great credit is due especially on account of the extensive tables he has published from which numerical computations may readily be made: "Tables of Complex Hyperbolic and Circular Functions," A. E. Kennelly.

See also:

"Eddy Currents in Large Slot-Wound Conductors," A. B. Field, TRANS., A. I. E. E., 1905, p. 761.

"Current Distribution in Armature Conductors," W. V. Lyon, *Electrical World*, July 12, 1919.

Since this present analysis was made, Mr. R. E. Gilman has presented at the Annual Convention, TRANS., A. I. E. E., 1920, p. 997 a paper entitled "Eddy Current Losses in Armature Conductors." This paper of Mr. Gilman's, although he uses real quantities exclusively, is more complete in one respect than the one here presented in that he considers the case of a laminated conductor with a finite number of strands.

method for handling a-c. problems is much superior to the original method in which simple trigonometric functions were used. With this lesson before us, it should require but little contact with the problem at hand to demonstrate the superiority of the vector method, even though it employs the possibly unfamiliar hyperbolic quantities. These hyperbolic vectors have been used for a number of years in the analysis of problems involving a-c. circuits, which have distributed inductance and capacitance, and have proved their usefulness. Here is another important problem in which they may be used to advantage, and doubtless others will appear from time to time.

The general method of solution is to obtain a vector expression for the voltage drop in the topmost element of any conductor due to its resistance, and to all slot leakage flux *below* this element, (Equation (**7a**)), together with the vector expression for the voltage drop produced in this element by the slot leakage flux within any conductor *above* it, (**8a** and **8c**). The proper combination of these two equations will give the impedance drop in any of the considered arrangements of conductors. These expressions (**7a**, **8a** and **8c**) are determined by the frequency and the resistivity and the dimensions and arrangement of the conductors. Since the impedance drop that is thus determined is in the vector form, both the resistance and reactance—due to slot leakage flux within the conductors—are determined. Only solid and finely laminated conductors are considered.

Since the present paper was written, the author has extended the method to the solution of the problem in which the conductors have a finite number of strands separated by insulation. With slight modifications expressions similar to equations (**7a**), (**8a**), and (**8c**) can be derived. The *M* and *N* functions are rather more complicated than here given, but curves similar to Figs. 3 and 4 can be plotted, by the aid of which numerical calculations can be made.

WITH the increase in the capacity of alternating-current generators, it has become more and more important to determine the exact relation between the heat developed in any conductor and the currents that it and other neighboring conductors carry. Solutions for the distribution of alternating current within conductors that are embedded in open rectangular slots have been obtained for a number of cases. The methods of attack and the results obtained have heretofore involved trigonometric and hyperbolic functions of real angles. For this reason the work has been unnecessarily complicated, and its scope considerably cramped. Had the investigators used hyperbolic functions of ***complex*** angles, they would have accomplished more with much less effort. These hyperbolic functions of *complex* angles are such a powerful tool in the solution of this current distribution problem that the author feels fully justified in presenting this discussion of their application, even though many of the results have been obtained before.

At the outset it should be observed that certain assumed ideal conditions are necessary in order to bring the problem within the range of our mathematical ability.[2] Briefly these conditions are (1) that an element of current in the slot produces a uniform parallel magnetic field above itself and none below it; (2) that the current density along any line parallel to the bottom of the slot is constant; (3) that the resistivity of the conductor is uniform throughout, even though more heat is developed in some portions than in others; (4) that voltages in the end connections due to leakage flux are the same for every element of the conductor.

1. The first assumption can be shown to be exactly true in the hypothetical case of an infinitely long rectangular conductor placed in an infinitely deep rectangular slot of the same width which is cut into an infinite medium of infinite permeability.

2. The second assumption is probably sufficiently accurate, except when conductors that carry different currents are placed side by side in the same slot, a condition which we will not consider.

3. The heat conductivity of copper is so high that the temperature of any one conductor is probably nearly uniform, except in the case of extremely deep conductors, and the resistivity would thus not vary appreciably from point to point. In the case of multiple layer coils, however, there may be such a difference in the amount of heat developed in successive layers that it may be desirable to use different resistivities for different layers. In order to carry out this refinement in the calculations, a considerable practical knowledge of the principles of heat radiation

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[2] Both A. B. Field and R. E. Gilman assume these ideal conditions in the derivation of their formulas.

in this problem would be necessary, and the final result would probably be obtained by making successive approximations.

4. The leakage flux about the end connections* is of course much less than that about the embedded portion of the coils, and is distributed in a totally different manner. Any rational consideration of the effect of this flux would lead to considerable complication in the mathematical analysis. Thus for the sake of simplicity—a feeble reason, no doubt—it is not considered. It is probable, however, that in a great many instances this coil-end leakage is of relatively minor importance.

The best test of the value of the mathematical deductions based on the foregoing assumptions lies in experimental research. The little evidence that we now have seems to confirm the theory within reasonable limits of error, and it is hoped that a more extended investigation, which is being carried on, will prove conclusive.

To the author, it seems nearer the physical reality to say that the increased heat loss in a conductor carrying alternating rather than direct current is caused by a redistribution of current over the cross-section of the conductor.[3] This redistribution is due to the electromotive forces set up by the magnetic flux *within* the conductor itself. Flux that is wholly without the conductor links all elements of it equally, produces the same voltage in each element, and thus does not affect the current distribution.

Consider any conductor lying in the midst of others, as shown in cross-section in Fig. A. Further, consider any element of this conductor of depth $d\,x$ situated x centimeters from the bottom of the conductor. With a solid conductor the length of this element should be taken only as the length of the armature core. The allowance that need be made for ventilating ducts, and more particularly for end turns, can only be

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* Within the conductor

[3] Others prefer to say that the increased heating is due to the eddy currents produced by the magnetic flux within the conductor. Either description is permissible.

determined by considerable experimental research. With finely laminated conductors, the current density is constrained to be the same in, at least, the length of a half turn, and the length of the element is then that of a half turn.

The net voltage acting on the element is the sum of the resistance drop and the voltage drop due to flux linkages. The former is $l_1 \rho c$; where l_1 is the length of the core with solid conductors, or a half turn with finely laminated ones, ρ is the resistivity and c is the current density—all in c. g. s. units. The voltage drop due to flux linkages may be divided into two parts; that due to flux set up by the current in the conductor itself, and that due to flux set up by current in other conductors in the slot *below* the one we are considering. Any current above this conductor produces flux that links all elements of it *alike,* and induces the *same* voltage in each. The manner in which a *given* current is distributed in any conductor below the one in question does not affect the amount of flux linking the element considered. Furthermore any flux due to these latter currents that passes across the slot above the conductor we are considering links all of its elements alike, and, since it produces the same voltage in each, need not be considered. Thus the total flux linking the element in question that need be taken into account is:

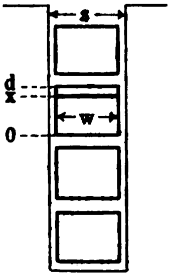

FIG. A

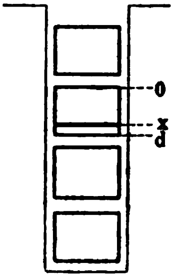

FIG. B

$$\varphi = 4\,\pi\,i_b\,\frac{d-x}{s}\,l_2 + \int_x^d \left\{ 4\,\pi \int_0^x w\,c\,\partial x \right\} \frac{l_2\,\partial x}{s}$$

The first term is the flux, linking the element due to a total current of i_b below the conductor of which the element is a part. The second term is the flux from x to d due to the current within the conductor itself from zero to x. l_2 is the length of the armature core, s is the width of the slot, and w that of the conductor.

The total voltage drop that need be considered is:

$$e = l_1 \rho c + \frac{\partial}{\partial t} \left\{ 4 \pi i_b \frac{d-x}{s} l_2 + \int_x^d \left\{ 4 \pi \int_0^x w c \, \partial x \right\} \frac{l_2 \, \partial x}{s} \right\} \qquad \text{(A)}$$

In a solid conductor this voltage drop is the same for every element, and $\frac{\partial e}{\partial x}$ will thus be zero. Also l_1 and l_2 are equal. Differentiating e and dividing by l_2 gives:

$$\rho \frac{\partial c}{\partial x} - \frac{4 \pi}{s} \frac{\partial i_b}{\partial t} - \frac{4 \pi}{s} \int_0^x w \frac{\partial c}{\partial t} \, \partial x = 0 \qquad \text{(B)}$$

With finely laminated conductors whose laminations are joined at the beginning and end of each half turn, the same result is obtained except that l_1 and l_2 are not equal. Then:

$$\frac{l_1}{l_2} \rho \frac{\partial c}{\partial x} - \frac{4 \pi}{s} \frac{\partial i_b}{\partial t} - \frac{4 \pi}{s} \int_0^x w \frac{\partial c}{\partial t} \, \partial x = 0$$

With finely laminated conductors whose end turns are untwisted and in which the laminations are continuous throughout a whole turn or a whole coil, the voltage in a half turn of any element is as given above. (Equation A). The sum of these half-turn voltages between the points at which the laminations are joined together must be the same for each lamination. This sum will consist of a number, n, of resistance drops, and an equal number of voltage drops due to flux linkages. The resultant drop is

$$e_1 = n l_1 \rho c + \frac{\partial}{\partial t} \sum_1^n 4 \pi i_b \frac{d-x}{s} l_2 + n \frac{\partial}{\partial t} \int_x^d \left\{ 4 \pi \int_0^x w c \, \partial x \right\} \frac{l_2 \, d x}{s} = 0$$

The current i_b, below the conductor of which the half-turn element is a part, is not the same for the different half-turn elements. Nevertheless, it is a simple matter to compute the average value of this quantity, *viz.*, $1/n \sum_{1}^{n} i_b$ for any arrangement of conductors. It is, of course, not necessary that the component i_b's should be in phase with each other. This computation is subsequently shown in detail. We will represent this average value of i_b by i_0. If the entire voltage for this element be divided by $n\, l_2$ and then differentiated with respect to x, we have:

$$\frac{l_1}{l_2}\,\rho\,\frac{\partial c}{\partial x} - \frac{4\,\pi}{s}\,\frac{\partial i_0}{\partial t} - \frac{4\,\pi}{s}\int_0^x w\,\frac{\partial c}{\partial t}\,\partial x = 0$$

In the case of finely laminated conductors that are twisted in the end connections so that the top lamination of one half turn becomes the bottom lamination of the next half turn, a similar equation may be derived. When the end turn is twisted in passing from one coil side to the next, the flux within the conductor linking the half-turn element of one side has already been given. (Equation A). The flux linking the next half turn of this element is, (Fig. B):

$$\rho = 4\,\pi\,i_b\,\frac{x\,l_2}{s} + \int_0^x \left\{ 4\,\pi \int_x^d w\,c\,\partial x \right\} \frac{l_2\,\partial x}{s}$$

The first term is the flux from zero to x due to a current of i_b below this conductor. The second term is the flux from zero to x due to current from x to d within the conductor itself. The second term may be re-written in this way:

$$\int_0^x 4\,\pi \left\{ \int_0^d w\,c\,\partial x - \int_0^x w\,c\,\partial x \right\} \frac{l_2\,\partial x}{s}$$

The voltage drop in this half-turn element becomes:

$$e = l_1\,\rho\,c + \frac{\partial}{\partial t}\left\{ 4\,\pi\,i_b\,\frac{x\,l_2}{s} \right.$$

$$+ \int_0^x 4\,\pi \int_0^d w\,c\,\partial x \,.\, \frac{l_2\partial x}{s}$$

$$- \int_0^x 4\,\pi \int_0^x w\,c\,\partial x \,.\, \frac{l_2\,\partial x}{s}$$

$\int_0^d w\, c\, \partial x$ is the entire current in the conductor of which the element is a part. Represent this current by i. Differentiate e with respect to x and divide by l_2. We have:

$$\frac{l_1}{l_2}\rho c + \frac{4\pi}{s}\ \frac{\partial i_b}{\partial t} + \frac{4\pi}{s}\ \frac{\partial i}{\partial t} - \frac{4\pi}{s}\int_0^x w \frac{\partial c}{\partial t}\,\partial x = 0 \qquad \text{(C)}$$

Thus in every case that we shall discuss, the following equation may be written:

$$\rho\frac{\partial c}{\partial x} - \frac{\partial}{\partial t}\ \frac{4\pi i_0}{s} - \frac{\partial}{\partial t}\ \frac{4\pi}{s}\int_0^x w\, c\, \partial x = 0$$ [4]

ρ is the resistivity in the case of solid conductors, and is the resistivity multiplied by the ratio of the length of a half turn to the length of the core in the case of infinitely laminated conductors. c is the instantaneous current density in amperes per square centimeter along a line x centimeters from the bottom of the conductor. s is the width of the slot and w, that of the conductor. The first term is the differential of the resistance drop per centimeter in any element. The second term is the differential of the voltage per centimeter due to the flux produced by other currents in the same slot. As we shall see, i_0 is determined by the arrangement of the conductors and the currents they carry. The third term is the differential of the voltage per centimeter due to the flux produced by current within the conductor itself below the element considered. If the currents vary sinusoidally with

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[4] An equation of this sort applies only to the conductor in which the current density is a continuous function with respect to x, such as is the case with solid or finely laminated conductors. When the laminations have appreciable depth the current density changes abruptly as we pass from one lamination to the next. The effect of this is that the vector constant i_0 is different in successive laminations. A comparison of equations (B) and (C) shows that twisting the end connections reverses the effect of the current, i_b, below the conductor we are considering.

the time, the differential operator $\frac{\partial}{\partial t}$ may be symbolically represented by $j\,\omega$; $j = \sqrt{-1}$, $\omega = 2\,\pi\,f$ where f = frequency.

The equation may now be written in the complex or vector form:

$$\frac{\partial\,\underset{\cdot}{c}}{\partial\,x} - j\,\frac{4\,\pi\,\omega}{\rho\,s}\,I_0 - j\,\frac{4\,\pi\,\omega}{\rho\,s}\int_0^x w\,\underset{\cdot}{c}\,\partial\,x = 0 \tag{1}$$

Differentiating a second time gives:

$$\frac{\partial^2\,\underset{\cdot}{c}}{\partial\,x^2} = j\,\frac{4\,\pi\,\omega}{\rho\,s}\,w\,\underset{\cdot}{c}$$

or:

$$\frac{\partial^2\,\underset{\cdot}{c}}{\partial\,x^2} = \alpha^2\,\underset{\cdot}{c} \tag{2}$$

$$\left.\begin{aligned} &\text{where} && \alpha^2 = j\,\frac{8\,\pi^2\,w\,f}{\rho\,s} \\ &\text{or} && \alpha = \sqrt{\frac{8\,\pi^2\,w\,f}{\rho\,s}}\ \underline{/45^\circ} \end{aligned}\right\}$$

The solution of equation (2) may be written in the form

$$\underset{\cdot}{c} = \underset{\cdot}{A}\cosh\alpha\,x + \underset{\cdot}{B}\sinh\alpha\,x \tag{3}$$

This is a vector equation for the root-mean-square current density at a point x centimeters from the bottom of the conductor. The constants of integration $\underset{\cdot}{A}$ and $\underset{\cdot}{B}$ are vector quantities and are usually determined by the current in the conductor considered and by the vector I_0 in equation (1). Substitution of equation (3) in equation (1) shows that:

$$\underset{\cdot}{B} = \alpha/w\,I_0$$

If the depth of the conductor is d centimeters, the current in it is

$$I_1 = \int_0^d w\,\underset{\cdot}{c}\,\partial\,x$$

from which it follows that:

$$\underset{\cdot}{A} = \frac{\alpha}{w}\left\{\frac{I_1}{\sinh\alpha\,d} - I_0\tanh\frac{\alpha\,d}{2}\right\}$$

Therefore, the general solution for the vector current density may be written:

$$\begin{aligned}\underset{\cdot}{c} = \frac{1}{w\,d} \Bigg\{ & \frac{I_1\,\alpha\,d \cosh \alpha\,x}{\sinh \alpha\,d} \\ & - I_0\,\alpha\,d \tanh \frac{\alpha\,d}{2} \cosh \alpha\,x + I_0\,\alpha\,d \sinh \alpha\,x \Bigg\} \qquad (4)\end{aligned}$$

A numerical calculation is helpful. Consider the case of two solid rectangular conductors situated as shown in Fig. 1. The 60-cycle currents are each 1000 amperes but the lower current leads the upper by 60 degrees as would be the case in some of the slots of a three-phase fractional pitch winding. As we shall presently see $I_0 = I_2$ in this case.

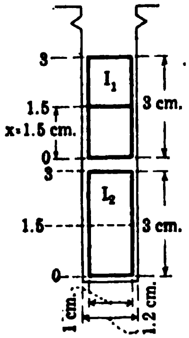

Fig. 1

$$\rho = 2100 \text{ c. g. s. units of resistance}$$
$$w = 1 \text{ cm.}$$
$$s = 1.2 \text{ cm.}$$
$$d = 3 \text{ cm.}$$
$$f = 60 \text{ cycles}$$

$$\alpha\,d = 3 \sqrt{\frac{8\,\pi^2 \times 1 \times 60}{2100 \times 1.2}} \;\underline{/45^\circ}$$
$$= 4.11 \,\underline{/45^\circ}$$
$$\alpha\,x = 2.06 \,\underline{/45^\circ}$$
$$\sinh \alpha\,d = 9.12 \,\underline{/166.^\circ 4}$$
$$\tanh \frac{\alpha\,d}{2} = 1.11 \,\underline{/1^\circ.41}$$

$$\sinh \alpha x = 2.24 \underline{/84.^\circ 1}$$
$$\cosh \alpha x = 2.03 \underline{/82.^\circ 7}$$

If we choose I_1 along the horizontal, *i. e.*, with zero phase:

$$I_1 = 1000 /0^\circ \ , I_0 = 1000 \underline{/60^\circ}$$

$$\underset{\cdot}{c}_{1.5} = \frac{1}{1 \times 3} \Big\{ (1000 \underline{/0^\circ} \times 4.11 \underline{/45^\circ} \times 2.03 \underline{/82.^\circ 4} + 9.12 \underline{/166.^\circ 4}) - (1000 \underline{/60^\circ} \times 4.11 \underline{/45^\circ} \times 1.11 \underline{/1.^\circ 41} \times 2.03 \underline{/82.^\circ 7}) + (1000 \underline{/60^\circ} \times 4.11 \underline{/45^\circ} \times 2.24 \underline{/84.^\circ 1}) \Big\} = \frac{1}{1 \times 3} \Big\{ 915 \underline{/-39.^\circ 0} - 923 \underline{/189.^\circ 1} + 923 \underline{/189.^\circ 1} \Big\}$$

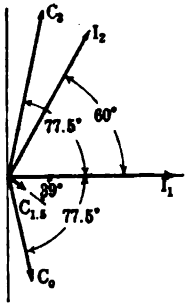

Fig. 2—Current Densities in Upper Conductor

Referred to I_1 the current densities are:

$$\underset{\cdot}{C}_0 = 1620 \underline{/-77.^\circ 5} \ \frac{\text{amperes}}{\text{sq. cm.}}$$
$$\underset{\cdot}{C}_{1.5} = 305 \underline{/-39.^\circ} \ \frac{\text{amperes}}{\text{sq. cm.}}$$
$$\underset{\cdot}{C}_3 = 2490 \underline{/77.^\circ 5} \ \frac{\text{amperes}}{\text{sq. cm.}}$$

$$\underset{\cdot}{c}_{1.5} = 305 \underline{/-39.^\circ 0}$$
$$\underset{\cdot}{c}_0 = 1620 \underline{/-77.^\circ 5}$$
$$\underset{\cdot}{c}_3 = 2490 \underline{/77.^\circ 5}$$

Fig. 2 is the vector diagram showing the current densities at the bottom, middle and top of the conductor, together with the total current in it, I_1, and the current below it, I_2.

The current density at the center, where αx equals $\frac{\alpha d}{2}$, is:

$$\underset{\cdot}{c} = \frac{I_1}{w\,d} \; \frac{\frac{\alpha d}{2}}{\sinh \frac{\alpha d}{2}}$$

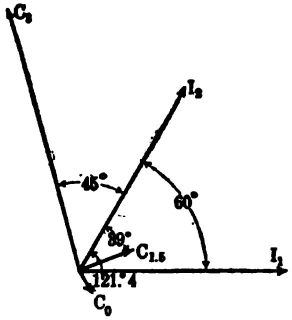

FIG. 2A—CURRENT DENSITIES IN LOWER CONDUCTOR

Referred to I_2 the current densities are:

$\underset{\cdot}{C}_0 = 150 \; \underline{/-121.^\circ 4} \; \frac{\text{amperes}}{\text{sq. cm.}} \; \underline{/\quad\quad}$

$\underset{\cdot}{C}_{1.5} = 305 \; /-39^\circ \; \frac{\text{amperes}}{\text{sq. cm.}} \; \underline{/\quad\quad}$

$\underset{\cdot}{C}_3 = 1380 \; \underline{/45^\circ} \; \frac{\text{amperes}}{\text{sq. cm.}} \; \underline{/\quad\quad}$

It depends only upon the average current density and the angular depth, αd, and is in no way affected by the position of the conductor in the slot. It is the same for solid and finely laminated conductors.

The current density is nowhere greater than at the top of the conductor, where it is:

$$\underset{\cdot}{c}_d = \frac{1}{w\,d} \left\{ I_1\, \alpha\, d \coth \alpha\, d + \frac{I_0}{2}\, \alpha\, d\, 2 \tanh \frac{\alpha d}{2} \right\} \tag{5}$$

The ratio of this maximum current density to the average is:

$$\frac{\varsigma_d}{\varsigma_{av}} = \alpha\, d \coth \alpha\, d + \frac{I_0}{2\, I_1}\, \alpha\, d\, 2 \tanh \frac{\alpha\, d}{2} \qquad (6)$$

The complex quantities $\alpha\, d \coth \alpha\, d$ and $\alpha\, d\, 2 \tanh \frac{\alpha\, d}{2}$ occur in all of the expressions which we shall develop, and thus it will be simpler to represent them by single letters. Hereafter

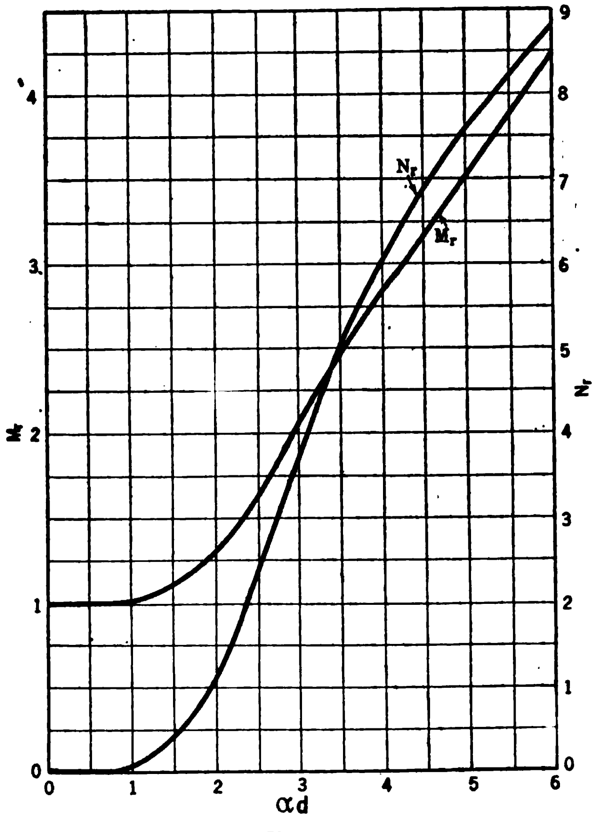

FIG. 3

$$\alpha\, d \coth \alpha\, d = M = M_r + j\, M_x$$

$$\alpha\, d\, 2 \tanh \frac{\alpha\, d}{2} = N = N_r + j\, N_x$$

In Figs. 3 and 4 the abscissas are the numerical values of αd and the ordinates are M_r, M_x, N_r, N_x. The real portions of M and N, *viz.*, M_r and N_r, appear in the expressions for resistance, and the imaginary portions, M_x and N_x, in the expressions for reactance.

The voltage drop per centimeter in the conductor considered due to its own resistance and to all of the leakage flux below its topmost layer is:

$$\rho\, ç_d = \frac{\rho}{w\, d} \left\{ I_1 M + \frac{I_0}{2} N \right\} \quad , \quad (7)$$

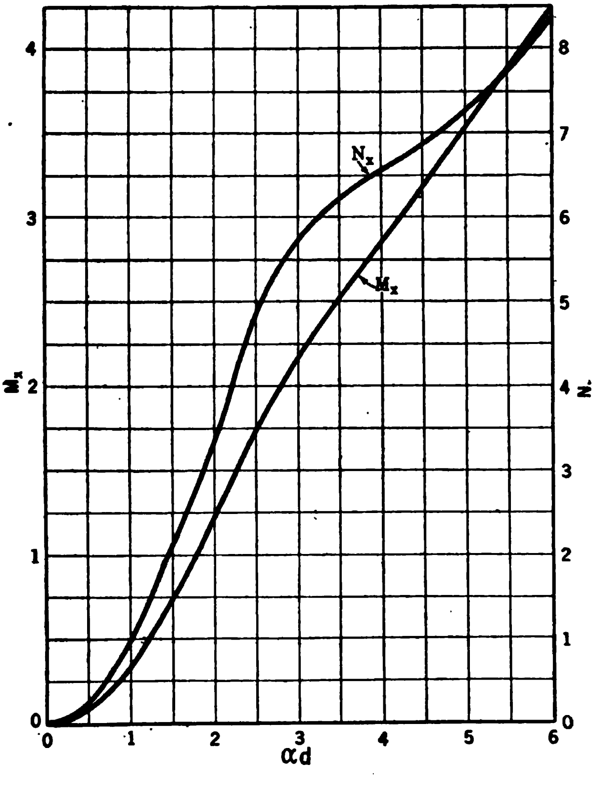

Fig. 4

The flux within the conductor due to its own current and all of the current, I_b, below it is:

$$\varphi = \int_0^d \partial x \frac{4\pi}{s} \int_0^x w\, ç\, \partial x + \frac{4\pi d}{s} I_b$$

On integration the expression for the flux may be written:

$$\varphi = \frac{1}{j\,\omega}\,\frac{\rho}{w\,d}\left\{\left(\frac{I_1}{2} + I_0\right)N \right.$$
$$\left. + (I_b - I_0)\,\alpha^2 d^2\right\}$$

The voltage drop per centimeter produced by this flux in each conductor below the one considered is $j\,\omega\,\varphi$, which may now be written:

$$E = \frac{\rho}{w\,d}\left\{\left(\frac{I_1}{2} + I_0\right)N \right.$$
$$\left. + (I_b - I_0)\,\alpha^2 d^2\right\} \qquad (8)$$

The relations expressed in equations (7) and (8) are very important since their proper combination will give the leakage impedance drop due to resistance and leakage flux within the conductors themselves for any arrangement of solid or infinitely laminated conductors. The reactance due to slot-leakage flux which does not pass through the conductors can be calculated by well-known methods and need not be considered here.

If the equations (7) and (8) are each multiplied by the length of the core, l, they will apply to the embedded portion of a solid conductor, the true resistance of which is R, and to the half turn of an infinitely laminated one, the true resistance of which is also R. Thus (7) and (8) may be written:

$$l\,\rho\,\underset{\cdot}{c}_d = R\left\{I_1 M + \frac{I_0}{2}N\right\} \qquad (7a)$$

$$l\,E = R\left\{\left(\frac{I_1}{2} + I_0\right)N \right.$$
$$\left. + (I_b - I_0)\,\alpha^2 d^2\right\} \qquad (8a)$$

The *additional* voltage produced in all conductors below the one in question by flux within it due to its own current is

$$lE' = R\left\{\left(\frac{I_1}{2} + I_0\right)N - I_0\,\alpha^2 d^2\right\} \cdot \qquad \textbf{(8b)}$$

Having found the vector impedance drop in the conductors of one phase by properly applying equations (7a) and (8a), the effective resistance and reactance of that phase are determined by dividing this drop by the vector current. The real portion of the result is the effective resistance and the imaginary portion, the effective reactance. This method, however, gives no indication of the distribution of the copper loss among the several conductors of the phase. This may be of considerable importance, especially in the case of solid conductors when the heat developed in the topmost conductor in a slot may be several times that developed in the bottom conductor.

The current through a conductor is non-uniformly distributed on account of flux *within* the conductor. This flux is due only to the current in the conductor itself and to current below it in the slot. Any current above the conductor in question has no effect on the current distribution within it. The heat generated within a conductor depends only upon the manner in which the current is distributed. The current density is completely determined by equation (1) and the total current in the conductor itself. For any particular value of I_0 (equation 1) the heat developed by a given current in the conductor does not depend upon whether I_0 is some particular current or some combination of currents. Thus if it is possible to find the heat loss when I_0 is some particular current, we will have obtained a general expression for the loss in terms of the current in the conductor, I_1, and the constant, I_0, in equation (1). The particular case which we will consider is that of a solid conductor carrying a current of I_1 with a total current of I_b below it. The special form of equation (1) is then,

$$\frac{\partial \underset{\cdot}{c}}{\partial x} - j\,\frac{4\pi\omega}{\rho s}\,I_b - j\,\frac{4\pi\omega}{\rho s}\int_0^x w\,\underset{\cdot}{c}\,\partial x = 0 \qquad \textbf{(1a)}$$

Thus for this arrangement, $I_0 = I_b$.

The heat loss in the conductor is equal to the total power supplied both to this conductor and to all of those below it less the power supplied to those below it when the conductor is removed from the slot. The addition of the conductor in question increases the power supplied to the lower conductors without increasing the heat loss in them on account of its mutual inductive effect upon them *i. e.*, as some would say, on account of the eddy currents which are produced in it by the total current I_b, below it. The power supplied to the upper conductor is, symbolically, since $I_0 = I_b$

$$I_1 R \left\{ I_1 M + \frac{I_b}{2} N \right\} \qquad \text{(See 7a)}$$

This indicates the product of the numerical values of the current, I_1, the voltage applied to the conductor and the cosine of the phase angle between them. Flux above the conductor produces a quadrature voltage and thus does not affect the power. The *additional* power supplied to the conductors below this one is symbolically

$$I_b R \left\{ \left(\frac{I_1}{2} + I_b \right) N - I_b \alpha^2 d^2 \right\} \qquad \text{(See 8b)}$$

The actual heat loss in the conductor is thus symbolically:

$$I_1 R \left\{ I_1 M + \frac{I_b}{2} N \right\} + I_b R \left\{ \left(\frac{I_1}{2} + I_b \right) N - I_b \alpha^2 d^2 \right\}$$

This reduces to:

$$R \{ I_1^2 M_r + (I_b^2 + I_1 I_b \cos \delta) N_r \}^5 \qquad \text{(9a)}$$

where I_1 and I_b are the numerical values of the currents and δ is the phase angle between them. Therefore the general expression for the heat loss in any conductor, solid or infinitely laminated, is:

$$R \{ I_1 M_r + (I_0^2 + I_1 I_0 \cos \delta) N_r \} \qquad \text{(9)}$$

where I_1 is the numerical value of the current in the

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5. M_r and N_r are calculated from the data pertaining to the conductor in question and bear no relation to other conductors.

conductor, I_0 is the numerical value of the vector constant in the differential equation (1), and δ is the phase angle between I_1 and I_0. The ratio of alternating-current to direct-current resistance is thus:

$$K = M_r + \left(\left| \frac{I_0}{I_1} \right|^2 + \left| \frac{I_0}{I_1} \right| \cos \delta \right) N_r \qquad (10)$$

The vertical lines | | indicate that the division is one of numerical values and not of vector values. The first term M_r accounts for the natural non-uniformity of current distribution due to the action of the current upon itself. The second term

$$\left(\left| \frac{I_0}{I_1} \right|^2 + \left| \frac{I_0}{I_1} \right| \cos \delta \right) N_r,$$

accounts for the additional heating produced by the "eddy currents" due to the action of I_0.

This equation (10) enables us to compute the ratio of alternating-current to direct-current resistance for any conductor carrying a specified current and for which a differential equation of the form given equation (1) can be written. In the case of solid conductors, the ratio only applies to the embedded portion. The following are the resistance ratios for some of the simpler arrangements of conductors.

1. The heat loss in an open-circuited bar with I_b amperes below it is:

$$\text{heat loss} = R\, I_b^2\, N_r \qquad (\text{equation } \mathbf{9a},\ I_1 = 0)$$

2. The resistance ratio for the pth conductor of a one-coil-side-per-slot bar winding is:

$$\begin{aligned} K &= M_r + [\,(p-1)^2 + (p-1)]\, N_r \\ &= M_r + (p^2 - p)\, N_r \end{aligned}$$

3. The resistance ratio for a one-coil-side-per-slot winding having n layers is:

$$\begin{aligned} K &= 1/n \sum_1^n \ [M_r + (p^2 - p)\, N_r] \\ &= M_r + \frac{n^2 - 1}{3}\, N_r \end{aligned}$$

This is also the ratio for the lower coil side of any bar winding having n layers. The upper coil side has no effect on the resistance of the lower coil side.

4. The resistance ratio for the upper coil side of a

two-coil-side-per-slot fractional pitch winding having n layers per coil side reduces to:

$$K = M_r + \left(\frac{4\,n^2 - 1}{3} + n^2 \cos\theta \right) N_r$$

θ is the phase angle between the currents in the upper and lower coil sides.

By combining this with the ratio just preceding, we obtain the resistance ratio for a coil, one side of which is above a coil side carrying a current which differs in phase by θ.

The hottest conductor is the one at the top of the coil side which has beneath it current of the same phase. The fact that, with solid bar windings, the heat developed is not uniformly distributed throughout the winding may be no inconsiderable argument against their use.

5. Our method of attack enables us to obtain a simple solution for the relation between the currents in a double squirrel-cage winding. Neglect the effect of the end rings. In this case the constant of integration, A, in equation (3) is determined by the fact that the resistance drop in the lowest element of the upper bar is the same as the impedance drop in the lower bar due to its resistance and to all of the leakage flux which does not link any portion of the upper bar. The vector equation for the current density in the upper bar may be written:

$$\underset{\cdot}{c} = \frac{I_2 \underset{\cdot}{Z}_2}{\rho} \cosh \alpha x + \frac{I_2 R_1}{\rho}\, \alpha\, d \sinh \alpha x$$

$I_2 \underset{\cdot}{Z}_2$ is the vector impedance drop in the lower bar per centimeter;[6] ρ and R_1 are respectively the resistivity and the true resistance per centimeter of the upper bar whose depth is d centimeters. α is calculated for the upper bar.

The vector current in the upper bar is:

$$I_1 = \frac{I_2 \underset{\cdot}{Z}_2}{R_1} \; \frac{\sinh \alpha d}{\alpha d} + I_2 \cosh \alpha d - I_2$$

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6. $I_2 Z_2$ is the voltage drop due to resistance and flux that does not link the upper bar.

The process of calculating the heat loss in the upper bar by substitution in equation (**9a**) is much simplified if we let

$$P = \frac{m\, \underset{.}{Z}_2}{R_1} \cos(\theta_2 + \beta) + n \cos \delta$$

and

$$Q = \frac{m\, \underset{.}{Z}_2}{R_1} \sin(\theta_2 + \beta) + n \sin \delta$$

where:

$$\underset{.}{Z}_2 = Z_2 \,/\underline{\theta_2}\,; \quad \frac{\sinh \alpha d\text{[7]}}{\alpha d} = m \,/\underline{\beta}\,;$$

$$\cosh \alpha d = n \,/\delta$$

The expression for the loss in the upper bar is:

$$I_2^2 R_1 \{ [(P-1)^2 + Q^2] M_r + P N_r \}$$

This method of solution for the relation between the currents in a double squirrel cage should prove of considerable value in any analysis of the design of such windings.

Finely laminated windings may be of three types: Those in which the laminations are joined at the ends of each half turn; those in which they are joined at the ends of each turn; and those in which the laminations are continuous throughout a single coil. The first is like a solid bar winding except that, as noted previously, the real resistivity of the copper should be multiplied by the ratio of the length of the half turn to the length of the core. The resistance ratio then applies to the whole winding and not to the embedded portion solely. The resistance ratios for the second type depend upon whether the end turn between the coil sides is untwisted or twisted. The resistance ratio for the third type depends upon whether the end turns are untwisted, twisted on one side only, or twisted on both sides. One considerable advantage of continuous laminations is that the heat developed is the same in all of the conductors.

6. Type two: End turn untwisted. The arrangement of the coil sides is shown in Fig. 5. The heavy

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[7] See Table IV, Tables of Complex Hyperbolic and Circular Functions.

line across the conductors indicates the same lamination. The current, I_2, below the upper coil side may be in phase with the current above it or differ from it by 60 or 90 degrees. The differential equation of the form (1) applying to this case for the pth layer from the bottom is:

$$2\,\rho\,\frac{\partial \underset{\cdot}{c}}{\partial x} - j\,\frac{4\,\pi\,\omega}{s}\left\{\,2\,(p-1)\,I_1 + I_2\,\right\}$$

$$- j\,\frac{4\,\pi\,\omega}{s}\;2\int_0^x w\,\underset{\cdot}{c}\,\partial x = 0$$

Comparing this equation (1) shows that the vector constant I_0 equals $(p-1)\,I_1 + \dfrac{I_2}{2}$; $I_2 = n\,I_1/\theta$,

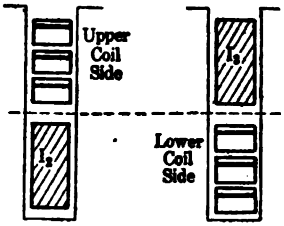

FIG. 5

n is the number of layers in the coil side and θ the phase angle between the currents in the upper and lower coil sides.

Making this substitution, equation (9) reduces to:

$$\text{Heat loss} = R\,I_1^2\,\{\,M_r + [p^2 - p + n\,(p - 1/2)\cos\theta + n^2/4]\,N_r\,\}$$

The resistance ratio for the entire coil is one-nth of the summation of this expression from $p = 1$ to $p = n$. It reduces to:

$$K = M_r + \left(\frac{7\,n^2 - 4}{12} + \frac{n^2}{2}\cos\theta\right)N_r$$

7. Type three: End turns untwisted. In this case the heat developed is the same in each conductor. The differential equation now becomes:

$$2\,n\,\rho\,\frac{\partial \underset{\cdot}{c}}{\partial x} - j\,\frac{4\,\pi\,\omega}{s}\sum_{1}^{n}\{2\,(p-1)\,I_1 + I_2\,\}$$

$$-j\,\frac{4\,\pi\,\omega}{s}\;2\,n\int_0^x w\,\underset{\cdot}{c}\,\partial\,x = 0$$

In this case $I_0 = \frac{n-1}{2}\,I_1 + \frac{I_2}{2}$. Making this substitution in equation (**10**) gives the resistance ratio for the whole coil.

$$K = M_r + \left(\frac{2\,n^2-1}{4} + \frac{n^2}{2}\cos\theta\right)N_r$$

8. Type two: End turns twisted. When the end turns are twisted on one side only the top laminations in one coil side become the bottom laminations of the other coil side in corresponding layers. See Fig. 6. The lines across the layers trace the positions of one continuous lamination—type three. In type two, however, the laminations are joined at the beginning and end of each turn. The differential equation which applies to the pth layer is:

$$\begin{aligned}&2\,\rho\,\frac{\partial\,\underset{\cdot}{c}}{\partial\,x} - j\,\frac{4\,\pi\,\omega}{s}\,I_2\\ &\qquad + \frac{\partial}{\partial\,x}\,j\,\frac{4\,\pi\,\omega}{s}\,\{\,(p-1)\,I_1\,(d-x)\\ &\quad + (p-1)\,I_1\,x\,\} - j\,\frac{4\,\pi\,\omega}{s}\left\{\int_0^x w\,\underset{\cdot}{c}\,\partial\,x\right.\\ &\qquad\qquad\left. + \int_d^x w\,\underset{\cdot}{c}\,\partial\,x\right\} = 0 \qquad (\mathbf{11})\end{aligned}$$

This readily reduces to:

$$\begin{aligned}&\frac{\partial\,\underset{\cdot}{c}}{\partial\,x} - j\,\frac{4\,\pi\,\omega}{s\,\rho}\left(\frac{I_2}{2} - \frac{I_1}{2}\right)\\ &\qquad - j\,\frac{4\,\pi\,\omega}{s\,\rho}\int_0^x w\,\underset{\cdot}{c}\,\partial\,x = 0\end{aligned}$$

Notice that the mutual effect of the layers upon each other is eliminated, by twisting the end connection (third term (11)). The resistance ratio is thus the same for each turn. It is independent of the current in the lower coil side, but it does depend upon the number of layers in the coil side.

$$K = M_r + \frac{n^2 - 1}{4} N_r$$

9. Type three: End connections twisted on one side only. The differential equation of the form (1) is:

$$\begin{aligned}
&2 n \rho \frac{\partial \underset{\cdot}{c}}{\partial x} \\
&+ \frac{\partial}{\partial x} j \frac{4 \pi \omega}{s} I_2 \left\{ (d - x) + x + (d - x) + \cdots\cdots \right. \\
&+ \frac{\partial}{\partial x} j \frac{4 \pi \omega}{s} I_1 \left\{ \begin{array}{l} (d - x) + 2x + 3(d - x) + \cdots\cdots \\ + x + 2(d - x) + 3x + \cdots\cdots \end{array} \right\} \\
&- j \frac{4 \pi \omega}{s} \left\{ n \int_0^x w \underset{\cdot}{c} \, \partial x + n \int_d^x w \underset{\cdot}{c} \, \partial x \right\}
\end{aligned}$$

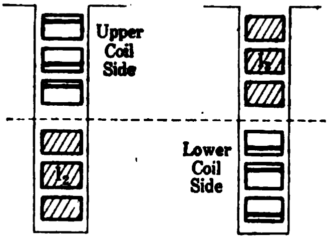

FIG. 6

The third term of this equation is always zero, but the second term may or may not be. It is thus apparent that there are two cases to be considered, *viz.*, when the number of layers is even and when it is odd. If n is even the second term is zero and the equation reduces to:

$$\frac{\partial \underset{\cdot}{c}}{\partial x} - j \frac{4 \pi \omega}{s \rho} \left(- \frac{I_1}{2} \right) - j \frac{4 \pi \omega}{s \rho} \int_0^x w \underset{\cdot}{c} \, \partial x = 0$$

Notice that this equation is independent of the number of layers and the current in the lower coil side. This arrangement of an even number of continuously laminated layers whose end turns are twisted on one side only gives the smallest resistance ratio of any of the cases considered.

$$K = M_r - 1/4\, N_r$$

From the forms of M_r and N_r this is readily shown to be the M_r for a conductor one-half as deep. This same condition of current distribution is obtained by having an even number of laminated conductors side by side in the slots if the end connections are twisted on one side only. The resistance ratio is then independent of the number of layers in the coil. If n is odd, the differential equation reduces to:

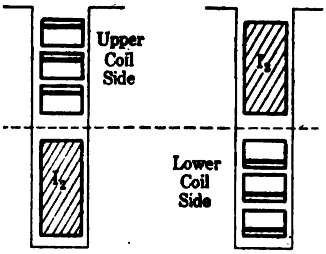

FIG. 7

$$\frac{\partial \text{ç}}{\partial x} - j\,\frac{4\pi\omega}{s\rho}\left\{\frac{I_2}{2n} - \frac{I_1}{2}\right\} - j\,\frac{4\pi\omega}{s\rho}\int_0^x w\,\text{ç}\,\partial x = 0$$

The resistance ratio is now:

$$K = M_r$$

This ratio is the same as in the case of a *single* solid conductor of the *same* depth, whereas if there are an even number of layers the ratio is the same as for a single solid conductor of one-half the depth of the laminated one.

10. Type three: End connections twisted on both sides (See Fig. 7). The differential equation of the form (1) is:

$$2n\rho\,\frac{\partial \text{ç}}{\partial x}$$

$$+ \frac{\partial}{\partial x} j \frac{4\pi\omega}{s} I_2 (d-x)\, n$$

$$+ \frac{\partial}{\partial x} j \frac{4\pi\omega}{s} I_1 \left\{ \begin{array}{r} (d-x) + 2x + 3(d-x) \\ + \ldots\ldots\ldots \\ + x + 2(d-x) + 3x \\ + \ldots\ldots\ldots \end{array} \right\}$$

$$- j \frac{4\pi\omega}{s} \left\{ n \int_0^x w\, \underset{\cdot}{c}\, \partial x + n \int_d^x w\, \underset{\cdot}{c}\, \partial x \right\} = 0$$

This reduces to:

$$\frac{\partial \underset{\cdot}{c}}{\partial x} - j \frac{4\pi\omega}{s\rho} \left(\frac{I_2}{2} - \frac{I_1}{2} \right)$$

$$- j \frac{4\pi\omega}{s\rho} \int_0^x w\, \underset{\cdot}{c}\, \partial x = 0$$

The resistance ratio is:

$$K = M_r + \frac{n^2 - 1}{4} N_r$$

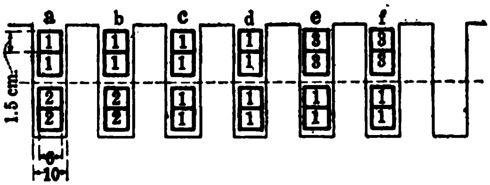

Fig. 8

It is independent of the current in the lower coil side. Notice that this is the same ratio as was obtained for case 8.

Enough illustrations of the method and the simplicity of its application have been given. There follows a numerical calculation of the resistance ratios for a given arrangement of conductors of various types. The winding data are: Three-phase with four slots per pole per phase; coil pitch of 10 slots; two turns per coil; conductors 1.5 cm. deep; length of embedded portion and of end turns the same; frequency 60 cycles, the ratio of width of copper to width of slot, 0.6; resistivity, 2100 c. g. s. units.

For solid conductors:

$$\alpha d = 1.5 \sqrt{\frac{8\pi^2 \times 60 \times 0.6}{2100}} \; \underline{/45^\circ}$$

$$= 1.74 \, \underline{/45^\circ}$$

From curve

$$M_r = 1.20$$
$$N_r = 0.73$$

For laminated conductor:

$$\alpha d = 1.5 \sqrt{\frac{8\pi^2 \times 60 \times 0.6}{2 \times 2100}} \; \underline{/45^\circ}$$

$$= 1.23 \, \underline{/45^\circ}$$

From curve

$$M_r = 1.05$$
$$N_r = 0.20$$

The arrangement of the conductors of one phase before one pole is shown in Fig. 8. The resistance ratios for phase one are given in the following table for the various cases considered.

TABLE I

SOLID CONDUCTORS	RATIO
Lower coil sides (slots c, d, e & f)	1.93*
Upper " " (" a and b)	6.31*
" " " (" c and d)	7.77*
Entire winding including end turns	2.75†
INFINITELY LAMINATED CONDUCTORS, TYPE 1.	
Lower coil sides (slots c, d, e & f)	1.25
Upper " " (" a and b)	2.45
" " " (" c and d)	2.85
Entire winding	1.95
INFINITELY LAMINATED CONDUCTORS, TYPE 2.	
Untwisted (slots c and d)	1.85
" (" a, b, e and f)	1.65
" (entire winding)	1.75
Twisted (entire winding)	1.20
INFINITELY LAMINATED CONDUCTORS, TYPE 3.	
Untwisted (slots c and d)	1.80
" (" a, b, e and f)	1.60
" (entire winding)	1.70
Twisted in one end connection (entire winding)	1.005
Twisted in both end connections (entire winding)	1.20

*Embedded portion.

†The ratio of the heat developed in the top conductor of slots, c or d to that developed in the bottom conductor is as $\frac{9.96}{1.20}$ or as 8.3 to 1.

This may be a very important consideration, even more than the resistance ratio for the entire winding.

Leakage Reactance Volts. As previously stated, the entire leakage impedance due to resistance and slot leakage flux lying wholly within the conductors themselves may be computed by the proper combination of equations (**7a**) and (**8a**). This method offers little or no advantage when calculating the resistance. It has been shown that in the case of solid bar winding I_0 equals I_b, (equation **8a**). Thus it is probable that the expressions for reactance are similar to those for resistance except that M_x and N_x would replace M_r and N_r. Such proves to be the case. In the case of laminated conductors, however, there is an added term in the expressions for reactance. Consider the general case of a three-phase fractional pitch winding, a typical arrangement of which is shown in Fig. 8. There will usually be slots in which both coil sides are in the same phase. There will also be slots in which the top coil side is in phase one, for example, and the lower coil side in phase two, together with an *equal* number of slots in which the lower coil side is in phase *one* and the upper coil side in phase three. In the general polyphase case of p phases there will be slots occurring in pairs in which the currents differ in phase by plus and minus π/p radians. Let us designate these symmetrical pairs as fractional pitch slots and those in which the upper and lower coil sides are in the same phase as full pitch slots. Accordingly there are two fractional pitch and two full pitch slots per pole per phase in the winding illustrated in Fig. 8. Let n be the number of layers per coil side and R the true resistance of the conductors considered.

1. Solid conductors: Full pitch slots. Apply equations (**7a**) and (**8a**), but divide by the phase current, I_1, in order to obtain the impedance directly. With solid conductors the coefficient of $\alpha^2 d^2$ in equation (**8a**) is zero. Let p be the number of any conductor measured from the bottom of the slot. There are $2n$ conductors in both layers in the slot.

The vector expression for the impedance is:

$$Z = \frac{R}{2n} \left\{ \sum_{1}^{2n} \left(M + \frac{p-1}{2} N \right) \right.$$

$$+ \sum_{1}^{2n} (p-1)\,(1/2 + p - 1)\,N \Big\}$$

The first term is the summation of the resistance drops (equation **7a**) divided by the current; the second term is the summation of the reactive drops per ampere produced in each of the $(p-1)$ conductors below the pth conductor (equation **8a**) by the flux within the latter.

This reduces to:

$$Z = R \left\{ M + \frac{4\,n^2 - 1}{3}\,N \right\}$$

The resistance is the real portion of this expression and the reactance the imaginary portion. Thus:

$$r = R \left\{ M_r + \frac{4\,n^2 - 1}{3}\,N_r \right\}$$

$$x = R \left\{ M_x + \frac{4\,n^2 - 1}{3}\,N_x \right\}$$

2. Solid conductors: Fractional pitch slots (taken in pairs as described). The expression for the impedance reduces to

$$\begin{aligned} Z = \frac{R}{2\,n} \Big\{ & \sum_{1}^{n} \left[M + \left(\frac{p-1}{2} + n\,\underline{/\theta} \right) N \right] \\ & + \sum_{1}^{n} \left[M + \frac{p-1}{2}\,N \right] \\ & + \sum_{1}^{n} (p-1) \left[\frac{1}{2} + (p-1) \right. \\ & \qquad \left. + n\,\underline{/\theta} \right] N \\ & + n \sum_{1}^{n} \left[\frac{\underline{/-\theta}}{2} + (p-1)\,\underline{/-\theta} \right. \\ & \qquad \left. + n \right] N \\ & + \sum_{1}^{n} (p-1) \left[\frac{1}{2} + (p-1) \right] N \Big\} \end{aligned}$$

The first two terms are respectively the summations of the resistance drops per ampere (equation **7a**) in the upper and lower coil sides; the third term is the summation of the reactive drops per ampere produced in each of the $(p - 1)$ conductors below the pth conductor of the upper coil side (equation **8a**) by the flux within the latter due to its own current and all of that below it in the slot; the fourth term is the reactive drop (equation **8a**) in the lower coil side due to the flux within the coil side above it which carries a current having a relative phase angle of $\underline{/-\theta}$; the last term is the summation of the reactive drops per ampere produced in each of the $(p - 1)$ conductors below the pth conductor of the lower coil side (equation **8a**) by the flux within the latter.

This reduces to:

$$Z = R \left\{ M + \left(\frac{5n^2 - 2}{6} + \frac{n^2}{2} \cos\theta \right) N \right\}$$

The resistance is:

$$r = R \left\{ M_r + \left(\frac{5n^2 - 2}{6} + \frac{n^2}{2} \cos\theta \right) N_r \right\}$$

The reactance is:

$$x = R \left\{ M_x + \left(\frac{5n^2 - 2}{6} + \frac{n^2}{2} \cos\theta \right) N_x \right\}$$

This expression is general for both fractional and full pitch slots. For the latter θ equals zero.

3. Finely and continuously laminated conductors (type three) with untwisted end connections. Consider the general case of symmetrical pairs of fractional pitch slots in which the currents in the coil sides lying in the same slot differ in phase by plus and minus θ. R is the true resistance of one coil. In this case

$$I_0 = \frac{n-1}{2} I_1 + \frac{I_2}{2} \; ;$$

where I_2 is the current in the lower coil side.

$$Z = \frac{R}{2n}$$

$$\Big\{ 2\sum_{1}^{n}\Big[M + \Big(\frac{n-1}{2\times 2} + \frac{n\,\angle\theta}{2\times 2}\Big)N\Big]$$

$$+ \sum_{1}^{n}(p-1)\Big[\Big(\frac{1}{2} + \frac{n-1}{2} + \frac{n\,\angle\theta}{2}\Big)N$$

$$+ \Big(p - 1 + n\,\angle\theta - \frac{n-1}{2} - \frac{n\,\angle\theta}{2}\Big)\alpha^2 d^2\Big]$$

$$+ n\sum_{1}^{n}\Big[\Big(\frac{\angle-\theta}{2} + \frac{n-1}{2}\,\angle-\theta + \frac{n}{2}\Big)N$$

$$+ \Big((p-1)\,\angle-\theta + n - \frac{n-1}{2}\,\angle-\theta$$

$$- \frac{n}{2}\Big)\alpha^2 d^2\Big]$$

$$+ \sum_{1}^{n}(p-1)\Big[\Big(\frac{1}{2} + \frac{n-1}{2} + \frac{n\,\angle\theta}{2}\Big)N$$

$$+ \Big(p - 1 - \frac{n-1}{2} - \frac{n\,\angle\theta}{2}\Big)\alpha^2 d^2\Big]\Big\}$$

The first term is the summation of the resistance drops per ampere (equation 7a) in the upper and lower coil sides. Due to the fact that laminations are continuous the current distribution is the same in each conductor of the coil. Thus the resistance drops are also the same for each conductor. The second, third and fourth terms respectively correspond to the third, fourth and fifth terms in the preceding case.
This reduces to:

$$Z = R\,\Big\{ M + \Big(\frac{2\,n^2 - 1}{4} + \frac{n^2}{2}\cos\theta\Big)N$$

$$+ \frac{4\,n^2 - 1}{12}\,\alpha^2 d^2 \Big\}$$

The resistance and reactance are respectively the real and imaginary portions of this expression. Thus:

$$r = R\,\Big\{ M_r + \Big(\frac{2\,n^2 - 1}{4} + \frac{n^2}{2}\cos\theta\Big)N_r \Big\}$$

$$x = R \left\{ M_x + \left(\frac{2\,n^2 - 1}{4} + \frac{n^2}{2} \cos\theta \right) N_x \right.$$
$$\left. + \frac{4\,n^2 - 1}{12} \left| \alpha \right|^2 d^2 \right\}$$

$| \alpha |^2$ is the square of the numerical value of α, *viz.*, $\frac{8\,\pi^2\,w\,f}{\rho\,s}$.

4. Finely and continuously laminated conductors (type three) with end connections twisted on both sides. Consider the general case of symmetrical pairs of fractional pitch slots in which the currents in the coil sides lying in the same slot differ in phase by θ. Due to the twist in the end connections the current density is the same at points equally distant from the bottom of half of the conductors, and from the top of the other half. The expression for the flux within the conductor has already been given for the first condition. When current density is measured from the top of the conductor, the expression for the flux within it is:

$$\varphi = \frac{4\,\pi}{s} \int_d^0 \partial x \int_d^x w\, \dot{c}\, \partial x$$

This readily reduces to:

$$\varphi = \frac{1}{j\,\omega}\;\frac{\rho}{w\,d} \left\{ (I_1 + I_0)\,\alpha^2\,d^2 \right.$$
$$\left. - \left(\frac{I_1}{2} + I_0 \right) N \right\}$$

The total flux within the conductor including that produced by the current, I_b, below it is:

$$\varphi_0 = \frac{1}{j\,\omega}\;\frac{\rho}{w\,d} \left\{ (I_1 + I_0 + I_b)\,\alpha^2\,d^2 \right.$$
$$\left. - \left(\frac{I_1}{2} + I_0 \right) N \right\}$$

The voltage produced in every conductor below the one in question by this flux is:

$$E = R \left\{ (I_1 + I_0 + I_b)\,\alpha^2\,d^2 - \left(\frac{I_1}{2} + I_0 \right) N \right\}$$

where R is the true resistance of a half turn.

For conductors in which the current density is given for values of x measured from the top, rather than from the bottom, the resistance drop $\rho\ \underset{\cdot}{c}$ is that in the bottom element. The flux within this conductor then produces an *additional* voltage in it. In this case

$$I_0 = \frac{I_2}{2} - \frac{I_1}{2}$$

$$Z = \frac{R}{2\,n}$$

$$\left\{ 2 \sum_{1}^{n} \left[M + \left(\frac{n \underline{/\theta}}{2 \times 2} - \frac{1}{2 \times 2} \right) N \right] \right.$$

$$+ \sum_{1}^{n} (p-1) \left[\left(\frac{1}{2} + \frac{n \underline{/\theta}}{2} - \frac{1}{2} \right) N \right.$$

$$\left. + \left((p-1) + n \underline{/\theta} - \frac{n}{2} \underline{/\theta} + \frac{1}{2} \right) \alpha^2 d^2 \right]$$

$$+ n \sum_{1}^{n} \left[\left(\frac{\underline{/-\theta}}{2} + \frac{n}{2} - \frac{\underline{/-\theta}}{2} \right) N \right.$$

$$\left. + \left((p-1) \underline{/-\theta} + n - \frac{n}{2} + \frac{\underline{/-\theta}}{2} \right) \alpha^2 d^2 \right]$$

$$+ \sum_{1}^{n} p \left[\left(1 + \frac{n}{2} \underline{/\theta} - \frac{1}{2} + (p-1) \right) \alpha^2 d^2 \right.$$

$$\left. \left. - \left(\frac{1}{2} + \frac{n}{2} \underline{/\theta} - \frac{1}{2} \right) N \right] \right\}$$

In this expression R is the true resistance of the coil. The terms are written in the same order as in the previous case.

This reduces to:

$$Z = R \left\{ M + \frac{n^2 - 1}{4} N + \left(\frac{7\,n^2 - 1}{12} \right. \right.$$

$$\left. \left. + \frac{n^2}{2} \cos\theta \right) \alpha^2 d^2 \right\}$$

The method of calculating the impedance should now be sufficiently clear. The final equations for the impedance of finely and continuously laminated conductors whose end turns are twisted on one side only are given without showing their detailed construction.

There are two cases to consider,—one with an even number of layers per coil side, and the other with an odd number of layers.

For n, even

$$Z = R \left\{ M - \frac{N}{4} + \left(\frac{10\, n^2 - 1}{12} + \frac{n^2}{2} \cos \theta \right) \alpha^2 d^2 \right\}$$

For n, odd

$$Z = R \left\{ M + \left(\frac{10\, n^2 - 1}{12} + \frac{n^2}{2} \cos \theta \right) \alpha^2 d^2 \right\}$$

The formulas are given in such detail that it must be evident how the effects of unbalanced currents may be calculated. If there are marked harmonics in the currents the heating loss for each harmonic may be calculated as if the others were absent. The resulting loss is the sum of the component losses. The resistance ratios increase with the frequency so that higher harmonics of any considerable magnitude may prove troublesome. For example, if the currents should contain 20 per cent fifth and seventh harmonics, the resistance ratio for the entire winding—solid conductors—would increase from 2.75 as given in Table I to 2.95. This neglects any skin effect in the end turns which would probably be considerable for these harmonics. It also neglects the fact that with higher harmonics there would be a marked magnetic skin effect in the laminations surrounding the conductor which might raise the saturation to such a point that the fundamental assumptions would no longer hold.

The increase in the ratio for the embedded portion only is much more marked. The ratio for the embedded portion of the entire winding as calculated from Table I is

$$\frac{4 \times 1.93 + 2 \times 6.31 + 2 \times 7.77}{8} = 4.49$$

The ratio for the entire embedded portion with harmonics present becomes 6.73. The ratio of the heats developed in top and bottom conductors of slots *c* or *d*

becomes $\frac{15.8}{1.39}$ or 11.4 when these harmonics are present instead of the value of 8.3 as given in the table.

By making the proper assumptions, this method of analysis allows us to account for the hysteresis and eddy current losses in the armature teeth and core due to the leakage flux, the effect of which we are discussing. Assume that, due to these iron losses, each tube of flux lags behind the net current that is producing it by the same angle, η. If this be the case the reactive drop will lead the resistance drop by $(\pi/2 - \eta)$ radians instead of by $\pi/2$ radians as we have assumed.

Thus $$\alpha^2 = \frac{8\,\pi^2 f\, w}{\rho\, s} \, \underline{/ -\frac{\pi}{2} - \eta}$$

and $$\alpha = \sqrt{\frac{8\,\pi^2 f\, w}{\rho\, s}} \, \underline{/ \frac{\pi}{4} - \frac{\eta}{2}}$$

New values of the complex quantities M and N may be calculated for this value of α and substituted in the expressions for effective resistance and reactance already obtained. Whether or not this method will produce accurate results can only be determined by much experimental research.

SUMMARY OF FORMULAS

Solid Conductors

Ratio $\dfrac{\text{Alternating-current resistance}}{\text{Direct-current resistance}}$

*p*th conductor from bottom one-coil-side-per-slot bar winding.

$$M_r + p\,(p - 1)\,N_r$$

One-coil-side-per-slot with *n* layers, or lower coil side with *n* layers.

$$M_r + \frac{n^2 - 1}{3}\,N_r$$

Upper coil side, n layers, two-coil-side-per slot, fractional pitch.

$$M_r + \left(\frac{4\,n^2 - 1}{3} + n^2 \cos \theta \right) N_r$$

Finely Laminated Conductors (laminations soldered at beginning and end of each turn) fractional pitch[1]

$$\text{Ratio } \frac{\text{A-C. resistance.}}{\text{D-C. resistance}}$$

End turn untwisted, pth conductor from bottom of upper coil side.

$$M_r + [p^2 - p + n\,(p - 1/2) \cos \theta + n^2/4]\, N_r$$

End turn untwisted, each coil side.

$$M_r + \left(\frac{7\,n^2 - 4}{12} + \frac{n^2}{2} \cos \theta \right) N_r$$

End turn twisted, each coil side.

$$M_r + \frac{n^2 - 1}{4}\, N_r$$

Finely Laminated Conductors, soldered at the beginning and end of each coil. Ratio of impedance to direct-current resistance is given for a pair of coil sides below one of which is current lagging by θ and abovethe other current leading by θ. n layers per coil side.[2]

End turns untwisted.

$$M + \left(\frac{2\,n^2 - 1}{4} + \frac{n^2}{2} \cos \theta \right) N + \frac{4\,n^2 - 1}{12}\, \alpha^2 d^2$$

End turns twisted both sides.

$$M + \frac{n^2 - 1}{4}\, N + \left(\frac{7\,n^2 - 1}{12} + \frac{n^2}{2} \cos \theta \right) \alpha^2 d^2$$

End turns twisted one side, n even.

$$M - \frac{N}{4} + \left(\frac{10\,n^2 - 1}{12} + \frac{n^2}{2} \cos \theta \right) \alpha^2\, d^2$$

End turns twisted one side, n odd.

$$M + \left(\frac{10\,n^2 - 1}{12} + \frac{n^2}{2} \cos \theta \right) \alpha^2 d^2$$

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[1] Two coil sides per slot, n layers per coil side.

[2] In calculating the impedance only leakage flux that lies within the conductors is considered. There are well known methods for calculating the reactance due to other leakage flux.

DISCUSSION ON "SYNCHRONOUS MOTORS FOR SHIP PROPULSION" (HENNINGSEN), "MAGNETIC PROPERTIES OF COMPRESSED POWDERED IRON" (SPEED AND ELMEN), AND "HEAT LOSSES IN CONDUCTORS IN A-C. MACHINES" (LYON), SALT LAKE CITY, UTAH, JUNE 24, 1921.

Wm. J. Foster: There has always been more or less uncertainty as to proper field of application of the induction and synchronous motor. I think Mr. Henningsen's paper describes the application of the synchronous motor in this particular case in a manner to justify it. I will not review that, but I recall a somewhat similar case many years ago where it had been generally decided that the proper motor for motor-generator sets, for transforming alternating current transmitted a distance to direct current for use on the Edison three-wire system was the induction motor, and one of our large companies installed a number of what were then very large motor-generator sets, with the idea that the induction motor was simpler in operation and in that particular application the synchronous motor was not to be considered. Well, it was not very long before the engineers of that company had come to the conclusion that they would try the synchronous motor, when increasing the size of the substation and it was discovered—probably they anticipated quite well what would happen—that the synchronous motor was superior to the induction motor in certain respects, such as its ability to stay in step. An argument frequently used for the induction motor is that you can get it back into step much easier. In that particular case it was found that if the potential was considerably reduced on the line, as happens occasionally the synchronous motor had the ability to carry the load and remain in step, which we all now know is characteristic of the synchronous motor with a given excitation. Another surprising difference was the convenience in manipulation, in starting up, as it was their practise after one set was in operation to start the other sets from the d-c. end, and it would have been expected in advance that the switch might be thrown on the induction motor without serious disturbance. It was found that the only way of deciding when to throw the switch was to go by the sound, and that operators were throwing in the switch on the induction motor in such a manner that it gave bad jolts to the system, whereas the synchronous motor could be put on the line without jolt. Regarding ship propulsion I wish to say that when the synchronous motor was first suggested it was looked upon as rather absurd, but if I am not mistaken there are one or two manipulations of the ship where the synchronous motor can do a little bit better than an induction motor. I hope to see not fewer applications of the induction motor but more of synchronous motors or synchronous condensers, as I think it will help out the situation of generator design very materially especially the steam turbine generators of the largest size and highest speed. It would be much better for the life of the machine and from consideration of the holding together of different parts of systems, if the requirement of low power factor on such generators could be dispensed with, and in the case of the largest sizes that they be built for unity power factor. I was pleased in listening to Mr. Baum's paper the other day to find him so strongly recommending the installation of synchronous condensers in connection with the high-voltage transmission that he is now working on. By such installation of synchronous condensers I see no reason why the generator should any longer be handicapped by the requirement of operation at 80, 85 or 90 per cent power factor. If that were removed then any given generator could be made suitable for operating on higher transmission circuits than at present, which is a very desirable feature, *i. e.*, it could be built so as to better hold down the potential for a given charging current

F. G. Baum: We have here given an illustration of the remarkable application of the synchronous motor, and my purpose now is to try to impress on the power men the great advantage of adding synchronous machinery to their system. Make your customer put them in wherever you can. You are adding to your generating capacity in doing so. The work of design will be very much reduced. Everybody today knows and says they want a generator designed for 80 per cent power factor, another 85 per cent and 50 per cent overload. If you will get rid of that power factor feature in designing generators, you will make the generator cheaper, simpler, and much less liable to overvoltage due to speed fluctuations of the system. Every synchronous motor added to the system is an asset, adding to generating capacity.

With respect to Mr. Lyon's paper. It is a peculiar characteristic of almost all electrical apparatus that it works best when kept in service all the time. The reason for that is that deterioration is largely due to the maximum temperature ranges that occur and the number of those cycles that occur in a given time. Putting a generator into service, loading it up so that it gets extremely hot and taking it out of service every day, is as though you take a pipe line out every day and fill it up and then empty it. You destroy that pipeline in a very short time and we found that out fifteen years ago in our generating stations. When the load is light we take a machine out of service at night and start it up again, a great deal of trouble results eventually from the extreme temperature changes. We should keep those machines going all of the time.

Wm. Fondiller: I wish to bring out several points in connection with the development of the powdered iron core which I think will be of interest.

The authors have referred briefly to the experiments leading up to the present form of powdered iron core. It became evident after the work of testing different iron mixtures was started, that special testing means must be devised for determining the characteristics in order to bring the development work to a conclusion in a reasonable time and at a reasonable cost. When the number of possible combinations is considered of varying pressure, insulating materials, composition of iron, fineness, etc., it will be appreciated that a formidable problem was presented from the laboratory standpoint.

To meet the situation, special apparatus was designed enabling tests for permeability and iron losses to be made without the necessity of applying a winding to the core rings. These two devices comprising a permeammeter and a core loss tester, enabled fairly accurate measurements to be made at telephone frequencies with great dispatch. It is hoped to make these new testing instruments the subject of a future paper.

Messrs. Speed and Elmen have described the major operations in the production of the powdered iron cores. It should be understood that in the actual carrying out of the processes, great care is needed in order to secure the uniformity demanded by the close limits imposed on telephone apparatus. This makes necessary careful checks on the successive operations by means of tests while the material is in process of manufacture. In this way it has been possible to keep the initial permeability of core rings made from powdered iron within a few per cent of the nominal value; for example, the permeability of the grade "A" core material is regularly maintained within limits of 58 ± 5. So far as I know this is not possible with any other ferrous material commerically available.

One of the most important properties of the powdered iron core is its self-demagnetizing characteristics. This is shown clearly in Fig. 17 on the return curve after superposing comparatively large values of direct current. It will be noted that for the grade "B" material the a-c. permeability is unaffected when the superposed direct current is reduced to zero and in the case of grade "A" material it is reduced by only 4 per cent. This must be compared with an alteration in the a-c. permeability in the wire core of approximately 40 per cent for the same magnetic experience. Even for values of direct current producing the saturation value of residual magnetism the effect on the a-c. permeability is quite small.

The authors have referred to the extensive use of the cores which they have described in the Bell plant in this country. I would add that the high efficiency of loading coils using these cores together with their satisfactory characteristics in connection with telephone repeater operation have caused their adoption as the standard core for loading coils in toll cables, not only in this country, but in Europe. The powdered core loading coil has been introduced abroad by the Western Electric Co. with great success. This improved loading coil has been adopted by the British Post Office for its toll cables and is being installed at the present time by the Western Electric Company in Sweden in the Stockholm-Goteborg cable.

H. L. Hibbard: I presume Mr. Henningsen's paper is simply to explain the successful application of synchronous motors, and I agree with Mr. Henningsen that probably a great many applications of this kind will be made in the future, since I think the day of the electrically operated ship is here; but this is the question I want to ask—Are we to understand from this paper that the author recommends the synchronous motor as a proper application for all merchant ships? I simply raise the question because it seems to me a large field is opening up along the line of oil engine propulsion, where d-c. apparatus would be found better suited.

G. Semenza: I only want to support what Mr. Foster has said about the synchronous motors with an instance coming from the other side of the ocean. In 1895 after the electrification of the tramways in Milan, a rather large system, synchronous motors had been used for motor-generators. After two years, enlarging the station somebody suggested to put in an induction motor because they thought it would be better under certain points of view. Well, after three years that motor was taken out and a synchronous motor substituted. That shows that the conclusions on the two sides of the ocean are just the same.

C. A. Copley: It might be of interest to have somebody explain why it was that synchronous motors were not used in the new pumping plant which is about 7 or 8 miles from here. I believe it contains about 2400 h. p. in induction motors and lifts the water 300 feet.

W. E. Thau (read by W. E. Skinner): The author has outlined two of the special operating requirements of ship propulsion machinery, namely, the torque requirement during rough weather and the torque requirement during reversing, and has shown how these conditions can be surmounted by the synchronous motor. There is a third special requirement, characteristic, particularly of multiple screw ships, namely, the excess torque required by the inboard screw, or screws, when making a turn with hard-over rudder (by inboard screws is meant the screws toward the center of the circle described while turning). In this case, if the propeller speed is maintained constant and the delivered power unlimited, the torque required particularly by the inboard screws is considerably in excess of the normal zero rudder requirement, and will easily reach 150 per cent or more of the normal. To overcome this condition, as far as practicable, the steam flow is limited to an amount corresponding to from 5 per cent to 10 per cent above normal. With the steam so limited, the additional torque required by the inboard screws causes a decrease in the speed of the propeller and prime mover when the ships is making the turn with hard-over rudder. With separate prime movers for the port and starboard sides, this effect is most noticeable, and in such cases the speed will drop from 20 to 25 per cent of normal, and as the steam flow, and consequently the kw. input to the motors is limited as stated, the excess torque will amount to 30 to 35 per cent.

Usually the speed of a ship is reduced when running in a heavy sea for reasons other than the load conditions on the propeller. Reducing the speed in this manner will decrease the excess torque requirements to values slightly in excess of the normal capacity of the machine.

These special torque requirements not only influence the motor characteristics, but also have an important bearing on the generator design as the generator must at all times be capable of maintaining voltage above the breakdown point for the excess load conditions. These conditions, particularly the rough sea and turning requirements, therefore, are the determining factors in the amount of generator field current to be carried for uninterrupted service. In the case of the synchronous motor, where special efforts are necessary to obtain sufficient torque for quick reversals, the generator field requirement under such conditions is of considerably more importance than in the case of a wound secondary induction motor drive. As the propulsive equipment for a ship is a self-contained unit, the requirements outlined necessitated special generator design, and the ordinary maximum rated machine such as is used in central stations, is not applicable.

The principal attraction of a synchronous motor drive as compared with the ordinary induction motor drive is the unity power factor with its consequent decrease in the cost and weight, as the author states. The third gain mentioned, namely, better efficiency, is of little importance as the net gain in the plant efficiency is inconsequential for the reason that the excitation for the synchronous motor must be supplied through an auxiliary d-c. turbine set, the unit steam consumption of which is at least twice that of the main turbine through which the excitation for the induction motor is supplied. From a ship viewpoint, therefore, the economy has little advantage, if any, over the ordinary induction motor.

However, the unity power factor advantage of the synchronous motor is equally obtainable by means of an induction motor system using a phase advancer for power factor correction to unity. The phase advancer is a small, simple, commutating machine, which is connected to the motor secondary (wound secondary). The function of the phase advancer is to supply the excitation for the induction motor just as d-c. excitation is supplied for the synchronous motor.

Thus, the induction motor drive with the phase advancer not only provides the advantages resulting from unity power factor, but in addition provides the superior torque characteristics of the wound secondary induction motor for maneuvering, and also obviates the necessity for synchronous operation with the generator.

The generator requirements are substantially the same for this type of ship drive as for that using the synchronous motor, and the net results of weight and cost are approximately the same.

As a matter of interest, the induction motor system using the phase advancer has the advantages of superior torque characteristics and of dissipating the energy of reversal in resistance external to the driving machinery. Furthermore, the control is simple, being no more complicated than that for the ordinary wound secondary induction motor.

In connection with the discussion of special features incorporated in the design of a-c. turbine electric systems, to meet the load requirements of ship propellers, it is important to note that no special features whatsoever must be considered in the case of the Diesel-electric d-c. system of propulsion. This system employs a number (three to six, depending upon the power required) of moderately high speed, small, reliable, Diesel engines driving direct-connected d-c. generators which supply power to direct-connected motors, the speed of which is regulated in the simplest and most economical manner by voltage control. With this system of drive, the prime movers, generators and motors need be designed for only the continuous normal requirements and no special precautions or additional material in the machines are necessary to keep the motors and generators in step when subjected to the overload torque conditions. The inherent characteristics of the machines are such that the latter automatically adjust themselves to the abnormal load conditions. The overloads are of short duration, and no cognizance need be taken of the consequent heating.

Paul P. Ashworth: The question was asked, why 2800 h. p. in induction motors have been installed in the pumping plant 7 or 8 miles north of Salt Lake. I had nothing to do with the installation and yet I can see fairly good reasons why motors of that type were chosen. One reason, of course—the most obvious reason—is the matter of cost, that, however, is not the controlling reason. Induction motors in pumping plants of that size always operate fully loaded, under which condition they have a power factor of somewhere around 85 to 93 per cent,—not a bad power factor at all. A further point is the character of the service—three or four months during the year and this during the time of minimum load on the power system; therefore, there is at that time a large excess in generating capacity—in current carrying capacity. Following out the suggestion of Mr. Baum that there is no particular objection, in fact there is an advantage, in loading the equipment to somewhere near capacity, so from that standpoint the pumping plant having induction motors is no disadvantage.

There is one point that might be mentioned in connection with our experience here with synchronous motors. There is a certain danger which should not be overlooked. We found for example at a large mining installation where a hoist operated by a synchronous motor was installed— a large 300 or 400 h. p. hoist operating 24 hours a day the year around,—that when the brushes on the exciter would begin to spark due to improper setting or inadequate maintenance, the operator would decrease the exciting current to the motor, to reduce sparking, so that instead of carrying unity power factor the motor was carrying a power factor of 50 per cent or less,—much less than any induction motor would carry under the same conditions. We have found it advisable to ask customers using synchronous motors to adjust the excitation to give 100 per cent power factor under approximately full-load conditions, and if possible to throw the rheostat handle down the mine or put it where the operator was not likely to use it to prevent sparking brushes. I merely want to indicate this danger, that with the use of the synchronous motor there is a possibility of getting very low power factor and thus to defeat one of the main reasons for installing synchronous equipment. The entrance of power factor into rate schedules will tend to force the installation and proper operation of equipment which will maintain good power factor. The nature of the service in any particular case will determine the type of motor equipment to be used.

S. P. Grace: A few weeks ago I had occasion to present a statement to the Public Service Commission of the City of New York showing the number of loading coils in use in New York City together with economies which resulted from their use. In the City of New York there are in use 100,000 loading coils in approximately 198,000 miles of telephone circuit. If the same transmitting efficiency had been obtained by the use of larger size copper wires there would have been an additional investment in the City of New York of $25,000,000, representing an annual charge of something like $4,000,000. You therefore can appreciate the very great savings which have been brought about through the loading coils.

A. M. Maccutcheon: I would like to ask Mr. Henningsen how they handle the synchronous motor when maneuvering a ship. It is very clear how they get the direct reversal, but to anyone who has been on a ship coming into a harbor they sometimes have to use two or three speeds coming up the channel,—forward speed, part speed, full speed, reversal; constant changes in the speed of the propellers.

H. W. Taylor (by letter): In the most general investigation of the problems dealt with in Mr. Lyon's paper there is no doubt that the use of hyperbolic functions of the complex variable afford the simplest form of solution. To those, however, who absorbed in practical work, or for other reasons prefer that the solutions of their problems should be presented to them if possible in still simpler forms, it is interesting to know that all the problems of eddy currents in stator conductors which occur in practical work can be dealt with by simple algebra.

In a paper by the present writer published in the *Journal of the Institution of Electrical Engineers,* in April 1920 (Vol. 58, page 279) the most general case involving the use of the complex hyperbolic functions was discussed, but the main part of the paper was devoted to the development of algebraic formulas.

The present occasion affords an opportunity of republishing the principal formulas in a form which continued practise with them has shown to be most useful.

The formulas for eddy current losses in stator conductors consist essentially of two factors, the first involving the mechanical dimensions of the conductor and the frequency, and the second involving the way in which the conductors are arranged in the winding.

The factors involved in the first factor of the formula are given in the expression

$$D = \frac{h^4 f^2 a^2}{80}$$

where h is the height of a lamination or section of the conductor in inches

f is the frequency in cycles per second

and a is the ratio in a slot of the copper width to the total slot width.

The numerical co-efficient assumes the copper of the conductor is operating at approximately 100 deg. cent.

If the height of the lamination is given in centimeters the numeric 80 becomes 2.

The expressions for the second factor of the complete expression may be divided under four headings as follows:

1. When the conductors are solid.
2. When the conductor is sub-divided with solid connections at the end of each half turn.
3. When the sub-divisions of a conductor are continued throughout a coil.
4. When the sub-divisions of a conductor are continued throughout a winding and are successively transferred in position.

SOLID CONDUCTORS

Where each lamination may be considered as a separate conductor, the *extra* loss factor for the complete slot is given by the formula

$$D\left(\frac{4}{45}+\frac{p^2-1}{9}\right) \tag{1}$$

or

$$D\left(\frac{p^2}{9}-\frac{1}{45}\right) \tag{1a}$$

where p is the number of conductors under consideration; in the present instance, the total number of separate conductors in the slot.

If the slot conductors are divided into an upper and a similar lower layer and it is required to know the separate *extra* loss factors for each layer, then for the bottom layer we have the average loss factor

$$D\left(\frac{4}{45}+\frac{p^2-1}{9}\right) \tag{1}$$

as before, p being the number of conductors under consideration, in this case the number of separate conductors in each layer, and for the upper layer the average extra loss factor is

$$D\left(\frac{4}{45}+\frac{7\,p^2-1}{9}\right) \tag{2}$$

When the upper layer carries current of a different phase to the bottom layer the last formula is modified as follows:

$$D\left(\frac{4}{45}+\frac{7\,p^2-1+6\,p^2\sin^2\phi/2}{9}\right) \tag{3}$$

or the equivalent expression

$$D\left(\frac{4}{45}+\frac{4\,p^2-1+3\,p^2\cos\phi}{9}\right) \tag{3a}$$

The former of these two expressions is preferable in that it shows directly what reduction in loss is produced by a different phase of current in the two layers.

SUB-DIVISION OF CONDUCTORS WITH SOLID CONNECTIONS AT END OF EACH HALF TURN

The formula for calculating this case consists of two parts, the first portion dealing with the eddy currents still localized in the section of each lamination and in the core portion of the length of it, and the second portion dealing with the eddy currents which circulate around the various sections and flow over the whole length of the conductor.

Two new co-efficients are introduced in the second portion of the formulas, *viz*:

b = ratio of core length to half the length of turn and c = ratio of the total height of the assembled laminations of the conductor to net copper height in the conductor.

The first co-efficient allows for the extra resistance experienced by the eddy currents in circulating around the more extended path, and the second co-efficient takes account of the flux which passes through the insulation between the sections.

If now n is the number of sections in each conductor, and a given conductor is situated at position p in the slot, counting upwards from the bottom, 1, 2, 3, etc. the extra loss factor in p^{th} conductor is given by the algebraic expression

$$D\left[\left\{\frac{n^2(p^2-p)}{3}+\frac{n^2-1}{9}+\frac{4}{45}\right\}+b^2c^2(n^2-1)\left\{\frac{4n^2-1}{45}+\frac{n^2(p^2-p)}{3}\right\}\right] \quad (4)$$

If there are in all, p such conductors under consideration, the average loss factor for such a group is

$$D\left[\left\{\frac{n^2(p^2-1)}{9}+\frac{n^2-1}{9}+\frac{4}{45}\right\}+b^2c^2(n^2-1)\left\{\frac{4n^2-1}{45}+\frac{n^2(p^2-1)}{9}\right\}\right] \quad (5)$$

If there is a further layer of p such conductors, (p^2-1) in both portions of the above expression is changed to $(7p^2-1)$ and when the phase of the current is different it is replaced by $(7p^2-1-6p^2\sin^2\phi/2)$ just as in the expressions (2) and (3) previously given for solid conductors.

SUBDIVISION CONTINUED THROUGHOUT A COIL

The formulas are similar to (4) and (5) just given but in all cases the second part of the expression is the same for each conductor or for each layer, and a value of p is determined for use in this part of the expression from a knowledge of the arrangement of the order of the laminations in the successive conductors.

The usual arrangement hitherto employed has been to have the order of the laminations in the top layer reverse of the order of the laminations in the bottom layer. In this case the value of p to be used in the second part of the expression is $\left(\frac{p+1}{2}\right)$ if p is the number of conductors in each layer.

In order to avoid confusion this equivalent value for the complete coil will be written as p in the formula about to be given.

Various improved arrangements were discussed in the writer's paper and equivalent values of P were derived for all cases arising in practise, including that shown as Fig. 6 in the present paper. It was shown, moreover, how the imperfection still existing in the coil with an odd number of turns can be remedied.

The formula for the extra loss factor in the bottom layer of a coil consisting of p turns, the conductor consisting of n separately insulated laminations is

$$D\left[\left\{\frac{n^2(p^2-1)}{9}+\frac{n^2-1}{9}+\frac{4}{45}\right\}\right.$$
$$\left.+\,b^2c^2(n^2-1)\left\{\frac{4n^2-1}{45}+\frac{n^2(P^2-P)}{3}\right\}\right] \quad (6)$$

For the top layer, when the currents in the slot are all in the same phase the (p^2-1) in the first portion only of the formula gives place to $(7p^2-1)$ and when the current in the bottom portion of the coil is in a different phase to $(7p^2-1-6p^2\sin^2\phi/2)$ as in the previous formulas (2) and (3). The second part of the expression is the same as for the bottom layer.

SUBDIVISION OF CONDUCTORS THROUGHOUT A WINDING WITH SUCCESSIVE TRANSFERENCE OF LAMINATION

This method was described by Gilman in his paper before the Institute last year, and the author's firm has used the principle in practical work since 1913. It consists essentially of choosing the number of laminations in the conductor the same as the number of coils in the winding, by continuously insulating the laminations of the conductor throughout the winding and by successively changing the position of the laminations in the conductor from coil to coil so that each lamination occupies each position in the conductor once by the time the winding is completed.

It will be obvious that when the phase relations of the currents in the upper and bottom layers are the same in each slot throughout the winding, there are no losses except those localized in each lamination in the core portion of the winding, in which case formulas (1), (2), (3) are directly applicable, taking p as the number of laminations in each layer or in the whole slot as required.

Where, however, the upper layers of conductors are not all influenced by the same phase of currents in the lower layers then some extra loss will occur as a result of currents circulating between the laminations.

The greatest effect will be produced when half the upper layers are influenced by one phase of current in the bottom layer and when the other half are influenced by another phase of current as in a three-phase winding with 5/6 pitch. The extra loss factor, in addition to those calculated from formulas (1), (2), (3) will be

$$\frac{D\, b^2\, c^2\, n^2\, (n^2 + 8\, Q^2)}{192\, Q^2} \qquad (7)$$

where the conductor has n laminations and the winding consists of n coils which are distributed over Q poles.

Other cases lying between the perfect and the most imperfect one may be readily estimated by interpolation.

Finally, all the above formulas are accurate to within a few per cent as long as $(n^4\, b^2\, D)$ is less than 2. Formula (7) is accurate for a much higher value.

These limits will be found to cover all cases arising in practise and the accuracy of the formulas have been confirmed by running tests on a number of large machines in which temperature detectors have been embedded.

Further at the conclusion of a paper read on the same subject by R. E. Gilman at the summer convention of last year, the results of a number of experiments on eddy current heating were given and it will be found that the present writer's formulas check up with the experiment results in all cases, except where the conductor consists of six sections solidly connected together at the end and giving an *extra* loss factor of 3.225, an arrangement obviously outside the range allowable in practise.

E. S. Henningsen: In answer to Mr. Hibbard's question as to whether it is considered that the synchronous motor is the proper application for all types of merchant ships. The answer is, of course, that it is not; any more than the synchronous motor or the induction motor can be always said to be particularly applicable to any and all installations. There are many installations, particularly of small ships where I think the d-c. equipment and the Diesel engine drive will be found more practical and more efficient than either the induction motor or the synchronous motor. The d-c. equipment, cannot, of course, compete in the large fields.

In answer to the question brought up in the letter read by Mr. Skinner. I was very much interested in the scheme that was outlined and I certainly hope it has a chance to be tried out. This is a brand new field; there is very little information available, and the more methods that are tried out the better the final solution will be. This country needs a merchant marine and certainly anything that will aid to build up this merchant marine and arrive at the best solution of the question is to be desired.

The matter of torque during turning has been alluded to in the paper. The requirement here is no different with the synchronous than with the induction motor, both have to supply torque enough to take care of this condition. This has been covered in the paper. In the matter of efficiency, even counting the much higher rating of the exciters required for the synchronous motor proposition, there results a saving of something like 2 per cent in the total steam consumption for a 3000-horse power equipment. Not a very tremendous saving, but something nevertheless.

In answering Mr. MacCutcheon's question as to the maneuvering: When a ship is coming into or going out of a port, it is practically always operated at either one quarter or half of normal speed. At low speed, as I pointed out, the torque required by the propellers is very materially less than that required at high speed, hence the control can be arranged with the control handle something similar to a street car controller, if you like, and the operation or reversal at these lower speeds is accomplished in a very short interval of time. On trial trips on one of our ships we answered 75 bells in 2½ minutes—quarter speed ahead to quarter speed reversed, throwing the lever from ahead position straight through to the astern position and bringing it back almost as fast as a man could operate the lever. Even under the full speed condition where we require almost 100 per cent of normal torque to reverse, the time that is required for full-speed reversal is rather remarkable. Using the 250-volt, *i. e.*, total excitation across the motor field the propeller is stopped from full speed in 3½ seconds and when you consider the fastest time that can be made with a steam engine is about a minute and a half, and that is expert manipulation, 3½ seconds is quite remarkable. On a trial using only the induction motor characteristic without making use of the braking characteristic, the full-speed stop was accomplished in 13 seconds, so that it will be seen that with the lower speed of the ship the reversal of the propeller can be accomplished very rapidly.

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ELECTRIC AUXILIARIES ON MERCHANT SHIPS

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WHEN we discuss the Merchant Marine, or any feature thereof, we must not lose sight of the fact that we are dealing with a commercial undertaking which is probably more highly competitive than any other. From its very nature this must be the case, for while each country can make laws to assist the merchant ship owners of that country, every effort to help them and penalize foreign shipping can and undoubtedly will be neutralized by laws of the countries with which they are trading. The only assistance, therefore, that can be given by legislation, outside of providing good port facilities, is to enact laws that will assure a good standard for ships and at the same time not impose penalties in operation to which owners of other countries are not subject.

So we see that the answer to the question, "Who is to carry the merchandise which has to be transported between the various ports of the world?" rests in a great measure with the owners and operators of ships; and because electricity makes possible many reductions in the cost of operation and at the same time enhances the earning power of a ship it is being used to an ever increasing extent for driving the machinery on ships.

On highly efficient new ships, especially motorships, practically all the auxiliaries are driven by electric motors. In the motorship the steam boiler becomes an auxiliary and it is apparent that much of the gain in economy secured by the oil engine would be sacrificed if steam auxiliary machinery were retained. In the steamship, the losses incident to the steam auxiliaries are not so apparent; nevertheless, they are there, a constant drain on the boilers and a continual handicap to any operator or engineer endeavoring to attain efficiency in operation.

It is recognized that a somewhat greater gain in fuel economy is generally secured on a motorship by the adoption of electricity for the reason that Diesel oil engines are employed to drive the generators. Oil engines might be used on steamships with a resultant reduction of fuel required for all purposes. However, there are certain good operating reasons why such an arrangement is not generally popular. It would be necessary to have an engineering force competent to operate and maintain the oil engine. As the pumps essential to the operation of the ship's main engine would be driven electrically, any interruption of the auxiliary oil engine might seriously interfere with the operation of the ship. Fuel oil would have to be suitable for the Diesel engine and in some cases this might necessitate carrying two kinds of fuel oil on ship with the incidental disadvantages. Duplicate equipments for heating, storing and filtering fuel oil would have to be installed. On a steamship, therefore, the most generally accepted practise is to install turbine-driven generator sets for auxiliary power.

At this particular time with the ships of the world tied up owing to lack of cargo, with other countries bending every effort to improve their merchant fleet, and with all men in this country who have the interests of our merchant marine at heart endeavoring to see into the future and maintain such advantage as we have secured due to the large increase in American registry, it would seem that the opportunity afforded by this joint meeting should prove of inestimable value, as engineering advancement can only be secured when a thorough knowledge and understanding of all conditions are recognized by both the manufacturers and users of machinery.

The problem is entirely an economic one. It is only because investigations show that the electrically equipped ship can be operated more economically and can earn more that the question is being discussed. It is the intention of the writer to endeavor to show why this is the case.

Not much information has been published relating to the details of costs of operation of ships. Studies indicate that on new ships electric auxiliaries will show a marked improvement in the economy of operation and will increase the net earning capacity. The future will show that many existing ships can be operated profitably by the substitution of electric for steam auxiliaries. The reasons for expecting such big savings are not at once apparent. Investigations indicate that the losses are partly due to innumerable small leaks and to radiation; in other words, it is the steam which is generated in the boilers but not put to useful work that in a great measure accounts for the high fuel consumption of many steam-driven ships. When it is recognized that steam is kept on hundreds of feet of piping from the boilers to the steering engine all the time, and in many ships it is always on all deck lines to avoid losses and leaks incident to expansion strains from alternately heating and cooling, and in the winter time there are often considerable extra losses incident to keeping steam on deck machinery to prevent freezing; it can be seen that it is not by any means entirely due to the inefficiency of steam auxiliaries themselves that we get a poor showing, but to the very nature of their application, which cannot be altered. The size of the evaporators fitted in many steamships is proof of the amount of steam that is made by the boilers and passed off into the atmosphere.

Auxiliary machinery on ships can be readily subdivided into two broad types:

(a) for deck use,

(b) for below-deck use.

The motors most suitable are enclosed, weather-proof for above deck, and ventilated for below deck.

It is not the intention to describe a number of different pieces of electric machinery for ships. A study of the technical papers shows an ever increasing amount of space being given to such descriptions.

Thoroughly reliable, simple and substantial machinery of various designs has been developed.

DECK MACHINERY

Deck machinery, properly speaking (that is, all machinery which is exposed to the elements and which must be built with this in view) consists generally of cargo winches, anchor windlass, a certain number of capstans, mooring winches and sometimes special machinery on particular ships. It is true that the steering machinery is not generally exposed to the elements, but is, however, very often housed in an extremely damp compartment. Continuous operation is vital to the safety of the ship. It will be evident that only machinery designed and built for the service should be considered for the application. The service of deck machinery is of an intermittent nature except in some special ships, that is, certain tankers where the motors for driving the cargo pumps are mounted on deck.

Electric deck machinery has been developed along two fundamentally distinct lines: one, in which the motor is mechanically geared to the drums, and the other where some form of hydraulic speed reducing gear is fitted between motor and drum. The latter class seems to have found considerable favor abroad, where certain well-known manufacturers have developed winches using either the Williams-Jenney or Hele-Shaw hydraulic power transmission. Electric hydraulic power transmission is particularly well adapted for steering gear work and has been developed in this country. For general winch service the hydraulic pump and motor are excessively costly. A brief comparison of winches developed abroad and in this country would indicate as follows:

(a) That the speeds for given load are somewhat lower for the foreign-made winch. A drum speed of approximately 175 ft. per minute for 5000 lb. and 250 ft. per minute for 2000 lb. would seem to be good practise.

(b) Certain manufacturers abroad have developed very neat worm-driven winches. These if properly built should be very quiet and from the descriptions appear to be quite compact. The writer does not know of any winches of this type developed in this country. One particular merit of such a winch is that the gear is readily encased, lubricated and protected from the action of the weather.

(c). From several descriptions there appears to be a tendency abroad to operate the motors by contactors. While this arrangement has much merit, it takes up additional space and costs more to install. In one description it is stated that the contactor controller is below deck. This, of course, is possible only in certain cases. Where the winches are located over the cargo holds special space must be provided on deck for the control panels and this space, of course, must be properly enclosed.

(d) There would seem to be a tendency on the part of the foreign winch manufacturers to considerably complicate the motor and control by the addition of special safety devices. In the writer's opinion this will be found undesirable. One manufacturer in this country who has fitted about two hundred electric winches on ships during the past five or six years claims that special safety devices are not only unnecessary but are actually undesirable. For the reason that it must be kept in perfect operating condition at all times so as to function properly when called upon at infrequent intervals, it will be recognized that apparatus for such service is the most difficult of all to maintain. It must be remembered that winches are operated in various parts of the world by longshoremen at the ports and not by the personnel of the ship. Experience indicates that properly designed and substantial equipment is entirely suitable for the service and does not require complicated safety-guarding features.

(e) With the majority of foreign-built winches it would appear that a handwheel is used for operation. This necessitates a tiring and unnatural movement on the part of the winch man. The natural motion and therefore one which can be carried on for hours at a stretch without unduly tiring the operator is similar to working a pump handle, that is, to control by means of a lever raised to raise the load and depressed to lower the load.

For gear winches the series motor or compound-wound with very small amount of shunt winding is the most desirable. Fig. 1 shows how the natural characteristic of the series motor makes it most suitable for winch service. It is found necessary to throttle the steam winch at light loads to reduce the speed. In practise, therefore, it approaches more nearly the speed of the electric winch. Many winches are fitted with winch heads. When handling cargo with these instead of the drum the rev. per min. will run up somewhat. However, the winch head being of smaller diameter than the drum, it is generally found that the rope speed on the winch head will be about right.

FIG. 1—CHARACTERISTIC CURVES OF ELECTRIC AND STEAM WINCHES

For all service using hydraulic gear, constant-speed motors are used, either alternating-current or direct-current.

Of all the electric apparatus aboard a ship the winch is subject to the most abuse. Everything about it, therefore, should be designed, manufactured, and installed in the most substantial and workmanlike manner.

Specifications for electric deck machinery should cover the following:

1. Insulation should be as highly moisture-resisting as it is possible to get by the use and treatment of the

best materials. This applies not only to windings but to all bushings, brush holder collars etc. which if hygroscopic are liable to result in grounds.

2. Motor frames should be thoroughly cleaned and painted on the inside to prevent so far as possible scale forming by corrosion.

3. Covers for inspection openings should preferably be hinged and arranged so as to clamp tightly. On all apparatus, motors, resistor boxes, controllers, etc., if it is impracticable to hinge the covers they should be attached by swinging bolts. Cap screws or cap bolts should not be used as they are liable to be dropped into the motor or left on deck and lost.

4. Bearings should be designed to prevent so far as possible ingress of water and egress of oil due to rolling of the ship.

5. All apparatus should be provided with some form of drain. It must be recognized that while machinery may be built in the factory so water-tight that it can be submerged, there is no assurance that this condition will exist after it has been once opened on deck. Further, any totally enclosed electrical apparatus is liable to breathe under varying temperatures which may result in an accumulation of moisture by condensation.

The cost of good electrically fitted machinery installed should be little, if any, more than that of high-grade steam machinery. Of course, until apparatus reaches a stage of standardized production the costs cannot be materially reduced. It must be remembered that while in steam machinery all kinds of economies may be practised at the cost of quality, in electrical apparatus built to withstand marine conditions and severe service a departure from the highest grade is most certain to be followed by failure and consequent cost to the operator. The making and insulating of electrical machinery cannot be materially hastened, as the successive dryings or bakings of the insulation must be given proper time—otherwise, it may be imperfect. The insulation in a marine motor must be moisture-resisting to the maximum practical extent—otherwise, it should not be deemed proper for the service.

Fig. 2 shows a deck winch developed in this country, several of which type will shortly be installed on ships. This winch is a radical departure from the generally recognized designs using either spur or worm gearing.

Electric steering gears have been developed for mechanical control of the rudder. For these the service is extremely intermittent, operating from two to ten times per minute, which means that the motor would be started, stopped and reversed thousands of times during one voyage. Such gears require the installation of a motor of sufficient torque to swing the rudder to the extreme angle, whereas during most of the time a very small amount of power is required. This means loss in efficiency as the motor is operating nearly all the time very much underloaded.

FIG. 2—NEW TYPE OF ELECTRIC CARGO WINCH HAVING THE REDUCTION GEAR INSIDE THE DRUM

For controlling the steering gear from the pilot house two electrical means are available, follow-up and non-follow-up. The first entails considerably more wiring, a multiple switch in the wheel house, a more complicated control in the steering engine compartment, and has the disadvantage of moving the rudder step by step a definite number of degrees. By the non-follow-up means the rudder can be moved by fractions of degrees in either direction; its use, however, calls for the installation of a rudder indicator in the wheel house. A device has been worked out to show positively the position of the rudder at any instant, using simple means already developed.

Special Deck Machinery. There are many special applications of electricity to machinery for shipboard not normally included as part of the regular equipment of a cargo ship wherein the use of electricity is particularly well suited. By the proper application of principles already worked out, it will be found that towing engines, mooring winches and other special pieces of machinery can be built to operate electrically

Fig. 3—Marine D-C. Motor—Enclosed, for Operating Deck Machinery

Fig. 4—Marine Controller for Deck Machinery Motors

in a very simple manner and with as great, or greater, reliability than steam machinery already developed.

The following is a table of deck machinery which with slight modification would be applicable to ships of any tonnage between 8000. and 10,000 tons dead weight. It should be borne in mind that the size of

	No. units	Assumed motor h. p.	Duty
Anchor Windlass	1	70	Very intermittent, severe Often submerged May be stalled in operation
Cargo Winches	12	35	Intermittent Fast cycle, severe duty Sometimes submerged Wide range in loads and speeds
Steering Gear	1	35	Seldom fully loaded Severe intermittent duty with mechanical gear Moderate continuous duty with hydraulic gear

TYPES DEVELOPED (ELECTRIC DECK MACHINERY)

	Drive	Motor	Speed Control
Anchor Windlass and Capstan	Spur-gear Worm-gear	Reversing	Electric
	Hydraulic	Constant-speed	Hydraulic
Cargo Winch	Worm-gear Spur-gear	Reversing	Electric with electric brake (general use)
		"	Electric with mechanical brake
		Constant-speed	Mechanical brake and clutch (free drum winch)
		" "	Mechanical brake hoisting and lowering clutches
		" "	Reverse gear and brake
		" "	No speed control (winch head only)
	Hydraulic	Constant-speed	Hydraulic
Steering Gear	Spur-gear	Reversing	Electric Remote
	Worm-gear	"	" "
	Hydraulic	Constant-speed	Hydraulic "

the cargo winches is based upon the best practise for general cargo and therefore does not vary greatly with the size of the ship. The number of winches, however, has to be modified to suit the number of hatches and derrick booms of the different ships.

BELOW-DECK MACHINERY

It should not be necessary to emphasize the importance of fitting equipment of proper design and of the highest grade material, particularly pumps vital to the operation of the ship and which must be relied upon to operate continuously day and night for weeks at a stretch.

The greater part of the electrical machinery below deck is naturally located in the engine room. The following table gives a list of below-deck auxiliaries suitable for a cargo ship of about 8000 to 10,000 dead weight tons and equipped with 2500 to 3000 shaft-h. p. steam turbine. A motorship requires somewhat fewer auxiliaries, and slightly less power is necessary for driving them. Tankers require a number of motor-driven pumps for discharging the cargo. These may be installed either in a special pump room or arranged with the motors on deck with vertical shafts to the pumps below. It will be noted that in the list there are only five sizes of motors. That is with the intent of simplification and to reduce the number of spare parts to be carried. A study of particular cases may show that it is possible to arrange satisfactorily the engine room equipment so as to have still fewer sizes.

Motors for these auxiliaries should be designed for continuous running, because while certain pumps may be started and stopped frequently, the service cannot be considered intermittent.

In the engine room, and in fact even if placed in the lowest part of the ship, totally enclosed motors are not recommended. For continuous operation they would have to be excessively large. With the changes in the atmosphere that take place below the water line, enclosed motors would be more liable to sweat and accumulate moisture internally than if

BELOW-DECK AUXILIARIES

	No. units	Assumed motor rating in h. p.	Duty
Propulsion			
1. Circulating pump	1	40	Continuous at sea
2. Boiler feed	2	25	One continuous at sea
3. Forced draft fan	1	20	Continuous at sea
4. Condensate	1	5	Continuous at sea
5. Lubricating oil	2	5	One continuous at sea
6. Oil cooler water	1	5	Continuous at sea
7. Fuel oil	2	5	One continuous at sea
8. Fuel oil trans.	1	5	Intermittent (assume 4 hr. per day
Service			
9. Fire and bilge	1	10	Intermittent (assume 6 hr. per day
10. General service	1	10	Intermittent (assume 6 hr. per day
11. Sanitary	1	5	Intermittent (assume 12 hr. per day
12. Fresh water	1	5	Intermittent (assume 2 hr. per day
13. Refrigerating	2	5	One continuous at sea
14. Evaporator	1	5	Intermittent (assume 3 hr. per day
15. Ballast	1	10	Intermittent (assume 4 hr. per day
16. Work shop	1	5	
17. Oil purifier	1	5	
18. Galley	1	5	

well ventilated. In general, enclosed self-ventilated motors are recommended for the reason that they are often located in congested places, where if open they would be liable to mechanical injury and in addition would have to be protected from dripping water. However, as electrical machinery when open is more readily inspected and kept clean, it is not essential that the motors be enclosed if located, *e. g.*, on a gallery and properly protected from dripping water. Such motors should be screened to prevent rats eating the insulation. On tankers, if the cargo pump motors are of the direct-current type and are located in a special pump room, they must be provided with some means of ventilation which will insure all explosive gases being driven off before the motors are started.

The motors in the engine room should be insulated with the same care and the castings as thoroughly cleaned and painted as the motors on deck. The insulation on all marine electrical apparatus should be made as highly moisture-resisting as possible.

As illustrating the adaptability of electrical apparatus, the writer recently saw a report from a chief engineer which stated that when the steam engines on his circulating pump and dry vacuum pump broke down he replaced them by two deck winch motors. The drive was so satisfactory that he intended to recommend that it be made permanent and incidentally the ship burned 1½ tons of fuel oil per day less after the change.

FIG. 5—MARINE D-C. MOTOR—ENCLOSED, VENTILATED, FOR OPERATING BELOW-DECK MACHINERY

Control. It would seem desirable that the means for starting and stopping each motor be located directly adjacent to it. Such starters are relatively inexpensive. They should be very substantial and moisture-resisting. Thin sheet iron should not be used, especially on any part of the construction which cannot be readily painted, as after a short time it is liable to rust and may be the cause of serious trouble.

On steamships the motors on the circulating pump, lubricating oil pump, boiler feed pump, hot well pump, balancer set or lighting motor-generator set if any, and steering gear, should be fitted with starters so that when power is restored after an interruption these particular motors will immediately start up automatically. The other motors can be restarted by the engineer at his convenience.

Generating Units. A study of the installations on a number of cargo ships of various tonnages indicates that on a steamship 150 kw. would give ample power for the deck machinery when in port and for the entire engine room equipment when at sea. On a motorship about 75 kw. is necessary at sea. Therefore, on cargo ships of about 10,000 dead-weight tons, two 150-kw. steam turbines or on the motorships three 75-kw. generator sets would give ample power with one unit for a standby at all times. The auxiliary power in many cases will be much greater than 150 kw. *e.g.*, refrigerator ships and ships fitted in part for passenger service. The larger the amount of auxiliary power the greater the reason for highly efficient auxiliary turbines. Some studies have shown requirements for auxiliary power as great as 1500 kw.

Small steam turbines should be substantial and simple as they will be classed as part of the propelling machinery and therefore vital to the safety of a ship. In sizes of 150 kw. and even smaller, gear reduction would be recommended, as the best direct-current generator operation cannot be expected at the speed at which the turbine should run in order to get good economy. It is expected that these sets would be more substantial and conservative than sets of similar capacity for land service where they are at all times readily accessible.

For the reason that on shipboard there is always possibility of scale or salt passing to the turbine from the boilers it is preferable for the governor to control the speed by means of an oil Servo motor. All parts should be readily accessible. Even with the greatest care there is always liability that the lubrication may be momentarily interrupted, and as the bearings should be examined before the machinery is placed in service they should all be readily removable for inspection. An overspeed or emergency governor of the simplest and most reliable type should be fitted. Very specific and simple instructions should be issued to show the operating engineer the necessity of testing the governing mechanism periodically and assuring himself that it is in perfect operating condition.

THE MOST SUITABLE ELECTRIC POWER.

All references indicate that at the present time direct current is being generally adopted for auxiliary power on merchant ships. Some time ago there was considerable discussion as to the relative merits of alternating current and direct current. The following tabulation will show why direct current is being used to the greater extent:

CARGO SHIPS

DIRECT CURRENT

Arguments for	Arguments against
1. Simple wiring.	1. Commutators require some attention.
2. Any speed control easily obtained.	
3. Equally suitable for continuous and intermittent duty.	

ALTERNATING CURRENT

1. Lower cost of motors and generators.	1. Wiring more expensive.
2. Absence of commutators.	2. Unsuitable for variable speeds necessitating hydraulic or other gear for winches and windlasses.

TANKERS

DIRECT CURRENT

1. Simple wiring.	1. Commutators require some attention.
2. Equally suitable for continuous and intermittent duty.	2. Little necessity for variable-speed motors. Special cases could be fitted with hydraulic or direct-current power furnished from small motor-generator set.
3. Speed of cargo pump can be varied to suit pressures and most efficient rate.	3. Special precautions must be taken to ventilate motors in tank room.

ALTERNATING CURRENT

1. Lower cost of motors and generators.	1. Wiring more expensive.
2. Absence of commutators, particularly desirable in pump room.	2. Special motors necessary to change speed.
3. Cargo handled by constant speed pumps.	

It would seem that for cargoships direct current can be used to the greatest advantage. On tankers this is not so apparent.

Except in the smaller ships, it is desirable to use not less than 230 volts. The lower voltage necessitates large or more expensive control; also the cost of wiring and switches is greater.

For lighting, the arguments seem to be in favor of 115 volts. This necessitates the installation of a small 115/230-volt motor-generator set. The use of incandescent lamps for 230 volts is not recommended. They are of necessity built with a very fine filament, and are, therefore, less substantial and further are not easily procured in seaports.

WIRING AND INSTALLATION

It is impossible to speak too forcibly on this subject. A great deal of critcism of electrical apparatus when thoroughly investigated has been found to be directly due to faulty, careless, slipshod methods of wiring and installation. Care and attention have been given to choosing apparatus, but the method of installation, the kind of wire, and many details of vital importance have been left to the wiremen's discretion with the inevitable result.

It is not the intention here to suggest that definite rules be laid down. Each engineer must work out his own particular problems. Certain underlying fundamentals, however, can generally be applied. The following are recommended:

That the wiring and distribution in the engine room be made as simple as possible, with relatively few circuits.

The switchboard should be largely a distribution panel designed with the idea of attaining maximum simplicity and occupying the least amount of engine-room space.

Circuits may be led from this distribution panel to different parts of the ship where they may be further subdivided, as *e. g.*, five circuits for deck machinery No. 1 to the steering engine, No. 2 to the after hatches No. 3 to the forward hatches, No. 4 to anchor windlasses, and forward capstans, No. 5 to after capstans. This will permit opening all the winch circuits when at sea and also allow for thorough inspection and try out of the capstans, anchor windlass or steering engine when in port even if cargo is being handled.

In the engine room, a similar method may be applied, one circuit to the engine room auxiliaries, port side and another to the starboard side. By such simplification it will be possible to obtain low cost with maximum reliability.

Cables should not be run in conduits except perhaps for very short lengths where necessary for mechanical protection. Cables in the engine room should be run overhead. All cables should be thoroughly anchored so that the covering will not be chafed due to vibration.

OPERATION

To study the relative merits of ship's auxiliaries, it is necessary to consider the part which they play in the economic operation of the ship.

For certain special types of ships designed and built to operate for some particular service, such as tankers and lake ore carriers, it is not difficult to show definitely why a certain installation will give the best return on the investment.

In the cargo ship, however, the problem is not so clearly cut. While it is true that a certain number of ships may be designed with the intention of travelling particular trade routes and handling a special cargo it is often found that their schedule must be modified. Therefore, the general cargo ship must be built to handle all kinds of cargo and at best, therefore, the apparatus with which it is equipped is somewhat of a compromise.

It is not possible to make any exact general statement as to the proportions of the various items constituting the cost of operating merchant ships. They may, however be listed as follows:

1. Fuel and lubricating oil at sea and in port.
2. Port charges including wharfage, lighterage,

pilot fees, canal dues, stevedoring, tug-boat charges, etc.

3. Salaries and subsistence.
4. Up-keep and repairs, deck department.
5. Up-keep and repairs, engine department.
6. Supplies, engine, deck and steward's departments.
7. Insurance.
8. Loss and damage.

If we assume a 7800-dead-weight ton ship fitted with 2500-h. p. steam turbine on a schedule for coastwise service between New York and Seattle, stopping at San Pedro to load and discharge cargo and making four round trips per year, the charges might be approximately as follows:

OPERATING DISBURSEMENTS

	Loaded both ways	Percentage	Loaded going one-half loaded returning
1. Fuel	$81,300	14.8	$81,300
2. Port charge	290,420	52.9	211,020
3. Salaries	60,490	11.0	60,490
4. Repairs, deck	10,000	1.8	10,000
5. Repairs, engine	20,000	3.7	20,000
6. Supplies	20,250	3.7	20,250
7. Insurance	62,400	11.4	62,400
8. Loss and damage	3,650	.7	3,650
Total	$548,510	100%	$469,110

Many of these would be affected by electrification of auxiliaries, and the net reduction would be very considerable.

1. *Fuel, etc.* In the usual marine geared turbine installation with steam auxiliaries, the pressures generally carried are as follows:

Boiler pressure	210 lb. gage
Turbine bowl	200 lb. "
Auxiliary steam line	100 lb. "
Auxiliary exhaust	10 lb. "
Superheat	75 deg. fahr

The auxiliary exhaust steam is used to heat the feed water and that which is in excess of feed-water heater requirements is by-passed to the main condenser.

Under full power, a fair operating average for this type of installation is as follows:

Steam consumption per hour:

Main turbine, 2500-h. p.	28875 lb.
Steam auxiliaries at sea	12500 "
Total steam consumption	41375 "

Steam per shaft horse power hour, all purposes:

Steam per shaft h.p-hr., all purposes.... $\frac{41{,}375}{2500} = 16.5$ lb.

Boiler Evaporation:

With water-tube boilers, Howden draft system, feed water delivered to boilers at 220 deg., 210-lb. gage pressure and 75 deg. superheat, a conservative estimate of the actual evaporation per pound of fuel oil is taken at 13.5 lb.

Fuel Consumption:

Fuel per hour $= \frac{41{,}375}{13.5} = 3065$ lb. .... = 9.6 bbl.

Fuel per day..........73,560 lb............. = 32.8 tons

Fuel in bbl. per day........................ 230

Fuel per shaft horse power hour:

Fuel per shaft horse power hour $= \frac{3065}{2500} = 1.23$ lb.

Fuel in barrels, per knot:

Assuming a speed of 10.5 knots $\frac{9.6}{10.5} = 0.915$ bbl. per knot

The economy to be gained through the application of electrically driven auxiliary machinery, in fuel consumption alone, may readily be seen from the following estimates.

ELECTRIC AUXILIARIES

Superheat 75 Deg. Fahr.

Heating feed water:

The proposed method would be to extract sufficient steam from the turbine for feed water heater requirements.

Steam consumption, per hour:

Main turbine 2500-h. p.	30,600 lb.
Turbine generator	2,640 "
Air ejector	1,000 "
Total	34,240 lb.

Note: 3600 lb. per hour steam will be extracted from main turbine at about 10 lb. gage to heat feed water.

Steam per shaft horse power, all purposes:

Steam per shaft h.p-hr., all purposes, $\frac{34{,}240}{2500} = 13.7$ lb.

Boiler Evaporation:

Estimated for comparative purposes at 13.5 lb. per lb. of fuel. With the lesser quantity of steam to generate, however, the boiler efficiency would be improved in actual practise.

Fuel consumption:

Fuel per hour $\frac{34{,}240}{13.5} = 2536$ lb. $= 7.9$ bbl.

Fuel per day 60864 lb. = 27 tons
Fuel per day in bbl. = 189 bbl.

Fuel per shaft horse power hour:

Fuel per shaft h.p-hr. $= \frac{2536}{2500} = 1.01$ lb.

Fuel in barrels per knot:

Assuming a speed of 10.5 knots, $\frac{7.9}{10.5} = 0.75$ bbl. per knot.

The application of high superheat, well within the limits of present-day design, and electric auxiliaries present a very interesting and high economic value in ship propulsion.

ELECTRIC AUXILIARIES

SUPERHEAT 200 DEG. FAHR.

Steam consumption, per hour:

Main turbine, 2500 h. p.	27,000
Turbine generator	2,400
Air ejector	1,000
	30,400

Note: 3000 lb. per hour steam will be extracted from main turbine at about 10 lb. gage to heat feed water.

Steam per shaft horse power, hour all purposes:

Steam per shaft h.p-hr., all purposes .... $\frac{30{,}400}{2500} = 12.15$

Boiler evaporation:

Assumed at 13 lb. per pound of fuel.

Fuel consumption:

Fuel per hour $= \frac{30{,}400}{13} = 2340$ lb. $= 7.33$ bbl.

Fuel per day 56,200 lb. ..... = 25.1 tons
Fuel in bbl. per day .... = 176 bbl.

Fuel per shaft horse power hour:

$$\text{Fuel per shaft h.p-hr.} = \frac{2340}{2500} = 0.936 \text{ lb.}$$

Fuel in barrels per knot:

$$\text{Assuming a speed of 10.5 knots } \frac{7.33}{10.5} = 0.698 \text{ bbl. per knot.}$$

These estimates show the saving in fuel consumption by the use of electric auxiliaries, as follows:

Saving in Fuel Consumption (at sea):

Steam auxiliaries	230 bbl.	
Electric "	189 "	17.3 per cent
Electric " with 200 deg. fahr. superheat	176 "	23.5 per cent

Saving per year:

208 days at sea, oil at $1.50 per bbl.

Electric auxiliaries	8320 bbl. at $1.50	$12,480
Electric " with 200 deg. fahr. superheat	11,250 " " $1.50	16,900

In the estimate, an allowance was made of 40 bbl. per day in port. With electric auxiliaries, and economic engine room machinery, it should be possible to reduce this by one-half.

157 days × 20 lb. × $1.50 .... = $4,710

With a good system in the engine room, the lubricating oil required would be greatly reduced.

2. *Port Charges.* In giving thoughtful consideration to improving the earning power of a ship, it will be recognized as essential to decrease its idle time, as certain charges are continuous, whereas the ship is actually earning money only when traveling between ports. When it is realized that the average cargo ship makes only about 36,000 miles per year and that at an average speed of 10 knots, this means she is at sea only about 150 days out of a year, it is very evident that there is a big field for improvement.

Port charges estimated for the coastwise schedule mentioned above are as follows:

	N. Y.	Colon	Los Angeles	San Francisco	Seattle	Total
(a) Wharfage......	$7800	....	$1560	$3120	$3120	$15,600
(b) Lighterage.....	....	....	....	....	....	....
(c) Pilots fees......	202.56	....	200	250	....	652.56
(d) Stevedoring....	7800	....	1560	3120	3120	15,600
(e) Tug-boat charges........	100	....	....	200	....	300
(f) Canal dues.....	....	$4150	....	....	....	4,150

Total per trip....................................	$36,302.56
Total per year (4 round trips).........................	$290,420.48

It will be evident that any means which will reduce the time a ship has to lie at the wharf loading or unloading cargo should lessen the two items *wharfage* and *stevedoring.* The writer has been informed of specific cases where ships have been delayed at docks due to freezing of steam deck machinery. He has also been informed of a specific case where two similar ships loading and unloading the same kind of cargo at the same dock and with the same stevedore foreman, the electrically equipped ship loaded in very much less time. Another specific case where a number of ships fitted with steam deck machinery had to await a derrick to assist in loading heavy cargo, where a ship fitted with electric machinery was able to handle its own cargo and saved a number of days delay.

Delays have been experienced with steam machinery due to low steam pressure. This may not be due to drop in boiler pressure but to loss in piping. With electric equipment, there is always ample power available for the winches.

By the use of the most suitable electric machinery, it should be possible to reduce the item of port charges 10 per cent. In the estimate given above this would mean approximately $30,000 per year saving.

3. *Salaries.* In all probability the salaries would not be directly affected. In the larger ships and in those where there is a very large amount of auxiliary power it might be found desirable to increase the salary slightly for one of the positions, in order to secure a man with electrical experience.

4. and 5. *Upkeep and Repairs.* Both of these items

should be reduced. With properly designed electric machinery, the charges for repairs and maintenance would be less than with steam machinery. If compared with many existing ships a 20 per cent reduction would in all probability be a conservative estimate. If we only allow 10 per cent, however, this would mean a saving of approximately $3000 per year on the above estimate.

6. *Supplies.* This item would not be appreciably affected in the deck department, but for the engine department, there should be a material reduction.

A saving of 10 per cent might be expected, which would amount to $2000 per year.

7. *Insurance.* The assured reliability of proper electrical machinery in the engine room, along with the elimination of a large amount of piping carrying high-pressure steam, should have a direct bearing on the insurance rate. Indirectly, by reducing the loss of steam it should be possible to maintain the water in the boilers in almost perfect condition. This should still further add to the safety of a ship. It would seem to be justifiable to expect that the insurance premiums can be decreased about 5 per cent; this would mean a saving of approximately $3000 per year.

8. *Loss and Damage.* This item in all probability would not be affected.

The sum of the different gains mentioned above totals $55,190 per year. The amount of saving that can be shown by other estimates will naturally vary with conditions. In any estimates the possibility of making a substantial gain in the earning capacity in a ship is a real one. Having in mind certain ships, there is every reason to believe that the figures mentioned above might be increased.

One of the latest British combined cargo and passenger ships is equipped electrically and is fitted with over 100 motors driving auxiliary apparatus. Needless to say, the owners of new foreign ships are fitting them with electrically driven machinery only because they have satisfied themselves that it is profitable to do so. We engineers in this country should combine our efforts and avail ourselves of every opportunity to improve the efficiency of our merchant ships to the end that they may be able to compete successfully with the modern ships being placed in service by the other counties.

Presented at the Joint Meeting of the American Institute of Electrical Engineers and the Society of Naval Architects and Marine Engineers, New York, N. Y., November 17, 1921.

ELECTRIC PROPULSION OF SHIPS

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THIS paper deals primarily with the electric propulsion of ships, except wherein a comparison of some particular feature or characteristic warrants a reference to some other type of drive. In dealing with electric propulsion, it is necessary to consider all classes of ships, and this leads to two broad, general classifications, such as merchant ships and war vessels.

Merchant Ship Pulsive Equipment

GENERAL REQUIREMENTS

The ultimate purpose of a merchant ship is to earn money. From this standpoint, the factors of reliability, economy, weight, space, cost, operation and maintenance are involved in the propulsive equipment. Therefore the type of drive most suitable is that which excels in all or the most important of these factors. The relative importance of these items varies with different ships, depending upon the trade route, cargo, etc., with the result that there is a definite and logical field for each of the principal types of drives, such as reciprocating engine, geared turbine, turbine-electric, Diesel and Diesel-electric. Since many general comparisons of the principal types of drives in regard to these factors have been given in recent articles in the technical press it is not the intent of the present paper to take up this phase of the subject, but rather to analyze the principal types of electric propulsive equipments and to show in general how they fulfill these requirements.

RELIABILITY

The universal use of, and the indisputable success of electrical apparatus on land is sufficient testimony in behalf of its reliability. The absence of reciprocating parts makes electrical apparatus with its simple rotation as reliable as can be desired. It can almost be said that there are no mechanical troubles with electrical machinery. Broadly speaking, there are no new principles involved in the application of electrical apparatus to ship propulsion. It is true that ship conditions differ from land conditions in certain respects, but there is no phase of the application which presents any really serious difficulty. The most important adverse condition is the deleterious effect of salt and moisture, which is easily surmounted by proper insulation of the windings and circuits, as is obvious from the several years of successful operation of present electric propulsion equipments. There can, therefore, be no question as to the reliability of electrical propulsive equipment.

ECONOMY

Economy is an important factor, and must be given due consideration. To properly analyze this item, it is necessary to consider all equipment involved in the propulsion, with respect to fuel, water, lubricants and supplies. The relative proportions of these items vary considerably in the different types of propulsive equipments. The turbine-electric and the geared turbine compare very closely in economy when all items are considered. The losses in the reversing elements of geared turbines, the losses in the gears and the power required to circulate the additional lubricating oil, detract appreciably from the gain which the geared turbine would otherwise have over the turbine-electric because of the inherent electrical losses in the latter. Generally speaking, the net economy of a properly designed and constructed geared turbine drive should be better than a turbine-electric drive, even though full advantage is taken of every practical source of gain in the latter. The difference, however, is perhaps hardly of sufficient magnitude to be the dominating factor in arriving at a final selection. The economy of a reciprocating engine drive is obviously poorer than that of a properly designed turbine drive of either type for the reason that the reciprocating engine cannot utilize the same expansion of the steam.

It has been advanced that the turbine for the turbine-electric system, being a one-direction rotation machine, can utilize higher superheat than the geared turbine, because of the reversing element of the latter, thus resulting in better overall economy. With the present installations, this condition is true to some extent. However, with proper attention given to this factor, geared turbines can be designed to operate without detriment with steam superheated 150 to 200 deg. fahr., which is fairly close to the practical limit of superheat on board ship, as there are other items aside from the turbines which are affected by high superheats to the extent of fixing limitations.

Obviously from a fuel consumption standpoint, the direct Diesel and Diesel-electric propulsive equipments offer by far the best economy. Of these two types, it would appear, offhand, that the direct Diesel drive is decidedly superior to the Diesel-electric; however, it will be shown later that there are certain limitations in the direct Diesel drive which offset its advantage in fuel per brake horse-power-hour over the Diesel-electric. Here again, it is obvious that all items related to the propulsive equipment must be taken into consideration to obtain the ultimate answer.

WEIGHT

The item of weight would probably show more variance than other items owing to differences of arrangement, design, foundations, etc., in the practise of the several ship builders. The importance of weight depends upon the type of ship, cargo, and trade route. Usually, however, weight is an important item as it has a direct effect upon the total fuel consumption and the amount of cargo that can be carried with a given displacement. Here again, it is necessary to consider all items related to the propulsive equipment. A correct comparison of weight necessitates that the equipments under consideration be on the same basis relative to overload, factor of safety and arrangement. This is particularly important in comparisons between electric drive equipments. Where one equipment affords an advantage in flexibility of reserve, however, it is usually at some sacrifice in weight, and an allowance must be made.

SPACE

Space is important in that it has a direct bearing upon the bulk of cargo that can be carried. Its relative importance depends somewhat upon the location of the machinery, *i. e.*, whether the machinery is located amidship or aft, or both. Space is affected by the distribution of machinery and the relative saving depends somewhat upon the practise of the various ship builders in that respect. General analysis of the space factors which have been made thus far gives the advantage to the direct-connected Diesel and Diesel-electric types of propulsive equipment, the saving being effected by the elimination of the boilers and reduction of fuel and water tanks. Of the turbine-electric and geared turbine types, the space factor is in favor of the geared turbine, except in special cases. The general arrangement of the engine room, number of propellers and the beam of the ship have a direct effect upon the space occupied as a result of machinery distribution. By locating the condensers underneath the turbines in electric drives, the total floor space can be greatly reduced.

COST

A definite comparison of costs is still a difficult task owing to the continued unsettled conditions. On the basis of equal performance in regard to propeller torque and speed, the cost including all items related to the propulsive equipment should run in the order of direct-Diesel, turbine-electric, geared turbine, and Diesel-electric, the latter being the cheapest. The paradox in the relative cost of direct-Diesel and Diesel-electric is explained by the condition that small Diesel engines and generators for Diesel-electric drives can be manufactured ultimately on a large production basis and stocked, whereas the engines for direct-Diesel drive, and to a large extent, the two types of turbine drive, because of their large size and weight, must almost of necessity be a building proposition. On the basis of standardized drives, there should not be a great deal in favor of the geared turbine as compared with the turbine-electric drive. This comparison will vary somewhat with the different manufacturers.

The initial cost of the propulsive equipment has a direct effect upon the net earning power of the ship, because of interest, depreciation and insurance charges, and therefore, cost is an important item.

OPERATION

In regard to operation, it is realized that the present operators are largely men who are more familiar with reciprocating engines than with other types of machinery, and that for this reason, certain difficulties are likely to be encountered in placing electrical equipments in their hands. The author believes that this thought should not be a consideration, as it is a temporary condition only. The horse car driver became the motorman of the electric car, the reciprocating plant operator became the turbine plant operator in the central station, the steam locomotive engineer became the electric locomotive engineer (engineers now operating electric locomotives are reluctant to return to the steam locomotive), and similarly countless examples may be mentioned to show that change in machinery represents no obstacle. Successful operators of electrical machinery need not have sufficient knowledge of it to understand the details of its design. This is not the case on land and there is no greater reason for it on the sea. The operator should, however, know the operating characteristics of electrical apparatus and how to take care of it.

The same question was raised in the case of geared turbines only a few years ago, yet today there is nearly a sufficient number of competent geared turbine operators to take care of all the geared turbine ships. The same will be the case with operators for electric ships. It is merely a matter of training and education and it is certainly a reflection upon the intelligence of the age to classify the present limited knowledge as an obstacle for consideration.

The following is a probable list of the operating personnel for the principal types of drives. The cost of operating personnel as based upon this list would, therefore, be in the order of,—direct-connected Diesel, turbine-electric, geared turbine, reciprocating engine, and Diesel-electric:

TABLE OF PROBABLE OPERATING PERSONNEL.

		Reciprocating engine	Geared turbine	Turbine electric	Direct connected diesel	Diesel electric
		*	*	*		
Total Crew	Chief..........	1	1	1	1	1
	1st. Asst........	1	1	1	1	
	2nd. Asst......	1	1	1	1	1
	3rd. Asst......	1	1	1	1	1
	Jr. Engrs......	0	0	0	3	0
	Electricians...	0	0	1	1	1
	Oilers..........	3	3	3	6	6
	Firemen.......	6	6	6	0	0
	Total.......	13	13	14	14	1
On each watch	1st., 2d or 3d..	1	1	1	1	1
	Junior Engrs...	0	0	0	1	0
	Electricians...	0	0	0	0	0
	Oilers.........	1	1	1	2	2
	Firemen.......	2	2	2	0	0
	Total.......	4	4	4	4	3

*Based on oil burning ships. For coal ships, the operating personnel would be augmented by three coal passers.

MAINTENANCE

Although there are practically no data available on the maintenance of electrical propulsive equipments (except battleships), there is no reason to anticipate any great difference between sea and land practise. As a matter of fact, there is reason to anticipate less maintenance for the reason that the load conditions and control operations are less severe than is the case with most land installations involving large machinery. If the equipment is given proper care and inspection, the maintenance item will be low, as the absence of rubbing parts (except for the bearings), leaves little to get out of order. Electrical machinery does not wear as is the case with other machinery. Furthermore, all probable repairs are such as can be made aboard the ship without the use of an elaborate machine shop.

PERFORMANCE CHARACTERISTICS

The inherent performance characteristics of electrical machines are particularly well suited to ship propulsion. Having identical operating characteristics in either direction of rotation, all types of electric drive inherently afford, or can be made to afford, full torque and power for reversal. For reasons of economy, space and cost, the reversing element of a geared turbine is designed to give only 40 per cent to 60 per cent power in the reverse direction. It has been claimed that full reverse power is not essential to a merchant ship, and this is true under ordinary conditions. In emergency, however, it is desirable to stop the ship very quickly, and in this connection it might be pointed out that the electric ship can be stopped in considerably less time than a geared turbine ship. This is not altogether the result of less backing power, but is due to a great extent to the inefficiency of the reversing element of the geared turbine causing an enormous draft on the boilers which greatly reduces the steam pressure.

In reversing, the energy put into the screws by the action of the water and the stored energy in the rotating parts attached to the propeller shaft, must be dissipated in some manner. In the case of the geared turbine, this energy is consumed in doing work on the steam. In the case of a-c. electric drives, the energy of reversal is dissipated in the motor and generator windings, the rotors of the motors, or in external resistors connected to the rotor circuits, depending upon the type of motor used. In d-c. electric drives, the reversal energy must be absorbed elsewhere in the system. The amount of energy to be dissipated or absorbed in the case of a given ship depends entirely upon the time taken to stop the screws. The instant the screws commence to turn over in the reverse direction, the system must supply the energy and all further stopping energy is dissipated at the propellers. There are two factors to be considered in stopping, namely, the energy returned through the propellers, and the stored energy in the propellers and the motor armatures. Analysis shows that reversing even at full speed is not a serious problem, and that it does not place as severe requirements upon the electrical machinery as does turning with hard-over rudder. The details of the distribution and absorption of the energy of reversal would occupy too much space to be discussed at this time. Suffice it for the present to say that the inherent facilities afforded by electrical systems for dissipating energy and for giving full power in either direction are what make the electric drives ideally suited for stopping. The time required to stop an electric ship is the same as, or less than, that of other drives.

Description of Electrical Propulsive Equipments

GENERAL CLASSIFICATION

Electrical systems for ship propulsion may be classified into two general types from the standpoint of the prime movers, namely, turbine-electric and Diesel-electric. Due to the inherent performance of these two types of prime movers, both kinds of electric machinery are used; a-c. machinery with turbine-electric because the a-c. generator is inherently suitable for direct connection to the economical high-speed turbine; and d-c. machinery with Diesel-electric drive because the inherent characteristics of the d-c. generator are ideally suited to Diesel engine performance.

The electrical equipment for turbine-electric drive may be further sub-divided as follows, in regard to the type of motor:

- 1 Induction
  - Wound secondary
    - Ordinary, and with power factor correction
  - Squirrel cage
  - Combined squirrel cage and wound secondary
- 2 Synchronous

In the case of the Diesel-electric drive, there is no broad subdivision. As a minor classification, this type of drive might be subdivided with respect to the method of generator operation, *i. e.*, series and parallel.

However, series operation is so vastly superior that parallel operation can be disregarded except for the purpose of comparison.

UNITS INVOLVED

A complete turbine-electric drive involves the following apparatus:

- Boiler plant
- Evaporation plant
- Condenser plant
- Turbine
- Generator
- Motor
- Oiling system
- Exciter set
- Control

A complete Diesel-electric drive involves the following apparatus:

- Diesel engines
- Generators
- Motors
- Small auxiliary air compressors
- Air bottles
- Exciters
- Fuel pumps, (if not attached to engine)
- Lubricating pumps, (if not attached to engine)
- Control

TURBINE-ELECTRIC

With turbine-electric drive, the electrical equipment is of the a-c. type, principally for the reason that a-c. turbo generators are inherently better suited for the high economical speeds of turbines. The speed at which the turbine operates is influenced by the propeller speed because of the limitation in the number of poles of the motor. Theoretically, an a-c. motor can be built for any even number of poles, but in practise such factors as power factor, (induction motor), diameter and assembly, fix the limit in the neighborhood of 60 to 72 poles. As the motor speed and number of poles fix the generator and turbine speed, there is consequently an approximately fixed limit to turbine speeds. Incidentally, in the case of practically all merchant ships, this speed is lower than the most economical speed of the turbine. As the propeller is most efficient when designed and operated at low speeds, it is advisable not to exceed 90 to 100 rev. per min. for the ordinary merchant ship.

Assuming a propeller speed of 100 rev. per min., a 60-pole motor and a two-pole generator, the generator and consequently the turbine would operate at 3000 rev. per min. (neglecting the slip in case of the induction motor). This gives a reduction from the turbine to the propeller of 30:1, which is approximately the same irrespective of the type of motor used.

Fig. 1 shows a diagrammatic scheme of connections for an induction motor drive of the wound secondary type. Power is supplied from the turbine-driven generator to the induction motor through one of the reversers. The generator is excited from one of the auxiliary geared turbine d-c. sets. Whether the auxiliary set would supply generator excitation only, or simultaneously furnish ship's auxiliary power, depends principally upon the electrification of engine room auxiliaries, winches, etc.

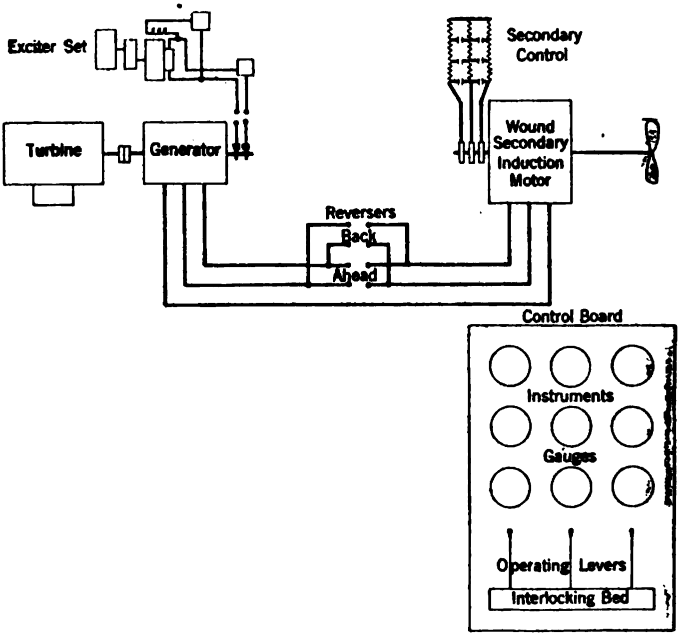

FIG. 1—WOUND-SECONDARY INDUCTION-MOTOR DRIVE
Diagrammatic scheme of connections.

The turbine is under the control of a governor capable of maintaining constant speed over about 75 per cent of the entire speed range. The governor speed control valve is regulated from the control stand by an oil relay valve or system or rods and levers, depending upon the type of governor used. The propeller speed is adjusted by throttling the turbine as in the case of a geared turbine drive. The turbine is started and brought up to its "idling speed" by the throttle valve at the turbine.

Similarly, the generator field switch and rheostat, and the ahead and back switches are controlled from the control stand by means of levers. These levers are mechanically interlocked so that it is necessary to follow the proper sequence of operations in starting, stopping and maneuvering.

Usually, the reversers are interlocked with the field lever so that the field lever must be in the "off" position before the reversers can be opened or closed. Similarly the field is interlocked with the turbine speed control lever so that the control valve must be set for low speed before the field can be opened or closed.

The secondary control is automatic, being either of the solenoid contactor or motor-operated contactor type. The actuating means is energized through contacts on the field lever near the end of its stroke. This arrangement insures the establishment of voltage at the motor before closing the secondary accelerating switches. Similarly, moving the field lever to the "off" position, opens the secondary switches.

The operating levers and a complete complement of electrical instruments and steam gages are arranged convenient to the operator, the instruments and gages being mounted on a panel directly above or in front of the levers. By observing the instruments, the operator will be kept informed at all times of the performance of all machines, even though the machines be obscured from his view.

By a suitable arrangement of the switches and control levers, the entire maneuvering of a ship of any size and any number of screws, can be under the complete control of one operator.

The interlocking system necessitates the following sequence of operation:

A—Starting Ahead (Turbine Idling):

1. Close **Reverser** in "Ahead" position,
2. Close **Field** and establish excitation,
3. Adjust **Turbine Speed** to desired value after secondary is completely short-circuited.(Indicated by pilot light)

B—Stopping:

1. Move **Turbine Speed** control lever to idling position,
2. Move **Field** lever to "off" position.
3. Move **Reverser** to "off" position.

C—Starting Back:

1. Close **Reverser** in "Back" position,
2. Close **Field** and establish excitation,
3. Adjust **Turbine Speed** to desired value after secondary is completely short-circuited.

D—Reversing (From Ahead Operation):

1. Move **Turbine Speed** control lever to idling position,
2. Move **Field** lever to "off" position,
3. Move **Reverser** from "Ahead" to "Back" position,
4. Move **Field** lever to full excitation,
5. Bring up **Turbine Speed** after motor has pulled into step.

The above description applies to a single-screw drive having but one turbine set. For a multiple-screw ship having generating sets for port and starboard sides, the operation would be the same for each side of the ship, as just described.

The above operations are based upon switching when the current in the circuits has been reduced to very low values, or nearly dead circuit conditions. This arrangement is not really necessary, as, with small powers, it is is not essential to open the generator field; however, it may be justified in the light of conservatism. In any event, the reversers are so designed that they are entirely capable of opening full power.

The salient features of the wound-secondary-induction-motor drive are its inherent torque characteristics and the ease of handling. While the secondary control necessitates a few additional switches, this is fully compensated for by the fact that the propeller energy of reversal, and the slip energy of reversal and starting is dissipated in resistors external to the motor. The importance of this is dependent upon the amount of reversing that is done, particularly from full speed.

This system, therefore, represents the most conservative arrangement of turbine electric drive.

The squirrel-cage motor system is shown in Fig. 2, and it will be noted that the electrical connections are the same as for the wound-secondary motor system, except that there is no secondary control. This system is, therefore, somewhat simpler than the wound-secondary motor system from an electrical connection standpoint, both inside and outside the motor. It also has a slight advantage in cost in that the motor is less expensive to build. The squirrel-cage motor is shorter because of the absence of collector rings. It has a disadvantage in conservatism and torque characteristics.

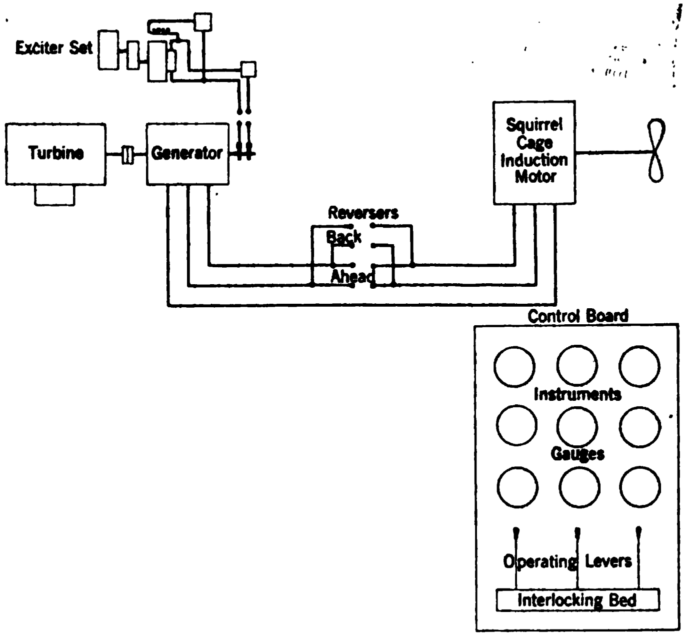

Fig. 2—Squirrel-Cage Induction-Motor Drive
Diagrammatic scheme of connections.

The power factor of either of the induction motor systems is less than unity, the exact value depending upon the number of poles and certain design features. For the ordinary merchant ship requirements, these motors would have power factors of approximately 70 per cent, the wound-secondary motor having the higher power factor of the two, by a small amount. The induction motor drive, therefore, requires a generator with kv-a. capacity in excess of its kw. capacity, which adds somewhat to its weight and size, and which detracts a very small amount from its efficiency.

The efficiency of the squirrel-cage induction motor of ordinary design is slightly less than that of the wound-secondary motor, for the reason that sufficient permanent resistance must be incorporated in the rotor windings to obtain the required torque for reversal without excessive current. In large motors with special double secondary windings, the required torque can be obtained without excessive current and the running efficiency can be improved somewhat. Such motors are in use on propeller drives at the present day.

TURBINE ELECTRIC
(Synchronous)

Fig. 3 shows a diagrammatic scheme of connections for a synchronous motor drive. Power is supplied from the turbine-driven generator to the synchronous motor through one of the reversers. The generator and motor fields are excited from a three-wire, d-c. exciter set. The synchronous motor system differs from the induction motor system only insofar as the synchronous motor itself affects the details of control and generator capacity, the main features of turbine-electric drive being otherwise the same.

Although the characteristics of the ordinary synchronous motors are not suitable for ship propulsion, the synchronous motor can be modified to give characteristics which meet the requirements. The modification consists in providing the rotor with a substantial induction winding of such design and arrangement as will not seriously detract from certain purely synchronous motor characteristics which are desirable.

The maneuvering operations can be accomplished in more than one way. If appreciable torque is required to reverse, the method which appears to be most favorable is to utilize the synchronous characteristics and the induction characteristics at different stages of the reversing cycle. The motor is stopped as a synchronous generator loading into the generator windings which form a dead load (generator field not being excited), then is brought up to nearly synchronous speed in the reverse direction as an induction motor, and finally is pulled into step with the generator as a synchronous motor. With this method, the sequence of operation for reversing would be approximately as follows:

1. Reduce turbine to idling speed (25 per cent.)
2. Open generator and motor fields,
3. Reverse motor connections,
4. Apply motor field excitation bringing motor to rest,
5. De-energize motor field,
6. Energize generator field to double value, bringing motor to nearly synchronous speed as induction motor,
7. Apply normal excitation to motor field, pulling motor into synchronism with generator,
8. Adjust speed to desired value.

The method described above is preferable where appreciable torque is required during reversing. Usually, however, sufficient torque will be developed by the simpler method of reversing as an induction motor, in which case the cycle of operation will be as follows:

1. Reduce turbine to idling speed (25 per cent),
2. Open generator and motor fields,
3. Reverse motor connections,
4. Energize generator field to double value, bringing motor to rest and reversing it to nearly synchronous speed, as an induction motor,
5. Apply normal excitation to motor field, pulling motor into synchronism with generator,
6. Reduce generator field to normal,
7. Adjust speed to desired value

This method, therefore, simplifies the sequence to the extent of omitting one step and eliminating the generator action of the synchronous motor.

Although eight and seven steps respectively have been indicated in the sequence, some of the steps can be combined so as to reduce the actual number of lever operations to a reasonable amount.

Although the synchronous motor requires special design and introduces additional complications in the control, it has the important inherent characteristic of unity power factor. The unity power factor results in slightly decreased weight and size, and consequently less cost of the motor and generator. Taking the drive as a whole, and considering that both motor and generator must be excited from a separate source at a cost of at least twice the steam per kw-hr. as the main turbine, the efficiency improvement over the induction motor drive is more apparent than real. Therefore, the principal advantages of the synchronous motor drive as compared with the ordinary induction motor drive are a slight saving in cost, weight and space, with a possible inappreciable margin in efficiency.

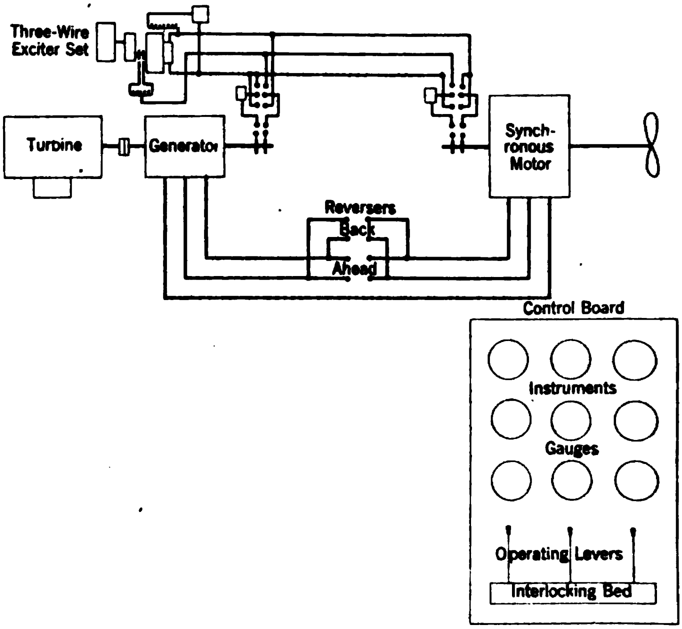

FIG. 3—SYNCHRONOUS MOTOR DRIVE
Diagrammatic scheme of connections.

TURBINE ELECTRIC

(Induction with Power Factor Correction)

The unity power factor advantage of the synchronous motor system is also available with a wound-secondary induction motor system in which the low lagging power factor is corrected to unity. This arrangement not only provides a system of the same weight, space and cost of the synchronous system, but in addition possesses the superior torque characteristics and simplicity of control of the wound-secondary induction system.

The diagrammatic scheme of connections is shown in Fig. 4. It will be noted that this is the same as the wound-secondary induction motor system shown in Fig. 1, except that power factor corrective apparatus has been added. The scheme functions in the same manner and sequence as that shown in Fig. 1 until the motor is in step with the generator, and at this point the power factor corrective apparatus is caused to function. The corrective apparatus consists of a Le Blanc phase advancer driven by a small d-c. motor, the speed of which may be varied to suit the power factor correction desired. The function of the phase advancer is somewhat similar to that of the d-c. exciter in the case of the synchronous motor in that it supplies excitation to the induction motor. The connection is made to the secondary or rotor winding and thus excitation is supplied through the secondary instead of through the primary, with the result that the primary current is all "power" current, which means "unity" power factor.

The phase advancer is a small commutating machine of very simple construction. The losses in the phase advancer consist of the internal copper loss due to the secondary current, almost negligible iron losses, friction, windage and brush drop. The total of these losses is very little and compares very favorably with the excitation power of the synchronous motor.

The induction motor used with this system is simple in construction, smaller, lighter and consequently less expensive than the motor used with the ordinary wound-secondary induction motor system. The generator is the same as that for the synchronous motor drive. Thus, the induction motor drive with the phase advancer not only provides the advantages resulting from unity power factor, but in addition provides the superior torque characteristics of the wound-secondary induction motor for maneuvering, and also obviates the necessity for synchronous operation with the generator. In fact, it combines all the desirable features and characteristics of both systems, without complications.

DIESEL-ELECTRIC

For practical reasons, direct current only is feasible with Diesel-electric drive. This will be evident by a proper analysis of the performance of Diesel engines in connection with the characteristics involved in applying a-c. and d-c. machinery, due consideration of ship requirements being taken into account. To obtain the best results with Diesel-electric drive, it is necessary to provide several relatively small and moderately high-speed generating sets for supplying power to single or double-unit direct-connected propelling motors. Not only must the generated power divide evenly or proportionately between the generating units, but the system must also be such as will conveniently and economically lend itself to speed control.

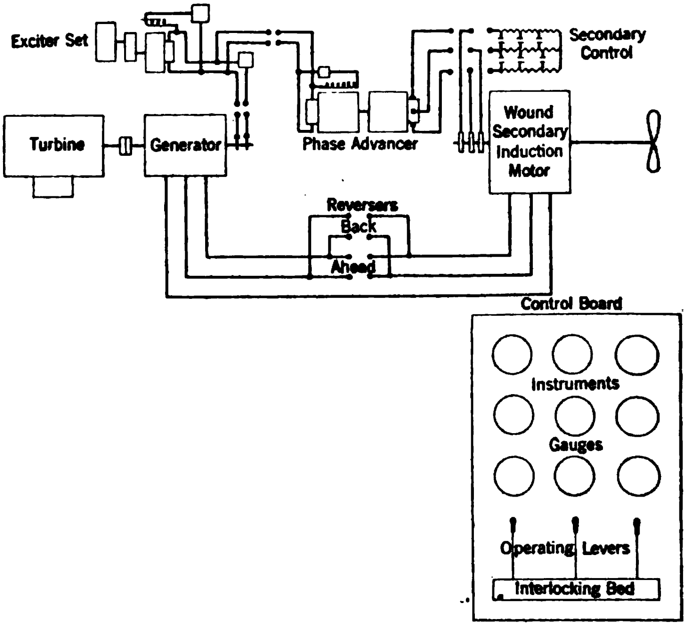

FIG. 4—WOUND-SECONDARY INDUCTION-MOTOR DRIVE WITH PHASE ADVANCER FOR POWER FACTOR CORRECTION
Diagrammatic scheme of connections.

In the case of alternating current, it would be necessary to operate the generators in parallel. To operate a-c. generators in parallel necessitates the very closest speed regulation and practically identical angular velocities of all prime movers. To visualize properly this exacting requirement, it must be remembered that satisfactory parallel operation of a-c. generators necessitates that the angular displacement of the field poles of one machine with respect to another must not vary more than approximately ± 3 electrical degrees, or a total of 6 electrical degrees. Since 360 electrical degrees constitute the space between adjacent like poles, the total variation in mechanical degrees, for example, in the case of a 20-pole machine, must not exceed 0.6 degree. While successful operation under such requirements is carried out in several land installations where the prime movers operate at constant speed, it is not considered safe practise on board ship *where the necessity for varying the speed of all sets simultaneously* introduces another very serious difficulty. To overcome this condition successfully, would require absolutely perfect engine governors which would function 100 per cent perfect at any speed setting. The speed of the motor could be varied by the rheostatic method, thus allowing the engines to operate at constant speed; however, this method is extremely wasteful at reduced speed operation, and at best offers a solution for only one of the many difficulties. It is for these reasons that alternating current is not suitable for Diesel-electric propulsion.

Direct current not only obviates all of the above difficulties, but possesses many advantages in the way of operation, control and reserve power. With direct current, we have the choice between two methods of generator operation, *i. e.*, parallel and series. From the standpoint of engine performance only, parallel operation of d-c. generators is entirely feasible and easily accomplished. However, when considering economical methods of speed control of the propeller motors, another factor enters which makes parallel operation difficult, even with d-c. machines. This is explained below.

With direct current, we have a choice between two methods of motor speed control, *i. e.*, armature rheostatic and generator voltage control. Armature control is not only unjustifiably wasteful at reduced speed operation, but also adds complication to the control. On the other hand, the voltage control method is practically 100 per cent economical and provides an ease and a flexibility of control unapproachable by other systems. In the case of very small drives, armature rheostatic control might be selected because of factors not related to the propulsive equipment making it preferable to have a constant voltage system which is common to the propulsion and auxiliary circuits. For a drive of any appreciable size, the best results are obtained by isolating the propulsive equipment so that immediate maneuvering can be done without affecting non-related circuits. Therefore, having an isolated plant for propulsion only, voltage control is obviously the method to use.

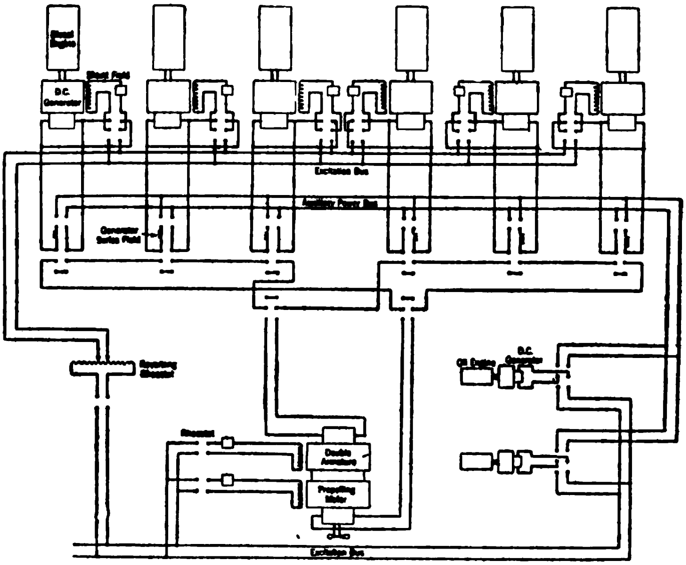

FIG. 5—DIESEL ELECTRIC DRIVE
Diagrammatic scheme of connections.

With parallel operation of generators, voltage control is not simple of accomplishment. To vary satisfactorily the voltage of two or more generators simultaneously over the full range from zero to maximum, necessitates very closely and very carefully adjusted field rheostats, generators with practically identical saturation curves, and engines with practically identical regulation; or, some complicated and delicate automatic voltage balancing instrument.

The series arrangement of generators, however, is ideal from every standpoint such as operation, control, economy, simplicity, flexibility, reserve, etc. The series arrangement, in eliminating parallel operation of generators, obviates the necessity for close regulation and hence simple engine governors and simple field rheostats are entirely satisfactory. In other words, satisfactory operation is independent of variation in voltage between the different generators.

Besides the operating advantages, the series arrangement inherently provides for full power from each of the remaining generators in case of casualty to one or more of the generating sets without providing additional capacity, and consequently additional weight in the motor. To obtain full power from each of the remaining sets with parallel operation would necessitate increasing the motor field in order to lower its speed to such a value as would require the total capacity of the remaining units, thus necessitating a larger and heavier motor.

Fig. 5 shows a diagrammatic scheme of connections for a single-screw Diesel-electric drive. In this particular case, there are six generating sets and one double-unit direct-connected motor. The six generators and the two motor units are connected in series. The machines are distributed electrically as follows: three generators, one motor unit, three generators and one motor unit, to reduce the voltage strain, or the maximum voltage to ground at any two points to one-half the total voltage of the system. The voltage of each generator being 250, we have in effect a 1500-volt system with only 750-volt insulation requirements. The advantages of this arrangement are obvious, especially in the case of large capacity drives and where there are several generators involved. The diagram shows an arrangement for using as many as may be desired of the main generating sets for supplying power to the ship's auxiliaries when in port. Although the generators (and motors) operate as pure shunt machines when driving the ship, series windings on the generators are automatically placed in circuit when the generators are connected to the auxiliary bus, and therefore, the generators operate as compound machines when supplying the auxiliary load, and when used for this purpose the generators are operated in parallel. Arranging the generators for supplying power to the ship's auxiliary bus determines the voltage of the individual machines (250 volts).

The motors and generators being pure shunt-wound machines, the motor speed is adjusted to any value within the requirements by the voltage control system. In this system, the generator and motor fields are separately excited (preferably from the same excitation source). The motor fields are excited at constant potential, and in one direction, whereas the generator field excitation is varied to obtain the motor speed desired. With this arrangement, the speed of the motors is directly proportional to the generator voltage and, therefore, any motor speed from zero to the maximum in either direction is obtained by merely manipulating the generator field rheostat (a common rheostat is used for all generators). Since the rheostat handles only the generator field current which is 1 per cent to 1½ per cent of the generator rating, the simplicity and economy of the control is obvious. With the type of rheostat used, the excitation of the generators may be varied from full excitation in one direction to full excitation in the opposite direction, without opening the field circuit, and therefore, the ship can be brought from full speed ahead to full speed astern without opening a single circuit.

Reserve power in the event of casualty to prime movers is greater with this type of drive than with any other. On the basis of the power varying as the cube of the speed, a three-engine unit Diesel-electric ship can make 88 per cent speed with two generators and 70 per cent speed with one generator.

The Diesel-electric has the greatest range of application of any of the economical drives (geared turbine and turbine-electric not excepted). Because of the inherent merits of this drive, it is very suitably applied to merchant ships, barges, river-boats, lake boats, ferry boats, small coast-wise vessels, yachts, fishing boats, coast guard cutters, cable laying ships, and any ship within its capacity requiring refined control and economical operation over a wide range of speed.

As compared with any type of steam drive, the principal advantages of the Diesel-electric are:

Fuel consumption,
Weight,
Control,
Considerably more reserve power in case of casualty to prime movers.

The principal advantages of the Diesel-electric drive as compared with direct Diesel drive are:

Reliability. Cylinder parts being thinner are not subjected to such high temperature strains in heads and liners as are the large low speed engines, and conquently, there will be fewer breakages of these parts. Years of application and service demonstrate beyond a doubt the full reliability of electrical machinery.

Maneuvering Ability and Control. The control is extremely simple, easily understood, and can be placed anywhere on the ship. The engines run at constant speed and hence the engine reversing gear is eliminated.

Weight. On a very conservative basis, the Diesel-electric should show at least 100 pounds less per propeller shaft horse power.

Propeller Application. Propeller speed not restricted, and in the case of large ships, one propeller would be used for Diesel-electric, whereas, because of engine conditions, two would be used with direct Diesel.

Reserve Power in Case of Casualty. Very much greater with the Diesel-electric.

Maintenance. For reasons under "Reliability", the maintenance should be less. Furthermore, due to smaller parts and reserve power, repairs to Diesel-electric engines can usually be made on board ship while under way, providing sea conditions permit. The engines for Diesel-electric are designed and built on the same conservative basis as direct-drive Diesels, and are not the high-speed, short-lived submarine type.

Less Starting Air. Diesel-electric requires starting air only during the initial start in port. Subsequently engines may be started electrically. No air is used during reversing and consequently, the air problem is reduced to simplest terms.

Fuel Consumption. There would be little difference in the net fuel oil and lubricating oil consumption as the increased efficiency of screw and the reduced strutt losses, with the low-speed single-propeller Diesel-electric, offset the twin-screw arrangement of the direct Diesel. From a standpoint of piston speed, the engines used for Diesel-electric drive are no different than direct-connected engines. (The former exceeds the latter only in *revolutions per minute*).

Cost. The cost of Diesel-electric in some cases is less than the cost of direct-connected Diesel drive on present day figures, and will generally show a greater gap when fully developed along standardized lines.

GENERAL SUMMARY FOR MERCHANT SHIP ELECTRIC DRIVES

In the way of a summary relative to all types of electric propulsive equipments for merchant ships, the following salient features may be reviewed:

1. Electric drive is as reliable as any drive suitable for ship propulsion.

2. Maintenance and repairs should not exceed those of other drives, and in some cases should show a saving.

3. Electric drive is ideal for ship propulsion, and will soon be recognized (if it is not already recognized) as a standard type along with the reciprocating engine, geared turbine and Diesel engine drives.

4. Electrical machines have longer life than engines or geared turbines (drives) and do not decrease in efficiency with age.

5. Electric drive (Diesel-electric) is as reliable as any economical drive generally; weighs less than any other drive; is as economical as the best; in most cases

costs less than any other drive;* provides more reserve power in case of casualty to prime movers; and affords simplest and most flexible control.

War Vessels

The electric propulsive equipments for war vessels have been described and discussed in many articles in the technical press, and therefore, only the principal phases will be dealt with here.

The fact that the last nineteen capital ships of the U. S. Navy are, or will be equipped with electric drive, is sufficient testimony in behalf of what the builders and users of war vessels think of its merits. The prime requisite of reliability in any type of machinery designed to propel war vessels was recognized in the electrical machinery at the time of the first installation. Also the calculations showed that the unit fuel consumption over a wide range of operating speeds should be better than anything yet proposed. Service operation of two 30,000-h. p. electrically propelled battleships has indisputably proved that the reliability is all that was claimed, and that the fuel economy as compared with other ships of the same type using direct-connected turbines with geared cruising turbines, is vastly superior.

Two other factors in which the electric drive shows a marked improvement over other drives, have been emphasized since the first battleship was built, namely, the superior protection from torpedo attack afforded the machinery by virtue of the arrangement of the electric plant, and the superior maneuvering qualities of the electric drive. The large horse power requirements of the present war vessels (60,000 h. p. and 180,000 h. p.) preclude the use of reciprocating engine drive, and this leaves electric drive with a decided maneuvering advantage over any other form of turbine drive.

Of the two types of electric propulsive equipments, only the turbine-electric is suitable for propelling war vessels, because of the large capacities required. The

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*It is predicted that future developments will bring the item of cost below that of any other drive.

nineteen drives installed and building employ essentially the same system in that induction motors are used in all cases. In details, the systems differ in regard to the type of induction motor. Of the three ships in service, (the *Maryland* having been recently commissioned), the *New Mexico* motors have the double squirrel-cage rotor winding, the *Tennessee* motors have the form-wound rotor with external starting and maneuvering resistance, and the *Maryland* motors have combined single squirrel-cage and form-wound rotors. Each of these arrangements has its advocates. However, continued service alone will decide which method is the most suitable, all factors being considered.

Because of limitations in weight and space factors, electric drive is not well suited to small, high-power, fast craft such as destroyers and scout cruisers. In the case of ships where conditions are suitable for electric drive, the following dicussion of the more important factors will be of interest:

RELIABILITY

In all phases of the industrial field where electricity has entered, it has proved its reliability. With a good record for reliability behind it, electricity has set out to establish a similar record on the sea, and the experience of the two large battleships thus far equipped with electric propelling machinery, and in service, shows that there will be a duplication of past satisfactory performance. The electrical machinery will be found to be in good condition long after the ship has become obsolete.

The arrangement of units and distribution of power make it possible to supply balanced power to all screws in the event of casualty to one of the prime movers. In other words, the electric drive possesses an inherent advantage in regard to reserve power.

ECONOMY

Regardless of calculations, the recorded performance of the electrically propelled battleship *New Mexico* has proved the superiority of the electric battleship in respect to fuel consumption. Recently published figures in the *Marine Review* show that the *Idaho*

ELECTRICALLY PROPELLED WAR VESSELS IN SERVICE AND BUILDING.

Ship	Kind	Total S. H. P.	Type of drive	Tonnage	Date
U. S. S. Jupiter	Collier	7,000	Turbine-electric	20,000	1912
" New Mexico	Battleship	28,000	" "	33,000	1918
" Tennessee	"	28,000	" "	"	1920
" Maryland	"	28,000	" "	"	1921
" California	"	28,000	" "	"	Building
" Colorado	"	28,000	" "	"	"
" Washington	"	28,000	" "	"	"
" West Virginia	"	28,000	" "	"	"
" South Dakota	"	60,000	" "	43,000	"
" Indiana	"	60,000	" "	"	"
" Montana	"	60,000	" "	"	"
" North Carolina	"	60,000	" "	"	"
" Iowa	"	60,000	" "	"	"
" Massachusetts	"	60,000	" "	"	"
" Lexington	Battle Cruiser	180,000	" "	43,500	"
" Constellation	" "	180,000	" "	"	"
" Saratoga	" "	180,000	" "	"	"
" Ranger	" "	180,000	" "	"	"
" Constitution	" "	180,000	" "	"	"
" United States	" "	180,000	" "	"	"
Japanese Fuel Ship	Collier	8,000	" "	20,000	"
4 Coast Guard Cutters	Cutter	2,600	" "	1,600	"

ELECTRICALLY PROPELLED MERCHANT & MISCELLANEOUS SHIPS IN SERVICE AND BUILDING.

Ship	Kind	Total S. H. P.	Type of drive	Tonnage displaced	Date
2 Ice Breakers at Niagara Falls	Tug	50	Trolley or cable fed, d-c.		1906
Joseph Medill	Fire boat	400	Turbine-electric d-c.		1908
Graeme Stewart	" "	400	" " "		1908
Electric Arc	Experimental Launch	25	Petrol-electric a-c.		1911
Tynemount	Cargo	500	Diesel-electric a-c.		1912
Mjolner	Cargo	950	Turbine-electric a-c.		1912
Wulsty Castle	Cargo	1,500	" " "		1918
Aquila, etc.	Cargo	1,200	" " "		1918-9
Mariner	Trawler	400	Diesel-electric d-c.	500	1919
Eclipse	Cargo	3,000	Turbine-electric a-c.	16,000	1920
Cuba	Cargo & Passenger	3,000	" " a-c.	3,580	1920
Elfay	Schooner Yacht	90	Diesel-electric d-c.	313	1920
Guinevere	" "	550	" " d-c.	1,160	1921
Invincible	Cargo	3,000	Turbine—electric a-c.		Building
Archer	"	3,000	" " "		"
Independence	"	3,000	" " "		"
Alcyone	Schooner Yacht	350	Diesel-electric d-c.		"
Velero II	" "	215	" " "		"
Fordonian	Cargo	850	" " "	2,200	"
8 Cargo Carriers		3,000	Turbine-electric a-c.	16,000	"
Poughkeepsie-Highland Ferry	Ferry	200	Diesel-electric d-c.	640 DWC	"

and *Mississippi* use 20 per cent more oil at 10 knots than the *New Mexico*; 42.7 per cent more at 13 knots, 48 per cent more at 16 knots, 40.1 per cent more at 19 knots, and 32 per cent more at full power. This superiority in fuel consumption is not altogether due to the main units, as the figures include the oil consumed by the auxiliaries. There is enough difference, however, to show conclusively that the comparison is very favorable to the electric ship.

To show that the advantage in fuel consumption demonstrated by the *New Mexico* is not a mere incident, it is well to note that the *Tennessee*, which is a later ship, is showing even better results than the *New Mexico*, as was indicated when the two ships steamed together during recent maneuvers of the Pacific Fleet. Accurate measurement of unit fuel consumption during the official trials of the *Tennessee* showed that the actual steam consumptions were less than the guaranteed figures by amounts varying from 3 per cent to 8 per cent approximately. Thus the art of electric propulsion is still progressing. The answer is found in the use of only a sufficient number of turbines for the load conditions, and in the two-speed motors, the combination of which maintains a higher average load on the turbines at a higher average speed.

MANEUVERING

Owing to the availability of full backing power in the case of the electric drive ship, the latter possesses a marked advantage over the turbine ship in maneuvering qualities. As these were referred to under "Merchant Ships," it is sufficient merely to mention at this time that electric battleships can be stopped in considerably less time than is required to stop a turbine ship. The advantage of this feature is obvious in the case of a war vessel. This is due to the combined action of quicker "set-ups" and greater backing power.

Further maneuvering advantages of the electric drive are apparent from recent publications. These advantages are chiefly concerned when entering and leaving ports and maneuvering therein. By operating the ship from one turbine set, the other, or others if there are more than two, can be held in readiness for immediate service in case of necessity such as would arise from a mudded condenser or other cause. When maneuvering to get under way, operation from a single generating set inherently enables exactly the same speed—but of opposite direction—to be obtained on the port and starboard screws. This is very desirable for the reason that the ship can be turned on its heel without making any headway. With different prime movers supplying power to the various screws, it would be difficult to maintain all the screws at the same speed and thereby turn in the same space.

CONTROL

The control for the propelling machinery is centralized in one compartment and can be easily arranged to be operated by one operator. The flexibility of the control is such that almost any emergency resulting from casualty to any equipment connected with the propulsive machinery proper, can be taken care of in brief time by disconnecting the disabled unit from the source of power.

MAINTENANCE

The maintenance and repairs should show to advantage because of the inherent reliability of electrical machines and the absence of wearing parts. Repairs of considerable magnitude can be made aboard the ship without removing the machinery. It is difficult to imagine a casualty to any one of the electrical units which could not be repaired on board the ship if circumstances warranted it.

STUDY OF PERFORMANCE

The electrical instruments enable accurate and convenient observations to be made of the performance of the screws at any instant. The electrical instruments also provide a means for quickly detecting improper performance of the screws due to excessive shaft friction or damaged blades. The performance of all units as indicated by the instruments is under the observation of the watch officer and control-room attendants at all times.

DISCUSSION ON "ELECTRIC AUXILIARIES ON MERCHANT SHIPS" (DICKINSON) AND "ELECTRIC PROPULSION OF SHIPS" (THAU), NEW YORK, N. Y., NOVEMBER 17, 1921.

W. L. R. Emmet: There are one or two points in Mr. Thau's paper where I think the case has been a little understated. In the matter of reliability I have always been of the opinion that the electric method of doing anything was the most reliable, and where anything was broken or damaged, electrical apparatus was easy to repair. I do not simply think it is on a parity with other methods.

As to weight and space. In Mr. Thau's statement about merchant ships, he has not called attention to the fact that in certain electric drive merchant ships already equipped, and possibly in many others, a very large amount of space, weight and cost can be saved by leaving out shafts and shaft alleys, and the arrangement of the ship can be made more convenient.

Cost is a question which I think could generally be decided about as Mr. Thau has decided it, but there are many contradictions in that respect. Some little time ago we bid on equipments for some 12,000-ton transports that were being constructed in considerable number. We were the lowest bidders on electric drive and offered the best guarantees. We also made our electric bids on exactly the same profit basis that our gear proposition was based upon, in the case of these ships, and the electric was the cheaper. There have been only a few electric-drive ships equipped, and a great many geared ships, and when these two methods are reduced to a basis of comparison it has in many cases been found that the electric drive is not much more expensive than a conservatively proportioned gear drive.

There is a suggestion in the paper of a possible difficulty through lack of trained men. I know Mr. Thau does not consider, any more than any other electric man does, that there is any such disadvantage in the electric drive, because I know that he is an enthusiast on the subject. Our whole experience with electrical application on land is that everybody is afraid of it before the apparatus is started, but it is very popular the first day after the apparatus is started, with the whole operating force, and that has been the experience on ships. The Jupiter started with a set of green men, and they were all enthusiastic about the apparatus immediately, and that has also been the experience with the various warships.

In the matter of maintenance, the impression is given in this paper that electrical machinery is on a parity in the matter of maintenance. The Jupiter has been operating for seven years without any maintenance expense, I am informed—at least, I do not know of it. I do not think there is much to wear out in an electrical ship, so far as the electrical apparatus is concerned. You might have to replace a bearing occasionally, but normally, electrical apparatus of that type is virtually everlasting. In other forms of drive it is not always so.

Another matter that I would take exception to, or at least state a little differently, is the matter of the efficiency of the synchronous motor, as compared with the induction motor. We have applied synchronous motors to several ships and what Mr. Thau says is in a way justified, because if you waste enough power on excitation, you may equalize the differences which exist between the efficiency of the two systems, but my idea of the electrical drive is a little different from anything that has ever been actually produced, because I would like to see the ship equipped with sufficient means for making electricity for auxiliary purposes, and if all the auxiliary operations in a ship were done electrically, and your electric power is made efficiently, the excitation would be secured at a very low cost.

If efficient power is obtained for excitation in connection with other auxiliary purposes, the synchronous motor will be something like 3 per cent better than the induction motor, and the apparatus will be materially lighter.

Another point is that the synchronous motor apparatus has an air gap on the order of three or four times as much as that which is practicable with the induction motor.

Furthermore, the synchronous motor can be made with removable poles, so, without disturbing the position of the machinery itself, you can take off a pole, get at the stator to replace the windings without removing or lifting anything. Such operations are very simple and easy. The synchronous motor is of rather simpler mechanism than the induction motor, because there are simple solenoids for field windings, the movable parts; in other words, there is a more easily repaired structure.

As to some of the remarks about the Diesel-electric. I would like to push the Diesel electric along if it is a good thing, and for the sake of bringing out discussion I want to state that certain people, who are well informed in the Diesel engine business, have given me the impression that the records to date indicate that the slow-speed Diesel engines were rather more practicable than the high speed. I do not see any very inherent reason why the high-speed Diesel-engine might not be made good, but combustion takes time and it may be that there is something in this point.

I do not think I could quite agree there with Mr. Thau's statement that the a-c. Diesel-electric drive is out of it. I would not go so far as to say that, although I might possibly agree with him if I had his reasons.

One other thing which has not been mentioned in this paper is the advantage afforded by interchangeability in electrical ship installations. On board the Maryland, the other day, we ran at 19 knots with one generator, a 21-knot ship; we ran 17 knots with only one generator and two motors. I say two motors —I mean two propellers trailing. In a passenger ship with two turbines designed to run 22 knots you could run at 18 knots with one generator. That is very desirable in many merchant ships—to be able to run economically at lower speed.

Mr. Thau has not mentioned the advantage afforded in warships of the change of ratio in the electrical motors. That is done in existing warships. I have heard statements to the effect that the Tennessee gained nothing through that change of poles. I do not understand the cause for that. The question was raised on board the Maryland lately, and trials were made at 15 knots, the maximum speed at which the low-speed connection can be run. At that speed the oil consumption was 10 per cent lower; and the water consumption, as reported to me was 7 per cent lower. At lower speeds there is, of course, a greater gain. In a warship this is a very important matter.

Charles F. Bailey: This discussion and investigation has been prepared in an impartial spirit with the purpose of emphasizing a few of the outstanding facts and conditions apparent in a comparison of the following types of marine propelling machinery, including Diesel-electric and steam-electric driven machinery, as covered in Mr. Thau's paper. Let us consider the following:

GROUP I.—2000 S. H. P

(*A*) Diesel-electric, twin screw, (*B*) Direct-Diesel, twin screw, (*C*) Single-reduction geared turbines, single screw, oil fuel, Babcock and Wilcox boilers, also Scotch boilers. (D_1) Triple-expansion reciprocating engine, single screw, oil fuel, Babcock and Wilcox boilers, also Scotch boilers. (D_2) Triple-expansion reciprocating engine, twin screw, oil fuel, Babcock and Wilcox boilers, also Scotch boilers.

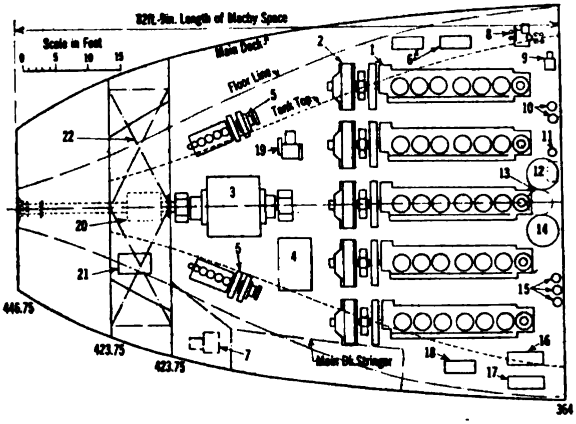

FIG. 1—GROUP II-*A*. DIESEL-ELECTRIC

1. 6 cyc.—600 B. H. P.—200 R. P. M. 2. Generator. 3. Main Motors 90 R. P. M. 4. Control Room. 5. Diesel Gen. 6. L. P. Fuel Oil Pumps. 7. Ice Machine on Main Deck Stringer. 8. Air Compressors. 9. H. P. Fuel Oil Pump. 10. Air Bottles. 11. F. O. Heater. 12. F. O. Pump. 13. Donkey Boiler. 14. F. O. Service Tanks. 15. Air Bottles. 16. Cooling Water. 17. Bal. & Cooling. 18. Standby Sub. Oil Pump. 19. Fire & Bilge Pump. 20. Thrust. 21. Semi-Diesel Gen. 22. F. W. Tanks on Main Deck.

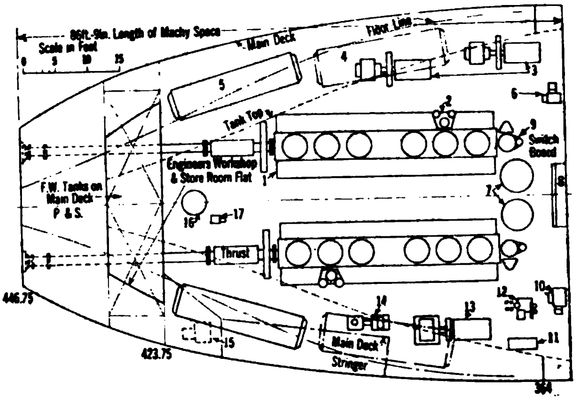

FIG. 2—GROUP II-*B*. DIRECT-DIESEL

1. Six—26″-43″—115 R. P. M. 2. Att. Blge. Sub. Oil—San—L. P. Fuel Oil & Cooling Pumps. 3. Diesel Gen. 4. Starting Air Tank over Main Deck Stringer. 5. Starting Air Tank under Stringer. 6. Standby H. P. F. O. Pump. 7. F. O. Service Tanks. 8. Switch Board. 9. Air Compressor. 10. Fire—Bal.—San.—Cooling. 11. Cooling Water Pump. 12. Lub. Oil Pump & Emergency Air Compr. 13. Elec. Motor-Driven Air Compr. 14. Semi-Diesel Light Gen. 15. Ice Machine. 16. Donkey Boiler for Heating. 17. Donkey F. O. Pump.

GROUP II.—2600 S. H. P.

(*A*) Diesel-electric, single screw. (Fig. 1.) (*B*) Direct-Diesel, twin screw. (Fig. 2.) (*C*) Geared turbines, single reduction, single screw, oil fuel, Scotch boilers, also Babcock and Wilcox boilers. (Figs. 3 and 6.) (*D*) Quadruple-expansion reciprocating engine, single screw, oil fuel, Scotch boilers, also Babcock and Wilcox boilers. (Figs. 4 and 6.) (*E*) Turbine electric machinery, eclipse type, single screw, oil fuel, Scotch boilers, also Babcock and Wilcox boilers. (Figs. 5 and 6.)

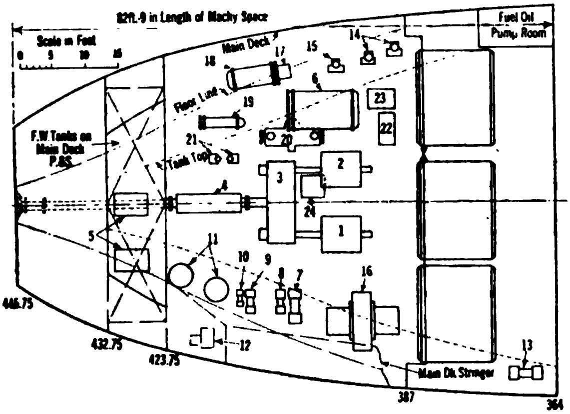

FIG. 3—GROUP II-*C*. GEARED TURBINE SINGLE REDUCTION

1. H. P. Turbine. **2.** L. P. Turbine. **3.** Red. Gear—90 R. P. M. **4.** Thrust. **5.** Generators. **6.** Main Cond. **7.** Bal. Pump. **8.** San. Pump. **9.** F. W. Pump. **10.** Evap. F. Pump. **11.** Evaporators. **12.** Ice Machine. **13.** Oil Trans. Pump. **14.** Main Feed Pumps. **15.** Aux. Feed Pumps. **16.** Blower. **17.** Comb. Air & Circ. Pump. **18.** Aux. Cond. **19.** Oil Coolers. **20.** Main Circ. Pump. **21.** Lub. Oil Pumps. **22.** Main Air Pump. **23.** Hotwell Tank. **24.** Oil Drain Tank.

Babcock and Wilcox boilers for installations (*C*) (*D*), (*E*), Fig 6.

These comparisons are based on merchant marine requirements. Small powers have been selected as more data for comparisons are available, and as installations of such powers would be practicable with each type of machinery.

It has been the endeavor to make the comparisons as carefully and fairly as would have been the case if they had been estimated upon for a proposed order.

The ratio of shaft horse power to indicated horse power is assumed as follows: Diesel-electric, 0.65; direct Diesel, 0.72; reciprocating engines, 0.92.

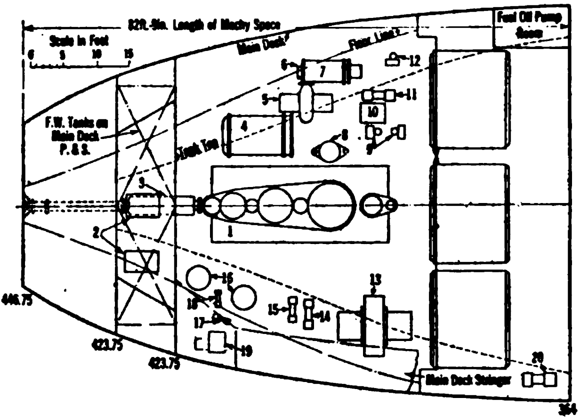

FIG. 4—GROUP II-*D*. QUADRUPLE EXPANSION RECIPROCATING ENGINES

1. 24" x 35" x 51" x 75" x 51" Stroke, 70 R. P. M. **2.** Generators. **3.** Thrust. **4.** Main Cond. **5.** Main Circ. Pump. **6.** Comb. Air & Circ. Pump. **7.** Aux. Cond. **8.** Att. Air & Bilge Pumps. **9.** Main Feed Pumps. **10.** Hotwell Tank. **11.** Donkey F. Pump. **12.** Aux. F. Pump. **13.** Blower. **14.** Bal. Pump. **15.** San. Pump. **16.** Evaporators. **17.** F. W. Pump. **18.** Evap. F. Pump. **19.** Ice Machine. **20.** Oil Trans. Pump.

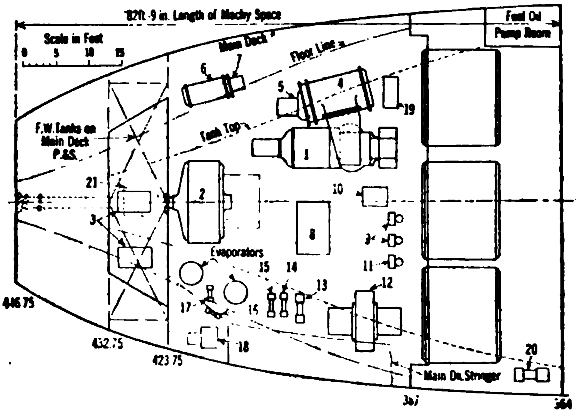

FIG. 5—GROUP II-*E*. TURBINE-ELECTRIC

1. Turbo Generator & Exciter. **2.** Motor, 100 R. P. M. **3.** Generators **4.** Main Cond. **5.** Main Circ. Pump. **6.** Aux. Cond. **7.** Comb. Air & Circ. Pump. **8.** Control Room. **9.** Main Feed Pumps. **10.** Hotwell. Tank. **11.** Aux. Feed Pump. **12.** Blower. **13.** Ballast Pump. **14.** San. Pump. **15.** Bilge Pump. **16.** F. W. Pump. **17.** Evap. Feed Pump. **18.** Ice Machine. **19.** Main Air Pump. **20.** Oil Trans. Pump. **21.** Thrust.

The installations of Group I are smaller than would usually be adopted in merchant service, but the comparisons will hold fairly closely. The information from which these comparisons were made was largely taken from detailed estimates and are closely approximate. The principal elements of each installation are tabulated in Tables I and II from which it will be noted in Table I covering Group I and Table II, covering Group II, comparisons are made with both Babcock and Wilcox watertube boilers, and Scotch boilers, allowance being made for some increase in heating surface of the watertube boilers. In a merchant vessel the installations, Group I could occupy more space athwartships, as the beam would be greater than here shown.

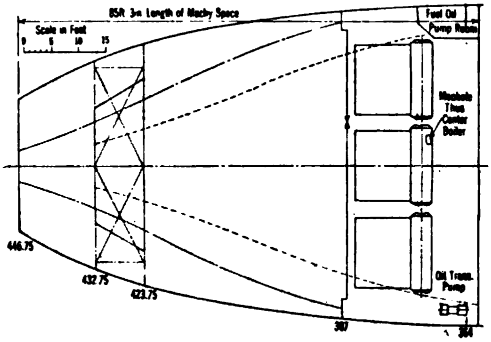

FIG. 6—GROUP II, B & W BOILERS FOR INSTALLATIONS *C D & E*

The principal points of total propelling machinery weights, which include auxiliaries, piping, engine and fire room floor plates, ladders and gratings, water, etc., weight per S. H. P. relative costs, fore and aft, space required for the machinery installations, fuel consumptions, etc., are plotted as indicated in Fig. 7.

These data, it will be seen, vary somewhat from those of Mr. Thau, particularly in regard to weight and costs for Diesel-electric machinery. Table III, compiled from Tables I and II, indicates that the comparison of wet weights, costs, fuel per day and space required, based on the geared turbines with watertube boilers, all as outlined under groups I and II, are as follows:

TABLE I—GROUP I—PARTICULARS OF MACHINERY

	(*A*) Diesel electric	(*B*) Direct Diesel	(*C*) Geared turbines	(D_1) S. S. triple	(D_2) T. S. triple
Main Engines	4-600 B. H. P. Engs. 4-410 K. W., 250 V., 250 R. P. M. gens 2-100 H. P. D. C. Motors	2-1000 B. H. P. 6 cyls. 4 cycle	1-H. P. & 1-L. P. Turbine driving one single reduction gear	1-2000 S. H. P.	2-1000 S. H. P.
Main Boilers—No.			2	2	2
Type			B. & W. or S.	B. & W. or S.	B. & W. or S.
Steam press., lbs., B. & W			250	200	200
Steam press., lbs., Scotch			220	200	200
Donkey Boiler—No. and type	1 Scotch	1 Scotch	1 Vert.	1 Vert.	1 Vert.
Type of auxiliaries	Electric	Electric	Steam	Steam	Steam
R. P. M.—propeller	120	125	90	70	100
S. H. P.	2000	2000	2000	2000	2000
M. E. P.—based on I. H. P.		96.5		31.8 ref. L. P.	30.4 ref. L. P.
Ratio—$\frac{\text{S. H. P.}}{\text{I. H. P.}}$	0.65	0.72		0.92	0.92
Oil per S. H. P. per hr., lbs. (all purposes)	0.55	0.50	0.95	1.10	1.20
Weight and space:					
Propel. mach., dry tons	571	436	325 (*b*) 370 (*s*)	375 (*b*) 429 (*s*)	362 (*b*) 425 (*s*)
Propel. mach., lbs., per S. H. P.	640	488	364 (*b*) 415 (*s*)	420 (*b*) 480 (*s*)	406 (*b*) 476 (*s*)
Propel. mach., wet tons	582	447	344 (*b*) 422 (*s*)	394 (*b*) 493 (*s*)	382 (*b*) 492 (*s*)
Propel. mach., wet lbs., per S. H. P.	650	500	385 (*b*) 472 (*s*)	441 (*b*) 552 (*s*)	428 (*b*) 550 (*s*)
Length machy. space, fore and aft	60′ 6″	55′ 0″	53′ 6″	53′ 6″	51′ 3″
Relative mach. costs	1.70	1.58	1.00	875 (*b*) 876 (*s*)	86 (*b*) 86 (*s*)

(*b*) With Babcock and Wilcox boilers.
(*s*) With single and Scotch boilers.

TABLE II—GROUP II—PARTICULARS OF MACHINERY

	(*A*) Diesel electric	(*B*) Direct Diesel	(*C*) Geared turbines	(*D*) S. S. quad.	(*E*) S.S. turbo-electric
Main Engines	5-600 B. H. P. Engs. 5-410 K.W.,250V., 250 R. P. M. gens. 1-2600 H. P. D. C. Motor	2-1300 B. H. 6 cyl. 4 cycle	1-H. P. & 1-L. P. Turbine driving single red. gear	1-2600 S. H. P.	1-Gen. 3000 R. P. M., 2300 V. 1 induction motor
***Main Boilers*—No.**	....	....	3	3	3
Type	....	....	B. & W. or S.	B. & W. or S.	B. & W. or S.
Steam press., lbs., B. & W.	....	....	250	250	250 at 150° F. S(*d*)
Steam press., lbs., Scotch	....	....	220	220	220 at 150° F. S (*d*)
***Donkey Boiler*—No. and type**	1 Scotch	1 Scotch	1 Vert.	1 Vert.	1 Vert.
Type of auxiliaries	Electric	Electric	Steam	Steam	Electric
R. P. M.—propeller	90	115	90	70	100
S. H. P.	2600	2600	2600	2600	2600
M. E. P.—based on I. H. P.	....	90.5	....	25.5 ref. L. P.	
Ratio—S. H. P./I. H. P.	0.65	0.72	....	0.92	
Oil per S. H. P. per hr., lbs.	0.55	0.50	0.95	1.00	0.90
Weight and space:					
Propel. mach., dry, tot. tons	640	626	373 (*b*) 461 (*s*)	497 (*b*) 585 (*s*)	387 (*b*) 475 (*s*)
Propel. mach., lbs. per S. H. P.	550	540	321 (*b*) 397 (*s*)	428 (*b*) 504 (*s*)	333 (*b*) 409 (*s*)
Propel. mach., wet, tot. tons	652	638	397 (*b*) 528 (*s*)	521 (*b*) 653 (*s*)	410 (*b*) 539 (*s*)
Propel. mach., lbs. per S. H. P.	563	550	343 (*b*) 455 (*s*)	450 (*b*) 563 (*s*)	354 (*b*) 465 (*s*)
Length machy. space, fore and aft	82′ 9″	86′ 9″	85′ 3″ (*b*) 82′ 9″ (*s*)	85′ 3″ (*b*) 82′ 9″ (*s*)	85′ 3″ (*b*) 82′ 9″ (*s*)
Relative mach. costs	1.90	163	1.00 (*b*) 0.97 (*s*)	1.09 (*b*) 1.10 (*s*)	1.23 (*b*) 1.21 (*s*)

(*d*) Service conditions—superheaters designed for 200° fahr. (*b*) With Babcock and Wilcox boilers. (*s*) With single end Scotch boilers.

TABLE III.

RELATIVE DATA GROUP I

	(*A*)	(*B*)	(*C*)	(D_1)	(D_2)
Wet weight	1.69	1.30	1.00 (*b*)	1.15 (*b*)	1.11 (*b*)
			1.23 (*s*)	1.43 (*s*)	1.43 (*s*)
Cost	1.70	1.58	1.00	0.875	0.86
Fuel consumption at sea	0.58	0.53	1.00	1.16	1.26
Fore and aft space	1.13	1.03	1.00	1.00	0.96

RELATIVE DATA GROUP II

	(*A*)	(*B*)	(*C*)	(*D*)	(*E*)
Wet weight	1.64	1.61	1.00 (*b*)	1.31 (*b*)	1.03 (*b*)
			1.33 (*s*)	1.64 (*s*)	1.36 (*s*)
Cost	1.90	1.63	1.00 (*b*)	1.09 (*b*)	1.23 (*b*)
			0.97 (*s*)	1.10 (*s*)	1.21 (*s*)
Fuel consumption at sea	0.58	0.53	1.00	1.05	0.95
Fore and aft space	0.97	1.02	1.00 (*b*)	1.00 (*b*)	1.00 (*b*)
			0.97 (*s*)	0.97 (*s*)	0.97 (*s*)

(*b*) With Babcock and Wilcox boilers.
(*s*) With Scotch boilers.

It is of course known that the weights and other characteristics of machinery constructed by different builders vary considerably, which doubtless accounts for much of the difference between the conclusions of Mr. Thau and the above.

These tables also indicate what is well known but often overlooked— that small engines and machinery generally weigh less per horse power than large machinery. These figures for the entire machinery installations, also generally correspond in this respect.

With the conditions in merchant work such as to permit of building on a manufacturing basis, development would take place resulting in many improvements, and it is conceivable that the relative improvement would favor the Diesel-electric installation.

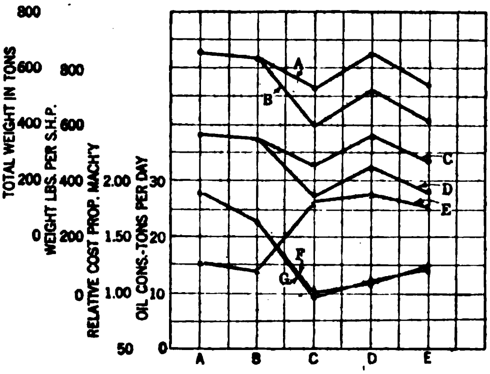

FIG. 7—COMPARISON OF WEIGHTS AND COST OF PROPELLING MACHINERY-STEAM, ELECTRIC AND DIESEL DRIVE—GROUP II—2600 S. H. P.

A—Total Wt. Tons with Scotch Boilers. B—With B & W Boilers. C—Weight Lbs. per S. H. P. with Scotch Boilers. D—Same with B. & W. Boilers. E—Fuel Oil Cons.—Tons per Day. F—Relative Cost with B. & W. Boilers. G—Same with Scotch Boilers.

The above outline installations are conservative in design and follow moderate practise. We know that some features of value might be incorporated to show more favorable results in a discussion of this character such, for example, as greater steam pressures, higher superheat, double reduction gears, etc., but such installations require more careful operation and while they may show theoretically better results, under the ordinary prevailing conditions, we would not now recommend them except where they are to be operated with the required knowledge and care.

In regard to fuel, with the present development and conditions it is frequently necessary to pay from 40 to 50 per cent more for Diesel engine fuel than for steaming oil fuel, depending upon the trade. New advances are modifying these conditions.

It will be understood that other arrangements in dissimilar vessels will work out somewhat differently, but the foregoing indicates substantially the condition in the arrangements described.

It is quite apparent that the comparative advantages of Diesel propelling machinery or Diesel-electric machinery are considerably less in installations for oil tankers, owing to the large amount of steam required for heating heavy oils during the voyage and when discharging.

William W. Smith: On page 1436 the author states that economically a geared turbine drive is generally more efficient than an electric drive. I have also found this to be true, the saving in steam consumption in favor of the geared-turbine machinery being from 4 to 8 per cent. This feature is of especial importance, because statements to the contrary have been made frequently.

It is also pointed out on the next page that geared turbine machinery can use high degree superheat. This is also a fact. Some fairly large passenger steamers with geared turbine machinery using 200 degrees superheat have recently been put in service by the Cunard and other leading British steamship lines. It is important to point out here, also, that misleading statements as to the inability of geared turbines to use high degree superheat have frequently been made.

We have made a number of designs for different types of machinery, but have not found the differences in space referred to by the author. We have found that all of the types referred to occupy about the same space except the turbine-electric machinery, which requires more space, and especially when the motor is located aft. I might add that where the motor is located aft, I do not think it is permissible to eliminate the shaft alley. I do not quite agree with some other gentlemen in this respect. I think it is essential for the engineer to be able to visit the motor room easily and frequently without having to go up on deck and make an excursion such as I had to make on an electric ship not long ago.

The author refers to the saving effected by eliminating the boilers, but neglects to say that Diesel machinery is far larger and heavier than the remaining machinery. The picture of eliminating boilers and pointing out the rest of the machinery as comparable with Diesel engines as to weight, space and cost, is often indulged in. It is, however, far from the facts, since the Diesel engine installations occupy about the same space, and weigh nearly twice as much as a complete steam installation including boilers.

On page 1438, the author's statement as to the cost of the various types of installations is at variance with my experience. I have found the cost per shaft horse power of complete machinery installations of cargo vessels of ordinary size to be relatively about as follows:

1. Geared turbine vessels —50 degrees superheat	$122
2. Steam engines—saturated steam	132
3. Diesel engine—direct drive, twin screw	240
4. Diesel engine—electric drive, twin screw	260

Variations in designs and conditions would modify these figures somewhat. This would apply to modifying item 4 to single screw. As the size of vessel decreases, the direct-drive Diesel installation works out to better advantage.

Referring to the table on page 1440 and to the number of men allowed for the Diesel electric, I should say that this class of machinery would require at least as many men as other types.

I understand from the paragraph on maintenance that the Diesel-electric is supposed to be less expensive. This, I think, is very doubtful. My experience with marine machinery is that high-speed reciprocating engines are more expensive in maintenance and are avoided for that reason. Certainly the slow-speed engine is the one most favored for reliability and low maintenance. I do not think many marine engineers will accept the author's appraisal of that item, which at best is a very uncertain one.

Referring to performance characteristics on page 1441, I wish to call especial attention to one feature of electric drive machinery which I think is very much over-rated and over-advertised—that is, its backing and maneuvering qualities. (It may be noted here that direct-turbine drive installations are not considered in the following or at all in this discussion.)

About the only time when the full backing power of the ordinary ship is required is when stopping in emergency at full speed or nearly full speed. I will therefore consider only this latter condition, because the ordinary requirements of backing are fully met by all of the types of machinery under discussion.

Many persons seem to have a misconception as to the backing power of the ordinary steam engine. It is supposed that the engine develops 100 per cent full power when stopping at full speed. This is not the fact; only about half of the full power is developed. (See tests of U. S. S. *Delaware, Birmingham, Salem,* etc.)

This is due to the fact that, when wide open in either direction, the m. e. p. and the torque of the engine are approximately the same. Due to the characteristics of the propeller in reversing, the full torque gives an average rev. per min. in stopping only half of the ahead rev. per min. Consequently, the astern power is only half of the ahead power. In this connection, it would appear better to refer to backing torque instead of backing power.

The torque of the turbine increases as the speed decreases, and it is also possible to allow an increased steam flow for emergency reversal, which, as is well known, is required very seldom indeed; consequently properly designed astern turbines will develop from 75 to 100 per cent of the ahead full torque when required. This has been proven to be quite ample; which is a point which is well to keep in mind before making assertions to the contrary. The above refers to compound reversing geared turbines.

It is also well to keep in mind that the thrust of the propeller under such conditions depends as much on the size of the wheel as on the torque applied to it. Consequently the large slow wheel of a geared turbine may retard more than a smaller and faster wheel of an electric drive. I mention this because we are nearly always urged to use from 20 to 40 per cent higher propeller speed for electric motor drives than for other types to reduce the size, weight and cost of the motor.

I believe that the motors of electric drives are good for a reversing torque of one and one-half times the ahead full torque, the pull-out torque being double. In order to obtain the superior performance referred to by the author and others a torque of one and one-quarter to one and one-half times the full torque is imposed on the motor in reversing. This results in one of two effects: Either the normally designed shafting, propeller, etc., are stressed beyond the safe limit; or the shafting, etc., must be increased in size, weight, and cost to allow for about 50 per cent more strength.

It is my opinion, from careful observation and study of this subject, that this feature is unnecessary and undesirable for ordinary vessels. I think the shafting, etc., should be designed as usual and the motor torque limited so as not to exceed the maximum designed stress. With such an installation, there would be practically no difference in the possible backing torques of different types. In this connection, I may call attention to the fact that the full backing power of steam engines and steam turbines is seldom used, and especially on vessels of high power, for the reason that heavy vibrations are set up. In very high-powered vessels these vibrations are unusually violent; so much so that I doubt the wisdom of applying even the full torque to vessels such as scout and battle cruisers.

In general, the backing power of steam engines and compound geared turbines is ample; it meets the requirements, and no more has been called for. Consequently, I fail to see the advantages of giving more than is needed or used.

On page 1463, also the author refers to the superior maneuvering qualities for naval vessels. Rapidity of reversal is a point often referred to in this connection. This advantage does not appear to be of great importance, since all types can be handled quicker than they usually are. Also, all types can be reversed in 10 to 20 seconds, which is satisfactory, considering that the propellers must act for a considerable period of time to overcome the momentum of the ship.

In general, I consider the superior backing and maneuvering qualities of electric drive as largely theoretical, and believe there is little if any real practical advantage for ordinary vessels.

On page 1457, the author states that the Diesel-electric is superior in fuel consumption, weight, etc., to other types. I have not found this to be the fact, and am giving particulars in Table I to show that there is a wide difference between these data and the author's opinions. In general, I think the author's claims and conclusions would be more convincing if specific data had been given. Specific and accurate comparisons are the best methods of determining which is the best type of machinery for a particular vessel and service, and this method is suggested to the shipowner who has to choose a new type of machinery. Also, if fair and reliable comparisons of this kind are published, there will be much less room for differences of opinion.

Referring to page 1457, the author's views as to the advantages of the Diesel-electric over the direct-drive Diesel are not concurred in. I should say that the direct drive is more reliable due to the lower r. p. m. I cannot see the alleged advantage in maneuvering. The absence of engine reversing gear is more than made up by switchboards, switching gear, etc. I find no advantage in propeller application except the additional complication when twin screws are used. In this connection, the trend seems to be towards single-screw engines. I also fail to see the advantages in reserve power and maintenance. In the designs which I have handled, the reserve power of the Diesel-electric has been more closely limited than in any other type.

The author states that the engines are designed and built on the same conservative basis as direct-drive Diesels. His views in regard to conservative designs and revolutions are evidently at variance with those of most marine engineers. It is the general view that low-revolution engines are the more reliable. I do not think engines at 250 to 350 rev. per min. will be accepted as equally as conservative as engines at 75 to 125 rev. per min. In general, the use of high-speed engines is regarded as questionable, and they are considered as not sufficiently conservative.

If a high-speed engine should prove desirable because of weight, cost, etc., it would seem that the mechanical gear offers a better solution of the speed-reduction problem than the electrical. It is far lighter, cheaper and more efficient. I note that a new vessel for the Hamburg-American Line (the *Havelland*) is being equipped with such an installation. It may be pointed out, however, that there may be special reasons for making this selection.

In connection with the use of high-speed Diesel engines, two of the oldest and most experienced builders of marine Diesel engines do not advocate this application, although they build high speed engines.

Referring to page 1458, we estimate that the fuel consumption of the Diesel electric will be from 12 to 15 per cent more than the direct drive, and that the propulsive efficiencies will be approximately equal.

In the general summary, the author states that the Diesel electric weighs less and costs less than any other type, which, as pointed out above, does not agree with our data.

The author states that geared turbines are better for destroyers and scouts than electric drive. Since the former type of machine is superior for such vessels, it is not clear to me why this superiority disappears when it comes to battleships and battle cruisers. The following seems to established:

1. The electric-drive machinery weighs from 75 to 100 per cent more than the corresponding geared turbines and costs about in the same proportion.
2. The steam consumption of the electric drive is from 4 to 8 per cent more at full speed, the boilers and auxiliaries being heavier to a slightly less extent.

To offset these, the advantages claimed for the electric machinery do not seem to be very substantial. The above are measurable and tangible advantages for the geared turbine, which are opposed to a number of rather intangible ones for the electric drive, which to me do not seem to be of equal importance.

In this connection it is interesting to note that the British battle cruiser *Hood* is equipped with geared turbines which develop 150,000 horse power. The machinery of this vessel has been a marked success. It would be of special interest to compare the machinery of this vessel with the electrically driven machinery of our vessels.

As noted in the beginning, the essence of this paper is electric drive. Electric-drive machinery is a splendid engineering achievement, and its mechanical operation is, without doubt, superior to mechanical gearing. The absence of meshing teeth and the smooth, flexible operation appeal to the engineer. However, these features are not the chief ones in deciding the type of transmission. The selection of the best type is largely a matter of economics. We must be guided by comparative data and statistics as to first cost, weight, fuel consumption, cost of operation, etc. These hard, cold facts will largely decide the best type.

I have made a great many investigations and comparisons of these transmissions, and so far the results have always shown the mechanical-gear machinery to be superior to the electric. In fact, the advantage has been found to be very large, so much so that the elimination of electric transmission except in special cases is indicated.

Personally, and as an engineer, I like the operation of electric transmission and will advocate its use whenever it is warranted. I am not opposed to electric drive, but I am opposed to attributing to it advantages which it does not possess.

In closing, I may say that American ships must have the most economic type of machinery so as to meet competition, and our purpose in the analysis and selection of machinery should be the accomplishment of this end.

TABLE IV.

	Steam engine	Geared turbine	Direct-drive Diesel	Diesel-electric
1. Number of Screws	1	1	2	2
2. S. H. P.*	2,700	2,600	2,600	2,000
3. Rev. per min.—propeller	80	80	115	120
4. Fuel consumption, lbs. of oil per S. H. P. (all purposes)†	1.30	1.08	0.45	0.53
5. Weight of all engines and boiler-room machinery—wet, tons	627	449	786	571
6. Weight per S. H. P.—lbs	509	386	676	671
7. Cost of machinery	$355,650	$319,000	$625,700	$526,000
8. Cost of machinery, $ per S. H. P.	132.0	122.5	241.0	263.0

*Good for 10 per cent more continuously.

†Represents good average performance; 5.7 per cent can be deducted for high performance.

Q. B. Newman: I wish to speak briefly on one application of the electric drive with which the Coast Guard has recently had, and is now having some new experience—the turbo-electric synchronous motor drive. The cost guard cutter *Tampa* was the first ship in the world for which a synchronous motor was ever proposed. When this type of drive was first suggested to us, and we began to look into it, we found that it appeared doubtful whether the synchronous motor would maneuver under the conditions that are met with in a ship—that is, whether it would start under a heavy load. In order to determine that point we asked the General Electric Company to build an experimental set and simulate ship conditions as nearly as they could. They built a 300-kilowatt set, which they coupled to a direct-current generator, and by that means they could put on any load they pleased. This apparatus was subjected to all the tests we could think of, and it maneuvered perfectly. Then we tried to wreck it by doing things wrong, but found it impossible to do any damage, and so we decided it was a pretty good motor. We had no way of determining whether in a seaway with a racing propeller, when the load is suddenly thrown off and suddenly reapplied, the motor might not fall out of step. So far we have not had an opportunity to determine that. The *Tampa* was built in Oakland, California, at the works of the Union Construction Company, and has made only one cruise, from San Francisco to New York, and the captain says he encountered no bad weather on the voyage to test that. However, we have no apprehension on that subject.

The *Tampa* is 240 feet long over all, 39 feet beam, and about 14 feet mean draught, 1640 tons displacement, and has a block coefficient of 0.4765. She has 16 knots speed, and will do better than 2600 horse power.

The chief advantage of the synchronous motor (which Mr. Emmet has already mentioned) is the matter of accessibility for repairs. By the removal of the pole pieces on the rotor, any part of the motor can be repaired without lifting anything heavier than one single pole piece. I do not anticipate that we shall have to repair the motor, but in case we should have to do so, all parts are easily accessible without lifting any weights.

The matter of weight was the determining factor in our selection of this type of motor. We looked into the induction motor, but the lines of the ship were all fine, and she would not carry the weight; and the lines of the appropriation were still finer, and they would not carry the cost, and the synchronous motor was automatically selected. The results we have obtained are not at all conclusive so far as fuel consumption is concerned. The results vary radically. We hope in the course of time to get some reliable information, and that will be published. As a basis of comparison, I will say on this ship we have installed two Babcock and Wilcox boilers built for installation in mine sweepers. The minesweeper contracts were cancelled, and the Navy then sold us the boilers for installation in these ships. We put on superheaters, and I believe we used higher air pressure than the Navy intended to be used on the mine sweepers. They were designed to develop 1400 indicated horse power on triple expansion, which I think is about 1300 shaft horse power. The *Tampa* has developed 2900 shaft horse power, a good deal more than 100 per cent over the estimated power of the mine sweepers. There is a difference to be expected in the economy of reciprocating and turbo-electric drive, but whether we should take this as a basis of comparison between the reciprocating engine and the turbo-electric ship, I am not prepared to say.

Our first requirement in the Coast Guard, I should say, is responsiveness, because the matter of maneuvering is of the first importance. It may not be so with the merchant ship, but we were very much interested to know how quickly we can get a response to a signal from the bridge. It has been found on a number of occasions, with the ship going at 15 knots speed, the motor will reverse in eleven seconds from the time the signal is given from the bridge. At that speed the ship can be brought dead in a little more than her own length. In backing and filling the response is instantaneous—you cannot tell when it starts.

There is one point that Mr. Thau brings out, in connection with synchronous motors, that I do not quite agree with. He says that the synchronous motor is a more complicated mechanism. If you eliminate the ordinary squirrel-cage induction motor, which I have never heard proposed for ship propulsion, the synchronous motor seems to me simpler than any other type of induction motor—that is, a motor in which you have external secondary resistance. You have a squirrel cage winding for maneuvering, and for a full power run you have an ordinary d-c. field, the same, in most respects, as the generator field. Where it differs at all is in the line of being more readily repaired, but the same sort of connections and switches and apparatus in general applies to both the generator and the motor. I believe the synchronous motor to be a simpler machine than the induction motor with external resistance.

A few words on the control. The handling gear consists of two levers, one being the direction lever and the other the steam lever. A man who can take charge of an installation with ordinary reciprocating engines can go on board and handle this ship without additional instructions.

The switches are operated on solenoids, but provision is also made for manual operation in case the solenoids are thrown out of operation. It is impossible to perform any operation out of its order. You cannot throw on or off the main circuit when the fields are excited, and you cannot throw on or off the fields if the main circuits are open; and so it is a very safe sort of thing so far as a man's being excited in an emergency and doing the wrong thing—you cannot do the wrong thing.

Elmer A. Sperry: Mr. Thau's paper devotes considerable space to Diesel-electric transmission. We all appreciate the suitability of the turbo-electric drive, where the turbine needs assistance in the fact that it will only run one way and is almost impossible when asked to go through severe maneuvers. But with the Diesel or oil engine the matter is entirely different. Here we have an arrangement which will run one way as well as the other, and in quick reversing may be made about the equal of the reciprocating steam engine.

In the case of the oil engine the greatest problem is simplified over the turbine in two ways. The speed is lower, and the other important difference is that the oil engine gives full and quick reversing, so we do not need the electric plant for the purpose of reversing, as we do with the turbine.

We should look at this matter squarely. The electric propulsion of ships is good and should be used if we do not know any better way. However I, for one, believe that there is a better way in the heavy duty air-gap drive that has now been under test for upwards of two years, and I give fair warning that this may be found to entirely supersede the electric propulsion of ships. It makes a number of substantial contributions, not the least of which is the opening up of new fields of usefulness for reciprocating oil engines by permitting gearing, and comparatively inexpensive gearing, to be directly driven therefrom under conditions of practically no wear and with entire success.

Many attempts have been made to drive gears with reciprocating engines, but the crank-whip and general thrash due to the irregularities in the crank effort have intervened and over-stressed the material at the surface of the teeth, causing pitting and peening and early destruction of the gear. The thrashing soon causes them to run so roughly as to become impossible. Examination indicates that not only the positive side, but also the negative faces of the teeth are pitted and peened and receive serious wear. After years in which the struggle was practically given up, it has suddenly reached a complete solution in the endeavor to secure extreme lightness in very large aircraft engines of 1000 horse power or more, where engine speeds have had to be pushed considerably beyond the economic speed of the air propeller.

At this juncture an Italian engineer, Pomellio, found a very complete solution. He divorces the pinion from the mass moments of the crank and allows the latter to "run wild," the pinion being driven through an elastic link (see Fig. 8). This is found to completely smooth out the action so as to make the gear drive perfectly successful. The elastic link does not require highly organized gears, simply spiral toothed spur gears of rather coarse pitch which are found to show no wear, contact on the positive side only, the negative faces not even indicating contact.

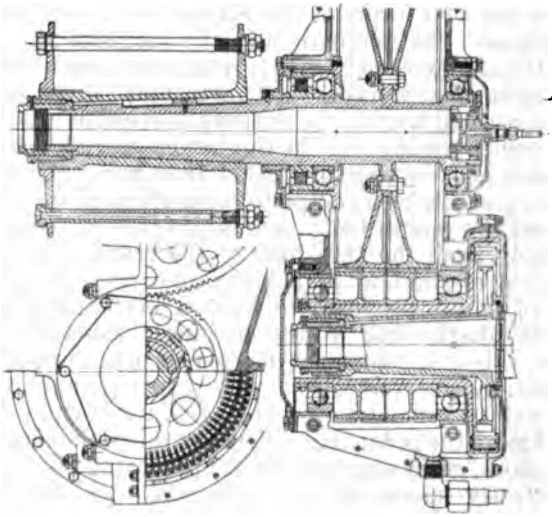

Fig. 8

Fig. 8 shows the crank shaft of a heavy airplane motor below and the short hollow propeller shaft above. The engine shaft operates a broad-faced pinion driving the gear, plainly to be seen on the upper shaft. The peculiarity of this drive is that, rigidly mounted on the conical end of the engine shaft, is a slender hub terminating at the extreme right in a thin disc with deep gear teeth of peculiar shape cut in its broadened periphery, shown also in elevation in the detailed quadrant in the little view below and to the left. The pinion is mounted independently of the crank shaft on heavy ball bearings, plainly to be seen in the lower part of the figure, and the only connection between them are 172 broad, highly tempered steel springs entering the teeth in the shape of radial hairpins, each held on two pintles. The thrash of the crank shaft is taken up completely by the springing back and forth on the part of the 172 sheet steel leaves, allowing the pinion full freedom to accommodate itself entirely to its master gear on the upper shaft. The smoothness of the operation of this arrangement leaves little to be desired.

There are two forms of the elastic link available for this purpose—the magnetic and the mechanical. The latter, though extremely highly organized and made up from a great many pieces, is lighter and better suited for aeronautical work. So entirely successful are these geared reciprocating sets in the larger geared engines, that one is now coming forward of 1600 horse power, all rendered possible by a complete separation of the crank shaft and the pinion teeth, which are thus safeguarded completely from the thrashing of the crank shaft.

The above method is not the one used in power plants of ships, because we have a better and more complete elastic link in the magnetic air-gap drive. Besides, this drive makes a number of other important contributions in connection with ship's plants, but I have dwelt in some detail upon the above hairpin drive to emphasize the point that whenever the pinion is given full freedom, gears operated by reciprocating oil engines are perfectly successful and are now available, this having received complete demonstration under service conditions.

The magnetic form of the elastic link is much simpler, having two as compared to some 260 parts in the mechanical drive. It also gives more complete and smoother operation. This is quite outside its important two-fold contribution in case of oil-engine ship propulsion, because, while for the first time it renders comparatively inexpensive gearing entirely successful with reciprocating engines, it goes still farther and takes care of all fractional speeds in the lower range, where the Diesels are found to draw too heavily on the starting air reserves. They run with good reliability at, say, one-quarter speed or below. Why go lower when the magnetic air-gap clutch takes care perfectly of all fractional speeds even down to complete stopping of the tail shaft?

The provocation for use of electric propulsion existing with turbines which will not reverse and are involved in such destructive superheating troubles whenever they are forced to go through this maneuver, does not exist with Diesels. The Diesel will run in either direction equally well and responds perfectly and instantly to the reversing maneuver.

As we all know, the reciprocating steam engine, barring foaming boilers and condensation troubles, makes by far the best engine for ship propulsion. It maneuvers perfectly and, while it has complete flexibility, yet it will give instantly full power astern or ahead at will. Compared with this performance, for instance, just what is supposed to be the contribution of Diesel-electric propulsion?

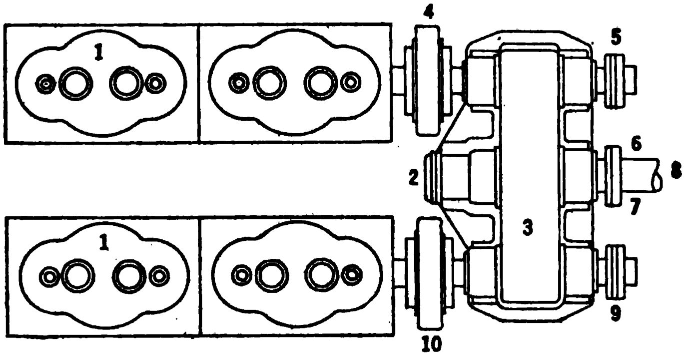

Fig. 9

1. Compound Diesel Engine, 950 B. H. P. 250 R. P. M. 2. Kingsbury Thrust Bearing. 3. Gear Reduction Unit. 4 & 10. Electro-Magnetic Clutch Coupling. 5 & 9. Flexible Steel Plate Coupling. 6. 80 R. P. M. 7. Tail Shaft. 8. 1000 H. P.

1. It is supposed to give both the naval architect and engine builder complete freedom in design to employ the best speed for propeller and engine. This would be realized were it not for the fact that both the electric generators and motors are too heavy and expensive if these speeds are kept low, so there is a constant urge toward too high speeds and the actual plants are a compromise at best. This is not at all true with gears, where the lower speeds are encouraged.

2. It gives divided prime mover units. Should an emergency arise, a part only of the plant is crippled. This is true with the gears and the air-gap clutches at a very great saving of weight, expense and space. Here a plurality of engines is always present. (See Fig. 9.)

3. *Flexibility.*—The Diesel will run with as great reliability as steam at all speeds but the lowest. Here the Diesels are found to draw too heavily on the starting air reserves, as stated, so they may be left running at full or fractional speeds while the electric transmission does the rest and allows the propeller shaft full range down to just turning over if necessary for slow headway. This is precisely the function of the loaded secondary in the air-gap clutch. The continuous operation at all fractional speeds is provided for and at many times the efficiency of the electric drive and without its weight and expense; and as to the important matter of space with a plant located within the flywheel of the engine itself.

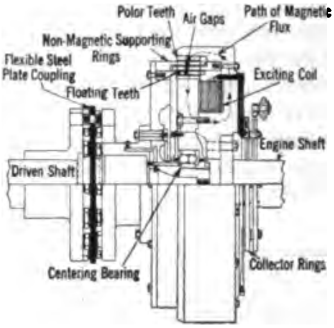

FIG. 10

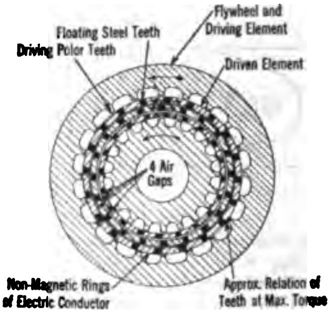

FIG. 11

4. It is supposed to make the farther doubtful contribution of avoiding reversing oil engines. Reversing Diesels were formerly so complex that there was little wonder that reversing relief was sought in the electric plant, but this has now been done away with. For instance, the 32 cams for each four cylinders for full air starting and reverse has in the new engines been

reduced to 5 and the problem no longer exists.* The maneuverability with these engines and the air-gap clutches accomplishes all that the full electric plant does, at a very great saving of plant and control equipment.

Taking up the detailed construction of these clutches, a brief statement might be made as follows:

The clutch is characterized by two kinds of torque operating by opposite phenomena; the greater the differential or relative velocity between the driver and driven parts (so indicated in Figs 10 and 11), the greater the torque available for starting and for bringing up to synchronism. This phenomenon also provides for slipping and continuous operation at all fractional speeds by means of the loaded secondary effect acting as an induction motor. The electrical conductor in the loaded secondary is indicated by the large light masses in the driven rings separating the blackened masses, which indicate the magnetic inserts. (Fig. 11.)

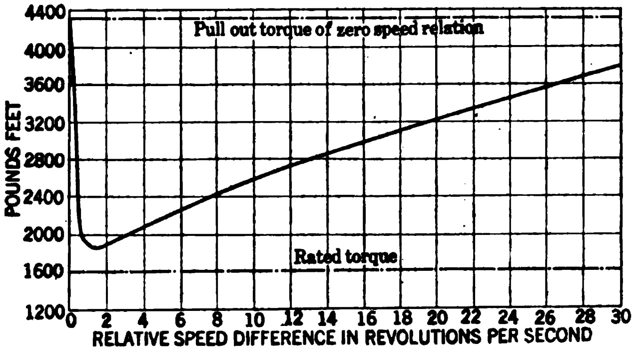

FIG. 12—SPEED-TORQUE CURVE OF ELECTRO MAGNETIC CLUTCH

The air-gap clutch drives by means of magnetic flux. There are four elements in the form of rings in the magnetic circuit, two of which are driving and two of which are driven. The flywheel proper accommodates an exciting coil (shown in Fig. 10) producing the magnetic flux. At all fractional speeds, or while this clutch is slipping, large currents are generated in the driven elements by magnetic induction, which are now acting as short-circuited secondaries, producing heavy drag torques under perfect control by varying the

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*See author's A. S. M. E., "Compound Combustion Engines," Annual Meeting, 1921.

amount of coil excitation. This is plainly seen by the height of the curve at the right in Fig. 12. However, when the speed comes up in the vicinity of synchronism, shown at the extreme left in Fig. 12, locking occurs and the parts assume the relative position shown to the right in Fig. 11 where enormous pull-out torques are present, as indicated by the height of the curve at the extreme left, as stated.

In Fig. 9 the casing containing the low-speed gears is an entity by itself, especially with respect to any extreme alignment requirements with the engine. The air-gaps in the fly-wheels allow of considerable leeway, both endwise and laterally. The pinions are mounted on hollow quills, and complete flexibility is assured by the steel plate coupling located at the after end of each pinion. No amount of "weaving" of the foundations forming a part of the ship's structure in changing the alignment, will disturb the perfectly smooth running of these low-speed gears.

With this clutch and the engine combination shown in Fig. 9, several very important advantages are secured:

1. We have available on a single propeller all the advantages and flexibility of a multiple engine equipment, where one engine may be shut down and completely disconnected for inspection, valve grinding, etc., and yet the ship is going forward at three-quarters its normal speed.

2. We have the complete flexibility of the electric drive without the expense, weight and space of the electric generators and motors, as stated and the cumbersome electric control equipment for handling the heavy currents in maneuvering, and the double losses of generators and motors which are of substantial amount and a constant drag on plant and fuel economy.

3. The simplest form of gear drive may be employed because the magnetic clutch allows the pinion to be a complete "floater." The pinion may thus accommodate itself to any want of precision and all sorts of idiosyncrasies of the main gear and teeth without shock. Any irregularities existing in either main gear or pinions thus have to deal only with the small masses of the pinion itself and its stub shaft, being completely isolated from the large mass moments of the engine.

4. The torque, being under complete control, can be lowered so as to safeguard the equipment against overloading, especially when sailing in obstructed harbors, near derelicts, and where floating obstacles are likely to be encountered by the propeller blades, thus providing an important emergency disconnecting gear breaking away from the large revolving engine

masses and allowing the propeller to "stop in its tracks" through the self-interruptibility of the magnetic clutch when reduced to fractional underload condition. In this way many disasters to the propelling machinery and interruptions to the service may be avoided.

5. Most revolving machinery is subject to periods, sometimes running into severe "criticals". These criticals always develop from the torque irregularities in the revolving masses within the engine pitted against outside mass moments aft. This can occur only when these are solidly coupled with each other ,but if instead they are isolated, as by the air gap of the magnetic clutch, these troublesome criticals with their excessive stresses are completely suppressed and can never develop.

Important ships that would be much better equipped with the single screw have gone to the trouble, weight and expense involved in using twin screws to secure the advantages of the divided unit and to obtain sufficient power while avoiding the expense of the larger engines required with the double efficiency losses of the electric drive.

As to larger powered engines, with the new compound much larger units are possible without approaching the size and space occupied by the simple Diesel engines.. Through compounding the combustion engine (see author's paper on this subject before the 1921 Annual Meeting of the American Society of Mechanical Engineers), tail shaft powers up to 12,000 horse power are available with the present cylinder and cylinder wall limitations, with only six combustion cylinders in line in each engine, utilizing the arrangement of Fig. 9. If a similar pair of engines is used aft of the gear, then a shaft horse power of 24,000 can easily be secured, and the weight can be held to a point far below the present weight per shaft horse power of combustion engines or steam plants for continuous heavy duty service.

With the simple device of the heavy duty air-gap drive, everything claimed to be accomplished by the electric drive is accomplished, and much better and with greater economy. The efficiency of the air-gap drives alone is better than 99.5 per cent. They weigh less than 2 per cent of the weight of the electric drive, and as to valuable space occupied, they are moved into the small flywheels of the engines themselves, where they are accommodated perfectly and from which point they make their varied and most important contributions to ship propulsion.

The following table gives the percentage of clutch excitation for fractional tail shaft speeds below the engine speed, the first half when the oil engine is

TABLE V.—ELECTROMAGNETIC CLUTCH OR AIR GAP DRIVE APPLIED TO A 900 H. P. DIESEL ENGINE, 140 REV. PER MIN. GEARED TO PROPELLER AT 90 REV. PER MIN.

Engine	Rev. per Min.	Propeller				Air gap drive	
		Rev. per min.	Per cent engine speed	H. P.	Torque lb-ft.	Torque lb-ft.	Per cent of normal excitation
Full speed	140	90	100	900	53,000	70,000	100.0
One-half speed	70	45	100	112.5	13,200	17,000	100 to 50.0
One-half speed	70	33	75	47.5	7,300	4,780	Slipping 50.0
One-half speed	70	22.5	50	14.0	3,260	2,120	Slipping 11.5
One-half speed	70	11	25	1.76	820	530	Slipping 2.0
One-half speed	70	5.5	12.5	0.22	206	133	Slipping 0.43
Full-speed	140	90	100	900	53,000	70,000	100.0
One-third speed	46.7	29.5	100	33.3	5,900	7,560	100 to 33.0
One-third speed	46.7	22.5	75	14.0	3,300	2,120	Slipping 33.0
One-third speed	46.7	15	50	4.15	1,470	945	Slipping 7.4
One-third speed	46.7	7.1	25	0.52	366	236	Slipping 1.3
One-third speed	46.7	3.7	12.5	0.07	91.5	59	Slipping 0.27

Full or normal excitation of magnetic drive = 1.4 kw. or 0.2 per cent efficiency = 99.8 per cent.

running at one-half normal speed, the second when running at one-third normal speed:

Fred C. Bates: In 1895 I made a trip from Germany to China on the North German Lloyd steamship *Prinz Heinrich* which was exclusively equipped with electrically operated cargo winches, the first ship that was so exclusively equipped. The electrical equipment, consisted of two 75-kw. and one 35-kw. direct-connected, direct-current, 125-volt generators and six cargo winches mounted on deck.

Many things have changed since 1895. I would, however, venture to assert that the weather conditions under which operation must be maintained are just as vicious in 1921 as in 1895, and that the tricks of the gentle stevedore, be he black, white, brown or yellow, are just as stupid and just as rough as ever.

The ship was built by Friederich Schichan & Company at Elbing, near Danzig. She was 11,000 tons displacement, made about 14 knots, and was built for mixed cargo and passenger service in the tropics, hence the use of electricity in order to maintain a cool ship. The electrical equipment was furnished by the Union Elektricitats Gesellschaft, since absorbed by the Allegemeine Elektricitats Gesellschaft.

The capacity of the winches was 6600 pounds at 1.64 foot-seconds or 3300 pounds at double speed. The motors were from 10 to 15 horse power capacity at 450 rev. per min. The winches were installed one forward and one aft on the upper deck, two forward and two aft on the main deck.

A merchant ship is only in port when unloading and loading cargo. The rest of the time she is at sea; therefore a winch that breaks down in service in port must be repaired at sea, perhaps with a rolling ship in a storm, in order to be ready for service in the next port.

The apparatus mounted on deck is exposed to extremes of temperature, making the problem of lubrication difficult and necessitating the greatest care in the design of armatures, fields and resistances.

Apparatus mounted on deck is exposed to all forms of moisture, rain, snow, sea water and fog. While at sea the apparatus can be protected by tarpaulins, but in port the apparatus must be uncovered and operate under any conditions of weather. The location with respect to hatches and overhead tackle determines the amount of protection that can be given to apparatus and operator, but as a general rule any sort of protection impedes operation. Complete housing would be expensive, as it would have to be strong enough to withstand wind and waves.

The duty of such winches is most difficult. Long pieces of cargo such as bar iron or fabricated steel, if unskilfully "slung" will jam across the hatch opening. The operators often run out 10 or 20 feet of chain and "break out" the cargo with a winch at full speed. All this abuse requires extraordinary strength in shafts, keys, couplings, gears, etc., and most careful selection of electrical protecting devices.

We sailed from Bremerhaven, having loaded ship with her own electric power. At Antwerp the hydraulic dock equipment was used for loading and unloading. Our electric power was used in Southhampton and also for light duty at Genoa and very heavy duty at Naples, where all the winches broke down, and we sailed for the Far East with 4000 tons of cargo and not a winch working. It was quite evident that this particular equipment was inadequate.

The controllers were changed when we returned to Germany, but they were not successful and were changed again upon the second return. This time they were found to be entirely successful. I secured my acceptance of the equipment at Port Said and returned home on another ship.

We left Germany without spare parts of any kind. At every port we made vain efforts to secure electrical supplies; none of the big shipyards had such supplies and none of the cities we visited had shops or stores for the sale of this material. When we got to Port Said a friend took me to his storehouse and loaned me a miscellaneous assortment of wire and switches.

The engines were very bad, and we were unable to obtain proper regulation. On an old English tramp built on the Clyde which came into port, we found some good governors built by a concern called Clark & Chapman. After the purchase and installation of these governors, we had no further trouble with the engines and, as far as we know, they are still in operation.

The operation of the electrical winches was alleged to be as simple as the operation of steam winches and, while this was true later on, it was by no means so at first. The North German Lloyd had contracts with stevedore gangs in different ports, and as they had been accustomed to the operation of steam winches we had a great deal of difficulty in teaching these stevedores to use the electrical winches. The Chinese operators were the best. All we needed to do was to tell "No. 1" what his men were to do, and they did it without variation hour after hour.

In 1896 the steamship *Bremen* was laid down in the yards of Blohm and Voss. She was equipped exclusively with electrical cranes which were very successful.

The *Prince Heinrich* is now the steamship *Porto* belonging to the Portuguese government and sailing from Lisbon. Information received within a month through confidential sources is to the effect that the electrical cargo winches on this ship are still operating. We had no electrical failures. Our troubles were entirely mechanical, due to improper selection of material and a lack of knowledge of the sea, and of the service which the winches were to perform, but the outstanding fact still remains that this electrical equipment put into service in January of 1895, is still in commercial service in November of 1921.

G. H. Jett: It is very gratifying to me that an engineer of one of the leading electrical manufacturers should so strongly advocate the simplifying of wiring and control for electrical equipment on board ship, as Mr. Dickinson has done in his article. It would appear that, until recently, manufacturers have not fully appreciated the conditions on board ship as differing greatly from those in shore plants. There are many examples of ship installations where recommendations have been made by electrical manufacturers, following closely the practise generally in use in power stations on shore resulting in the use of unsuitable motors and equipment and in some cases a far too elaborate and complicated system of wiring and control apparatus. In general I concur in Mr. Dickinson's opinions.

In our merchant ship installations, in my opinion, the following are the most essential points to be borne in mind:

First, that the proper type and capacity of motor be selected, particular attention to be paid to the waterproofing of motors for all deck equipment. Without question the characteristics of the series d-c. motor make it particularly well adapted for cargo winches, windlasses and capstans.

Second, that the control equipment for all electric motors and apparatus be limited to the very minimum consistent with safety, hand-operated devices being used wherever practicable to eliminate danger of failure through burned-out shunt coils or other parts.

Third, that all protective devices limiting current to motors or equipment be installed in engine-room compartments or at least where it will be under the supervision of the personnel of that department, eliminating the possibility of deck hands or stevedores having access.

Fourth, that in all wiring, as far as practicable, marine armored cable not enclosed in conduit be used and that the amount be limited to the minimum consistent with proper grouping of circuits.

In this connection I want to say it is not my idea to eliminate any particular thing being proposed by the electrical people, but I do think it is necessary to limit to the very maximum the amount of equipment, and to simplify it as far as it is possible to do so. In Mr. Emmet's talk he called attention to the fact that—and I agree with him—the problem of training personnel for electrically driven ships is not what it is understood to be by many. In public service corporations, electric light and power plants, they do not have the engineers of these power plants make repairs to electrical equipment. They have specialized men for armature winding and winding of shunt coils who look after all the details of the equipment, and the steamship operator does not like the idea of facing the possibility of highly trained specialized men on shipboard, and for that reason I think it is most important, in view of the personnel going to sea at the present time, to eliminate to the very last degree the installation of unnecessary equipment. Every foot of wire and every shunt coil makes another possibility of trouble.

The motors as now supplied for ships are rugged and will stand a lot of abuse, but they do need a certain amount of protection.

The subject of rope speeds in handling cargo with deck winches is a very important one, on which there is a great divergence of opinion, there being but little reliable data and records available. Many of the steamship companies contemplating new construction are frequently demanding rope speeds which I am satisfied are far in excess of the speeds at which it would be practicable to handle cargo. .In most cases their demands are based on incorrect information as to speeds at which cargo is handled by steam winches. I have made an extensive study of this subject, and it is my opinion that only in exceptional cases is a rope speed of 250 feet a minute reached in handling sling loads of cargo even as light as 1000 pounds but the items of greatest importance are the acceleration and the speed of raising and lowering light hooks. In the design of electric cargo winches, in deciding on the size of the motor, you must take into consideration the speed at which the various weights of cargo are to be handled.

I do not agree with Mr. Dickinson's recommendations as to the size of motors required for deck winches on 8000 to 10,000-ton cargo ships. In my opinion 25-horse power motors are ample for any cargo winch except in case of very deep holds of the largest vessels. The majority of 8000 to 10,000-ton deadweight vessels have but eight steam winches, usually with engine cylinders of 8¼ inches by 8 inches or the equivalent. It has been demonstrated to my entire satisfaction that an electric winch equipped with a 25-horse power series d-c. motor will more than equal in every respect the performance of an 8¼-inch by 10-inch steam cargo winch. It is my belief that the load factor or ratio of average to maximum load, and consequently the size of winch motors required, is overestimated.

Referring to Mr. Dickinson's comparison between electric and steam operated auxiliaries as to fuel consumption because of the many elements to be considered, it is very difficult to determine the possible fuel saving to be effected in the operation of the engine-room auxiliaries this being a matter on which there are very little accurate data available. Advocates of steam equipment will no doubt take exception to the figures presented in Mr. Dickinson's paper. An important item to be considered in this connection is the fact that electrically operated equipment can be maintained at a higher operating efficiency than steam equipment. Electric motors will continue to operate at practically maximum efficiency as long as continued in service, as compared with steam equipment, which is subject to the usual adjustment and wear of steam valves, wear in cylinder liners, broken or loose piston rings, condition of steam packing, etc. The figures presented by advocates of steam equipment would of course be based on the equipment being in its most efficient operating condition, which is not generally maintained in service.

In my opinion Mr. Dickinson has been entirely too conservative in his estimate of the possible economy of electric deck winches over steam equipment, both in the case of fuel for operation and repair costs. There are considerable accurate data available on this subject.

The following data were obtained as a result of recent carefully conducted tests under actual operating conditions on a vessel of 11,600 tons deadweight equipped with three Scotch boilers, oil fired; main propulsion electric drive; engine room and deck auxiliaries steam-driven; deck equipment included twelve cargo winches, steam cylinder sizes 7 inches by 10 inches:

Usual engine-room auxiliaries operating 24 hours and an average of 10 cargo winches operating from 8 to 9 hours. Average fuel consumption per day, tons 11.

Usual engine-room auxiliaries in operation 24 hours, no cargo winches or other deck auxiliaries operating. Average fuel consumption per day, tons 4.

One cargo winch in operation for 5 hours continuously handling 1000-pound sling loads of cargo from hold of ship to dock. Average steam consumption per hour, lbs., 1200.

Calculating boiler evaporation at 13 pounds per pound of fuel, to supply steam for this winch operated under above conditions would require a minimum fuel consumption per hour of 92.3 lbs.

To determine the amount of steam consumed in the above operation, exhaust steam from this winch alone was condensed into a specially constructed measuring tank.

In comparison with the above, the following report on the performance of the motorship *Kennecott* is quoted. The *Kennecott* is a 6000-ton deadweight vessel equipped with Diesel engine main propulsion, all engine-room and deck auxiliaries being electrically driven from auxiliary Diesel engine-driven generating sets. Deck equipment includes eight 25-horse power dynamic lowering type electric cargo winches:

Vessel was at Seattle pier for a period of 10 days, during which time 3,000,000 feet of lumber were loaded. During this period the engineer's log shows that but 31 barrels of fuel oil were used for all purposes, including auxiliary Diesel engine generating set consumption for operating engine room auxiliaries and cargo winches. Average daily fuel consumption, 3.1 barrels.

Later reports of the *Kennecott* show that—

Under average operating conditions engine room and auxiliary equipment in operation 24 hours per day, deck winches in operation from 8 to 9 hours per day. Average daily fuel consumption 4½ barrels.

The above data are evidence of the economy to be effected in the use of electrically operated deck auxiliaries, but of course cannot be used as a comparison of fuel consumption for engine-room or other auxiliaries.

In giving these figures I made no attempt to make a detailed comparison or make any deductions. The figures I have given are unquestionable evidence of the possibility of economy, and, taking these figures, you can work it out on any basis you wish, and it will result in showing very decidedly in favor of electric auxiliaries.

William W. Smith: On page 1417 the author states that the cost of electrical deck machinery is little if any higher than steam machinery; I have found the reverse to be true to a very marked degree. For example, the cost of the steam deck machinery for a 10,000-ton cargo vessel was $33,000, whereas for electrical machinery, to perform exactly the same work, the cost was $80,000. It may also be pointed out that the cost of a 5-ton steam winch was about $1500, whereas for an electric winch of the same capacity the cost was about $4300. In view of these figures it is difficult for me to understand the author's assertion.

Referring to the comparison given on pages 1428 to 1431, I would suggest that the author add a brief description of these installations to give a better understanding of the comparisons.

On page 1428 the author states that the excess auxiliary exhaust steam is by-passed to the condenser. Thus, all of the available energy in this steam is wasted, which is not done in properly designed installations. Approximately 4550 pounds of auxiliary steam are condensed in the feed heater. This leaves 7950 pounds which could develop power in a low-pressure turbine under efficient conditions. Since there are no data for the turbine referred to, let us assume that this steam is passed into the low-pressure element of a Parsons turbine and expanded from 5 pounds guage to 28¾ inches vacuum. It is assumed that superheated steam (75 degrees) is supplied to the auxiliaries; that it is approximately saturated upon arrival at the turbine; and that the exhaust pressure is reduced from 10 to 5 pounds. With saturated steam, the low-pressure turbine will develop a horse power on 23 pounds of steam; so that 346 horse power could be developed by the steam which is wasted. This represents about 14 per cent of the total power of the turbine. It is needless to say that this is not a suitable basis for an accurate comparison.

The steam consumption given for the auxiliaries is about 50 per cent higher than I would estimate it to be for properly designed auxiliaries. It is also noted that this consumption is about 40 per cent of that of the main turbine. I would say that this figure would represent inefficient machinery or performance.

On page 1429, the steam consumption per S. H. P. is given as 16.5 pounds. This is not representative of efficient machinery of this class, for which the consumption should be 14½ pounds or less. Also the fuel consumption per S. H. P. is higher than it should be for such machinery with reasonably good operation.

It is not clear whether the turbo-generator is condensing or non-condensing, and where the exhaust goes to. It would also be interesting to know the horse power and other particulars upon which this performance is based.

On page 1431, under "saving in fuel consumption at sea," the author has allowed the same quantity of auxiliary steam for both 75 and 200-degree superheat. This cannot be considered accurate, since the power and steam consumption of the auxiliaries should be approximately proportional to the turbine steam consumption in two equally well-designed installations. It is not clear, but it is assumed that the main turbines for both steam and electrical auxiliaries operate under the same steam conditions. Otherwise the comparison would be of little value.

As pointed out above, 14 per cent in equivalent turbine power is wasted, and consequently this comparison cannot be considered as reliable. The same applies to the saving per year. Under this heading, also, no account is taken of depreciation, repairs, etc., which amount to about 12 to 14 per cent of the first cost, which is considerably higher for the electrical auxiliaries.

My conclusions after investigating the subject of electrical auxiliaries for cargo vessels were as follows:

1. Two large turbo generators were required.
2. We could not get electrical auxiliaries into the same engine room as used for steam auxiliaries, and additional space had to be allowed.
3. The electrical auxiliaries were heavier and more expensive than the steam auxiliaries.
4. The saving in steam and fuel consumption was not sufficient to justify the use of electrical auxiliaries.

I regret that I cannot give more specific data (including weight, cost, fuel consumption, etc.), since this would be desirable.

It is implied that electric winches will handle cargo faster than steam winches. I do not think this can be considered as an accepted fact. For machinery of the same capacity, I do not believe there will be enough difference to be of importance in the usual class of cargo handling. In special cases there may be advantages of importance, which, of course should be given due consideration.

Failure of steam to flow through pipes I do not believe can be considered as a very serious defect of steam machinery and any failure of boiler pressure would affect both types in the same way.

Referring to the cost of insurance, the fact is that this is somewhat greater because the first cost is greater.

Referring to the other savings mentioned there appears to be no sound basis for these assumptions which I should say were very doubtful. This also applies to the total saving of $55,190 on page 1433, which is also rendered inaccurate by the engine-room comparison as mentioned above.

There is no doubt a substantial saving in fuel in port and a minor one at sea. There may also be a slight saving in supplies, repairs, etc. Altogether, however, I do not believe the investment will pay.

Steam deck machinery is without question inefficient, and there are large heat losses in piping, etc. However, it is a great deal lighter and cheaper and so far appears to have the advantage for steam cargo vessels.

However, for motorships and passenger vessels the conditions and considerations are different, and for such vessels, especially the former, electrical auxiliaries seem to be the more suitable. In motor ships no main boilers are available, as in steam vessels; and in passenger vessels the considerations are often other than economic.

In general, although electrical auxiliaries, and especially those outside of the engine room, are generally preferable mechanically and from an engineering standpoint, they cannot be used in all cases because of the economic requirements. I may say in closing that reduction in weight and first cost would greatly accelerate the use of electric auxiliaries on shipboard.

G. A. Pierce: Referring to the question, "who is to carry the merchandise which has to be transported between the ports of the world," we are all too familiar with recent legislation to hold the owners and operators entirely responsible. On the other hand, we believe it should be shared equally by legislation, the architect and engineer who can save in many features, the builder who can govern the maintenance to an extent, and finally the owner and operator.

Motorships answer the question of electrical auxiliaries as far as reliability and economy are concerned, and it is to be regretted that we are compelled to refer to foreign-built ships for the principal data of their performance as no less than sixty-six of one type are in successful operation and foreign yards are building motorships today in greater number than our combined effort in all classes. The motorship with steam auxiliaries is a failure, as was proven in the case of the S .S. *California*. This was the wrong application of an otherwise perfectly good auxiliary, as steam auxiliaries in many instances are to be preferred to electrical, and it is to be hoped the advocates of the electrical auxiliaries will not duplicate the mistake made on that vessel.

Paragraph 4 does not appear consistent with the remainder of the paper in endeavoring to establish operating economies by the use of electrical auxiliaries, as greater economy can be realized by the use of Diesel prime movers for generating current than by the use of electrical auxiliaries in place of steam, as the fuel for the Diesel engine would cost only one-third of that of the steam turbine. The adoption of electrical auxiliaries will involve trained men, the handicap mentioned in connection with the Diesel, and it is my opinion that at no remote date licensed engineers will be required to be familiar with steam, oil and electrical machinery and there are, no doubt, many instances today of cargo ships which would not only warrant the expense of additional machinery and personnel but would show a substantial saving, and on the basis of the author's conclusions three times as much.

Referring to paragraphs 5, 6, and 7, relative to the cost of carrying cargo, the answer is not alone in electrical auxiliaries, as that cannot be a deciding feature, but in the motorship, which includes electrical auxiliaries.

Relative to deck machinery, we agree absolutely with the author in that none but the most careful design and the best of materials and workmanship should be used, as the apparatus is exposed to all sorts of weather and operated by the least intelligent. The deck winches largely used in this country, those with series motor and small shunt winding with spur reduction gear and manual control are simple and efficient and have been developed to a high degree of satisfactory operation. Safety appliances other than overload and no-voltage are unnecessary. Improvements can be made by the addition of automatic control, just as it has been for land practise thus eliminating the personnel element in operation. This, however, cannot be done with success until the ship operators are willing to pay for competent maintenance men to keep the apparatus in repair, and the expense for competent men should be considered in any scheme of electrical auxiliaries. It may be of interest to many to know that on the recently built motorship *William Penn* the 5000-pound hook speed was 170 feet per minute hoist, 470 feet lower; 2000-pound hoist 245 feet lower 380 feet; no load hook speed, hoist 457 feet, lower 337 feet, which corresponds to the author's recommendations and which speeds are in excess of general practise for electric winches; and that with these speeds and with the general cargo handled it was impossible to make up and discharge loads sufficiently fast to keep the winches in operation, thus removing a common complaint that electric winches are slow. A vertical handle of a new type for ship-board work was used, which required less movement of the body and consequently less tiring effect than any other type previously used.

The author's specifications for deck machinery motors cannot be too strongly endorsed.

Relative to the steering gear, it is questionable if a more satisfactory type employing the electric motor, than the hydroelectric gear has been developed. This type is ideal for control and makes a minimum demand on the generating plant with an efficiency equal to that of any other type, and should be considered seriously for new ships. The electric motor for the steering gear offers the greatest saving of any single auxiliary on the ship and, no doubt, in many ships the steam steering gear could be replaced by a hydroelectric gear with considerable saving and without increasing the size of the generating sets.

There has been considerable discussion in the past relative to the use of follow-up and non-follow-up system of control; while the non-follow-up gear may serve the purpose, it depends on a rudder indicator, a separate piece of apparatus for proper operation, and for this reason I believe the follow-up system, which is self-contained is to be preferred and its use will consume less power.

Relative to the horse powers of motors for cargo winches and steering gear, if we are to realize the maximum economies for electrical auxiliaries these should be worked out for each particular vessel.

Referring to the list of engine-room auxiliaries and the horse power required in view of the statement, "A motorship requires somewhat fewer auxiliaries and slightly less power is necessary to drive them," I believe the following comparisons should be made: Steamship 15 motors, motorship 5 motors; steamship aggregate horse power 160, motorship 55; fuel consumption, steamship, 41 barrels, motorship 2.5 barrels.

Relative to the types of motors for shipboard use, the greatest enemy of electrical apparatus is foreign substances and it is therefore essential that apparatus should be enclosed, particularly the rotating type with commutators. Therefore we are compelled to take issue with the author. The governing feature should be reliability; space, weight, and first cost should be secondary considerations. It is not so important that a certain frame size motor should develop so many horse power and be assisted by some sort of ventilation to do it as it is that it should work continuously for long periods without repair. Further, we believe that ball bearings are a very essential feature for continuous operation. Realizing certain limitations for enclosed motors, we believe, motors for below decks and engine rooms should be enclosed except where the size prohibits, and then they should be open with protection against drip and condensation from pipes and other apparatus, and this practise has been followed on foreign-built ships with success.

Relative to the location of starters, I desire to emphasize the author's opinion that they should be as close to the motors as possible.

Relative to the most suitable electric power for cargo ships, this has been answered by a failure of almost every installation of alternating current. For tankers, the same troubles would be experienced with the delicate a-c. regulators as on cargo ships and with most of the ships burning oil today the dangers in the engine room of a tanker would not be increased, and with alternating current there will be the operation of the switchboard switches and the exciter must have a commutator.

With regard to the wiring and installation, it may be of interest to the author and those present to know that the A. I. E. E. has recently issued a set of marine rules which amply cover all phases of the question and for power wiring are the only ones in existence. I do not believe the author's insinuation relative to the wireman's discretion should pass by unnoticed. From personal observation covering a period of 28 years, I have seen more failures of generating sets than bus wires, more failures of motors, controllers and starting panels than feeder wires, and I do not believe the author's contentions can be proven except in isolated cases and those during the war period.

Relative to operation, this is most difficult to discuss as the author has assumed certain fundmentals which cannot be reconciled and can be in keeping only with ships which are laid up due to their excessive cost of operation. I refer particularly to the figures of 12,500 pounds of steam for auxiliaries at sea, which is 30 per cent of the boiler capacity and 43 per cent of the main engines. These figures, to say the least, are ridiculous, and any deductions based on them are not only misleading, if used for comparison, but an injustice to the cause of electrical auxiliaries where they can be economically applied. Let me give you the figures from actual tests:

H. P.	*Aux.*	*Fuel*	
2,500	30%	1.23	calculated steam auxiliaries.
2,500	12%	1.01	calculated at 75 deg. superheat electrical auxiliaries.

ACTUAL TESTS STEAM AUXILIARIES

H. P.	*Aux.*	*Fuel*		
27,500	12.3%	0.87	No.	Superheat
20,000	13%	1.085	No.	Superheat
18,200	12.3%	0.947	No.	Superheat
2,880	11%	1.02	Qudruple Ex No.	Superheat
3,300	4%	0.41	oil engine	

Electrical auxiliaries have a place in the steamship when the generators are driven by engines or turbines, and that is outside the engine room for steering gear, windlass and deck winches. Electrical auxiliaries can only show a saving in the engine room when the genertors are driven by oil engines. This arrangement would require extracting steam from the main turbine for all heating of feed water, which is extremely bad practise and is not recommended for shipboard use in any degree. The adaptability of electric motors has been proven beyond question, and the answers to who shall carry the merchandise of the world is—motorship with electrical auxiliaries.

Charles Rettie (Communicated): It is only of recent years that electric auxiliaries have been introduced into ships. On the earlier ships that I worked on, which included the Empresses running out of Vancouver, which were built in 1890 in Barrow in Furness, no motors were installed though they were all equipped with the electric light—the *Empress of Japan* and the *Empress of China* had each four dynamos which I worked on, the *Empress of India* having already been completed.

There is a large field for the use of electric auxiliaries on board our merchant marine, there are still a good many places on ships where the electric motor might be used with advantage and, as already pointed out by our leading electricians in this country, including Mr. Wordingham, late president of the I. E. E. and head during the war of the Admiralty Electrical Department for ship works, that while there is a doubt as regards the economy of using electric motors for driving our ships, there is no question of the advantage of the use of electric auxiliaries over every other system, and they should be immediately installed on all our ships; electricity should be used for all power purposes except the actual driving of the ship.

With reference to Mr. Dickinson's remarks regarding the use of enclosed motors on deck and partially enclosed below deck, the latter being shown on Fig. 5, I take it this would only apply in some cases, but surely not in the engine rooms and boiler rooms; it need not be necessary to be watertight but all openings would have to be covered to keep out dirt, oil and dripping water, especially in the case of the turning motor, used for turning the main engines in port, where it has to be fitted low down in the engine room and likely to be covered with falling dirt and water and oil.

I think the best power for use on board ship is unquestionably direct curent as pointed out by the author, but as the tendency lately is to use submersible pumps on board ship, and as the same can only be worked by alternating current, it will be necessary in all up-to-date plants to have a rotary converter to supply current; that is a point which has been omitted by the author. As is well known the squirrel type of a-c. motor will work under water.

In the description of wiring systems, nothing has been said about the possibility of using ring mains; that is the only way to reduce the number of circuits as suggested by the author in another part of the paper; the number of circuits on a distributing system cannot be reduced with safety; a large number of circuits must be run to supply the different parts of the ship, either for the lighting or power.

I also notice the author does not recommend the use of conduits for carrying the wires and cables. In this country the tendency at the present time is to use screwed conduits galvanized wherever possible in the electric lighting of our ships; in fact the latest Cunarder being built on the Mersey, I understand, is mostly wired in galvanized steel tubes solid screwed.

In most of the ships I have worked on recently the systems have been divided up. For instance, on one ship armored and lead-covered cables are used in the engine room and boiler room, casing on the passages, galvanized screwed conduits in the holds and portable fittings in emigrant quarters. The last ship I worked on was a refrigerator ship of about 7000 tons for carrying bananas. She had three generators, about 80 kw. each; most of the electric power was used for driving huge fans for cooling the holds where the bananas were stored; all the passengers' quarters, of which a few first class were carried, and officers' rooms were heated by electricity. The steering gear was steam. The hoist motors in the boiler rooms were worked with a lever up and down to start and stop.

In conclusion, referring to the question of salaries, there is another point I would like to raise, and that is the question of the status of an electrician on board ship. On one of the Norwegian-American liners, the *Stavangerfiord,* which I worked on, they had a very good arrangement. Instead of the electrical department being subject to the lowest graded engineer, as in this country, it was run as an entirely separate department. The chief electrician ranked with the chief machinist. There was a commander engineer over all. The chief electrician messed with the chief machinist, and the chief commander had his quarters with them. The junior electricians messed with the junior engineers. I think the above is a very important point to raise because, as the electric machinery used on board ship gets more complicated, a higher type of man will have to be employed, and unless sufficient remuneration is given and more respect shown, it will be difficult to get a good man to go to sea on ships as an electrician.

At the opening meeting of the Liverpool Engineering Society, November 3, an address was given by the president, James B. Wilkie, on the "History and Progress of Marine Engineering." He gave details of a new ship belonging to the company he is interested in. The name of the vessel is the *Aba* of about 7000 tons, oil driven; *all her auxiliaries are electrically driven. The generators of which are three in number, are* 200 *kw. each, and are driven by Diesel engines.*

W. McClelland: In the British navy we have always pinned our faith to the geared turbines with the single-reduction drive. I think the author of the propulsion paper has stated the case exceedingly fairly. He has not gone in for any of the extravagant claims for electric propulsion which I have seen published in certain papers from time to time, but there is one statement in the paper on the comparison of the economies claimed by the United States warship *New Mexico* over the *Idaho* and *Mississippi*. In that connection, while the author, I believe, states facts—the *Idaho* and *Mississippi* are direct-turbine drives with an auxiliary turbine-geared drive.

That installation is now somewhat behind present practise and would not be repeated in any modern ship, and therefore I feel that a comparison which shows such marked economy by the electric drive is not one which should be passed over without reference in the discussion. I believe that a practical trial of the latest practise in steam-turbine geared work would show that there was very little difference between the electric drive and the turbo-geared drive. At various points on the curve, you would find that the electric drive gains considerably, whereas at other points on the curve I think you would find that the steam-geared drive gains. The steam gearing, I believe, will gain at maximum speed. The electric drive will gain at cruising speeds, and it is a matter of policy, I think for the various governments designing these ships, as to whether maximum speed is required or economy at cruising speed. That the electric drive is economical over most of the range of speed of a capital ship, that it is reliable and generally free from breakdown is admitted.

The discussion has turned in large measure on the Diesel electric drive. Whilst I am not a Diesel expert, there is one question I would like to put to the gentlemen who advocate Diesel drives, either geared or electric in the present stage of development, and that is this—if you have a single-screw ship, is there any owner who would rely on, say a single 3000 to a 5000 h. p. Diesel engine, and send that ship to sea on a scheduled service? I do not know whether there is in this country or not. I am rather doubtful as to whether there is in our country. In this respect the reliability of the Diesel appears to be regarded as much less than either the turbine or the reciprocating engine.

Several remarks were made about the different classes of main motor machinery. It was my good fortune to come to America in the fruit ship referred to by the last speaker. In that ship the drive is by means of a synchronous motor, and one speaker particuarly referred to the question of the racing of electric motors when the propeller of the ship was out of the water. We had very heavy seas—at one stage of the crossing we ran into a hurricane and the propeller was out of the water over and over again, and there was no racing whatever—the motor stood up perfectly to its work and I believe that with a properly designed synchronous motor, you will get in addition to high efficiency equally good results as with any other type of motor.

Passing on to the auxiliaries paper, I am in general agreement with the author. In the British Navy we we have for many years run most of our auxiliary machinery electrically. We have winches capstans, pumps, refrigerating machinery, fans, air compressors, almost every conceivable kind of machinery, running by electricity and we have had very little difficulty with that machinery; I speak with some authority, because during my eighteen years of service with the Admiralty, fifteen years of that period was spent as head of the electrical repair department, and I have had to deal with all classes of electrical machinery, not only machinery connected with the British Navy, but during the war, of the American Navy.

There is one point to which I would particularly like to refer, and that is the question of insulation. We hear a lot about water washing electrical machinery on the decks. I do not really think that in this country the importance of proper insulation for electrical work for deck machinery has as yet been appreciated. I have visited many of the works in this country, and I am quite sure most of them can make satisfactory material, but most of the materials used are composite materials, and these materials absorb moisture. This means breakdown sooner or later in moist atmosphere laden with salt.

I am giving you the result of our experience. We have found that the only insulation which stands up under salt water and sea atmosphere conditions is mica and micanite. For instance, with control gear, with fingers clamped to a diamond shaped or square bar, which has been insulated with moulded micanite or wrapped micanite thoroughly baked and finished, you will have a thoroughly satisfactory insulating material; whilst at the present time we are carrying out tests on practically every known composite material, I have not yet met with the material which I should consider suitable for insulating electrical machinery on deck.

I was much interested in what Mr. Bates said about the winches on deck being washed with sea water and that they were not satisfactory; he then went on to say that the whole of the defects were mechanical, not electrical. I could not follow his argument, unless it was that the sea water damaged the mechanical parts, which speaks well for the electrical gear. Another speaker referred to the maximum speed of lift at which winches should be used. He stated they had standardized 250 feet per minute. I think that is a good speed for full load. Sometime ago we tried a speed of 300 feet per minute, but experience showed it to be too fast for a short lift, and we dropped our full load speed for winches to 200 feet per minute.

I believe in direct current for ships, and also in the two-wire system rather than the three-wire system. Earths or grounds are so prevalent on a ship's electrical system that I think the simplicity of the two-wire system more than counterbalances any slight advantages which the three-wire system has. 220-volt incandescent lamps are now satisfactory on board ship, and there appears no necessity for the third wire.

With regard to submersibles, although it is a difficult problem, I think time will show that we shall get a satisfactory continuous current submersible pump—I am hoping so. Alternating current will not then be required for this service.

Ernest H. B. Anderson: It seems to me that Mr. Thau has given the Society no definite information regarding the fuel consumption performance of steam electric-geared vessel.

There must be a great deal of data available, and there is too much doubt about the fuel consumption performance of such ships; this applies to naval vessels and also to ships of the merchant marine.

For instance, there are eleven freighters which are having the original mechanical geared turbines replaced by electric gearing. The first of these, the *Eclipse*, has completed a voyage of 26,000 miles and, as far as one can learn the machinery worked splendidly throughout the voyage but nothing reliable has been published regarding the fuel consumption. Competent authorities who have had an opportunity of studying the "engine-room log" state that the oil fuel consumed by

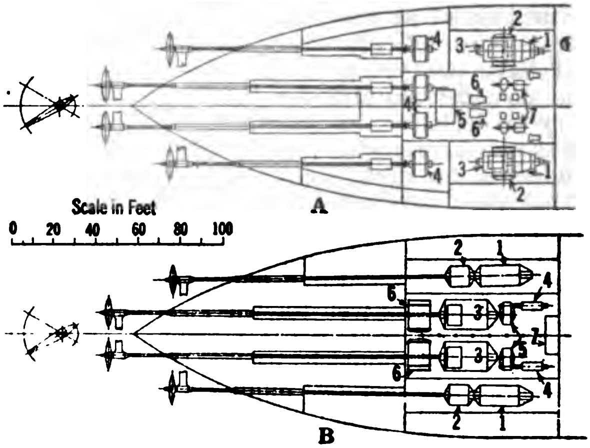

Fig. 13—*A*—Battleship *New Mexico*
B—Battleship *Idaho*

the main engines and auxiliary machinery averaged about 1.30 pounds per S. H. P. per hour. Further, it should not be overlooked that the boilers were equipped with superheaters giving 200 deg. fahr., and in view of this, the reported performance of the machinery is poor.

A double-reduction geared steam-turbine vessel operating under the same conditions has a fuel consumption of 0.90 pound of oil per S. H. P. per hour for all purposes.

It seems to me that the builders of the electrical machinery in these freighters did not quite do justice to the system they were advocating, for it was necessary to increase the revolutions of the propeller from 90 to

100 per minute which is hardly suitable for a freighter of 16,000 tons displacement and sea speed of 10.5 knots. Shaft revolutions of 75 to 80 would have ensured a much better performance but to accomplish this mechanical gearing of the single-reduction type would require to be arranged between the propelling motor and line shafting. This arrangement was adopted by Llungstrom in the vessels *Mjolner* and *Wulsty Castle,* where two motors are in parallel, each driving a pinion in mesh with one gear wheel.

Dealing with warships, in view of the great interest taken in the machinery installations of the battleships *New Mexico* and *Idaho,* Nos. 40 and 42 respectively, Fig. 13 shows a plan view of the propelling machinery, and it will be seen that the engine-room spaces in these two ships are alike, but the propeller revolutions at the designed power and speed in the *New Mexico* are 170 per minute, whereas in the *Idaho* they are 240 per minute. Needless to say, the slow-turning propellers of the former have a considerable advantage over the latter.

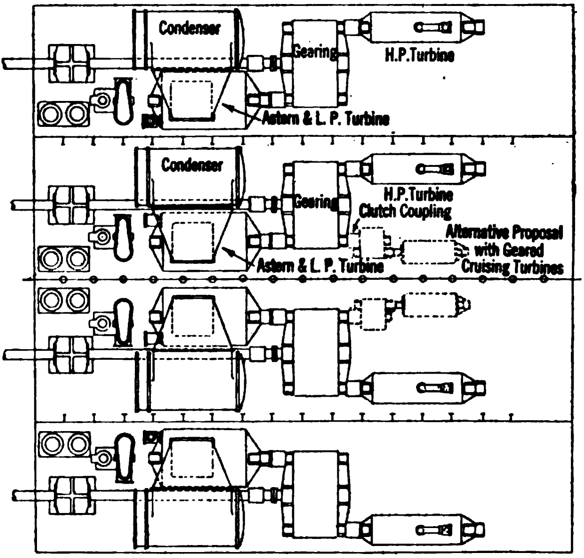

FIG. 14—PROPOSED ARRANGEMENT OF GEARED TURBINE MACHINERY ON U. S. BATTLESHIPS

Whilst bids for battleships Nos. 40, 41 and 42 were in hand during 1914, geared-turbine machinery was making rapid progress, and we submitted alternative proposals with this type to the shipbuilders, and two firms offered to build these battleships with geared turbines driving four shafts, as shown in Fig. 14.

Battleships Nos. 43 and 44, *Tennessee* and *California,* were designed during 1915, having a four-shaft arrangement of "electric gearing" for the propelling equipment, in which the machinery arrangement is absolutely novel as compared with all previous battleships.

We submitted alternative propositions to the Navy Department, but it is almost impossible to install or arrange mechanical geared steam-turbine machinery in spaces specially designed to suit electric gearing.

Fig. 15 shows a plan view of the *Tennessee* and *California* arrangement of machinery and a proposal having twin screws, driven by two sets of Parsons single-reduction geared steam turbines. The revolutions of the electric-geared ships are 170 per minute, whereas in the twin-screw turbine proposal they are 125 per minute.

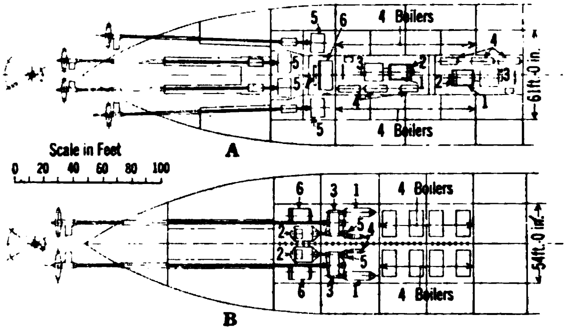

FIG. 15—U. S. BATTLESHIPS *Tennesee* AND *California*. PROPOSED ARRANGEMENT OF MACHINERY

On referring to the plan view of the electric geared machinery, it will be seen that there are two central compartments, each of which contains a complete turbo-generator and the various auxiliary machinery. There are eight boilers divided into two groups, four being arranged in separate compartments on each side of the turbo-generator spaces, the total width of the machinery spaces being approximately 61 feet. The uptakes from the four boilers are led to two funnels, arranged on the center line of vessel and directly above the turbo-generator compartments.

Multiple shaft arrangements of machinery came into use solely to suit direct-driven steam turbines, and it is rather curious that the electrical firms merely copied a type that was never considered suitable for battleships of 28,000 S. H. P. to 32,000 S. H. P. by many naval constructors and naval engineers in Washington.

Referring again to Mr. Thau's paper, electric gearing has its limitations just as well as all other forms of propelling machinery; among these may be mentioned:

Backing qualities. Experience has shown that it is not necessary to have more than 60 per cent astern power, and it is overlooked by many that it is "stopping qualities" which are required. In other words, two large-diameter slow-turning propellers will bring any large vessel to rest quicker than four fast-turning propellers which at all high speeds of revolution do not take a grip on the water but tend to cavitate in a vortex.

The electric-geared battleship does not maneuver or go-astern with full "ahead" shaft horse power. I believe it is now an official order in the Navy that all maneuvering has to be carried out with one turbo-generator transmitting current to the four propellers in parallel.

This limits the maneuvering capabilities to a large extent, for all propellers must revolve at the same speed, if in operation. For instance, the two port propellers cannot run at maximum speed "ahead" whilst the starboard propellers revolve "slow astern." A complete explanation for this limitation when maneuvering will be found in a paper published in the *Journal of the American Society of Naval Engineers*, August, 1921, in the article "Propulsion Wiring Circuits, U. S. S. *New Mexico*," under the sub-title "The Steam Limit Device" on pages 509-511.

Weights, space and economy are all in favor of mechanical geared turbine machinery, but until further data are available regarding these items in connection with electric gearing in war vessels, it is useless to attempt to discuss these features.

The battleship *North Dakota*, built in 1909, has had the original direct-driven twin turbines replaced by twin sets of single-reduction Parsons geared turbines, and the new machinery has resulted in a gain of 31 per cent in fuel consumption at all speeds. For further information on this point, reference should be made to the report of the Engineer-in-Chief, U. S. N., for 1919.

I should also like to mention that this new machinery effected a saving of at least 50 per cent in the weight, went into the same engine-room space with very few changes, and has done very well ever since the vessel went back into commission. Further, this replacement could not have been carried out with any of the present forms of electric gearing.

Referring to the data accompanying the performance of the *New Mexico* and the so-called sister ships, I think the author cannot have realized that these figures were quoted in a paper read by Eskil Berg at a meeting of A. I. E. E. during May of this year. Mr. Berg gave the source of his information; this data was submitted to the editor of *Marine Engineering* and published in an editorial in the issue of May 1920, entitled "Two Years of Electric Propulsion on *New Mexico*.

I shall not comment further on this point but suggest that anyone who is interested in the question obtain the August 1920, issue of that journal and see the other view, in the article "U. S. Battleships of the Year 1914 and Later Classes."

I was much interested in listening to Mr. Newman's remarks regarding the performance of the new coast guard cutters, but unfortunately very little was said regarding the actual fuel performance of the electric geared machinery.

The *Army and Navy Register*, in its issue of September 10, gave particulars of the trials of the U. S. S. *Tampa*. It was a short article and one paragraph read as follows:

U. S. S. TAMPA

STANDARDIZATION RUNS

Knots..........	8	10.50	11.80	14.20	16.20
Revolutions..	60	80	90	110	128

"The total fuel consumed on the four-hour run was 2008 gallons. The consumption was high on account of unsatisfactory pump operation." That is all. As Captain Newman stated, the contract conditions of the vessel were as follows: Knots 16.00; S. H. P., 2600; revolutions, 130. There are superheaters also installed on these vessels, and if you use the design figures as a basis, you will find that the fuel consumption average about 1.35 pounds of oil per S. H. P. per hour for all purposes.

E. A. Stevens, Jr.: (Communicated): Before discussing this paper in detail, I think it would be well to consider the question of transmission in general, whether it be electric, mechanical gear or hydraulic. The only advantage of any of these is the ability to run the main machinery at a different speed than that of the propeller, thereby obtaining greater economy than what would be possible if the two were operating at the same speed. With this in view, the Diesel electric (except in a few special cases) would be eliminated. As the Diesel engine is more reliable as well as more economical at the lower speeds, it is far better to connect direct to the propeller than to use any of the transmissions mentioned above.. It has been argued that when the cylinders reach a certain size trouble occurs. This can be eliminated by increasing the number of cylinders up to eight to one shaft, or by the use of twin or even triple screws. When the power required is greater than what would be practicable with three screws, it would be better to use steam, as the weight, first cost, and complications of the Diesel electric system would offset any advantage, if any, that this system would have in economy.

Mr. Thau states: "The economy of a reciprocating engine drive is obviously poorer than that of a properly designed turbine of either type, for the reason that the reciprocating engine cannot utilize the same expansion of steam." This is true for high powers, but for a slow ship of 3000 horse power or less, the reciprocating engine has shown as good economy as the average geared turbine and better than the electric drive, in spite of the fact that no superheat was used with the engine while 50 degrees superheat was used with the geared turbine and 180 degrees with the electric drive. The cost of the electric drive outfit installed is over double that of the reciprocating engine, while the geared turbine is about the same or a little less than the latter.

If three junior engineers are required for the direct-connected Diesel as shown in the table on page 1440, why are they not required for the Diesel electric, which is more complicated?

The fact that the U. S. Navy has adopted the electric drive for battleships and battle cruisers speaks well for it, but cannot the same thing be said about the geared turbine which is being used by the British Admiralty in the above-mentioned classes?

The protection against torpedo attack afforded by the electric drive is not much greater, as the motors on the outboard shafts are as near the skin of the shid as the geared turbine would be; besides, the ship fittep with the latter could be better protected against gun fire as machinery is lighter, while the maneuvering ability of the geared turbine is all that is desired.

It is hardly fair to compare the *New Mexico* and *Tennessee* with the *Idaho* and *Mississippi*, as the two latter are fitted with direct-drive main turbines and geared cruising turbines. A considerable amount of the saving was due to the propellers.

Mr. Thau neglects to state that, while the battleships and battle cruisers of our Navy are, or are to be, fitted with the electric drive, the light cruisers and destroyers are being equipped with geared turbines. The U. S. Navy refrained from using the latter in the battle cruisers where weight is of great importance, because they did not believe that gears could be built that would transmit the necessary power (45,000 S. H. P. per shaft). However, the British Admiralty has been able to transmit 39,000 S. H. P. per shaft successfully.

S. M. Robinson: (Communicated): Turbo-electric propulsion is being used to such an extent at the present time and is so well known to the marine engineering world that it hardly seems necessary to dwell much on this subject, but Diesel-electric propulsion is a comparatively new art and still has its way to make in the marine field. It seems to me to be an ideal system of propulsion for cargo vessels. By its use it should be possible to greatly increase the reliability of Diesel engines, since it will not be necessary to start them up under load nor reverse them. The importance of these two points is very great and cannot be emphasized too much in any comparison of direct-connected Diesel engines and Diesel-electric propulsion; submarine experience has shown that many of the troubles with Diesel engines are directly traceable to these causes and, while air starting is still fitted on these engines, it is only used in case of emergency when the motors are out of commission.

With Diesel-electric propulsion it will be possible to use multiple units, thus keeping down piston diameters; this will add greatly to the reliability and will also operate to reduce the maintenance cost. It also makes it possible to carry out engine repairs on one engine at sea without suffering any very great reduction in the speed of the ship.

Diesel-electric propulsion is frequently criticized as being about 12 per cent less efficient than the direct-Diesel drive. No general statement can be made which will cover all types of ships, but for cargo vessels of the usual low horse power it can be said that there will be little difference in the overall economy of the two systems, and what difference there is will generally be in favor of the Diesel-electric. This arises trom the fact that it is necessary to use twin screws running at comparatively high propeller speeds for the direct Diesel, while a single screw of lower speed can be used with the Diesel-electric; with the latter arrangement the losses in the struts are done away with and a more efficient screw is provided due to the lower speed at which it runs.

I believe that the voltage proposed by Mr. Thau is somewhat higher than should be used on board ship, and this will not be necessary if the number of units is reduced; a three-generator and two-motor installation would seem to give all the flexibility desired and at the same time obviate the necessity for the use of such a high d-c. voltage. This will give three combinations of generators and motors, the first being all units in use, the second being two generators and two motors, and the third being one generator and one motor. At the maximum capacity of each of these conditions the motor and generator efficiency will be practically the same as at full power.

In connection with the flexibility of the series system of Diesel-electric propulsion, Mr. Thau points out the simplicity of the speed control which is obtained by varying the generator field strength; this method can be combined with that of variation of motor field strength so as to give the most efficient operating condition for any of the various combinations of motors and generators.

H. L. Hibbard (Communicated): The two papers presented this afternoon cover subjects of the greatest importance to our merchant marine industry, but it is our own feeling that much the larger field for the application of electric drive lies in the direction of the ship auxiliaries.

Mr. Dickinson's very interesting paper has covered this subject of electric auxiliaries in an able manner, but we could wish that he might have been more specific with regard to a number of the detailed points which he has raised.

He refers to the two types of electric steering gears now in use but does not mention the dividing line where the hydroelectric gears for this purpose would have a distinct preference. In our opinion, the direct application of motor drive to the steering gear can be used to the best advantage in horse powers up to about fifteen. For twenty horse power and beyond, the hydroelectric has unquestionable advantages.

Reference is made to contactor equipments especially for deck winches but apparently the wisdom of this form of control in most cases is questioned. For the severe service met in the case of these auxiliaries, the contactor control, we feel, is especially suited, and foreign practise has already clearly demonstrated the feasibility of its use and of readily locating the contactor control below decks or in suitable housings.

Sub-paragraph (*d*) on page 1415 touches upon the wisdom of omitting, as far as possible, all safety devices. While these should unquestionably be reduced to a minimum, we would ask Mr. Dickinson, for the benefit of the profession, what devices he would recommend for deck auxiliaries. In our opinion, stalling devices at least must be furnished in connection with anchor windlasses, capstans, steering gears and overload contactors or circuit breakers for deck winches.

On page 1425 are discussed the relative merits of direct and alternating current for auxiliary purposes and it is stated that while on the cargo ships direct current can be used to the greatest advantage, on tankers it is not so apparent. On this latter point we would take some issue, as it is possible to furnish motors entirely enclosed, gas and watertight, or where location on tank vessels renders the same desirable to furnish forced ventilation through the enclosed motor casings. Several tank vessels in this country have already been equipped in this manner, and there are others under construction.

With regard to the question of economy of engine auxiliaries on steam-driven vessels, Mr. Dickinson has furnished some interesting figures, although we feel that perhaps his assumption for the steam required for auxiliaries at sea is a little too high a percentage of the total. The advantages obtained from the use of electric drive for all auxiliaries on motorships is, we believe, now apparent, and similarly the advantages of the electric drive for deck auxiliaries on steam vessels as well as motorships. The question, however, of the use of electricity for auxiliaries in the engine room on steam vessels furnishes the most debatable ground. A certain amount of exhaust steam from engine auxiliaries is always diverted to feed water heating, but beyond the point where exhaust steam can be used economically for this purpose lies considerable possibility in economy for electric drive as well as the advantages of convenient operation and freedom from leaking steam pipes, etc.

We heartily endorse the statement of the author in his last paragraph that engineers of this country should combine their efforts and avail themselves of every opportunity to improve the efficiency of our merchant ships to the end that they may be able to compete successfully with the modern ships of other countries. In this connection, we were much impressed on a trip this summer to the Pacific Coast, to find that numerous European and Scandinavian motorships, electrically equipped, were making regular trips through the Canal to the Pacific Coast ports. In addition to the conducting of a satisfactory cargo-carrying business, these vessels were buying California oil on the coast at $1.50 per barrel, sufficient for a round trip, this same oil selling in their own home ports at $8 to $9 per barrel.

G. A. Pierce: In view of the fact that there has been considerable discussion relative to the Diesel-electric drive, I might say that we are all familiar with the specifications sent out for a tender on a ship for Diesel-electric. The Diesel-electric equipment for that ship was 58 per cent heavier, had 20 per cent more fuel consumption, and was 10 per cent more costly than the direct-Diesel.

W. L. R. Emmet: As to the question of the relative economy, the turbine being the same for both, the difference must be small. In a large ship, for which we have recently designed electrical transmission machinery, we would only lose 4.5 per cent. The *San Bonito* which just came over, and which ran in the Mediterranean for a long distance, had a rate corresponding to 1 pound of fuel per shaft horse power. Any of these other electric ships will do pretty nearly that. The difference is, in any case, small, provided the turbine is equally good. I have tested a large number of ship gears by actually running them on generators at a given load, and I have actually found the efficiencies of a double reduction ship gear as low as 96. I have tested 6000 h. p. gears and two 3000-h. p. gears, and know the losses are considerable in the gears alone.

I think it quite probable that Mr. Anderson's criticism of the 100-rev. per min. propellers in the Shipping Board boats equipped may be correct, although, when these jobs were undertaken, statements to the contrary were given us by the best authorities.

W. E. Thau (Communicated:) Mr. Emmet says that I have understated a few of the points of advantage or of attraction in regard to electric drive. I can merely reply to this by saying that I endeavored to be ultraconservative throughout the entire paper, so as not to invite undue criticism from gentlemen who oppose electric drive or who are not yet prepared to accept it. This is one reason why I placed maintenance on not worse than a parity with other drives. I am sure that the electrically driven ships in operation have already shown a surprisingly low maintenance cost.

I have given considerable thought to the efficiency of synchronous drive, as compared with induction drive, and have always concluded that there can be only a very inappreciable difference in efficiency. The suggestion by Mr. Emmet that the adoption of electric auxiliaries throughout will enable the installation of larger auxiliary turbines which would be conducive to lower steam consumption for excitation is, of course, correct, but I think that, considering everything, the ultimate difference in efficiency of the two drives would be inconsequential. The largest attraction of the synchronous drive is in the weight, space and cost saving resulting from unity power factor. As I have shown later in the paper, these advantages can be obtained with the induction drive using the power factor corrective apparatus.

The larger air gap and better access of the synchronous motor were mentioned in the last paragraph of my description of the synchronous motor drive.

By "high-speed Diesels" I do not have in mind high piston speeds. The matter of piston speed must be treated with conservatism in high rev. per min. engines, as well as in low rev. per min. engines. The reciprocating parts being smaller, the cylinder walls and cylinder heads thinner (this being conducive to quicker heat transfer and lower temperature strains), and the absence of water cooling on the pistons should decrease rather than increase the maintenance of the engines. Repairs are easier to make because of the smaller parts to be handled. There are engines of 200-h. p. capacity at 250 rev. per min. that have been operating continuously, except for periodic valve grinding, since 1914, and during this time the maintenance was practically negligible.

Regarding the application of alternating current for Diesel-electric drive, I am quite sure that the flexibility in control advantages alone of the direct current would go a long way to favor the direct current, even though parallel operation of a multiplicity of a-c. units were entirely feasible. It has been shown definitely in the case of land installations that Diesel driven alternators do work satisfactorily in parallel, but it must be remembered that these engines operate at constant speed instead of at adjustable speed as would be necessary in the case of ship drives. Where the Diesel engine units are sufficiently large so that one unit would supply one motor, as in the case of a twin-screw drive, alternating current is feasible and will undoubtedly be used under certain conditions.

Mr. Emmet mentions that the interchangeability of electrical units in a ship installation was not brought out in the paper. I did not deem it desirable to go into this matter in detail, as the principal part of the paper was on merchant ships, whereas such opportunities are only offered on high-powered ships having two or more generators. Reference was, however, made to this feature under the captions of "Reliability," "Economy," and "Control" in the section covering war vessels. This advantage was also referred to in connection with the Diesel-electric drive. For large ships these advantages are important, as is perfectly obvious, for the reason that balanced power can be obtained on all screws, regardless of the number of generator sets in operation.

The advantage resulting from the change in ratio in motor speeds for a given frequency is also mentioned in the paper under the caption of "Economy" in the section covering war vessels. This item was not discussed in detail, as it has been given considerable airing in recent technical publications. Mr. Emmet brings out the comparison that the advantage resulting from the change in pole ratios of the motors is more pronounced on the *Maryland* than on the *Tennessee*. This is true for speeds between 13 and 15 knots, but for lower speeds the larger number of poles show better economy. This characteristic can only be explained by the combination of turbine and motor and generator efficiency. performance. I think the performance of the *Tennessee* is more or less incidental, as such a condition would not be anticipated. The turbines installed on the *Tennessee* are particularly economical at a very wide range of speed.

Three of the discussions, at least, dwelt at considerable length on weights and submitted some data which are at variance with the author's analysis of weights, space, cost, etc., for the different principal types of propulsion. Any data of this nature must of necessity be considered upon its hypothesis, as there are several ways of comparing such items relating to propulsive machinery. There is, however, only one correct way, and that is to include every single item which by virtue of its function is directly related to the propulsive equipment, such as engines proper, boilers, condensers, propulsive equipment auxiliaries, shafting, foundations, seatings, water in machinery, reserve water for machinery, stacks, piping, ladders, platforms, thrust bearings, shaft alley bearings, propellers, generators, motors, control, cable, exciters, fuel, lubricating oil, etc. A comparison of the bare machinery weights means nothing.

The analysis of the Diesel-electric propulsive machinery in the paper is based upon a single-screw drive in which the propeller rev. per min. is uninfluenced by the motor speed limitations, because with Diesel-electric drive, using direct current, the propeller speed can very conveniently be made to suit the preference of the propeller designer, as there is absolutely no fixed relation between the generator speed and the motor speed.

Because of the well-known fact that practically all of the direct-drive Diesel ships today are twin screw, this arrangement has been considered in the case of such ships.

It is probably unfortunate that a table of comparative weights showing all items considered was not incorporated in the original paper. The author's statements in comparing the different factors of the various drives were of a general nature, and this system was used purposely to avoid contention on details. To substantiate the statements in the paper, particularly in connection with weight, the following table, which forms the basis of the author's analysis, is included in this reply for reference:

TABLE VI.—TABLE OF DETAIL WEIGHTS FOR A 3000 S. H. P., 90 R. P. M. DRIVE

Item	Double-reduction geared turbine	Turbine-electric	Direct-Diesel (twin screw)	Diesel-electric
Prime mover	*100,000	*206,000	*1,200,000	*1,050.000
Boilers and superheaters	†360,500	†360.500	‡11,200	‡11,200
Condensers and auxiliaries	50,000	50,000	....	....
Water in machinery	200,000	200,000	45,000	45,000
Reserve water for machinery	250,000	250,000	....	....
Propeller shafting	115,000	115,000	135,000	115,000
Propeller shaft bearings	15,000	§30,000	§45,000	§30,000
Gratings, ladders, etc.	60,000	60,000	50,000	50,000
Control and cable	....	18,000	....	¶
Steam and water piping	100,000	100,000	32,000	32,000
Independent auxiliaries	32,000	32,000	130,000	20,000
Uptakes, air box, stack, etc.	70,000	70,000	11,000	14,000
Totals	1,352,500	1,491,500	1,659,200	1,368,200
Lbs. per S. H. P. total machinery	451	497.5	552.5	452.5
Ratio, geared turbine, unity	1	1.103	1.227	1.003

Note—Using water-tube boilers, the two turbine drives would be reduced about 250,000 pounds. However, the installations using such boilers are relatively very few in comparison with those using Scotch boilers.

*180 rev. per min. engines with exciters.

†Scotch boilers.

‡Vertical boilers.

§Include thrust bearing.

¶Included in prime mover.

A brief discussion of this table will reply to several points raised by Mr. Bailey and Mr. Smith. It will be noted that at least every essential item on which there is any difference in the various types of drives has been included. Unfortunately, I have no reliable data on foundations which must be made a part of the ship's structure for supporting the propulsive machinery. However, I believe that these items should just about balance in the various types of drives, and what little difference might exist would certainly be of little influence in the ultimate results, or might even favor the Diesel-electric.

The Diesel engines considered in the table for the Diesel-electric drive operate at 180 rev. per min. and complete with their accessories, generators, exciters, the motor and control, weigh 350 pounds per shaft horse power. Of this figure, the electrical equipment consumes 104 pounds, leaving 246 pounds for the engines. Certainly no one will question the conservatism of such an engine. This engine is available today in sizes suitable for electric drive.

Another absolutely reliable Diesel engine for electric drive is available, weighing 180 pounds per brake horse power for the engine alone and operating at 250 rev. per min. The complete Diesel-electric drive using this engine instead of the one used in the table is 402 pounds per shaft horse power, and the ratio of this weight to the weight of the geared turbine drive is 0.892.

Developments will undoubtedly be undertaken by some present Diesel engine manufacturers to commercially produce a lighter Diesel engine which will be suitable for electric-drive units. The ultimate outcome of this development should produce a conservative engine weighing not more than 125 pounds per shaft horse power and operating at 300 rev. per min. Using these engines instead of those in the table, the weight of the complete Diesel electric drive would be 328 pounds per shaft horse power, and the ratio of this figure to that for the geared turbine is 0.727.

The weight of 400 pounds per brake horse power for the direct-drive Diesel used in the table is lower than the average engine actually installed and operating today, which, according to authoritative data, is 483 pounds per brake horse power. On the 483-pound basis, the weight per shaft horse power for a complete direct Diesel drive is 635 pounds, and the ratio of this figure to that for the geared turbine is 1.41.

The analysis in the table does not include fuel. Taking fuel consumption roughly at 0.55 pound per effective shaft horse power hour for the Diesel and Diesel-electric (which is very conservative), and twice this amount per shaft horse power hour for the geared turbine (which is likewise conservative), and 5 per cent more for the turbine-electric than for the geared turbine, and allowing sufficient fuel for a round trip of 3300 miles each way, for a 3000 S. H. P. ship, operating at 11 knots, the total fuel consumption would be as follows:

1,648,000 pounds for the geared turbine; 1,730,000 pounds for the turbine-electric; 874,000 pounds for the direct Diesel; 874,000 pounds for the Diesel-electric

Adding these figures to the total weights in the table, we have:

3,500,000 pounds for the geared turbine drive;

3,221,500 pounds for the turbine-electric; 2,533,200 pounds for the direct-drive Diesel; 2,242,200 pounds for the Diesel-electric.

The corresponding ratios as compared with the geared turbine would then be:

Geared turbine = 1; Turbine electric = 1.07; Direct drive Diesel = 0.845; Diesel-electric = 0.747.

The above results agree with the general statements in the writer's paper, but are at variance with the figures given by Mr. Bailey and Mr. Smith, particularly the latter. I am quite sure that if these gentlemen would have used the same engine for their Diesel-electric drives, their figures would have been substantially in agreement with the table, provided all related items as listed were included.

The tables given by Mr. Bailey and Mr. Smith also show considerably higher cost figures for the Diesel-electric than seem justifiable in the light of my experience. I feel quite certain that the price of Diesel-engines is still higher than it should be. This is particularly true in the case of engines for Diesel-electric drive. I have no figures on the installation of the machinery, shafting, propellers, etc., but I am sure that the engines, generators, exciters, motors and control can be bought today for $130 to $140 per shaft horse power, provided the proper Diesel-electric units are used. Previous quotations might run at variance with this statement, but until recently electrical manufacturers have been forced to quite relatively low-speed Diesels. My remarks on cost referred to future developments, except in a few present cases.

Rather than point out the detailed differences of the comparisons in the tables prepared by Mr. Bailey and the table given above in this reply, the reader is requested to review the table for himself. I have stated the basis on which my tables has been compiled, and presuming Mr. Bailey's table has been compiled in much the same manner, the largest discrepancy appears in the cases of the Diesel-direct and Diesel-electric. The probable reasons for this have been stated above. Mr. Bailey's analysis shows that, in the case of the single-screw Diesel-electric, the space favors this type of drive slightly, and it is safe to say that with later developments in electric-drive Diesels the space factor will show greater favor in behalf of the Diesel-electric.

In regard to relative fuel consumption, Mr. Bailey has used the same figure for the single-screw Diesel as for the twin-screw Diesel, and according to analyses of propeller performance that have come to my attention, I believe that the fuel consumption per ton-mile should be very nearly the same for the Diesel and the Diesel-electric, for the reason that the twin-screw arrangement using the higher speed propellers and additional struts will require more effective horse power to drive a given tonnage through the water. Furthermore, the fuel consumption figure for turbine electric is given as 0.95 as compared with the geared turbine of 1.0. Mr. Bailey, as stated, used single-reduction geared-turbine drive in this analysis. I think the figure would have shown the reverse had double-reduction gearing been used. It is also probable that the figure of 0.95 in comparison represents guaranteed economy rather than actual performance. The above paragraph will also reply to similar remarks by Mr. Smith.

I believe that with machinery in proper working condition, the fuel consumption per shaft horse power, or rather per ton-mile, should run in the order of 1 for the geared turbine, 1.04 to 1.05 for the turbine electric, and approximately 0.5 to 0.55 for Diesel-electric and direct-connected Diesels (the latter being twin screw).

Such discussions as Mr. Bailey's are very constructive and will undoubtedly be very beneficial in the final solution of the selection of propulsion machinery. Just at present, it is expected to find considerable difference in the analyses made on Diesel and Diesel-electric drive, owing to the wide variety of engines available, and since the engine forms a large portion of the weight of the Diesel-electric drive, a considerable variation in this item would show a large difference in the total weight.

Mr. Smith and Mr. Stevens questioned the omission of the junior engineers. The reason why the junior engineers have been omitted from the list of personnel for the Diesel-electric drive is because one man is sufficient to operate the control, and this man would always be one of the assistant engineers. In the case of the twin-screw Diesel, it is necessary to station an engineer at each engine, and this requires two men, whereas in the case of the electric drive one man is sufficient, regardless of the number of screws, as the controllers are easier to operate and require less manipulation than the ordinary surface electric car. This practise will vary with different operating concerns.

It will be noted that Mr. Smith takes considerable exception to the value of the backing qualities of an electric-drive ship. If a ship and its shafting, etc., will withstand only a definite amount of backing torque, surely it is inadvisable to apply an excessive amount. In this connection, the electric drive can be regulated to give any desired amount of backing torque from the minimum to the maximum, as it is merely a function of the control. The principal idea in incorporating in the paper a discussion on backing qualities of electrical machinery was simply to show that this type of drive is as good as any type of drive, and can be made better than some types. In regard to battleships, however, it has always been my understanding that quick stopping is essential and that the Navy Department lay some stress on this point. Whether or not ships are so operated as to not utilize the full backing powers of any type of drive, it is of interest to note that, on the trials, tests are made to determine the quickness with which a battleship can be stopped. In this connection it is interesting to note that the *Tennessee* can be stopped from full speed in less than three minutes. I think it is plausible to conceive a condition where this difference in stopping time would avoid a wreck.

Mr. Smith mentions that the facts in his table of comparative weights, fuel consumption, etc., show a wide difference from the author's opinions. To substantiate the author's opinions, reference is made to the table given previously where the facts on which these opinions were based are recorded. Mr. Smith takes exception to the author's statement and places direct-Diesel above Diesel-electric in regard to reliability. In this connection, it is interesting to note that present direct-drive Diesels are twin-screws. Furthermore, obviously a ship having four engines is more reliable when considered from the "get there" idea than one having two. With a single-screw Diesel-electric, the full power of any number of sets can always be utilized for effective balanced propulsion. This is not the case with any other type of drive. Certainly the control gear of a Diesel-electric ship cannot be considered in the same category as the reversing gear of a direct-drive Diesel engine when it comes to complication. All control for a Diesel-electric ship is effected through a simple, small field rheostat which handles only a very small fraction of the total current, and which in going from the full speed ahead to the full speed astern positions, does not even open the circuit. In discussing reserve power I clearly identified it as reserve power in case of casualty to a prime mover. In comparing the Diesel-electric with the Diesel or any other type of drive, the Diesel-electric is obviously superior to any of them in this respect. For instance, on a 3-unit Diesel-electric, the failure of one engine would only necessitate the loss of 12 per cent in speed, and this cannot be approached by the other drives in case of failure of one of the units, and particularly the direct-Diesel.

It is but natural for some Diesel engine builders to manifest a reluctant spirit in the advocation of high-speed Diesel engines for electric drive, because the net returns to their coffers are naturally going to be enormously reduced. Such recommendations are probably influenced by commercial analysis rather than engineering analysis. However, as a matter of fact, this reluctance might not represent the most expedient commercial analysis, as the manufacture of engines on a large production basis for an advantageous drive would eventually further the sale of engines, and thus result in greater and more profitable business.

The reason that turbine-electric drive is not well suited to destroyers or scout cruisers is because of construction conditions. These conditions do not obtain in battleships and battle cruisers.

Following Mr. Smith's specifications for the selection of the most suitable drive, I think the analysis as given in the author's paper and reply will clearly show that the electrical apparatus fulfills his requirements which he classifies as the "hard, cold facts." In comparing the turbine-electric with double-reduction gears there is very little difference, but what little there is in cost and weight favors the geared turbine. In the author's mind, however, these are not sufficient reasons to eliminate turbine-electric drive, particularly in the light of past performance.

Captain Newman has given a very instructive description of the U. S. cost guard cutter *Tampa* and its propelling machinery. There is one point, however, in the discussion that I would like to clear up, and that is Captain Newman's reference to the writer's allusion to a synchronous motor as being more complicated than an induction motor. Possibly Captain Newman might have meant this for someone else, as certainly the author made no such statement in his paper. I did refer, however, to the additional complication of the control in connection with synchronous motor drive as compared with the induction motor drive, and I feel quite sure that those who visited ships containing both types of drive will bear me out in this conclusion.

I cannot agree with Mr. Sperry in his comparisons of the electric-clutch system with the Diesel-electric system using motors and generators as obviously the latter is considerably more flexible than the former and possesses distinct advantages that are not common to the two systems. The clutch, for instance, does not eliminate the reversing gear of the engine and does not eliminate the necessity for varying the engine speed in order to obtain speed control of the screw. Even assuming that the screw can be reduced by engine throttling to half speed and controlled from there to zero by slipping the clutch, I am sure that if this were continued for any length of time it would be necessary to use special means for dissipating the heat resulting from the slip energy in the clutch, and this introduces a complication of some kind. The energy resulting from the slipping of the clutch below its synchronous speed is comparable to that which exists in the case of an induction motor and with this type of machinery it has always been found necessary to dissipate excessive slip energy externally; for this reason, when adjustable speed induction motors are required, it is necessary to furnish the wound secondary type so that the slip resistance can be incorporated external to the motors. It is true that the slip energy at low propeller speeds is considerably less than at high propeller speeds, for the reason that the propeller power varies approximately as the cube of the speed, but the powers are hardly sufficiently small below half speed to enable slip energy to be absorbed in the clutch, without providing some means for dissipating the heat.

Mr. Sperry gives four items of performance contributed by the Diesel-electric system of propulsion. In the first place, he endeavors to show that the propeller speed is compromised by the application of a motor. This, however, is not the case, as with d-c. motors we can accommodate any desired propeller speed. Furthermore, the generators can accommodate any engine speed, so that the selection of propeller speed is, therefore, not influenced. There are no limitations in d-c. motors and generators which influence their speeds for ship drive.

Second, the amount of reserve power in the case of the air-gap clutch drive, based on an equal number of engine units, is not as great as with the Diesel-electric drive using generators and motors, as the engine speed in the case of the air-gap clutch drive must be reduced in proportion to the reduction in the speed of the ship, therefore reducing the available horse power of the remaining engines.

Third, in varying the speed of an air-gap clutch drive, it is necessary to vary the speeds of all engines simultaneously, and the engines must govern at any speed; otherwise there will be an interchange of power between the engines and a waste of energy. With the Diesel-electric using motors and generators, the generators run at constant speed for any conditions of propeller speed and need have only the crudest type of governors, because with series operation it is not even necessary to have the engines running at the same speed. The motor speed is controlled by varying the generator voltage, which is affected through the operation of a simple field rheostat, so that in going from full speed ahead to full speed astern, it is merely necessary to move the lever from one extreme to the other extreme. Certainly nothing more flexible than this could be desired, and these advantages in flexibility do not obtain with the air-gap clutch Diesel drive. The operation at slip speeds of the air-gap clutch has been discussed previously. When the clutch is slipped, the losses vary directly with the speed reduction and power. This means poorer efficiency at low speeds than is the case with straight electric. The matter of cost is something which the author does not propose to know anything about, but it seems that the cost of generators, motors, and control, which are all simple apparatus, should not be much in excess of the cost of the air-gap clutch, which is a refined piece of apparatus, flexible couplings, gears, larger air compressor plant, refined engine governors, and engine reversing gear. Another point to be remembered is that this apparatus requires very careful alignment.

Fourth, in addition to eliminating the necessity for reversing Diesel engines as viewed merely from a matter of reversing gear, the one-direction rotation, electric-drive Diesel engine offers considerable simplicity to the air problem, since it is only necessary to start one engine by means of air in getting under way, as the remainder of the units can be started electrically. Therefore, the compressor equipment, air bottles, etc., together with reversing gear, must be balanced against the cost of the electrical apparatus in the Diesel-electric system. I am, therefore, not prepared to agree with Mr. Sperry in that the "maneuverability with these engines and the air-gap clutches accomplished all that the full electric plant does at a very great saving of plant and control equipment." I think that if Mr. Sperry's clutch were reversible, however, it would represent an advance in the art of ship drive, particularly as related to Diesel engines.

Later in his discussion, Mr. Sperry gives five important advantages secured by the application of the air-gap clutch system, on which I would like to comment in numerical order:

1. As pointed out previously, such a system does not give all the advantages and flexibility of a multiple engine unit with as great reserve power as a Diesel-electric system would.

2. As stated previously, the air-gap clutch system does not possess the complete flexibility of the electric drive, and it is questionable when all items which the electric drive eliminates are considered, together with the clutch, flexible coupling and gears, whether the expense would be an item for consideration. Mr. Sperry's allusion to the "cumbersome electric-control equipment for handling the heavy currents in maneuvering" is not well founded, as the only thing that is handled is the field rheostat in the generator excitation circuit, and this handles only a small fraction (not exceeding 1½ per cent of the total power), and at that does not even open the circuit. The notice taken of the double losses in motors and generators brings out, of course, a point which does exist when comparing the air-gap clutch drive with the electric system, as there is possibly 8 or 10 per cent additional loss with the electric drive when using the same number of propellers. If the electric uses fewer screws, this economy difference vanishes.

4. The safeguards due to the setting of the torque developed can be accommodated just as well by electric drive.

5. The subject of "criticals" as mentioned here will not exist with the type of units proposed for Diesel-electric drive, as the generator armature furnishes the only rotational mass connected to the engine, and this has little, if any more, inertia than the fixed half of the air-gap clutch. The air-gap fluxes of the generators and the motor are comparable to the air gap of the clutch.

As Mr. McClelland states, the comparison of the *New Mexico* and *Tennessee* with the *Idaho* and *Mississippi* is not a comparison of what might be done with a full gear drive, for the reason that the two latter ships have direct-drive turbines with auxiliary cruising turbines. Nevertheless it will be noted that even at the cruising speeds the electric ships show better performance. Mr. McClelland's statements that the geared-turbine drive of an up-to-date installation would show slightly better economy at full speed than the electric drive, and that the electric drive would gain at the cruising speeds, is in fact the analysis that is conceded in this country, as far as economy is concerned.

I am quite sure, however, that the concession must be given to electric drive when considering flexibility, both of arrangement of apparatus and reserve power in case of casualty to prime movers. There are other reasons substantiating electric drive which have been covered in recent articles in the technical press.

Mr. Anderson makes the inference that a geared-turbine drive, particularly for merchant ships, should show better steam consumption than a turbine-electric drive, and requests information on the performance of existing electric-drive cargo ships. I regret that I do not have authentic figures in these cases. It would seem to me, however, that with the turbines operating at the same speeds and other things being equal, or at least comparable, that geared-turbine drives should show a slightly better economy. The value of this small difference is questionable. Personally, I think there are other features of greater concern than a slight difference in efficiency. The figures which Mr. Anderson quoted for the electric drive of existing cargo ships seem to me to be rather high and out of proportion for the figure he quotes for the geared-turbine drive. At best, I cannot see more than 5 or 6 per cent difference.

I do not propose to reply further to the discussion regarding the selection of twin and four-screw ships and electric and geared drive, as this is a matter that concerns the Navy Department.

All the maneuvering that I have witnessed, particularly as concerns backing, has been done with all the engines in use at the time, and I know of no ruling to do all such reversing on only one machine. As far as I can see, there is no reason for it.

I do not agree at all with Mr. Stevens in his analysis of Diesel-electric drive as given in the first paragraph of his discussion, and a reference to previous paragraphs of the author's reply to discussion will clearly show the reasons why I do not agree with him.

Referring to the second paragraph of Mr. Steven's discussion, his statements regarding the comparable economy of the reciprocating engine in sizes of 3000 horse power or less do not agree with any figures that have ever come to my attention, and reference to Mr. Bailey's table of comparison will also show that both triple-expansion, single-screw, and triple-expansion, twin-screw engines consume 16 per cent and 27 per cent respectively more fuel than the single-reduction geared turbine in the case of a 2000 S. H. P. drive. Mr. Bailey also gives a fuel consumption of 6 per cent more for a quadruple-expansion reciprocating engine in the case of a 2600-h. p. drive.

The writer's reference to the horse-car driver who became the motorman, etc., was merely done to show the little difficulty that electrical apparatus had in replacing other means of motive power on land. As far as repairs to electrical machinery aboard ship are concerned, owing to the reliability of such apparatus, there is nothing likely to occur that cannot be taken care of by an ordinary electrician, and furthermore, I do not believe the marine engineer would want to place himself in the position of saying that he could never learn to repair an electrical machine, as this would indicate that the height of progress for marine engineers was already attained. Also, due to the simple construction of electrical apparatus, repairs should be very infrequent.

The matter of electric drive and geared drive for war vessels and the manner in which the different layouts affect the protection of the ship, etc., have been covered in many previous articles, and a discussion of it will, therefore, not be entered into at this time. Mr. Stevens asks why I neglected to mention that, while battleships and battle cruisers are to be fitted with electric drive, the light cruisers and destroyers are being equipped with geared turbines. A reference to the fifth paragraph of the paper under the section of "War Vessels" will show that this matter was mentioned in the paper. Naturally, as an electrical man, I would prefer to pin my faith to a large electric unit, particularly in the light of past experiences.

Commander Robinson has given a very good discussion on the Diesel-electric section of the paper and explains the reason for using the same fuel consumption with single-screw Diesel-electric as exists with twin-screw Diesel direct.

I do not believe that a voltage of 750 is too high to be used aboard ship in connection with propelling machinery, as this constitutes an isolated plant and can be very easily insulated and protected. If the engines for the electric drive are sufficiently large, so as to reduce the number of units, the voltage, of course, can also be reduced in proportion.

John K. Robison: About ten years ago I was called upon to discuss an article presented by W. L. R. Emmet on the subject of "Electric Drive" and I said then that I was from Missouri. Well, I have seen a few things since. Concerning the economy proposition, I can state for the benefit of the Society that on trial trips we have had figures that have given us in no case so much as 0.9 of a pound of fuel per shaft horse power, under any speed between 10 and 21 knots. Within the last week I attended a trial where that took place. The best performance we have gotten on the trial-trip conditions is on a geared-turbine drive, on a destroyer, which was 0.83; the best we have on the electric drive is 0.86.

Concerning the geared-turbine drive for the *North Dakota* the current operating efficiency of the ship has not been so satisfactory as we had hoped. We do not lay that to the machinery. We lay it to conditions that are temporary. We lay it the lack of skill of our own people on board the ship, and we expect in the future on the *North Dakota* a degree of efficiency that will become comparable with what we have been getting on the *New Mexico*; for example, the *New Mexico* burned about one-half to two-thirds as much fuel when steaming in squadron with the *North Dakota* as the *North Dakota* burned.

In port, on the electric auxiliary question, we have extended very considerably the use of electric auxiliaries. That has been done notably on the *Tennessee*. The fuel consumption of the *Tennessee* is less than 11 tons a day in port, and nothing is steam driven except an electric generator, condensing or non-condensing, forced draft blower, and a few pumps. The exhaust steam from the auxiliaries and the non-condensing generators is used for the operation of the evaporators; also when sufficient exhaust steam is available for heating the ship and in the galley. The pressure of the exhaust steam is maintained at 12 pounds gage in order to provide sufficiently high pressure to operate the boilers in the galley. That ship is running with materially less fuel than any other battleship, and we figure that the electric auxiliaries on that ship are saving us approximately $165.00 a day.

Ernest H. B. Anderson: May I make one comment in regard to the *North Dakota* in relation to the other ships? I do not know if it is clear to everyone here that the revolutions of the propellers on the *North Dakota* are 240 a minute, as compared with 170 for the *Tennessee* and sister ships.

Rear Admiral Robison: That is true—the *North Dakota* has single-reduction gears.

Mr. Anderson: She has single-reduction gearing, but when the change was made it was not possible to renew the shafting and reduce the propeller revolutions to 125, we will say—it could have been done so far as the geared turbines were concerned, but it was really a question of cost and structural limitations.

W. L. R. Emmet: When we were figuring on the alterations for the *North Dakota* we were told it was not worth while to change the propellers, although I said that it would be a practicable thing to put new shafting and propellers into the ship, but I was told we would not gain much.

Mr. Anderson: It could not have been done, Mr. Emmet.

Mr. Dickinson: Mr. Pierce got at me rather hard. I deserve it, because I rather carelessly referred to steam for auxiliaries. That is not quite true, but it is probably true that the steam is generated in the boilers and not all put to useful work. I have not a great deal of data. I had hoped that we would get some positive information this afternoon on the subject of operation. I have engineers' logs and reports on something like 500 voyages. Throwing out about one half of these as unreliable and estimating the horse powers as accurately as we can, reckoning on the vacuum and steam conditions under which the ship was operated, and also knowing approximately the power that would be necessary to drive the ship between the ports stated in the log, we arrived at a fairly accurate figure for horse power. Based on this we can estimate the fuel per horse power hour. These figures will run, on similar ships with similar equipments, all the way from less than 1 pound to nearly 2 pounds. The figure of 1.23 pound which I took, so far as I can find is fair. Assume a boiler efficiency of about 75 per cent, which means an evaporation under conditions of operation of approximately 13.5 pounds; this gives us the total amount of steam. We know that the turbine can pass only a limited and definite quantity of steam through its first stage nozzles. With operating pressure more will not go through. The difference, therefore is the amount of steam generated by the boilers and charged to auxiliaries.

We are all looking forward to the time when we will have a steamship entirely equipped with electric auxiliaries. Comparison made between our merchant ships similar to the comparisons that have been made between naval vessels, I think, will vindicate the figures which I have used.

Mr. Anderson, in his remarks, seems to settle on 0.9 pound, which, with fair assumption, will allow only 6500 pounds of steam for all purposes on the ship, including heating feed water. That sounds too good for a ship equipped with steam auxiliaries. I do not think that there is anything else I wish to bring out this afternoon, but as the chairman has pointed out, economy is the vital question, and we should get accurate studies and positive knowledge of the evaporation on our ships; then we will all be in a better position to discuss gains which are possible by the general application of electricity.

Mr. Bates' account of the electrical equipment on the *Prinz Heinrich* gives conclusive proof, if such be necessary, as to the reliability of suitably designed electrical machinery on ships. The apparatus, built 25 years ago, is still in service. This is what should be expected of properly designed and properly built electrical equipment. In other words, practically all the maintenance charge of suitable electrical apparatus will be covered in the first cost.

Mr. Jett's recommendations should be given the most serious consideration. He has devoted much time and thought to the study and investigation of electric deck machinery. Recommendations based upon his findings that a properly designed geared-electric winch with 25-h. p. motor is in every way the equivalent of a steam winch having two 8¼ by 10-inch cylinders will most likely be excellent practise to follow.

In making such comparisons it must be borne in mind that a cargo winch is at best a compromise; in other words, for the reasons that winches will be called upon to handle miscellaneous cargo and that the length of the lift varies with the depth of the cargo in the hold and the height of the dock or lighter on which the cargo is being handled, it will be necessary for the owner or operator of the ship, with his naval architect and engineer, to arrive at a design of winch which, all things considered, will be the best for the average conditions. In larger ships with deeper holds it may be found desirable to somewhat increase the rope speed and fit a larger motor.

The horse power rating of a winch motor is not definite. Electric motors are capable of considerable overload for short periods of time. The rating will be considerably less if based on a one-hour test rather than on one-half-hour test. Experience indicates that handling cargo on ships gives approximately the same heating as a rated full load for the half hour.

Mr. Jett also points out the need for more accurate data on fuel consumption that may be charged against ships' auxiliaries. . The author wishes that Mr. Jett had put even greater stress on this vital point.

A reply to Mr. Smith's criticism would become very lengthy. He has given the subject so much detailed thought and consideration that in the author's opinion a proper and fair reply could only be made by discussing a number of specific cases in like detail with Mr. Smith. In all fairness, however, it should be pointed out that, as stated in the introduction of the author's paper, the comparisons were based upon the cost of electrical equipment installed. In all probability the individual units electrically driven will in many cases be somewhat more costly than steam-driven apparatus of the same quality and for the same work. On the other hand, the cost of installing the steam machinery with the extra piping will be considerably greater than the cost of installing the electrical machinery, which requires only cable to transmit the power from the engine room. The cost of $4,300, which Mr. Smith took as the cost of an electric winch, is very high. Further, the cost of suitable electrically driven ships' auxiliaries will be reduced as the demand increases.

The author would point out that on the earlier motor ships steam-driven auxiliaries were fitted, and it was found these required so much fuel that electric auxiliaries had to be fitted in order to realize the high efficiency expected from a motor-driven ship.

Mr. Smith's argument as to the amount of power that might be secured by admitting 7950 pounds of exhaust steam to the low-pressure turbine is based on the assumption that this is steam. When it is considered that a great part of the heat in the 12,500 pounds of steam referred to in the author's paper has been given up to heating the atmosphere, that condensation has been going on continuously in the thousands of feet of piping with approximately 2500 square feet of radiating surface, it must be recognized that there is a great deal of hot water returned to the engine room and that the theoretical advantage cannot be realized.

If Mr. Smith will refer to the comparisons, he will find that the author allowed somewhat less for the auxiliary turbine when using 200 degrees superheat than with 75 degrees.

It has not been the author's contention that steam machinery is of itself always inferior to electrical. It is a question of application, and the future will show that it is not economical to operate a number of small steam units distributed in different parts of a ship. When shipowners realize the gain that can be effected by substituting one steam engine driven, or even oil engine driven generating set, for the multiplicity of small pieces of steam machinery, they will fit their ships with electrically driven apparatus.

Particular attention should be called to Mr. Pierce's remarks, "in many ships the steam steering gear could be replaced by a hydroelectric gear with considerable saving and without increasing the size of the generating sets." Mr. Pierce is a man of experience; the hydroelectric steering gear is one of the most expensive single pieces of equipment on a ship; his recommendation therefore to a great measure vindicates the author's contention as to the desirability of entire electrification.

Referring to Mr. Pierce's recommendation that enclosed motors be used below deck except where the size prohibits, it would seem that if it be granted that enclosed motors must be used in order to assure reliability, this rule would apply with the greatest force to the larger motors, and in the higher ratings the size would be found to be impracticable. The author would point out that motors which are designed to run continuously become tremendously heavy and expensive when enclosed; further, if they are to be located in a damp place, they will become wet inside and are just as liable, or perhaps even more liable, to deteriorate when not running than are ventilated motors. Experience has shown that ventilated motors are entirely reliable on shipboard if designed for the conditions and built of suitable materials.

Referring to Mr. Pierce's remark that this practise (referring to the use of enclosed motors below deck) has been followed on foreign ships with success, the author would refer to an article in the *Electrician* (London) of July 29, 1921, on page 131, in which it is stated "but for all ordinary purposes a semi-enclosed and preferably drip-proof design is best." This article refers to British practise.

In making a general recommendation in favor of enclosed ventilated motors for below deck installation, the following points were given consideration: Open motors would have to be protected from dripping water by shields which would cost the shipbuilder something to install. In the smaller sizes the cost of such shields would be high in proportion to the first cost of the motor. In many instances such shields would occupy valuable space and would interfere with accessibility of the motor and other apparatus located nearby. The cost of the enclosed ventilated motor is slightly more than the open motor and very much less than the enclosed motor for continuous operation. Motors suitable for marine service can be built with open frames. They would cost but little less than ventilated motors designed to keep out dripping water.

Referring to Mr. Pierce's criticism of alternating current for tankers, while it is true that troubles have been experienced, I believe the particular tankers referred to were a war product and many details of application were responsible for the troubles. There are certain very definite reasons in favor of alternating current for particular applications on ships, and the fact that some installations have not been successful is due to improper application rather than to the fact that alternating current was used. The author is of the opinion that in most cases direct current will be found to be more suitable for auxiliary power on ships; he believes, however, that very careful consideration should be given to special applications where alternating current might be preferable.

Regarding Mr. Pierce's remark that the author was making insinuations relative to the wireman's discretion it would seem that the author had been somewhat unfortunate in the way he expressed himself on the subject and that Mr. Pierce had been unfortunate in the experience he had had with generators, motors, controllers, and starting panels. What the author wished to bring out was the fact that a great deal of trouble had been experienced with wiring on ships and that the application of electricity suffered in consequence. It is essential, in order not to discredit the use of electricity, that the installation be well and carefully done, and that every precaution be taken to see that apparatus fitted on ships is in every way suitable for the application.

Mr. Pierce remarks that the figure of 12,500 pounds of steam per hour which was charged to auxiliaries, is ridiculous. To substantiate this he gives figures on some 18,000 to 27,000-h. p. equipments, presumably destroyers. The author regrets that Mr. Pierce did not give actual figures, by tests, of evaporation with segregated steam, required for main-drive turbines and auxiliaries on cargo ships. The one case cited of 2880 h. p. quadruple-expansion engine where 11 pounds of steam were required for auxiliaries is possible and, might be obtained under trial conditions. The author's contention is that, for any operating conditions on cargo ships at sea, this figure will not be realized. The author has knowledge of certain geared-turbines ships with steam-driven auxiliaries which are also showing approximately 1 pound of fuel consumption per shaft horse power hour. Mr. Pierce does not state whether the 2880 horse power for the engine was shaft or indicated. This makes a great deal of difference.

The author is in general agreement with Mr. Pierce that in all probability the greatest part of the saving, will result from having deck auxiliaries electrically operated rather than steam driven. There are two apparent reasons for this—one, that a great amount of steam piping will be removed; and perhaps the most important reason, that the steam-driven auxiliaries in the engine room will be at all times under the direct observation of the engineer, who if conscientious and competent, will be in a position to maintain them in better operating condition than can be expected in case of steam-driven deck machinery, which of necessity stands idle for long periods of time and is subject to considerable abuse when in operation; also, the length of the steam piping on deck makes it a subject to considerable expansion strains which cause leak and loss of steam at joints.

The author agrees with Mr. Pierce's suggestion that great saving can be realized by the electrification of all ship's auxiliaries, power being furnished by reliable oil-engine generating sets.

In concluding, the author would gather from his critics that, with but one exception, there is a unanimity of opinion as to the desirability of electrifying merchant vessels to the end that greater economy of operation may be realized.

It will be recognized that each ship must be given special study, and all factors entering into its economical operation must receive due and proper consideration in order that the most suitable apparatus be fitted. So long as the art is advancing, it is to be expected that there will be a considerable divergence of opinion as to the best means of attaining the end in view. Much has already been done in this country, and it is gratifying to find that the question of reliability of electrical apparatus has been laid at rest.

The author felt that he was liable to certain criticism in drawing the comparisons in fuel consumption which he did between ships fitted with steam and electrical apparatus. We have available data as to the fuel consumption of ships, but very little published data as to how much of this fuel is required for the propulsion and how much should be charged against auxiliaries. Any engineer who is in a position to obtain absolutely reliable information on this important subject can materially assist shipowners and operators in this country in their endeavor to improve the efficiency of their ships. The data of course, must be on ships actually in service. Trial trip information, when every valve and all fittings are in perfect condition is misleading.

REPORT OF THE BOARD OF DIRECTORS

FOR THE FISCAL YEAR ENDING APRIL 30, 1921

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Thirty-seventh Annual Report, for the fiscal year ending April 30, 1921. A general balance sheet showing the condition of the Institute's finances on April 30, 1921, together with other detailed financial statements, is included herein. The following is a brief summary of the principal activities of the Institute during the year; more detailed information has been published from month to month in the Institute JOURNAL.

Directors' Meetings.—The Board of Directors held nine regular meetings during the year; four of these were held in New York, one at White Sulphur Springs, W. Va., one at Philadelphia, one at Chicago, one at Akron and one at Pittsburgh.

Information regarding the more important activities of the Institute which have been under consideration of the Board of Directors, the committees, and the various officers, is published each month in the section of the JOURNAL devoted to "Institute Activities."

President.—During the year President Berresford has attended many Institute and Section meetings including the Annual and Midwinter Conventions and meetings in New York, Philadelphia, Chicago, Akron, Pittsburgh, Cleveland, Detroit-Ann Arbor, Indianapolis-Lafayette, Milwaukee, St. Louis and Schenectady.

Annual Meeting.—The Annual Business Meeting was held at Institute headquarters, New York, on May 21, 1920. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1920, was presented as published in full in the July 1920 issue of the JOURNAL. The Tellers Committee presented its report upon the election of officers for the year beginning August 1, 1920.

Directly following the business meeting came the ceremony of the presentation of the Edison Medal to W. L. R. Emmet.

Annual Convention.—The Thirty-sixth Annual Convention was held at "The Greenbrier," White Sulphur Springs, W. Va., on June 29 to July 2, 1920. The arrangement of the program by which the five technical sessions were confined to four mornings and one evening session met with commendation. Thirty-eight papers were presented at four of the five sessions, the first session being devoted to the Presidential address and the Technical Committee Reports. The annual conferences of the Sections Committee were held and thirty Sections of the Institute were represented by delegates. Among subjects discussed were the following: Geographical divisions; Section territorial limits; Section financial support, etc.

Pacific Coast Convention.—The Ninth Annual Pacific Coast Convention was held in Portland, Oregon, July 21-24, 1920. Eight technical papers were presented. Resolution adopted advocated the holding of 1921 Annual Convention in conjunction with Pacific Coast Convention at Salt Lake City, Utah.

Philadelphia Meeting.—The 364th Institute meeting was held in Philadelphia, October 8, 1920 and consisted of a celebration of the centenary of the discoveries of Oersted, Ampere, Arago and Davy, also a technical session at which two papers were presented.

Chicago Meeting.—The 365th Institute meeting was held in Chicago, November 12, 1920, under the joint auspices of the Chicago Section and the Protective Devices Committee, the Western Society of Engineers participating. Four papers were presented on "Lightning Protection."

Akron-Cleveland Meeting.—The 366th Institute meeting was held in Akron and Cleveland, January 14, 1921, under the joint auspices of the two Sections and the Industrial and Domestic Power Subcommittee on the Rubber Industry. At the technical session a symposium on "Electric Power in the Rubber Industry" was presented.

Mid-Winter Convention.—The ninth Mid-Winter Convention was held in New York on February 16-18, 1921. Total attendance more than 1000. Seventeen technical papers were presented during five technical sessions. The convention closed with the presentation of the Edison Medal to Dr. M. I. Pupin and a lecture by the medalist.

New York Meeting.—The 368th Institute meeting was held in New York on March 11, 1921. One technical paper was presented under the auspices of the Power Stations Committee.

Pittsburgh Meeting.—The 369th Institute meeting was held in Pittsburgh, April 16, 1921 under the auspices jointly of the Pittsburgh Section and the Association of Iron and Steel Electrical Engineers. Three papers were presented during the two technical sessions.

Abstracts of the reports of the chairmen of many of the Institute delegations and committees are included herein under various headings.

Meetings and Papers Committee.—The Meetings and Papers Committee held meetings every month of the year except July and August.

The results of its work are set forth in the form of the list of meetings held, given elsewhere in this Report.

The policy of this committee has been considerably influenced this year by the state of the finances of the Institute which required economy in all the activities. The committee has endeavored to reduce the number of papers presented at the various "National" meetings and in some cases to substitute lectures or addresses by prominent engineers for the usual technical papers. A notable example of this was the Historical Memorial meeting in Philadelphia in November 1920. The December meeting was omitted. On the other hand the number of meetings of local sections has been very great, probably greater than in any preceding year.

The experience of this year has suggested to the committee two changes in practise in the interest of economy, raising of standards and equality of treatment of sections, which suggestions are offered for the consideration of the membership.

First: That hereafter the Meetings and Papers Committee establish a subcommittee within itself, to be known as its editing committee, whose duty it shall be to carefully scrutinize every paper accepted, with the object of reducing the volume to a minimum consistent with clearness, thus saving time at meetings, and space in the publications, and giving opportunity for the presentation of a greater number and variety of papers with less overlapping of matter by different individuals.

Second: That it be not attempted to hold "National" meetings every month of the season but that local Section meetings be encouraged by assigning to them a greater proportion of the papers offered through the Meetings and Papers Committee.

Coordination of Institute Activities.—At the beginning of the administrative year in August 1920, the Board of Directors appointed a "Committee on Coordination of Institute Activities", the duties of which are "to consider and advise on all questions arising as to Institute activities of whatever nature, particularly those in which uncertainty, difference of opinion, actual conflict, or duplication may appear to exist; and where questions of Institute procedure, policy, or precedent are involved, or final decision is necessary, to report the conditions to the Board with appropriate recommendations."

This Committee, which includes the Chairmen of several of the more important Institute Committees, held a number of meetings and reported its actions to the Board of Directors from time to time.

Among other subjects considered were the awarding of prizes to authors of worthy papers presented before the Institute, and later the formulation of the procedure to be followed in making awards, as published in the April and May issues of the JOURNAL.

Various matters relating to Institute Branches which had been referred to the Committee for consideration by the Directors were acted upon, and the recommendations of the Committee, after approval by the Directors, were forwarded to the various Branches.

Another important matter considered was the coordination of the Standardization activities of the Institute and the various joint organizations with which the Institute is affiliated. The Committee's recommendations have been transmitted to the Directors and are scheduled to be acted upon at the May meeting.

Institute Prizes.—At various times the desirability of establishing prizes to be awarded by the Institute to authors of papers has been discussed.

The subject has again been active recently, and at a meeting of the Committee on Coordination of Institute Activities, resolutions were adopted and were approved at the January meeting of the Board of Directors and referred back to the Coordination Committee for the formulation of the necessary details of procedure in making the awards.

All papers presented at meetings of Sections of the Institute during the year 1921 by any member of the Institute who has never before presented a paper before the Institute or any of its Sections are eligible for this competition.

The Coordination Committee also considered a specific offer from the Jeffery-Dewitt Company to donate to the Institute $100 each year for the purpose of establishing a prize for the best paper on a subject within the field of high-tension transmission and distribution. The Committee recommended that "the offer of the Jeffery-Dewitt Insulator Company be accepted as applying to an award for the calendar year 1921." The Board approved this recommendation and referred the matter back to the Coordination Committee for the purpose of formulating the necessary plan of procedure.

The procedure to be followed in connection with the award of prizes will be published in a later issue of the JOURNAL.

Publication Committee.—This Committee, which has supervision of the monthly JOURNAL and the annual TRANSACTIONS, has held several meetings during the year, has considered various matters relating to the Institute's publications, and has formulated the procedure regarding publication of papers, news items, reports, and other material in these publications.

The general policy, as formulated and recommended by the Committee on Development and approved by the Board of Directors in 1919, has been carried out to the extent that the available finances would permit. For more detailed information regarding the activities of this Committee, reference should be made to the publications issued during the past year, which practically constitute the report of the Committee.

Geographical Divisions.—The Special Committee on Geographical Divisions and Election Procedure, authorized in June 1920, studied in cooperation with the local Sections the question of grouping the membership into geographical districts. A plan was formulated, dividing the membership into ten districts, which was favorably acted upon by the Board at its November 1920 meeting. This plan was used as the basis for the nomination and election of Vice Presidents this Spring. For complete details see the December 1920 JOURNAL.

Sections and Branches.—The statement was made in the Report of the Board of Directors for last year that, "It may be inferred from the present term that there will be further increase of activities (Sections) next year" and results demonstrate the correctness of that inference. This is indicated partly by the figures given in the following table showing the number of Section meetings held and the attendance at them, but more particularly by the large increase in the number of Sections, an increase which is very much greater than in any previous year.

During the past year Sections have been organized at Akron, Ohio, Cincinnati, Ohio, Syracuse, N. Y., Omaha, Neb., Lehigh Valley with headquarters at Bethlehem, Pa., and Connecticut with headquarters at New Haven, Conn. This interest in Section activities shows, if the Sections may be considered one of the most important members of its body politic, that the Institute is in a very healthy condition.

In some cases the organization of these new Sections has lead to controversies as to conflicting Section boundaries, but in all cases these difficulties have been amicably adjusted by the Sections interested.

There is a growing demand from the members residing in the more sparsely settled sections of the country for very much extended Section limits, and while each case as it has come up has been settled in its own merits some very serious thought should be given to amending the By-laws to take care of the situation.

Cooperation between the Sections of the Institute and those of other engineering societies, looking to the increase of the welfare of the members and a further development of their civic duties, has continued to increase and in many localities this has resulted in the engineers being called upon to take a more active part in civic affairs.

The Branches are now upon a healthful basis the equal or superior to that enjoyed before the war. Attendance is good and the meetings have been of particular interest due to the stimulus of the war in technical matters and the activity of students in presenting programs, as a result of their maturity and experience during the war. Programs involving papers and discussions presented by students are of the greatest interest and value, although contact with Institute officers is considered of utmost importance.

Social functions including banquets addressed by prominent engineers and representatives of the Institute, which have a materially broadening effect, have been generally adopted. The use of motion picture films illustrating industrial processes is becoming general.

Educational institutions, where several Branches are located, give partial credit toward graduation for work done in connection with study of the A. I. E. E. JOURNAL and presentation of papers at Branch meetings. In other institutions the JOURNAL is used for reference from which articles are abstracted for discussion at meetings and in the classroom.

The number of enrolled Students has greatly increased and new Branches have been authorized at Case School of Applied Science, Cooper Union, Virginia Military Institute and University of Southern California.

	For Fiscal Year Ending						
	May 1 1915	May 1 1916	May 1 1917	May 1 1918	May 1 1919	May 1 1920	May 1 1921
Sections							
Number of Sections........	31	32	32	34	34	36	42
Number of Section meetings held....................	246	251	265	245	217	262	303
Total Attendance..........	23,507	28,553	31,299	34,614	25,837	30,741	37,823
Branches							
Number of Branches........	52	54	59	59	61	62	65
Number of Branch meetings held....................	328	360	368	268	156	360	443
Attendance................	12,712	15,166	16,107	10,683	6,441	16,827	21.629

Standards Committee.—The Standards Committee has held six regular meetings during the year for the transaction of its business. The final touches were given the new edition of the Rules which had been prepared during the two preceding years under Chairman Robinson. The edition is now available.

A difference arose over the phraseology and interpretation of certain definitions in the telephone section of the Rules, but the Committee was fortunate in being able to adjust this in a meeting at which representatives of the National Electric Light Association and the American Telephone and Telegraph Company attended. The adjustment received approval from the Board of Directors and is embodied in the new edition of the Rules.

As some differences of interpretation of the Rules on rating of electrical machinery seemed possible, the Committee (with the approval of the Board of Directors) is responsible for the formation of a Sectional Committee under the procedure of the American Engineering Standards Committee so that differences, if any, may be thrashed out and the interpretations be fully established.

The Institute is also represented on Sectional Committees on Terminal Markings of Electrical Machinery and on Specifications for Insulated Wires and Cables for other than Telephone and Telegraph Purposes.

A request from the Committee that the A. I. E. E. be made sponsor for the formulation of a Standard of Aluminum for Conducting Purposes has been approved by the Board of Directors and forwarded to the American Engineering Standards Committee.

The Committee has given much consideration to the relation of the Standards Rules of the Institute as a whole, to the procedure of the American Engineering Standards Committee, and by direction of the Board of Directors the matter is now in the hands of the Committee on Coordination of Institute Activities, who will report recommendations on the situation.

The opinion of the Standards Committee that the A. I. E. E. is the appropriate body to be sponsor for Standards Rules and definitions in all electrical engineering matters, as defined in Section 28 of the By-laws has been expressed in a series of resolutions which were adopted by the Committee and transmitted to the Board of Directors.

Subcommittees of the Standards Committee have been active in work. A new Subcommittee on Insulators was appointed during the course of the year. Special committees on magnetic units, nomenclature and other pertinent subjects have also been active and have produced important reports.

American Engineering Standards Committee.—In the very rapid increase of the activities of the American Engineering Standards Committee during the past year the following facts stand out: The By-laws and Rules of Procedure have been completely revised and expanded; many additional bodies have been admitted to representation on the Committee, until it is now composed of 49 members representing 17 bodies or groups of bodies, including 6 national engineering societies, 5 government departments and 13 national industrial associations; the Committee is now in cooperative touch with 10 similar foreign organizations. Eight standards have been officially approved, 9 more submitted for approval, and 36 active projects are in hand.

The Annual Report of the Committee for the year 1920 is now available; an abstract was printed in the May JOURNAL.

U. S. National Committee of the I. E. C.—This Committee has held several meetings during the year. Its work has been interfered with somewhat by the inactivity of the International Commission during the last year. It was expected that the meetings of the I. E. C. National Committees, held at Brussels, March 27th to April 4th, 1920, would be followed soon by various other meetings of the Advisory and Special Committees of the I. E. C., including a meeting of the Committees on International Electrical Votabulary and Graphical Symbols, which was to have been held at Zurich, in June, 1920, and meetings of the Advisory Committee on Rating of Electrical Machinery, which was to have been held at Paris, in December, 1920. These meetings and also meetings of other Advisory Committees, including the Advisory Committee on Standard Pressures, Symbols, Nomenclature, and also Screw Lamp Sockets and Bases, have had to be postponed for various reasons and the date for holding them has not yet been set. The Committee, which has always taken a leading part in the work of the Advisory Committee on Rating of the Commission, has found it desirable to suspend its work in the preparation of new proposals to the Commission, so as to have the benefit of the comprehensive study now being made of the entire question of the rating of electrical machinery by the A. E. S. C. Sectional Committee on Rating of Electrical Machinery, which was recently formed by the A. E. S. C. on the initiative of the A. I. E. E. Standards Committee, the latter Committee being the sponsor body for that Sectional Committee.

The Committee, with the approval of the Board of Directors, has, during the last year, effected changes in its organization, for the purpose of allowing other electrotechnical bodies, such as the Electric Power Club, the National Electric Light Association, etc., to have official representation in the Committee and to help meet its expenses. This cooperation of other electrotechnical bodies, which is in accordance with the plan of organization of several of the European National Committees of the I. E. C., will add to the influence and facilities of the U. S. National Committee, and will react favorably upon its activities and upon its work.

Research Committee.—The Research Committee of the Institute, appointed at the January 1921 meeting of the Board, held its first meeting on Friday, April 1st. As this committee was created primarily to act as the Advisory Board on Electrical Engineering of the Engineering Division, National Research Council, much of the discussion at this meeting consisted of the presentation of possible fields of activity. A committee of five was appointed to consider and report on all suggestions submitted.

Committee on Code of Principles of Professional Conduct.—Through correspondence and conference the Institute's Committee, upon invitation from the corresponding Committee of the American Society of Mechanical Engineers, has suggested modifications in the proposed Code of Ethics for that Society.

Committee on Safety Codes.—The Chairman of the Committee on Safety Codes continued to represent the Institute on the Electrical Committee of the National Fire Protection Association. A committee was formed, under the American Engineering Standards Committee, for the preparation of a standard elevator code; the Institute is represented by a member of the Codes Committee and sessions are in progress. A member of the Codes Committee also represents the Institute on an American Engineering Standards Sectional Committee on Floor Openings, Railings and Toe Boards.

American Committee on Electrolysis.—The Institute representatives on the American Committee on Electrolysis have attended several meetings, either of the main committee or of the various subcommittees, during the year.

The result of the work of the subcommittees was considered by the main committee in New York recently, and a report agreed upon, which will probably be issued in the near future, after consideration by the associations represented on the main committee.

Board of Examiners.—The Board of Examiners during the year held fifteen meetings, averaging over three hours each. It considered and referred to the Board of Directors a total of 4336 applications for admission or transfer to the higher grades. This is an increase of about 33% over last year.

The policy of dividing the work among subcommittees, as adopted last year was continued. Final action in all cases was taken by the entire Board and all doubtful or borderline cases were referred for consideration to the Board as a whole. The growth of the Institute is becoming so rapid that it is only through such a division of work among subcommittees of the Board that it is possible to keep the required number of meetings within reasonable limits.

The result of the Board's work for the year is given in the following tabulated statement:

APPLICATIONS FOR ADMISSION

Recommended for grade of Associate	2293	
Not recommended	4	2297
Recommended for grade of Member	126	
Not recommended for admission to this grade	76	202
Recommended for grade of Fellow	5	
Not recommended for admission to this grade	14	19
Recommended for enrolment as Students	1475	
Not recommended for enrolment	3	1478

APPLICATIONS FOR TRANSFER

Recommended for grade of Member	237	
Not recommended for transfer to this grade	44	281
Recommended for grade of Fellow	49	
Not recommended for transfer to this grade	10	59
Total number of applications considered		4336
Applications reconsidered		6
Total		4342

Membership.—In spite of the strenuous financial conditions of the past year the Membership Committee by earnest effort has greatly exceeded the results secured during the years ending May 1, 1919 and May 1, 1920 both of which were banner years.

Of the 37 sections existing August 1, 1920, 14 have sent in applications in excess of 25% of their membership as of that date.

During the five years ending May 1, 1918 the net increase was only 1628, an average of 336, while the years ending May 1, 1919 and May 1, 1920 showed net increases of 970 and 1093 respectively. The year ending May 1, 1921 shows a net increase of 1870 or an 71% increase over the preceding banner year.

The total applications received were 2442 as compared with 2033 last year and 1596 the year before.

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1920.	6	498	1615	9226	11345
Additions:					
Transferred	....	45	225	....	....
New Members Qualified	....	5	124	2218	....
Reinstated	....	3	6	78	....
Deductions:					
Died	....	3	6	46	....
Resigned	....	4	12	138	....
Transferred	....	....	35	235	....
Dropped	....	3	14	338	....
Membership, April 30, 1921	6	541	1903	10765	13215

Net increase in membership during the year....................................1870

Deaths.—The following deaths have occurred during the year.

Fellows: James Mitchell, Cecil P. Poole, Samuel Sheldon.

Members: Donald Bowman, Louis H. Flanders, Richard Lamb, F. A. Pickernell, Nathan C. Solomon, Joel W. Stearns.

Associates: Edwin G. Birren, Charles Blizard, G. J. G. Brandt, D. W. Burnham, Willard L. Candee, Joseph F. Chinlund, Leser R. S Cohen, H. J. Conover, Leigh R. Crawford, J. Hubert Davies, George M. Denniss, G. B. Diem, Timothy S. Eden, Charles G. Edwards, Axel Ekstrom, John Ellis, Horace S. Geutsch, E. S. Fletcher, Albert H. Foote, Lewis T. Glaser, Oscar Hansen, Philip E. Hart, O. B. Hodgson, Henry Hovelson, Arnold Keller, Jr., Frederick R. Keller, William H. Knierim, G. H. Lukes, William A. Lynn, W. T. Masters, Angus K. Miller, James R. Nelson, Albert A. Nimis, George M. Parsons, James B. Rogers, J. A. Runchey, E. D. N. Schulte, Kenneth L. Scranton, E. M. Shepard. Jr., E. F. Sherwood, M. M. Shrader, Maurice N. Shugren, George L. Thompson, Louis E. Waugh, R. S. Whitright, H. Wygod-Wygodsky,

Total deaths, 55.

Employment Service.—The employment service which has been maintained for many years at Institute headquarters and which during the latter part of 1918 was coordinated with the similar service of the other Founder Societies, was transferred to the auspices of the newly organized American Engineering Council on January 1, 1921 upon the recommendation of the secretaries, and the Joint Finance Committee, of the four Founder Societies. It is to be carried on under the auspices of the Council by a board consisting of the secretaries of all the societies represented in The Federated American Engineering Societies. At present the secretaries of the National Societies of Mining, Mechanical and Electrical Engineers are acting as a special managing committee on the request of Council.

In addition to a direct service, the Bureau publishes an engineering service bulletin each month in the Institute JOURNAL and it has served to place many members in positions of responsibility, both in this country and abroad. The bulletin is subdivided into two parts: one containing announcements of vacancies, and the other containing lists of men available, with condensed records of their experience. All announcements are published without charge either to the employers or to the members of the Institute seeking positions.

The Federated American Engineering Societies.—A very harmonious transfer was made of the activities of Engineering Council beginning with the first of this year. American Engineering Council has both largely succeeded to the reputation and benefits of its predecessor and has the added advantage of a more democratic organization, a wider support and far greater publicity. Attendance at meetings has been uniformly large, the spirit of cooperation very strong, and the willingness to devote time and energy to the work of Council most gratifying. It is believed the Institute has taken a wise step in this organization and support should be continued.

In addition to the organization meeting held in Washington, D. C., in November 1920, the Executive Board held meetings subsequently in New York in December; in Syracuse in February, and at Philadelphia in April.

Institute members have been appointed to the following offices and committees: H. W. Buck, member Standing Committee on Publicity and Publications; Professor Charles F. Scott, member of Committee on Constitution and By-Laws; L. B. Stillwell, member of Committee on Public Affairs; William McClellan, Chairman of Finance Committee; Calvert Townley, ranking Vice-President, Chairman of Committee on Procedure and member of Finance Committee.

Complete details of organization of the Federated body were given in the December 1920 JOURNAL, and its activities have been liberally chronicled from month to month.

United Engineering Society.—This Society performs for the national societies of Civil, Mining, Mechanical and Electrical Engineers, certain specific acts which are governed by contracts; the primary function of the United Society being to hold in trust and to administer for these societies the Engineering Societies Building, in which the headquarters of the National societies are located.

Extracts from the annual financial report of the United Engineering Society were published in the March 1921 JOURNAL

Engineering Societies Library.—The library of the Institute is combined with the libraries of the national societies of Civil, Mining and Mechanical Engineers, administered as the "Engineering Societies Library" under the direction of the Library Board of the United Engineering Society; this board is composed of representatives of each of the four societies referred to above.

In order to place the facilities of the library at the disposal of persons residing at a distance from New York, a Library Service Bureau has been established, and a staff of expert searchers and translators is employed to cover almost any engineering topic, in the following manner: abstracting, translating, bibliographing, statistical searches and reports, searches for patent purposes, copying, preparing reference cards, etc.

An abstract of the annual report of the Engineering Societies Library covering the calendar year 1920, was published in the March 1921 JOURNAL.

Engineering Foundation.—Engineering Foundation is a trust fund established in 1914 by Ambrose Swasey, of Cleveland, Ohio, by gifts to United Engineering Society as a nucleus of a large endowment "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It is administered by the Engineering Foundation Board upon which the Institute and other national engineering societies are represented. The Board is a Department of United Engineering Society.

The annual report of the Engineering Foundation for the sixth year, ending February 10, 1921, was published in the April 1921 JOURNAL.

Representatives.—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years, and in addition has appointed representatives upon a number of new organizations such as American Engineering Council and various Sectional Committees of American Engineering Standards Committee. A complete list of representatives is published frequently in the JOURNAL.

Edison Medal.—The Edison Medal for 1919, which was awarded to W. L. R. Emmet "For Inventions and Developments of Electrical Apparatus and Prime Movers" was presented to Mr. Emmet with appropriate ceremonies at the Annual Meeting of the Institute held in New York on May 21, 1920.

The Edison Medal for 1920 was awarded to Dr. Michael I. Pupin "For Work in Mathematical Physics and its Application to Electrical Transmission of Intelligence". The presentation ceremonies took place at the closing session of the Midwinter Convention of the Institute, New York, February 18, 1921.

John Fritz Medal.—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of Civil, Mining, Mechanical and Electrical Engineers, awarded the 1921 medal to Sir Robert Hadfield for the invention of manganese steel. It is planned that a delegation of engineers representing the four societies make the presentation in London during the month of June.

Finance Committee.—During the year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws.

Haskins and Sells, certified public accountants, have audited the books, and their report follows:

NEW YORK
CHICAGO
PHILADELPHIA
DETROIT
CLEVELAND
SAINT LOUIS
BOSTON
BALTIMORE
PITTSBURGH
SAN FRANCISCO
LOS ANGELES
BUFFALO
CINCINNATI
NEW ORLEANS

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS
CABLE ADDRESS "HASKSELLS"
30 BROAD STREET
NEW YORK

KANSAS CITY
SEATTLE
PORTLAND
DENVER
ATLANTA
DALLAS
SALT LAKE CITY
TULSA
WATERTOWN

LONDON
PARIS
HAVANA
SHANGHAI

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CERTIFICATE OF AUDIT

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1921, and

We Hereby Certify that the accompanying General Balance Sheet properly exhibits the financial condition of the Institute at April 30, 1921, that the Summary of Income and Profit & Loss for the year ended that date is correct, and that the books of the Institute are in agreement therewith.

HASKINS & SELLS,
Certified Public Accountants.

New York,
May 14, 1921.

AMERICAN INSTITUTE OF

EXHIBIT A.

GENERAL BALANCE SHEET,

ASSETS

REAL ESTATE:			
One-fourth Interest in United Engineering Society's Real Estate, 25 to 33 West 39th Street:			
Land and Building		$472,500.00	
Real Estate Equipment		14,292.79	
Total Real Estate			$486,792.79
EQUIPMENT:			
Library—Volumes and Fixtures		$ 40,204.99	
Works of Art, Paintings, etc		3,001.35	
Office Furniture and Fixtures		13,853.36	
Total		$ 57,059.70	
Less Reserve for Depreciation		9,470.07	
Remainder—Equipment			47,589.63
INVESTMENTS:			
City of Wilmington, Delaware, 4½% bonds, 1934, Par Value $15,000.00 (Pledged as Collateral to Loan Payable)		$ 15,677.77	
United States Third Liberty Loan 4¼% bonds		10,000.00	
Total Investments			25,677.77
WORKING ASSETS:			
Publications entitled "Transactions," etc.		$ 12,906.50	
Text and Cover Paper		478.63	
Paper for Volume 39		2,000.00	
Badges		2,238.61	
Total Working Assets			17,623.74
CURRENT ASSETS:			
Cash		$ 4,939.25	
Notes Receivable—Advertisers		530.00	
Accounts Receivable:			
Members—for Dues		10,167.71	
Advertisers		3,868.61	
Miscellaneous		1,106.30	
Accrued Interest on Investments		109.38	
Accrued Interest on Bank Balances		105.10	
Total Current Assets			20,826.35
FUNDS:			
Life Membership Fund:			
Cash	$1,438.67		
Chicago, Burlington & Quincy Railroad Company Bonds, 4%, 1958, Par Value $5,000.00	4,868.75		
Accrued Interest	33.33	$ 6,340.75	
International Electrical Congress of St. Louis—Library Fund:			
Cash	$ 417.56		
New York City Bonds, 4½%, 1957, Par Value, $2,000.00	2,229.57		
New York Telephone Company Bond, 4½%, 1939, Par Value $1,000.00	878.75		
Accrued Interest	67.50	3,593.38	
MAILLOUX FUND:			
Cash	$ 231.60		
New York Telephone Company Bond, 4½%, 1939, Par Value	1,000.00		
Accrued Interest	22.50	1,254.10	
Midwinter Convention Fund-Cash		462.26	
Total Funds			11,650.49
Total			$610,160.77

NOTE: No provision has been made for depreciation of real estate.

ELECTRICAL ENGINEERS.

APRIL 30, 1921.

LIABILITIES

CURRENT LIABILITIES:		
Accounts Payable—Subject to Approval by the Finance Committee	$ 12,132.18	
Loan Payable and Accrued Interest	10,155.00	
Due to United Engineering Society on Account of Building Addition, Including Accrued Interest.	5,084.40	
Dues Received in Advance	4,423.93	
Entrance Fees and Dues Advanced by Applicants for Membership	473.21	
Total Current Liabilities		$ 32,268.72
FUND RESERVES:		
Life Membership Fund	$6,340.75	
International Electrical Congress of St. Louis Library Fund	3,593.38	
Mailloux Fund	1,254.10	
Midwinter Convention Fund	462.26	
Total Fund Reserves		11,650.49
SURPLUS: Per Exhibit "B"		566,241.56
Total		$610,160.77

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

SUMMARY OF INCOME AND PROFIT AND LOSS

FOR THE YEAR ENDED APRIL 30, 1921.

EXHIBIT B.

REVENUE:			
Entrance Fees		$ 12,768.00	
Dues		*137,147.71	
Students' Dues		9,207.00	
Transfer Fees		2,575.00	
Advertising		56,545.62	
Subscriptions		6,595.08	
Sales of "Transactions," etc		4,356.69	
Badges Sold	$ 7,377.75		
Less Cost	6,794.16	583.59	
Interest on Investments		1,100.00	
Interest on Bank Balances		770.93	
Interest on Notes Receivable		12.35	
Total			$231,661.97
EXPENSES:			
Publications:			
Journal	$88,787.34		
Transactions	34,339.05		
Year Book	7,416.88	$130,543.27	
Meetings		9,804.62	
Administrative Expenses		41,496.39	
Sections Committee		20,563.89	
Law Committee		196.50	
Membership Committee		4,306.17	
Standards Committee		1,054.52	
Finance Committee		150.00	
Code Committee		60.00	
Committee on Institute Development		1,122.54	
International Electrotechnical Commission		263.20	
Interest on United Engineering Society Building Loan		206.49	
President's Special Appropriation		303.15	
Honorary Secretary		4,000.00	
American Engineering Standards Committee		1,500.00	
John Fritz Medal Award		145.44	
Engineering Societies Employment Bureau		2,000.00	
Engineering Council		3,333.28	
Engineering Societies Library:			
Maintenance	$ 4,500.00		
Recataloging	2,499.96	6,999.96	
Forward		$228,049.42	$231,661.97

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*Includes $56,725.00, applicable to subscriptions to the JOURNAL.

TOTAL REVENUE—Forward)		$231,661.97
EXPENSES—(Forward)	$228,049.42	
United Engineering Society, Assessment	5,080.00	
Federated American Engineering Society	9,000.00	
Interest on Loan Payable	155.00	
Headquarters Committee	47.18	
Amortization of Premium on City of Wilmington Bonds	52.14	
Total	$242,383.74	
Less Decrease in Accounts Payable for Expenses Undistributed	452.67	
Remainder—Expenses		241,931.07
NET LOSS		$ 10,269.10
OTHER PROFIT & LOSS CHARGES:		
Uncollectible Dues Written off	$ 3,221.50	
Office Furniture and Fixtures discarded	401.52	
Total		3,623.02
GROSS DEFICIT		$13,892.12
PROFIT AND LOSS CREDIT—ADJUSTMENT OF INVENTORY OF LIBRARY VOLUMES AND FIXTURES, APRIL 30, 1920		50.44
DEFICIT FOR THE YEAR		$ 13,841.68
SURPLUS, MAY 1, 1920		580,083.24
SURPLUS, APRIL 30, 1921		$566,241.56

NOTE: No provision has been made for depreciation of real estate.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STATEMENT OF CASH RECEIPTS AND DISBURSEMENTS FOR DESIGNATED PURPOSES, FOR THE YEAR ENDED APRIL 30, 1921.

EXHIBIT C.

RECEIPTS:	
Life Membership Fund..	$258.08
International Electrical Congress of St. Louis Library Fund—Interest and Royalties..	136.55
Mailloux Fund—Interest..	45.00
Midwinter Convention Fund..	339.16
Total..	$778.79
DISBURSEMENTS:	
Life Membership Fund..	$258.08

RECEIPTS AND DISBURSEMENTS PER MEMBER.

During each fiscal year for the past eight years.

Year ending April 30......	1914	1915	1916	1917	1918	1919	1920	1921
Membership, April 30, each year..................	7876	8054	8212	8710	9282	10252	11345	13215
Receipts per Member.....	$14.08	$14.06	$13.62	$13.30	$13.17	$13.18	$15.01	$17.87
Disbursements per Member	12.86	13.54	13.74	12.75	11.99	12.92	15.62	18.90
Credit Balance per Member	$1.22	$ .52	*$ .12	$ .55	$1.18	$ .26	*$ .61	*$1.03

*Deficit.

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, *Secretary.*

New York, May 20, 1921.

STANDARDS

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

1921 Revision

[Printed, April 1921]

Published by
THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 West Thirty-ninth Street, New York

PREFACE TO 1921 EDITION

PURPOSE OF THE STANDARDS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

In framing these standards the chief purpose has been to define the terms and conditions which characterize the rating and behavior of electrical apparatus, with special reference to the conditions of acceptance tests.

It has not been the purpose of the standards to standardize the dimensions or details of construction of any apparatus, lest the progress of design should be hampered

NOTE

The Standards Committee takes this occasion to draw the attention of the membership to the value of suggestions based upon experience gained in the application of the Standards to general practise.

Any suggestions looking toward improvement in the Standards should be communicated to the Secretary of the Institute for the guidance of the Standards Committee in the preparation of future editions.

DEVELOPMENT OF THE STANDARDS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

The A. I. E. E. recognized at an early date in the development of electrical engineering the importance of standardization of electrical apparatus and at a meeting of its members in January, 1898, there was an important discussion on the "The Standardization of Generators, Motors, and Transformers." This resulted in the appointment of a Committee on Standardization, consisting of seven members representing qualifications and experience from designing, manufacturing, and operating standpoints. The report of this Committee on standardization was presented and accepted at a meeting of the Institute in June, 1899, and the rules embodied became the authoritative basis of American practice.

Experience gained in applications of the Standardization rules and further developments in electrical apparatus and methods showed the necessity of revision, and a committee was appointed which after consultation with manufacturing and operating engineers presented the first revised report on Standardization Rules of the A. I. E. E. in June, 1902.

The next revision was undertaken by a committee of ten, which presented its report in May, 1906.

In September, 1906, a Standards Committee of eleven members was appointed for further revision, and its report was presented in June, 1907.

The appreciation of the importance and value of standardization resulted in the formation of a Standing Committee, with the title of Standards Committee of the A. I. E. E. This became effective in the Constitution of June, 1907. The scope and amount of work has necessitated increasing the number of members from time to time to the present membership of 37, within which are a number of sub-committees specializing on various subjects.

The Standards Committee is appointed each year by the President of the Institute and the practise has been to reappoint a number of the previous committee, so that it is practically a continuous operating body.

The present Standards of the A. I. E. E. are therefore the result of over twenty-one years of work on standardization by the Institute, conducted by members actively engaged in the design, manufacture, operation, and specifying of electrical apparatus. These men have freely contributed their time and knowledge, and have conducted much experimental work for the purpose. The Standards record the best American practise and experience.

SCOPE OF THE 1921 REVISION

This edition of the Standards has been completely revised in form. This was considered necessary in view both of certain intrinsic defects in the original form, and the increase in complexity due to this form not being adapted to receive the additions which are made from year to year. Furthermore several changes in substance have been made and a few sections added.

OTHER APPROVED STANDARDS

The following resolution, adopted by the Standards Committee, was approved by the Board of Directors on April 14, 1916:

"The Standards Committee, with the approval of the Board of Directors, recommends the use of the following rules and standards as adopted by other societies. These have been formally presented to the Standards Committee by the societies concerned and are found not to be incompatible with the Standards of the American Institute of Electrical Engineers."

Standardization of Service Requirements for Motors, as printed in the 1915 report of the National Electric Light Association.

Standardization of Sizes, Voltages and Taps for Transformers, as printed in the 1916 report of the Electrical Apparatus Committee of the National Electrical Light Association.

Standard Specifications for Magnetic Tests of Iron and Steel, of the American Society for Testing Materials.

Report of the Joint Rubber Insulation Committee, published in the April, 1917, PROCEEDINGS of the American Institute of Electrical Engineers.

Accuracy Specifications in Sections IV and V of the **Joint Meter Code** of the Association of Edison Illuminating Companies and of the National Electric Light Association.

Accuracy Specifications in Section II of Circular 56 of the Bureau of Standards entitled **Standards for Electric Service.**

Report of the **Boiler Code Committee** of the American Society of Mechanical Engineers.

Suggested Safety Rules for Installing and Using Electrical Equipment in Bituminous Coal Mines, issued as Technical Paper 138 by the Bureau of Mines.

COOPERATING SOCIETIES

The following societies directly and through the committees named, have given helpful cooperation in the preparation of these Rules:

American Society for Testing Materials,
Committee B-1.

Association of Edison Illuminating Companies,
Committee on Meters.

Illuminating Engineering Society,
Committee on Nomenclature and Standards.

Electric Power Club.
Committee on Engineering Recommendations; Standardization Committee.

National Electric Light Association
Committee on Meters.
Committee on Apparatus.

Association of Railway Electrical Engineers
Committee on Wires and Cables.

American Electric Railway Engineering Association,
Committees on Equipment and Distribution.

Institute of Radio Engineers,
Committee on Standardization.

Society of Automotive Engineers,
Standards Committee.

Railway Signal Association.

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STANDARDS

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CHAPTER I

GENERAL PRINCIPLES UPON WHICH THE A. I. E. E. STANDARDS ARE BASED

(All temperatures in this and the following chapters are given in centigrade degrees.)

HEATING

1000 General Principles.—The General Principles by reference to which the ratings of electrical machines are fixed, so far as their heating is concerned, admit that the life of insulating materials depends upon the temperatures to which these materials are subjected. Taking, as a basis, the results of experience with machinery in practical service and the results of laboratory tests of various insulating materials, limiting "hottest-spot" temperatures have been established for various classes of insulation *for purposes of standardization*. Limiting "observable" temperatures are deduced from these limiting "hottest-spot" temperatures by subtracting therefrom a specified number of degrees which, *for purposes of standardization* represents the margin fixed between the limiting hottest spot and the limiting observable temperatures.

This margin may be designated as the "*conventional allowance.*"

1001 Methods of Temperature Measurement.—There are three fundamental methods of temperature measurement, namely:

1. The Thermometer Method.
2. The Resistance Method, and,
3. The Embedded-Detector Method.

The General Principles stated in Section 1000 permit of the use of whichever method is best suited to the class of machine, or part thereof, to be tested, by introducing appropriate values for the limiting observable temperature by each method. All the values of the observable temperatures are based upon the "hottest-spot" limitation adopted *for purposes of standardization* for the class of insulation employed.

1002 Methods of Temperature Measurement Defined.—These three fundamental methods of making temperature measurements are designated Methods 1, 2 and 3, and are defined as follows:

TABLE 100

Methods of Temperature Measurement

Method	Description of Method
1.	**Thermometer Method.** This method consists in the measurement of the temperature, by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the completed machine. This method does not include the use of thermocouples or resistance coils embedded in the machine as described under Method No. 3.
2.	**Resistance Method.** This method consists in the measurement of the temperature of windings by their increase in resistance. In the application of this method, *thermometer measurements shall also be made whenever practicable without disassembling the machine,** in order to increase the probability of obtaining the highest observable temperature. The measurement indicating the higher temperature shall be taken as the "observable" temperature.
3.	**Embedded Temperature-Detector Method.** This method consists in the measurement of the temperature by thermocouple or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When Method No. 3 is used, it shall, when required be checked by Method No. 2. The highest observable temperature obtained from the readings of the embedded detectors shall not exceed the values permitted by the Rules for Method 3, and the highest observable temperature obtained by Method 2 shall not exceed the values permitted by the Rules for Method 2.

*Note. As one of the few instances in which the thermometer check cannot be applied in Method II, the rotor of a turbo alternator may be cited.

1003 Conventional Allowances for the Three Methods of Temperature Measurement.—The specified differences by which the "observable" temperatures shall, *for purposes of standardization*, be assumed to be lower than the "hottest spot" temperatures, (which may be designated the "Conventional Allowances"), are as follows:

Method 1	15°C
" 2	10°C
" 3	(See following table).

TABLE 101

Conventional Allowance for Method 3

Method 3.	
For windings with two coil-sides per slot with detectors between top and bottom coil-sides (and between coil-sides and core).	5°C
For windings with one coil-side per slot for 5000 volts or less, with detectors between coil-side and core and between coil-side and wedge.	10°C
For windings with one coil-side per slot for more than 5000 volts, with detectors between coil-side and core and between coil-side and wedge.	10°C plus 1°C for every kv. of terminal pressure of the machine above 5 kv.

1004 Classification of Insulating Materials.—The insulations employed in Electrical Machinery are subdivided into three main classes designated A, B and C and defined as follows:

TABLE 102

Classification of Insulating Materials

Class	Description of Material.
A.	Cotton, silk, paper and similar materials when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire. When these materials are not treated, impregnated, or immersed in oil, they are not included in Class A.
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing the insulation or mechanical qualities of the insulation. (The word "impair" is used in the sense of causing any change which could disqualify the insulation for continuous service.)
C.	Materials capable of resisting higher temperatures than Class B, such as pure mica, porcelain, quartz, etc.

1005* Limiting "Hottest Spot" Temperatures.—The limiting "hottest spot" temperatures are, *for purposes of standardisation*, taken at the following values:

For Class A material...........105°C (See Note 1)
For Class B material...........125°C (See Note 2)
For Class C material...........no limit yet specified.

If different insulating materials are used on various parts of one winding (for instance in the slot and for the end windings) the temperature of each material shall not exceed the limit set for that material.

When insulation consists of layers of materials having different temperature-limits (for instance high-temperature limit material adjacent to the copper and lower-temperature limit material adjacent to the iron or to the air) the temperature of each material shall not exceed the limit set for that material.

1006 Limiting Observable Temperatures.—The limiting observable temperatures for use with methods 1, 2 and 3, are arrived at by subtracting the "conventional allowances" from the limiting "hottest-spot" temperatures for insulating materials. They are set forth as follows:

TABLE 103
Limiting Observable Temperatures

		Class A Material	Class B* Material
Method 1		90° C.	110° C.
Method 2		95° C.	115° C.
Method 3	For windings with two coil-sides per slot with detectors between top and bottom coil-sides and between coil-sides and core.	100° C.	120° C.
	For windings with one coil-side per slot with detectors between coil-side and core and between coil-side and wedge.	95° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).	115° C. (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).

*See also note 2 Section 1005.

(1005) Note 1. For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of observable temperature and temperature rise shall be 15°C below the limits fixed for these materials when impregnated.

(1005) Note 2. The Institute recognizes the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150°C or even higher. However, as sufficient data covering experience over a period of years at such temperatures are at present unavailable, the Institute adopts 125°C as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

1007 Limiting Observable Temperature of Oil.—The oil in which apparatus is permanently immersed, shall, in no part, have a temperature, observable by thermometer, in excess of 90°C.

1008 Standard Ambient Temperatures of Reference.—The following values are adopted for the standard ambient temperatures of reference:

For Air	40°C
For Water	25°C

These values for the standard ambient temperatures of reference apply to all conditions where the actual ambient temperature does not exceed them.

The limiting observable temperature rise must not be increased even when the ambient temperature is lower than the standard ambient temperature of reference.

1009 Limiting Observable Temperature Rises.—The limiting observable temperature rises in the following table 104 are obtained by subtracting the standard ambient temperatures of reference given in §1008 from the limiting observable temperatures given in Table 103. The limiting observable temperature rises to be used in practise are given later in the Rules. They are in some cases greater and in other cases smaller than those given in Table 104. See §1010.

TABLE 104

Limiting Observable Temperature Rises

		Air Cooled	
		Class A	Class B*
Method 1		50°C	70°C
Method 2		55°C	75°C
Method 3	For windings with two coil-sides per slot, with detectors between top and bottom coil-sides and between coil-sides and core.	60°C	80°C
	For windings with one coil-side per slot with detectors between coil-side and core and between coil-side and wedge.	55°C (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).	75°C (minus 1 degree for every 1000 volts of terminal pressure of the machine above 5000 volts).

*See also Note 2, Section 1005

1010 **General Comments on Special and Specific Cases.**—In the foregoing it has been assumed for the purpose of presenting a comprehensive, logical and consistent plan, that the Rules actually used in the industry are exactly in accord with the General Principles. Practical experience indicates the necessity of establishing definite Rules to cover Special as well as Specific Cases. These Cases are set forth in later chapters. Any case not specifically dealt with may come under the General Principles.

1011 **Comments on the Method of Measurement to be Employed.**—In the absence of definite Rules, the manufacturer may, on the occasion of the acceptance test, use any of the three methods for the temperature measurements. In most cases, however, restrictions on the choice of method are imposed. These are set forth in the Rules.

1012 **Comments on Temperature Limits in Special Cases.**—Temperature limits are prescribed in the Rules for special cases where conditions determined by practice, by experience, or by agreements, require departures (often arbitrary) from the limits of temperature rise corresponding to the General Principles.

1013 **Hottest Spot Temperature the Primary Point of Reference.**—The hottest spot temperature is the primary point of reference, of the "bench-mark" used as the basis for the foregoing scheme or temperature delimitation. It is not employed in commercial transactions or in the ordinary course of testing or operation of electrical machinery.

1014 **Observable Temperature Rise the Working Standard.**—The observable temperature rise is the working standard. A summary of working data with explanatory notes, will be found in Table 200.

1015 **Duration of Temperature Test and Correction to Time of Shut Down.**—Whatever method of temperature measurement be employed, it is required that

(a) operation shall be continued until constant temperatures are determined if the machine has a continuous rating, or for the full period if the machine has a short time rating, and

(b) when measurements cannot be made while the machine is loaded, appropriate corrections to raise the temperature readings to the time of shut down shall be applied. See Chap. II.

MECHANICAL AND COMMUTATION LIMITATIONS.

These limitations are set forth in subsequent Chapters dealing with specific kinds of machines.

WAVE SHAPE.

1200 The sine wave shall be considered as standard except where the departure therefrom is inherent in the operation of the system of which the machine forms a part.

DIELECTRIC STRENGTH AND INSULATION RESISTANCE.

(See §§2350 to 2380 incl.)

1300—The injury produced by dielectric stress applied to insulation is related to the time during which the stress is applied. A stress up to a certain limit may be applied for an indefinite period without injury to the insulation. A somewhat greater stress will cause heating of the insulation and a progressive deterioration, eventually resulting in breakdown. Higher values of stress cause more rapid deterioration and a quicker breakdown. It is customary to determine whether machinery will withstand the voltage stresses met in practice by a preliminary test for a definite period of time at a voltage considerably higher than the normal voltage to which the machinery is to be subjected, but not high enough to produce injury to the insulation during the period of test.

1301—The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machine, and its operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

1400—The insulation resistance of machinery is of doubtful significance as compared with the dielectric strength. It is subject to wide variation with temperature, humidity and cleanliness of the parts. When the insulation resistance falls below prescribed values it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying the machine. The insulation resistance therefore may afford a useful indication as to whether the machine is in suitable condition for application of the dielectric test.

EFFICIENCY

(See §§2331 to 2333 incl.)

1500 The conditions under which efficiency is determined are those normal to the operation of the machine. These include voltage, current, power factor, frequency, wave shape, speed, temperature, or such of them as may apply in each particular case.

1501 The efficiency at all loads of all apparatus shall be corrected to a reference temperature of 75°C.

1502 In the case of machinery, two efficiencies are recognized, conventional efficiency (**§3524**) and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed. When the efficiency of a machine is stated without specific reference to the load conditions rated load is always to be understood, whether the efficiency be the conventional or directly measured efficiency.

RATING

(See §§2202 to 2232 incl.)

1600 **Principle of Machine Rating.**—(a) *Rating by Temperature Rise*: The principle upon which machine rating is based, so far as relates to thermal characteristics, has been stated in earlier sections.

(b) *Rating by Limitations Other Than Temperature Rise*: In some machines, the rating is limited by other than thermal considerations. In such cases, the principle upon which machine rating is based is that the rated load applied continuously or for a stated period, shall not cause the various limitations specified in later chapters; *e. g.*, **§§4250-4252** inclusive, to be exceeded. The rating shall be based upon the capacity as limited by heating unless the capacity as limited by other characteristics, is less.

CHAPTER II.

GENERAL RULES

The expressions "machinery" and "machines" are here employed in a general sense, in order to obviate the constant repetition of the words "machinery or induction apparatus."

To ensure satisfactory results, electrical machinery should be specified to conform to the Institute Standards, in order that it shall comply in operation, with approved limitations in the following respects, so far as they are applicable.

Operating temperature
Mechanical strength
Commutation
Dielectric strength
Insulation resistance
Efficiency
Power factor
Wave shape
Regulation

OPERATION

Temperature Limits

2104 Permissible Temperatures with Insulations of More Than One Class.—(a) If different insulating materials are used on various parts of one winding (for instance in the slot and for the end windings) the temperature of each material shall not exceed the limit set for that material.

(b) When insulation consists of layers of materials having different temperature limits (for instance high-temperature-limit material adjacent to the copper and lower-temperature-limit material adjacent to the iron or to the air) the temperature of each material shall not exceed the limit set for that material.

21 Temperatures of Metallic Parts of Machines.—(*a*) ***Parts Adjacent to Insulating Material***: Metallic parts of machines in contact with or adjacent to any kind of insulation, shall not attain a temperature in excess of that allowed for the adjacent insulation.

(*b*) ***Parts not Adjacent to Insulating Material***: All parts of machines other than those covered by §2116 (a) may be operated at such temperatures as shall not be injurious in any other respect.

2120. Protection against Short Circuit.—The Institute recognizes the self-destructibility, both mechanical and thermal, of certain sizes and types of machines, when subjected to severe short-circuits, and recommends that ample protection be provided in such cases, external to the machine if necessary.

RATING

General

2202 Expression of Rating.—Except where otherwise specified the machines shall be rated in terms of their available ***output.*** For exceptions see §§**4223, 5203, 6204** and **6223.**

2204 Institute Rating.—The Institute Rating of a machine shall be its rating when operating with a cooling medium of the ambient temperature of reference specified in §§**2211** and **2212** and with barometric conditions within the range given in §**2215.** See §§**2300, 2310, 2311, 4110** and **4300.**

Ambient Temperature of Reference and Altitude Correction

2211 Ambient Temperature of Reference for Air.—The standard ambient temperature of reference, when the cooling medium is air, shall be 40°C.

2212 Ambient Temperature of Reference for Water-Cooled Machinery.—For water-cooled machinery, the standard temperature of reference for incoming cooling water shall be 25° C, measured at the intake of the machine.

2213 Machines Cooled by Other Means.—Machines cooled by means other than air or water shall receive special consideration.

2214 Outdoor Machinery Exposed to Sun's Rays.—Outdoor machinery not protected from the sun's rays at times of heavy load, shall receive special consideration.

2215 Altitude.—Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information in regard to the height above sea level at which a machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters (3300 feet.) For machinery operating at an altitude of 1000 meters or less, a test at any altitude less than 1000 meters is satisfactory, and no correction shall be applied to the observed temperatures. Machines intended for operation at higher altitudes shall be regarded as special. It is recommended that when a machine is intended for service at altitudes above 1000 meters (3300 ft.) the permissible temperature rise at sea level, shall be reduced by 1 per cent for each 100 meters (330 ft.) by which the altitude exceeds 1000 meters.

Kinds of Rating

There are various kinds of rating such as:

2220 Continuous Rating.—A machine rated for continuous service shall be able to operate continuously at its rated output, without exceeding any of the limitations established herein.

In the absence of any specification as to the kind of rating, the continuous rating shall be understood.

2221 Short-Time Rating.—A machine rated for discontinuous or short-time service (*i. e.* service including runs alternating with stops of sufficient duration to ensure substantial cooling), shall be capable of operating at its rated output during a limited period, to be specified in each case, without exceeding any of the limitations established herein. Such a rating is a short-time rating.

2222 Duty-Cycle Operation.—Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load may be selected, which shall simulate as nearly as possible the thermal conditions of the actual duty-cycle.

2223* Standard Short-Time Ratings.—The following periods shall be used for short-time ratings: 5, 10, 15, 30, 60 and 120 minutes.

2224 A.I.E.E. and I. E. C. Ratings.—When the prescribed conditions of test are those of the A. I. E. E. Standards the rating of the machine is the Institute Rating. (See **§2401**) When the prescribed conditions of the test are those of the I. E. C. Rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate. I. E. C. stands for "International Electrotechnical Commission."

2225 Continuous Rating Implied.—Machines marked "A. I. E. E. Rating" or "I. E. C. Rating" shall be understood to have a continuous rating, unless otherwise marked in accordance with **§§2223, 5201** or **5202.**

Rating by Temperature Rise

2230 Limiting Observable Temperature Rises.—The following limiting observable temperature rises have been adopted.

(2223) When, for example, a short-time rating of 10 minutes duration is adopted, and the thermally equivalent load is 25 kw. for that period, then such a machine shall be stated to have a 10-minute rating of 25 kw.

In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are within 5° C. of the ambient temperature at the time of starting the test.

TABLE 200

Limiting Observable Temperature rises for machines for operation in locations where the ambient temperature will not exceed 40°C. for Air or 25°C. for Water.

For Class A insulation use the values in the Table

For Class B insulation use 20 °C. higher values (or 45°C. higher in the cases covered by the Note in §1606).

For Class C insulation no limits yet specified.

	Items	Method 1	Method 2	Method 3	
				For windings with two coil-sides per slot with detectors between top and bottom coil-sides and between coil sides and core.	For windings with one coil-side per slot with detectors against core and against wedge.
Windings on Stators	1–Insulated windings other than 2.3. Note 1	50°C. Note 1	55°C. Note 1	60°C. Note 1	55°C. minus1°for every 1000 volts by which the terminal pressure of the machine exceeds 5000 volts). Note 1
	2–Single layer field windings with exposed surfaces uninsulated	60°C.	60°C.		
	3–Short circuited insulated windings	60°C.			
Windings on Rotors	4–Field Windings (other than 5.)		55°C.		
	5–Single layer field windings with exposed surfaces uninsulated	60°C.	60°C.		
	6–Windings in slots	50°C.	55°C.		
	7–Short-circuited insulated windings	60°C.			
	8–Transformers and Induction Regulators		55°C.		

Note 1—(a) The temperature of the windings of transformers and induction regulators is always to be ascertained by Method 2.

(b) In measuring the temperature of air blast transformers, the air supply shall shut off immediately at the end of the temperature run and air intake shall be closed to prevent further admission of cooling air. In checking the temperatures ascertained by resistance, the readings of thermometers well distributed and in good contact with the coils shall be noted and the maximum temperature indicated by them, if higher than that determined by resistance, shall be taken as the maximum observable temperature of the windings. With the above procedure, the observable temperature rise for air-blast transformers may attain a value not in excess of 60°C. as determined by thermometer, although it must not exceed 55°C. as determined by resistance.

(c) Method 3 shall be applied to all stators of machines with cores having a width 50 cm. and over; it shall also be applied to all machines of 5000 volts and over if of over 500 kv-a. regardless of core width.

(d) Method 2 shall not be used for circuits of low resistance (other than transformer windings), such as interpole windings, where external joints and connections form a considerable part of the total resistance.

(e) For all other cases it is optional to employ either Method 1 or Method 2. (This is equivalent to authorizing Method 1 with a 5°C. lower limit of observable temperature than is permitted for Method 2).

Note 2.—For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of observable temperature rise shall be 15 degrees below the limits in the above table fixed for these materials when impregnated.

Note 3.—For enclosed machines (rotating) the limiting observable temperature rise shall be taken as 5 degrees higher than the values set forth in the Table for Items 1 and 6.

Note 4. A further limitation to this Table relates to the restriction of its application to machinery for operation in locations whose altitude is not more than 1000 meters above sea level. Recommendations relating to the limiting temperature rise for machines for operation at higher altitudes are given in §§2215 and 2231.

Note 5. If different insulating materials are used on various parts of one winding (for instance in the slot and for the end windings) the temperature of each material shall not exceed the limit set for that material.

When insulation consists of layers of materials having different temperature-limits (for instance high-temperature limit material adjacent to the copper and lower temperature limit material adjacent to the iron or the air) the temperature of each material shall not exceed the limit set for that material.

2231 Exceptions to Table 200.—(a) For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of observable temperature rise shall be 15°C. below the limits fixed for these materials when impregnated.

(b) When the thermometers are applied directly to the surfaces of bare windings, such as an edgewise strip conductor, or a cast copper winding, the limiting observable temperature rise shall be 10°C. higher than given for Method 1 in the Table.

(c) For commutators, collector rings, or bare metallic surfaces not forming part of a winding, the limiting observable temperature rise shall be 15°C. higher than given for Method 1 in the Table.

(d) Any machinery destined for use with higher ambient temperatures of cooling mediums, and also any machinery for operation at altitudes for which no provision is made in **§2215**, should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these Rules, will, however, afford guidance in such cases.

2232 Limiting Observable Temperature of Oil.—The oil in which apparatus is permanently immersed shall, in no part, have a temperature, observable by thermometer, in excess of 90°C.

TESTS

Ambient Temperature

2300* **Measurement of the Ambient Temperature During Tests of Machinery.**—(*a*) *General:* The ambient temperature is to be measured by means of several thermometers placed at different points around and half way up the machine at a distance of 1 to 2 meters (3 to 6 feet), and protected from drafts, and abnormal heat radiation, preferably as in §2301.

(*b*) *Mean Temperature*: The value to be adopted for the ambient temperature during a test, is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

(*c*) *Use of Idle Unit*: It is sometimes desirable to avoid errors due to time lag in temperature changes, by employing an idle unit of the same size and subjected to the same conditions of cooling as the unit under test, for obtaining the ambient temperature.

2301 **Oil Cup.**—In order to avoid errors due to the time lag between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitably heavy metal cup. This can be made to respond to various rates of change, by proportioning the amount of oil to the metal in the containing cup. A convenient form for such an oil cup consists of a massive metal cylinder, with a hole drilled partly through it. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The larger the machine under test, the larger should be the metal cylinder employed as an oil cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a metal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in. high).

Machine Temperatures

2310 **Temperature Rise for Any Ambient Temperature.**—A machine may be tested at any convenient ambient temperature, preferably not below 10°C., but whatever be the value of this ambient temperature, the permissible rises of temperature must not exceed those given in Table 200.

2311 **Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference.**—Numerous experiments have shown that deviation of the temperature of the cooling medium from that of the standard of reference, at the time of the heat run, has a negligible effect upon the temperture rise of machines; therefore, no correction shall be applied for this deviation.

(2300) The cooling fluid may either be led to the machine through ducts, or through pipes, or merely surround the machine freely. In the former case the ambient temperature is to be measured at the intake of the machine itself.

2312 Duration of Temperature Test of Machine for Continuous Service.—The temperature test shall be continued until sufficient evidence is available to show that the maximum temperature and temperature rise would not exceed the requirements of the rules, should the test be prolonged until the attainment of a steady final temperature.

2313 Duration of Temperature Test of Machine with a Short-Time Rating.—The duration of the temperature test of a machine with a short-time rating shall be the time required by the rating. In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are within 5°C. of the ambient temperature at the time of starting the test. See **§2235.**

2314 Duration of Temperature Test for Machine having more than One Rating.—The duration of the temperature test for a machine with more than one rating shall be the time required by that rating which produces the greatest temperature rise. In cases where this cannot be determined beforehand, the machine shall be tested separately under each rating.

2315 Temperature Measurements during Heat Run.—When possible temperature measurements shall be taken during operation, as well as when the machine is stopped. The highest figures thus obtained shall be adopted. In order to abridge the long heating period, in the case of large machines, reasonable overloads of current during the preliminary period are suggested for them.

2316 Rules for Correcting to Time of Shut-Down.—(a) Whenever a sufficient time has elapsed between the instant of shut-down and the time of the final temperature measurement to permit the temperature to fall, suitable corrections shall be applied, so as to obtain as nearly as practicable the temperature at the instant of shut-down. This can sometimes be approximately effected by plotting a curve with temperature readings as ordinates and time as abscissas, and extrapolating back to the instant of shut-down. In other instances, acceptable correction factors can be applied; *e. g.*, In the case of machines manufactured in large quantities, the correction obtained from tests made on representative machines may be used.

(b) Exception. In cases where successive measurements show *increasing* temperatures after shut-down, the highest value shall be taken.

Details of Testing Methods

2320 Covering of Thermometer.—Thermometers used for taking temperatures of machinery shall be covered by felt pads 4 cm. x 5 cm. (1½ in. x 2 in.), 3 mm. (⅛ inch) thick cemented on; oil putty may be used for stationary and small apparatus.

2321 Temperature Coefficient of Copper.—The temperature coefficient of copper shall be deduced from the formula $1/(234.5 + t)$. Thus, at an initial temperature $t = 40°C.$, the temperature coefficient of increase in resistance per degree centigrade rise is $1/(274.5 = 0.00364)$. The following table, deduced from the formula, is given for convenience of reference.

TABLE 201

Temperature Coefficients of Copper Resistance.

Temperature of the winding, in degrees C. at which the initial resistance is measured.	Increase in resistance of copper per °C., per ohm of initial resistance.
0	0.00427
5	0.00418
10	0.00409
15	0.00401
20	0.00393
25	0.00385
30	0.00378
35	0.00371
40	0.00364

2322 Temperature Measurement of Low Resistance Circuit.—In circuits of low resistance, where joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used. (Except transformers, for which see **§6320.**)

2323* Location of Embedded Temperature Detectors.—Embedded temperature detectors should be placed in at least two sets of locations. One of these should be between a coil-side and the core and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge. A liberal number of detectors shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur. See **§1002.**

Efficiency

2331^{*b} **Efficiencies Recognized.**—Two efficiencies are recognized, conventional efficiency and directly measured efficiency. Unless other-

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(2321) Temperature by Resistance: The temperature by resistance may be calculated by the following formula:

Let r_t = resistance at t°C.

r_T = resistance at T°C.

Then $$T = \frac{r_T}{r_t}(234.5 + t) - 234.5$$

(2323) A coil side is one of the two active sides of the coil lying in a slot.

(2331) The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electrical machinery are practically indeterminable, and must, in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for themin arriving at the "conventional efficiency."

wise specified, the conventional efficiency is to be employed. See **§§3514** and **3524.**

Input and output determinations of efficiency may be made directly, measuring the output by brake, or equivalent, where applicable. Within the limits of practical application, the circulating power method, sometimes described as the Hopkinson or "loading-back" method, may be used.

2332* **Normal Conditions for Efficiency Tests.**—(*a*) *General*: The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave-shape, speed, temperature, or such of them as may apply in each particular case.

(*b*) *Load*: When the efficiency of a machine is stated without specific reference to the load conditions, rated load is always to be understood whether the efficiency be the conventional or directly measured efficiency.

(*c*) *Wave Shape*: The sine wave shall be standard, unless a different wave form is inherent in the operation of the system. See **§2350.**

*(*d*) *Temperature of Reference*: The efficiency of all apparatus at all loads, shall be corrected to a reference temperature of 75° C, but tests may be made at any convenient ambient temperature, preferably not less than 15° C.

(*e*) *Power Factor*: The efficiency of alternators and transformers shall be stated at the rated power factor.

2333 **Direct Measurement of Efficiency.**—(*a*) *General*: Electric power shall be measured at the terminals of the apparatus.

(*b*) *Polyphase Machines*: In polyphase machines, sufficient measurements shall be made on all phases to avoid errors of unbalance.

(*c*) *Mechanical Power*: Mechanical power delivered by machines shall be measured at the pulley, gearing or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. See, however, an exception in **§5202.**

Wave Shape.

2340 **Standard Wave Shape.**—The Sine Wave shall be considered as standard, except where departure therefrom is inherent in the operation of the system of which the electrical machine forms a part.

Tests of Dielectric Strength

2350 **Condition of Machine to be Tested.**—Commercial tests shall, in general, be made with the completely assembled machine and not with individual parts. The machine shall be in good condition, and high-voltage tests, unless otherwise specified, shall be applied

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(2332 d) In calculating plant or system efficiency it may be desirable to calculate the losses in each individual machine or part of the system at the actual temperature of that transformer or part during the specified interval. These losses may be appreciably different from the losses at 75° C, which latter shall be the standard temperature of reference for all efficiency guarantees.

before the machine is put into commercial service, and shall not be applied when the insulation resistance is low due to dirt or moisture. High voltage tests to determine whether specifications are fulfilled are admissible on new machines only.

2351 Where High-Voltage Tests are to be Made.—Unless otherwise agreed upon, high-voltage tests of machines shall be made at the factory.

2352 Temperature at which High-Voltage Tests are to be made.—High-voltage tests shall be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial testing.

2353 Points of Application of Voltage.—(*a*) *General:* The test voltage shall be successively applied between each electric circuit and all other electric circuits and metal parts grounded.

(*b*) *Interconnected Polyphase Windings:* Interconnected polyphase windings shall be considered as one circuit. All windings except that under test shall be connected to ground.

2354 Frequency and Wave Shape of Test Voltage.—The frequency of the testing voltage shall be not less than the rated frequency of the machine tested. A sine wave shape is recommended, (see §§**2340** and **4351**). The test shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the specified test voltage.

2355 Duration of Application of Test Voltage.—(a) *General*: The testing voltage for machines shall be applied continuously for a period of 60 seconds. See exception §**2355** (b).

(b) *Standard Machines and Devices produced in large quantities*: Standard machines and devices produced in large quantities for which the standard test pressure is 2500 volts or less, may be tested for one second with a test pressure 20 per cent higher than the one minute test pressure.

2356 Standard Test Voltage.—(a) *General:* The standard test voltage for all machines, except as otherwise specified, shall be twice the normal voltage of the circuit to which the machine is connected plus 1000 volts. See exceptions §§**2357, 4361, 6361.**

2357 Assembled Apparatus.—Where a number of pieces of apparatus are assembled together and tested as an electrical unit they shall be tested with 15 per cent lower voltage than the lowest required on any of the individual pieces of apparatus.

2358 Measurement of Voltage in Dielectric Strength Tests.—There are two methods of measuring the voltage used in making dielectric strength tests, namely

1. The voltmeter method.
2. The spark gap method, using either the sphere spark gap or the needle spark gap.

2359* Use of Voltmeters and Spark-gaps in Dielectric Tests.—When making high voltage tests on electrical machinery every precaution

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(2359) The resistance will damp high frequency oscillations at the time of breakdown and limit the resulting current.

Carbon resistors should not be used because their resistance may become very low at high voltages.

must be taken against the occurrence of spark-gap discharges in the circuits from which the machine is being tested. A non-inductive resistance of about one ohm per volt of test pressure shall be inserted in series with one terminal of the spark gap. If the test is made with one electrode grounded, this resistance shall be inserted directly in series with the non-grounded electrode; if neither terminal is grounded one-half shall be inserted directly in series with each electrode. In either case this resistance shall be as near the measuring gap as possible and not in series with the tested apparatus. A water tube is the most suitable form of resistor.

2360 Use of Spark-gap with Machines of Low Capacitance.—When the machine under test does not require sufficient charging current to distort the high-voltage wave shape, or change the ratio of transformation, the spark-gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark-gap just breaks down. This adjustment should be made with the machine under test disconnected. The machine should then be connected, and with the spark-gap about 20 per cent longer, the testing apparatus again adjusted to give the voltage of the former breakdown, which is the assumed voltage of test. This voltage shall be maintained for the required interval.

2361* Use of Spark-gap with machines of High Capacitance.—When the charging current of the machine under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage shall be made with the machine under test connected to the circuit and in parallel with the spark-gap.

2362 Measurements with Voltmeter.—In measuring the voltage with a voltmeter, the instrument should preferably derive its voltage from the high-pressure circuit, either directly, or by means of a voltmeter coil placed in the testing transformer, or through an auxiliary *ratio transformer*. It is permissible to measure the voltage at other places such as the transformer primary, provided corrections can be made for the variations in ratio caused by the charging current of the machine under test, or provided there is no material variation in this ratio. In any case when the capacitance of the machine to be tested is such as to cause wave distortion, the testing voltage must be checked by a spark gap as set forth in §§**2364** and **2366** or by a crest-voltage meter. If the crest-voltage meter is calibrated in crest volts, its readings must be reduced to the corresponding r. m. s. sinusoidal value by dividing by $\sqrt{2}$.

(2361) When making arc-over tests of large insulators, leads, etc. partial arc-over of the tested apparatus may produce oscillations which will cause the measuring gap to discharge prematurely. The measured voltage will then appear too high. In such tests the "equivalent ratio" of the testing transformer should be measured by gap to within 20 per cent of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. The measuring gap should then be greatly lengthened out and the voltage increased until the tested apparatus arcs over. This arc-over voltage should then be determined by multiplying the voltmeter reading by the equivalent ratio found above. Direct measurement of the spark-over voltage over one gap by another gap should always be avoided.

2363 Measurements with Spark Gaps.—(*a*) *General:* If proper precautions are taken, spark gaps may be used to advantage in checking the calibration of voltmeters for high voltage tests of machines.

(*b*) *Range of Voltages*: For the calibrating purposes set forth above the sphere gap shall be used for voltages above 50 kv., and is preferred down to 30 kv. The needle spark gap may, however, be used for voltages from 10 to 50 kv.

2364 Needle Spark Gap.—The needle spark gap shall be between new sewing needles, supported axially at the ends of linear conductors, which are at least twice the length of the gap. There must be a clear space around the gap for a radius at least twice the gap length.

2365 Needle Gap Sparking Distances.—The sparking distances in air between No. 00 double long sewing needle points for various root-mean-square sinusoidal voltages shall be assumed to be as shown in Table 202.

TABLE 202

Needle-Gap Spark-Over Voltages

(At 25° C and 760 mm. barometer).

R. M. S. Kilovolts	Millimeters	R. M. S. Kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41		

The values in Table 202 refer to a relative humidity of 80 per cent. Variations from this humidity may involve appreciable variations in the sparking distance.

2366* Sphere Spark-Gap.—The standard sphere spark gap shall be between two suitably mounted spheres. No extraneous body, or external part of the circuit, shall be nearer the spheres than twice their diameter.

The shanks shall be not greater in diameter than $^1/_5$th the sphere diameter. Metal collars etc., through which the shanks extend, shall be as small as practicable and shall not, during any measurement, come closer to the sphere than the maximum gap length used in the measurement.

The sphere diameter should not vary more than 0.1 per cent, and the curvature, measured by a spherometer, should not vary more than 1 per cent from that of a true sphere of the required diameter.

(2366) When used as specified, the accuracy obtainable should be approximately 2 per cent.

2367* Use of Spherometer.—In using the spherometer to measure curvature, the distance between the points of contact of the spherometer feet shall be within the limits as indicated in Table 203.

TABLE 203

Spherometer Specifications

Diameter of sphere in. mm.	Distance between contact points in mm.	
	Maximum	Minimum
62.5	35	25
125	45	35
250	65	45
500	100	65

2368 Sphere-Gap Sparking Distances.—The sparking distance between spheres for various r. m. s. sinusoidal voltages shall be assumed to be as shown in Table 204.

2369* Correction of Gap Spacing for Air-Density.—The spacing at which it is necessary to set a gap to spark over at some required voltage, is found as follows. Divide the required voltage by the correction factor given in Table 205 and use the new voltage thus obtained, to find the corresponding spacing from Table 204, using a graph of the latter, if more convenient.

2370* Correction of Voltage for Air-Density.—The voltage at which a gap sparks over is derived from the voltage corresponding to the spacing in Table 204 by multiplying by the correction factor.

(2367) In using sphere gaps constructed as indicated in §2366 and §2367, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap, *e. g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

(2369 and 2370) Effect of Air Density on Spark-Over Voltage. The spark-over voltage, for a given gap, decreases with decreasing barometric pressure and increasing temperature. This variation may be considerable at high altitudes. When the variation from sea level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table 204 in which

$$\text{Relative air density} = \frac{0.392\,b}{273 + t}$$

b = barometric pressure in mm.
t = temperature in deg. C.

Corrected curves may be plotted for any given altitude, if desired. It will be noted in Table 213 that for values of relative air density above 0.9 the correction factor does not differ greatly from the relative air density.

TABLE 204

Sphere-Gap Spark-Over Voltages

(At 25°C and 760 mm. barometric pressure)

Kilo-volts	Sparking Distance in Millimeters.							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	..	..	..	..	..	..
20	8.6	8.6	..	..	..	..	..	..
30	14.1	14.1	14.1	14.1	..	..	..	..
40	19.2	19.2	19.1	19.1	..	..	..	..
50	25.5	25.0	24.4	24.4	..	..	..	..
60	34.5	32.0	30.	30.	29	29	..	..
70	46.0	39.5	36	36	35	35	..	..
80	62.0	49.0	42	42	41	41	41	41
90		60.5	49	49	46	45	46	45
100			56	55	52	51	52	51
120			79.7	71	64	63	63	62
140			108	88	78	77	74	73
160			150	110	92	90	85	83
180				138	109	106	97	95
200					128	123	108	106
220					150	141	120	117
240					177	160	133	130
260					210	180	148	144
280					250	203	163	158
300						231	177	171
320						265	194	187
340							214	204
360							234	221
380							255	239
400							276	257

The sphere gap is more sensitive than the needle gap to momentary rises of voltage and the voltage required to spark over the gap should be obtained by slowly closing the gap under constant voltage, or by slowly raising the voltage with a fixed setting of the gap. Open arcs should not be permitted in proximity to the gap during its operation, as they may affect its calibration.

Table 205

Air Density Correction Factors for Sphere Gaps.

Relative air density	Diameter of standard spheres in mm.			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

Insulation Resistance

2380 General.—The insulation resistance test shall be made with all circuits of equal voltage above ground connected together. Circuits or groups of circuits of different voltage above ground shall be tested separately.

2381 Voltage for Insulation Resistance Test.—Insulation resistance tests shall, if possible, be made at a d-c. pressure of 500 volts. Since the insulation resistance varies with the pressure, it is necessary that, if a pressure other than 500 volts is to be employed in any case, this other pressure shall be clearly specified.

2382* Minimum Values.—The insulation resistance of a machine at its

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(2382) The order of magnitude obtained by this rule is shown in the following table.

TABLE 206

Insulation Resistance of Machines Excluding Oil-Immersed Apparatus.

Rated voltage of machine	Megohms		
	100 kv-a.	1000 kv-a.	10,000 kv-a.
100	0.091	0.05	—
1,000	0.91	0.50	0.091
10,000	9.1	5.0	0.91
100,000	—	50	9.1

operating temperature shall be not less than that given by the following formula:

$$\text{Insulation Resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rating in kv-a.} + 1000}$$

The formula applies only to dry apparatus. Such high values are not attainable in oil-immersed apparatus.

Regulation

2390 Conditions for Tests of Regulation.—(a) *Speed and Frequency:* The regulation of generators shall be determined at constant speed, and that of alternating current machines at constant frequency.

(*b*) *Wave Form:* A sine wave of voltage shall be assumed in determining the regulation of alternating current machinery receiving electric power, except where expressly specified otherwise. See **§2340.**

(*c*) *Temperature*: It is desirable that all parts of the machine affecting the regulation be maintained at constant temperature between the two loads and where the influence of temperature is of consequence, a reference temperature of 75° C. shall be considered as standard. If change of temperature should occur during the tests the results shall be corrected to the reference temperature of 75° C.

CONSTRUCTION

Rating Plates

2401 Marking of Rating Plate.—(a) *Distinctive Marking*: It is recommended that the rating plate of machines which comply with the Institute Rules shall carry a distinctive special sign, such as "A.I.E.E. 1920 Rating" or "A20" Rating.

(b) *Significance of Marking*: The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature. See §§**2211, 2212, 2215**, and **2220.**

(c) *Marking for Various Ratings*: The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

CHAPTER III.

GENERAL DEFINITIONS

In this chapter are given definitions which are of general application to electric circuits, machines and systems. Definitions pertaining to a specific class of apparatus are given in the chapter on the class of apparatus in question. The definitions here given are primarily descriptive rather than scientifically precise.

The definitions given below for currents are also applicable, in most cases, to electromotive forces, potential differences, magnetic fluxes, etc.

DEFINITIONS

General

3000 **Ambient Temperature.**—The ambient temperature is the temperature of the air or water which comes into contact with the heated parts of a machine and carries off its heat. See **§§2300 and 2301.**

Resistivity

3020 **Resistivity.**—The resistivity of a material is the resistance expressed in ohms between two opposite faces of a centimeter cube of the material, and is usually coupled with a statement of the temperature. See **§9050.**

Apparatus

3064 **Resistor.**—A resistor is a device used primarily because it possesses the property of electrical resistance. Resistors are used in electric circuits for purposes of operation, protection, or control. See **§7018.**

3070 **Inductor.**—An inductor is a device used primarily because it possesses the property of inductance.

3078 **Reactor.**—A reactor is a device used primarily because it possesses the property of reactance. Reactors are used in electric circuits for purposes of operation, protection or control.

Kinds of Currents

3104 **Direct Current.**—A direct current is a unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

3108 **Pulsating Current.**—A pulsating current is a current which has regularly recurring variations in magnitude. As ordinarily employed the term refers to a unidirectional current.

3112 **Continuous Current.**—A continuous current is a practically non-pulsating direct current.

3116 Alternating Current.—An alternating current is a current the direction of which reverses at regularly recurring intervals. Unless distinctly otherwise specified, the term *alternating current* refers to a periodically varying current with successive half waves of the same shape and area. See §3212

3120 Oscillating, or Free Alternating-Current.—An oscillating, or free alternating-current is the current following any electro-magnetic disturbance in a circuit having capacity, inductance, and less than the critical resistance. When the critical resistance of a circuit is reached the current becomes aperiodic.

Alternating Currents

3204 Cycle.—A cycle is one complete set of positive and negative values of an alternating current.

3206 Period.—The period of an alternating current is the time required for the current to pass through one cycle.

3208 Frequency.—The frequency of an alternating current is the number of cycles through which it passes per second, that is, the reciprocal of the period.

3212 Wave Shape.—The wave shape, or wave form, of an alternating current is the shape of the curve obtained when the instantaneous values of the current are plotted against time in rectangular coordinates.

Two alternating quantities are said to have the same wave shape when their ordinates of corresponding phase bear a constant ratio to each other. The wave shape, as thus understood, is therefore independent of the frequency of the current and of the scale to which the curve is plotted.

3214 Sine-Wave, or Simple Alternating-Current.—A sine wave, or simple alternating-current is a current whose wave shape is sinusoidal.

3218* Root-Mean-Square or Effective Value.—The root-mean-square or effective value of an alternating current is the square root of the mean of the squares of the instantaneous values for one complete cycle. It is usually abbreviated r. m. s. Unless otherwise specified, the numerical value of an alternating current refers to its r. m. s. value. The word "virtual" is sometimes used in place of r. m. s., particularly in Great Britain.

3222 Phase.—Phase is the fraction of the period of an alternating current which has elapsed since the current passed through the zero position of reference.

This fraction is usually expressed in angular measure, and the period corresponding to one complete cycle is taken as representing 2π radians or 360 degrees. The angles are frequently called electric angles, and the degrees electric degrees.

(3218) The r. m. s. value of a sine wave (see Section 3214) is equal to its maximum, or crest value, divided by $\sqrt{2}$.

In the usual equation

$$i = I_m \sin(\omega t + \varphi)$$

the quantity $(\omega t + \varphi)$ is the phase and φ is the phase angle of the current.

3224* **Phase Difference; Lead and Lag.**—The phase difference of two alternating quantities of the same frequency is the difference between their phases at any instant. That quantity whose maximum occurs first in time is said to lead the other, and the latter is said to lag behind the former.

3228 **Vector Representation and Angular Velocity.**—A sine-wave current or voltage may be represented by a vector of constant length rotating counter-clockwise at a constant angular velocity ($\omega = 2\pi f$); this angular velocity is frequently termed the angular velocity of the current or voltage.

3230* **Counter-clockwise Convention.**—It is recommended that, in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector, as in Fig. 3—1 where *O I* represents the vector of a current in a simple alternating current circuit lagging behind the vector *O E* of impressed electromotive force

FIG. 3-1

3234 **Power.**—Power is the rate of transfer of energy. In the case of an alternating-current circuit the word power is generally used to denote the average value of the power over a cycle. The power in an electric circuit at any instant is equal to the product of the values of the current and voltage at that instant, and is generally called the instantaneous power.

3238 **Apparent Power or Volt-amperes.**—The apparent power, or volt-amperes, in an alternating current circuit is the product of the r. m. s. value of the voltage across the circuit by the r. m. s. value of the current in the circuit. Apparent power is also expressed in kilo-volt-amperes, abbreviated kv-a.

3242* **Power Factor.**—Power factor is the ratio of the power to the apparent power.

3246* **Reactive Volt-amperes.**—The reactive volt-amperes in a circuit is the square root of the difference between the square of the apparent power and the square of the power.

3250* **Reactive Factor.**—The reactive factor is the ratio of the reactive volt-amperes to the total volt-amperes.

(3224) When the two alternating quantities do not have the same wave form, the phase-difference as here defined may not be identical with equivalent phase-difference as defined in Section 3262.

(3230) See Publication 12 of the International Electrotechnical Commission (Report of Turin meeting, Sept. 1911, p. 78.)

(3242) The power factor when both the current and voltage are sinusoidal is equal to the cosine of the angle which expresses their difference in phase (see Section 3224).

(3246) The reactive volt-amperes, when both current and voltage are sinusoidal, is equal to the volt amperes times the sine of the angle which expresses the phase difference between current and voltage.

(3250) The reactive factor, when both current and voltage are sinusoidal, is equal to the sine of the angle which expresses their phase difference.

3254* **Active Component.**—The active component of the current in a circuit is the average power divided by the voltage.

3256* **Reactive Component.**—The reactive component of the current in a circuit is the square root of the difference between the square of the current and the square of the active component of the current.

3260 **Equivalent Sine Wave.**—An equivalent sine wave is a sine wave which has the same frequency and the same r. m. s. value as the actual wave.

3262 **Equivalent Phase Difference.**—The equivalent phase difference (applicable to non-sinusoidal currents and voltages) is the phase difference between the equivalent sine waves of current and voltage when so related as to have the same power factor as the non-sinusoidal quantities.

There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave, or in both, may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e. g.*, the case of an a-c. arc. In such cases, the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

3266* **Crest Factor or Peak Factor.**—The crest factor or peak factor of a wave is the ratio of the crest, or maximum, value to the r. m. s. value.

3270* **Form Factor of a Wave.**—The form factor of a wave is the ratio of the r. m. s. to the algebraic mean ordinate taken over a half cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle.

3274 **Deviation Factor of a Wave.**—The deviation factor of a wave is the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave to the maximum ordinate of the equivalent sine wave when the waves are superposed in such a way as to make this maximum difference as small as possible.

3278 **Telephone Interference Factor of a Wave.** (See §4352)—The telephone interference factor is the ratio of the square root of the sum of the squares of the weighted values of all the sine wave components (including in alternating waves both fundamental and harmonics) to the r. m. s. value of the wave.

(3254) The active, or in-phase component of the current in a circuit corresponds to average power passing in a given direction through the circuit. With sine wave voltage and current, the active component of the current is in phase with the voltage.

(3256) The reactive, or quadrature, component of the current in a circuit corresponds to power alternating in direction in the circuit so that the average value of the power transferred in a given direction through a cycle is zero. With sine wave current and voltage the reactive component of the current is in quadrature with the voltage.

(3266) The crest factor of a sine wave is $\sqrt{2}$.

(3270) The form factor of a sine wave is $\frac{\pi}{2\sqrt{2}}$ or 1.11.

Circuits and Phases

3304 Electric Circuit.—An electric circuit is a path in which an electric current may flow. Strictly speaking, an electric circuit is a complete circulatory path, but the term circuit is commonly employed to designate a specific part of a complete path. When part of a complete path is referred to, such as a branch circuit, a derived circuit, or a conductor, both the terminals and the conductor which form that path should be specified in order to avoid ambiguity; *e. g.*, the circuit *a-b-c*. When the whole circuit is referred to, it may be designated as a complete or closed circuit.

3324* Single-Phase Circuit.—A single-phase circuit is a circuit energized by a single alternating electromotive force.

3326* Three-Phase Circuit.—A three-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by one-third of a cycle; *i. e.*, 120 degrees.

3328* Quarter-Phase or Two-Phase Circuit.—A quarter-phase or two-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by a quarter of a cycle; *i. e.*, 90 degrees.

3330* Six-Phase Circuit.—A six-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by one sixth of a cycle; *i. e.*, 60 degrees.

3332 Polyphase Circuit.—A polyphase circuit is a circuit of more than a single phase. This term is ordinarily applied to symmetrical systems.

3344 Symmetrical Voltages and Currents.—Polyphase voltages or currents are symmetrical when the voltages or currents have the same wave shape and r. m. s. value and differ in phase each from the next by the same angle.

3348 Symmetrical Polyphase System.—A symmetrical polyphase system is a polyphase system in which the voltages are symmetrical.

3352* Balanced Polyphase System.—A balanced polyphase system is a polyphase system in which both the currents and voltages are symmetrical.

Loads

3404 Reactive Load.—A reactive load is a load in which the current lags behind or leads the voltage across the load.

(3324) A single-phase circuit is usually supplied through two wires. The currents in these two wires, counted outwards from the source, differ in phase by 180 degrees or a half cycle.

(3326) In practise the phases may vary several degrees from the specified angle.

(3328) In practise the phases may vary several degrees from the specified angle.

(3330) In practise the phases may vary several degrees from the specified angle.

(3352) The term balanced polyphase system is applied also to a quarter-phase (or two-phase) system in which the voltages have the same wave form and r. m. s. value and in which the currents have the same wave form and r. m. s. value and differ in phase by ninety electrical degrees.

3406 Non-reactive Load.—A non-reactive load is a load in which the current is in phase with the voltage across the load. (The term non-inductive load is sometimes used for non-reactive load.)

3408 Inductive Load.—An inductive load is a reactive load in which the current lags behind the voltage across the load.

3410 Condensive Load.—A condensive load is a reactive load in which the current leads the voltage across the load.

3414* Balanced Polyphase Load.—A balanced polyphase load is a load to which symmetrical currents are supplied when it is connected to a system having symmetrical voltages.

3424 Connected Load.—The connected load on any system, or part of a system, is the combined continuous rating of all the receiving apparatus on consumers' premises which is connected to the system, or part of the system under consideration.

3434 Peak Power.—The peak power is the average power during a time interval of specified duration occurring within a given period of time, that interval being selected during which the average power is greatest.

3438 Load Factor.—The load factor is the ratio of the average power to the peak power.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

3442 Plant Factor.—The plant factor is the ratio of the average load to the rated capacity of the power plant; *i. e.*, to the aggregate ratings of the generators.

3454 Demand of an Installation or System.—The demand of an installation or system is the load which is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time. Demand is expressed in kilowatts, kilovolt-amperes, amperes, or other suitable units.

3458 Maximum Demand.—The maximum demand of an installation or system is the greatest of all the demands which have occurred during a given period. It is determined by measurement, according to specifications, over a prescribed time interval.

3460 Demand Factor.—The demand factor of any system or part of a system, is the ratio of the maximum demand of the system, or part of a system, to the total connected load of the system, or of the part of the system under consideration.

3464 Diversity Factor.—The diversity factor of any system, or part of a system, is the ratio of the sum of the maximum power demands

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(3414) The term balanced polyphase load is applied also to a load to which are supplied two currents having the same wave form and r. m. s. value and differing in phase by ninety electrical degrees when it is connected to a quarter-phase (or two-phase) system having voltages of the same wave form and r. m. s. value.

of the subdivisions of the system, or part of a system, to the maximum demand of the whole system, or part of the system under consideration, measured at the point of supply.

Machinery and Apparatus

3504 Capacity (or Properly, Capability).—The word "capacity" is frequently used in the general sense of "capability". It is also used in a more exact sense to denote the load which, when carried by a machine, apparatus, or device will, under specified conditions of test, cause it to reach *any one of its physical limitations*, such for example, as operating temperature or ability to maintain required voltage.

Capacity should be distinguished from rating. On account of the different senses in which it has been employed (see **§3508**), capacity is less used than it formerly was, rating being more useful commercially.

3508* Rating.—A rating of a machine, apparatus or device is an arbitrary designation of an operating limit.

(The rating of a machine is the output marked on the rating plate, and shall be based on, but shall not exceed the maximum load which can be taken from the machine under prescribed conditions of test. This is also called the rated output. *Maximum possible rating obviously corresponds with capability as defined in §3504*).

3514 Efficiency.—The efficiency of an electric machine or apparatus is the ratio of its useful output to its total input. Unless otherwise specified the above output and input shall mean the power output and the power input respectively.

3524* Conventional Efficiency.—The conventional efficiency of an electric machine or apparatus is the ratio of the output to the sum of the output and the losses, or of the input minus the losses to the input, when, in either case conventional values are assigned to one or more of these losses.

3534 Plant, or System, Efficiency.—Plant, or system, efficiency is the ratio of the energy delivered from the plant or system to the energy received by it in a specified period of time. In calculating plant, or system, efficiency it may be desirable to calculate the losses in each individual machine, or part of the system, at the actual temperature of that machine, or part, during the specified interval. These losses may be appreciably different from the losses at 75° C., which latter shall be the standard temperature of reference for all efficiency guarantees. This definition is not applicable to storage batteries. See **§2332.**

3535 Regulation.—The regulation of a machine in regard to some characteristic quantity (such as terminal voltage or speed) is

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(3508) The term maximum load does not refer to loads applied solely for mechanical commutation, or similar tests.

(3524) The need for assigning conventional values to certain losses, arises from the fact that some of the losses in electric machinery are practically indeterminable, and must, in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

the change in that quantity occurring between any two loads. Unless otherwise specified, the two loads considered shall be zero load and rated load, and at the temperature attained under normal operation. The regulation may be expressed by stating the numerical values of the quantity at the two loads, or it may be expressed by the "percentage regulation", which is the percentage ratio of the change in the quantity occurring between the two loads, to the value of the quantity at either one or the other load, taken as the normal value. The normal value may be either the no-load value, as the no-load speed of induction motors; or it may be the rated-load value, as in the voltage of a-c. generators.

It is assumed that all parts of the machine affecting the regulation maintain constant temperature between the two loads, and where the influence of temperature is of consequence a reference temperature of 75° C. shall be considered as standard.

TABLE 301.

3604* SYMBOLS AND ABBREVIATIONS

Name of Quantity.	Symbol for the Quantity.	Unit.	Abbreviation for the Unit.
Acceleration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
Admittance	Y, y	mho	....
Angular velocity	ω	radian per second	....
Capacitance (Electrostatic capacity)	C	farad	....
Conductance	g	mho	....
Conductivity	γ	*mho per centimeter	mho per cm.
Current	I, i	ampere	....
Dielectric constant	K	....	....
Efficiency	η	per cent	....
Electromotive force, abbreviated e. m. f.	E, e	volt	....
Electrostatic field intensity	F	....	....
Electrostatic flux	Ψ	....	....
Electrostatic flux density	D	....	....
Energy, in general	U or W	joule, watt-hour	....
Frequency	f	cycle per second	~
Impedance	Z, z	ohm	....
Inductance (or coefficient of self induction)	L	henry	....
Intensity of magnetization	J	....	....
Length	l	centimeter	cm.
Magnetic field intensity	H, $\mathcal{H}$	gilbert per centimeter or gauss*	gilbert per cm. ....
Magnetic flux	Φ, φ	maxwell	....
Magnetic flux density	B, $\mathcal{B}$	gauss	....

Magnetomotive force, abbreviated m. m. f.	$\mathcal{F}$	gilbert*	....
Mass	m	gram	g
Mutual Inductance (or coefficient of mutual induction)	M	henry	....
Number of conductors or turns	N	convolution or turn of wire	....
Permeability	$\mu = B/H$	....	
Phase displacement	θ, φ	degree or radian	° ....
Potential difference, abbreviated p. d.	V, v or E, e	volt	....
Power	P, p	watt	....
Quantity of electricity	Q, q	coulomb, ampere-hour	....
Reactance	X, x	ohm	....
Reluctance	$\mathcal{R}$	....	....
Resistance	R, r	ohm	....
Resistivity	ρ	* ohm-centimeter	ohm-cm.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980.665*	g_0	centimeter per second per second	cm. per sec. per sec.
Susceptance	b	mho	....
Susceptibility	$\kappa = J/H$	....	....
Temperature	θ	degree centigrade	°C
Time	t	second	sec.
Velocity of rotation	n	revolution per second	rev. per sec.
Voltage	E, e or V, v	volt	....

3608 Symbols for Maximum, Instantaneous and R. M. S. Values.—E_m, I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r. m. s. values (see §3218) and P for the average value of the power, or the active power. These distinctions are not necessary in dealing with direct-current circuits. In print, vector quantities should be represented by boldface capitals.

BIBLIOGRAPHY

Associazione Elettrotecnica Italiana: Simboli e Notazioni.
International Electrotechnical Commission: International Symbols.

(3604) The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric.

An aditional unit for magnetomotive force is the "ampere-turn", for flux the "line", for magnetic flux-density "maxwells per sq. in.".

The numerical values of resistivity and conductivity are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question,. but the correct names are as given, not ohms and mhos per cm. cube, as commonly stated

The value 980.665 for g_0 has been the accepted standard value for many years and was formerly considered to correspond accurately to 45° latitude and sea level. Later resiarches, however, have shown that the most reliable value for 45° and sea-level is slightly defferent; but this does not affect the standard value given above.

CHAPTER IV.

STANDARDS FOR ROTATING MACHINES (OTHER THAN RAILWAY MOTORS, RAILWAY SUBSTATION MACHINERY CARRYING TRACTION LOADS, AND AUTOMOBILE PROPULSION MACHINES).

The A. I. E. E. Standards for Rotating Machines are the General Standards shown in Chapters II and III and the Standards in other chapters which are applicable to the devices involved, together with the modifications and extensions given in this chapter.

DEFINITIONS

General.

Certain rules applying exclusively to railway machinery have, for convenience, been placed in Chapter V, with cross references in all cases in this chapter. The rules of Chapter IV apply to railway machinery except as they are modified by rules of Chapter V.

4000 **Classification of Electric Rotating Machinery.**—Rotating electric machinery may be classified in various ways, these classifications over-lapping or interlocking in considerable degree. *First,* Rotating electric machinery may be classified as Direct-Current and Alternating-Current; *Second,* according to the function of the machines; *e. g.,* Motors, Generators, Boosters, Motor-Generators, Dynamotors, Double-Current Generators, Converters and Phase Advancers; *Third,* according to construction or principle of operation; *e. g.,* Commutating, Synchronous, Induction, Unipolar, Rectifying. Obviously, some of these machines could be rationally included in either classification, *e. g.,* Motor-Generators and Rectifying Machines.

In the following, self-evident definitions have for the most part been omitted.

Functional Classification of Rotating Electric Machines.

4001 **Generator.**—A generator is a machine which transforms mechanical power into electric power.

4002 **Motor.**—A motor is a machine which transforms electric power into mechanical power.

4003 **Booster.**—A booster is a generator inserted in series in a circuit to change its voltage. A booster may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

4004 **Motor-Generator Set.**—A motor-generator set is a transforming device consisting of one or more motors mechanically coupled to one or more generators.

4005 **Dynamotor.**—A dynamotor is a transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

4006 **Direct-Current Compensator or Balancer.**—A direct current compensator or balancer is a machine which comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

4007 **Double-Current Generator.**—A double-current generator is a machine which supplies both direct and alternating currents from the same armature-winding.

4008 **Converter.**—A converter is a machine which employs mechanical rotation in changing electric energy from one form into another. There are several types of converters, as defined in §§ **4009** to **4013** below.

4009 **Direct-Current Converter.**—A direct-current converter is a machine which converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor-generator set or a dynamotor.

4010 **Synchronous Converter.**—A synchronous converter (sometimes called a rotary converter) is a machine which converts from an alternating to a direct current, or vice-versa. It is a synchronous machine with a single closed-coil armature winding, a commutator and slip rings.

4011 **Cascade Converter.**—A cascade converter (also called a motor converter) is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i. e.*, a synchronous converter concatenated with an induction motor.

4012 **Frequency Converter.**—A frequency converter is a machine which converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

4013 **Rotary Phase-Converter.**—A rotary phase-converter is a machine which converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

4014 **Phase Advancer.**—A phase advancer is a machine which supplies reactive volt-amperes to the system to which it is connected. Phase advancers may be either synchronous or asynchronous.

4015 **Synchronous Condenser or Synchronous Phase Advancer.**—A synchronous condenser or synchronous phase advancer is a synchronous machine, running either idle or with load, the field excitation of which may be varied so as to modify the power factor of the system, or through such modification to influence the load voltage.

Constructional Classification of Rotating Electric Machines

4016 Direct-Current Commutating Machines.—A direct current commutating machine comprises a magnetic field of constant polarity, an armature, and a commutator connected therewith. Specific types of direct-current commutating machines are: Direct-Current Generators; Direct-Current Motors; Direct-Current Boosters; Direct-Current Motor-Generator Sets and Dynamotors; Direct-Current Compensators or Balancers; and Arc Machines.

4017 Alternating-Current Commutating Machine.—An alternating current commutating machine comprises a magnetic field of alternating polarity, an armature, and commutator connected therewith. See §§ **4071** to **4074**.

4018 Synchronous Commutating Machine.—Synchronous commutating machines include synchronous converters, cascade-converters, and double-current generators.

4019 Synchronous Machine.—A synchronous machine comprises a constant magnetic field and an armature receiving or delivering alternating-currents in synchronism with the motion of the machine; *i. e.*, having a frequency strictly proportional to the speed of the machine. Specific types of synchronous machines are defined in §§ **4020** to **4023** below.

4020 Alternator.—An alternator is a synchronous alternating-current generator, either single-phase or polyphase.

4021 Polyphase Alternator.—A polyphase alternator is a polyphase synchronous alternating-current generator, as distinguished from a single-phase alternator.

4022 Inductor Alternator.—An inductor alternator is an alternator in which both field and armature windings are stationary, and in which masses of iron or inductors, by moving past the coils, alter the magnetic flux through them. It may be either single-phase or polyphase.

4023 Synchronous Motor.—A synchronous motor is a machine structurally identical with an alternator, but operated as a motor.

4024 Induction Machine.—An induction machine is a machine wherein primary and secondary windings rotate with respect to each other; *e. g.*, induction motors, induction generators, certain types of frequency converters and certain types of rotary phase-converters.

4025 Induction Motor.—An induction motor is an alternating-current motor, either single-phase or polyphase, comprising independent primary and secondary windings, one of which, usually the secondary, is on the rotating member. The secondary winding receives power from the primary by electromagnetic induction.

4026 **Induction Generator.**—An induction generator is a machine structurally identical with an induction motor, but driven above synchronous speed as an alternating-current generator.

4027 **Engine Type Generator.**—An engine type generator is one coupled to an engine in such a way that it cannot be run independently of the engine.

4028 **Unipolar or Acyclic Machine.**—A unipolar, or acyclic machine, is a direct-current machine, in which the voltage generated in the active conductors maintains the same direction with respect to those conductors.

Speed Classification of Motors.

4035 **Constant-Speed Motor.**—A constant speed motor is one whose speed is either constant or does not materially vary; such as a synchronous motor, an induction motor with small slip, and an ordinary direct-current shunt motor.

4036 **Multispeed Motor (or Change Speed Motor).**—A multispeed motor is a motor which can be operated at any one of several distinct speeds (these speeds being practically independent of the load), but which cannot be operated at intermediate speeds.

4037 **Adjustable-Speed Motor.**—An adjustable-speed motor is one in which the speed can be varied gradually over a considerable range, but when once adjusted remains practically unaffected by the load; such as a shunt motor designed for a considerable range of speed variation.

4038 **Base Speed of an Adjustable-Speed Motor.**—The base-speed of an adjustable-speed motor is that speed of the motor obtained with full field under full load with no resistor in the armature circuit.

4039 **Varying-Speed Motor.**—A varying speed motor is one whose speed varies with the load, ordinarily decreasing when the load increases; such as a series motor, a compound-wound motor, and a series-shunt motor. As a subclass of varying-speed motors, may be cited adjustable varying-speed motors, or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted, varies with the load; *e. g.*, compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

Classification of Rotating Electric Machines Relative to their Degree of Enclosure.

4041 **Open Machine.**—An open machine is of either the pedestal-bearing or end bracket type where there is no restriction to ventilation, other than that necessitated by good mechanical construction.

4042 **Protected Machine.**—A protected machine is one in which the armature, field coils, and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

4043 **Enclosed Ventilated Machine.**—An enclosed ventilated (or semi-enclosed) machine is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding ½ square inch (3.2 sq. cm.) in area. See §4316.

4044 **Totally Enclosed Machine.**—A totally enclosed machine is one so enclosed as to prevent circulation of air between the inside and the outside of the case, but not sufficiently to be termed air-tight.

4045 **Separately Ventilated Machine.**—A separately ventilated machine has its ventilating air supplied by an independent fan or blower external to the machine.

4046 **Self-Ventilated Machine.**—A self-ventilated machine differs from a separately ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a pipe attached to the machine, this should be so stated.

4047 **Water-Cooled Machine.**—A water-cooled machine is one which mainly depends on water circulation for the removal of its heat.

4048 **Drip-Proof Machine.**—A drip-proof machine is one so protected as to exclude falling moisture or dirt. A drip proof machine may be either open or semi-enclosed, if it is provided with suitable protection integral with the machine, or so enclosed as to exclude effectively falling solid or liquid material.

4051 **Explosion-Proof Machine (or Flame-Proof Machine).**—An explosion-proof machine is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

4052 **Machine with Explosion-Proof Slip-Ring Enclosure.**—A machine in which the slip rings and brushes alone are included within an explosion-proof case should not be described as an explosion-proof machine, but as a machine with explosion-proof slip-ring enclosure.

Classification of Alternating-Current Commutator Motors.

(An alternating current commutator motor may be classified under more than one of the following groups.)

Classification by Phases of Energy Supply.

4061 **Single-Phase Commutator Motor.**—A single-phase commutator motor is one that receives the whole of its energy from only one phase of an alternating-current supply system, without requiring external phase-converting apparatus.

4062 **Polyphase Commutator Motor.**—A polyphase commutator motor is one that receives its energy from a plurality of phases of an alternating-current supply system, or from a single-phase system through phase-converting apparatus external to the motor.

Classification by Speed Characteristics.

4063 **General.**—For convenience, alternating-current commutator motors may be classified with reference to their speed characteristics as (1) constant-speed motors, (2) multi-speed motors, (3) adjustable-speed motors, and (4) varying-speed motors. Definitions of these terms as given in §§ **4035** to **4039** for motors in general, should be adopted for alternating-current commutator motors, in so far as they are applicable.

Classification by Excitation.

4064 **Stator-Excited Commutator Motor.**—A stator-excited commutator motor is one in which the torque-producing field is due to a current in a winding located on the stator. By the "torque producing field" is meant that component of the magnetic field which, with the in-phase component of the current, produces the torque of the motor.

4065 **Rotor-Excited Commutator Motor.**—A rotor-excited commutator motor is one in which the torque-producing field is due to a current in a winding located on the rotor. See **§4064.**

4066 **Stator- and Rotor-Excited Commutator Motor.**—A stator- and rotor-excited commutator motor is one in which the torque producing field is due to currents in windings located on the stator and on the rotor. See **§4064.**

4067* **Constant-Field Commutator Motor.**—A constant-field commutator motor is one in which the torque-producing field remains practically constant, independent of the load. See **§4064.**

4068* **Varying-Field Commutator Motor.**—A varying-field commutator motor is one in which the torque-producing field varies in some proportion with the current in the armature (which latter is generally the rotor.) See **§4064.**

Classification by Neutralization and Compensation.

4069 **Neutralized Commutator Motor.**—A neutralized commutator motor is one in which use is made of a winding for producing a magnetizing force which at each instant and at each point in the air-gap under the pole face is practically equal and opposite to the magnetizing force due to the armature current.

4070 **Compensated Commutator Motor.**—A compensated commutator motor is one in which means, other than a neutralizing winding, are provided within the motor for improving the power-factor.

Classification by Energy Reception

4071 **Conduction Commutator Motor.**—A conduction commutator motor is one in which the working energy is supplied to only one

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(4067) Alternating-current commutator motors of this class will in general have load-speed characteristics similar to those of the direct-current shunt motor, but not all alternating-current commutator motors having such load-speed characteristics are constant-field machines.

(4068) Such a motor will in general have load-speed characteristics similar to those of the direct-current series motor.

of the members, and is conveyed to it by conduction. By "working energy" is meant the energy which is directly converted into mechanical energy, and which includes the shaft energy output plus core losses and friction.

4072 **Transformer Commutator Motor.**—A transformer commutator motor is one in which the working energy is transmitted from one member to the other by transformer action.

A motor in which the energy required by its armature (which is generally the rotor) is conveyed to it by electromagnetic induction or transformer action, may properly be referred to either as an "induction motor," or as a "transformer motor". Although it is equally applicable to a motor having a commutator, the term "induction motor" is usually applied to a motor without a commutator. The term "transformer commutator motor" is therefore recommended for use with motors of the induction, or transformer type, having commutators.

4073 **Transformer-Conduction Commutator Motor.**—A transformer-conduction commutator motor is one in which the energy required by its armature (which is generally the rotor) is conveyed to it by both conduction and electromagnetic induction.

4074 **Repulsion Commutator Motor.**—A repulsion commutator motor is a transformer commutator motor in which use is made of brushes for short-circuiting a number of coils of the commutated winding.

Miscellaneous Definitions

4085 **Saturation Factor.**—The saturation factor of a machine is the ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

4086 **Percentage Saturation.**—The percentage saturation of a machine at any excitation may be found from its saturation curve (generated voltage as ordinates, against excitation as abscissas), by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in per cent, is the percentage saturation, and is independent of the scales selected for excitation and voltage. This ratio as a fraction, is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity; or, if f be the saturation factor and p the percentage saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

4088* **Variation in Alternators.**—The variation in alternators, or alternating-current circuits in general is the maximum angular displacement, expressed in electrical degrees (see §3222) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover. See §§ **14010** and **14011.**

4089 **Per cent Resistance Drop.**—The per cent resistance drop in an electric machine is the ratio of the internal resistance drop at 75° C. to the terminal voltage expressed in per cent.

Unless otherwise specified this per cent drop shall be referred to rated load and rated power factor.

The per cent resistance drop in an induction motor is expressed in terms of the internally induced electromotive force.

4090 **Per cent Reactance Drop.**—The per cent reactance drop in an electric machine or apparatus is the ratio of the internal reactance drop to the terminal voltage, expressed in per cent.

Unless otherwise specified this per cent drop shall be referred to rated load and rated power factor.

The per cent reactance drop in an induction motor is expressed in terms of the internally induced electromotive force.

4091 **Per cent Impedance Drop.**—The per cent impedance drop in an electric machine is the ratio of the internal impedance drop at 75° C. to the terminal voltage, expressed in per cent.

Unless otherwise specified this per cent drop shall be referred to rated load and rated power factor.

The per cent impedance drop in an induction motor is expressed in terms of the internally induced electromotive force.

4092 **Magnetic Degree.**—A magnetic degree is the 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One *mechanical degree* is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

4094 **Regulation of D-C. Generators.**—The regulation of a d-c. generator is usually stated by giving the numerical values of the voltage at no load and rated load, and in some cases it is advisable to state regulation at intermediate loads. The regulation of d-c. generators refers to changes in voltage corresponding to gradual changes in load, and does not relate to the comparatively large momentary fluctuations in voltage that frequently accompany instantaneous changes in load.

4095 **Regulation of Constant-Potential A-C. Generators.**—In constant-potential a-c. generators, the regulation is the rise in voltage (when the specified load at specified power factor is reduced to zero) expressed in per cent of normal rated-load voltage.

4096 **Regulation of Constant-Current Machines.**—In constant-current machines the regulation is the ratio of the maximum difference of

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(4088) If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct-connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

current from the rated-load value (occurring in the range from rated-load to short-circuit, or minimum limit of operation), to the rated-load current.

4097 **Regulation of Constant-Speed Motors.**—In constant-speed direct-current motors and induction motors, the regulation is the ratio of the difference between full-load and no-load speeds to the no-load speed.

4098 **Regulation of Converters, Dynamotors, Motor-Generators and Frequency Converters.**—In converters, dynamotors, motor-generators, and frequency converters, the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal voltage at rated load.

OPERATION

Temperature Limits

4105 **Exceptions to General Temperature Limits Given in Chapter II.**—

(a) Railway Motors: See §§**5202** and **5101.**

(b) Automobile Propulsion Machines: See §**5205.**

(c) Railway Substation Machines: See §§**5201** and **5102.**

(d) Squirrel Cage and Amortisseur Windings. The temperature may attain any value such as will not occasion mechanical injury to the machine.

(e) Field Control Railway Motors: See §**5204.**

4106 **Collector Rings.**—The observable temperature of collector rings shall not be permitted to exceed the values set forth in §**2231** (c) for the insulations employed either in the collector rings themselves or in adjacent insulations whose life would be affected by the heat from the collector rings.

4107 **Commutators.**—The observable temperature shall in no case be permitted to exceed the values given in §**2231** (c) for the insulation employed either in the commutator or in an insulation whose life would be affected by the heat of the commutator. These temperature limits are intended only to protect the insulation of the commutator and of the adjacent parts and are not intended as a criterion of successful commutation.

4108 **Cores.**—The observable temperature of those parts of the iron core in contact with insulating materials shall in no case be permitted to exceed the values given in §§**2231** (c) for the insulation employed.

4109 **Other Parts, (Such as Brush-Holders, Brushes, Bearings, Pole-Tips, Cores, etc.)**—All parts of electrical machinery other than those whose temperature affects the temperature of the insulating material may be operated at such temperatures as shall not be injurious in any other respect.

4110 **Maximum Temperature Rise in Service.**—Whatever may be the ambient temperature when the machine is in service, the limits of the maximum observable temperature or of temperature rise specified in the rules should not be exceeded in service; for, if the maximum temperature be exceeded, the insulation may be endangered, and if the rise be exceeded, the excess load may lead to injury, by exceeding limits other than those of temperature; such as commutation, stalling load and mechanical strength. For similar reasons, loads in excess of the rating should not be taken from a machine.

RATING

Units in Which Rating Shall be Expressed

4220 **Rating of D-C. Generators.**—The rating of direct-current generators, shall be expressed in kilowatts (kw.) available at the terminals at a specified voltage.

4221 **Rating of Alternators.**—The rating of alternators shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified voltage and power factor.

4222* **Rating of Motors.**—It is strongly recommended that the rating of motors shall be expressed in kilowatts (kw.) available at the shaft. (An exception to this rule is made in the case of railway motors, which, for some purposes, are also rated by their *input*. See §5208.

4223 **Rating of Auxiliary Machinery.**—Auxiliary machinery, such as regulators, balancer sets, synchronous-condensers, etc., shall have their ratings appropriately expressed. It is also essential to specify the voltage (and frequency, if a-c.), of the circuits on which the machinery may appropriately be used.

Limitations other than Temperature Rise

4250* **Mechanical Limitations.**—*(a) *General*: All types of rotating machines shall be so constructed that they will safely withstand an over-speed of 25 per cent, except in the case of steam turbines, which, when equipped with emergency governors, shall be constructed to withstand 20 per cent over-speed.

(b) *Generators*: Water-wheel generators shall be constructed for the maximum runaway speed which can be attained by the combined unit.

(c) *Motors*: Motors for continuous service shall, except when otherwise specified, be required to develop running torque at least 175 per cent of that corresponding to the running torque at their rated load, without stalling. Obviously, duty-cycle machines must carry their peak loads without stalling.

(4222) Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practise of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

Kw.————————Approx. equiv. h.p.————————

For the purposes of these rules the horsepower shall be taken as 746.0 watts.

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.

One kilowatt is equal to 102 kilogrammeters per second.

(4250-a) In the case of series motors, it is impracticable to specify percentage values or the guaranteed overspeed, on account of the varying service conditions.

4251 Commutation Limitations.—(*a*) *Continuously Rated Machines*: Continuously rated machines shall be required to commutate successfully momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation. Successful commutation is such that neither brushes nor commutator are injured by the test. See §§**2220** and **5203**.

(*b*) *Machines for Duty-Cycle Operation*: Machines for duty-cycle operation with widely fluctuating loads, shall commutate successfully under their specified operating conditions. See §§**2222** and **2223**.

4252 Limitations of Stability.—Continuously rated machines shall be required to carry momentary loads of 150 per cent of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation.

In the case of direct-connected generators, this clause is not to be interpreted as requiring the prime mover to drive the generator at this overload.

TESTS

Ambient Temperature

4300 Measurement of the Ambient Temperature During Tests of Machines.—(See §**2300**) (a) *Machines Cooled by Forced Draught*: In the testing of rotating machines, cooled by forced draught, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts and a weight of one to the surrounding room air. See §**2300** Note.

(*b*) *Machines Below Floor Line*: Where machines are partly below the floor line in pits, the temperature of the rotor shall be referred to a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the rotor in and above the pit. Parts of the stator constantly in the pit shall be referred to the ambient temperature in the pit.

Machine Temperatures

4316 Machines with Small Ventilating Apertures.—Machines having ventilating openings smaller than 0.02 sq. in. (0.13 sq. cm.) in area, when intended to be operated in locations or under conditions where the openings are liable to become clogged, should be considered as totally enclosed machines and tested as such with openings closed, and in all cases the rating on this basis should be indicated on the rating plate.

4319 Exception to Temperature Limits Used in Method 1.—In the case of enclosed motors and generators, the limits of the observable temperature rise shall be 5°C. higher than allowed by the general rule. This rule does not apply to those types of machines defined in §§ **4043**, **4045** and **4046**.

4320 Exception to Temperature Limits Used in Method 2.—In the case of enclosed motors and generators, the limits of the observable temperature rise shall be 5°C. higher than allowed by the general rule. This rule does not apply to those types of machines defined in §§. **4043**, **4045** and **4046**.

4321 Method of Temperature Measurement Used in Determining Temperature of Stators of Machines.—Method 3 should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) or over. It should also be applied to all machines of 5000 volts or more, if rated over 500 kv-a., regardless of core width.

Efficiency

4334* Classification of Losses.—Losses are classified as shown in Table 401.

4335 Losses to be Considered in Machines.—Conventional efficiencies shall be based upon the losses listed in Table 402, and these losses shall be measured as specified in §§**4336-4342** inclusive.

TABLE 401

Classification of Losses in Machinery

Accurately Measurable	Approximately Measurable or Determinable	Indeterminable
No-load core losses including eddy-current losses in conductors at no-load	Brush Friction loss	Iron loss due to flux distortion
Load I^2R losses in windings No-load I^2R losses in windings	Brush-contact loss	Eddy-current losses in conductors due to transverse fluxes occasioned by the load currents
	Losses due to windage and to bearing friction	Eddy-current losses in conductors due to tooth saturation resulting from distortion of the main flux
		Tooth-frequency losses due to flux distortion under load
	Dielectric losses	Short-circuit loss of commutation

(4334) The losses in constant-potential machinery, either of the stationary type, or of the constant-speed rotary type, are of two classes; namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also I^2R losses in any shunt windings. The latter include I^2R

4336 **$I^2 R$ Loss.**—(*a*) *General*: The I^2R loss shall be based upon the current and the measured resistance.

(*b*) *Polyphase Induction-Motor Rotor*: The I^2R loss in the rotors of polyphase induction motors should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2 R \text{ loss} = \frac{\text{output} \times \text{slip}}{1 - \text{slip}}$$

TABLE 402

Losses in Rotating Electric Machines

(References are to Sections)

	$I^2 R$ Loss Windings	Friction and Windage	Brush Friction	Core Loss	Brush Contact $I^2 R$ Loss	Stray Load Losses
D-C commutating machines (Note 1)	4336(a)	4337(a)	4338	4339	4341 5341	Note 5
A-C commutating machines (Note 1)	4336(a)	4337(a)	4338	4339	4341	Note 5 5339
Railway motors	4336(a)	5337 5338	5338 5339	5339	4341	Note 5 5339
Synchronous motors and generators (Note 4)	4336(a)	4337(a)	4338 Note 3	5339 4339	4341 Note 3	4342(b)
Synchronous converters	4336(c)	4337(a)	4338	4339(a) 4339(b)		Note 5
Induction machines	4336(b)	4337(a)	4338	4339(a) 4339(c)	4341 Note 2	4342(b)

Notes:—(1) Except railway motors.

(2) When there are collector rings.

(3) Brush friction and brush contact losses are negligible except in the case of revolving armature machines.

(4) For the booster type of synchronous converter, where the booster forms an integral part of the unit, its losses shall be included in the total converter losses in estimating the efficiency.

(5) These losses, while usually of low magnitude, are erratic, and the Institute is not at this time prepared to make recommendations for approximating them.

losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no load, deducting any series $I^2 R$ losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.

(4335) This simple method of determining the losses and hence the efficiency is only approximate, since the losses which are assumed to be constant do actually vary to some extent with the load, and also becaue the actual loss in the copper windings is sometimes appreciably greater than the calculated $I^2 R$ loss. The difference between the approximate losses, as above determined, and the actual losses, is termed "stray load losses." These latter are due to distortions in electric or magnetic fluxes from their no-load distributions or values, brought about by the load current. They are usually only approximately measurable, or may be indeterminable, but certain of them reach values in various kinds of machinery, which require that they should be taken into account.

Dielectric losses are usually negligible.

The stray load losses include the items in the column of Table 401 headed "Indeterminable" but do not include the increased core losses due to increased excitation for compensating internal drop under load.

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor I^2R loss shall be determined by direct resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to three-phase rotors. For rotors wound for two phase, use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 kw. or larger. The factor K usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

(*c*) *Synchronous Converter*: The I^2R losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using suitable factors.

4337 Bearing Friction and Windage.—(*a*) *General*: Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have its brushes removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

(*b*) *Induction Motors*: The bearing friction and windage of induction motors may be measured by running motors free at the lowest voltage at which they will rotate continuously at approximately rated speed; the watts input, minus I^2R loss, under these conditions being taken as the friction and windage.

(*c*) *Engine-Type Generators*: In the case of engine-type generators, (See **§4027**) the windage and bearing friction loss is ordinarily very small, amounting to a fraction of one per cent of the output. This loss shall be neglected owing to its small value and the difficulty of measuring it.

(*d*) *D. C. Railway Motors*: See **§5337.**

4338 Brush Friction of Commutator and Collector Rings.—(*a*) *General*: Drive the machine from an independent motor, the output of which shall be suitably determined. The brushes shall be in contact with the commutator or collector rings, but the machine shall not be excited. The difference between the output obtained in the test in **§4337** and this output shall be taken as the brush friction. The surfaces of the commutator and brushes should be smooth and glazed from running when this test is made.

(*b*) *D. C. Railway Motors*: See **§5338.**

4339 Core Losses.—(*a*) *General*: Drive the machine from an independent motor, the output of which shall be suitably determined. The brushes shall be in contact, and the machine shall be excited, so as to produce at the terminals a voltage corresponding to the calculated internal voltage for the load under consideration. The difference between the output obtained by this test and that obtained by test under **§4338** (*a*) shall be taken as the core loss.

(*b*) *Synchronous Machines*: The internal voltage of synchronous machines shall be determined by correcting the terminal voltage for the resistance drop only.

(*c*) *Induction Motors*: The core loss of an induction motor may be determined by measuring the watts input to the motor when running free at rated voltage and frequency and subtracting therefrom the no-load copper loss, bearing friction and windage.

(*d*) *D. C. Railway Motors*: See **§5339.**

4341* Brush-Contact $I^2 R$ Loss.—(*a*) *General*: One volt drop per brush shall be considered as the Institute standard drop corresponding to the I^2R brush-contact loss, for carbon and graphite brushes with pigtails attached. One and one-half volts per brush shall be allowed where pigtails are not attached. Metal-graphite brushes shall be considered as special.

(*b*) *Automobile Motors*: See **§5341.**

4342* Stray Load-Losses.—(*a*) *Synchronous Machines*: These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load-losses shall be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the Institute is not yet prepared to specify a method for measuring them.

(*b*) *Induction Machines*: These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, measure the power input to the stator with different values of current at the rated frequency. The curve plotted with these values gives the combined I^2R and stray load-losses due to eddy-currents in the stator copper. Deduct the I^2R loss determined from the resistance, and the difference will represent the stray load-losses corresponding to the various currents. While this method is not accurate for some types of motors it usually represents a sufficiently good approximation.

(4341) The brush-contact I^2 *R* loss depends largely upon the material of which the brush is composed.

As indicating the range of variation the following table will be of interest:

TABLE 403

Brush-Contact Drop

Grade of brush	Volts drop across one brush-contact (Average of positive and negative brushes)
Hard carbon..........................	1.1
Soft carbon..........................	0.9
Graphite..........................	0.5 to 0.8
Metal-graphite types..............	0.15 to 0.5 (The former for largest proportion of metal)

(4342) Values of the indeterminate losses may also be obtained by brake or other direct test and used in estimating actual efficiencies of similar machines by the separate-loss method.

4343 Miscellaneous Losses.—(*a*) *Field-Rheostat Losses*: Field-Rheostat losses shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

(*b*) *Ventilating Blower*: When a blower is supplied as part of a machine set, the power required to drive it shall be charged against the complete unit, but not against the machine alone.

(*c*) *Other Auxiliary Apparatus*: Auxiliary apparatus, such as a separate exciter for a generator or motor, shall have its losses charged against the plant of which the generator and exciter are a part, and not against the generator. An exception should be noted in the case of turbo-generator sets with direct-connected exciters, in which case the losses in the exciter shall be charged against the generator. The actual energy of excitation and the field-rheostat losses, if any shall be charged against the generator. See **§4343** (*a*).

Wave Shape

4351 Deviation Factor of a Wave.—The deviation factor of the open circuit terminal voltage wave of synchronous machines shall not exceed ten per cent unless otherwise specified. See **§3274.**

4352* Telephone Interference Factor of a Wave. (For trial only.) (See **§3278.**)—(*a*) *Conditions of Test.* The weighting of the sine wave components of different frequencies shall be as given in Fig. 4—1.

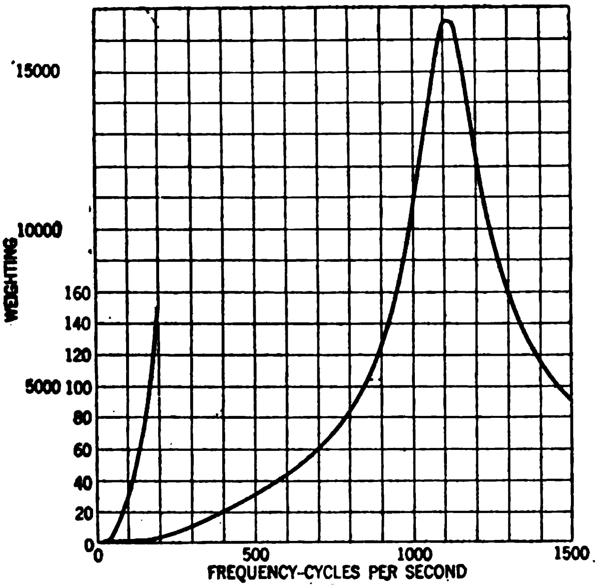
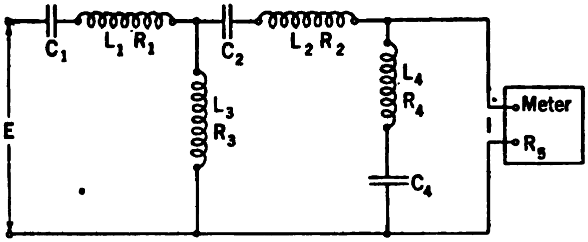


FIG 4-1

The telephone interference factor of a voltage wave, corresponding to this weighting, may be measured by the use of the network shown in Fig. 4—2.



Network Constants

$C_1 = 0.9$ mf.
$C_2 = 0.9$ "
$C_4 = 7.5$ "
±0.5%

$L_1 = 0.023$ henry
$L_2 = 0.0205$ "
$L_3 = 0.068$ "
$L_4 = 0.019$ "
±0.5%

$R_1 = 5$ ohms ±2%
$R_2 = 12$ " ±2%
$R_3 = 73$ " ±1%
$R_4 = 22.5$ " ±2%
$R_5 = 43$ " ±1%

FIG. 4-2

With this network the telephone interference factor of a voltage wave is the ratio of the current I in micro-amperes in the meter branch of the network to the voltage E applied to the external terminals of the network. The measurement may be made on the low tension side of a potential transformer. A sensitive vacuum thermocouple provided with a shunt, and a direct-current mil-ammeter have been found convenient for measuring the current.

(*b*) The appropriate limiting value of the telephone interference factor of a wave (See §3278), either for machines or for circuits, has not yet been determined, and cannot now be specified. The whole matter of interference, including reasonable requirements for both power and communication systems, is under discussion, in consultation with power, telephone, and other interests concerned.

Tests of Dielectric Strength

4358 Frequency of Test Voltage.—In d-c. machines, and in general commercial application of a-c. machines, the testing frequency of 60 cycles per second is recommended.

4361* Exceptions to Standard Test Voltage Given in Section 2356.

(*a*) *Field Windings of Alternating Current Generators*: Field windings of alternating current generators shall be tested with 10 times the exciter voltage, but in no case with less than 1500 volts nor more than 3500 volts.

*(b) *Field Windings of Synchronous Machines*: Field windings of synchronous machines including motors and converters which are to be started with alternating current are to be tested as follows:

When machines are to be started with field short circuited, the field windings shall be tested as specified in §4361 (a).

When machines are to be started with fields open circuited and

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(4361-*b*) Series field windings should be regarded as part of the armature circuit and tested as such.

sectionalized while starting, the field windings shall be tested with 5000 volts.

When machines are to be started with fields open circuited and connected all in series while starting, the windings shall be tested with 5000 volts for less than 275 volts excitation and 8000 volts for excitation of 275 volts to 750 volts.

*(c) *Phase-Wound Rotors of Induction Motor*: The secondary windings of wound rotors of induction motors shall be tested with twice their normal induced voltage, plus 1000 volts. When induction motors with phase-wound rotors are to be reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage plus 1000 volts.

(d) *Small Motors and Generators*: Small machines taking not over 660 watts or having an output not exceeding ½ h. p. (373 watts), such as fractional horse power motors, and intended solely for operation on supply circuits not exceeding 275 volts, shall be tested with 900 volts.

(e) *Alternating Current Machines Connected to Permanently Grounded Single-Phase Systems*: Alternating current machines connected to permanently grounded single-phase systems, for use on permanently grounded circuits operating at more than 300 volts shall be tested with 2.73 times the voltage of the circuit to ground, plus 1000 volts. This does not refer to three-phase machines with grounded star neutral.

*(f) *Machines for Use on Circuits of* 25 *Volts or Lower*: Machines for use on circuits of 25 volts or lower, such as bell ringing apparatus, electric machines used in automobiles, machines used on low voltage battery circuits, etc., shall be tested with 500 volts.

Regulation

4390 Conditions for Tests of Regulation (See **§2390**).—(*a*) *Power Factor*: In alternating current generators the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is, to a load in which the current is in phase with the e. m. f. at the terminals of the machine.

(*b*) *Excitation*: In communtating machines, rectifying machines and synchronous machines, the regulation shall be determined under such conditions as to maintain the field adjustment constant at a value which gives rated-load voltage at rated-load current. These conditions are as follows:

In the case of separately excited fields: constant excitation.

In the case of shunt machines: constant resistance in the shunt-field circuit.

In the case of series or compound machines: constant resistance shunting the series field windings.

4394* Tests and Computation of Regulation of A-C. Generators.—(a) *Methods Available:* The regulation of alternating-current gen-

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(4361-c) By normal induced voltage is here meant the voltage between slip rings on open circuit at standstill with normal voltage impressed on the primary.

(4361-*f*) The present National Electrical Code limit for a single outlet is 660 watts.

erators may be determined by any one of the three following methods, which are given in the order of preference:

(b) *Method I. By Loading:* The regulation can be measured directly, by loading the generator at the specified output and power factor, then reducing the load to zero, and measuring the terminal voltage, with speed and excitation adjusted to the same values as before the change. This method is not generally applicable for shop tests, particularly on large generators and it becomes necessary to determine the regulation from such other tests as can be readily made.

*(c) *Method II. From Test Curves:* This method consists in computing the regulation from experimental data of the open-circuit saturation curves and the zero-power-factor saturation curve. The latter curve, or one approximating very closely to it, can be obtained by over-exciting the generator while carrying

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(4394-c) Method II for deducing the load saturation curve, at any assigned power factor, from no-load and zero power-factor saturation curves obtained by test, must be regarded as empirical. Its value depends upon the fact that experience has demonstrated the reasonable correctness of the results obtained by it.

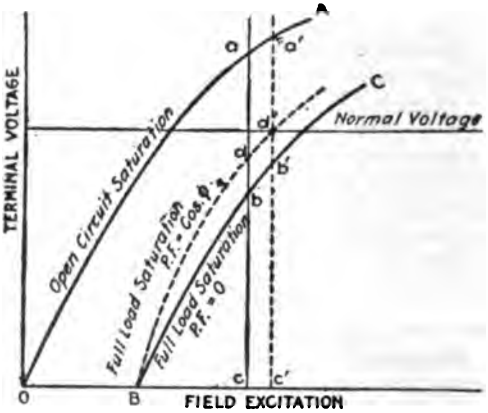

FIG- 4-3

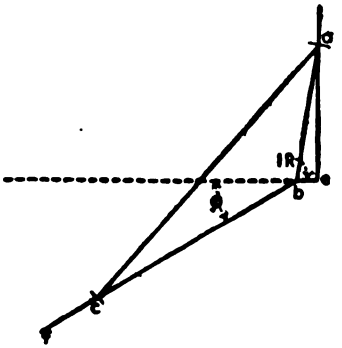

FIG. 4-4

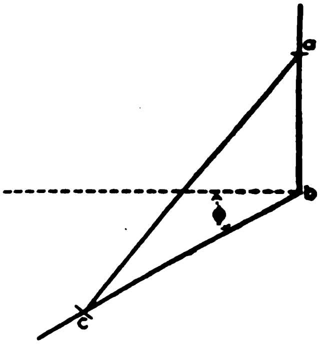

FIG. 4-5

a load of idle-running under-excited synchronous motors. The power factor under these conditions is very low and the load saturation curve approximates very closely the zero power-factor saturation curve. From this curve and the open circuit curve, points for the load saturation curve for any specified power factor can be obtained by means of vector diagrams.

*(d) *Method III. From Estimated Zero Power Factor Curve* Where it is not possible to obtain by test a zero power factor curve as in Method II this curve can be estimated closely from open-

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To apply method II, it is necessary to obtain from test the open circuit saturation curve Fig. 4-3, and the load saturation curve $B\,C$ at zero power factor and rated-load current. At any given excitation $O\,c$, the voltage that would be induced on open circuit is $c\,a$, the terminal voltage at zero power factor is $c\,b$ and the apparent internal drop is $a\,b$. The terminal voltage $c\,d$ at any other power factor can then be found by drawing an e.m.f. diagram as in Fig. 4-4. where ϕ is an angle such that cos ϕ is the power factor of the load, $b\,e$ the resistance drop ($I\,R$) in the stator winding, $b\,a$ the total internal drop and $a\,c$ the total induced voltage; $b\,a$ and $a\,c$ being laid off to correspond with the values obtained from Fig. 4-3.

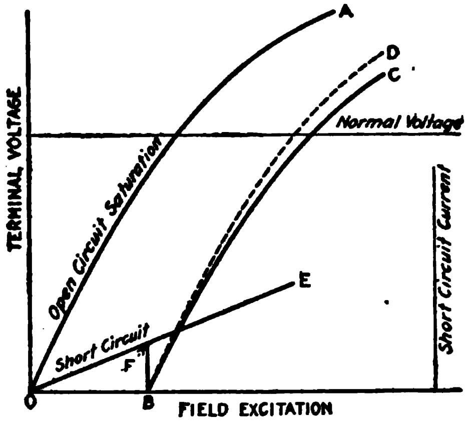

FIG. 4-6

The terminal voltage at power factor cos ϕ is then $c\,b$ Fig. 4-4, which when laid off in Fig. 4 3 gives point d. By finding a number of such points, the curve $B\,d\,d'$ for power factor cos ϕ is obtained and the regulation at this power factor (expressed in per cent) is $\dfrac{100 \times a'\,d'}{c'\,d'}$ since $a'\,d'$ is the rise in voltage when the load at power factor cos ϕ is thrown off at normal voltage $c'\,d'$.

Generally, the ohmic drop can be neglected as it has little influence on the regulation, except in very low-speed machines where the armature drop is relatively high or in some cases where regulation at unity power factor is being estimated. For low power factors its effect is negligible in practically all cases. If resistance is neglected, the simpler diagram Fig. 4-5, may be used.

(4394-d) Method III is the same as Method II except that the zero power factor curve must be estimated. This may be done as follows. In Fig. 4-6, $O\,A$ is the open-circuit saturation curve and $O\,E$ the short-circuit line as obtained from test. The zero power-factor curve corresponding to any current $B\,F$ will start from point B, and for machines designed with low saturation and low reactance, will follow parallel to $O\,A$ as shown by the dotted curve $B\,D$, which is $O\,A$ shifted horizontally parallel to itself by the distance $O\,B$. In high speed machines, or in others having low reactance, and a low degree of saturation in the magnetic circuit and short-circuit curves, by reference to tests at zero power factor on other machines of similar magnetic circuit. Having obtained the estimated zero power-factor curve, the load saturation for any other power factor is obtained as in Method II, §4894 (c).

4895 Compound Wound D-C. Generator.—In determining the regulation of a compound-wound d-c generator, two tests shall be made, one bringing the load down and the other bringing the load up, between no-load and rated load. These may differ somewhat, owing to residual magnetism. The mean of the two results shall be used.

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circuit, the zero power factor curve will be quite close to $B\ D$ particularly in those parts that are used for determining the regulation. This is the case with many turbo-generators and high-speed water-wheel generators.

In many cases, however, the zero power-factor curve will deviate from $B\ D$, as shown by $B\ C$ and the deviation will be most pronounced in machines of high reactance, high saturation and large magnetic leakage. The position of curve $B\ C$ with relation to $B\ D$ can be approximated with sufficient exactness by investigating the corresponding relation as obtained by test at zero power factor on machines of similar characteristics and magnetic circuit. Curve $B\ C$ can also be calculated by methods based on the results of tests at zero power factor. After curve $B\ C$ has been obtained, the load saturation curve and regulation for any other power factor can be derived as in Method II, §4894 (c).

CHAPTER V.

STANDARDS FOR ELECTRIC RAILWAYS AND FOR AUTOMOBILE PROPULSION MACHINES

The A. I. E. E. Standards for Electric Railways and for Automobile Propulsion Machines are the General Standards shown in Chapters II and III, and the Standards in other Chapters which are applicable to the devices involved together with the modifications and extensions given in this Chapter.

DEFINITIONS

General

5000 Contact Conductors.—A contact conductor is that part of the distribution system other than the traffic rails, which is in immediate electrical contact with the circuits of the cars or locomotives.

Contact Rails

5003* Contact Rail.—(a) *General:* A contact rail is a rigid contact conductor.

*(b) *Overhead Contact Rail:* An overhead contact rail is a contact rail which is above the elevation of the maximum equipment line.

(c) *Third Rail:* A third rail is a contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

(d) *Center Contact Rail:* A center contact rail is a contact conductor placed between the track rails, having its contact surface above the ground level.

(e) *Underground Contact Rail:* An underground contact rail is a contact conductor placed beneath the ground level.

(f) *Gage of Third Rail:* The gage of a third rail is the distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the contact surface of the third rail.

(g) *Elevation of Third Rail:* The elevation of a third rail is the elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

(h) *Third Rail Protection:* A third rail protection is a guard for the purpose of preventing accidental contact with the third rail.

Trolley Wires

5004 Trolley Wire.—A trolley wire is a flexible contact conductor, customarily supported above the cars.

(5003b) The maximum equipment line is the contour which embraces cross-sections of all rolling stock under all normal operating conditions.

5005 Messenger Wire or Cable.—A messenger wire or cable is a wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

5006 Classes of Construction.—(a) *General*: Overhead trolley constructions are classed as *Direct Suspension* and *Messenger or Catenary Suspension.*

(b) *Direct Suspension:* A direct suspension is the form of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

(c) *Messenger or Catenary Suspension:* A messenger or catenary suspension is the form of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *Simple Catenary, i.e.*, by primary messengers, or in *Compound Catenary, i.e.*, by secondary messengers.

5007 Supporting Systems.—(a) *General*: Supporting systems for trolley wires shall be classed as follows:

(b) *Simple Cross-Span Systems:* Simple cross-span systems are those having at each support a single flexible span across the track or tracks.

(c) *Messenger Cross-Span Systems:* Messenger cross-span systems are those having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

(d) *Bracket Systems:* Bracket systems are those having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

(e) *Bridge Systems:* Bridge systems are those having at each support a rigid member, supported at both sides of the track or tracks.

5030* Transmission System.—When the current generated for an electric railway is changed in kind or voltage, between the generator and the cars or locomotives, that portion of the conductor system carrying current of a kind or voltage substantially different from that received by the cars or locomotives, constitutes the *transmission system.*

5031* Distribution System.—That portion of the conductor system of an electric railway which carries current of the kind and voltage received by the cars or locomotives, constitutes the *distribution system.*

(5030 and 5031) These definitions are identical in sense, although not in words, with those of the Interstate Commerce Commission, as given in their Classification of Accounts for Electric Railways.

5082 Substation.—A substation is a group of apparatus or machinery which receives current from a transmission system, changes its kind or voltage, and delivers it to a distribution system.

OPERATION

Temperature Limits

5101* Railway Motors in Continuous Service.—The following maximum observable temperatures are permissible in the windings of railway motors, when in continuous service.

TABLE 501

Temperatures of Railway Motors in Continuous Service.

Class of Material See §1004	Temperature	
	By Thermometer See §1002	By Resistance See §1002
A	85°C	110°C
B	100°C	130°C

5120 Railway Substation Machines and Transformers.—Under conditions specified in **§5201**, the windings of railway substation machines and transformers carrying traction loads may have observable temperature rises 5°C in excess of the limiting observable temperature rises specified in Table 200.

5130* **Automobile Propulsion Machines.**—On stand test, the *observable* temperature rises shall not exceed the limits specified in **§5205**.

RATING

Ratings of Railway Substation Machinery and Transformers.

5201* Nominal Rating of Railway Substation Machines and Transformers.—The nominal rating of a substation machine or transformer carrying traction loads shall be the kv-a. output at a stated power factor input, which, having produced a constant temperature in the machine or transformer may be increased 50 per cent for two hours, without producing temperature rises exceeding by more than 5°C. the limiting values given in Table 200. These

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(5101) Under extreme ambient temperatures it is permissible to operate, for short infrequent periods, at 15°C. higher temperature than specified in this rule.

(5101 and 5130) Owing to space limitations and the cost of carrying dead weight on vehicles, it is considered good practise to operate propulsion machinery at higher temperatures than would be advisable in stationary machines. (See Table 501).

machines or transformers should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked "nominal rating."

Ratings of Railway Motors

5202* Nominal Rating of Railway Motors.—The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90°C. at the commutator, and 75°C. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature as measured by resistance, shall not exceed 100°C. The statement of the nominal rating shall include the corresponding voltage and armature speed.

5203* Continuous Ratings of Railway Motors.—The continuous ratings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at ½, ¾ and full voltage respectively, without exceeding the observable temperature rises specified in Table 502, when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

TABLE 502

Stand-Test Temperature Rises of Railway Motors

Class of Material See §1004	Temperature Rises of windings	
	By Thermometer See §1002	By Resistance See §1002
A	65°C.	85°C.
B	80°C.	105°C.

(5201 and 5202) In the absence of any specification as to the kind of rating the "nominal" rating shall be understood.

(5203) The temperature rise in service may be very different from that on stand-test. See §5502 for the relation between stand-test and service temperatures as affected by ventilation

5204 Field-Control Railway Motors.—The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it, without exceeding the specified temperature rises.

Ratings of Automobile Propulsion Machines

5205 Automobile Propulsion Machines: The rating of automobile motors and generators shall be based upon temperature rise, on a stand test and with motor covers arranged as in service, fifteen degrees by thermometer or twenty-five degrees by resistance, above those of Table 200.

Ratings of Electric Locomotives

5210 Rating.—Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort and corresponding speeds.

5211 Weight on Drivers.—The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

5212 Nominal Tractive Effort.—The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their nominal (one-hour) rating.

5213 Continuous Tractive Effort.—The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in **§5203**.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for ½ or ¾ voltage, but in such cases the voltage shall be clearly specified.

5214 Speed.—The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

TESTS

Efficiency

Losses in D-C. Railway Motors

5337 Losses in Gearing and Axle Bearings.—The losses in gearing and axle bearings for single-reduction single-geared motors, varies with the type, mechanical finish, age and lubrication. The following values, based upon accumulated tests, shall be used in the comparison of single-reduction single-geared motors **§5339.**

TABLE 503

Losses in Axle Bearings and Single-Reduction Gearing of Railway Motors

Per cent of input at nominal rating	Losses as per cent of input
200	3.5
150	3.0
125	2.7
100	2.5
75	2.5
60	2.7
50	3.2
40	4.4
30	6.7
25	8.5

NOTE:—Further investigation may indicate the desirability of giving separate values of the losses for full and tapped fields, or low- and high-speed motors.

5338. Brush Friction, Armature Bearing Friction and Windage.—The brush friction, armature-bearing friction and windage, shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. Drive the machine idle as a series motor on low voltage. The product of armature counter-electromotive-force and amperes at any speed shall be the sum of the above losses at that speed. See **§5339.**

5339* No-Load Core Loss, Brush Friction, Armature-Bearing Friction and Windage.—The no-load core loss, brush friction, armature-bearing friction and windage shall be determined as a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of brushes and the brush pressure shall be the same as in commercial service. With the field separately excited, such a voltage shall be applied to the armature terminals as will give the same speed for any given field current as is obtained with that field current when operating at normal voltage under load. The sum of the losses above-mentioned, is equal to the product of the counter-electromotive force and the armature current.

The no-load core loss is obtained by deducting from the total

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(5339) In comparing projected railway motors, and in case it is not possible or desirable to make tests to determine mechanical losses, the following values of these losses, determined from the averages of many tests over a wide range of sizes of single-reduction single-geared motors, will be found useful, as approximations. They include axle-bearing, gear, armature-bearing, brush-friction, windage, and stray-load losses.

losses thus obtained the power required to drive the motor at corresponding speeds as determined under §5338.

The core loss under load shall be assumed to have the values given in Table 504.

TABLE 504

Core Loss in D-C. Railway Motors at Various Loads

Per cent of input at nominal rating	Loss as per cent of no-load core loss
200	165
150	145
100	130
75	125
50	123
25 and under	122

NOTE:—With motors designed for field control the core losses shall be assumed as the same for both full and permanent field. It shall be the mean between the no-load losses at full and permanent field, increased by the percentages given in the above Table.

5341 Automobile Motors: When automobile motors are of low voltage, the great influence of brush-contact losses on the efficiency requires that these losses be determined experimentally for the type of brush used.

CHARACTERISTIC CURVES OF RAILWAY MOTORS

5401 General.—The Characteristic Curves of railway motors shall be plotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of a-c. motors, the power factor shall also be plotted as ordinates.

5402 Voltage.—Characteristic curves of direct current motors shall be based upon full voltage, which shall be taken as 600 volts, or a multiple thereof.

5403 Field-Control Motors.—In the case of field-control motors, characteristic curves shall be given for all operating field connections.

TABLE 505.

Approximate Losses in D-C. Railway Motors.

Input in per cent of that at nominal rating	Losses as per cent of input
100 or over	5.0
75	5.0
60	5.3
50	6.5
40	8.8
30	13.3
25	17.0

The core loss of railway motors may also be determined as specified for other machines.

SELECTION OF RAILWAY MOTOR FOR SPECIFIED SERVICE

5501 Data Required in Selecting Motor.—The following information relative to the service to be performed, is required, in order that an appropriate motor may be selected,

(a) Weight of total number of cars in train (in tons of 2000 lb.) exclusive of electrical equipment and load.
(b) Average weight of load and durations of same, and maximum weight of load and durations of same.
(c) Number of motor cars or locomotives in train, and number of trailer cars in train.
(d) Diameter of driving wheels.
(e) Weight on driving wheels, exclusive of electrical equipment.
(f) Number of motors per motor car.
(g) Voltage at train with power on the motors—average, maximum and minimum.
(h) Rate of acceleration in miles per hour per second.
(i) Rate of braking (in miles per hour per second).
(j) Speed limitations, if any (including slowdowns).
(k) Distances between stopping points.
(l) Average duration of stops.
(m) Schedule speed, including stops, in miles per hour.
(n) Train resistance in pounds per ton of 2000 pounds at stated speeds.
(o) Moment of inertia of revolving parts, exclusive of electrical equipment.
(p) Profile and alignment of track.
(q) Distance coasted as a percentage of the distance between stoping points.
(r) Duration of layover at end of run, if any.

5502* Method of Comparing Motor Capacity with Service Requirements.—When it is not convenient to test motors under actual specific service conditions, recourse may be had to the following method of determining temperature rise from the stand-tests.

The essential motor losses affecting temperatures in service are those in the motor windings, core and commutator. The mean service conditions may be expressed, as a close approximation, in terms of that continuous current and core loss which will produce the same losses and distribution of losses as the average in service.

(5502) Calculation for comparing motor capacity with service requirements. The heating of a motor should be determined, wherever possible, by testing it in service, or with an equivalent duty-cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilized as follows to determine its temperature rise.

The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with the voltage and current, according to curves which can be supplied by the manufacturers. The procedure is therefore as follows:

(a) Plot a time-current curve, a time-voltage curve, and a time-core loss curve for the duty-cycle which the motor is to perform, and calculate from these the root-mean-square current and the average core loss.

(b) If the calculated r.m.s. service current exceeds the continuous rating, when run with

A stand test with the current and voltage which will give losses equal to those in service, will determine whether the motor has sufficient capacity to meet the service requirements. In service, the temperature rise of an enclosed motor (§4044), well exposed to the draught of air incident to a moving car or locomotive, will be from 75 to 90 per cent (depending upon the character of the service) of the temperature rise obtained on a stand test with the motor completely enclosed and with the same losses. With a ventilated motor (§4045 and §4046), the temperature rise in service will be 90 to 100 per cent of the temperature rise obtained on a stand test with the same losses.

In making a stand test to determine the temperature rise in a specific service, it is essential in the case of a self-ventilated motor (§4046) to run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

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average service core loss and speed, the motor is not sufficiently powerful for the duty-cycle contemplated.

(c) If the calculated r.m.s. service current does not exceed the continuous rating, when run with average service core loss and speed, the motor is ordinarily suitable for the service.

In some cases, however, it may not have sufficient thermal capacity to avoid excessive temperature rises during the periods of heavy load. In such cases a further calculation is required, the first step of which is to compute the equivalent voltage which, with the r.m.s. current, will produce the average core loss. Having obtained this, determine, as follows, the temperature rise due to the r.m.s. service current and equivalent voltage.

$$\text{Let }\left.\begin{array}{l} t = \text{temperature rise} \\ p_e = I^2R \text{ loss, kw.} \\ p_c = \text{core loss, kw.} \end{array}\right\} \text{with r.m.s. service current, and equivalent service voltage.}$$

$$\left.\begin{array}{l} T = \text{temperature rise} \\ P_e = I^2R \text{ loss, kw.} \\ P_c = \text{core loss, kw.} \end{array}\right\} \begin{array}{l}\text{with continuous load current corresponding to the equivalent} \\ \text{service voltage.}\end{array}$$

Then

$$t = T\,\frac{p_e+p_c}{P_e+P_c}\text{, approximately.}$$

(d) The thermal capacity of a motor is approximately measured by the ratio of the electrical loss in kw. at its nominal (one-hour) capacity, to the corresponding maximum observable temperature rise during a one hour test starting at ambient temperature.

(e) Consider any period of peak load and determine the electrical losses in kilowatt-hours during that period from the *electrical* efficiency curve. Find the excess of the above losses over the losses with r.m.s. service current and equivalent voltage. The excess loss, divided by the coefficient of thermal capacity, will equal the extra temperature rise due to the peak load. This temperature rise added to that due to the r.m.s. service current, and equivalent voltage, gives the total temperature rise. If the total temperature rise in any such period exceeds the safe limit, the motor is not sufficiently powerful for the service.

(f) If the temperature reached, due to the peak loads, does not exceed the safe limit, the motor may yet be unsuitable for the service, as the peak loads may cause excessive sparking and dangerous mechanical stresses. It is, therefore, necessary to compare the peak loads with the short-period overload capacity. If the peaks are also within the capacity of the motor, it may be considered suitable for the given duty-cycle.

CONSTRUCTION

5601* Standard Height of Trolley Wire on Street and Interurban Railways.—It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 feet (5.5 m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 feet (6.4 m.) above the top of rail, under conditions of maximum sag.

5602 Standard Gage of Third Rails.—The gage of third rails shall be not less than 26 inches (66 cm.) and not more than 27 inches (68.6 cm.)

5603 Standard Elevation of Third Rails.—The elevation of third rails shall not be less than 2¾ inches (7 cm.) and not more than 3½ inches (8.9 cm.)

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CHAPTER VI.

STANDARDS FOR TRANSFORMERS AND OTHER STATIONARY INDUCTION APPARATUS

Wherever the General Standards in Chapters II and III apply to transformers they are referred to in the following Chapter by cross references.

Certain rules applying exclusively to railway machinery have, for convenience, been placed in Chapter V with cross reference in all cases to this Chapter. Rules in Chapter VI apply to railway machinery except as they are modified by the rules in Chapter V.

Note: The work "Transformer" will be used throughout this Chapter as an abbreviation of "Transformer or other stationary induction apparatus."

DEFINITIONS

Apparatus

6000 **Stationary Induction Apparatus.**—For the purpose of these Standards stationary induction apparatus is defined as electric apparatus which changes electric energy to electric energy through the medium of magnetic energy, without mechanical motion. It comprises several forms, as defined in §§ **6001** and **6010** to **6015**.

6001 **Transformer.**—A transformer is a form of stationary induction apparatus in which the primary and secondary windings are ordinarily insulated one from another.

6010 **Auto-Transformer.**—An auto-transformer is one which has a part of its turns common to both primary and secondary circuits.

6011 **Voltage-Regulator.**—A voltage-regulator is a form of stationary induction apparatus which has turns in shunt and turns in series with the circuit, so arranged that the voltage ratio of the transformation, or the phase relation between the circuit-voltages, is variable at will.

6012 **Contact Voltage Regulator.**—A contact voltage regulator is a voltage regulator in which the number of turns in one or both of the coils is adjustable.

6013 **Induction Voltage Regulator.**—An induction voltage regulator is one in which the relative position of the primary and secondary coils is adjustable.

6014 **Magneto Voltage Regulator.**—A magneto voltage regulator is one in which the direction of the magnetic flux with respect to the coils is adjustable.

6015 **Reactor.**—A reactor is a device used primarily because it possesses the property of reactance. Reactors are used in electric circuits for purposes of operation, protection or control.

Parts of Apparatus

6020 High-Voltage and Low-Voltage Winding.—The terms "high voltage" and "low voltage" are used to distinguish the winding having the greater from that having the lesser number of turns.

6021 Primary and Secondary Windings.—The term "primary" and "secondary" serve to distinguish the windings in regard to energy flow, the primary being that which receives the energy from the supply circuit, and the secondary that which receives the energy by induction from the primary.

Properties of Apparatus

6031 Rated Current of a Constant-Potential Transformer.—The rated current of a constant-potential transformer is that secondary current which, multiplied by the rated-load secondary voltage, gives the kv-a. rated output. That is, a transformer of given kv-a. rating must be capable of delivering the rated output at rated secondary voltage, while the primary impressed voltage is increased to whatever value is necessary to give rated secondary voltage.

6032 Rated Primary Voltage of a Constant-Potential Transformer.—The rated primary voltage of a constant-potential transformer is the rated secondary voltage multiplied by the turn ratio.

6033 Ratio of a Transformer.—The ratio of a transformer, unless otherwise specified, shall be the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding; *i. e.*, the "turn-ratio."

6034 Voltage Ratio of a Transformer.—The voltage ratio of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified conditions of load.

6035 Current Ratio of a Transformer.—The current ratio of a current-transformer is the ratio of the r.m.s. primary current to the r.m.s. secondary current, under specified conditions of load.

6036 Volt-Ampere Ratio of Transformer.—The volt-ampere ratio, which should not be confused with real efficiency, is the ratio of the volt-ampere output to the volt-ampere input of a transformer, at any given power factor.

6050* Per Cent Resistance Drop.—The per cent resistance drop in a transformer is the ratio of the internal resistance drop at 75°C. to the secondary terminal voltage expressed in per cent.

6051* Per Cent Reactance Drop.—The per cent reactance drop in a transformer is the ratio of the internal reactance drop to the secondary terminal voltage expressed in per cent.

6052* Per Cent Impedance Drop.—The per cent impedance drop in a transformer is the ratio of the internal impedance drop at 75°C. to the secondary terminal voltage expressed in per cent.

6053 Regulation of Constant-Potential Transformer.—In constant-potential transformers, the regulation is the difference between the

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(6050-6051-6052) The internal drop in a transformer is the sum of the primary drop (reduced to secondary terms) and the secondary drop.

no-load and rated-load values of the secondary terminal voltage at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage. See **§3390.**

Ambient Temperature.—See **§3000.**

RATING

General

6201

TABLE 601

Limiting Observable Temperatures and Temperature Rises for Transformers Using Class A* Insulation.

	†Air Cooled and Air Blast	Oil Cooled	Water Cooled
Limiting Observable Temperature......................	95°C.	95°C.	80°C.
Standard Ambient Temperature......................	40°C.	40°C.	25°C.
Limiting Observable Temperature Rise.................	**55°C.**	**55°C.**	**55°C.**

The temperature of the windings of transformers is always to be ascertained by Method 2.

*For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of the observable temperature rise shall be 15°C. below the limits fixed for these materials when impregnated.

†For exceptions in the case of Air Blast Transformers, see **§6320** (*b*).

6202 Limiting Observable Temperature of Oil (From §2232).—The oil in which apparatus is permanently immersed shall, in no part, have a temperature, observable by thermometer, in excess of 90°C.

Permissible Temperatures of Insulations of More Than One Class.—See **§2104.**

Temperatures of Metallic Parts of Transformers.—See **§2116.**

Protection Against Short Circuit.—See **§2120.**

Nominal Rating of Railway Substation Transformers.—See **§5201.**

Expression of Rating.—See **§2202.**

Institute Rating.—See **§2204.**

6204* Rating of Protective Reactors.—Protective reactors shall be rated by the following characteristics:

(*a*) Kilovolt-amperes absorbed by normal current.

(*b*) Normal current, frequency and line (delta) voltage.

(*c*) Current which the device is required to stand under short circuit conditions.

(6204) Reactors shall be so designed as to be capable of withstanding the sudden application, without mechanical injury, of rated current at normal frequency.

Ambient Temperature of Reference

Ambient Temperature of Reference for Air.—See §2211.

Ambient Temperature of Reference for Water-Cooled Transformers.—See §2212.

Transformers Cooled by Other Means.—See §2213.

Outdoor Transformers Exposed to Sun's Rays.—See §2214.

Altitude Correction

Altitude.—See §2215.

6215 **Exception to "Altitude".**—See §2215—Water-cooled oil-immersed transformers are exempt from this reduction.

Units in Which Rating Shall be Expressed

6221 **Rating of Transformers.**—The rating of transformers shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at a specified frequency and voltage.

6223 **Rating of Other Stationary Induction Apparatus.**—Other stationary induction apparatus such as auto-transformers, regulators, reactors, etc., shall have their ratings appropriately expressed. It is also essential to specify the voltage and frequency of the circuits on which the apparatus may be used.

Kinds of Rating

Continuous Rating.—See §2220.

Short-Time Rating.—See §2221.

Duty-Cycle Operation,—See §2222.

Standard Short-Time Ratings.—See §2223.

A. I. E. E. and I. E. C. Ratings.—See §2224.

Continuous Rating Implied.—See §2225.

6236 **Nominal Ratings.**—Nominal ratings are ratings which do not conform with § §2220 and 2221. They are sometimes used for railway substation transformers carrying traction loads. Transformers with nominal rating shall be capable of operating under the conditions enumerated in §5201.

Rating by Temperature Rise

Permissible Temperature Rises for Various Ambient Temperatures above Standard.—See §2231 (*d*).

TESTS

Ambient Temperature

Measurement of Ambient Temperatures during Tests of Transformers.—See §2300.

6300 **Measurement of the Ambient Temperature During Tests of Water-Cooled Transformers.**—The temperature rise of water-cooled transformers shall be based entirely upon the temperature of the cooling water and it is not necessary to take into account the heat carried off by the air, unless it exceeds the amount specified below. If under assumed standard conditions of water at 25° C, and air at 40° C, the amount of heat which would be carried off by the air is 15% or more of the total, the temperature of the cooling water, during test, should be maintained within 5° C. of that of the surrounding air. Where this is impracticable the ambient temperature should be determined from the change in the resistance of the windings, using a disconnected transformer, supplied with the normal amount of cooling water, until the temperature of the windings has become constant.

Oil Cup.—See **§2301.**

Transformer Temperatures

Temperature Rise for Any Ambient Temperature.—See **§2310.**

Correction for the Duration of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test, from the Standard Ambient Temperature of Reference.—See **§2311.**

6311* **Correction for the Deviation of the Ambient Temperature of the Cooling Medium, at the Time of the Heat Test of Air-Blast Transformers from the Standard Ambient Temperature of Reference.**—A correction shall be applied to the observed temperature rise of the windings of air-blast transformers due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i. e.* the ratio $274.5/(234.5 + t)$; where t is the ingoing cooling-air temperature.

Duration of Temperature Test of Transformers for Continuous Service.—See **§2312.**

Duration of Temperature Test of Transformer with a Short-Time Rating.—See **§2313.**

Duration of Temperature Test for Transformer Having More Than One Rating.—See **§2314.**

Temperature Measurements during Heat Run.—See **§2315.**

6317 **Methods of Loading Transformers for Temperature Tests.** (*a*) *General*: Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load. See §**§2312** to **2314.**

An approved method of making these tests is the *loading-back* method. The principal variations of this method are given in **§6317** (b,) (c) and (d).

(*b*) *Loading-back with duplicate single-phase transformers*: Duplicate single-phase transformers may be tested in banks of two, with

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(6311) Thus, a cooling-air room temperature of 30° C. would correspond to an inferred absolute temperature of 264.5° on the scale of copper resistivity, and the correction to 40° C. (274.5° inferred absolute temperature) would be 274.5/264.5 = 1.04, making the correction factor 1.04; so that an observed temperature rise of say 50° C. at the testing ambient temperature of 30° C. would be corrected to 50 × 1.04 = 52° C. this being the temperature rise which would have occurred had the test been made with the standard ingoing cooling-air temperature of 40° C.

both primary and secondary windings connected in parallel. Normal magnetizing voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions while the other may be operating under slightly abnormal conditions.

(*c*) *Loading-back with one three-phase transformer*: One three-phase transformer may be tested in a manner similar to **§6317** (*b*) provided the primary and secondary windings are each connected in delta for the test. Normal three-phase magnetizing voltage should be applied and the required current circulated from an auxiliary single-phase source.

(*d*) *Loading-back with three single-phase transformers*: Duplicate single-phase transformers may be tested in banks of three in a manner similar to that described in **§6317** (*c*), by connecting both primary and secondary windings in delta, applying normal three-phase magnetizing voltage and circulating the required current from an auxiliary single-phase source.

(*e*) *Other Methods*: Among other methods that have a limited application and can be used only under special conditions may be mentioned:

Applying dead load by means of some form of rheostat.

Running alternately for certain short intervals of time on open circuit and then on short-circuit, alternating in this way until the transformer reaches a steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss as in normal operation.

6320 Method of Temperature Measurement.—(*a*) *Description*: The temperature of transformer windings shall be measured by their increase in resistance, corrected to the instant of shut-down when necessary, and by thermometers. Whichever measurement yields the higher temperature, that temperature shall be taken as the highest observable temperature by Method 2.

(*b*) In the case of air-blast transformers, it is important to have the thermometers well distributed and in good contact with the coils, and it is especially important to note the temperature near the air outlet. In measuring the temperature of air-blast transformers, the air supply shall be shut off immediately at the end of the temperature run and the air intake closed to prevent further admission of cooling air. With the above procedure, the observable temperature rise for air-blast transformers may attain a value not in excess of 60°C. as determined by thermometer, although it must not exceed 55°C. as determined by resistance.

(*c*) *Temperature Correction for Cooling of Transformer Windings after Shut-Down*: Since a drop in temperature occurs in a winding between the instant of shut-down and the time of measuring the hot resistance, a correction shall be applied to the temperature determined from this measurement so as to obtain, as nearly as practicable, the temperature at the instant of shut-down. This correction may be determined approximately by plotting a time-temperature curve with temperatures as ordinates and times as abscissae and extrapolating back to the instant of shut-down.

In cases where successive measurements show increasing temperatures after shut-down the highest value shall be taken.

In certain cases, however, other correction factors may be applied as follows:

Oil-Immersed Transformers: For the purpose of simplifying the application of the rule to transformers when the weight of copper in each winding is known and the copper loss as determined by wattmeter measurement does not exceed 30 watts per lb., the extrapolation method has been reduced to the following form which is recommended on account of the greater accuracy obtainable under ordinary conditions of testing. The correction in degrees C. shall be the product of the watts loss per lb. of copper for each winding multiplied by a factor depending upon the time elapsed between shut-down and the time of the temperature reading as given in the following table:

Time in Minutes	Factor
1	0.19
2	0.32
3	0.43
4	0.50

For intermediate times, the value of the factor can be obtained by interpolation.

When the copper loss, measured by wattmeter, does not exceed 7 watts per lb. an arbitrary correction of one degree per minute may be used provided the time elapsed between the instant of shut-down and the measurement of the hot resistance does not exceed 4 minutes.

For determining the copper loss in watts per lb., the total loss in both windings as measured by the wattmeter should be apportioned between the high and low voltage windings in the same ratio as their respective I^2R losses.

Air-Blast Transformers: An arbitrary correction of one degree per minute may be used provided the time elapsed between the instant of shut-down and the measurement of the hot resistance does not exceed four minutes.

(*d*) *Covering of Thermometers*: Thermometers used for taking the temperature of air-cooled or air-blast transformers shall have their bulbs covered for protection from air currents. This shall be done by felt pads, approximately 4 cm. x 5 cm. (1 1/2 in. x 2 in.) and

3 mm. (1/8 in.) thick, except that where pads are inconvenient, as in ventilating ducts between coils, grooved wooden sticks may be used.

Temperature Coefficient of Copper.—See **§2321.**

Efficiency

Efficiencies Recognized.—See **§ 2331.**

Normal Conditions for Efficiency Tests.—See **§ 2332.**

Direct Measurement of Efficiency.—See **§ 2333.**

6334 **Classification of Losses.**—(*a*) *General*: Losses are classified as shown below.

(*b*) *No-Load Losses*: No-load losses include the core loss, the I^2R loss due to the exciting current and the dielectric loss in the insulation.

(*c*) *Load Losses*: Load losses include I^2R losses, and stray load-losses due to eddy-currents caused by fluxes varying with load.

6335 **Losses to be Considered in Transformers.**—Conventional efficiencies shall be based upon the losses listed in **§6334** and these losses shall be measured as specified in **§§6336** and **6337.**

6336 **No-Load Losses.**—The no-load losses shall be measured with open secondary circuit at the rated frequency, and with an applied primary voltage giving the rated secondary voltage plus the $I\,R$ drop which occurs in the secondary under rated load conditions.

6337 **Load Losses.**—The load losses include I^2R and stray load-losses. They shall be measured by applying a primary voltage, at rated frequency, sufficient to produce rated load current in the windings, with the secondary windings short-circuited.

Wave Shape

Standard Wave Shape.—See **§ 2340.**

Tests of Dielectric Strength

Condition of Transformers to be Tested.—See **§2350.**

Where High Voltage Tests are to be Made.—See **§2351.**

Temperature at which High Voltage Tests are to be Made.—See **§2352.**

Points of Application of Voltage.—See **§2353.**

Frequency and Wave Form of Test Voltage.—See **§2354.**

Duration of Application of Test Voltage.—See **§2355.**

6356 **Standard Test Voltage.**—(From **§2356.**) *General*: The standard test voltage for all machines, except as otherwise specified, shall be twice the normal voltage of the circuit to which the machine is connected plus 1000 volts. See exception **§6361.**

6360 **Transformers for Star Connection.**—Transformers which may be used in star connection on three-phase circuits shall be tested on the basis of the line to line voltage for which they are rated. See **§6361-f.**

6361* **Exceptions to Standard Test Voltage Given in Section 6356.**—(*a*) *Distributing Transformers*: Transformers for primary pressures from 550 to 4500 volts, the secondaries of which are directly connected to consumers' circuits and commonly known as distributing transformers, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary windings shall be tested with twice their normal voltage plus 1000 volts.

(*b*) *Auto-Transformers:* Auto-transformers used for starting purposes, shall be tested with the same voltage as the test voltage of the apparatus to which they are connected.

(c) *Household Devices:* Transformers taking not over 660 watts and intended solely for operation on supply circuits not exceeding 275 volts, shall be tested with 900 volts.

* (*d*) *Transformers for Use on Circuits of* 25 *Volts or Lower*: Transformers for use on circuits of 25 volts or lower, such as bell-ringing apparatus, shall be tested with 500 volts.

(e) *Alternating Current Transformers Connected to Permanently Grounded Single Phase Systems, for use on Permanently Grounded Circuits of more than* 300 *Volts:* Transformers used under these conditions shall be tested with 2.73 times the voltage of the circuit to ground plus 1000 volts. This does not refer to three-phase transformers operating with grounded neutral.

(f) *Transformers to be used on star-connected three-phase circuits:* Transformers which may be used in star connection on three-phase circuits shall have the line to line (as distinguished from line to neutral) voltage of the circuits on which they may be used indicated on the rating plate and the test shall be based on the line to line voltage. See **§6360.**

(g) *Protective Reactors*: Protective reactors shall be tested from conductors to ground with 2000 volts plus 2¼ times the line voltage.

6362* Testing Transformers by Induced Voltage.—Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings in place of using a separate testing transformer. By "required voltage" is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

6363 Transformers with Graded Insulation.—Where transformers have graded insulation they shall be so marked. They shall be tested by inducing the required test voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. See **§6361.**

Use of Voltmeter and Spark-gaps in Dielectric Tests.—See **§2359.**

Use of Spark-gap with Transformers of Low Capacitance.—See **§2360.**

Use of Spark-gap with Transformers of High Capacitance.—See **§2361.**

(6361-d) This rule does not include bell-ringing transformers of ratio 125 to 6 volts.

(6362) This test can be made by connecting the windings of two or more transformers in series, with one end of the series grounded and a voltage impressed such as will give the test from the free end to ground required by the above rule.

Measurements with Voltmeter.—See §2362.
Measurements with Spark-gap.—See §2363.

Regulation

Conditions for Tests of Regulation.—See §2390.

6390 Conditions for Tests of Regulation.—(*a*) *Frequency*: The regulation of transformers is to be determined at constant frequency.

(*b*) *Power Factor:* In transformers, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is, to a load in which the current is in phase with the e.m.f. at the output side of the transformer. See §2390.

6391* Tests and Computation of Regulation.—*(a) *Method I. By Loading:* The regulation of a constant potential transformer can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power factor.

(*b*) *Method II. From Impedance Watts and Volts*: The regulation of a constant potential transformer for any specified load and power factor can be computed from the measured impedance watts and impedance volts as follows:

Let:

P = impedance watts, as measured in the short-circuit test and corrected to 75°C.
E_s = impedance volts, as measured in the short-circuit test.
IX = Reactance Drop in Volts.
I = Rated Primary Current.
E = Rated Primary Voltage.
q_r = per cent drop in phase with current.
q_x = per cent drop in quadrature with current.

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}$$

$$q_r = 100\frac{P}{EI}$$

$$q_x = 100\frac{IX}{E}$$

Then—

For *unity power factor*, we have approximately,

$$\text{Per cent regulation} = q_r + \frac{q_x^2}{200}$$

For *inductive loads* of power-factor *m* and reactive-factor *n*,

$$\text{Per cent regulation} = m\,q_r + n\,q_x + \frac{(m\,q_x - n\,q_r)^2}{200}$$

(6391-a) This method is not generally applicable for shop tests, particularly on large transformers.

CONSTRUCTION

Rating Plates

Marking of Rating Plates.—See §2401.

Transformer Connections

(These rules do not apply to auto-transformers)

General

6402* **Scope.**—These rules specify the markings of leads brought out of the case but not the markings of winding terminals inside of the case, except that these terminals shall be marked with numbers in any manner that will permit of convenient reference and that cannot be confused with the markings of the leads brought out of the case.

TRANSFORMER LEAD MARKINGS SINGLE PHASE TRANSFORMERS

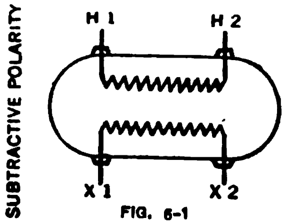


FIG. 6-1

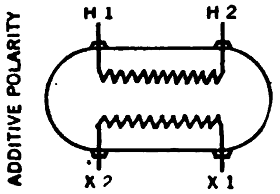


FIG. 6-2

Simple High and Low-Voltage Windings Without Taps

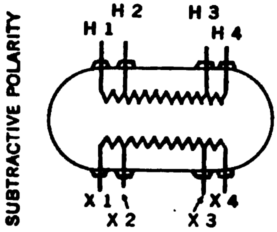


FIG. 6-5

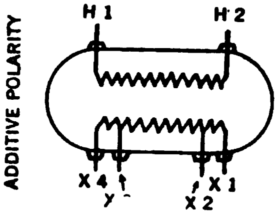


FIG. 6-4

Simple High and Low-Voltage Windings With Taps

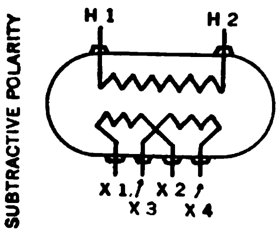


FIG. 6-3

Series Multiple Low-Voltage Winding Without Taps

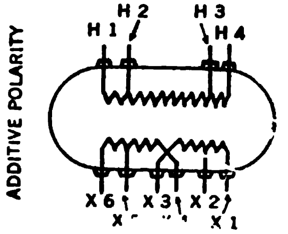


FIG. 6-6

Series Multiple Low-Voltage Winding With Taps

NOTE:—The above figures illustrate the application of the rules on lead markings to transformers having subtractive and additive polarity.

(6402) It is recognized that special cases will arise from time to time that these rules will not cover and that it would be very difficult to cover by any set of general rules.

6403* **Markings of Leads.**—*(*a*) *General:* The leads shall be distinguished from one another by marking each lead with a capital letter followed by a number. The letters to be used are: *H* for high voltage leads, *X* for low voltage leads and *Y* for tertiary winding leads. The numbers to be used are 1, 2, 3, etc.

*(*b*) *Neutral Lead:* A neutral lead shall be marked with the proper letter followed by *O*, *e.g.*, *HO*, *XO*.

6404 **Diagrammatic Sketch of Connections.**—The manufacturer shall furnish with each transformer a complete diagrammatic sketch showing the leads and internal connections and their markings and the voltages obtainable with the various connections.

This sketch should preferably be on a metal plate attached to the transformer case.

Single-Phase Transformers

6405 **Order of Numbering Leads in any Winding.**—The leads of any winding (high-voltage, low-voltage or tertiary) brought out of case shall be numbered 1, 2, 3, 4, 5, etc., the lowest and highest numbers marking the full winding and the intermediate numbers marking fractions of winding or taps. All numbers shall be so applied that the potential difference from any lead having a lower number toward any lead having a higher number shall have the same sign at any instant.

If a winding is divided into two or more parts for series parallel connections, and the leads of these parts are brought out of case, the above rule shall apply for the series connection with the addition that the leads of each portion of winding shall be given consecutive numbers. See Figs. 6-5 and 6-6.

6406 **Relation of Order of Numbering Leads of Different Windings.** The numbering of the high-voltage and low-voltage leads shall be so applied that when H_1 and X_1 are connected together and voltage applied to the transformer, the voltage between the highest numbered *H* lead and the highest numbered *X* lead shall be less than the voltage of the full high-voltage winding.

The same relation shall apply between high-voltage and tertiary and low-voltage and tertiary winding.

6407 **Polarity.**—When leads are marked in accordance with the above rules, the polarity of a transformer is

Subtractive when H_1 and X_1 are adjacent. See Figs. 6-1, 6-3 and 6-5.

(6403-a) By "tertiary winding" is meant a third winding that, compared with both of the other two windings, has smaller kv-a. rating than either or, if the kv-a. rating is the same as one or both of the other two, has lower voltage. *E. g.*, if a transformer has three separate windings, one for 1000 kv-a., 33,000 volts, one for 600 kv-a., 550 volts and one for 400 kv-a. 6,600 volts, the 400 kv-a. winding is the tertiary winding; or, if a transformer has three separate windings each with a capacity of 1,000 kv-a., and with voltages of 33,000, 6600 and 550 respectively, the 550 volt winding is the tertiary winding.

According to this definition neither one of two similar windings arranged for series-parallel connection is to be classed as a tertiary winding.

(6403-b) A lead brought out from the middle of a winding for some other use, than that of neutral lead, *e.g.*, a 50 per cent starting tap, shall be marked as a tap lead.

Additive when H_1 is diagonally located with respect to X_1. See Figs. 6-2, 6-4 and 6-6.

6408 Location of H_1 Lead.—To simplify the work of connecting transformers in parallel it is recommended that the H_1 lead shall be brought out on the right hand side of the case, facing high-voltage side of the case.

TRANSFORMER LEAD MARKINGS AND VOLTAGE VECTOR DIAGRAMS FOR THE USUAL THREE PHASE TRANSFORMER CONNECTIONS

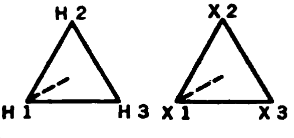
<table>
<tr><td></td><td colspan="2">THREE PHASE TRANSFORMERS WITHOUT TAPS</td></tr>
<tr><td>GROUP-1
ANGULAR DISPLACEMENT 0°</td><td>

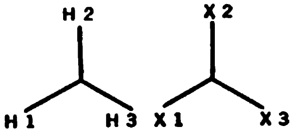
FIG. 6-7</td><td>

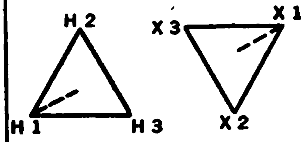
FIG. 6-8</td></tr>
<tr><td>GROUP-2
ANGULAR DISPLACEMENT 180°</td><td>

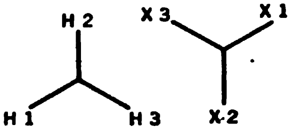
FIG. 6-9</td><td>

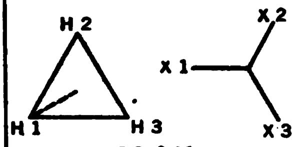
FIG. 6-10</td></tr>
<tr><td rowspan="2">GROUP-3
ANGULAR DISPLACEMENT 30°</td><td>

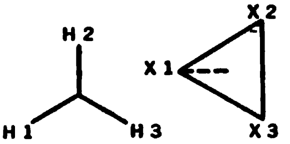
FIG. 6-11</td><td>

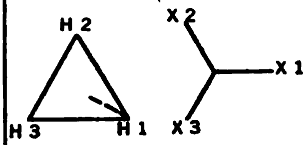
FIG. 6-12</td></tr>
<tr><td>

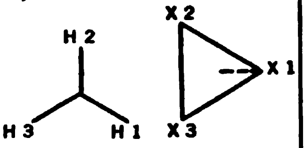
FIG. 6-13</td><td>

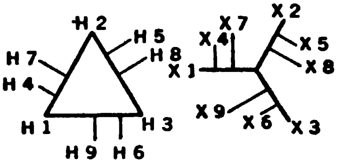
FIG. 6-14</td></tr>
<tr><td></td><td colspan="2">THREE PHASE TRANSFORMERS WITH TAPS</td></tr>
<tr><td>GROUP-3
ANGULAR DISPLACEMENT 30°</td><td colspan="2">

FIG. 6-15</td></tr>
</table>

NOTE:—The above figures are included to illustrate the method of marking transformer leads that are brought out of the case and are not intended to standardize connections, vector diagrams or polarity.

6409* Parallel Operation.—Transformers having leads marked in accordance with these rules may be operated in parallel by connecting similarly marked leads together, provided their ratio, voltages, resistances and reactances are such as to permit parallel operation.

Three-Phase Transformers

6410 Marking of Full Winding Leads.—The three high-voltage leads and the three low-voltage leads which connect to the full-phase windings, shall be marked H_1, H_2, H_3, and X_1, X_2, X_3. The full-phase winding of a tertiary winding shall be marked Y_1, Y_2, Y_3.

TRANSFORMER LEAD MARKINGS AND VOLTAGE VECTOR DIAGRAMS FOR THE USUAL SIX-PHASE TRANSFORMER CONNECTIONS

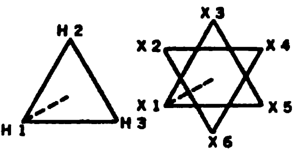
<table>
<tr><td></td><td colspan="2">SIX PHASE TRANSFORMERS WITHOUT TAPS</td></tr>
<tr><td>GROUP 4
ANGULAR DISPLACEMENT 0°</td><td>

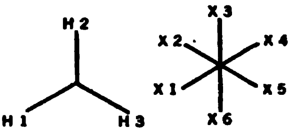
FIG. 6-16</td><td>

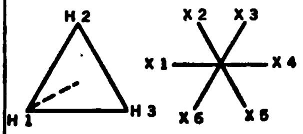
FIG. 6-17</td></tr>
<tr><td>GROUP 5
ANGULAR DISPLACEMENT 30°</td><td>

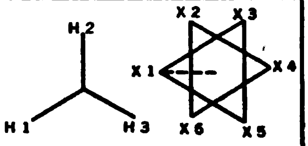
FIG. 6-18</td><td>

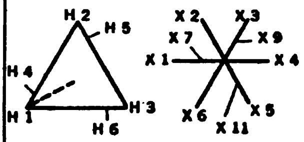
FIG. 6-19</td></tr>
<tr><td></td><td colspan="2">SIX PHASE TRANSFORMERS WITH TAPS</td></tr>
<tr><td>GROUP 5
ANGULAR DISPLACEMENT 30°</td><td>

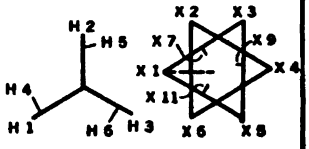
FIG. 6-20</td><td>

FIG. 6-21</td></tr>
</table>

NOTE:—The above figures are included to illustrate the method of marking transformer leads that are brought out of the case and are not intended to standardise connections, vector diagrams or polarity.

6411* Relation between High-Voltage and Low-Voltage Windings.—(*a*) *General:* The markings shall be so applied that if the phase sequence of voltage on the high voltage side is in the time order H_1, H_2, H_3 it is in the time order of, X_1, X_2, X_3 on the low-voltage side and Y_1, Y_2, Y_3 for a tertiary winding.

(6409) In some cases design may be such as to permit parallel operation, although due to the difference in the number of tap leads, the leads to be connected together may not have the same number.

*(*b*) *Angular Displacement:* In order that the markings of lead connections between phases shall indicate definite phase relations, they shall be made in accordance with one of the three three-phase groups as shown. The angular displacement between the high-voltage and low-voltage windings is the angle in each of the voltage vector diagrams (Figs. 6-7 to 6-14 inclusive) between the lines passing from its neutral point through H_1 and X_1 respectively.

6412 Tap Leads.—(*a*) *General:* Where tap leads are brought out of the case (neutral lead excepted) they shall be marked with the proper letter followed by the numbers 4, 7, etc., for one phase, 5, 8, etc., for another phase and 6, 9, etc., for the third phase. See Fig 6-15.

(*b*) *Delta Connection:* The order of numbering tap leads shall be as follows: 4, 7, etc., from lead 1 toward lead 2; 5, 8, etc., from lead 2 toward lead 3; and 6, 9, etc., from lead 3 toward lead 1. See Fig. 6-15.

(c) *Star Connection:* The order of numbering tap leads shall be as follows: 4, 7, etc., from lead 1 towards neutral; 5, 8, etc., from lead 2 towards neutral; and 6, 9, etc., from lead 3 towards neutral. See Fig. 6-15.

6413 Interphase Connection made Outside of Case.—Where the interphase connections are made outside of case, the leads shall be marked with the proper letter followed by the numbers 1, 4, 7, 10, etc., for one phase; 2, 5, 8, 11, etc., for the second phase; and 3, 6, 9, 12, etc., for the third phase.

The markings shall be so applied that when a star connection is made by joining together the highest numbered leads of each phase, all rules here given, excepting §6403 (b) apply.

6414* Parallel Operation.—Transformers having leads marked in accordance with these rules may be operated in parallel by connecting similarly marked leads together provided their angular displacements are the same and provided also their ratios, voltages, resistances, and reactances are such as to permit parallel operation.

6415 Location of H1 Lead.—To simplify the work of connecting transformers in parallel it is recommended that the *H 1* lead shall be brought out on the right hand side of the case, facing the high-voltage side of the case.

Three-Phase to Six-Phase Transformers.

6416 Rules that are Applicable for Three-Phase Transformers.—Sections **6411** (b) and **6413** shall apply to three-phase to six-phase transformers.

(6411-b) Any three phase transformer having a delta Y connection may be represented by voltage vector diagram either in accordance with Fig. 6-11 or Fig. 6-13. Any three phase transformer having Y delta connection may be represented by voltage vector diagram either in accordance with Fig. 6-12 or Fig. 6-14. Since these voltage vector diagrams are equivalent, it is recommended that the terminal markings for three phase transformers having delta Y connection be always made in accordance with Fig. 6-11 and that the terminal markings for three phase transformers having Y delta connection be always made in accordance with Fig. 6-12.

(6414) In some cases designs may be such as to permit parallel operation although, due to a difference in the number of tap leads, the leads to be connected together are not similarly marked.

Rules **6410** and **6412** shall apply to three-phase windings but not to six-phase windings.

6417 Markings of Six-Phase Leads.—The six leads which connect to the full-phase windings shall be marked *X1*, *X2*, *X3*, *X4*, *X5*, *X6* See Figs. 6-16 to 6-19 inclusive.

6418 Relation between Three-Phase and Six-Phase Windings.—(*a*) *General:* The markings shall be so applied that if the phase sequence of voltage on the three-phase side is in the time order *H1*, *H2*, *H3*, it is in the time order of *X1*, *X2*, *X3*, *X4*, *X5*, *X6* on the six-phase side.

(*b*) *Angular Displacement:* In order that the markings of lead connections between phases shall indicate definite phase relations, they shall be made in accordance with one of the four six-phase groups shown in Figs. 6-16 to 6-19 inclusive. The angular displacement between the high-voltage and low-voltage windings is the angle in each of the voltage vector diagrams from its neutral through *H1* and *X1* respectively.

6419* Tap Leads.—(*a*) *General:* Where tap leads from low-voltage windings are brought out of the case (neutral lead excepted), they shall be marked as follows:

(*b*) *Diametrical Connection:* Diametrical connection tap leads shall be marked from the two ends of each phase winding towards the middle or neutral point in the following order; *X7*, *X13*, etc., from *X1* towards neutral; *X8*, *X14*, etc., from *X2* towards neutral; *X9*, *X15*, etc., from *X3* towards neutral; *X10*, *X16*, etc., from *X4* towards neutral; *X11*, *X17*, etc., from *X5* towards neutral; *X12*, *X18*, etc., from *X6* towards neutral. See Fig. 6-20.

A tap from the middle point of any phase winding, not intended as a neutral, shall be given a number determined by counting from *X1*, *X2* or *X3* and not from *X4*, *X5*, or *X6*; *e.g.*, if the only taps brought out are 50 per cent starting taps, they shall be numbered *X7*, *X8*, and *X9*.

*(c) *Double Delta Connection:* Tap leads shall be marked in the following order; *X7*, *X13*, etc., from *X1* towards *X3*; *X8*, *X14*, etc., from *X2* towards *X4*; *X9*, *X15*, etc., from *X3* towards *X5*; *X10*, *X16*, etc., from *X4* towards *X6*; *X11*, *X17*, etc., from *X5* towards *X1*; *X12*, *X18*, etc., from *X6* towards *X2*. See Fig. 6-21.

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(6419-c) For starting purposes it is generally customary to bring out only two taps from one delta and start three-phase.

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CHAPTER VII.

STANDARDS FOR SWITCHING, CONTROL AND PROTECTIVE APPARATUS

The A. I. E. E. Standards for Switching Control and Protective Apparatus are the General Standards shown in Chapters II and III and the Standards in other Chapters which are applicable to the devices involved, together with the modifications and extensions given in this Chapter.

DEFINITIONS

Devices

7000* **Switching and Control Apparatus.**—For the purpose of these Standardization Rules switching and control apparatus is defined as electric apparatus whose function is primarily to control or protect in some predetermined manner electric apparatus to which it is connected.

7001 **Switch.**—A switch is a device for making, breaking or changing the connections in an electric circuit.

7002 **Master-Switch.**—A master-switch is a switch which serves to govern the operation of contactors and auxiliary devices of an electric controller.

7003 **Control Switch.**—A control switch is a switch for controlling electrically-operated switches and circuit breakers.

7004 **Auxiliary Switch.**—An auxiliary switch is a switch actuated by some main device, for signalling, interlocking, etc.

7005 **Circuit-Breaker.**—A circuit-breaker is a device (other than a fuse) constructed primarily for the interruption of a circuit under ***infrequent abnormal*** conditions.

7006 **Contactor.**—A contactor is a device for repeatedly establishing and interrupting an electric circuit under normal conditions.

7007* **Electric Controller.**—An electric controller is a device, or group of devices, which is designed to control in some predetermined manner the operation of the apparatus to which it is connected.

7008* **Motorstarter.**—A motorstarter is an electric controller designed for accelerating a motor to normal speed in one direction of rotation.

7009 **Automatic Motorstarter.**—An automatic motorstarter is a motorstarter designed to automatically control the acceleration of a motor.

(7000) The "National Electrical Code" of the National Fire Protection Association deals with certain circuit breakers up to 550 volts rating and switches and fuses up to 600 volts rating fuses.

(7007) A switch (see §7001) should not be called a controller.

(7008) A device designed for starting a motor in either direction of rotation is called a controller (see §7007).

7010 **Auto-Transformer Motorstarter.**—An auto-transformer motor-starter is a motor-starter having an auto-transformer to furnish a reduced voltage for starting. The device includes the necessary switching mechanism, and is frequently called a Compensator or Auto-Starter.

7015* **Fuse.**—A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

7016 **Relay.**—A relay is a device by means of which contacts in one circuit are operated by change in conditions in the same or other circuits.

7018 **Rheostat.**—A rheostat is a resistor which is provided with means for readily varying its resistance. See **§3064.**

7019 **Protective Reactor.**—A protective reactor (See **§3078**) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short circuit conditions.

7020* **Lightning Arrester.**—A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

7021 **Under-Voltage or Low-Voltage Release Switching and Control Apparatus.**—Under-voltage or low-voltage release switching and control apparatus is apparatus which, on the reduction or failure of voltage, operates to cause the interruption of power to the main circuit, but which does not prevent the re-establishment of the main circuit on return of voltage.

7022 **Under-voltage or Low-Voltage Protection Switching and Control Apparatus.**—Under-voltage or low-voltage protection switching and control apparatus is apparatus which, on the reduction or failure of voltage, operates to cause and maintain the interruption of power to the main circuit.

7023 **Phase-Failure Protection Switching and Control Apparatus.**—Phase-failure protection switching and control apparatus is apparatus which, on the failure of power in one wire of a polyphase circuit, operates to cause and maintain the interruption of power on the circuit.

7024 **Phase-Reversal Protection Switching and Control Apparatus.**—Phase-reversal protection switching and control apparatus is appara-

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(7015) Any terminals, tubes, etc., integral with this element are included as part of the fuse.

Fuses may be divided into two classes:

(a) Those designed to protect the circuit and apparatus both against short-circuit and against definite amounts of overload (*e. g.* fuses of the National Electric Code which open on 25 per cent overload.)

(b) Those designed to protect the system only against short circuits; (*e. g.* expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

(7020) Lightning arresters may be divided into two classes:

(a) Those intended to discharge for a very short time.

(b) Those intended to discharge for a period of several minutes.

tus which, on the reversal of the phase relations in a polyphase circuit, operates to cause and maintain the interruption of power on the circuit.

Characteristics of Devices

7030 **"Air" as a Prefix.**—The prefix "air" applied to a device which interrupts an electric circuit indicates that the interruption occurs in air.

7031 **"Oil" as a Prefix.**—The prefix "oil" applied to a device which interrupts an electric circuit indicates that the interruption occurs in oil.

7032 **Fume-Resisting.**—Fume-resisting switching and control apparatus is apparatus so constructed that it will not be readily injured by the specified fumes.

7033* **Drip-Proof.**—Drip-proof switching and control apparatus is apparatus so protected as to exclude falling moisture or dirt.

7034 **Dust-Proof.**—Dust-proof switching and control apparatus is apparatus so constructed or protected that the accumulation of dust within or without the device will not interfere with its successful operation.

7035 **Dust-Tight.**—Dust-tight switching and control apparatus is apparatus so constructed that the dust will not enter the enclosing case.

7036 **Explosion-Proof.**—Explosion-proof switching and control apparatus is apparatus so constructed that explosions of gas within the casing will not injure it or ignite inflammable gas outside it.

7037 **Gas-Proof.**—Gas-proof switching and control apparatus is apparatus so constructed or protected that the specified gas will not interfere with its successful operation.

7038 **Gas-Tight.**—Gas-tight switching and control apparatus is apparatus so constructed that the specified gas will not enter the enclosing case.

7039 **Moisture-Resisting.**—Moisture-resisting switching and control apparatus is apparatus so constructed or treated that it will not be readily injured by moisture. (Such apparatus shall be capable of operating in a very humid atmosphere, such as found in mines, evaporating rooms, etc.).

7040 **Splash-Proof.**—Splash-proof switching and control apparatus is apparatus so constructed or protected that external splashing will not interfere with its successful operation.

7041 **Submersible.**—Submersible switching and control apparatus is apparatus so constructed that it will operate successfully when submerged in water under specified conditions of pressure and time.

7042 **Sleet-Proof.**—Sleet-proof switching and control apparatus is apparatus so constructed or protected that the accumulation of sleet will not interfere with its successful operation.

(7033) Drip-proof apparatus may be either open or semi-enclosed, if it is provided with suitable protection integral with the apparatus, or so enclosed as to exclude effectively falling solid or liquid material.

Parts of Devices

7050 Conducting Parts.—Conducting parts of switching and control apparatus are those designed to carry current or which are conductively connected therewith.

7051 Contact.—A contact is a surface common to two conducting parts, united by pressure, for the purpose of carrying current.

7052 Magnet Brake.—A magnet brake is a friction brake controlled by electro-magnetic means.

7053 Grounded Parts.—Grounded parts are those parts which may be considered to have the same potential as the earth.

Properties of Devices.

7060 Interrupting Rating.—Interrupting (breaking or rupturing) rating is a rating based upon the r. m. s. current at normal voltage which the device can interrupt under prescribed conditions at stated intervals a specified number of times.

OPERATION

Temperature Limits

7101* Circuit Breakers, Relays and Switches.—The maximum observable temperature rises of the various parts of circuit breakers, relays and switches shall not exceed the following limits for ambient temperatures up to and including but not greater than 40°C. See **§7301.**

Contacts in air, when clean and bright	30°C.
Oil and contacts therein	30°C.
Coils, if insulation is of unimpregnated fibrous material	35°C.
Coils, if insulation is of fibrous material treated to withstand heat	50°C.
Coils, if insulation is of asbestos, mica or similar heat resisting material	70°C.

Coils on which a thermometer can be applied directly to the surface of the bare winding, such as those having bare edgewise strip conductors, shall be allowed 10°C. higher maximum observable temperature rise than permitted above for each kind of insulation.

Other parts: All other parts than those whose temperature affects the temperature of the insulating material may be operated at such temperatures as shall not be injurious in any other respect.

7102 Magnetic Contactors.—The maximum observable temperature rises of the various parts of magnetic contactors shall not exceed the following limits for ambient temperatures up to and including but not greater than 40° C. See **§7302.**

Laminated contacts	65°C.
Operating coils	70°C.
Solid contacts	100°C.

(7101) The Institute calls attention to the inherent decrease in current which can be carried by switch and circuit breaker contacts in air, due to oxidization of the contact surfaces. The rating of air switches and circuit-breakers is, therefore, based on sufficient maintenance to keep the temperature rise within the specified limits. Relays which form part of controllers are to have the temperature limits specified in §7102.

Current-carrying parts insulated with asbestos or other fireproof material.................................. 150°C.

7105* **Fuses.**—The maximum observable temperature rise of coils or windings, measured by thermometer, shall not exceed the following limits for ambient temperatures up to and including but not greater than 40°C.

If insulation is of unimpregnated fibrous material......... 35°C.
If insulation is of fibrous material treated to withstand heat 50°C.
If insulation is of asbestos, mica or similar heat resisting material with a cotton binder........................ 70°C.

7106 **Cast Grid Resistors.**—The maximum observable temperature rises of cast grids used as resistors shall not exceed 350°C. for ambient temperatures up to and including but not greater than 40°C.

RATING

Expression of Rating

7201 **Rating of Circuit Breakers and Switches.**—The rating of a circuit breaker or switch shall include the following items:

(a) the normal r. m. s. current which it is designed to carry.

(b) the normal r. m. s. pressure (voltage) of the circuit on which it is intended to operate.

(c) the normal frequency of the current.

(d) the interrupting rating of the device. See **§7060.**

7202 **Continuous Current-Carrying Capacity of Fuses.**—Fuses shall be so constructed that they will carry continuously 110 per cent of their rated current.

7205 **Rating of Lightning Arresters.**—The rating of a lightning arrester shall be the voltage of the circuit on which it is to be used.

TESTS

Heat Tests

7301 **Circuit-Breakers, Relays and Switches.**—The rated current of circuit-breakers, relays and switches at rated frequency shall be applied continuously until the temperature becomes constant. The temperature rises measured by thermometer shall not exceed the limits specified in **§7101.**

7302 **Magnetic Contactors.**—The rated current of magnetic contactors at rated frequencies shall be applied continuously or until the temperature becomes constant when continuous duty is specified. It shall be applied for the specified length of time when given a short time rating. The temperature rises measured by thermometer shall not exceed the limits specified in **§7102.**

Tests of Dielectric Strength

7323* **Standard Test Voltage.**—(*a*) *Apparatus rated at* 600 *volts or less:* The standard test voltage for all switching and control apparatus

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(7105) Coils or windings such as accompany fuses of the magnetic blow-out type.

(7323) This assumes a precipitation of 1/10th inch (2.54 mm.) per minute at an angle of 45° from the perpendicular with water having a resistivity as low as 7000 ohm-centimeters.

rated at 600 volts or less shall be twice the normal voltage of the circuit to which the apparatus is to be connected plus 1000 volts.

(*b*) *Apparatus rated above* 600 *volts*: Apparatus rated above 600 volts shall be tested at 2¼ times rated voltage, plus 2000 volts, at a specified altitude.

*As a supplementary test, devices for outdoor use should be capable of withstanding for 10 seconds a dielectric wet test at twice rated voltage plus 1000 volts.

(*c*) *Auto-Transformers for Motorstarters*: Auto-transformers for motorstarters shall be tested with the same voltage as the test voltage of the apparatus to which they are to be connected.

Tests of Lightning Arresters.

7371 Resistance.—The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

7372 Arrester with Gap.—In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60 cycle a-c. excitation.

7373 Equivalent Sphere Gap.—The equivalent sphere gap under disruptive discharge shall be measured, using a considerable quantity of electricity.

7374 Continuous Surges.—The endurance of the arrester to continuous surges shall be tested.

7375 Dielectric Strength.—See §§ **2355** and **7323**.

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CHAPTER VIII.

STANDARDS FOR METERS, INSTRUMENTS AND INSTRUMENT TRANSFORMERS

The A. I E. E. Standards for Meters, Instruments and Instrument Transformers are the General Standards shown in Chapters II and III, and the Standards in other Chapters which are applicable to the devices involved, together with the modifications and extensions given in this Chapter.

DEFINITIONS.

8000* Meter. A meter is a device which registers through a totalizing mechanism, the integral, with respect to time, of the electrical quantity to which it responds. (This definition does not preclude the general use of "meter" as a suffix or in compound words, to mean a "measuring device.")

8001* Instrument. An instrument is a device which indicates or records the present value of the quantity under observation.

8002 General Nomenclature. In general, the names of meters and instruments are self-defining. The following names are preferred to others sometimes used for the same devices: Reactive-Factor Meter, Power-Factor Meter, Watthour Meter, Reactive Volt-Ammeter (or Reactive Volt-Ampere Indicator) etc.

8003 Recording Instruments. Recording ammeters, voltmeters, wattmeters, etc. are instruments which record graphically, upon time charts, the values of the quantities they measure.

8004 Crest Voltmeter. A crest voltmeter is a voltmeter depending for its indications upon the crest, or maximum value of the voltage of the system to which it is connected. Crest voltmeters shall be marked in true crest volts and also in the r. m. s. value of the sinusoidal wave having the same crest value. (See **§2362.**)

8005 Synchronoscope (also called a Synchroscope or Synchronism Indicator). A synchronoscope is a device which indicates synchronism between two machines, and in addition shows whether the incoming machine is fast or slow.

8006 Line-Drop Voltmeter Compensator. A line-drop voltmeter compensator is a device used in connection with a voltmeter which causes the latter to indicate the voltage at some distant point of the circuit.

(8000 & 8001) While the word "instrument" is a general term which may properly include indicating, integrating and recording devices, there is a tendency to restrict its use to indicating devices and to recording (graphic or curve drawing) devices. Integrating devices are then denoted by the word "meter." This distinction gives rise to the above general definitions.

8007 Demand-Meter. (a) *General*: A demand-meter is a device which indicates or records the demand or maximum demand. In practise, two types are recognized. See §§ **3454, 3458, 3460** and **3464.**

(*b*) *Integrated-Demand-Meter*: An integrated-demand-meter is a demand-meter which indicates or records the maximum demand obtained through integration.

(*c*) *Lagged-Demand-Meter*: A lagged-demand-meter is a demand-meter in which the indication of maximum demand is subject to a characteristic time lag.

8020* Period of an Instrument. The period of an instrument, sometimes called the "periodic time," is the time taken for the pointer to make one complete oscillation (two consecutive swings). A swing is a complete movement in either direction.

8030 Instrument Transformer. An instrument transformer is a transformer suitable for use with measuring instruments; that is, one in which the conditions of phase and of current or potential in the primary circuit, are represented with acceptable accuracy in the secondary circuit. An instrument transformer may be either an instrument current transformer or an instrument potential (voltage) transformer.

8031* Secondary Burden. The secondary burden of a current transformer is an expression in ohms and henrys of the resistance and inductance of the external circuit connected to the secondary of that transformer.

8032 Voltage Ratio of Instrument Transformer. The voltage ratio of an instrument potential transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified secondary burden.

8033 Current Ratio of Instrument Transformer. The current ratio of an instrument current transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified secondary burden.

8034 Marked Ratio of Instrument Transformer. The marked ratio of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage or current, frequency, load and secondary burden.

OPERATION.

8101 Permissible Temperature in Shunts.—(*a*) *General*: The limiting observable temperature of shunts measured by Method I shall not exceed 120°C.

(b) *Exceptions*: The above rule shall not apply to shunts having no soldered joint and made of material which is not per-

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(8020) In strongly damped instruments, the period is influenced by the amplitude of the movement.

(8031) Considerable uncertainty of meaning has been occasioned by the use of the terms, load, secondary load, and secondary connected load for this quantity, and such use is discouraged.

manently changed in resistance if continuously subjected to a higher temperature.

8110 **Grounding of Meters and Instruments.** The covers of meters and instruments, which are used with current and potential transformers, shall be connected to the grounded sides of the secondary circuits of such transformers in all cases where the indications of the instrument are liable to be influenced by electrostatic action.

8111 **Instrument Current Transformers on Open Secondary Circuit.** Under conditions of open secondary circuit, current transformers shall be capable of carrying continuously rated primary current without damage to the primary insulation and without interruption of service.

8112 **Instrument Current Transformers on Closed Secondary Circuit.** Under conditions of closed secondary circuit, current transformers shall withstand 40 times rated current applied for 1 second, without injury.

RATING

8200 **General.** The rating of a meter is a designation assigned by the manufacturer to indicate its operating limitations. The full scale marking of an instrument does not necessarily correspond to its rating, but if the rating differs from the full scale marking, the rating shall be marked on the instrument.

8201 **Standard Ambient Temperature.**—For purposes of rating meters and shunts, the standard ambient temperature shall be 40°C. See §§**8301** and **2211.**

8202 **Rating Limitation of the Circuits of Meters and Instruments.** No circuit of a meter or instrument shall be given a rating higher than that corresponding to the maximum current or voltage to which it may be continuously subjected.

8203* **Temperature Rise of Meter and Instrument Windings.** The permissible temperature rises in meters and instruments shall be based upon the temperatures specified in §**1005** and the standard ambient temperature of 40° C.

8204 **Temperature Rise in Shunts.** Shunts shall be rated in accordance with their observable temperature rise by Method 1, assuming the ultimate temperatures specified in §**8101** and an ambient temperature specified in §**8201.**

TESTS.

8300 **Measurement of Temperature Rise of Shunts.** Observable temperature shall be measured in such a manner as not to cause local change of temperature.

8301 **Standard Temperature of Reference for Meter and Instrument Characteristics.** The standard temperature of reference for meter and instrument characteristics shall be 20° C. See §§**8201, 2211.**

(8203) Heating is frequently an immaterial consideration in determining the rating of meters and instruments. Losses, impairment of accuracy and other factors often determine the rating.

8302 **Damping.** The pointer being at zero before any load is applied, damping shall be measured by suddenly applying and maintaining a load which will give a steady deflection of one-half full angular scale, and observing the following quantities:

(*a*) The number of swings taken by the pointer in coming to rest.

(*b*) The time, in seconds, required for the pointer to come to rest.

(*c*) The overshooting, in per cent of the angular displacement due to the disturbance.

Dielectric Strength of Instrument Transformers.

8310 **Test Voltage Instrument Potential Transformers.** The test voltage for instrument potential transformers shall be twice the normal voltage of the circuit to which it is connected plus 1000 volts.

8311 **Test Voltage of Instrument Current Transformers.** The test voltage of instrument current transformers shall be 2¼ times the rated voltage plus 2000 volts.

8312 **Test Voltage for Meters and Instruments.** (The Institute is not at present in a position to make recommendations.)

SPECIFICATION OF CHARACTERISTICS.

8500 **Errors of Indicating Instruments.** In specifying the accuracy of an indicating instrument, the error at any point on the scale shall be expressed as a percentage of the full scale reading.

8501 **Torque.** The torque of meters and instruments shall be expressed in millimeter-grams.

8502 **Damping.** The damping of an instrument shall be expressed in terms of the quantities enumerated in §8302, all three of which are essential to a complete description.

8503* **Marking of Switchboard Shunts.** The marking of switchboard shunts shall include the rating in amperes, the drop in volts at that rating, and the serial number of any instrument in connection with which the shunt may be calibrated. When shunts are designed to be used with devices taking sufficient current to be an appreciable proportion of the whole, this fact shall be indicated.

BIBLIOGRAPHY.

United States.

Association of Edison Illuminating Companies and National Electric Light Association: Joint Meter Code.

Bureau of Standards, Circular No. 56, entitled "Standards for Electric Service."

Foreign

British Engineering Standards Association: Standard Specifications for Indicating Ammeters, Voltmeters and Wattmeters; Standard Specifications for Recording (Graphic) Ammeters, Voltmeters, and Wattmeters, Standard Specifications for Instrument Transformers; Standard Specifications for Electricity Meters.

(8503) For example, if with 100 amperes rated load in the main circuit, a measuring device takes 10 amperes, leaving 100 less 10 amperes in the shunt with a drop of 0.050 volts, the shunt shall be marked: Volts 0.050. Amperes 100 less 10.

CHAPTER IX.

STANDARDS FOR WIRES AND CABLES

DEFINITIONS.

9000* **Wire.**—A wire is a slender rod or filament of drawn metal.

9001* **Conductor.**—A conductor is a wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

9002* **Stranded Conductor.**—A stranded conductor is a conductor composed of a group of wires, or of any combination of groups of wires.

9003 **Strand.**—A strand is one of the wires, or groups of wires, of any stranded conductor.

9004* **Cable.**—A cable is either a stranded conductor (single-conductor cable), or a combination of conductors insulated from one another (multiple-conductor cable).

9005* **Stranded Wire.**—A stranded wire is a group of small wires, used as a single wire.

(9000) The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

(9001) The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents. Rolled conductors (such as bus-bars) are, of course, conductors, but are not considered under the terminology here given.

(9002) The wires in a stranded conductor are usually twisted or braided together.

(9004) The first kind of cable is a single conductor, while the second kind is a group of several conductors. The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. The term "cable" is applied by some manufacturers to a solid wire heavily insulated and lead-covered; this usage arises from the manner of the insulation, but such a conductor is not included under this definition of "cable." The term "cable" is a general one, and in practise, it is usually applied only to the larger sizes. A small cable is called a "stranded wire" or a "cord", both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead, or with steel wires or bands.

(9005) A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used as a single wire, it is called a "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable". If used as a wire, for example in winding inductance coils or magnets, it is called a stranded wire and not a cable. If it is substantially insulated, it is called a "cord", defined below.

9006* **Cord.**—A cord is a small cable, very flexible and substantially insulated to withstand wear.

9007 **Concentric Strand.**—A concentric strand is a strand composed of a central core surrounded by one or more layers of helically-laid wires or groups of wires.

9008 **Concentric-Lay Cable.**—A concentric-lay cable is a single-conductor cable composed of a central core surrounded by one or more layers of helically-laid wires.

9009* **Rope-Lay Cable.**—A rope-lay cable is a single-conductor cable composed of a central core surrounded by one or more layers of helically-laid groups of wires.

9010* **N-Conductor Cable.**—An N-conductor cable is a combination of N conductors insulated from one another.

9011* **N-Conductor Concentric Cable.**—An N-conductor concentric cable is a cable composed of an insulated central conductor with (N-1) tubular stranded conductors laid over it concentrically and separated by layers of insulation.

9012* **Duplex Cable.**—A duplex cable is a cable composed of two insulated stranded conductors twisted together.

9013 **Twin Cable.**—A twin cable is a cable composed of two insulated stranded conductors laid parallel, having a common covering.

9014 **Twin Wire.**—A twin wire is a cable composed of two small insulated conductors laid parallel, having a common covering.

9015* **Triplex Cable.**—A triplex cable is a cable composed of three insulated single-conductor cables twisted together.

9016* **Twisted Pair.**—A twisted pair is a cable composed of two small insulated conductors, twisted together, without a common covering.

9017* **Sector Cable.**—A sector cable is a multiple-conductor cable in which the cross-section of each conductor is substantially a sector, an ellipse, or a figure intermediate between them.

9018 **Round Conductor.**—A round conductor is either a solid or stranded conductor of which the cross-section is substantially circular.

(9006) There is no sharp dividing line in respect to size between a "cord" and a "cable," and likewise no sharp dividing line in respect to the character of insulation between a "cord" and a "stranded wire." Rubber is used as the insulating material for many classes of cords.

(9009) This kind of cable differs from the preceding in that the main strands are themselves stranded.

(9010) It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable" etc. In referring to the general case, one may speak of a "multiple-conductor cable" (as in §9004 above.)

(9011) This kind of cable usually has only two or three conductors. Such cables are used particularly for alternating currents. The remark on the expression "N-conductor" given for the preceding definition also applies here.

(9012) They may or may not have a common insulating covering.

(9015) They may or may not have a common insulating covering.

(9016) The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

(9017) Sector cables are used in order to obtain decreased overall diameter and thus permit the use of larger conductors in a cable of given diameter.

9019* **Split Conductor.**—A split conductor is a conductor which is divided into two or more parts, separated from one another by insulation which is thin compared with the insulation around the conductor.

9030 **Factor of Assurance.**—The factor of assurance of wire or cable insulation is the ratio of the voltage at which it is tested to that at which it is used.

9031 **Insulation Resistance.**—The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

9032* **Circular Mil.**—A circular mil is a unit of area equal to $\frac{\pi}{4}$ ($=0.7854\ldots$) of a square mil. The cross-sectional area of a circle in circular mils is therefore equal to the square of its diameter in mils. A circular inch is equal to a million circular mils.

9033* **Lay.**—The lay of any helical element of a cable is the axial length of a turn of the helix of that element.

9034 **Direction of Lay.**—The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

ANNEALED COPPER STANDARD

9050* **Standard Annealed Copper.**—(*a*) *General:* The following shall be taken as normal values for standard annealed copper.

(*b*) *Resistance:* At a temperature of 20° C., the resistance of a wire of standard annealed copper one meter in length and of a uniform section of 1 square millimeter is $1/58$ ohm $= 0.017241\ldots.$ohm.

(*c*) *Density.* At a temperature of 20°C., the density of standard annealed copper is 8.89 grams per cubic centimeter.

(*d*) *Temperature Coefficient of Resistance:* At a temperature of 20°C., the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between two potential points

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(9019) The term split conductor usually designates a conductor in two parts or splits, which may be either concentric or external to one another.

(9032) A mil is the one-thousandth part of an inch. There are 1974 circular mils in a square milimeter.

(9033) Among the helical elements of a cable may be each strand in a concentric-lay cable, or each insulated conductor in a multiple conductor cable.

(9050) See I. E. C. Publication No. 28, "International Standard of Resistance for Copper", March, 1914.

Paragraphs (b) and (e) define what are sometimes called "Volume Resistivity" and "Mass Resistivity", respectively. This may be expressed in other units as follows:

Volume Resistivity $=1.7241$ microhms–cm. (microhms in a centimeter cube) at 20° C.

Mass Resistivity $=$ 875.20 ohms (mile, pound) at 20° C.

For detailed specifications of commercial copper see the Standard Specifications of the American Society for Testing Materials.

rigidly fixed to the wire, is $0.00393 = 1/254.45\ldots.$ per degree centigrade.

(*e*) *Resistance of Standard Annealed Copper at* 20° *C:* As a consequence, it follows from (*a*) and (*b*) that, at a temperature of 20° C. the resistance of a wire of standard annealed copper of uniform section, one meter in length and weighing one gram, is $(1/58) \times 8.89 = 0.15328\ldots.$ ohm.

OPERATION

Temperature Limits.

9100* Maximum Temperatures.—The temperature of the insulation of a wire or cable at the surface of the conductor shall not be allowed to exceed the following values.

Let t = maximum safe temperature

E = r. m. s. operating electromotive force in kilovolts between conductors

Impregnated paper, $t = 85 - E$

Varnished cambric, $t = 75 - E$

Rubber insulation, $t = 60 - \frac{E}{4}$

DESIGNATION

9200 Designation of Wires by Diameter or Gage Number.—The sizes of wires shall be stated by their diameters in mils, the American Wire Gage (Brown and Sharpe) sizes being taken as standard. For brevity, in cases where the most careful specification is not required, the sizes of wires may be stated by the gage number in the American Wire Gage.

9201 Designation of Cables by Cross-Sectional Area.—The sizes of stranded conductors shall be stated by their cross-sectional area in circular mils or circular inches, except in the case of flexible stranded conductors, for which see §9402. The cross-sectional area of a

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(9100) For example: At a working pressure of 3.3 kv., the maximum safe limiting temperature at the surface of the conductor, or conductors, in a cable would be as follows:

For	impregnated paper	81.7°C.
"	varnished cambric	71.7°C.
"	rubber insulation	59.2°C.

The life of the insulation of a cable depends in a great measure upon the actual temperature attained by the insulation. The result of operating at temperatures in excess of the safe limit is to shorten the life of the insulating material. When the safe limits are exceeded, deterioration is rapid and permanent, the damage increasing with the length of time that the excessive temperature is maintained and with the amount of excess temperature until finally the insulation breaks down.

Some of the older types of cable for voltages above 7500 have a dielectric loss that is so high that it may add considerably to the heating that would otherwise result. In such cases the dielectric loss is a material factor in determining the safe load to be carried by the cable, and the safe operating temperature will be determined by the temperature at which cumulative heating occurs under the conditions of service, if this occurs at a lower temperature than that at which the insulation deteriorates.

cable shall be considered to be the sum of the cross-sectional areas of its component wires, when measured perpendicular to their axes. The sizes of stranded conductors smaller than 250,000 circular mils (*i.e.*, No. 0000 A.W.G. or smaller) may be stated by means of the gage number of a solid wire having the same cross-sectional area.

9202* **Conductivity.**—The conductivity of the metal of wires shall be expressed in terms of the conductivity of the Annealed Copper Standard, as defined in §9050.

9203* **Copper-Wire Tables.**—The copper-wire Tables published by the Bureau of Standards in Circular No. 31 are adopted. Table VI therein gives the values of diameters and cross-sections of A. W. G. sizes to four significant figures. These Tables are based upon the Annealed Copper Standard described in §9050.

TESTS.

General

9300 **Cable Lengths Tested.**—Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

9301 **Immersion in Water.**—(*a*) *General:* The outer surface of the insulation of complete insulated wires and cables shall be grounded while being electrically tested. If the insulation is not provided with a conducting covering, and if the covering is not liable to injury by water, the ground shall be obtained by immersing the insulated wire or cable in water for at least twelve hours and testing at the end of that period while immersed. If the outer covering is susceptible to injury by immersion, the insulated conductor shall be tested before the application of such covering.

Dry core paper insulated lead covered cables, such as telephone and telegraph cables, for use in water, shall be tested after at least twelve hours immersion.

(b) *Multiple-Conductor Cable:* In the case of multiple-conductor cables, without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

Tests of Dielectric Strength

9310 **Object of Tests.**—High voltage tests are intended to detect weak spots in the insulation and to determine whether its

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(9202) For any given wire, let

C = conductivity, in per cent of Annealed Copper Standard
L = length, meters
R = resistance, ohms
W = weight, grams
t = temperature, degrees centigrade

Then the conductivity may be derived from the following formula:

$$C = \frac{15.328}{\frac{WR}{L^2} + 0.000597\,(20 - t)}$$

(9203) For detailed specifications of commercial copper, see the Standard Specifications of the American Society for Testing Materials.

dielectric strength is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

9311 Nature of Tests.—High-voltage tests shall be made at the factory, by applying an alternating voltage between the conductor and sheath or water. The initially applied voltage must not be greater than the working voltage, and the rate of increase shall be approximately uniform and not over 100 per cent in 10 seconds.

9312* Magnitude and Duration of the Test Voltage.—(a) *General:* Wires and cables shall be tested at the place of manufacture for five consecutive minutes, except as provided in § **9312** (b) and (f).

(*b*) *Rubber Insulation, National Electrical Code:* Rubber covered wires and cables for working pressures up to 600 volts alternating, insulated in accordance with the requirements of the National Electrical Code, shall be tested in accordance with that Code.

(*c*) 30% to 40% *Hevea Rubber Insulation for Pressures up to* 600 *Volts, a-c.*: Wires and cables for working pressures up to 600 volts alternating, insulated with 30% to 40% Hevea rubber compound, unless the insulation thickness is less than specified in **§9405**, shall be tested in accordance with Table 901.

TABLE 901

High Voltage Tests for Rubber Insulated Wires and Cables.

(30% to 40% Hevea Rubber Insulation for working pressures up to 600 Volts a-c.)

Size A. W. G. or Cir. Mils.	Size Sq. mm.	Test pressure kilovolts
14–8	2.081 - 8.366	3.0
7–0000	10.55 -107.2	3.5
250,000 & larger	127 and larger	4.0

(*d*) *Thirty to Forty per cent Hevea Rubber Insulation for Pressures over* 600 *Volts A-C:* Wires and cables insulated with 30% Hevea rubber compound for working pressures over 600 volts alternating, shall be tested with one kilovolt per 64th inch of thickness (2.53 kv, per mm.) up to 10/64th inch, (3.96 mm.) Above 10/64ths inch, (3.96 mm.), the test pressure shall be 10 kilovolts plus 1.5 kilovolts per 64th inch (3.79 kv. per mm.) additional up to 30/64ths inch (11.89 mm.). Where the insulation thickness is 16/64ths inch (6.34 mm.) or over, this rule shall apply only to conductors over 26,000 cir. mils (13.2 sq. mm.) area.

(e) *Varnished Cambric and Impregnated Paper Insulation:* Varnished cambric and impregnated paper insulated wires or cables shall be tested in accordance with Table 902.

(9312-c) Hevea rubber is rubber from the Hevea Brasiliensis tree. Compounds containing 30 to 40% of Hevea rubber have electrical and mechanical properties superior to compounds insulated in accordance with the requirements of the National Electric Code.

(9312-e) Different engineers specify different thickness of insulation for the same working voltages. Therefore, at the present time the test kv. corresponding to working kv. given in Table 902, are based on the *minimum* thickness of insulation specified by engineers and operating companies.

TABLE 902

High-Voltage Tests for Varnished Cambric or Impregnated Paper Insulated Cables.

(Minimum Values.)

Operating kv.	Test kv.	Operating kv.	Test kv.
Below 0.5	2.5*	5	14
0.5	3	7.5	19.5
1	4	10	25
2	6.5	over 10	2½ times operating pressure
3	9		
4	11.5		

*The minimum thickness of insulation shall be 1/16 in. (1.6 mm.)

For intermediate working voltages, the test voltage shall be interpolated.

(*f*) *Telephone, Telegraph and Annunciator Wires and Cables*: Section **9312** shall not apply to wires and cables for telephone, telegraph, annunciator and similar devices.

9313 Frequency of Test Voltage.—The frequency of the test voltage shall not exceed 100 cycles per second, and should approximate as closely as possible to a sine wave. The source of energy should be of ample capacity.

9314 Dielectric Strength Tests.—Ultimate dielectric strength tests, when required, shall be made on samples not more than 6 meters (20 ft.) long. The maximum allowable temperature, at which the test is made, for the particular type of insulation and the particular working pressure, shall be not greater than the temperature limits given in **§9100.**

9315 Multiple-Conductor Cables.—If a multiple conductor cable is designed for the same operating voltage between conductors and sheath or water as between conductors, each conductor shall be tested against the other conductors connected together and to the sheath or water. If the cable is designed for an operating voltage between conductors and ground different from that between conductors, the test between conductors and the sheath or water shall be made separately and shall be based on the normal operating voltage between conductors and sheath or water as prescribed in **§9312.**

Insulation Resistance

9320* Expression of Insulation Resistance.—Insulation resistance shall be expressed in megohms. Linear insulation resistance, or the insulation resistance of unit length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet, and shall be corrected to a temperature of 15.5° C., using a

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(9320) In the case of dry core paper insulated cables, the temperature coefficient of insulation resistance cannot be closely determined on account of variations in design and manufacture. Therefore no temperature corrections shall be applied to insulation resistance tests. Tests should be made at a temperature of 15.5 ° C. or higher.

temperature coefficient determined experimentally for the insulation under consideration.

9321 Megohms Constant.—The megohms constant of an insulated conductor shall be the factor "K" in the following equation:

$$R = K \log_{10} \frac{D}{d}$$

where R = insulation resistance, in megohms, for a specified unit length.

D = outside diameter of insulation.

d = diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

9322 Measurement of Insulation Resistance.—The apparent insulation resistance should be measured after the high-voltage test, measuring the leakage current after a one-minute electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained negative to the sheath or water.

9323 Insulation Resistance of Multiple-Conductor Cables.—The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from each conductor to all the other conductors in multiple with the sheath or water.

Capacitance or Electrostatic Capacity

9330* Expression of Capacitance.—Capacitance shall be expressed in microfarads. Linear capacitance, or the capacitance of unit length, shall be expressed in microfarads per unit length (kilometer, or mile, or one thousand feet), and shall be corrected to a temperature of 15.5° C., using a temperature coefficient determined experimentally for the insulation under consideration.

9331 Microfarads Constant.—The microfarads constant of an insulated conductor shall be the factor "K" in the following equation:

$$C = \frac{K}{\operatorname{Log}_{10} \frac{D}{d}}$$

where C = capacitance in microfarads per unit length.

D = outside diameter of insulation.

d = diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

(9330) In the case of dry core paper insulated cables, the temperature coefficient of capacitance cannot be determined closely on account of variations in design and manufacture. Therefore no temperature corrections shall be applied to capacitance tests. Tests should be made at a temperature of 15.5° C. or higher.

TABLE 903

Proposed Standard Cables

(This table is offered for consideration but will not be recommended for final adoption until ratified by other societies interested.)

Strands			Total nominal cross section circular mils	Total diam. inches
	Individual wires			
Number & Size. See Note 4.	Nominal diam. mils	Nominal cir. mils.		
127 No. 8	128.5	16,510	2,097,000	1.671
127 No. 9	114.4	13,090	1,662,000	1.487
91 No. 8	128.5	16,510	1,502,000	1.414
91 No. 9	114.4	13,090	1,191,000	1.258
61 No. 8	128.5	16,510	1,007,000	1.157
61–121 mils	121.0	14,641	893,100	1.089
61 No. 9	114.4	13,090	798,500	1.030
61–107 mils	107.0	11,449	698,400	.963
61 No. 10	101.9	10,380	633,200	.917
37–116 mils	116.0	13,456	497,900	.812
37 No. 10	101.9	10,380	384,100	.713
37–97 mils	97.0	9,409	348,100	.679
37 No. 11	90.74	8,234	304,700	.635
19 No. 9	114.4	13,090	248,700	.572
19–107 mils	107.0	11,449	217,500	.535
19 No. 11	90.74	8,234	156,400	.454
19 No. 12	80.81	6,530	124,100	.404
19 No. 13	71.96	5,178	98,380	.360
19 No. 14	64.08	4,107	78,030	.320
7 No. 10	101.9	10,380	72,660	.306
7 No. 11	90.74	8,234	57,640	.272
7 No. 12	80.81	6,530	45,710	.242
7 No. 14	64.08	4,107	28,750	.192
7 No. 16	50.82	2,583	18,080	.152
7 No. 18	40.30	1,624	11,370	.121
7 No. 20	31.96	1,022	7,154	.096
7 No. 22	25.35	642.4	4,497	.076
7 No. 24	20.10	404.0	2,828	.060

Note 1. Nominal diameters and circular mils of the individual wires are taken from Table VI, circular No. 31 of the Bureau of Standards.

Note 2. The variation of the mean diameter of any wires shall not exceed 1 per cent above or below the nominal diameter.

Note 3. The variation of the total cross-section of the cable shall not exceed 1 per cent above or below the nominal cross-section.

Note 4. Sizes are expressed as A. W. G. numbers except where diameters are given in mils.

9332 Measurement of Capacitance.—The capacitance of cable shall be measured with alternating current by comparison with a standard condenser. It is preferable that the measurement be made either at a frequency approximating that of operation or at a frequency giving results approximating those corresponding to the operating frequency or frequencies.

9333 Capacitance of Paired Cables.—The capacitance of paired cables shall be measured between the two conductors of any pair, the other wires being connected to the sheath or ground.

9334 Capacitance of Multiple-Conductor Cables (not paired).—The capacitance of multiple conductor (not paired) cables shall be measured between conductors, and also between each conductor and the other conductors connected to the sheath or ground.

CONSTRUCTION

Stranding

9400* Proposed Standard Cables.—Insulated cables not requiring special flexibility shall be made of the number and size strands specified in Table 903.

9401 Cables not Requiring Special Flexibility.—Cables not requiring special flexibility and not made in accordance with §9400 shall be stranded in accordance with Table 904.

TABLE 904

Standard Stranding of Concentric-Lay Cables

SIZE (See note 1.)	Sq. mm.	Number of Wires (See note 2)	
		A Bare, insulated or weatherproof cables for aerial use.	B Insulated cables for other than aerial use.
2.0 Cir. Inches	1013	91	127
1.5 "	760	61	91
1.0 "	507	61	61
0.6 "	304	37	61
0.5 "	253	37	37
0.4 "	203	19	37
0000 A. W. G.	107	19 or 7 (See note 3.)	19
00 "	67.4	7	19
2 "	33.6	7	7
7 and smaller	10.5	..	7

Note 1. For intermediate sizes, use stranding for next larger size.

Note 2. Conductors of 0000 A. W. G. and smaller are often made solid and this table of stranding should not be interpreted as excluding this practice.

Note 3. Class A cable, sizes 0000 and 000 A. W. G., is usually made of 7 strands when bare and 19 strands when insulated or weatherproof.

(9400) The basis of this rule is the use of strands of American Wire Gage sizes. To meet existing operating conditions, four sizes of strands other than American Wire Gage sizes have been deemed necessary and their diameters are shown in mils.

9402* Flexible Cables.—Conductors of special flexibility should ordinarily be made with wires of regular A.W.G. sizes, and rated by the number and size of wires. The stranding of flexible cables is given in Table 905.

TABLE 905

Stranding of Flexible Cables

Nearest A.W.G. size (see Note 1)	Circular mils (see Note 2)	Diam. of cable, mils	No. of wires	Size of each wire		Construction (see Note 3)
				A.W.G.	Diam. mils	
..	2039000	1885.	703	15.5	53.9	37 × 19
..	1816000	1779.	"	16.0	50.8	"
..	1617000	1679.	"	16.5	48.0	"
..	1440000	1584.	"	17.0	45.3	"
..	1284000	1496.	"	17.5	42.7	"
..	1103000	1372.	427	16.0	50.8	61 × 7
..	874600	1222.	"	17.0	45.3	"
..	693600	1088.	"	18.0	40.3	"
..	550000	969.	"	19.0	35.9	"
..	436200	863.	"	20.0	32.0	"
..	345900	768.	"	21.0	28.5	"
..	274300	684.	"	22.0	25.3	"
..	264600	671.	259	20.0	32.0	37 × 7
0000	209800	598.	"	21.0	28.5	"
000	171300	538.	133	19.0	35.9	19 × 7
00	135900	479.	"	20.0	32.0	"
0	107700	427.	"	21.0	28.5	"
1	82780	332.	91	20.5	30.2	Concentric
2	65650	295.	"	21.5	26.9	"
3	52060	263.	"	22.5	23.9	"
4	39190	228.	61	22.0	25.3	"
5	31080	203.	"	23.0	22.6	"
6	24650	181.	"	24.0	20.1	"
8	17410	152.	"	25.5	16.9	"
10	10560	118.	37	25.5	16.9	"
12	6640	94.	"	27.5	13.4	"
14	4176	74.	"	29.5	10.6	"
Smaller	....	....	To equal Required Size	30.0	....	Bunched

NOTE 1. The A.W.G. cross-sectional areas except for 61 strands, are approximated within 2 per cent. In the case of 61 strand cables the approximation is 6 per cent.

NOTE 2. Circular mils are based on theoretical diameters of A.W.G. sizes, which vary above or below values given in table by less than 0.1 mil.

NOTE 3. "61 × 7" in the rating of a rope-lay cable signifies 61 strands of 7 wires each.

(9402) . Where necessary to closely approximate a regular size cable, the strands may be made of half-size wires from No. 15 to No. 30 A. W. G.

9403* Correction for Lay.—Two per cent shall be taken as the standard increment of resistance and of mass, due to stranding. In cases where the lay is definitely known, the increment should be calculated and not assumed.

Thickness of Insulation

9405 Thickness of Insulation for Rubber Insulated Wires and Cables.—Unless special conditions warrant departures from this rule, the thickness of insulation for rubber compounds containing from 30 to 40 per cent of Hevea rubber, shall be in accordance with Table 906.

TABLE 906

Thickness of Insulation

30 to 40 per cent Hevea Rubber Compound

Recommended Walls of Insulation, 64ths. Inch.

Size A. W. G. or Cir. Mils	Sq. mm.	Working pressure, volts alternating										
		600 or less	1500	2500	3500	5000	6000	7000	8000	9000	10000	11000
14–8	2.08–8.37	3	6	8	10	12	14	16	18	20	22	24
7–2	10.6–33.6	4	7	9	10	12	14	16	18	20	22	24
1–0000	42.4–107	5	8	10	10	12	14	16	18	20	22	24
250,000–500,000	127–253	6	9	10	11	12	14	16	18	20	22	24
550,000–1,000,000	279–507	7	10	10	12	12	14	16	18	20	22	24
1,250,000–2,000,000	633–1013	8	10	10	12	14	16	18	18	20	22	24

NOTES. In multiple conductor cables, the thickness of insulation on each conductor shall be based on the highest r. m. s. voltage between the conductor and the outside of this insulation. The above table is based upon alternating voltages of commercial frequencies. For voltages over 600, the insulation thickness for direct-current cable has not been established. For intermediate sizes the insulation thickness should be the same as for the next larger sizes.

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CHAPTER X.

STANDARDS FOR STORAGE BATTERIES

Rules to be included in the Chapter have been prepared, and await final consideration before publication.

CHAPTER XI.

STANDARDS FOR ILLUMINATION

This chapter consists of extracts from the Report of the Committee on Nomenclature and Standards of the Illuminating Engineering Society for the year 1918. It is here included by permission.

General

11000 **Radiant flux,** ϕ, is the rate of flow of radiation evaluated with reference to energy, and is expressed in ergs per second or in watts.

11001 **Luminous flux,** F, is the rate of flow of radiation evaluated with reference to visual sensation, and is expressed in lumens.

11002 **Visibility,** K_λ, of radiation of a particular wave-length is the ratio of the luminous flux at that wave-length to the corresponding radiant flux.

Defining equation:

$$K_\lambda = \frac{F_\lambda}{\Phi_\lambda}$$

11003* **The Mechanical equivalent of light** is the ratio of radiant flux to luminous flux for the wave-length of maximum visibility, and is expressed in ergs per second per lumen, or in watts per lumen. It is the reciprocal of the maximum visibility.

11004 **Luminosity** of a particular wave-length is the product of the visibility of that wave-length and the corresponding ordinate of the spectral curve of radiant flux, and is represented by the ordinate of the spectral curve of luminous flux. This curve is called the spectral luminosity curve and is different with different sources.

11005 The **Luminous efficiency** of any source is the ratio of the luminous flux to the radiant flux from the source and is expressed in lumens per watt.

11006 **Luminous intensity** I, of a source of light in a given direction is the solid angular density of the luminous flux emitted by the source in the direction considered, when the flux involved acts as far as computation and measurements are concerned, as if it came from a

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(11003). This term has been used in a variety of senses. As here defined it refers only to the minimum mechanical equivalent of light. The reciprocal of this quantity is sometimes called the luminous equivalent of radiation.

point. Or, it is the flux per unit solid angle from that source in the direction considered. The flux from any source of dimensions which are negligibly small by comparison with the distance at which it is observed, may be treated as if it were emitted from a point.

Defining equation:

$$I = \frac{dF}{d\omega}$$

or, if the intensity is uniform,

$$I = \frac{F}{\omega}$$

where ω is the solid angle.

11007 **Illumination,** E, of a surface at any point is the luminous flux density on the surface at that point, or the flux per unit of intercepting area.

Defining equation:

$$E = \frac{dF}{dS}$$

or, when uniform,

$$E = \frac{F}{S}$$

where S is the area of the intercepting surface.

11008* **Candle** is the unit of luminous intensity maintained by the national laboratories of France, Great Britain and the United States.

11009 **Candlepower,** cp., is luminous intensity expressed in candles.

11010* **Lumen,** *l.*, is the unit of luminous flux equal to the flux emitted in a unit solid angle (steradian) by a point source of unit candlepower.

11011 **Lux** is a unit of illumination equal to one lumen per square meter. Using the centimeter as the unit of length, the unit of illumination is one lumen per square centimeter, for which Blondel has proposed the name **phot.** One millilumen per square centimeter (**milliphot**) is more useful as a practical unit. One **foot-candle** is one lumen per square foot, and is equal to 1.0764 milliphots. The milliphot is recommended for scientific records.

11012 **Brightness** of an element of a luminous surface may be expressed in either of two ways: (*a*) in terms of intensity, I, (*b*) in terms of flux, F.

(*a*) Brightness in terms of the luminous intensity I (or candlepower) per unit of projected area of the surface (candlepower brightness) corresponds to the

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(11008). This unit, which is used also by many other countries, has frequently been referred to as the international candle.

(11010) A uniform source of one candlepower emits 4π lumens.

$$\text{defining equation, } b_I = \frac{d\,I}{d\,S\cos\theta}$$

where θ is the angle between the normal to the surface and the line of sight.

(*b*) Brightness in terms of the flux, F, proceeding from a unit area of the surface, on the assumption that the surface is a perfect diffuser; *i. e.*, that it obeys the cosine law of emission or reflection, (lumen brightness) corresponds to the

$$\text{defining equation, } b_F = \frac{d\,F}{d\,S}$$

(perfect diffusion assumed).

The units in which brightness is measured according to (*a*) and (*b*) differ only in numerical value.

11013 Lambert, L, is the unit of brightness in the lumen system. The lambert is the brightness of a perfectly diffusing surface emitting or reflecting one lumen per square centimeter. For most purposes the **millilambert,** 0.001 lambert, is the preferable practical unit.

To say that the brightness of a surface as viewed from a given point is n lamberts, signifies that its brightness is the same as that of a perfectly diffusing surface emitting or reflecting n lumens per square centimeter.

In practice no surface obeys exactly the cosine law of emission or reflection; hence the brightness of a surface generally is not uniform but varies somewhat with the angle at which it is viewed.

A perfectly diffusing surface emitting one lumen per square foot will have a brightness of 1.076 millilamberts.

Brightness expressed in candles per square centimeter may be reduced to lamberts by multiplying by $\pi = 3.14$.

Brightness expressed in candles per square inch may be reduced to lamberts by multiplying by $\pi/6.45 = 0.487$.

Surfaces and Media Modifying Luminous Flux

11020 Diffusing surfaces and media are those which break up the incident flux and distribute it more or less in accordance with the cosine law, as for example, white plaster and opal glass.

11021 Redirecting surfaces and media are those which change the direction of the luminous flux in a definite manner; as for example, a mirror or a lens.

11022 Scattering surfaces and media are those which redirect the luminous flux and break it up into a multiplicity of separate pencisl; as for example, ripple glass, reflecting or transmitting.

11023* Reflection factor, of a body ρ, is the ratio of the flux reflected by the body to the flux incident upon it. The reflection from a

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(11023)(11024)(11025) These terms are introduced to replace the more commonly used terms, Coefficient of reflection, Coefficient of absorption, Coefficient of transmission, which latter terms refer to the specific properties of materials rather than to the behavior of bodies under specified conditions, such as angle of incidence, etc.

body may be regular, diffuse or mixed. In regular reflection the flux is reflected at an angle of reflection equal to the angle of incidence. In diffuse reflection the flux is reflected in all directions. In perfectly diffuse reflection, the distribution of the reflected flux is in accordance with Lambert's cosine law. In most practical cases, there is a superposition of regular and diffuse reflection.

11024* **Absorption factor,** of a body a, is the ratio of the flux absorbed by the body to the flux incident upon it.

11025* **Transmission factor,** of a body τ, is the ratio of the flux transmitted by the body to the flux incident upon it.

$$\rho + a + \tau = 1$$

Illumination

11030 **Unidirectional** illumination on a surface is that produced by a single light source of relatively small dimensions. It is characterized by the fact that a small opaque object placed near the illuminated surface casts a sharp shadow.

11031 **Multidirectional** illumination on a surface is that produced by several separated light sources of relatively small area. It is characterized by the fact that a small opaque object placed near the illuminated surface casts several shadows.

11032 **Diffused** illumination is that produced either by primary or secondary light sources having dimensions relatively large with respect to the distance from the point illuminated, and scattering light in all directions. It is characterized by relative lack of shadow. Diffused illumination ·may be derived principally from a single direction as in the light from a skylit window or from all directions as in the open air. Perfectly diffused illumination on a surface is shadowless.

In any practical case of illumination on a surface there is usually a mixture of the above types.

11033 **Coefficient of utilization** of an illumination installation on a given plane is the total flux received by that plane divided by the total flux from the lamps illuminating it. When not otherwise specified, the plane of reference is assumed to be a horizontal plane 30 inches (76 cm.) from the floor.

11034 **Variation factor** of an illumination installation is the ratio of either the maximum or minimum illumination on a given plane to the average illumination on that plane.

11035 **Variation range** of illumination on a given plane is the ratio of the maximum illumination to the minimum illumination on that plane.

11036 **Hemispherical ratio** for a given lighting unit is the ratio of the luminous flux in the upper hemisphere to that in the lower hemisphere.

11037 **Brightness ratio** is the ratio of the brightness of any two surfaces. When the two surfaces are opposed, the brightness ratio is commonly called the "brightness contrast."

Illuminants

11040 The **output** of all illuminants should be expressed in lumens.

11041 **Illuminants should be rated** upon a lumen basis rather than a candlepower basis.

11042 **Lamp efficiency** is the ratio of the luminous flux output to the power input.

11043 **The lamp efficiency** or **specific output of electric lamps** should be stated in terms of lumens per watt and that of illuminants depending upon combustion should be stated in lumens per British thermal unit per hour.

11044 **The power consumption of auxiliary devices** which are necessarily employed in circuit with a lamp should be included in the input of the lamp. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

11045 **The specific consumption** of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes watts per mean horizontal candle.

11046 **Life Tests.**—Electric incandescent lamps of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

11047 **In comparing different luminous sources** not only should their candlepower be compared, but also their relative form, brightness, distribution of illumination and character of light.

Lamp Accessories

11048 A **reflector** is an appliance the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

11049 A **shade** is an appliance the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

11050 A **globe** is an enclosing appliance of clear or diffusing material the chief use of which is either to protect the lamp or to diffuse its light.

Photometry

11060 **Performance curve** is a curve representing the behavior of a lamp in any particular (candlepower, consumption, etc.) at different periods during its life.

11061 **Characteristic curve** is a curve expressing a relation between two variable properties of a luminous source, as candlepower and volts, candlepower and rate of fuel consumption, etc.

11062 **Mean horizontal candlepower** of a lamp is the average candle power in the horizontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

11063 **Mean spherical candlepower** of a lamp is the average candlepower of a lamp in all directions in space. It is equal to the total luminous flux of the lamp in lumens divided by 4π.

11064 **Mean hemispherical candlepower** of a lamp (upper or lower) is the average candlepower of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp in that hemisphere divided by 2π.

11065 **Mean zonal candlepower** of a lamp is the average candlepower of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone divided by the solid angle of the zone.

11066* **Spherical reduction factor** of a lamp is the ratio of the mean spherical to the mean horizontal candlepower of the lamp.

TABLE 1100

11067 **Photometric Units and Abbreviations.**

Photometric quantity	Name of unit	Symbols and defining equations	Abbreviation for name of unit
1. Luminous flux	Lumen	$F \,.\, \psi$	l.
2. Luminous intensity	Candle	$I = \frac{dF}{d\omega},\ \Gamma = \frac{d\psi}{d\omega}$	cp.
3. Illumination	Phot, foot-candle, lux	$E = \frac{dF}{dS} = \frac{I}{r^2}\cos\theta.$	ph. fc.
4. Exposure	Phot-second Micro phot-second	$E\,t$	phs. μ phs.
5. Brightness	Apparent candle per sq. cm. Apparent candle per sq. in.	$b_i = \frac{dI}{dS\cos\theta}$	—
	Lambert	$b_l = \frac{dF}{dS}$	L. mL.
6. Reflection factor	—	ρ	—
7. Absorption factor	—	α	—

(11066). In the case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.

* Perfect diffusion assumed.

8.	Transmission factor	τ
9.	Mean spherical candlepower	scp.
10.	Mean lower hemispherical candlepower	lcp.
11.	Mean upper hemispherical candlepower	ucp.
12.	Mean zonal candlepower	zcp.
13.	Mean horizontal candlepower	mhc.

14. 1 lumen is emitted by 0.07958 spherical candlepower.

15. 1 spherical candlepower emits 12.57 lumens.

16. 1 lux = 1 lumen incident per square meter = 0.0001 phot = 0.1 milliphot.

17. 1 phot = 1 lumen incident per square centimeter = 10,000 lux = 1,000 milliphots = 1,000,000 microphots.

18. 1 milliphot = 0.001 phot = 0.929 foot-candle.

19. 1 foot-candle = 1 lumen incident per square foot = 1.076 milliphots = 10.76 lux.

20. 1 lambert = 1 lumen emitted per square centimeter of a perfectly diffusing surface.

21. 1 millilambert = 0.001 lambert.

22.*1 lumen, emitted, per square foot = 1.076 millilamberts.

23.*1 millilambert = 0.929 lumen, emitted, per square foot.

24. 1 lambert = 0.3183 candle per square centimeter = 2.054 candles per square inch.

25. 1 candle per square centimeter = 3.1416 lamberts.

26. 1 candle per square inch = 0.487 lambert = 487 millilamberts.

CHAPTER XII.

STANDARDS FOR TELEPHONY AND TELEGRAPHY

Many of the following definitions are tentative and not yet fully established. Criticisms and suggestions, addressed to the Secretary of the Standards Committee, will be welcomed. Some of the definitions are specific to telephony, and differ in detail from similar definitions appearing in other parts of the rules.

DEFINITIONS

Line Circuits

12000 **Ground-Return Circuit.**—A ground-return circuit is a circuit consisting of one or more metallic conductors in parallel, with the circuit completed through the earth.

12001 **Metallic Circuit.**—A metallic circuit is a circuit of which the earth forms no part.

12002 **Two-Wire Circuit.**—A two-wire circuit is a metallic circuit formed by two parallel conductors insulated from each other.

12003 **Superposed Circuit.**—A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

12004 **Phantom Circuit.**—A phantom circuit is a superposed circuit, each side of which consists of the two conductors of a two-wire circuit in parallel.

12005 **Side Circuit.**—A side circuit is a two-wire circuit forming one side of a phantom circuit.

12006 **Non-Phantomed Circuit.**—A non-phantomed circuit is a two-wire circuit, which is not arranged for use as the side of a phantom circuit.

12007 **Simplexed Circuit.**—A simplexed circuit is a two-wire telephone circuit, arranged for the superposition of a single ground-return signalling circuit operating over the wires in parallel.

12008 **Composited Circuit.**—A composited circuit is a two-wire telephone circuit, arranged for the superposition on each of its component metallic conductors, of a single independent ground-return signalling circuit.

12009 **Quadded or Phantomed Cable.**—A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

12010 **Simplex Circuit.**—A simplex circuit in telegraphy is one arranged for operation in one direction at one time.

12011 **Duplex Circuit.**—A duplex circuit in telegraphy is one arranged for simultaneous operation in opposite directions.

12012 **Diplex Circuit.**—A diplex circuit in telegraphy is one arranged for the simultaneous transmission of two messages in the same direction.

12013 **Quadruplex Circuit.**—A quadruplex circuit in telegraphy is one arranged for the simultaneous transmission of two messages in each direction.

12014 **Multiplex Circuit.**—A multiplex circuit in telegraphy is one arranged for the simultaneous transmission of one or more messages in both directions. Both duplex and quadruplex are examples of multiplex whereas diplex is not.

12015 **Linear Electrical Constants.**—The linear electrical constants of a line are the electrical constants per unit length of the line, *e. g.* linear resistance, linear inductance, etc.

12016 **Smooth Line.**—A smooth line is a line whose electric elements are all continuously and uniformly distributed throughout its length.

12017* **Periodic Line.**—A periodic line is a line consisting of successive similar sections in each of which one or more electric elements are not distributed uniformly. As examples of periodic lines are (1) loaded lines and (2) artificial lines consisting of successive similar sections of lumped constants.

12018 **Equivalent Smooth Line.**—An equivalent smooth line of a periodic line is a smooth line having the same electrical behavior as the periodic line, at a given single frequency, when measured at terminals or at corresponding section junctions.

12019 **Equivalent Periodic Line.**—An equivalent periodic line of a smooth line is a periodic line having the same electrical behavior, for an assumed single frequency, as the smooth line, when measured at terminals or at corresponding section junctions. The terms conjugate smooth line and conjugate periodic line are also sometimes used.

12020 **Composite Line.**—A composite line is a line consisting of a plurality of successive sections having different linear electrical constants, as in the case where an underground cable section is joined to an overhead open-wire section.

12021 **Loaded Line.**—A loaded line is one in which the normal reactance of the circuit has been altered for the purpose of increasing its transmission efficiency.

12022 **Series Loaded Line.**—A series loaded line is one in which the normal reactance has been altered by reactance serially applied.

12023 **Shunt Loaded Line.**—A shunt loaded line is one in which the normal reactance of the circuit has been altered by reactance applied in shunt across the circuit.

(12017) The term periodic in this definition refers to the line constants and not to time relations.

12024 **Continuous Loading.**—A continuous loading is a series loading in which the added inductance is uniformly distributed along the conductors.

12025* **Coil Loading.**—A coil loading is one in which the normal inductance is altered by the insertion of lumped inductance in the circuit at intervals.

Circuit Constants and Characteristics

12050 **Damping of a Circuit.**—The damping at a given point in a circuit from which the source of energy has been withdrawn, is the progressive diminution in the effective value of electromotive force and current at that point resulting from the withdrawal of electrical energy.

12051* **Damping Constant.**—The damping constant of a circuit is a measure of the ratio of the dissipative to the reactive component of its admittance or impedance.

12052* **Mutual Impedance.**—The mutual impedance for single frequency alternating currents, between a pair of terminals and a second pair of terminals of a network, under any given condition, is the negative ratio of the electromotive force produced between either pair of terminals on open circuit to the current flowing between the other pair of terminals.

12053* **Self-Impedance.**—The self-impedance between a pair of terminals of a network, under any given condition, is the ratio of the electromotive force applied across the terminals to the entering current.

12054* **Characteristic Impedance.**—The characteristic impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current upon a line of infinite length and uniform structure, or of periodic recurrent structure.

(12025) This lumped inductance may be applied either in series or in shunt.

As commonly understood, coil loading is a series loading, in which the lumped inductance is applied at uniformly spaced recurring intervals.

(12051) Applied to the admittance of a condenser or other simple circuit having capacity reactance, the damping constant for a harmonic electromotive force of given frequency is the ratio of the conductance G, of the condenser or simple circuit at that frequency to twice the capacitance, C, of the condenser at the same frequency, $(G/2\,C)$.

Applied to the reactance of a coil or other simple circuit having inductive reactance, the damping constant for a harmonic current of a given frequency is the ratio of the resistance, R, of the coil or circuit at that frequency to twice the inductance, L, at the same frequency $(R/2\,L)$.

(12052) A receiving-end impedance is an example of a mutual impedance.

Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

(12053) Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

(12054) In practise, the terms (1) line impedance, (2) surge impedance, (3) iterative impedance, (4) sending-end impedance, (5) initial sending-end impedance, (6) final sending-end impedance, (7) natural impedance and (8) free impedance, have apparently been more or less indefinitely and indiscriminately used as synonyms with what is here defined as "characteristic impedance."

Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

12055* **Sending-End Impedance.**—The sending-end impedance of a line is the ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

12056* **Propagation Constant.**—The propagation constant of a uniform line, or section of a line of periodic recurrent structure, is the natural logarithm of the ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite length. The ratio is determined by dividing the value of the current at the point nearer the transmitting end by the value of the current at the point more remote.

12057 **Attenuation Constant.**—The attenuation constant for a single frequency is the real part of the propagation constant taken at that frequency.

12058 **Wave-Length Constant.**—The wave-length constant is the imaginary part of the propagation constant.

12059 **Standard Cable.**—A standard cable is an ideal uniform line in terms of which the attenuation of a line or network may be specified. It is characterized by the following constants: Linear resistance, 88 ohms per loop mile (54.7 ohms per loop km.). Linear capacitance between wires 0.054 microfarad per loop mile (0.03355 microfarad per loop km.). Linear inductance and linear leakance, 0.

Equivalent Circuits

12102* **Equivalent Circuit.**—An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network.

12103* **"*T*" Equivalent Circuit.**—A "*T*" equivalent circuit is a triple-star or "*Y*" connection of three impedances externally equivalent to a complex network. See Fig. 12-1 for symbol.

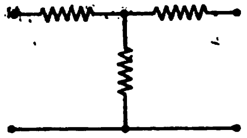

FIG. 12-1

12104* **"*I*" Equivalent Circuit.**—An "*I*" equivalent circuit is a connection of five impedances in the form shown in Fig. 12-2, which is externally equivalent to a complex network. It differs from the "*T*" equivalent circuit in that the impedances are arranged symmetrically

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(12055) See note under "Characteristic Impedance," In case the line is of infinite length of uniform structure or of periodic recurrent structure, the sending-end impedance and the characteristic impedance are the same.

Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

(12056) Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

(12102 to 12106 Incl.) As ordinarily considered, the simple networks as defined, are the electrical equivalents of complex networks only with respect to definite pairs of terminals.

on the two sides of the circuit, which is often desirable in connection with practical problems, as indicating that the circuit is balanced with respect to ground.

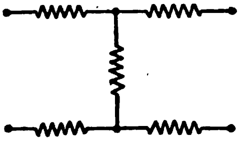

FIG. 12-2

12105* **"Π" Equivalent Circuit.**—A "Π" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "*U*" equivalent circuit. See Fig. 12-3 for symbol.

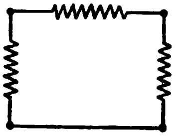

FIG. 12-3

12106* **"*O*" Equivalent Circuit.**—An "*O*" equivalent circuit is a connection of four impedances in the form shown in Fig. 12-4, externally equivalent to a complex network. It differs from the Π equivalent circuit in that the impedances are arranged symmetrically on the two sides of the circuit, which is often desirable in connection with practical problems, as indicating that the circuit is balanced with respect to ground.

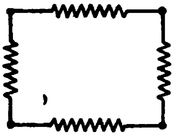

FIG. 12-4

Telephony

12200 **Manual Telephone System.**—A manual telephone system is one in which the calling party gives his order to an operator who completes the call directly by hand, either with or without the assistance of one or more additional operators.

12201 **Automatic or Full Mechanical Telephone System.**—An automatic or full mechanical telephone system is one in which the calling party is enabled to complete a call by remote-control switches without the aid of an operator.

12202 **Semi-Automatic or Semi-Mechanical Telephone System.**— A semi-automatic or semi-mechanical telephone system is one in which the calling party gives his order to an operator who completes the call through remote-control switches.

12203 **Telephone Exchange.**—A telephone exchange consists of one or more central offices with associated plant, by means of which telephone service is rendered in a specified local community.

12204 **Telephone Exchange Area or District.**—A telephone exchange area or district is the area or district served by a telephone exchange.

12205 **Central Office.**—A central office is a switching center for interconnecting lines terminating therein.

12206 **Toll Central Office.**—A toll central office is one in which toll and long distance lines terminate.

12207 **Local Central Office.**—A local central office is one in which subscriber's lines terminate.

12208 **Private Branch Exchange (Generally Abbreviated "P. B. X.").**—A private branch exchange is a telephone system generally installed on the premises of a subscriber, including a switchboard and extension sets, and connected to a central office, affording intercommunication between the extension sets and also between these sets and the central office.

12209 **Private Exchange.**—A private exchange is one which serves one business organization or individual, and is not connected to a central office.

12210 **Private Automatic Exchange.**—A private automatic exchange is an automatic exchange which serves one business organization or individual, and is not connected to a central office.

12211 **Subscriber Set (Often Abbreviated to "Subset").**—A subscriber set is an assembly of apparatus for sending and receiving telephone calls.

12212 **Subscriber Station (Often Abbreviated to "Substation").**— A subscriber station is an installed subscriber set connected to a central office for the purpose of sending and receiving telephone calls.

12213 **Pay Station.**—A pay station is a subscriber station available for the use of the public on the payment of a fee. The fee may be either deposited in a coin box or paid to an attendant.

12214 **Toll Station.**—A toll station is a pay station located outside of a local service area and affording toll and long distance service only.

12215 **Subscriber line or Subscriber Loop.**—A subscriber line or subscriber loop is the wire connection between a subscriber station and the central office.

12216 **Subscriber Line Circuit.**—A subscriber line circuit is a subscriber line with its associated individual central office apparatus.

12217 **Individual Line.**—An individual line is a subscriber line which connects one subscriber station to a central office, though it may have one or more extension sets.

12218 **Party Line.**—A party line is a subscriber line which connects two or more subscriber stations to a central office.

12219 **Tip Side or Tip Wire, Ring side or Ring Wire.**—The tip side or wire, or the ring side or wire, is that conductor of a circuit which is associated with the corresponding member of a jack.

12220 **Negative Side or Negative Wire, Positive side or Positive Wire.**—The negative side or wire, or the positive side or wire, is that conductor of a circuit which is normally connected to the corresponding pole of a battery.

12221 **Main Distributing Frame.**—A main distributing frame is a structure for terminating the permanent inside and outside wires of a central office and for effecting flexible junctions between them.

12222 **Intermediate Distributing Frame.**—An intermediate distributing frame is a structure for terminating permanent inside wires of a central office and for effecting flexible junctions between them.

12223 **Switchboard.**—A switchboard is an assemblage of apparatus in a coordinate structure for switching talking and signaling circuits.

12224 **Switchboard Section.**—A switchboard section is an element or unit one or more of which constitutes a complete manual switchboard.

12225 **Operating Room.**—An operating room is a room which contains a manual switchboard and associated apparatus.

12226 **Combination Current.**—A combination current consists ot two or more currents of different characterisitics in the same circuit. As ordinarily used the term refers to currents whose characteristics are steadily maintained, as for example, a combination of direct current and an alternating current.

12227 **Manual Ringing.**—Manual ringing is ringing which is affected by and continues with the operation of a key.

12228 **Machine Ringing.**—Machine ringing is intermittent and is caused to act periodically by the apparatus itself.

12229 **Superimposed Ringing Current.**—A superimposed ringing current is a combination current for ringing, consisting of a direct and an alternating current.

12230 **Pulsating Ringing Current.**—A pulsating ringing current is a current for ringing in which the succeeding impulses are separated by intervals approximately equal to those of the impulses themselves.

12231 **Harmonic Selective Signaling.**—Harmonic selective signaling employs devices tuned mechanically or electrically to the frequency of the ringing current, so that each device will not operate when receiving current intended to operate another device.

12232 **Multiple Harmonic Signaling.**—Multiple harmonic signaling employs frequencies which are integral multiples of the lowest frequency.

12233 **Non-Multiple Harmonic Signaling.**—Non-Multiple harmonic signaling employs frequencies which are not integral multiples of the lowest frequency.

12234 **"To Call".**—"To call" is to originate a telephone call.

12235 **"To Dial".**—"To dial" a number is to use a dial type of calling device in order to control automatic switches.

12236 **"To Set Up".**—"To set up" a number is to use a key type or multiple lever type of calling device in order to control automatic switches.

12237 **Calling Device.**—A calling device is an apparatus by means of which automatic switches are controlled for the purpose of establishing a connection.

12238 **Calling Party.**—A calling party is a person who originates a telephone call.

12239 **Called Party.**—A called party is the person who answers when a station is called.

12240 **Reverting Call.**—A reverting call is one between two stations on the same subscriber line..

12241 **Telephone Traffic.**—Telephone traffic is the aggregate volume of communication handled in a given time.

12242 **"Busy".**—"Busy" is the condition of a line or an apparatus when it is in use.

12243 **Free.**—Free is the condition of a line or an apparatus when it is not in use. Free is the opposite of busy.

12244 **"To Make Busy".**—"To make busy" is to cause a line or an apparatus to appear to be busy.

12245 **"To Release" or to "Disconnect.**—"To release" or "to disconnect" is to terminate a telephone connection by disengaging the apparatus.

12246 **"To Clear".**— To clear" is to restore a line or an apparatus to the free condition.

12247 **Trunk.**—A trunk is the wire connection between switching devices or central offices.

12248 **Trunk Circuit.**—A trunk circuit is a trunk with its associated individual apparatus.

12249 **Trunked Call.**—A trunked call is one which employs an interoffice trunk or a trunk between two switchboard positions.

12250 **Relay.**—A relay is a device by means of which contacts in one circuit are operated by a change in conditions in the same circuit or in one or more associated circuits. (See Rule 4016 Standardization Rules, A. I. E. E., 1918).

12251 **Polar Relay.**—A polar relay is a relay which operates in response to a change in the direction of the current in the controlling circuit.

12252 **Quick Operating Relay.**—A quick operating relay is one which operates its contacts within a specified brief time limit.

12253 **Quick Release Relay.**—A quick release relay is one which releases its contacts within a specified brief time limit.

12254 **Quick Acting Relay.**—A quick acting relay is one which has the properties of both a quick operating and a quick release relay.

12255. **Slow Operating Relay.**—A slow operating relay is one which will not operate until after a specified delay.

12256 **Slow Release Relay.**—A slow release relay is one which when operated will not release until after a specified delay.

12257 **Slow Acting Relay.**—A slow acting relay is one which has the properties of both a slow operating and a slow release relay.

12258 **Line Relay.**—A line relay is one whose coil is normally in the line circuit.

12259 **Cut-Off Relay.**—A cut-off relay is one which when operated disconnects from a line apparatus normally connected to it.

12260 **Relay Coil Section.**—A relay coil section is one of two or more windings of a coil on one and the same core. The several sections may be concentric or placed side by side on the core.

12261 **Tension Spring.**—A tension spring is one which functions to exert mechanical pressure but does not carry an electrical current.

12262 **Contact Spring.**—A contact spring is one which takes an electrical part in switching a circuit.

12263 **Main Contact Spring.**—A main contact spring is one which may switch a circuit between two or more other contact springs.

12264 **Armature Spring.**—An armature spring is the first of a group to be moved by the armature. It may or may not be a main contact spring.

12265 **Plunger Spring.**—Aplunger spring is the first of a group to be moved by the plunger.

12266 **Impulse Springs.**—Impulse springs are those which act to make or break a circuit for the purpose of sending impulses.

12267 **Make-Before-Break Contact Springs (Abbreviation "M. B. B.").**—make-before-break contact springs are those in which the main spring touches the front contact before it breaks away from the back contact. Also called a continuity preserving contact.

12268 **Back Contact Spring.**—A back contact spring is one against which the main contact spring rests when in the normal position.

12269 **Front Contact Spring.**—A front contact spring is one against which the main contact spring rests when in the operated position.

12270 **Automatic Signaling.**—Automatic signaling is affected without the aid of an operator.

12271 **Automatic Switch.**—An automatic switch is a remote control device for controlling talking or signaling circuits.

12272 **Finder Switch.**—A finder switch is a switch connected to one of a smaller number of circuits and which finds automatically a circuit out of a larger number of circuits from whence the signal comes.

12273 **Line Switch.**—A line switch is a switch connected to one of a larger number of circuits from which a signal comes and which finds automatically a circuit out of a smaller number of circuits.

12274 **Selector Switch.**—A selector switch is a switch whose duty is to select a particular group of trunks and one trunk of the group selected. In particular cases, one of these functions may be omitted.

12275 **Connector Switch or Final Selector.**—A connector switch or final selector is a switch whose duty is to establish a connection with the called line. It is usually operated by the last digit or digits of the call number.

12276 **Switch Frame.**—A switch frame is a structure for mounting an assembly of switching apparatus which may be integral therewith.

12277 **Section of Switches.**—A section of switches, considered from a trunking standpoint, is a group of adjacent switches whose banks are multipled together.

12278 **Switchroom.** A switchroom is a room which contains an assemblage of automatic switches and associated apparatus.

12279 **Bank Wires.**—Bank wires are those wires which multiple adjacent switch banks to each other.

12280 **Bank Cable.**—A bank cable is one which connects a switch bank to a terminal rack.

12281 **Multiple Cable.**—A multiple cable is one which multiples together two or more sections of switch banks by connecting together their terminals.

12282 **Impulse.**—An impulse is any sudden change of brief duration produced in the current of a circuit.

12283 **Make Impulse.**—A make impulse is an impulse due to a temporary flow of current.

12284 **Break Impulse.**—A break impulse is an impulse due to a temporary interruption of current.

12285 **Impulse Frequency.**—The impulse frequency is the number of impulses occurring per second. The reciprocal of this is the impulse period.

12286 **Impulse Period.**—The impulse period is the period of time included between the corresponding points in periodically recording impulses. It thus corresponds to the period of alternating current.

12287 **Impulse Ratio.**—Impulse ratio is the ratio of duration of an impulse to the impulse period.

12288 **Impulse Circuit.**—An impulse circuit is one through which impulses are transmitted.

12289 **Telephone Impulse Repeater.**—A telephone impulse repeater is a device for repeating impulses from one line circuit into another and for performing other duties.

12290 **Supervisory Signal.**—A supervisory signal is a device for attracting attention of an attendant to a duty in connection with switching apparatus or its accessories. This includes cord supervisory lamps on a manual switchboard and the supervisory lamps in an automatic exchange which indicates that a switch has been occupied but has not completed its function.

12291 Tell-Tale Signal.—A tell-tale signal is a device for locating the failure of some apparatus; for example, the blowing of a fuse, the continued drawing of heavy current by apparatus intended to receive only momentary current, etc.

12292 Alarm Signal.—An alarm signal is a sound producing device for attracting attention to either a supervisory or a tell-tale signal

12293 Amplifier.—See §13040.

12294 Telephone Repeater.—A telephone repeater is a device for amplifying a voice current from one line circuit into another line circuit.

12300 Telephone Receiver.—A telephone receiver is an electrically operated device designed to produce sound waves or vibrations which correspond to the electromagnetic waves or vibrations actuating it.

12301 Microphone.—A contact device designed to have its electrical resistance directly and materially altered by slight differences in mechanical pressure.

12302 Telephone Transmitter.—A telephone transmitter is a sound-wave-operated or vibration-operated device designed to produce electromagnetic waves or vibrations which correspond to the sound waves or vibrations actuating it.

12303* Coefficient of Coupling of a Transformer.—The coefficient of coupling of a transformer at a given frequency is the ratio of the mutual impedance between the primary and secondary of the transformer, to the square root of the product of the self-impedances of the primary and of the secondary.

12304 Repeating Coil.—A term used in telephone practice meaning the same as transformer, and ordinarily a transformer of unity ratio.

12305* Retardation Coil.—A retardation coil is a reactor (reactance coil) used in a circuit for the purpose of selectively reacting on currents which vary at different rates.

Telegraphy

12500 Relay.—A relay is a device by means of which contacts in one circuit are operated by a change in conditions in the same circuit or in one or more associated circuits.

12501 Polar Relay.—A polar relay is a relay which operates in response to a change in the direction of the current in the controlling circuit.

12502 Non-Polar Relay, or Neutral Relay.—A non-polar relay is a relay which operates in response to a change in the strength of the current in the controlling circuit, irrespective of the direction of the current.

12503 Neutral Relay.—See non-polar relay.

12504 Selector.—A selector is a device which performs certain functions such as causing an electric lamp to light, or an electric bell to sound, in response to a definite signal or group of successive signals received over a controlling circuit.

(12303) Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

(12305) In telephone and telegraph usage, the terms "impedance coil," "inductance coil," "choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

12505 **Direct-Point Repeater.**—A direct-point repeater is a repeater in which the receiving relay controlled by the signals received over a line repeats these signals into another line or lines without the interposition of any other repeating or transmitting apparatus.

12506 **Concentrator.**—A concentrator is a traffic distributing device by means of which a number of telegraph or telephone lines, and connections to operating instruments are brought together at one point to facilitate their interconnection at such times as signals or messages are to be transmitted from one to the other.

12507 **Transmitter.**—A transmitter is a device for effecting electrical changes in a controlled circuit. The term transmitter is commonly applied principally to devices which in response to a controlling means effects in a main line telegraph circuit electrical changes necessary to send signals over the line.

12508 **Synchronous System.**—A synchronous system of telegraphy is one in which the proper transmission and reception of signals is dependent upon the synchronous operation of similar commutators or other devices located at the sending and receiving stations of a circuit.

12509 **Differential Duplex.**—A differential duplex is a duplex system in which at each station one of two portions of the receiving instrument is connected in series with the line wire and the other in series with an artificial line of such electrical characteristics that the effects upon the receiver of currents passing through the main and artificial lines, as a result of outgoing signals, are neutralized.

12510 **Bridge Duplex.**—A bridge duplex is a duplex system in which the receiving instruments at each station is connected across two impedances, one in series with the line wire and the other in series with the artificial line in such manner that no electrical change in the receiver circuit is effected by outgoing signals.

12511 **Half-Set Repeater.**—A half-set repeater is a repeater used for connecting together a simplex circuit and a duplexed circuit converting them into the equivalent of a single simplex circuit.

12512 **Intermediate Current Supply.**— An intermediate current supply is an ungrounded source of current connected in series with a line wire at a station other than a terminal on a ground return telegraph circuit.

12513 **Phantoplex Circuit.**—A phantoplex circuit is a superposed circuit operated by alternating current over a simplex, duplex or quadruplex circuit operated from direct current sources.

12514 **Spark Condenser.**—A spark condenser is a condenser, with or without associated non-inductive resistance, connected with a pair of instrument contact points for the purpose of diminishing sparking at these points.

12515 **Current Margin.**—In a non-polar simplex system, the difference between the current flowing through a receiving instrument when operated to that flowing when not operated.

12516 **Margin Ratio.**—In a non-polar simplex system, the ratio of the current flowing through a receiving instrument when operated to that flowing when not operated.

12517 **Percentage Margin.**—In a non-polar simplex, the current margin expressed as a percentage of the current flowing through the relay when operated.

12518 **Main Circuit.**—A main circuit is a major electrical circuit of a telegraph system and includes both transmitting and receiving devices.

12519 **Local Circuit.**—A local circuit is a circuit, within the limits of the station, usually controlled by a receiving instrument in a main circuit or controlling a transmitter effecting changes in a main line circuit

CHAPTER XIII.

STANDARDS FOR RADIO COMMUNICATION

General

This chapter has been mainly abstracted from the report of the Standardization Committee of the Institute of Radio Engineers, and is here included by permission, until further revised. For full particulars, see the I. R. E. Standardization Committee report.

13000 **Acoustic Resonance Device.**—One which utilizes, in its operation, resonance to the audio frequency of the received signals.

13001 **Antenna.**—A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

13002 **Atmospheric Absorption.**—That portion of the total loss of radiated energy due to atmospheric conductivity.

13003 **Audio Frequencies.**—Frequencies corresponding to the normally audible vibrations. These are assumed to lie below 10,000 cycles per second.

13004 **Capacitive Coupler.**—An apparatus which, by electric fields joins portions of two radio-frequency circuits, and which is used to transfer electrical energy between these circuits through the action of electric forces.

13005 **Coefficient of Coupling (Inductive).**—The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

13006 **Direct Coupler.**—A coupler which magnetically joins two circuits having a common conductive portion.

13007 **Counterpoise.**—A system of electrical conductors forming one portion of a radiating oscillator, the other portion of which is the antenna. In land stations a counterpoise forms a capacitive connection to ground.

13008 **Damped Alternating Current.**—A damped alternating current is an alternating current whose amplitude progressively diminishes.

13009 **Damping Factor.**—The damping factor of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let I_0 = initial amplitude

I_t = amplitude at the time t

ϵ = base of Napierian logarithms

a = damping factor

Then: $I_t = I_0 \, \epsilon^{-at}$

13010 **Detector.**—That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio-frequency energy into a form suitable for operation of the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

13015 **Electromagnetic Wave.**—A periodic electromagnetic disturbance progressing through space.

13016 **Forced Alternating Current.**—A current, the frequency and damping of which are equal to the frequency and damping of the exciting electromotive force.

13017 **Free Alternating Current.**—The current following any electromagnetic disturbance in a circuit having capacitance, inductance, and *less* than the critical resistance.

13018 **Critical Resistance of a Circuit.**—That resistance which determines the limiting condition at which the oscillatory discharge of a circuit passes into an aperiodic discharge.

13019 **Group Frequency.**—The number per second of periodic changes in amplitude or frequency of an alternating current.

NOTE 1. Where there is more than one periodically recurrent change of amplitude or frequency, there is more than one group frequency present.

NOTE 2. The term "group frequency" replaces the term "spark frequency."

13020 **Inductive Coupler.**—An apparatus which, by magnetic forces, joins portions of two radio-frequency circuits and is used to transfer electrical energy between these circuits, through the action of these magnetic forces.

13025 **Logarithmic Decrement.**—The logarithmic decrement of an exponentially damped alternating current is the logarithm of the ratio of successive current amplitudes in the same direction.

NOTE: Logarithmic decrements are standard for a complete period or cycle.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction.

d = logarithmic decrement

Then: $$d = \log_e \frac{I_n}{I_{n+1}}$$

13026 **Radio Frequencies.**—The frequencies higher than those corresponding to the normally audible vibrations, which are generally taken as 10,000 cycles per second. See also Audio Frequencies.

NOTE: It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience.

13027 **Resonance.**—Resonance of a circuit to a given exciting alternating e. m. f. is that condition due to variation of the inductance or capacity in which the resulting effective current (or voltage) in that circuit is a maximum.

13028 Standard Resonance Curve.—A standard resonance curve is a curve the ordinates of which are the ratios of the square of the current at any frequency to the square of the resonant current, and the abscissas are the ratios of the corresponding wave length to the resonant wave length; the abscissas and ordinates having the same scale.

13029 Sustained Radiation.—Sustained radiation consists of waves radiated from a conductor in which an alternating current flows.

13030 Tuning.—The process of securing the maximum indication by adjusting the time period of a driven element. (See Resonance.)

13035 Wave-Meter.—A wave-meter is a radio-frequency measuring instrument, calibrated to read wave lengths.

13036 Decremeter.—An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

13037 Attenuation, Radio.—The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

13038 Attenuation, Coefficient of (Radio).—The coefficient which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

13039 Coupler.—An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

13040 Amplifier.—An amplifier is an instrument which modifies the effect of a local source of energy in substantial accordance with the waveform of the received energy, and gives out a wave of greater amplitude than that which it receives.

13041 Interference.—See §12045.

13042 Phase Angle Defect.—The phase angle defect of a condenser is the departure from quadrature of the phase difference between potential and current at terminals. This is sometimes called the phase angle of a condenser: although strictly speaking the phase angle of a condenser is 90° less the phase angle defect, and is therefore exactly 90° when the phase angle defect is zero.

13043 Impulse E. m. f.—An e. m. f. the effective value of which becomes small compared with its maximum value in a time which is short compared with the duration of the current which it causes.

13044 Directive Coefficient.—The directive coefficient of a transmitting antenna at a given distance therefrom on the surface of the earth or sea, for a given wave length, is the ratio of average field intensity within an angle of stated degrees centered about the direction of maximum radiation, to the average field intensity in all directions.

13045 Directional Selectivity.—The directional selectivity of a receiving antenna at a given wave length is the ratio of the average e. m. f. induced in that antenna for waves of equal intensity coming from directions comprised within an angle of stated degrees centered about the direction of best reception, to the average e. m. f. induced in the antenna for waves of equal intensity coming from all directions.

13046 Radiation Efficiency.—The radiation efficiency of an antenna at a given wave length is the ratio of radiation resistance to the antenna resistance.

13047 Selectivity.—The (overall) selectivity of a receiving system is the product of the several selectivities of that system.

13048 Average Selectivity.—The average selectivity of a receiving system is the *nth* root of the product of the *n* selectivities of that system.

13049* Radio-Frequency Selectivity.—The radio-frequency selectivity of a simple element* of a receiving system is the ratio of resonant response (in terms of effective voltage or current measured at the indicator) to the non-resonant response when the radio-frequency portions of the elements of that system are detuned by one per cent of the resonant frequency.

(13049) A simple element as referred to a combination of an inductance, a capacitance and optionally a resistance; or their mechanical equivalent.

CHAPTER XIV.

STANDARDS FOR PRIME MOVERS AND GENERATOR UNITS

General

14000 **Regulation of Steam Engines, Steam Turbines and Internal Combustion Engines.**—In steam engines, steam turbines and internal combustion engines, the percentage speed regulation is usually expressed as the percentage ratio of the maximum variation of speed, to the rated-load speed in passing slowly from rated-load to no-load (with constant conditions at the supply.)

14001 **Fluctuation of Steam Engines, Steam Turbines and Internal Combustion Engines.**—The percentage fluctuation of a steam engine, steam turbine or internal combustion engine, is the immediate percentage speed regulation corresponding to a sudden change from rated-load to no-load.

14002 **Regulation of Hydraulic Turbines.**—In a hydraulic turbine, or other water motor, the percentage speed regulation is expressed as the percentage ratio of the maximum variation is speed in passing slowly from rated-load to no-load (at constant head of water), to the rated-load speed.

14003 **Regulation of Generator Units.**—In a generator unit, consisting of a generator combined with a prime mover, the speed or voltage regulation shall be based upon constant conditions of the prime mover; *i. e.*, constant steam-pressure, head, etc. It includes the inherent speed variations of the prime mover. For this reason, the regulation of a generator unit is to be distinguished from the regulation of either the prime mover, or of the generator combined with it, when taken separately.

14010* **Variation in Prime Movers.**—The variation in prime movers which do not give an absolutely uniform rate of rotation or speed, as in reciprocating steam engines, is the maximum angular displacement in position of the revolving member expressed in degrees, from the position it would occupy with uniform rotation, and with one revolution taken as 360 degrees. See §4088.

14011 **Pulsation in a Prime Mover, or in the Alternator Connected Thereto.**—The pulsation in a prime mover, or in the alternator

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(14010) If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct connected, and $p\ n$ times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

connected thereto, is the ratio of the difference between the maximum and minimum velocities in an engine-cycle to the average velocity.

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CHAPTER XV.

STANDARDS FOR TRANSMISSION LINES AND DISTRIBUTION LINES

NOTE:—For flash-over tests of insulators, see foot-note to §2361.

General

15000 Regulation of Transmission Lines, Feeders, etc.—The regulation of transmission lines, feeders, etc., is the change in the voltage at the receiving end between rated non-inductive load and no-load, with constant impressed voltage upon the sending end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

CHAPTER XVI.

MISCELLANEOUS STANDARDS

HEATING DEVICES

16000 Value of A-C. Test Voltage for Household Devices.—Heating devices taking not over 660 watts, intended solely for operation on supply circuits not exceeding 275 volts, shall be tested with 500 volts at operating temperature.

INTERNATIONAL ELECTROTECHNICAL COMMISSION RULES

INTERNATIONAL ELECTROTECHNICAL COMMISSION

I. E. C. RULES FOR ELECTRICAL MACHINERY

VOLUME I.

(Adopted at the Plenary Meeting, held in London, October, 1919)

These rules apply to rotating machines of which the terminal pressure does not exceed 5000 volts or of which the rated output does not exceed 750 KVA., or of which the stator cores do not exceed 50 cm. in length axially, and to all transformers which are not water-cooled.

PART I. GENERAL.

I. Scope of Rules.

1. *Rotating Machines.*—The rules of the I. E. C. contained in this publication apply to rotating machines, of which the terminal pressure does not exceed 5000 volts or of which the rated output does not exceed 750 kVA, or of which the stator cores do not exceed 50 cm. in length axially.

2. *Transformers.*—These rules also apply to all transformers which are not water cooled. (For water-cooled transformers, *see* Appendix II.)

3. *Altitude.*—In the absence of any information in regard to the height above sea level at which the machine is intended to work in ordinary service, this height is assumed not to exceed 1000 meters. If the machine is intended to work at an altitude above 1000 metres a correction to the temperature rise should be applied. The value for this correction has not yet been fixed by the I. E. C.

4. *Temperature.*—In the absence of any information to the contrary. it is assumed that the temperature of the cooling air shall not exceed 40°C,

II. Definitions.

5. *Rating.*—(*See* Appendix IV.)

6. *Use of the term "Machine."*—The term "machine" is used in these rules in its most general sense so as to avoid the constant repetition of the words "machines, transformers and other electromagnetic induction apparatus."

7. *Use of the term "Power."*—It is usual to speak of a machine by its *power*. It is necessary to note that the term "power" should be used in the following way:—

(*a*) For direct current generators, the electric power at the terminals expressed in watts (W) or kilowatts (kW).

(*b*) For alternators, the apparent power at the terminals, expressed in volt-amperes (VA) or kilovolt-amperes (kVA).

(*c*) For motors, the mechanical power available at the shaft, expressed in watts (W) or kilowatts (kW).

(*d*) For transformers, apparent output at the secondary terminals, expressed in volt-amperes (VA) or kilovolt-amperes (kVA).

III. I. E. C. Rating.

8. *Test Rating.*—The I. E. C. rating has been established as a *test*, rating which will enable an exact comparison to be made between machines of different makes.

9. *Classes of Rating.*—There are two classes of I. E. C. rating:—

(*a*) The I. E. C. continuous rating (*see* Clause 10).

(*b*) The I. E. C. short time rating or limited time rating (*see* Clause 12).

10. *Continuous Rating.*—The I. E. C. continuous rating is the load which can be carried on test, under the conditions of that rating, for an unlimited period without the limits of the I. E. C. rules, as regards temperature rise, being exceeded.

11. *Service thermally equivalent to the Continuous Rating.*—Any machine intended for continuous service on fluctuating load may be given for test purposes a thermally equivalent I. E. C. continuous rating, provided that the service for which it is intended shall not cause in any of its parts temperatures or temperature rises in excess of those allowed by the I. E. C. rules when the machine is tested under the conditions of its continuous rating.

General Note re Classes of Fluctuating Load Service inserted by the Editing Committee.—It is desirable to distinguish between two kinds of fluctuating load service;—

(*i*) *That in which the overload peaks can be sustained be a machine of ordinary construction, without modification, and without exceeding the limits of temperature rise allowed by these rules for the machine when tested under its I. E. C. continuous rating.*

(*ii*) *That in which the overload peaks involve special provisions in design or construction either for mechanical or for electrical reasons.*

To designate this second class of service it is customary in Great Britain and the United States of America to employ the term "duty cycle rating," and the word "cycle" in this case signifies a period of time sufficiently long to include all the variations of load which might influence either the electrical construction or the mechanical construction of the machine.

12. *Short Time Rating.*—The I. E. C. short time rating is the load which can be carried on test for the time specified in the rating, the test being started with the machine cold and carried out under all the conditions of the rating, without the limits fixed by these I. E. C. rules, as regards temperature rise, being exceeded.

13. *Service thermally equivalent to the Short Time Rating.*—Any machine intended for service on loads which vary considerably may be

given for test purposes a thermally equivalent I. E. C. short time rating provided that the service for which it is intended shall not occasion in any of its parts temperatures or temperature rises in excess of those allowed by these rules when the machine is tested under the conditions of its short time rating.

PART II. INFORMATION TO BE GIVEN WITH ENQUIRIES AND ORDERS FOR ELECTRICAL MACHINES.

IV. General Information.

NOTE.—The term *machine* is used in these rules in its most general sense so as to avoid the constant repetition of the words *machines, transformers* and other *electro-magnetic induction apparatus.*

14. *General Information.*—The inquiry or order for an electrical machine should give the following general information:—

(*a*) The service output.

(*b*) The class of service required.

In the absence of any indication to the contrary continuous service is understood.

(*c*) The maximum temperature of the cooling air in which the machine is intended to work when it exceeds 40°C.

In the absence of any definite information it is understood that the temperature of the cooling air will not exceed 40°C.

(*d*) The altitude of the place where the machine is intended to work if its exceeds 1000 metres. In regard to altitude, *see* Clause 3.

(*e*) Any special requirements, if necessary, with regard to windings, methods of connection, neutral points and special tapping points, etc.

(*f*) When the apparatus is intended to operate in parallel with other apparatus the fact should be stated.

(*g*) Any special requirements in regard to electrical and mechanical details such as protective devices, cooling arrangements, etc.

(Specific recommendations regarding these details will be made at a later date by the I. E. C.)

V. Supplementary Information.

15. *Supplementary Information.*—The above general information should be completed by the following supplementary information in regard to the particular machine forming the subject of the order:—

16. *Direct-current Generator.*

Output at the terminals, in watts (W) or kilowatts (kW).
Pressure between terminals, in volts.
Current, in amperes.
Speed, in revolutions per minute.
Method of excitation.

17. *Direct-current Motor.*

Output at the shaft, in watts (W) or in kilowatts (kW).
Pressure between terminals, in volts.
Current, approximate, in amperes.
Speed at rated output, approximate, in revolutions per minute.
Method of excitation.

18. *Alternating-current Transformer.*
Frequency, in periods per second.
Number of phases.
Output, in voltamperes (VA), or in kilovoltamperes (kVA).
Primary pressure between terminals, in volts.
Secondary pressure between terminals, in volts, at no-load and at rated output with statement as to the power factor of the circuit fed by the secondary. If the power factor is not specified it shall be taken as 0.8.
Secondary current, in amperes.
For transformers intended to work in parallel, the primary pressure, current, and power factor on short circuit test, shall also be stated.
For three-phase transformers the method of connection shall also be indicated in accordance with the vector diagrams (*see* Appendix I.).
Any special requirements as to the accessibility of neutral points and special tapping points shall be indicated.

NOTE.—Whatever may be the nature of the transformers (step-up or step-down) the primary terminals are those which are connected to the source of electrical energy and the secondary terminals those which receive the electrical energy.

19. *Synchronous Alternator for Alternating Currents, Single or Poly phase.*
Frequency, in periods per second.
Number of phases.
Output between terminals, in voltamperes (VA) or kilovoltamperes (kVA).
Pressure between terminals, in volts, corresponding to the rated output.
Power factor of the system to be supplied. If this is not specified it shall be taken as 0.8.
Current, in amperes.
Speed, in revolutions per minute.
Excitation pressure, in volts (if the alternator is not provided with a special exciter).
Maximum exciting current available, in amperes (if the alternator is not provided with a special exciter).

20. *Synchronous Motor for Alternating Currents, Single or Polyphase.*
Frequency, in periods per second.
Number of phases.
Mechanical output at the shaft, in watts (W) or in kilowatts (kW).
Current, approximate, in amperes.
Pressure, in volts, of supply available.
Speed, in revolutions per minute.
Unless otherwise specified, the motor must be capable of giving its rated mechanical output at unity power factor.
If the motor is required to act as a device for improving the

power factor, the value of the reactive power required shall be stated.

Excitation pressure, in volts (if the motor is not provided with a special exciter).

Method of starting to be employed and source of power available for this purpose.

Maximum exciting current available, if limited.

21. *Non-Synchronous Motor for alternating currents, Single or Polyphase*

Frequency, in periods per second.

Number of phases.

Mechanical power at the shaft, in watts (W) or in kilowatts (kW)

Pressure between terminals, in volts.

Current, approximate, in amperes.

Speed, in revolutions per minute, approximate, at the rated output.

Rotor, whether wound or squirrel cage.

Method of starting.

Unless otherwise specified it is assumed that the stator receives the supply current.

Starting torque in kilogrammes at one metre.

Ratio of the starting current to the current corresponding to the rated output.

Ratio of the starting torque to the torque corresponding to the rated output.

The last three items are to be stated for the motor with its starting accessories.

PART III. CONDITIONS TO BE FULFILLED BY ELECTRICAL MACHINERY.

VI. General Remarks.

22. *General.*—This section deals with the conditions to be fulfilled by a machine purporting to comply with the I. E. C. Rules.

VII. Limits of Temperature and Temperature Rise.

TEMPERATURE LIMITS.

23. *Table of Temperature Limits.*—The following table gives the limits for the observable temperatures and temperature rises of windings and of certain parts of machines.

The permissible temperature limits are indicated in column 1 of the table.

The permissible limits of temperature rise are given in column 2. The temperature rises measured on any machine which has worked for the specified time at the output corresponding with its I. E. C. rating shall not exceed in any of its parts the limiting values given in column 2 of the table. The highest permissible temperature given in column 1 and the temperature rises given in column 2 of the table should never be exceeded by a machine operating in service.

(For exception *see* Clause 27.)

TEMPERATURE LIMITS.

Item No.	Nature of the insulation of the winding or name of part.	*Column* 1. Highest permissible observable temperature.	*Column* 2. Highest permissible observable temperature rise for the purpose of fixing the international rating.
		Degrees C.	Degrees C.
1	Cotton, paper or silk, non-impregnated ..	80	40
2	" " " impregnated (*see* Clause 24)........................	95	55
3	Cotton, paper or silk, immersed in oil.....	95	55
4	Enamelled wire (*see* Clause 25)	95	55
5	Mica, asbestos, glass, porcelain, micanite and similar compositions............	115	75
6	Insulated windings permanently short circuited	100	60
7	Non-insulated windings permanently short circuited..........................	110	70
8	Oil (for temperature limits, *see* Appendix II.).	—	—
9	Commutators, slip rings (*see* Clause 27)....	90	50
10	Bearings	80	40
11	Iron core immersed in oil..............	95	55
12	Iron core in contact with windings.......	Same as the windings.	
13	Iron core not in contact with windings nor immersed in oil. The temperature and temperature rise shall not exceed that allowed for the windings themselves, and in no case shall the temperature and temperature rise exceed 110°C. and and 70°C. respectively.		
14	Single layer windings: An increase of 5°C. above the temperatures given for items 1, 2 and 4 shall be permitted in the case of coils, revolving or stationary, with single layer windings when not immersed in oil.		

24. *Impregnated Cotton, Paper or Silk.*—An insulation is considered to be "impregnated" when a suitable substance replaces the air between its fibres, even if this substance does not completely fill the spaces between the insulated conductors. The impregnating substance, in order to be considered suitable, must have good insulating properties; must entirely cover the fibres and render them adherent to each other and to the conductor; must not produce interstices within itself as a consequence of evaporation of the solvent or through any other cause; must not flow during the operation of the machine at full working load at the temperature limit specified; must not deteriorate under prolonged action of heat.

25. *Enamelled Wire.*—When employing the temperature limits in the table for enamelled wire the maker must satisfy himself that the enamel employed is of good quality.

26. *Compound Insulations made up of Different Materials.*—When the insulation consists of layers of several different materials, the lowest of the temperatures permitted for the different insulating materials employed (*see* Clause 23) is to be adopted as the limiting temperature. The insulating material, even when forming the support, shall always be assumed as forming part of the winding.

27. *Commutators and Slip Rings.*—The observable temperature and temperature rise of commutators and slip rings may exceed the values

given in item 9 of the table, provided that the three following conditions are fulfilled:—

(*a*) The temperatures of the insulating materials in the commutator and on the adjoining windings shall not exceed those allowed in the table for the insulating materials of those parts.

(*b*) The manufacturer shall give a special guarantee that the high temperature attained shall not impair the commutation.

(*c*) The temperature shall not be so high as to affect the quality of the soldered joints and the connections.

REFERENCE TEMPERATURE OF COOLING MEDIUM.

28. *Reference Temperature of Cooling Medium.*—(*a*) *Temperate Climates.* In the absence of any indication to the contrary the maximum temperature of the air in which the machine is intended to operate in service shall be deemed to be 40°C.

(*b*) *Cold Climates.* In cold climates, when the actual temperature of the air in which the machine is intended to operate in service is not much different from 40°C. it is recommended that this conventional reference temperature of 40°C. should be adopted.

(*c*) *Tropical Climates.* The question of a reference temperature for cooling air for machines intended to operate in service in tropical climates will be dealt with by the I. E. C. at a later date.

(*d*) *Water Cooling* (*see* Appendix II.)

PERMISSIBLE LIMITS FOR TEMPERATURE RISE.

29. *Permissible Limits for Temperature Rise.*—The limits permitted for temperature rise are deduced from the values allowed for the highest permissible observable temperature (*see* Clauses 23—27) by subtracting therefrom 40°C. (the value assumed as that of the maximum cooling air temperature of the place in which the machine may be required to work in service) (*see* Clause 28).

TEMPERATURE MEASUREMENTS.

30. *Value of Temperature of Cooling Medium.*—A machine may be tested at any convenient cooling air temperature less than 40°C., but whatever be the value of this cooling air temperature the permissible rises of temperature shall not exceed those given in column 2 of the table (*see* Clause 23).

Corrections for variations in the cooling air temperature are not considered necessary within the limits of cooling air temperature obtaining in general practice.

In the case of cooling by means of forced ventilation the temperature of the air measured where it enters the machine shall be considered as the cooling air temperature.

For all machines cooled by other means, special rules will be necessary. (For water cooling, *see* Appendix II.)

31. *Measurement of Cooling Air Temperature during Tests.*—The cooling air temperature shall be measured by means of several thermometers placed at different points around and half-way up the machine at a distance of one to two metres, and protected from all heat radiation and draughts.

The value to be adopted for the temperature of the cooling air during a test shall be the mean of the readings of the thermometers (placed as mentioned above, taken at equal intervals of time during the last quarter of the duration of the test.

In order to avoid errors due to the time lag between the temperature of large machines and the variations in the cooling air, all reasonable precautions shall be taken to reduce these variations and the errors arising therefrom.

METHODS OF MEASUREMENT OF THE TEMPERATURES OF MACHINES.

32. *Measurement of the Temperatures of Machines.*—Two methods of determining the temperature of windings and other parts of machines are recognized:—

(*a*) Thermometer method.

(*b*) Resistance method.*

*NOTE.—With a view to brevity, the expression "method of variation of resistance of the winding" is replaced by the term "resistance method," or simply "by resistance."

33. *Thermometer Method.*—In this method the temperature is determined by thermometers applied to the accessible surfaces of the completed machine. The term "thermometer" also includes thermocouples and resistance-thermometers.

34. *Resistance Method.*—In this method the temperature rise of the windings is determined by the increase in the resistance of the windings themselves and checked by thermometers applied to the accessible surfaces of the windings to ascertain whether there is any higher local temperature. The highest of the temperatures thus found shall be taken as the observable temperature.

35. *Temperature of Windings.*—The temperature of windings as a rule shall be measured by the resistance method. The thermometer method alone is permitted in the following cases:—

(*a*) When it is not practicable to determine the temperature rise by the resistance method, as for example with low resistance commutating coils and compensating windings, and in general in the case of low resistance windings, especially when the resistance of joints and connections forms a considerable portion of the total resistance. In this case the temperature limits given in the table apply without correction.

(*b*) Single layer windings, revolving or stationary, when not immersed in oil. In this case an increase of 5°C. above the limits of temperature and of temperature rise given in the table is permitted.

(*c*) When, for reasons of manufacturing in quantity the thermometer method is used alone, although the resistance method would be possible. In this case the value of the highest permissible observable temperature and temperature rise given in the table shall be reduced by five degrees except in the case of stationary field coils, when the values given in the table shall be reduced by the difference between resistance and thermometer measurements as determined on similar machines, but in no case shall such reduction be less than 5°C.

36. *Corrections of Measurements taken after the machine has shut down.*—If the temperature is measured only after shut-down, the highest temperature attained while running shall be deduced by extrapolation on the time-temperature curve.

37. *Measuring Temperature of Direct-Current Generators and Motors.*—The temperature of field windings shall be measured in the manner described in Clauses 35 and 36.

The temperature of the armature shall be determined as a rule by thermometers placed on the windings at the hottest accessible parts, and when this method is employed the value of the highest permissible observable temperature and temperature rise shown in the table shall be reduced by 5°C.

38. *Measuring Temperature of Transformers.*—The temperature of transformer windings shall always be ascertained by resistance.

39. *Measuring Temperature of Synchronous Alternators and Motors.*—The temperature of the field windings shall always be ascertained by resistance. The temperature of stator windings shall be ascertained either by resistance or by thermometer in the manner described in the preceding clauses.

40. *Measuring Temperature of Non-Synchronous Motors without Commutators.*—The temperatures of the stator and rotor shall be ascertained in the same manner as those of the stator of a synchronous alternator (*see* Clause 39), except in the case of a permanently short-circuited winding, when the thermometer method shall be employed.

41. *Coefficients of Variation of Resistance of Copper with Temperature.*—In the case of resistance measurements the temperature coefficient of copper shall be taken from the values stated in the accompanying table, which have been deduced from the formula $1/(234.5 + t)$. Thus, at an initial temperature $t = 30$°C. the temperature coefficient or increase in resistance per degree Centigrade rise is $1/(264.5) = 0.00378$.

Temperature of the windings in degrees C., at which the initial resistance is measured.	Copper—increase in resistance per ohm per degree C.
0	0.00427
5	0.00418
10	0.00409
15	0.00401
20	0.00393
25	0.00385
30	0.00378
35	0.00371
40	0.00364

42. When the temperature of a winding is to be determined by resistance, the temperature of the winding before the test measured by thermometer shall not differ much from that of the cooling air.

43. *Duration of Temperature Test for Continuous Rating.*—For machines with I. E. C. continuous rating the temperature test shall be continued until it is evident that the maximum temperature rise attained

would not exceed the limits given in the table (*see* Clause 23), if the test were to be prolonged until the final steady temperature were attained. If possible, the temperature shall be measured both while running and after shut-down.

44. *Duration of Temperature Test for Short-time Rating.*—For machines with I. E. C. short-time rating the duration of the temperature test shall be that corresponding to the short-time test rating as indicated upon the rating plate.

At the commencement of the test the temperature of the machine must be practically that of the cooling air.

VII. Dielectric Tests.

(*See* Appendix III. for proposals.)

IX. Mechanical Tests.

(Not yet prepared.)

X. Commutation.

(Not yet prepared.)

PART IV. MARKINGS.

XI. Rating Plates.

45. *Rating Plate.*—Every machine shall bear the information necessary to define the limitations of the service for which it is intended.

For this purpose it shall have in all cases a rating plate and also such diagrams and terminal markings as may be necessary.

46. *Information on Rating Plate.*—The rating plate of a machine complying with the I. E. C. rules shall have a distinctive special sign and give the following information:—

(*a*) The name of the maker.

(*b*) The maker's machine number.

(*c*) The class of rating or the necessary information if the machine is intended to operate under more than one class of rating.

(*d*) The altitude at which the machine is intended to work if such altitude exceeds 1000 metres.

(*e*) The following technical information according to the character of the machine:—

In the absence of any indication in regard to the class of rating it is understood that the machine is intended for continuous service.

47. *Direct-current Generator.*

Generator—Direct-current.

Output, in watts (W) or in kilowatts (kW), with statement as to the class of rating.

Pressure between terminals, in volts.

Current, in amperes.

Speed, in revolutions per minute.

48. *Dierct-current Motor.*

Motor—Direct-current.

Output, in watts (W) or in kilowatts (kW), with statement as to the class of rating.

Pressure between terminals, in volts.

Current, approximate, in amperes.

Speed, in revolutions per minute.

49. *Transformer.*
    Frequency, in periods per second.
    Number of phases.
    Apparent output at the secondary, in voltamperes (VA) or in kilovoltamperes (kVA), with statement as to the class of rating.
    Primary pressure between terminals, in volts.
    Secondary pressure, in volts, at no load and at rated load, with statement as to the power factor.
    Short circuit pressure, in volts.
    Secondary current, in amperes.
    In addition, for three-phase transformers, a vector diagram indicating the method of connection of the windings in accordance with the figures. (*See* Appendix I.)

50. *Alternator.*
    Frequency, in periods per second.
    Number of phases.
    Apparent output, in voltamperes (VA) or in kilovoltamperes (kVA), with statement as to the class of rating.
    Pressure between terminals, in volts, corresponding to the rated output.
    Current, in amperes.
    Power factor corresponding to the rated output.
    Speed, in revolutions per minute.
    Excitation pressure, in volts.
    Maximum exciting current, in amperes.

51. *Synchronous Motor.*
    Frequency, in periods per second.
    Number of phases.
    Mechanical output, in watts, (W) or in kilowatts (kW), with statement as to the class of rating.
    Pressure between terminals, in volts, corresponding to the rated output.
    Current, approximate, in amperes.
    If the motor is intended to work with a power factor different from unity, the necessary information to be given.
    Speed, in revolutions per minute.
    Excitation pressure, in volts.
    Maximum exciting current, in amperes.

52. *Non-Synchronous Motor.*
    Frequency, in periods per second.
    Number of phases.
    Mechanical output, in watts (W) or in kilowatts (kW), with statement as to the class of rating.
    Pressure between terminals, in volts.
    Current, approximate, in amperes.
    Speed, in revolutions per minute, at rated output.
    Maximum pressure between slip rings, in volts.

APPENDIX I.

At the meeting of the Advisory Committee on Rating held in September, 1913, the question of terminal marking and vector diagrams was referred to Messrs. Everest and la Cour. The following rules were forwarded to the Central Office, but as they have not been submitted to the National Committees, the Editing Committee decided to include them as an Appendix only. They will, therefore, be submitted to the next Plenary Meeting for ratification.

Terminal Markings for Transformers.

1. *Single-phase Transformers.*—The terminals of all single-phase transformers shall be marked with the letter T for the high pressure side and *t* for the low pressure side.

The neutral terminal, if provided, shall be marked by N or *n*.

The letters T and *t* should be accompanied by subscripts 0, 1, 2, etc., arranged in order of progression in the same direction as the electromotive force in each circuit at the same instant, as shown in the diagram.

If the transformer has two or more windings intended to be coupled in series or in parallel, the subscripts shall be single numbers for the first of such windings (1, 2, etc.), double numbers for the second windings (11, 22, etc.), and so on.

2. *Polyphase Transformers.*—The terminals of all polyphase transformers shall be marked as follows:—

(*a*) Phase Identification. The terminals of the high pressure and low pressure windings of any one phase shall be marked with the same letter, using capital letters on the high pressure terminals and small type letters on the low pressure terminals.

The letters, A. B. C. *a*. *b*. *c*. shall be used.

The neutral terminal, if provided, shall be marked N or *n*.

(*b*) Polarity Identification. The relative polarity of the corresponding high pressure and low pressure windings in each phase shall be indicated by the addition of subscripts (0) and (1) after the phase letters, so placed that at the instant when (in, for instance, phase A) the high pressure terminal marked A_1 is positive to terminal A_0, the low pressure terminal a_1 shall be simultaneously positive to that marked a_0.

Vector Diagrams for Polyphase Transformers.

3. *Polyphase Transformers connected together.*—When two or more polyphase transformers are to be grouped together with their windings connected to the same primary and secondary systems, it is essential that the transformers shall correspond, not only as regards the pressures for which they are intended, but also as regards the exact phase relation of the secondary winding to the primary winding.

4. *Scope of Vector Diagrams.*—All polyphase transformers shall bear a vector diagram which shows accurately the phase relation between primary and secondary terminals. To secure the correctness of such a diagram the following requirements shall be complied with:—

(*a*) The identification of each phase of the secondary winding with the corresponding phase of the primary winding shall be clearly indicated by the same terminal markings (*see* Paragraph 2 above).

(*b*) To avoid error arising from differences in methods of winding, the relative instantaneous polarity of primary and secondary windings in each phase shall be indicated at the terminals of the various phase windings (*see* Paragraph 3 above).

5. *Vector Diagrams.*—The vector diagram of connections shall show the phase letter and the polarity marking for each phase of the windings, and shall show correctly how the various phases are connected together. But to avoid the complexity of marking both phase letter and polarity mark at each end of every winding vector it shall be sufficient to show the phase letter once, together with an arrow head to indicate polarity, the arrow head in every case pointing away from that end of the phase which has the polarity mark (0) on its terminal.

6. The following are some typical vector diagrams which embody the principles laid down in these rules:

APPENDIX II.

This Appendix contains proposals prepared by the Advisory Committee on Rating for submission to the National Committees, but not yet presented to a Plenary Meeting for ratification.

1. *Temperature Limits for Oil.*

Temperature limit for oil measured by thermometer..	90°C.
Temperature limit for the windings (measured by the increase of resistance) and other parts immersed in oil..	95°C.

NOTE.—The adoption of these temperatures implies the employment of a good oil of which the quality may be verified by ascertaining the flash point and measuring the deposit produced by heating.

The I. E. C. has not yet sufficient data to fix limiting values for the flash point or to prescribe the methods of measurement of the deposit.

2. *Reference Temperature of Cooling Water.*—For water-cooled apparatus, in the absence of any indication to the contrary, the maximum temperature of the cooling water in service shall be deemed to be 25°C. at the point of entry.

3. *Temperature Limits for Water-cooled Transformers.*—In the case of oil-immersed water-cooled transformers the limits of highest permissible observable temperature given in the table are to be reduced by 10°C.; therefore, the corresponding limits of temperature rise shown in the table may be increased 5°C.

APPENDIX III.

Dielectric Tests.

This Appendix contains proposals in regard to Dielectric Tests prepared by the Advisory Committee on Rating for submission to the National Committees, but not yet presented to the Plenary Meeting for ratification.

Dielectric Tests.—The high pressure test shall be applied between the winding and the frame with the core connected to the frame and to the winding not under test, and shall be applied only to a new and completed machine with all its parts in place under conditions equivalent to normal working conditions, and unless otherwise specified the test shall be carried out at the maker's works at the conclusion of the temperature test of the machine.

The test pressure shall be alternating, preferably of sine wave form.

The test shall be commenced at a pressure of less than one-third the test pressure and shall be increased to the full test pressure as rapidly as is consistent with its value being correctly indicated by the measuring instrument. The full test pressure shall then be maintained for one minute in accordance with the values as indicated in the following table:—

Item No.	Machine or Part.	Test Pressure (R. M. S.).
1	Rotating machines of size less than 1 kW................	500 V. + twice the rated pressure.
2	Rotating machines of size 1 kW to 3 kW..............	1000 V. + twice the rated pressure.
3	Rotating machines of size above 3 kVA.............	1000 V. + twice the rated pressure with minimum, 2000 V.
4	Field windings for synchronous generators when the excitation pressure does not exceed 750 V.	10 times the excitation pressure. Minimum, 2000 V. Maximum, 3500 V.
5	Field windings for synchronous motors:—	
	(*a*) When intended to be started up with the field windings short circuited.	10 times the excitation pressure. Minimum, 2000 V. Maximum, 3500 V.
	(*b*) When intended to be started up with the field windings separated by a break-up switch.	5000 V.
	(*c*) When intended to be started up with the fields on open circuit and without a break-up switch.	5000 V. when the excitation pressure is less than 275 V. 8000 V. when the excitation pressure is equal to or exceeds 275 V.
6	Exciter.....................	Not yet decided.
7	Transformers in general......	1000 V. + twice the rated pressure.

Item No.	Machine or Part.	Test Pressure (R. M. S.).
8	Transformers for primary pressures over 550 V., the secondaries of which are for direct connection to public or private distribution systems or public or private consumers (*i. e.*, secondary pressures less than 550 V.).	Primary windings: 1000 V. + twice the rated primary pressure with minimum, 10000 V. (adopted as a protection to human life). Secondary windings: 1000 V. + twice the rated secondary pressure.
9	Secondary (rotor) windings of induction motors not permanently short circuited.	For non-reversing motors: 1000 V. + twice the maximum pressure which could be induced between the slip rings. For reversing motors: 1000 V. + 4 times the pressure between the slip rings at standstill on open circuit with full primary pressure applied to tator windings.
10	Alternating current apparatus connected to a single-phase system of more than 300 V. pressure permanently earthed.	Not yet decided.
11.	Assembled apparatus.........	When the test is made on an assembled group of several pieces of new apparatus each one of which has previously passed its high presure test, the test on such assembled group shall not exceed 85 per cent. of the lowest test pressure appropriate for any part of the group.

APPENDIX IV.

Definitions dealing with the subject of "Rating":—

Gt. Britain.—The rating of an electrical machine is the output assigned to it by the maker, together with the associated conditions, all of which are marked on the Rating Plate.

NOTE.—A machine may have a test rating or a service rating, or both, assigned to it, and marked on the rating plate.

United States of America.—The rating of a machine is the output marked on the Rating Plate and shall be based on, but shall not exceed the maximum load which can be taken from the machine under prescribed conditions of test. This is also called the Rated Output.

(The term "maximum load" does not refer to loads applied solely for mechanical, commutation, or similar tests.)

France.—The rating of a machine is determined by the conditions of working such as speed, pressure, current, power factor, etc., as indicated on the Rating Plate.

Italy.—The output of a machine is the normal or average output, that is to say, the load at which the machine can work under normal conditions.

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THE LIMITATIONS OF THE STOP WATCH AS A PRECISION INSTRUMENT

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4. INSULATION AND DIELECTRIC PHENOMENA

THE MAXIMUM SAFE OPERATING TEMPERATURE OF LOW-VOLTAGE PAPER-INSULATED CABLES

W. A. Del Mar **Vol. xl—1921, pp. 97-105**

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D. W. Roper **Vol. xi—1921, pp. 131-136**

Chicago experience and practise.

Discussion incorporated with that of paper by L. L. Elden on "Permissible Operating Temperatures of Impregnated Paper Insulation in Which the Dielectric Stress is Low."

NOTES ON THE EFFECT OF HEAT ON IMPREGNATED PAPER FROM CABLE INSULATION

W. S. Clark **Vol. xl—1921, pp. 137-141**

The results of tests made to determine at what temperature marked deterioration in the paper of impregnated paper cables took place.

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THE EFFECT OF HEAT ON PAPER INSULATION

H. W. Fisher and R. W. Atkinson **Vol. xl—1921, pp. 143-166**

A discussion is given in detail of the mechanical properties of paper especially as influenced by drying, heating, and impregnating. Tests for measuring the changes due to these causes are discussed. A measurement of tearing resistance is found to be satisfactory and two machines for this purpose are described. Measurements are given of rate of deterioration of paper at different temperatures. The relation of these data to allowable operating temperature is considered.

The rapid increase of deterioration with temperature is shown.

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L. L. Elden **Vol. xl—1921, pp. 167-176**

Practise in connection with low-voltage cables including data over a ten year period.

Discussion (including that of papers by W. A. Del Mar, P. Torchio, D. W. Roper, W. S. Clark, and H. W. Fisher and R. W. Atkinson), pages 177-203, by Messrs. F. M. Farmer, G. B. Shanklin, E. B. Meyer, W. I. Middleton, W. A. Del Mar, C. A. Adams, H. R. Woodrow, P. H. Chase, R. J. Wiseman, W. Maver, Jr., A. E. Kennelly, F. D. Newbury, H. C. Dean, D. C. Jackson, P. Torchio, D. W. Roper, H. W. Fisher, R. W. Atkinson, and L. L. Elden.

A general discussion.

MODERN PRODUCTION OF SUSPENSION INSULATORS

Edwin H. Fritz and G. I. Gilchrest **Vol. xl—1921, pp. 1127-1153**

This paper pictures the progress made during the past few years in the production of electrical porcelain. The information covers: First: The engineering and works organization. Second: The manufacture. Third: Design and test.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

A SOLUTION OF THE PORCELAIN INSULATOR PROBLEM

E. E. F. Creighton and F. L. Hunt **Vol. xl—1921, pp. 1173-1180**

A description of tests to which insulators were subjected in order to determine main causes of failure. Particular emphasis is laid upon the following factors: mechanical strength; electrical tests; line testing; aging of porcelain; open porosity of porcelain, etc.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

THE ELECTRIC STRENGTH OF AIR UNDER CONTINUOUS POTENTIALS AND AS INFLUENCED BY TEMPERATURE

J. B. Whitehead and F. W. Lee **Vol. xl—1921, pp. 1201-1237**

The paper describes a series of experiments on the influence of temperature on corona-forming continuous potentials. The observations have been made on three sizes of wire of diameters 0.0251 cm., 0.0803 cm., and 0.0933 cm., and in each case at several values of temperature within the range 5 deg. cent. and 70 deg. cent. At each temperature the pressure has been varied from a value in the neighborhood of that of the atmosphere downwards, reaching in the extreme cases the value 6.03 cm. of mercury. Within the range of values reached, as indicated above, the general form of the law of corona as developed experimentally by a number of other observers, is found to be fulfilled. There are separate families of curves for positive and negative potentials as obtained by varying the pressure for each constant value of temperature.

Discussion (including that of papers by Imlay, Bailey, Baum, Lewis, Elden, Fritz and Gilchrest, Peek, Creighton and Hunt, Peters and Skinner) pages, 1238-1308, by Messrs. W. I. Slichter, L. P. Ferris, B. Speed, F. W. Peek, Jr., M. E. Skinner, C. L. Fortescue, H. J. Ryan, J. T. Barron, H. W. Smith, A. O. Austin, K. A. Hawley, R. H. Marvin, G. I. Gilchrest, E. E. F. Creighton, A. W. Copley, L. H. Burnham, J. P. Jollyman, S. Barfoed, A. H. Lawton, H. R. Summerhayes, J. H. Foote, G. Cameron, H. L. Wallau, R. G. McCurdy, D. I. Cone, J. B. Whitehead, R. J. C. Wood, H. Michener, R. Bailey, F. G. Baum, W. W. Lewis.

5. ELECTRIC CONDUCTORS

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W. A. Del Mar **Vol. xl—1921, pp. 97-106**

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A general discussion.

HEAT LOSSES IN THE CONDUCTORS OF ALTERNATING-CURRENT MACHINES

Waldo V. Lyon **Vol. xl—1921, pp. 1361-1395**

The principal object of this paper is to show how hyperbolic functions of *complex angles* may be applied to the solution of the problem of heat losses in rectangular conductors that are embedded in open slots. A certain knowledge of the functions themselves is presupposed. Inasmuch however, as they are handled like trigonometric functions of real angles—except in regard to the plus and minus signs—it is a simple matter to acquire the requisite technical skill to use them.

Since the present paper was written, the author has extended the method to the solution of the problem in which the conductors have a finite number of strands separated by insulation.

Discussion (including that of papers by Henningsen, Speed and Elmen), pages 1396-1409, by Messrs. Wm. J. Foster, F. G. Baum, W. Fondiller, H. L. Hibbard, G. Semenza, C. A. Copley, W. E. Thau, P. P. Ashworth, S. P. Grace, A. M. MacCutcheon, H. W. Taylor, E. S. Henningsen.

6. MAGNETIC PROPERTIES AND TESTING OF IRON

HYSTERESIS EFFECTS WITH VARYING SUPERPOSED MAGNETIZING FORCES

W. Fondiller and W. H. Martin **Vol. xl—1921, pp. 563-579**

The hysteresis effects discussed in this paper occur when magnetic fields are produced in iron by electrical circuits carrying simultaneously currents of different frequencies, as in composited circuits carrying telephone and telegraph circuits over the same wires.

Discussion, pages 580-587, by Messrs. M. I. Pupin, C. W. Burrows, B. A. Behrend, W. Fondiller, W. H. Martin.

MAGNETIC PROPERTIES OF COMPRESSED POWDERED IRON

Buckner Speed and G. W. Elmen **Vol. xl—1921, pp. 1321-1359**

This paper describes a new magnetic material which is peculiarly suited to the construction of cores in small inductance coils and transformers such as are used in a telephone plant. The material which was developed to meet these requirements is formed by fine grains of powdered iron, insulated and compressed. There is described the circumstances and experiments which led to this development and also the method of commercial production. Tables and curves are given showing the magnetic, electrical and mechanical properties of the material.

Discussion incorporated with that of paper by Waldo V. Lyon on "Heat Losses in the Conductors of Alternating-Current Machines."

8. TRANSFORMERS

TRANSFORMERS FOR INTERCONNECTING HIGH-VOLTAGE TRANSMISSION SYSTEMS

For Feeding Synchronous Condensers from a Tertiary Winding

J. F. Peters and M. E. Skinner **Vol. xl—1921, pp. 1181-1199**

Owing to the advantages to be realized from the use of the star-star connection in interconnecting high-voltage transmission systems and from the fact that this connection requires the use of an auxiliary winding connected in delta to stabilize the neutral point or to decrease the inductance in the ground connection, a great majority of the transformers designed for interconnecting transmission lines are three-winding transformers. Another type of transformer which would be included in this general class would be that having an auxiliary winding for feeding a synchronous condenser.

There are a number of important features peculiar to three-winding transformers for these classes of service that complicate the design and operation to a considerable extent.

This paper calls attention to these special problems and indicates the way in which the design and performance of transformers for these classes of service are influenced by them.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

9. ELECTRICAL MACHINERY AND APPARATUS

THE APPLICATION OF ELECTRIC POWER TO THE RUBBER INDUSTRY

By the Subcommittee on the Rubber Industry
of the Industrial and Domestic Power Committee **Vol. xl—1921, pp. 1-37**

A report designed to increase the efficiency of electric power in the rubber industry, the largest individual user of electric power. The report is divided into power consumption, power economy, protection of operatives, basic operations, motor selection, and recommendations.

Discussion, pages 38-53, by Messrs, A. P. Lewis, J. F. Lincoln, B. T. Mottinger, H. McFarland, J. H. Vance, W. H. Horton, Jr., C. W. Drake, W. S. Scott, E. W. Pilgrim, G. A. Maier, B. H. Cunningham, B. A. Waltz, M. Berthold, A. M. MacCutcheon, B. C. Dennison, L. B. Timmermann, H. W. Eastwood, P. M. Lincoln, F. H. Oberschmidt, W. E. Date.

PRESENT DAY PRACTISE LIMITATIONS OF OIL CIRCUIT BREAKERS

Subcommittee on Oil Circuits Breakers of Protective Devices Committee **Vol. xl—1921, pp. 55-60**

The operating requirements and limitations of oil circuit breakers as summarized from replies to a questionaire to large operating companies.

Discussion incorporated with that of paper by P. Torchio on "High-current Tests on High-Tension Switchgear."

HIGH-CURRENT TESTS ON HIGH-TENSION SWITCHGEAR

Philip Torchio **Vol. xl—1921, pp. 61-86**

The article describes a series of tests on oil circuit breakers and disconnecting switches to determine their strength at brush contacts and supports in withstanding the mechanical stresses engendered by the magnetic flux due to the flow of large currents of the order of 100,000 amperes, as may exist at times of short circuits on large systems. Other tests were made on current transformers and potential transformer fuses.

For the first time, a synchronized motion picture machine and an oscillograph, were coupled to reproduce the coincident actions of the apparatus tested, and the variations of voltage and current in the circuit. The tests emphasized the importance of strong locks for disconnecting switches. Only single-turn primary-type current transformers and potential transformer fuses with resistance in series, were found adequate to give the service requirements.

Discussion (including that of paper by H. R. Woodrow on "Present Day Practise Limitations of Oil Circuit Breakers"), pages 87-96, by Messrs P. Junkersfeld, E. P. Peck, N. J. Conrad, N. L. Pollard, E. E. F. Creighton, H. E. Trent, W. A. Moore, L. B. Chubbuck, P. Torchio, S. Haar, and H. R. Woodrow.

A general discussion of experience under various conditions of practise.

SHORT-CIRCUIT CURRENT OF INDUCTION MOTORS AND GENERATORS

R. E. Doherty and E. T. Williamson **Vol. xl—1921, pp. 509-539**

There has been a rather prevailing opinion that a sudden short circuit of an induction generator would not cause a serious initial rise in current such as occurs in synchronous generators. This has led to the proposal of the use of such machines as a partial solution of the short-circuit problem on a-c. systems. Theoretical considerations and experimental data given in the paper show that, on the contrary, the rise in the induction generator, just as in the synchronous machine, a serious initial rush of current which is limited only by the leakage reactance of the machine.

Discussion, pages 540-551, by Messrs. V. Karapetoff, L. E. Widmark, M. I. Pupin, N. S. Diamant, S. Haar, R. E. Doherty.

DEVELOPMENTS IN CONVERSION APPARATUS FOR EDISON SYSTEMS

J. F. Barton and J. J. Hambleton **Vol. xl—1921, pp. 663-692**

A description of the conditions existing in Edison systems which have led to the adoption of various types of converter apparatus. Facts which should be considered in selecting the more suitable type of conversion apparatus for a particular service.

Discussion, pages 693-716, by Messrs B. G. Lamme, A. A. Nims, F. D. Newbury, A. M. Garrett, R. Bailey, P. Torchio, S. Haar, H. C. Albrecht, D. W. Roper, T. T. Hambleton, T. F. Barton.

COLFAX POWER STATION OF THE DUQUESNE LIGHT COMPANY, PITTSBURGH

D. L. Galusha and C. W. E. Clarke **Vol. xl—1921, pp. 717-748**

Description of the new steam power station of the Duquesne Co., with eventual output of 300,000 kw., units 60,000 kw.

Discussion, pages 749-762, by Messrs. C. S. Cook, G. F. Brown, F. C. Hanker, G. G. Bell, C. S. Hershfeld, F. Hodgkinson, W. T. Snyder, R. H. Keil, E. C. Stone, W. E. Clarke, D. L. Galusha.

HYDROELECTRIC DEVELOPMENT AT NIAGARA FALLS

John L. Harper and J. A. Johnson **Vol. xl—1921, pp. 881-923**

This paper traces briefly the progress in power development at Niagara, describing particularly recent developments and those to be undertaken under recent license granted to the Niagara Falls Power Company.

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ADVANCES IN THE ART OF WATERWHEEL DESIGNS AND SETTINGS

W. M. White **Vol. xl—1921, pp. 925-963**

Description of waterwheel development. Selection of proper unit discussed in detail with relation to speed, speed regulation, runner material, draft tubes, shafts and bearings, guide vanes, governors, casings, vertical vs. horizontal units, control valves, settings.

Deiscussion (including that of paper by Harper and Johnson), pages 964-973, by Messrs. E. A. Pragst, W. M. Moody, W. J. Foster, E. M. Breed, J. A. Johnson, W. M. White.

SYNCHRONOUS MOTORS FOR SHIP PROPULSION

E. S. Henningsen **Vol. xl—1921, pp. 1309-1319**

A description of the advantages and disadvantages of the synchronous motor for propulsion of various types of ships.

Discussion incorporated with that of paper by Waldo V. Lyon on "Heat Losses in the Conductors of Alternating-Current Machines."

ELECTRIC AUXILIARIES ON MERCHANT SHIPS

H. D. Dickinson **Vol. xl—1921, pp. 1411-1484**

A discussion of the problem of electrically driven auxiliaries for merchant ships particularly from the economic standpoint and as affected by the type of drive of the ship itself.

Discussion incorporated with that of paper by W. E. Thau on "Electric Propulsion of Ships."

ELECTRIC PROPULSION OF SHIPS

W. E. Thau **Vol. xl—1921, pp. 1435-1464**

This paper deals primarily with electric propulsion of ships except wherein comparison warrants reference to some other type of drive. All classes of ships are considered, divided into two general classes, merchant ships, and war ships.

Discussion (including that of paper by Dickinson), pages 1465-1539, by Messrs. W. L. R. Emmet, C. F. Bailey, W. W. Smith, J. B. Newman, E. A. Sperry, F. C. Bates, G. H. Jett, G. A. Pierce, C. Rettie, W. McClelland, E. H. B. Anderson, E. A. Stevens, Jr., S. M. Robinson, H. L. Hibbard, W. E. Thau, J. K. Robison, H. D. Dickinson.

11. POWER PLANTS AND CENTRAL STATIONS

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13. TRANSMISSION LINES

LONG DISTANCE TRANSMISSION OF ELECTRIC ENERGY

L. E. Imlay **Vol. xl—1921, pp. 975-994**

The paper discusses long-distance transmission of electric energy dealing with (1) the economic conditions which justify it, (2) the plant involved, and (3) the service that may be expected.

In dealing with the plant required for long-distance transmission some of the considerations that affect the design are discussed. A graphic method of determining line performance is illustrated by an example and some essential data on other lines are given. Right of way, spacing of towers, line insulators, high-tension switches and lightning arresters are discussed.

Service is considered from the viewpoints of, what people demand, what perfect service will cost, and the service that may be expected from a large interconnected system consisting of steam plants at the mines, hydro plants wherever available and local steam plants.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

VOLTAGE AND POWER FACTOR CONTROL OF 66,000-VOLT TRANSMISSION LINES CONNECTING TWO GENERATING STATIONS

Raymond Bailey **Vol. xl—192, pp. 995-1015**

The problem which confronted The Philadelphia Electric Company of providing for the control of voltage and power factor of the two 66,000-volt transmission lines connecting its Schuylkill and Chester generating stations is presented in this paper.

The comparison made to determine upon the most satisfactory type of regulating equipment and the reasons for the selection of three-phase induction regulators are given. Data on the performance characteristics of the lines, with the induction regulators are included.

In the discussion of this problem of voltage and power factor control, certain conclusions of a more or less fundamental character are brought out.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

VOLTAGE REGULATION AND INSULATION FOR LARGE POWER LONG DISTANCE TRANSMISSION SYSTEMS

Frank G. Baum **Vol. xl—1921, pp. 1017-1077**

Heretofore the distance to which power could be transmitted has been limited. This limitation is now removed by a simple method of loading the line with synchronous condensers, so that the current and voltage may be kept practically in phase. High power factor and hence high efficiency result, and the voltage rises of the system are very much reduced, thus reducing insulation strains.

A standard frequency of 60 cycles is advocated for the national system, and 220,000 volts is proposed as standard for extra large-power, long-distance transmission. The system of regulation proposed will result in practically constant voltage at all points of the line at all loads. And power may be taken from or supplied to the line at any point, and the power over sections of the line or over the entire line may be reversed and the constant voltage system maintained.

A simple diagram is given, and this shows that for a 60-cycle, 220,000-volt line, the line-charging current supplies the capacity current required for about 0.8 load or 320 amperes load current, and that for larger loads the synchronous condensers supply leading and for smaller loads lagging current.

The problems of the lines insulation are discussed, and especial attention is called to the necessity for low air and leakage resistance stresses. Results of a large number of tests are given.

A new diagram is given which results from analysis of experimental data, from which the characteristics of long insulator strings may be calculated.

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SOME TRANSMISSION LINE TESTS

W. W. Lewis **Vol. xl—1921, pp. 1079-1119**

A description of some interesting features of a series of tests on the 30-cycle 140,000-volt system of the Consumers Power Company in western Michigan.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

NOTES ON OPERATION OF LARGE INTERCONNECTED SYSTEMS

L. L. Elden **Vol. xl—1921, pp. 1121-1126**

Description of the physical arrangement of connections and the operation of the interconnected systems of the Boston Edison, the Eastern Massachusetts Electric Company and the New England Power Company.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

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Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

VOLTAGE AND CURRENT HARMONICS CAUSED BY CORONA

F. W. Peek, Jr. **Vol. xl—1921, pp. 1155-1172**

The results of an investigation made to study the effects of corona in producing voltage and current harmonics in transmission systems.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

A SOLUTION OF THE PORCELAIN INSULATOR PROBLEM

E. E. F. Creighton and F. L. Hunt **Vol. xl—1921, pp. 1173-1180**

A description of tests to which insulators were subjected in order to determine main causes of failure. Particular emphasis is laid upon the following factors: mechanical strength; electrical tests; line testing; aging of porcelain; open porosity of porcelain, etc.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

16. CONTROL, REGULATION AND SWITCHING

DEVELOPMENTS IN CONVERSION APPARATUS FOR EDISON SYSTEMS

T. F. Barton and T. T. Hambleton **Vol. xl—1921, pp. 663-692**

A description of the conditions existing in Edison systems which have led to the adoption of various types of converter apparatus. Facts which should be considered in selecting the more suitable type of conversion apparatus for a particular service.

Discussion, pages 693-716, by Messrs. B. G. Lamme, A. A. Nims, F. D. Newbury, A. M. Garrett, R. Bailey, P. Torchio, S. Haar, H. C. Albrecht, D. W. Roper, T. T. Hambleton, T. F. Barton.

LONG DISTANCE TRANSMISSION OF ELECTRIC ENERGY

L. E. Imlay **Vol. xl—1921, pp. 975-994**

The paper discusses long-distance transmission of electric energy dealing with (1) the economic conditions which justify it, (2) the plant involved, and (3) the service that may be expected.

In dealing with the plant required for long-distance transmission some of the considerations that affect the design are discussed. A graphic method of determining line performance is illustrated by an example and some essential data on other lines are given. Right of way, spacing of towers, line insulators, high-tension switches and lightning arresters are discussed.

Service is considered from the viewpoints of, what people demand, what perfect service will cost, and the service that may be expected from a large interconnected system consisting of steam plants at the mines, hydro plants wherever available and local steam plants.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

VOLTAGE AND POWER FACTOR CONTROL OF 66,000-VOLT TRANSMISSION LINES CONNECTING TWO GENERATING STATIONS

Raymond Bailey **Vol. xl—1921, pp. 995-1015**

The problem which confronted The Philadelphia Electric Company of providing for the control of voltage and power factor of the two 66,000-volt transmission lines connecting its Schuylkill and Chester generating stations is presented in this paper.

The comparison made to determine upon the most satisfactory type of regulating equipment and the reasons for the selection of three-phase induction regulators are given. Data on the performance characteristics of the lines, with the induction regulators are included.

In the discussion of this problem of voltage and power factor control, certain conclusions of a more or less fundamental character are brought out.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

VOLTAGE REGULATION AND INSULATION FOR LARGE POWER LONG DISTANCE TRANSMISSION SYSTEMS

Frank G. Baum **Vol. xl—1921, pp. 1017-1077**

Heretofore the distance to which power could be transmitted has been limited. This limitation is now removed by a simple method of loading the line with synchronous condensers, so that the current and voltage may be kept practically in phase. High power factor and hence high efficiency result, and the voltage rises of the system are very much reduced, thus reducing insulation strains.

A standard frequency of 60 cycles is advocated for the national system, and 220,000 volts is proposed as standard for extra large-power, long-distance transmission. The system of regulation proposed will result in practically constant voltage at all points of the line at all loads. And power may be taken from or supplied to the line at any point, and the power over sections of the line or over the entire line may be reversed and the constant voltage system maintained.

A simple diagram is given, and this shows that for a 60-cycle, 220,000-volt line, the line-charging current supplies the capacity current required for about 0.8 load or 320 amperes load current, and that for larger loads the synchronous condensers supply leading and for smaller loads lagging current.

The problems of the line insulation are discussed, and especial attention is called to the necessity for low air and leakage resistance stresses. Results of a large number of tests are given.

A new diagram is given which results from analysis of experimental data, from which the characteristics of long insulator strings may be calculated.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

SOME TRANSMISSION LINE TESTS

W. W. Lewis **Vol. xl—1921, pp. 1079-1119**

A description of some interesting features of a series of tests on the 30-cycle 140,000-volt system of the Consumers Power Company in western Michigan.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

NOTES ON OPERATION OF LARGE INTERCONNECTED SYSTEMS

L. L. Elden **Vol. xl—1921, pp. 1121-1128**

Description of the physical arrangement of connections and the operation of the interconnected systems of the Boston Edison, the Eastern Massachusetts Electric Company and the New England Power Company.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

TRANSFORMERS FOR INTERCONNECTING HIGH-VOLTAGE TRANSMISSION SYSTEMS

For Feeding Synchronous Condensers from a Tertiary Winding

J. F. Peters and M. E. Skinner **Vol. xl—1921, pp. 1181-1190**

Owing to the advantages to be realized from the use of the star-star connection in interconnecting high-voltage transmission systems and from the fact that this connection requires the use of an auxiliary winding connected in delta to stabilize the neutral point or to decrease the inductance in the ground connection, a great majority of the transformers designed for interconnecting transmission lines are three-winding transformers. Another type of transformer which would be included in this general class would be that having an auxiliary winding for feeding a synchronous condenser.

There are a number of important features peculiar to three-winding transformers for these classes of service that complicate the design and operation to a considerable extent.

This paper calls attention to these special problems and indicates the way in which the design and performance of transformers for these classes of service are influenced by them.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

19. ELECTRICITY IN THE ARMY AND NAVY

SYNCHRONOUS MOTORS FOR SHIP PROPULSION

E. S. Henningsen **Vol. xl—1921, pp. 1309-1319**

A description of the advantages and disadvantages of the synchronous motor for propulsion of various types of ships.

Discussion incorporated with that of paper by Waldo V. Lyon on "Heat Losses in the Conductors of Alternating-Current Machines."

ELECTRIC AUXILIARIES ON MERCHANT SHIPS

H. D. Dickinson **Vol. xl—1921, pp. 1411-1424**

A discussion of the problem of electrically driven auxiliaries for merchant ships particularly from the economic standpoint and as affected by the type of drive of the ship itself.

Discussion incorporated with that of paper by W. E. Thau on "Electric Propulsion of Ships."

ELECTRIC PROPULSION OF SHIPS

W. E. Thau **Vol. xl—1921, pp. 1435-1464**

This paper deals primarily with electric propulsion of ships except wherein comparison warrants reference to some other type of drive. All classes of ships are considered, divided into two general classes, merchant ships, and war ships.

Discussion (including that of paper by Dickinson), pages 1465-1439, by Messrs. W. L. R. Emmet, C. F. Bailey, W. W. Smith, J. B. Newman, E. A. Sperry, F. C. Bates, G. H. Jett, G. A. Pierce, C. Rettie, W. McClelland, E. H. B. Anderson, E. A. Stevens, Jr., S. M. Robinson, H. L. Hibbard, W. E. Thau, J. K. Robison, H. D. Dickinson.

20. MISCELLANEOUS APPLICATIONS OF ELECTRICITY

THE APPLICATION OF ELECTRIC POWER TO THE RUBBER INDUSTRY

By the Subcommittee on the Rubber Industry
of the Industrial and Domestic Power Committee **Vol. xl—1921, pp. 1-37**

A report designed to increase the efficiency of electric power in the rubber industry, the largest individual user of electric power. The report is divided into power consumption, power economy, protection of operatives, basic operations, motor selection, and recommendations.

Discussion, pages 38-53, by Messrs, A. P. Lewis, J. F. Lincoln, B. T. Mottinger, H. McFarland, J. H. Vance, W. H. Horton, Jr., C. W. Drake, W.S. Scott, E. W. Pilgrim, G. A. Maier, B. H. Cunningham, B. A. Waltz, M. Berthold, A. M. MacCutcheon, B. C. Dennison, L. B. Timmermann, H. W. Eastwood, P. M. Lincoln, F. H. Oberschmidt, W. E. Date.

REGULATION OF FREQUENCY FOR MEASUREMENT PURPOSES

B. H. Smith **Vol. xl—1921, pp. 425-433**

Frequency can be transmitted without any change for practically any distance and lends itself as a quantity which can be made proportional to a given indication. The purpose of this paper is to consider a number of metering systems where the frequency of a circuit is controlled in order to transmit an electrical condition to a remote point and to bring out the adaptability of this quantity for such purposes.

Discussion, pages 434-438, by Messrs. J. R. Craighead, C. F. Scott, W. H. Pratt, B. H. Smith.

SYNCHRONOUS MOTORS FOR SHIP PROPULSION

E. S. Henningsen **Vol. xl—1921, pp. 1309-1319**

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21. TELEPHONY AND TELEGRAPHY

CARRIER CURRENT TELEPHONY AND TELEGRAPHY

E. H. Colpitts and O. B. Blackwell **Vol. xl—1921, pp. 205-300**

This paper briefly outlines first the history of the development of carrier multiplex telegraphy and telephony. The fundamental principles underlying particularly the newer developments of the art are then discussed. Consideration is likewise given to the propagation characteristics of open wire lines, including those containing intermediate lengths of cable. Commercial types of apparatus and actual installations are then described and a brief statement made as to further applications of the art.

Discussion incorporated with that of paper by Stanley Rhoads on "Some Phases of Railroad Telegraph and Telephone Engineering."

SOME PHASES OF RAILROAD TELEGRAPH AND TELEPHONE ENGINEERING

Stanley Rhoads **Vol. xl—1921, pp. 301-380**

Statement of size of N. Y. C. Lines telegraph and telephone plant and variety of engineering problems involved.

Problems include electric protection, inductive interference, electrolysis transmission, traffic, necessitating continual experiment and investigation.

Battery consumption data. Oscillograms of single-line telegraph current waves, when line insulation varies.

Telephone selector current waves given. Defects of quadruplex discussed. Limiting practicable lengths stated for various kinds of wire for telegraph and telephone circuits.

Discussion (including that of paper by Colpitts and Blackwell), pages 381-424, by Messrs. G. O. Squier, A. E. Kennelly, D. Mc Nicol, E. C. Keenan, H. W. Drake, J. L. Niesse, R. D. Duncan, Jr., L. Cohen, S. Rhoads, E. H. Colpitts.

22. MISCELLANEOUS TOPICS AND INSTITUTE AFFAIRS

MEASUREMENT OF RELATIVE EDDY CURRENT LOSSES IN STRANDED CABLES

James A. Cook **Vol. xl—1921, pp. 439-446**

Description of a method which will provide accurate measurements of eddy current losses on a comparative basis. The method represents the accumulated experience of the Test Dept. of the N. Y. Edison Company.

Discussion, pages 447-449, by Messrs. J. B. Whitehead, R. W. Atkinson, F. V. Magalhaes, J. A. Cook.

AN ELECTROMECHANICAL DEVICE FOR RAPID SCHEDULE HARMONIC ANALYSIS OF COMPLEX WAVES

Fred. S. Dellenbaugh, Jr. **Vol. xl—1921, pp. 451-475**

The ease with which electric circuits may be combined by multiple switches and the accuracy with which measurements may be made, suggests the use of an electric network with some adjustable members to solve curves under analysis. The device described suggests one way in which this may be done.

Discussion, pages 476-478, by Messrs. V. Karapetoff, A. E. Kennelly, F. S. Dellenbaugh, Jr.

THE LIMITATIONS OF THE STOP WATCH AS A PRECISION INSTRUMENT

A. L. Ellis **Vol. xl-1921, pp. 479-502**

Several types of watches are discussed to illustrate the sources and character of errors due to principle of operation, mechanical restrictions and design. The errors due to these sources entirely mask those known as "isochronal" and "thermal" which are therefore not considered.

Discussion, pages 503-507, by Messrs. V. Karapetoff, H. M. Smith, W. J. Hammer, L. M. Potts, A. L. Ellis.

SHORT-CIRCUIT CURRENT OF INDUCTION MOTORS AND GENERATORS

R. E. Doherty and E. T. Williamson **Vol. xl—1921, pp. 509-539**

There has been a rather prevailing opinion that a sudden short circuit of an induction generator would not cause a serious initial rise in current such as occurs in synchronous generators. This has led to the proposal of the use of such machines as a partial solution of the short-circuit problem on a-c. systems. Theoretical considerations and experimental data given in the paper show that, on the contrary, the rise in the induction generator, just as in the synchronous machine, a serious initial rush of current which is limited only by the leakage reactance of the machine.

Discussion, pages 540-551, by Messrs. V. Karapetoff, L. E. Widmark, M. I. Pupin, N. S. Diamant, S. Haar, R. E. Doherty.

HYSTERESIS EFFECTS WITH VARYING SUPERPOSED MAGNETIZING FORCES

W. Fondiller and W. H. Martin **Vol. xl—1921, pp. 553-579**

The hysteresis effects discussed in this paper occur when magnetic fields are produced in iron by electrical circuits carrying simultaneously currents of different frequencies, as in composited circuits carrying telephone and telegraph circuits over the same wires.

Discussion, pages 580-587, by Messrs. M. I. Pupin, C. W. Burrows, B. A. Behrend, W. Fondiller, W. H. Martin.

LONGITUDINAL AND TRANSVERSE HEAT FLOW IN SLOT-WOUND ARMATURE COILS

Carl J. Fechheimer **Vol. xl—1921, pp. 589-645**

A general determination of the internal temperature of a machine cannot be obtained with any reasonable degree of accuracy (except the maximum and minimum temperatures in long machines) unless the simultaneous transverse and longitudinal heat flow be considered. A solution of that problem is offered in this paper.

Discussion, pages 646-661, by Messrs. M. A. Savage, R. B. Williamson, B. A. Behrend, C. Hering, G. E. Luke, C. J. Fechheimer.

PERSONAL OBSERVATIONS IN THE INDUSTRY

President's Address

Arthur W. Berresford **Vol. xl—1921, pp. 763-777**

No discussion.

TECHNICAL COMMITTEE REPORTS

Vol. xl—1921, pp. 779-879

No discussion.

ADVANCES IN THE ART OF WATERWHEEL DESIGNS AND SETTINGS

W. M. White **Vol. xl—1921, pp. 925-963**

Description of waterwheel development. Selection of proper unit discussed in detail with relation to speed, speed regulation, runner material, draft tubes, shafts and bearings, guide vanes, governors, casings, vertical vs. horizontal units, control valves, settings.

Discussion (including that of paper by Harper and Johnson), pages 964-973, by Messrs. E. A. Pragst, W. M. Moody, W. J. Foster, E. M. Breed, J. A. Johnson, W. M. White.

MODERN PRODUCTION OF SUSPENSION INSULATORS

Edwin H. Fritz and G. I. Gilchrest **Vol. xl—1921, pp. 1127-1153**

This paper pictures the progress made during the past few years in the production of electrical porcelain. The information covers: First: The engineering and works organization. Second: The manufacture. Third: Design and test.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

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E. E. F. Creighton and F. L. Hunt **Vol. xl—1921, pp. 1173-1180**

A description of tests to which insulators were subjected in order to determine main causes of failure. Particular emphasis is laid upon the following factors: mechanical strength; electrical tests; line testing; aging of porcelain; open porosity of porcelain, etc.

Discussion incorporated with that of paper by Whitehead and Lee on "Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature."

THE ELECTRIC STRENGTH OF AIR UNDER CONTINUOUS POTENTIALS AND AS INFLUENCED BY TEMPERATURE

J. B. Whitehead and F. W. Lee **Vol. xl—1921, pp. 1201-1237**

The paper describes a series of experiments on the influence of temperature on corona-forming continuous potentials. The observations have been made on three sizes of wire of diameters 0.0251 cm., 0.0803 cm., and

0.093 cm., and in each case at several values of temperature within the range 5 deg. cent. and 70 deg. cent. At each temperature the pressure has been varied from a value in the neighborhood of that of the atmosphere downwards, reaching in the extreme cases the value 6.03 cm. of mercury. Within the range of values reached, as indicated above, the general form of the law of corona as developed experimentally by a number of other observers, is found to be fulfilled. There are separate families of curves for positive and negative potentials as obtained by varying the pressure for each constant value of temperature.

Discussion (including that of papers by Imlay, Bailey, Baum, Lewis, Elden, Fritz and Gilchrest, Peek, Creighton and Hunt, Peters and Skinner) pages, 1238-1308, by Messrs. W. I. Slichter, L. P. Ferris, B. Speed, F. W. Peek, Jr., M. E. Skinner, C. L. Fortescue, H. J. Ryan, J. T. Barron, H. W. Smith, A. O. Austin, K. A. Hawley, R. H. Marvin, G. I. Gilchrest, E. E. F. Creighton, A. W. Copley, L. H. Burnham, J. P. Jollyman, S. Barfoed, A. H. Lawton, H. R. Summerhayes, J. H. Foote, G. Cameron, H. L. Wallau, R. G. McCurdy, D. I. Cone, J. B. Whitehead, R. J. C. Wood, H. Michener, R. Bailey, F. G. Baum, W. W. Lewis.

HEAT LOSSES IN THE CONDUCTORS OF ALTERNATING-CURRENT MACHINES

Waldo V. Lyon **Vol. xl—1921, pp. 1361-1395**

The principal object of this paper is to show how hyperbolic functions of *complex angles* may be applied to the solution of the problem of heat losses in rectangluar conductors that are embedded in open slots. A certain knowledge of the functions themselves is presupposed. Inasmuch however, as they are handled like trigonometric functions of real angles—except in regard to the plus and minus signs—it is a simple matter to acquire the requisite technical skill to use them.

Since the present paper was written, the author has extended the method to the solution of the problem in which the conductors have a finite number of strands separated by insulation.

Discussion (including that of papers by Henningsen, Speed and Elmen), pages 1396-1409, by Messrs. Wm. J. Foster, F. G. Baum, W. Fondiller, H. L. Hibbard, G. Semenza, C. A. Copley, W. E. Thau, P. P. Ashworth, S. P. Grace, A. M. MacCutcheon, H. W. Taylor, E. S. Henningsen.

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