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APPENDIX.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 26, 1912.

INDUSTRIAL ILLUMINATION AND THE AVERAGE PERFORMANCE OF LIGHTING SYSTEMS

BY C. E. CLEWELL

Illumination in the past has been looked upon largely as an accessory. Modern illuminating engineering, however, is concerned with the adaptation of the available types of lamps to certain supply circuits, to various classes of service, and to given conditions of building construction.

A few years ago the older type of arc lamp and the carbon filament lamp, typifying a large and a small unit, covered the range of types of lamps available for illumination work in the industries. This limitation in candle power has gone through an evolution by the introduction in more recent years of the enclosed arc, the open flame-carbon arc, the metallic flame arc and the long burning flame carbon arc lamp, as improvements on the original arc lamp; and the metallized filament, the tantalum and the tungsten lamp, as improvements on the original filament lamp. The Moore tube, the Nernst and the mercury vapor lamps are also available as new types.

The candle-power values of these various lamps are shown in Fig. 1 where, in an approximate manner, the average mean spherical candle-power values of all types, both old and new, are indicated. Fig. 2 shows the over-all dimensions of the various lamps, from which it is apparent that the dimensions for given candle-power values have been modified by changes in design.

Re-directing the light where most useful, should be included in development of high-efficiency lamps as additional to the matter of total light flux per watt. The growing tendency to rate electric lamps according to the effective illumination produced on the work, rather than in terms of the watts per mean spherical candle power, is evidence that this item will probably be included in the considerations of lamp efficiency more in the future than it has been in the past.

Quantity of light is no longer the sole criterion of excellence, but its uniformity over the work, diffusion, adequate intensities on the sides of the work, absence of glare, color values and similar items are now given an importance almost if not quite equal to mere satisfaction in the matter of vertically downward intensities.

Factory work, generally speaking, may be grouped into work on a horizontal plane, as bench work of some kinds, which, in the main, requires only downward illumination; and other work, such as that included under machine tool operations, foundry moulds, rolling mills, assembly, and the like, where, in addition to vertically downward light, side components effective on vertical planes, as well as shadow elimination, play an important part in the excellence of results.

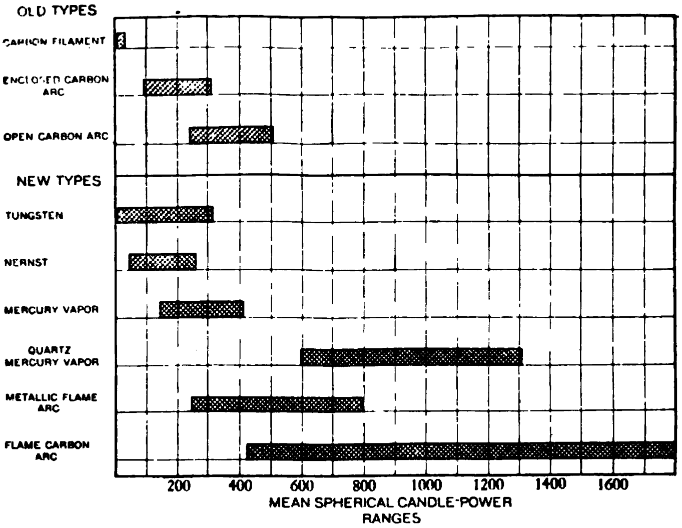

FIG. 1—AVERAGE CANDLE POWER RANGES OF OLD AND NEW LAMPS.

The height of ceiling, roof or trusses limits in a very large measure the size and type of lamp to be employed. Experiment and usage demonstrate the disadvantage of using very large lamps for low ceilings, while lack of economy prohibits the use of small lamps for high areas. In former years arc lamps were used for low factory bays, while in some extremes no appreciable general illumination was possible due to the absence of sufficient clearance between cranes and ceiling for an arc lamp. In like manner very high bays have been inadequately lighted due to the lack of lamps possessing sufficient candle power and suitable distribution characteristics. To-day, however, lamps of enormously greater candle power and more suitable distribution are available for the higher areas, while lamps with corresponding advantages are available for low areas.

Open spaces simplify the problem by permitting the use of lamps spaced comparatively far apart, while the interference of belting calls for a type and arrangement of lamps which will provide diffusion, so as to reduce the shadows ordinarily produced by belts. In an atmosphere filled with dust and dirt a penetrating light should be employed, and in spaces of the latter class the maintenance is apt to be greatly increased with the rapid accumulation of dirt on the lamps and reflectors. These items will be clearer by a reference to Figs. 3 and 4, which compare free space with one filled with belting.

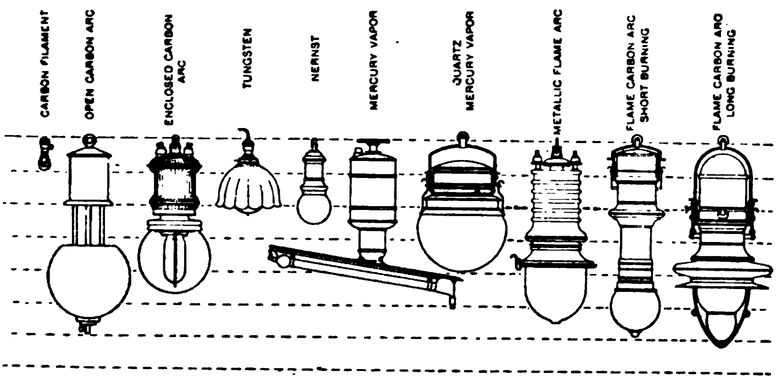

FIG. 2—CHART SHOWING RELATIVE AVERAGE OVER-ALL DIMENSIONS OF VARIOUS LAMPS.

Typical ceiling constructions as found in average shops are shown in Figs. 5, 6, 7, and 8. The arrangement of lamps should not be influenced primarily by the ceiling construction. Plans made up without regard to the ease of installation may sometimes be modified so as to yield equally satisfactory results, however, with a considerable reduction in first cost for installing, by taking into account certain features of the beams or girders.

Illumination Factors

The spacing distance of lamps is a first consideration. Experiments have shown, for example, that in certain office locations with moderate ceiling heights, a spacing distance not exceeding 7 ft. 6 in. is most advantageous. This results in a uniform illumination on the desks if the proper reflectors are used, and the light from a sufficient number of sources thus secured insures a diffusion of the resulting illumination. The directional features of the light are furthermore far superior to those cases where larger spacing distances are employed.

The spacing also governs the size of lamp to be used. As an illustration, whether one 250-watt or four 60-watt tungsten lamps are to be installed for a given area will be determined largely by the desired directional features of the light.

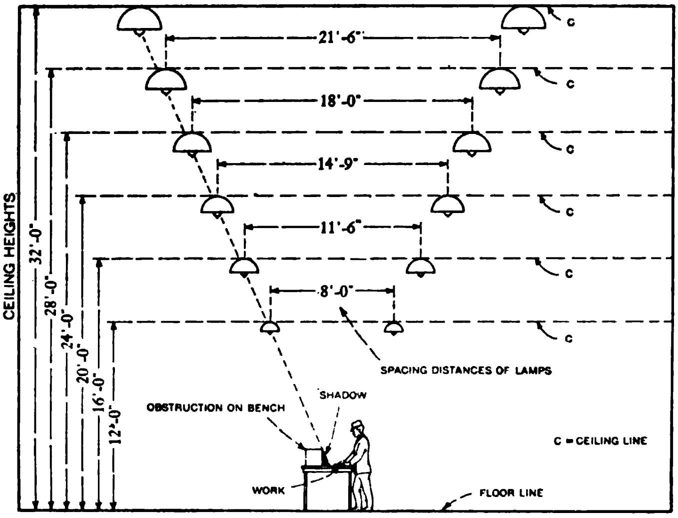

Fig. 9—Chart Showing Relation of Shadows to Mounting Height and Spacing.

The mounting height should be determined on a basis of the avoidance of glare and of the ease in getting at the lamps for maintenance. The lamps should be mounted high enough to be out of the line of vision, and where the ceilings are too low to admit this, lamps of small size should be selected to reduce the quantity of light flux which enters the eye or is effective thereon when looking into any lamp. Fig. 9 shows the effect of height on the directional qualities of the resulting illumination

[CLEWELL]

FIG. 3—FACTORY SPACE FREE FROM OBSTRUCTIONS.

[CLEWELL]

FIG. 4—FACTORY SPACE WHERE MUCH BELTING IS USED.

on the working surface. This illustration shows graphically the need of closer spacing to maintain a given minimum shadow effect for low ceilings.

Typical installations with accompanying data are indicated in Table I. Such a table of actual cases may serve as a guide to others with similar problems to solve, and also gives an idea of the varying requirements of different classes of industrial work from the fact that the installations here recorded have been the object of careful study for a number of years and furthermore are the results of carefully prepared plans. Obviously, these results are not intended to be used as rules for general lighting work, but the experiences recorded for these representative locations will show clearly how they have been solved and what constants apply in each of the several cases.

Efficiency of Utilization

The term efficiency is here used to express the relation between total light flux furnished by the lamps to the work, on the one hand, and the total flux emanating from the lamps of the system in all directions, whether useful or otherwise, on the other hand.

Such a use of the term refers of course to the efficiency of the lamps themselves coupled with surroundings and reflectors in the matter of the useful illumination they furnish to the work. The numerical values expressing this efficiency will thus be less than unity and expressed in per cent of the ideal condition if the total light flux available were wholly useful on the work.

Heretofore the measure of illumination efficiency, if it may be so called, has been changed in turn from watts per square foot required to furnish presumably satisfactory light, to lumens per watt (or foot-candles per watt per square foot), and finally to efficiency or the utilization of the total light flux of the lamps. The latter is a measure of the total losses from all causes, such as absorption by globes or reflectors, by dark ceilings and walls, as well as by dust, dirt, belting, or other obstructions, and therefore adapts itself in an excellent manner to practical usage. One other feature should be noted in connection with the efficiency, namely, the importance of considering average performance, in distinction from results obtained when lamps and reflecting devices are new and clean.

The need for data on the *average performance* of illumination systems has been felt for some time. With the view of meeting this need, and also for the purpose of establishing some certainty

TABLE I. DATA ON TUNGSTEN INDUSTRIAL LIGHTING SYSTEMS

Height of ceiling or girder line.	Mounting height above floor.	Rating of lamp.	Style of reflector	Class of work.	Spacing distance	Intensity in foot-candles.	Lumens per watt.	Efficiency of system. Lumens on working plane divided by total lamp lumens	Condition of reflectors.	Character of surroundings.
			General offices							
10 ft.1½ in.	9 ft.5½ in.	60-watt	I Satin-finish prismatic	Office	5 ft.8 in. by 7 ft.9 in.	3.9	2.85	34.4	Clean	Light ceiling and walls
10 ft.8 in.	10 ft.0 in.	60 "	F " " "	"	7 ft.0 in. by 7 ft.4 in.	3.6	3.1	37	"	" " " "
10 ft.8 in.	10 ft.0 in.	60 "	I " " "	"	6 ft.3 in. by 6 ft.10 in.	4.4	3.08	35.8	"	" " " "
10 ft.8 in.	10 ft.0 in.	60 "	F Clear prismatic	"	5 ft.7 in. by 7 ft.4 in.	3.2	2.19	26.5	"	" " " "
10 ft.10 in.	10 ft.2 in.	60 "	I Satin-finish prismatic	"	5 ft.9 in. by 7 ft.3 in.	4.5	3.14	37.8	"	" " " "
10 ft.10 in.	10 ft.2 in.	60 "	I " " "	"	5 ft.1½ in. by 6 ft.9 in.	3.7	2.06	24.8	Slightly soiled	" " " "
13 ft.0 in.	11 ft.6 in.	60 "	F " " "	"	6 ft.6 in. by 6 ft.10 in.	4.3	3.17	38.2	Clean	Dark walls and ceiling
15 ft.0 in.	12 ft.10 in.	60 "	I Opalescent	Drafting	8 ft.3 in. by 9 ft.6 in.	7.2	2.34	28.2	Slightly soiled	Rather dark walls and ceiling
		(4)	Factory offices							
8 ft.9 in.	8 ft.0 in.	60-watt	I Opal	Office	6 ft.0 in. by 7 ft. 6 in.	4.25	3.17	38.3	Clean	No ceiling—fairly light walls
9 ft.0 in.	8 ft.6 in.	60 "	I Clear prismatic	"	5 ft.7 in. by 5 ft. 9 in.	2.9	2.75	33	Fairly clean	" " rather dark "
11 ft.6 in.	10 ft.9 in.	60 "	F " "	"	5 ft.7 in. by 7 ft. 1 in.	5.4	3.47	42	Clean	Light ceiling-glass partitions
13 ft.9 in.	13 ft.9 in.	60 "	F " "	"	5 ft.4 in. by 5 ft. 7 in.	3.5	1.75	21	"	" " light walls
16 ft.0 in.	14 ft.0 in.	150 "	F " "	"	8 ft.2 in. by 9 ft. 0 in.	4.5	2.22	26.7	"	" " glass partitions
16 ft.0 in.	10 ft.0 in.	60 "	I " "	"	7 ft.0 in. by 7 ft. 6 in.	3.5	3.07	37	"	" " " "
			Factory space							
8 ft.1 in.	7 ft.6 in.	60-watt	I Opal	Factory	8 ft.0 in. by 8 ft. 0 in.	3.2	3.42	41.1	Clean	Light ceiling—no walls
11 ft.9 in.	11 ft.0 in.	100 "	I Clear prismatic	Machine shop	8 ft.0 in. by 8 ft. 9 in.	4.3	2.74	33	"	Dark " —dark walls
12 ft.6 in.	12 ft.0 in.	100 "	I " "	" "	8 ft.0 in. by 10 ft. 0 in.	3.1	2.46	29.6	"	" " —no "
13 ft.6 in.	9 ft.0 in.	150 "	I " "	" "	8 ft.0 in. by 8 ft. 6 in.	6.6	2.98	35.9	"	" " —dark "
13 ft.9 in.	13 ft.0 in.	100 "	I " "	Factory	8 ft.0 in. by 8 ft. 0 in.	3.2	2.02	24.3	"	Light " —light "
13 ft.9 in.	13 ft.0 in.	100 "	I Opal	"	8 ft.0 in. by 8 ft. 0 in.	3.8	2.40	29	"	" " — " "
13 ft.9 in.	13 ft.0 in.	100 "	I Clear prismatic	"	8 ft.0 in. by 8 ft. 0 in.	3.8	2.40	29	"	" " — " "
24 ft.9 in.	21 ft.3 in.	250 "	F " "	Power house	12 ft.0 in. by 15 ft. 0 in.	2.7	1.92	22	Soiled	" " — " "

regarding the various factors involved, extensive tests have been conducted during the past year, and the results of the same are now herewith presented for the first time, in the hope that they may furnish useful information on this important phase of illumination systems, and also serve to further additional work, thus begun in this particular direction.

Practical Results under Working Conditions. At the outset a study was made of the items involved in the determination of the average performance, that is, the variation in the illumination intensities furnished by the lamps day in and day out, and a number of typical locations representative of average industrial conditions were selected for the test. These tests were made on the vertically downward (or so-called horizontal) intensities of the illumination produced by a fairly large number of lamps in each location, thus securing a more general idea of the changing conditions than would likely result from individual tests on single lamps or reflectors. By these tests it has been sought to establish the actual efficiency of the various illumination systems considered, as compared to the theoretical efficiency which might be supposed to exist from calculation based on candle-power distribution curves. Four conditions were chosen, as follows: (1) new lamps and reflectors; (2) clean lamps which have been in service for several months, and clean reflectors; (3) clean lamps several months old and soiled reflectors, ready to be washed in the routine of the plant; and (4) soiled lamps and soiled reflectors ready to be cleaned. This series of conditions represents lowering steps in the efficiency of the system, and the results show by how much each of these factors may reduce the total efficiency. It will be apparent that the reduction in efficiency by these three items refers to losses in the system itself. These losses further obviously determine the inherent performance of the system, and great care was required in making these tests to maintain conditions unchanged throughout the tests, that is, under shop conditions, to be sure that the dust and dirt on reflectors was left undisturbed.

Five typical factory locations were selected for this test, which covered seventeen weeks in itself, but which represents a considerably longer period of time in preliminary tests made throughout the past few years leading to the determination of ultimate reductions of light due to dust and dirt. These five locations were equipped with tungsten lamps and glass reflectors. The locations included a regular office in an office building; a long narrow factory office ; a low factory space with no walls and very dark ceiling; a medium high factory space with light walls and light ceilings; and a moderately high factory space with dark walls and no ceiling, the lamps being mounted on stringer boards attached to the girders. Observations of voltage were taken and all intensities corrected for the normal lamp voltage. Table II shows the results of these tests and the attending surrounding circumstances, while Table III shows the averages of the results. The value of these constants can hardly be overestimated when considered in the light of their usefulness in the calculation of factory lighting systems, which can thus be based on absolute experience. The foregoing notes apply to the performance of a system as installed and in regular service.

TABLE II

TEST RESULTS ON TUNGSTEN SYSTEMS WITH GLASS REFLECTORS

Efficiency values* Conditions of test	Low office	Fairly high factory office	Low factory space	Medium high factory space	Fairly high factory space
Ceiling	Light	Light	Dark	Light	None
Wall	Light	Light	None	Light	Dark
Lamps	60-W Cl.	60-W. Cl.	100-W. Cl	100-W. Cl	100-W. Cl
Reflectors	I-60 SF.	I-60 Cl.	I-100 Cl.	I-100 Cl.	F-100 Cl.
Class of work	Desk	Desk	Machines	Bench	Bench
Time between washings	14 weeks	17 weeks	9 weeks	11 weeks	13 weeks
Results		Efficiency	in per cent		
Soiled lamps Soiled reflectors	19.7	24.2	22.4	25	20.1
Clean lamps Soiled reflectors	20.7	24.9	22.5	27	23.6
Clean lamps Clean reflectors	34.1	29.3	31.2	35.3	33.6
New lamps Clean reflectors	34.1	31.2	31.9	36.1	39.1

*All efficiency values corrected for normal lamp voltage.

Depreciation Items. In the calculation of illumination systems additional factors must be taken into account, namely, (1) the effect due to the operation of the lamps at a voltage other than their rating, frequently the case in tungsten systems; (2) the depreciation of candle power due to the aging of the lamps; (3)

the depreciation due to surroundings which are liable to become dark; and (4) the effect of dust and dirt accumulations.

The losses due to *voltage* conditions can readily be calculated from the curves showing the variation of candle power with voltage; the effect of *age* of the lamps, although somewhat more uncertain, can be determined with a fair degree of accuracy from the life curves of the lamps as made by the lamp manufacturing companies; tests have been conducted, as previously referred to, in the determination of the effect of *surroundings* on the illumination results. The following material has resulted from extended tests on a variety of lighting systems to determine the dust and dirt characteristic depreciation curves with elapsed time of service. While the tests just described for the determination of practical efficiencies at the beginning and at the end of a cleaning period were difficult in the matter of maintaining conditions unchanged, these same difficulties encountered in this particular test were considerably greater. To insure value, it was deemed essential to perform the tests in factory spaces where the regular manufacturing operations were in progress from day to day. This necessitated constant watchfulness to make sure that the systems were undisturbed in the matter of the dust and dirt accumulations.

TABLE III

AVERAGE TEST RESULTS ON TUNGSTEN SYSTEMS WITH GLASS REFLECTORS*

	Average efficiency of system
Low office	27.1 per cent
Fairly high factory office	27.4 " "
Low factory space	27 " "
Medium high factory space	30.8 " "
Fairly high factory space	29.1 " "

*All efficiency values corrected for normal lamp voltage.

At the outset the results anticipated rather seemed to promise indefinite results. Figs. 10, 11, 12, 13 and 14 indicate the characteristic curves of illumination intensities over a number of weeks as the result of the tests, and from these curves the very interesting and instructive conclusions may be roughly drawn, that under average factory conditions the deterioration of glass reflectors due to dust and dirt follows a fairly definite rate of candle power reduction, in so far as conclusions can be deduced from the number of cases on which these tests were conducted. This reduction as shown in the curves is due alone to dirt accumulations on the reflectors, since the new lamps were inserted before each test and all observations were corrected to correspond to normal lamp voltage.

The curve sheet shown in Fig. 15 has been derived from the deterioration curves. This curve sheet shows, for example, that based on the average cleaning cost of three cents per reflector, with energy at two cents per kilowatt-hour, the integrated cost of light lost at the end of sixteen days in one of the cases, is equal to the cost of cleaning. This point (namely sixteen days) would then naturally determine the economical interval for cleaning reflectors in this particular location, provided always that the reduction in intensity at the end of this interval is not below that which is necessary for satisfactory vision. It is of interest to note that apparently the effect of dust and dirt takes place far more rapidly in the first week or ten days than during the succeeding weeks.

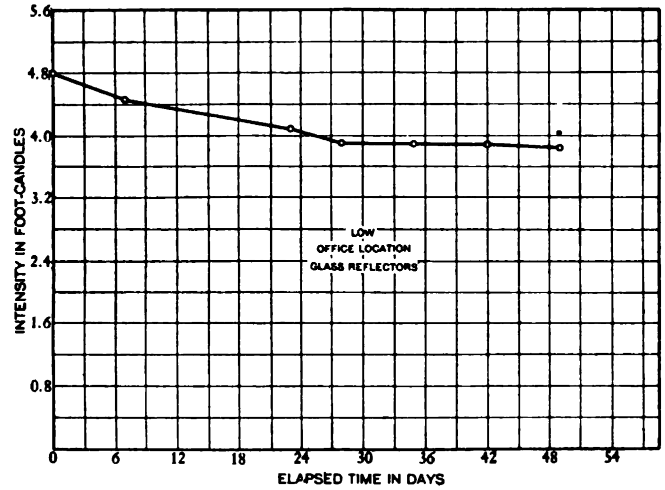

FIG. 10—DETERIORATION FROM DIRT ACCUMULATIONS.

Other useful information may be deduced from these curves as follows; if, for example, the loss of light at the end of sixteen days equals 25 per cent, which means, for an initial intensity of four foot-candles, that there remain, at the end of sixteen days,

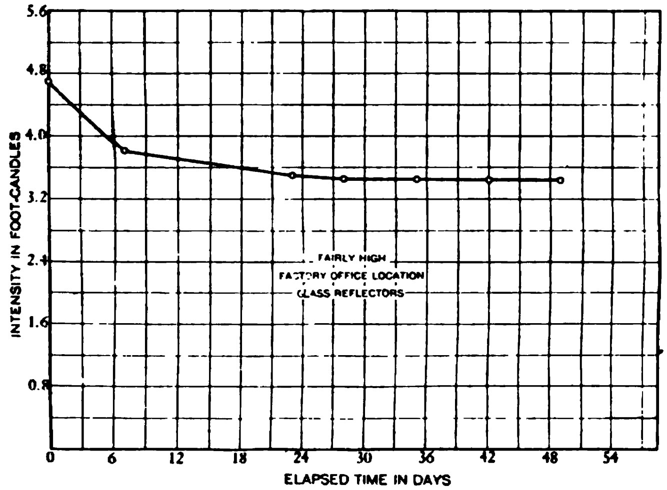

FIG. 11—DETERIORATION FROM DIRT ACCUMULATIONS.

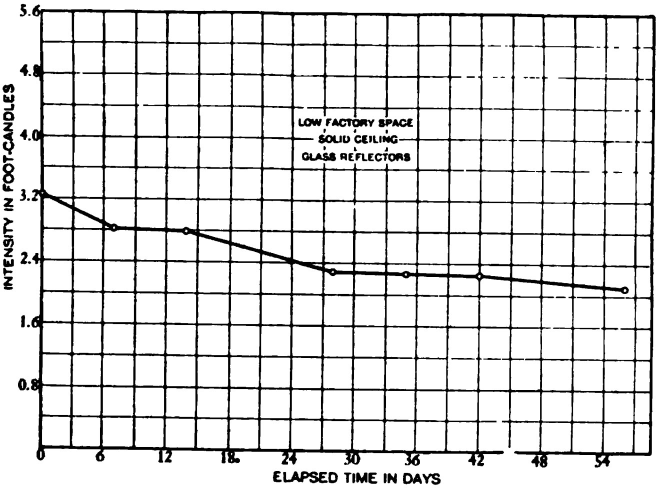

FIG. 12—DETERIORATION FROM DIRT ACCUMULATIONS.

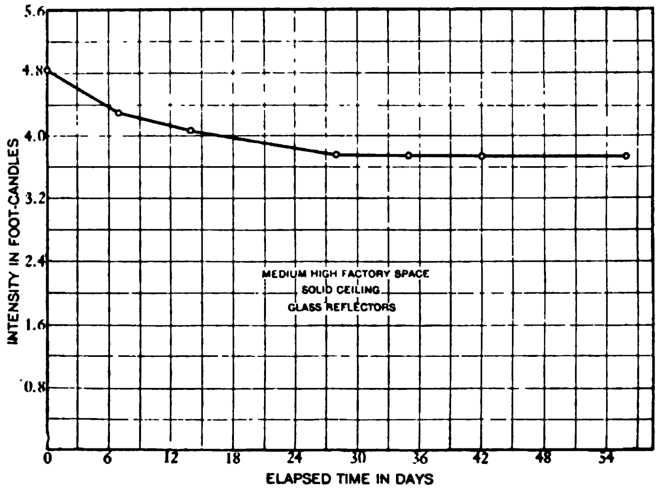

FIG. 13—DETERIORATION FROM DIRT ACCUMULATIONS.

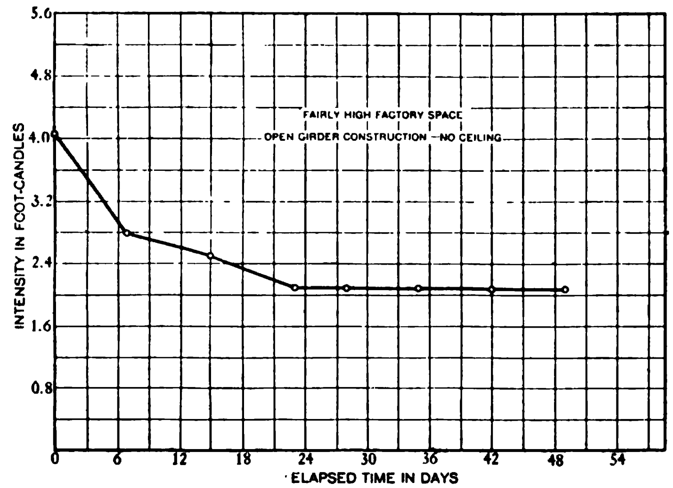

FIG. 14—DETERIORATION FROM DIRT ACCUMULATIONS.

only three foot-candles, the average intensity throughout the sixteen-day interval may be approximated at three and one-half foot-candles, provided the reflectors are cleaned once every sixteen days.

If an additional sixteen days without cleaning means a still further reduction from three to two foot-candles, the average intensity of the illumination throughout the thirty-two days interval may be approximated at three-foot candles. Hence the cleaning of the reflectors at intervals of sixteen instead of thirty-two days should insure an average intensity of say three and one-half instead of three foot-candles, or in other words to maintain an average intensity of three and one-half foot-candles would require approximately twenty per cent more lamps in the installation for a thirty-two days than for a sixteen days cleaning interval.

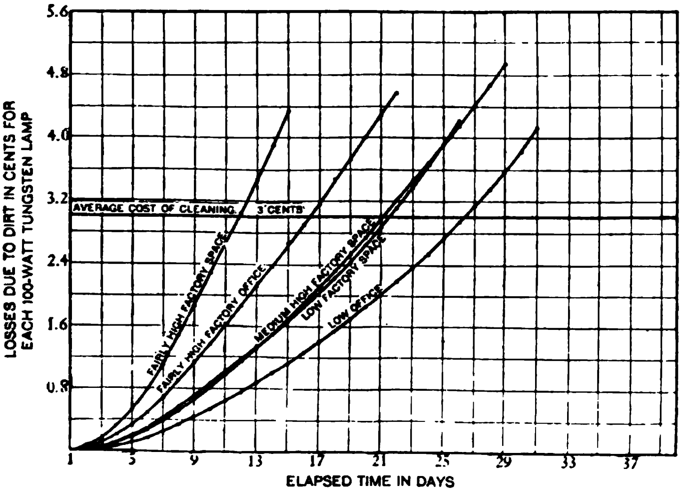

FIG. 15—SUMMARY OF CURVES OF DETERIORATION COSTS FROM FIGS. 10, 11, 12, 13 and 14.

This would mean in an installation of say 1200 tungsten lamps, a saving of 200 lamps in the original installation, or roughly, $1,000 in a total of $6,000, the first cost, by the adoption of a sixteen days instead of a thirty-two days cleaning interval. To clean 1200 reflectors every thirty-two days involves in practise an expenditure of approximately $432 per annum, while to clean the smaller number of 1000 reflectors once per sixteen days involves approximately $720 per annum, or an increase of say $288 per annum. The increased cost of cleaning, with shorter cleaning intervals, is, therefore, small in comparison to the reduced first cost, to the lower energy consumption with a smaller number of lamps, and to the improved average service.

The foregoing hypothetical instance can be worked out with accuracy for any of the locations found in the deterioration curve sheets, by the substitution of actual for the assumed values, and when applied to practical illumination design will be found to affect the results in a significant manner.

MAINTENANCE

Necessity for Systematic Maintenance. From the foregoing statements the necessity for careful and systematic maintenance will at once be apparent. In one large system of 10,000 tungsten lamps, the losses of light per day due to dust and dirt interpreted into money values, that is to say, evaluating the energy in watts represented by light wasted through absorption by the dirt, to its kilowatt-hour cost, amounts approximately to $20 per day, or $7,500 per annum. If the systems are allowed to go uncleaned beyond the economical point, these losses become aggravated. The expenditure of an amount like the foregoing, for energy which represents no return, serves to indicate in a startling manner the significance of adequate maintenance.

This illustration and the ones previously mentioned in connection with deterioration have been based on tungsten systems, but the results will show what may be expected in lighting systems of other types of lamps from the accumulation of dust and dirt, and it is hoped that these tests and statements will be but forerunners of additional data along these and similar lines in the near future.

General Methods. The limitations of this paper prevent more than a passing reference to the details of maintenance work. It will suffice to say that systematic methods are now being worked out and are in operation for handling this feature of lighting system operation. It is the desire that data like the foregoing will be a stimulus to further and more liberal attention in the matter of such work, and that they will promote more system in short cleaning intervals and other similar work.

ECONOMIC RELATIONS

Relation of Wages to Illumination. The chart shown in Fig. 16 has been prepared to give an idea of the relation of average wage

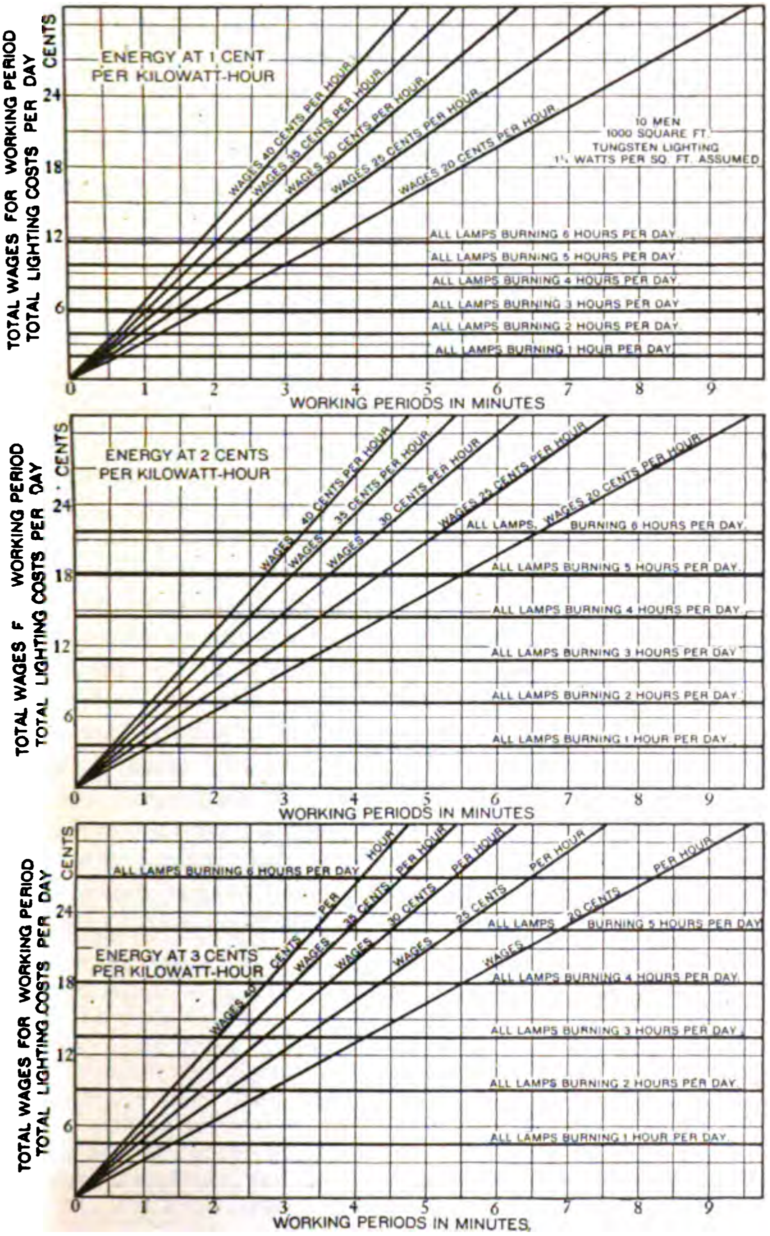

Fig. 16—Curves Showing Relation of Average Wages to Lighting Costs.

conditions and lighting costs. The values are taken from actual average cases and show in a graphical manner the small percentages of the total wages represented by the average lighting costs. When one pauses to consider the fact that the wages for six minutes per day in average shops, pays not only for meagre, but also for entirely adequate illumination, and when one further considers that nearly all shops have some lighting facilities, poor as they may be, the difference between poor and excellent lighting in its relations to improved surroundings and better workmanship is apparent.

PRESENT ACTIVITY IN INDUSTRIAL LIGHTING

In one large shop where extensive installations of high efficiency lamps have been under way for nearly three years, a summary shows an increase of nearly 30 per cent in actual candle power for a 5 per cent increase in total operating and maintenance costs. This increase of 30 per cent in candle power in no way, however, indicates the enormous improvements in the matter of excellence in distribution and refinement of results; it merely shows what great advances have been made in the possibilities of industrial illumination by the newer types of lamps. Added to this candle power increase there are, of course, many advantages which have been brought about by the careful and scientific adaptation of the lamps best suited to each condition.

It will be impracticable to indicate in a definite manner the extent of present activity in terms of exact installations, but it is of both interest and significance to note the progress which is being made in the growing intelligence among factory owners regarding the proper illumination for their plants. The work of the past few years along this line, if taken as an indication of what may be expected, promises great advances in the immediate future.

came round one day and said, "We want to get this place lighted, and if your committee will stop this foolish experimenting you may accomplish something. You look as if you did not know what to do. Ask the people who are using the lights what to do, and then go away and leave it, and we can go ahead and light this factory."

That illustrates the type of man who is frequently met in the work of installing lighting systems. People do not understand these things, and the kind of analysis which Mr. Clewell has given shows in a simple way how the putting up of ordinary lights, with bell-shaped reflectors over them, is not a thing to be done in the abstract, but in the concrete. It is a place where theory and practise do combine, and where different kinds of practise may be combined with theory.

From the demonstration we have seen, we all know it is most obvious, when it is pointed out, that the shadow effect and color effect depend on the direction of light, intensity of light, the color of light, etc. It took a quarter of a century for the electric lamp to realize that it was not to replace the gas jet, but the electric lamp did overcome the use of the chandelier. We have got rid of the chandelier, but still we try to imitate the candles which are a thousand years old; we cannot seem to get away from the old things. We must learn to be illuminating engineering decorators.

In reference to Mr. Clewell's interesting diagram showing the spacing of the lamps and the direction of the light, a rough approximation to what he has there is to divide the space above the plane of the table into cubes and put a lamp at the center of each cube. The height of the ceiling from the floor is 12 ft. (3.6 m.), and if the table is 4 ft. (1.2 m.) high, then the ceiling is 8 ft. (2.4 m.), above the plane of the table, and therefore the lamps should be 8 ft. (2.4 m.) apart, and that is what he has. This rule does not carry out fully, but is a close approximation to what Mr. Clewell's diagram shows.

Not long ago I visited the office of one of the largest lighting companies in this country. The engineer showed me about, and incidentally showed me the lighting in some of the offices. There were two drafting offices. One had indirect lighting and the other was lighted by a wretched type of illumination, the bare tungsten lamps hanging over each desk, about 18 in. (46 cm.) above the desk. It was a remarkable illustration of faulty and criminal illumination, which it is our purpose to do away with, and to educate the people to a knowledge of its shortcomings. I said to the chief draftsman who had charge of both rooms: "I see you have both kinds of lighting here—the indirect lighting and the bare tungsten lamp. Suppose you had to use one room altogether, for the sake of getting work out for the company, if it took eight hours to do a certain piece of work in this poorly lighted room, in how many hours would you expect to do the work in the other room?" He replied, "It would probably take from an half hour to three-quarters of an hour less to do the work in the other room." In other words, there was a gain of from one-half to three-quarters of an hour by having good light. I then asked him the cost of the draftsmen and the cost of the lighting to compare one with the other, and he said that the difference in the cost of the lighting was equivalent to the cost of the draftsmen's services for a period of five minutes in each day, so that if the lighting had been as good in one room as in the other, there would have been a saving of from one-half to three quarters of an hour each day. We ought to realize, therefore, what a great economy there is in efficient lighting.

A. E. Kennelly: In pursuance of the idea which Professor Scott has given, I would like to draw attention to one detail of Mr. Clewell's paper, which is, by the way, a plea for the duster, and shows us that, in illuminating engineering, cleanliness is next to luminescence. The constants are worked out very clearly as to the money value of cleanliness and, of course, they are convincing as a matter of simple arithmetic, from the standpoint of producer and consumer combined. Say it costs one dollar an hour to light a certain hall, if all the light is cut off by dirt, all that dollar is wasted, and if half the light is cut off fifty cents an hour is wasted. An important point was touched upon by Mr. Scott—the value to the consumer alone, as distinguished from the combination of producer and consumer. Suppose the lighting in a work room, as compared with the original illumination when the installation was first made, is cut down by dirt to the extent of 10 per cent, without making any noticeable difference in the amount or quality of work done in that room, the question arises whether the cost to the consumer of cleanliness is anything like the proportional value of the lost light, as long as the depreciation in the illumination value of the lamps does not interfere with the work. The moment dirt begins to interfere with the work, and cuts down the volume of the work, so that the consumer cannot earn as much as he did before, his production is less in volume, and there is manifestly a rapid rise in the cost of the dirt from his standpoint.

E. B. Rowe: I do not know that I can answer specifically the question raised by Dr. Kennelly, but there is one point which might be brought up in connection with Mr. Clewell's paper, which he omitted, perhaps intentionally, and which I might point out in connection with the poor conditions under which the tests were made. These tests did not include any consideration of the effect of depreciation of the walls and ceilings, which are important factors in many cases. For example, in certain industrial installations, in light manufacturing spaces, it is customary to have light walls and ceilings which, by means of their diffused reflection, increase materially the total efficiency of the installation. The effect of dirt and dust depreciation of walls and ceilings may therefore be considerable. In one series of tests which were made under average city conditions this loss by decrease in reflection from ceiling and walls, which were originally white, amounted in the course of three months to from 10 to 14 per cent. These figures, of course, are only approximate and hold true only for the conditions under which the tests were made.

C. E. Clewell: In connection with Mr. Rowe's suggestion, I may say that practically all the installations tested were surrounded with very dark walls and the tests on the installation at the end of the run showed the illumination to be practically the same as at the start, so far as the surroundings are concerned. It would be very effective in the case of surroundings of light color.

Charles F. Scott: Referring to Dr. Kennelly's remarks, in illumination we have to do some things that are big steps. It becomes a concrete rather than an abstract theoretical science. To illustrate what I mean, I will refer to the computations which you make on long-distance transmission lines. You figure out the resistances to three or four distant places, and the efficiencies to several points, and then you take the nearest size of wire, which may take a 25 per cent jump. So in illumination, in considering a certain room we may say, if we can get along with 10 per cent less light, what is the need of cleaning lamps? Or, we might have put on, in the beginning, 10 per cent less of lamps, and got our necessary illumination, that is, might have secured a given amount of light from a few clean lamps, instead of from a greater number of dirty lamps. In a large hall where the lamps are inaccessible, it may be cheaper to let the lamps run somewhat dim and have more of them, than to have a man climb up to the ceiling every week or two and dust them off. The particular cost of the cleaning in the particular place, as well as the cost of power and the number of hours burning per day, are all factors, but to get a given amount of light, we can in many cases put in fewer lamps to begin with, and by keeping them clean can secure the maximum amount of illumination from those lamps.

Clayton H. Sharp: Referring to Mr. Clewell's paper, I think it contains a good deal of matter of value, and a considerable amount which is not entirely new. The efficiency values which he gives, the ratio of the lumens generated by the illuminant to the illumination effective upon a certain plane, have been worked out for a good many classes of installations before, but it is useful to have the additional data on this question which Mr. Clewell gives us in his paper, particularly since they refer to shop lighting. The deterioration values for the plant as a whole have also considerable novelty and a great deal of value. I think, however, we should very clearly bear in mind that the illumination of a shop is not a question of simply so and so many foot-candles upon a certain uniform plane, but that the illumination required is dependent to a very large degree upon the character of the work to be done, and particularly upon the reflecting power of the surface upon which the operator is working. The direction from which the major part of the rays of light comes, the diffusion of the light, the proper ratio of direct to general illumination, the protection of the eyes of the operators are also of very great importance in machine shop illumination. It follows that the problems involved in shop lighting can be solved only by a careful study of individual cases and of individual machines. No wholesale method, no general solution, such as producing three foot-candles of illumination on a plane 30 in. (76 cm.) from the floor, suffices at all as an answer to the questions involved in the proper illumination to enable operators to see and carry out their work as rapidly and conveniently, and with as little fatigue, as possible. From this point of view, the data which Mr. Clewell gives in showing the wages value of the lighting of the shop, the cost of lighting interpreted in wages value, are extremely interesting. They show how insignificant a factor the cost of the lighting really is, and how uneconomical it is to use anything less than the most full and most effective illumination. To curtail the amount of light used by operators is the worst possible kind of economy. At the same time it must be remembered that the word of the operative as to the amount of light he needs cannot be taken at its full face value. The amount of light which is really required is something which itself requires experimental study and careful measurement. The elimination of disturbing factors, such as glare and specular reflections, has a very strong influence on this, so that the judgment of the operative on the question needs to be supplemented by that of some one of more experience, the judgment of an illuminating engineer, who can determine these things with more certainty. It is clear, therefore, that the purely utilitarian illumination of a workshop is not a simple matter but a complex one, requiring the exercising of the best talents of the illuminating engineer.

Mr. Jones has shown us how carefully the decorative effects demanded in an entirely different class of illumination require to be studied, how the shadows and shades and the colors of the light have to be very carefully worked out, and that is very complex and requires experimental study.

It used to be said that illuminating engineering consisted in using tungsten lamps and holophane glassware. I think that what we have learned from these papers and demonstrations shows that there is a good deal more than that in the science and art of illuminating engineering.

F. C. Caldwell: There are two points that may be deduced from these two papers. The deterioration in the light due to the aging of the lamps, and especially to the lack of cleanliness, ought to be taken into account in the original design of the illumination. In many cases this is overlooked, and the illumination is designed on the basis of what the lights will give in their original condition.

Another point, which is very important in some cases, is the difference between illumination for use during the evening and for use during even a short period following daylight. It appears that in many cases a higher degree of illumination is really needed for a short period following daylight than for the whole evening, because the user of the illumination compares it with the daylight that he has been working with. The effect of the strain, on the eyes of a person who uses the artificial illumination for only a short time after daylight, may be quite severe, owing to the great change from the use of daylight to the use of artificial light.

G. H. Stickney: It is interesting to note that these two papers illustrate the scope of illuminating engineering problems, as well as different typical methods of solution. Mr. Jones has treated problems of the class in which the dominating consideration is artistic effect, while Mr. Clewell has selected installations where utility and cost are the prevailing factors. In the first case cost is a secondary consideration, while in the latter the esthetic appearance is of minor importance.

Again, in treating the problems, Mr. Jones has followed the laboratory method, while Mr. Clewell has adopted the practical installation method, or, as a lawyer would say, the "case system." Each has its advantages and limitations and is at its best when supplemented by the other.

The question of depreciation was mentioned by Dr. Kennelly. Depreciation is sometimes divided into two components, which have been designated as "inherent depreciation" and "acquired depreciation." "Inherent depreciation" is that due to the peculiarities of the lamp independent of its environment. It includes the internal coating of globes, decreased activity of illuminating materials, etc. All types of lamps are subject to inherent depreciation, but some types are more affected than others. "Acquired depreciation" is that due to the external conditions under which the lamp is operated. For example, the accumulation of dust and the darkening of ceilings and walls. "Acquired depreciation" is independent of the type of lamp, though it may be largely dependent on the character of the maintenance. Proper cleaning will keep it at a minimum.

This question of cleaning has been often discussed, but in spite of this it has not received the practical attention which it deserves. The illumination from an ordinary installation is either much poorer than it ought to be, or more expensive, due to lack of proper cleaning. Mr. Clewell shows how profitable cleaning is. Experience indicates that, in a large establishment, proper cleanliness can only be secured by organized cleaning at regular intervals.

Other points which have been brought out and which deserve particular emphasis are the low cost of operating a good lighting installation in proportion to the value of the illumination.

It is hard to understand why some plants still cling to an obsolete lighting equipment, when a modern installation requires but a small investment, as compared to the cost of a year's operation. Initiative in this direction is amply rewarded in improved illumination and often even a reduced annual cost of operation.

William J. Hammer: I wish to express my appreciation of the practical value of these two papers. One point I wish to bring up, which Mr. Scott has already referred to. It is a thing in regard to which every electrical engineer should take a firm stand—that is, the criminality of placing brilliant and bare incandescent lamps in positions where the eyes of operators and workers will be injured. I will cite one instance which recently came under my personal observation. I recently went into the offices of one of the leading scientific and engineering organizations in this country and noticed the stenographer writing at her typewriting machine with a powerful tungsten lamp throwing light directly into her eyes, and the light reflected from the white paper she was writing upon. I said, " Don't you feel a good deal of eye strain?" She said, " Yes, the writing gets so blurred at times that I cannot read it." I said, " You have a good deal of headache?" She answered, " I have headache all the time." I then remarked, " You have a good deal of dandruff?" She said, " Yes, it bothers me a great deal." I said, " If that light is not changed you will lose your hair as well as your eyesight." I took a string and tied the lamp back so that the light came over her shoulder and was kept away from her face, and I think it is still hanging in the position in which I tied it, at least it was when I went in there the last time. A good many people who knew about the bad effects of such an exposure of the eyes to a strong light went into that office and saw that lamp hanging there before I did. Many of us now walk along the street and see powerful tungsten and other lights blinding the people passing the store windows and in the homes, offices and shops the people are not only destroying their sight but their hair. We should take that matter up and use our influence in having that corrected by the proper placing of the lamps, and the use of proper shades and diffusers.

One other thing occurred to me during the discussion, the importance of taking care of the deposits on the reflecting surfaces, besides the surfaces of the mere shade itself. A prominent efficiency engineer told me that he had succeeded in getting the cleaning of windows in a factory down to four motions, and hoped to get it down to three motions. We all realize, though we do not bother our heads much about it, the need of keeping windows clean so as to let in the daylight. If we are efficient engineers in regard to illuminating problems, let us take care of that factor also, and see that all reflecting surfaces are kept clean and in the best possible condition. I asked the same efficiency expert if it was not better at times to replace the glass windows instead of attempting to clean them. He replied that this was frequently the case.

E. A. Champlin: Reference has been made to lighting drafting rooms and also the manner of interior lighting through windows in the daytime, and I would like to ask if any particular effort is made to use the same direction of illumination with artificial illumination as you get through the window? In the drafting room the tables will always be so arranged that the lighting is most effective and in the proper direction for the use of a draftsman during the daytime. The window lighting will give him light so directed that the shadows will not interfere with his work, but I have noticed in most drafting rooms that the artificial lighting is not so placed, but is often placed so that it directly reverses that condition, so that the draftsman has to work on the other side of his triangle, and perhaps even of his T square. I wonder whether there is any effective means of duplicating the direction of lighting from the windows when artificial lighting has to be resorted to. Of course, if we do not get the direction right the draftsman will " plug in " somewhere and use a portable light, much to the detriment of his eyes, as has been pointed out by Mr. Hammer in the case of the stenographer.

C. E. Clewell: Answering the question of Mr. Champlin, I may say that very often the artificial light can be made to exceed in its advantages the direction of daylight; that is mainly brought about by the use of so-called semi-indirect lighting, which has been used in a great many cases under my own observation, and produces results which really exceed the advantages of daylight. The directional features in the semi-indirect lighting are such that the shadows are not reversed from what they are in the daylight.

Dr. Sharp called my attention to the possibility that my paper may have given the idea that the refinements or problems of industrial lighting were very simple compared to the decorative features which had to be considered in such problems as have been described by Mr. Jones. I did not wish to give the impression, by the various items which are set forth in my paper, that the problems in industrial work are not complex. For example, in one large installation it was found necessary to make a study extending over several months, in order to get the directional features of the light properly proportioned and placed with respect to the individual class of work. It was found, for example, after making a study of the needs of the installation, that merely distributing the light uniformly over the work, with a uniform capacity of the light, to a certain point on the average, would not at all solve the problem in this case, and it was necessary to raise and lower the lamps, and try different classes of fixtures so as to increase the light on a vise, for example, and for different classes of very fine work.

Another interesting problem has been the feeling on the part of workmen that individual lamps must be used in connection with some classes of work. In one installation, where three 100-watt tungsten lamps were installed on the eighth floor, and in which, prior to the installation of the new system, a good many hundreds of incandescent lamps were used, the superintendent, foremen and workmen themselves said that the individual lamp could not be dispensed with. We requested the foremen of the various floors to permit us to remove the individual lamps for a period of one month, during which time the workmen should try to perform their duties by the use of the overhead light, with the understanding that if it was not satisfactory we would put back all the individual lamps called for. We removed something like 1200 individual lamps, and after the month was over we were called on to put back merely two or three dozen on a floor space of 250,000 sq. ft. (23,225 sq. m.). This shows that the notions of the workmen, or even the superintendents themselves, cannot always be relied on in the matter of the light that is required.

The idea that I wish to emphasize in closing is that the problems are exceedingly complicated, even in those cases which seem most simple, for example, in industrial work, where the matters of reducing shadow effects and producing certain color effects are most important, in interior work, and you will therefore see that there are many difficult and important problems in connection with the proper lighting of industrial plants.

Charles F. Scott: A man in the mechanical engineering profession, Mr. Hunt, said to me something I want to say to the illuminating engineers particularly. He had a drafting room and a factory, and had tried different kinds of light. He said, " The great thing now is that we can lay out our factory and drafting room without reference to windows, considering only the efficiency of the machines and the progress of the work, and we can get our light from artificial illumination, which is better than daylight."

M. Luckiesh (communicated after adjournment): In reply to Mr. Champlin's question I would like to present my experience in attempting to imitate daylight distribution in an interior by the use of artificial light. A room with three windows—two on one side and one on the other—was fitted with removable dummy windows made of white diffusing cardboard. These dummy windows were placed in the window openings and illuminated by means of a special reflector hung on a bracket about 2 ft. (61 cm.) from the wall and near the top of the window. These reflectors were so adjusted that about the same relative distribution of brightness on the windows was obtained by artificial light as that presented to the view under daylight conditions. The distribution of light in the room was quite like that prevailing under the natural lighting conditions. The effect was pleasing. No measurements of the percentage of total lumens effective on a horizontal plane were made, but an idea of the possible " efficiency " of the installation is gained from such measurements on daylight in the same room. It was found that 33 per cent of the total lumens of natural light which entered the room was incident on a horizontal plane 36 in. (91 cm.) from the floor.

This shows that the " efficiency " in a room with light walls and ceiling need not be prohibitively low with this kind of an installation. I believe, however, that in many cases artificial lighting can be made far superior to natural lighting. Certainly special cases will arise where such a scheme will be useful.

Some experience with this trial installation gives some information relating to the point which Mr. Caldwell brought forth, namely, that more artificial light is needed just as daylight fails than later in the evening. This of course depends entirely on conditions. If daylight fails gradually and the lights are switched on at the proper time the eye will have become adapted to its new condition and no change will be noted. From a practical standpoint the eye becomes adapted to a change in illumination in a very short time. The installation just described permitted the closing of the dummy windows in a few seconds, thus changing from natural lighting of about 50 foot-candles on the test plane to artificial lighting of about 2 foot-candles. No more than a minute or two was required to become quite adapted to this abrupt change.

Roscoe Scott (communicated after adjournment): After reading Mr. Clewell's instructive paper, I am convinced that the test data he gives should be a valuable addition to the notebook of any illuminating engineer, especially of those who have to deal with the lighting problems of shops and mills, including the maintenance of lighting equipment. I wish to confine my discussion, however, to that section of the paper, near its close, entitled " Economic Relations."

The three charts comprising Fig. 16 bring out in a very forceful manner the pettiness of the illumination cost as compared with the cost for labor in the average industrial plant. One conclusion must certainly be drawn from these charts, namely, that a very considerable percentage increase in lighting expense may be justified if it will produce an increase—even a small increase—in the efficiency of labor. Some time ago I worked out sets of curves intended to show graphically the general relations between the several variables which must be considered in estimating that increase in lighting expense which will result in the maximum net saving for an industrial concern.* One of these charts may be worth reproducing in this connection. On it the net saving is plotted (see figure) as ordinates against increase in lighting expense as abscissas. As this is intended to be a general graphical solution of the problem, the variables are necessarily expressed as percentages rather than in absolute measure.

The increase in labor efficiency (*a* on the chart) should be understood as being measured by the resulting decrease in cost or the profitable improvement in quality of the manufactured product; it may or may not be directly measurable in terms of the increase in individual production.

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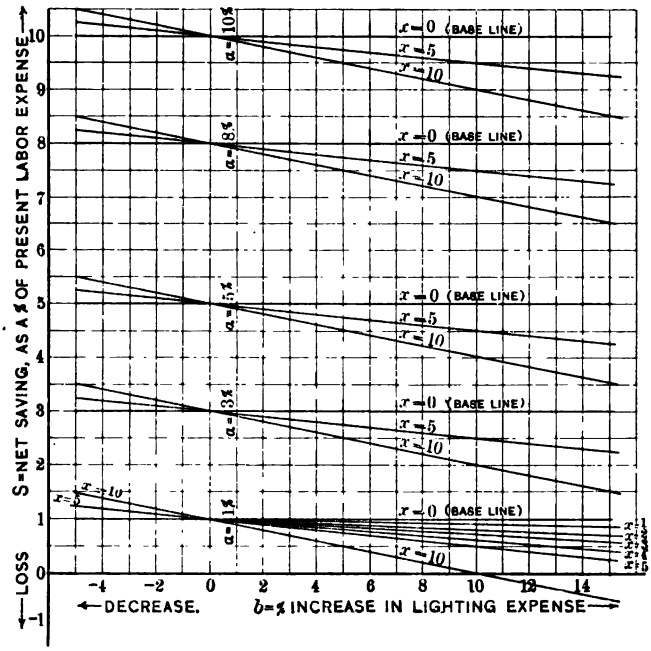
*See *Electrical World*, Feb. 10, 1912, pp. 317-319.

The chart really consists of several distinct sets of curves, one set for each value of *a* (the expected per cent increase in labor efficiency). In using the chart one picks out the particular bundle of curves labelled to correspond with the assumed value of *a* and then follows up the line corresponding to the given value of *x* (for definition of this symbol see chart), on which line the saving corresponding to the assumed increase or decrease in lighting expense may be found as an ordinate. As a numerical example:



Definitions: x = Ratio of lighting to labor expense (percentage)
a = Increase expected in labor efficiency (percentage)

$$S = a - \frac{b\,x}{100}$$

Ten compositors employed on a night shift in a large print shop receive an average wage of $25 a week. The present lighting system costs $1.75 per week.

Then $$x = \frac{1.75}{250} = 0.7 \text{ per cent.}$$

The manager estimates that the improvements in the illumination system necessary to produce a 1 per cent increase in efficiency of the men will increase his operating expenses for lighting by, say, 15 per cent. Referring on the chart to the bundle of lines marked "$a = 1$" we find by interpolation the point where a line corresponding to $x = 0.7$ would cross coordinate $b = 15$. This point is seen to correspond with a value of S, the saving, of 0.9 per cent. That is, the net weekly saving expected is 0.9 per cent of $250 = $2.25. By trying different values for b, with the corresponding estimated values for a, a condition which will give the maximum net saving (" on paper ") may be found.

Of course, the value of a—by far the most important factor in the calculations—must be estimated from the proposed changes in the illumination, rather than directly from the increase or decrease in operating cost consequent upon such changes. The difficulty of estimating it is enhanced because so many factors, such as diffusion, direction and color, as well as intensity of light, must be taken into account in deciding the comparative value of two or more industrial lighting installations from the labor-efficiency standpoint.

We must rather ruefully admit that the illuminating engineer who has amassed any considerable amount of data of value to a practical man in determining a for his particular case, be it the lighting of a silk mill, a clerical office or what not, is the exception rather than the rule. Such data—into which the human element enters so largely—must invariably be based on experience or special test, and are particularly hard to obtain. If those who have reliable figures would place them—in addition to the purely physical data that Mr. Clewell has presented—before the members of the national technical societies they would be of untold benefit in the future application of industrial lighting economics.

Bassett Jones, Jr.: Mr. Moore brought up the question of the diffusion of daylight. We have heard a great deal in the last few years of the necessity of copying daylight in interior illumination, both as to color and diffusion. My own personal opinion is that rarely can the problems of interior illumination be solved by any attempts to copy daylight. The differences between all sources of artificial light and the sources of daylight are to great to permit any true similarity in their effects. Having read Mr. Luckiesh's communicated discussion I should like to add that I entirely agree with his statement that daylight can even be improved upon by artificial means. I tried to draw attention to the fallacy of the superiority of daylight some time ago in a discussion of a paper by Prof. Nichols presented before the Illuminating Engineering Society, but at that time daylight and efficiency were the passwords of the art, and my attempt was quite bare of results. As far as the diffusion of daylight is concerned, the relation of directed daylight to diffused daylight can be very readily discovered by so holding a piece of white cardboard that one side is exposed to direct rays from the sun and looking at the other side. The difference in intensity between the two sides of that sheet of paper will be enormous. In other words, a large proportion of daylight is directed light. The moment we have an overcast sky, so that the light is thoroughly diffused, we have trouble in seeing, and particularly if the sky is not very dense. There is under such conditions a decided tendency to shade one's eyes. Perfect diffusion is not good for the eye, because the eye is not given a chance to perform its proper function.

Of course, in interiors it would be ridiculous to attempt to reproduce the intensity of daylight. In the first place, if we are going to do work in the open daylight, work which requires close application of the eyesight, we want to be shaded from the daylight. If you are reading a book in the daylight, you usually seek a shaded place in which to read, or if there is no shaded place you will open your umbrella and read the book under the umbrella. Consequently, for artificial interior illumination, the solution of the problem cannot be determined wholly from the conditions of daylight illumination.

Mr. Moore asked whether the effects obtained in my demonstration were secured by the use of colored screens. They were. He also suggested the use of the different artificial illuminants, each for its own color value. This has been done in the case of the Soldiers' Memorial in Pittsburgh, where incandescent lamps were used for their color value, the Moore tube for its color value, and the mercury-vapor lamp for its color value, and the color values of the different illuminants play a very large part in the general color scheme of the design. The green light from the mercury-vapor lamp, slightly modified by a particular form of opal glass, produces a moonlight effect, which has become a part of the color scheme in the ceiling. So with the light from the Moore tubes. The flame arcs serve to produce sparkling centers of an orange hue. The efficiency, of course, is low, because the lamps are not used to give light on the floor, but simply to give an effect of a jewel-studded ceiling.

In regard to the color of daylight, I performed some simple experiments a short time ago for the benefit of an architect, with reference to the problem of the color in which rooms should be painted. The average architect, like the average decorator, still believes that red, yellow and blue are the primary colors, and also that a north room should be painted yellow and a south room should be painted blue.

The experiments were carried on in a building in which there is a long corridor, on the south side of which is a series of offices with windows opening to the south. On the north side of the corridor is a series of offices with windows opening to the north. That light from the north sky is decidedly blue, and the light from the south sky decidedly yellow, was shown by giving the architect a little piece of cardboard, which he held before his eyes, so as to cover the window. The moment he covered the window with the piece of cardboard, that is the moment he covered his eye with the cardboard so that he could not see the window, he was asked to state the color of the unpainted plaster walls. In the north room he said blue. In the south room he said they were light buff. Therefore, the proposition was put to him that the north room should be painted blue, in order that the blue light should be reflected from a blue surface. If it was painted buff, it would absorb and not reflect blue light. The south room should be painted buff, because the buff walls would reflect the yellow light better than if the walls were painted blue, which would absorb the yellow light.

The result of this and other experiments was that the north rooms were painted a light blue and the south rooms were painted a light buff, and then came the question of artificial light. We were going to use tungsten lamps with reflectors, but we did not want to make the north rooms blue at night, and we had to mix with the blue a little green which would respond to the tungsten light at night. The yellow walls in the south rooms did respond to the artificial light without any modification.

These experiments give a practical example of how far the question of illuminating engineering can be carried. In fact, by such methods the best balance of color values for wall decorations can be determined in many interiors with a resulting heightening of the effects. Thus it is possible to determine for a given southern interior that the general color tone should be, say a buff corresponding nearly to number *x* in any given scale of pigment hues, and that on top of that color another color must be applied, say about 50 per cent of the wall area, must be painted quite red laid on in any design the architect may desire. A room painted that way, with consideration of the daylight sources, will give a very much more heightened effect and will incidentally prove more efficient from the standpoint of illumination than if a decorator painted it as he saw fit. Now, while this is true, tell it to almost any architect and see what he will say.

Mr. Millar said he thought it would have been interesting if the numerical results of the experiments had been given. The trouble with these experiments is that they have to be taken with a very large grain of salt; that is, it is impossible to conduct such a study, and apply the results promiscuously.

A report presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 27, 1912.

INDUSTRIAL EDUCATION

PRELIMINARY REPORT BY THE EDUCATIONAL COMMITTEE

I. INTRODUCTION

The Institute Committee on Education was reorganized last November as it was impossible for the original chairman to serve. At the meeting held at that time, it was decided to study the status of vocational education, that subject being at the present moment of paramount interest to the industrial interests of the country. The time available has been so short that it is impossible to present more than a preliminary report of progress, but this may possibly be of sufficient interest and value to warrant future committees of the Institute in continuing the work.

In laying out the plan of procedure of the Committee, no specific effort was made strictly to confine the study to educational conditions as applied to the electrical industries. This attitude was taken because it was believed that the proper establishment of vocational education for *all* children who cannot advance beyond the rank of hand workers is essential to the highest success of the country as a whole in its industrial and commercial functions, and, as a result, to the success of the electrical, or any other particular branch of the industries.

It is believed by the committee, since the Institute contains a large and intelligent membership widely distributed over the entire United States, that much good may be accomplished by gathering data together in the TRANSACTIONS for ready reference which will aid the individual members to effectively influence the development of this most valuable kind of education in their respective commonwealths and communities.

Probably there is no more important problem to be solved by the industrial communities of this country today than the proper preparation of the new generation for efficient, skilful, intelligent, and loyal labor. It is now quite generally known that we have fallen behind Germany, Austria, France, and some other European nations in this regard. To a certain extent, this is indicated by the fact that many of our exports carry from three to fifteen per cent of labor cost, while a large part of the exports of the countries named carry from forty to eighty per cent of such cost. Indeed, we have occasionally exported large quantities of comparatively crude and unmanufactured products to Europe to have them improved and refined to many times their original export value and then have brought them back to this country for our consumption. These conditions must exist to some extent always, but the balance against us is so excessive that it behooves us to take it into consideration.

In regard to the effect of applied education, Mr. H. E. Miles, chairman of the National Manufacturers Association's Educational Committee, makes this statement in a recent report: "By industrial education it now devolves upon us in very important respects to shape the lives of the children of today and thereby to make the men and women of tomorrow. Each year 2,500,000 children graduate from or leave our elementary schools proud and confident in having accomplished the first great task of their lives in successfully finishing the eight years' course with credit. But this same vast army of 2,500,000 little ones, most of them only 14 years of age, leave the schools soon to be discouraged, to prove unsuccessful, aimless; most of them have gotten no further than the sixth grade, having learned little else than the three R's, not educated in any sense, but only possessed of the rudiments whereby real education may be acquired. They then, in a way, learn in school only how to fail. These are the children who come into the industries, and deserve or require industrial or trade education."

This injurious condition, as set forth by Mr. Miles, is to be found to a more or less serious extent in almost every manufacturing community in the United States and also to some degree in the rural communities. The difficulty has been largely relieved in Germany by the development of her magnificent system of trade and "continuation schools." In this system, after a boy has reached the age of fourteen, he has the opportunity to continue in schools which are particularly adapted by the character of their teaching and organization to aid him in making himself a skilful and intelligent workman. A compulsory attendance law makes it necessary for most of the boys, whether working or otherwise, to attend these continuation schools at least one-half a day each week until sixteen years of age. The expense of the schools is little greater than that required for maintaining the ordinary types of public school curricula with which we are familiar in this country. Though trades are taught—as many as two score in one of the cities of Germany—the cost of equipments required is comparatively small; only sufficient apparatus is used to teach the fundamental movements of the processes called for by a particular trade. Because of the large number of pupils who are employed in labor and attend for part time only, these foreign schools cost per pupil, per year, a small fraction of the amount expended per pupil in our best full time trade and industrial schools.

It is considered by well qualified industrialists who have studied the question, that many classes of workmen of continental Europe are more skilful and accurate than similar classes of American workmen, even after due allowance is made for the American's native resourcefulness, energy, and ability. Therefore, if the truth of this statement is conceded, active means should evidently be adopted for the development of educational methods which will cause our manual workers of the future to reach a higher stage of efficiency. This is particularly so since our country must, perforce—as its population grows and natural resources relatively decrease—in order to maintain its prosperity, wealth, and the happiness of its people, put forth increasingly greater efforts to maintain its share of the world's trade.

With the exception of a comparatively few successful experiments with continuation and free vocational schools such as are to be seen here and there scattered over the country, as yet comparatively little has been either attempted or accomplished in the United States in the form of publicly supported training of the character demanded; and a beginning only has been made in the establishment of industrial schools supported by private benevolence, or by industrial corporations for preparing workers for the ranks of their own employees. The number of pupils enrolled in such schools, the number of teachers employed, and the buildings and equipments in use are small compared with those in some of the European nations. Statisticians estimate that only from ten to twenty per cent of the children of this country of the age of sixteen, whom necessity drives from school to work, are so situated that they can learn a trade. The remainder work at casual employment or in such places as fail to develop their full usefulness to their communities. This condition of inefficiency is apt to remain with them throughout life to their detriment, and to a considerable degree the character of our export trade undoubtedly is influenced thereby.

It seems probable that this country could, without heavy burden beyond that incurred in maintaining the present more or less inflexible public school system, so modify the pedagogical methods in use as to make it possible for the great majority of sound children to take positions in the world of labor where they could be classed as skilled. Such training of the mass of the people should lead to increased sense of responsibility, good spirit, orderliness, and efficiency and should go far toward removing much of the unrest and dissatisfaction rapidly becoming prevalent.

On account of the limited time at the committee's disposal, it was decided to study certain schools in the New England and Middle States—the thought being that if the work is continued by future committees, a further study can be made of the conditions in other parts of the country. Even in the districts chosen it was found wise to confine attention to but a few of the most typical schools and to neglect many institutions of great merit. The work of gathering data was divided among the membership of the committee somewhat as follows: Professor H. H. Norris of Cornell University undertook the burden of reporting upon certain schools to be found in New England and New York; adding thereto, with some assistance from the Chairman, descriptions of various schools maintained by the railroad systems of the country. Professor Samuel Sheldon of the Brooklyn Polytechnic Institute was assigned certain typical schools in New York City.

Insomuch as vocational education, to serve the entire population of the country, eventually must be supported largely from the public purse, and insomuch as many of the commonwealths of the Union are now endeavoring to inaugurate such work by the enactment of special legislation relating to the subject, a special section of the committee's report is devoted to a study of the laws already in existence. Dr. W. I. Slichter of Columbia University was assigned the duty of making an investigation of this subject and preparing a brief report thereupon.

It is hoped that the short descriptions of the few schools that are named hereafter and, also, the brief discussion of laws which seem to be suitable for the establishment of effective vocational educational systems may be of service to members of the Institute, who have not already given the subject special study, in aiding them to direct the development of this important phase of education in their own commonwealths. The committee, of course, does not pretend that its findings are complete, but the data given may prove useful by indicating the direction in which the development is tending.

Before proceeding with the more detailed discussion, it seems well to point out here certain salient classifications and facts concerning industrial schools. They may be divided properly into three general classes, namely:

1. Those maintained at public expense and open to all children of their respective districts.
2. Those maintained through private benevolences and also open largely to children of their districts.
3. Those maintained by corporations for preparing skilled employees for their own purposes.

These schools, without including those that are giving instruction in drawing, manual arts, etc., for purposes of general training rather than for direct vocational preparation, are frequently divided into two types, namely:

a. Full time schools.
b. Continuation schools.

In the former, the youth attends the school continuously until he has been prepared so far as possible, both mentally and manually, for the particular trade or vocation which he proposes to enter. The continuation schools are those to which pupils, already at work, give only part time—such as evenings, or a day or part of a day each week. The third general division named above consists of continuation schools, while the first and second divisions include both types, or a combination of the two.

It may be safely stated that the continuation school in which the pupil, already regularly employed, gives a part of the working hours each week to school work, shows distinct and positive signs of being best suited to the conditions facing the great majority of young men.

These schools, whether maintained at public expense or by industrial corporations, should aim to develop the mental judgment and physical skill required for promoting the industries in the localities in which they are situated. This means very close correlation between the school work and the shop work in which the youth is engaged, and as a result demands efficient co-operation between the school and shop staffs.

Continuation schools need not be materially more expensive than the common schools, as the practical applied part of the training can be obtained to a large extent during the portion of the time the pupils are at work.

Experience with laws relating to the organization of industrial schools (continuation and full time), carried on at public expense, seems to indicate that certain more or less well defined conditions of organization are desirable. Some of these, which appear to be of especial importance, are presented below for consideration:

1. Young men who leave the common schools at fourteen years of age should be required ordinarily to spend at least two years thereafter in either a continuation or full time vocational school. Those leaving at fifteen should give at least one year to work of the same kind.

2. Opportunity should be given all residents of the community over sixteen years of age to enroll in the continuation school upon the payment of a small tuition fee, especially those persons between the ages of sixteen and twenty-five.

3. Each commonwealth should have a commission composed of representatives of the industries, with power to direct its industrial school work, under the condition that its actions are subject to the approval of the regular state board of education.

4. Local communities should have commissions selected from the personnel of the local industries, with power to direct the work of the local industrial schools, but subject in their actions to the approval of the local school boards.

5. The commissions named above need not interfere with the regular public school organization of the state, but should be correlated therewith.

6. In order to encourage the establishment of vocational schools, and to give a proper central authority over the school officials of local communities, the state should give material financial aid to those institutions which comply with its regulations and are approved by its commission on industrial education.

Lack of state and local boards, whose membership is selected from the officials and ranks of the industries, having sufficient power to enforce the adoption of their methods, must result, as a rule, in industrial schools failing to give the full possible measure of usefulness. The modern school teacher usually knows his particular business; but this does not include, in general, the direct preparation of his pupils for industrial pursuits, nor can he have the opportunity to learn the requirements essential to giving such preparation except through close contact with, and the active cooperation of, the industrialists who are to absorb his pupils into their ranks of labor.

The term vocational education is used in this report to cover any kind of education that leads to a vocation; industrial education is included in this and refers to the bulk of the manual vocations other than agriculture and the domestic arts (see hereafter).

II. PROVISION BY LAW FOR VOCATIONAL TRAINING IN THE UNITED STATES

A survey of the educational enactments of the various states shows that 24 states have active provisions for vocational training, six have permissive provisions and fifteen have no provision at all. In twenty of the states vocational schools are in practical operation.

Massachusetts, Wisconsin, New York and Maine seem to have given the subject the most careful consideration and special commissions to study the subject have rendered elaborate reports on the subject. The State of Massachusetts seems to be not only the pioneer but the leader in this branch of education and while other states may have studied the subject and made provisions for the training yet Massachusetts is the only state in which elaborate provisions are in extensive operation. As the term vocational training is used in a very broad sense and includes any training intended to prepare the scholar to become economically productive, it is desirable to distinguish between the various forms of training to be discussed. The amended acts of the State of Massachusetts carefully define the various forms of education as follows:

1. " Vocational education " shall mean any education the controlling purpose of which is to fit for profitable employment.

2. " Industrial education " shall mean that form of vocational education which fits for the trades, crafts, and manufacturing

pursuits, including the occupations of girls and women carried on in workshops.

3. " Agricultural education " shall mean that form of vocational education which fits for the occupations connected with the tillage of the soil, the care of domestic animals, forestry and other wage-earning or productive work on the farm.

4. " Household arts education " shall mean that form of vocational education which fits for occupations connected with the household.

5. " Independent industrial, agricultural, or household arts school " shall mean an organization of courses, pupils and teachers, under a distinctive management, approved by the board of education, designed to give either industrial, agricultural or household arts education as herein defined.

6. " Evening class " in an industrial, agricultural, or household arts school shall mean a class giving such training as can be taken by persons employed during the working day, and which, in order to be called vocational, must in its instruction deal with the subject-matter of the day employment, and be so carried on as to relate to the day employment.

7. " Part-time, or continuation, class " in an industrial, agricultural, or household arts school shall mean a vocational class for persons giving a part of their working time to profitable employment, and receiving in the part-time school, instruction complementary to the practical work carried on in such employment. To give " a part of their working time " such persons must give a part of each day, week, or longer period to such part-time class during the period in which it is in session.

8. " Independent agricultural school " shall mean either an organization of courses, pupils and teachers, under a distinctive management, designed to give agricultural education, as hereinafter provided for, or a separate agricultural department, offering in a high school, as elective work, training in the principles and practise of agriculture to an extent and of a character approved by the board of education as vocational.

9. " Independent household arts school " shall mean a vocational school designed to develop on a vocational basis the capacity for household work such as cooking, household service, and other occupations in the household.

Practically all states offer vocational education in the state normal and training schools for teachers, and work of a collegiate grade in the state land grant colleges established under the Morrill act. In a majority of the states there is permissive legislation relative to the introduction of manual training, including drawing, in the elementary schools. In many states instruction in these branches is required in all towns having above a certain specified population. In twenty-four states legal provision has already been made for the encouragement or support of industrial education beyond the general provision for the manual training in elementary schools. The following gives an outline, according to such information as was obtainable, of the provisions in those states having such provisions:

Alabama—Provides for the establishment and maintenance of a branch agricultural experiment station in each congressional district. The annual appropriation for each school is $4500.

Arkansas—Has four state public schools of agriculture, appropriating annually $160,000 for their support.

California—Permits but does not provide for.

Connecticut—Aids in the support of two schools giving instruction in the principles and practise of trades. Total amount is $50,000 for both schools.

Georgia—Aids district agricultural high schools to the limit each of $2000.

Illinois—No special provision, local option.

Indiana—Authorizes industrial and manual training in cities of more than 100,000 and confers power to raise money by taxes.

Iowa—Has no law but aid is given for manual training.

Kansas—Authorizes local boards to levy tax of one half mill for the equipment of industrial training schools or departments. State aids such schools to the limit of $250 annually.

Kentucky—Does not provide but the cities do.

Maine—Provides for and aids to the extent of two-thirds the salaries of the instructors, subject to the approval of state superintendent. Has a commission which has made valuable recommendations.

Maryland—Gives state aid to county manual training schools or departments, limit $1500 each. Also aids high schools having commercial courses.

Massachusetts—Has a deputy commissioner of education whose duty it is to encourage and supervise forms of vocational education supported by the state. Grants permission to towns and cities to provide independent vocational schools and to provide evening and part time courses for persons already employed. Permits two or more cities to join for the purpose of maintaining vocational courses or schools; aids to the extent of one-half the net expense of such schools, provided the school has been approved by the state authorities.

Michigan—Authorizes and aids county schools of agriculture and domestic economy to the extent of ⅔ of the cost if approved by state authorities.

Minnesota—Gives state aid to departments of agriculture, manual training, and domestic science in state high, graded, and consolidated schools if approved by state board. Maximum limit of $2500 to any school.

Nebraska—Does not provide but the cities do.

New Jersey—Contributes half the cost of maintainance and authorizes the locality to levy a tax for the remainder; maximum limit of aid is $10,000.

New York—Authorizes local board to establish such schools and gives aid to the extent of $500. Has a state director of trade schools.

North Dakota—Authorizes and aids such schools.

Ohio—Provides for manual training but the cities do most.

Oregon—Provides for courses in any high school under supervision of state board.

Pennsylvania—Requires that manual training courses shall be provided and aids, by direct appropriation, established vocational schools. Has three deputy state superintendents of education in charge of work.

Texas—Gives aid to the extent of half the cost of maintaining courses in agriculture, domestic economy, and manual training subject to the approval of state board. Maximum limit $500. Aid is not permanent.

Utah—Permits vocational courses to be prescribed in existing schools.

Vermont—Aids schools with approved manual training courses to the extent of $250 per year.

Virginia—Provides by law and has ten schools in operation.

Wisconsin—Has a State Board of Industrial Education and a Commission to encourage Industrial Education; aids county schools having industrial courses which are approved by state.

Thus in the majority of cases, heretofore, the vocational training has been almost altogether in the form of agriculture or home-making and with manual training as an addition or incidental to existing courses in high and secondary schools. The problem, therefore, of true *industrial* education is comparatively new and has been met in only a few states such as Massachusetts, Pennsylvania, Maine, New York, Indiana, and Wisconsin. In order to study the subject and learn the best methods of accomplishing the desired object we need therefore only consult the records of the results in these States.

An especially appointed commission in Maine has made a very careful study of the subject and placed the results of its conclusions in a valuable report. This report is dated 1910. The records do not show that the conclusions of this commission have been carried out to the extent of perfecting an operating system.

While there are a great many institutions of vocational training in New York State they appear to be not as fully correlated as those in Massachusetts and Wisconsin and the initiative appears to be in the cities and localities themselves. The state board is ready and prepared to give advice but does not have the control that is provided for in Massachusetts and Wisconsin.

In the opinion of this committee the feature of the Massachusetts and Wisconsin laws which causes them to excel is the provision that a vocational school, to receive state aid, must receive the state's approval of many of its important features, such as courses, teachers, buildings, methods, time, and accounts. This clause is used as an inducement to encourage the local boards to consult with the proper representative of the state board from the beginning of the organization of the school, rather than to await the exact period when money is requested of the state. The state board includes an assistant superintendent who has made a special study of the subject of vocational training, and, members of the board, private citizens representing the points of view of employers and employees. The new Pennsylvania laws bearing upon this subject are also much similar in effect.

To crystallize and collect the best ideas on the subject of legislation and provisions for vocational training it is deemed sufficient to pick out the best points of the methods of Massachusetts and Wisconsin as representative of good practise.

OUTLINE OF A SCHEME FOR INDUSTRIAL EDUCATION BASED LARGELY ON THE LAWS OF MASSACHUSETTS AND WISCONSIN

Either a state board of industrial education containing representatives of both employers and employees and independent of the usual state board should be appointed, or an advisory board of similar character should work with the regular board of education.

The state superintendent of education or, in case the duties are sufficient to warrant the appointment, an assistant for industrial education should be authorized to approve, with the board, the courses of study and to certify that the work of the various schools is satisfactory. The industrial assistant should be authorized to attend industrial conventions and make investigations outside the state as well as within.

The board of education should have control over all state aid given, and aid should only be extended to those schools that have received the approval of the board and superintendent or assistant. The industrial board of education should be authorized to investigate and aid in the introduction of vocational education and to initiate and superintend the establishment and maintenance of the schools. Three classes of independent schools should be recognized, such as industrial, agricultural, and household arts, and each of these schools should have day instruction, part-time, and evening classes. Attendance upon such day or part-time classes should be restricted to those between fourteen and twenty-five years of age and should be compulsory for those between fourteen and sixteen. Attendance at evening classes should be restricted to those over seventeen. The local board of education should be authorized to establish and maintain independent vocational schools; and in the establishment of such schools should call in the advice of the state superintendent and after adopting a plan of organization and administration submit this plan for approval to the state board. It is desirable that local and district boards of trustees appoint an advisory committee composed of members representing local trades, industries, and occupations. The state should reimburse the local district to the extent of one-half the net expenses of the school, provided the form of organization, control, location, equipment, courses of study, qualification of teachers, methods of instruction, conditions of admission, employment of pupils, and expenditures of money are in accordance with the approved methods of the state board.

The community should provide the buildings and equipment and sufficient money for the operation of the schools and after a year's operation the state should reimburse the community the amount stipulated. In order that this amount may be easily determined uniform methods of accounting in the schools should be required.

Each locality should endeavor to make its courses meet its local needs and, if possible, should endeavor to secure cooperation between the schools and the local industries so that the school shall prepare the students to be successful in those industries, and, if possible, so that the local industries shall supply the opportunity for practical work. To this end it is desirable that, either on the local board or the local advisory board, persons interested in the local industries be represented.

It is desirable that a reasonable tuition fee be charged in order to discourage from attending those persons who have no serious purpose.

It is desirable that all children from fourteen to sixteen years of age be compelled to attend these classes at least one day per week or the equivalent thereof and that their working hours, if employed, should be such that this attendance would not be an unreasonable burden.

Provision should be made that illiterate minors over seventeen years of age should be required to attend the evening schools.

The training given should be designed to encourage the children of the locality to enter the local industries and to fit them to become expert workmen in those industries; thus the children would be kept at home, would be assured useful and successful careers and the local industries would be kept in the hands of natives of the community.

LAWS OF MASSACHUSETTS ON STATE-AIDED VOCATIONAL SCHOOLS

STATE ADMINISTRATION AND SUPERVISION

Section 2. The board of education is hereby authorized and directed to investigate and to aid in the introduction of industrial, agricultural, and household arts education; to initiate and superintend the establishment and maintenance of schools for the aforesaid forms of education; and to supervise and approve such schools, as hereinafter provided. The board of education shall make a report annually to the general court, describing the condition and progress of industrial, agricultural, and household arts education during the year, and making such recommendations as the board may deem advisable.

TYPES OF SCHOOLS

Section 3. In order that instruction in the principles and the practise of the arts may go on together, independent industrial, agricultural and household arts schools may offer instruction in day, part-time, and evening classes. Attendance upon such day or part-time classes shall be restricted to those over fourteen and under twenty-five years of age; and upon such evening classes to those over seventeen years of age.

LOCAL ADMINISTRATION AND CONTROL

Section 4. Any city or town may, through its school committee or through a board of trustees elected by the city or town to serve for a period of not more than five years and to be known as the local board of trustees for vocational education, establish and maintain independent industrial, agricultural, and household arts schools.

Section 5. 1. Districts composed of cities or towns, or of cities and towns, may, through a board of trustees to be known as the district board of trustees for vocational education, establish and maintain independent industrial, agricultural, or household arts schools. Such district board of trustees may consist of the chairman and two other members of the school committee of each of such cities and towns, to be appointed for the purpose by each of the respective school committees thereof; or any such city or town may elect three residents thereof to serve as its representatives on such district board of trustees.

2. Such a district board of trustees for vocational education may adopt for a period of one year or more a plan of organization, administration and support for the said schools, and the plan, if approved by the board of education, shall constitute a binding contract between the cities or towns which are, through the action of their respective representatives on the district board of trustees, made parties thereto, and shall not be altered or annulled except by vote of two thirds of the board, and the consent of the state board of education to such alteration or annulment.

Section 6. Local and district boards of trustees for vocational education, administering approved industrial, agricultural, or household arts schools, shall, under a scheme to be approved by the board of education, appoint an advisory committee composed of members representing local trades, industries, and occupations. It shall be the duty of the advisory committee to counsel with and advise the local or district board of trustees and other school officials having the management and supervision of such schools.

REIMBURSEMENT

Section 8. Independent industrial, agricultural, and household arts schools shall, so long as they are approved by the board of education as to organization, control, location, equipment, courses of study, qualifications of teachers, methods of instruction, conditions of admission, employment of pupils, and expenditures of money, constitute approved local or district independent vocational schools. Cities and towns maintaining such approved local or district independent vocational schools shall receive reimbursement as provided in sections nine and ten of this act.

Section 9. 1. The commonwealth, in order to aid in the maintenance of approved local or district independent industrial and household arts schools, and of independent agricultural schools consisting of other than agricultural departments in high schools, shall, as provided in this act, pay annually from the treasury to cities and towns maintaining such schools an amount equal to one half the sum to be known as the net maintenance sum. Such net maintenance sum shall consist of the total sum raised by local taxation and expended for the maintenance of such a school, less the amount, for the same period, of tuition claims, paid or unpaid, and receipts from the work of pupils or the sale of products.

2. Cities and towns maintaining approved local or district independent agricultural schools consisting only of agricultural departments in high schools shall be reimbursed by the commonwealth, as provided in this act, only to the extent of two thirds of the salary paid to the instructors in such agricultural departments: provided, that the total amount of money expended by the commonwealth in the reimbursement of such cities and towns for the salaries of such instructors for any given year shall not exceed ten thousand dollars.

3. Cities and towns that have paid claims for tuition in approved local or district independent vocational schools shall be reimbursed by the commonwealth, as provided in this act, to the extent of one half the sums expended by such cities and towns in payment of such claims.

Section 10. On or before the first Wednesday of January of each year the board of education shall present to the general court a statement of the amount expended previous to the preceding first day of December by cities and towns in the maintenance of approved local or district independent vocational schools, or in payment of claims for tuition in such schools, for which such cities and towns should receive reimbursement, as provided in this act. On the basis of such a statement the general court may make an appropriation for the reimbursement of such cities and towns up to such first day of December.

III. DESCRIPTION OF A FEW TYPICAL VOCATIONAL AND INDUSTRIAL SCHOOLS

The few schools hereafter described were selected for the dual reason that they illustrate types and because information concerning them was readily available to the committee. There are numbers of other schools which would have served the purpose equally well and which are fully as efficient.

A. Certain Schools in New York City

Pratt Institute. This Brooklyn private school, founded by Charles M. Pratt in 1887 and now under the control of his six sons, is adequately endowed and gives day and evening instruction to over four thousand students. There are at present five divisions of instruction. Among these is the "School of Science and Technology" which offers thorough practical courses planned to meet the needs of four different classes of students:

"First. Day Industrial Courses in Mechanics, Electricity, and Chemistry, for young men who cannot afford the time and expense required for four-year college or engineering courses, but who are nevertheless ambitious to fill positions above the grade of skilled mechanics in manufacturing and industrial plants.

"Second. Day Trade Courses in Machine Work, Carpentry and Building, and Tanning, for those who wish practical and theoretical instruction in these trades.

"Third. Evening Technical Courses for those employed during the day in mechanical, electrical, and chemical industries and related occupations.

"Fourth. Evening Trade Courses for apprentices and journeymen.

"The courses offered are as follows:

Day Industrial Courses	
Steam and Machine Design	A two-year course
Applied Electricity	A two-year course
Applied Chemistry	A two-year course
Applied Leather Chemistry	A one-year course
Day Trade Courses	
Machine Construction	A one-year course
Carpentry and Building	A one-year course
Tanning	A one-year course

Evening Technical Courses

- Technical Chemistry
  - General Chemistry
  - Qualitative Analysis
  - Quantitative Analysis
  - Organic Chemistry
- Mechanical Drawing and Machine Design
  - Mechanical Drawing
  - Machine Design
  - Mechanism
- Industrial Electricity
  - Electricity and Mechanics
  - Electrical Machinery
  - Electrical Design
- Practical Electricity
- Practical Mathematics
- Steam and the Steam Engine
- Strength of Materials

Evening Trade Classes

- Machine-Work
- Tool-Making
- Carpentry and Building
- Pattern-Making
- Sheet-Metal Work
- Plumbing
- Advanced Wood-Working for Teachers "

Requirements for admission to these courses are based largely upon the personality of the applicant rather than upon his prior scholastic achievements. A moderate honorarium is charged for each course.

The purpose of the school is to reach and help all classes of practical workers, both artists and artisans, and to give every student practical skill along some line of work. As a rule the instruction is intended to be more theoretical and less practical than that usually given in trade schools, whereas it is more practical and less theoretical than that usually given in engineering schools and colleges. This type of instruction is a unique feature of the Institute's work and its conception was inspired by the personal experiences of its founder, who was a self-made man of unusual breadth and power, and who started life as a machinist. In this connection there appear the following statements in a report by Samuel S. Edmands from the Department of Science and Technology:

" The trained workers in the electrical and mechanical fields are, in a general way, divided into three different classes, the first and highest comprising the comparatively few men of superior ability and attainments who originate and direct operations requiring the services of many. In this class we find the engineering experts, designing and consulting engineers, and many others who bear the prime responsibility for the successful operation of industrial and engineering enterprises. The third

Experience in trade taught	Cabinet making	Pattern making	Carpentry and joinery	Plumbing	Blacksmithing	Machine shop practise	Steam engineering	Physics and elect. engineering	Advanced elect. engineering	Elect. wiring and installation	Chemistry	Freehand drawing	Mech. drawing	Architectural drawing	Total
None	15	37	53	11	53	6	21	144	9	36	43	57	117	81	683
Less than one year	2	5	6	6	0	3	15	0	6	15	6	16	12	17	109
One to two years	2	7	1	18	2	3	6	1	10	14	15	12	6	23	120
Two to three years	2	1	2	22	1	9	6	1	12	6	13	5	2	10	92
Over three years	3	1	0	45	0	16	4	3	9	4	10	6	0	2	103
Aim in taking trade course															
To improve knowledge of trade	7	14	9	91	1	31	21	11	28	40	40	31	50	52	426
To learn trade	9	28	50	5	8	3	21	47	15	30	31	55	87	78	467
To gain general information	8	9	3	6	47	3	10	91	3	5	16	10	0	3	214
Number of students admitted to different trade classes	24	51	62	102	56	37	52	149	46	75	87	96	137	133	1107
Average number of night students remaining in each class after reg.	58	48	36	45	34	71	33	44	71	65	60	46	51	57	50
Number of pupils who have obtained any industrial benefit as shown by advancement in position or wages	4	7	2	35*	14	2	0	2	6	21	6	12	4	21	136

*Increase of wages is governed principally by unions. All of present students declare they have been greatly benefited in theory and practise.

and last class is composed of the skilled laborers and trained mechanics. Between the highest and lowest class there is a constantly widening field, the workers in which constitute the second class and occupy positions secondary and subordinate to the members of the first class, but nevertheless of great importance. They are the assistants to the engineers, the supervisors of skilled labor, or the specialists performing operations requiring a degree of knowledge and training in excess of that possessed by those in the third class. The commercial demand for technically trained workers of this second or intermediate grade is keen, and it is to afford a means for them to obtain the training that they need that the two-year technical courses in the Institute are primarily intended."

During 1910 the National Association of Tanners, desiring to affiliate with some educational institution in the formation of a tanning school, found that the Pratt Institute was prepared to train young men for its employ in the manner desired.

The formal report of the Tanning School Committee of this association contains an outline of the equipment and courses of instruction proposed by Pratt Institute. Its study is recommended to those interested in the formation of effective industrial curricula.

Public Schools. There are three public high schools in New York City which offer opportunities for instruction in vocational subjects, Stuyvesant, at 245 E. 15th St., Manhattan, for boys and men, Manual Training, on 7th Ave., Brooklyn, for boys and girls, and Bryant, on Wilbur Ave., Long Island City, for boys and girls. The courses of study, which are directed towards the technical industries, are similar to the ordinary high school courses, except that biology and history are omitted and manual training is given throughout four years.

Applied Mechanics, Steam, and Electricity forms a special course at Stuyvesant which is given to fourth-year students and is open only to students of exceptional ability. It is designed to prepare its graduates for giving efficient service immediately after leaving the school. The physical equipment of all these schools is adequate for the purpose and the laboratories are better equipped with apparatus than many engineering colleges, as will be evident after an inspection of the accompanying illustrations of the engine room at Stuyvesant. Though such extensive facilities as shown in the illustration are desirable it should be distinctly understood that much excellent and practical industrial instruction can be given with simple and quite inexpensive equipments. No community, therefore, need be deterred from entering upon this kind of educational work because of the burden of the primary plant cost.

The day instruction at this school is duplicated in the evening with some modifications, attending students being of the same general class as the day students but being commonly from 8 to 10 years older. The evening instruction has for its motive increased earning capacity of the student. Besides preparing some evening students for entrance to college, others are fitted for positions in the trades. The effectiveness and characteristics of this work may be judged from the data contained in the foregoing table, which is based upon information supplied by the students and which refers to the academic year 1910–11.

B. A FEW SCHOOLS SITUATED IN THE MIDDLE AND NEW ENGLAND STATES.

The Privately Endowed Industrial School. As an example of the recent development in privately endowed trade schools, Wentworth Institute, of Boston, Mass., may be considered as representative of modern ideas. The Institute is designed to be a high-grade trade school, that is, one which places a rational scientific foundation under the direct preparation for mechanical trades and industry. The Director states that the aim is to develop artisans and skilled mechanics, and also to train men who wish to become inspectors, shop foremen, master mechanics, and superintendents in industry.

As a school of this kind attracts young men of all kinds of preparation, the courses have to be adapted to various needs. There are, therefore, short one-year day courses for beginners and others with little practical experience, two-year day courses for those with some experience who wish to train themselves for positions of foremanship grade, and also evening courses where men employed in mechanical occupations during the day may either increase their skill and practical knowledge of their trade or study such supplementary subjects as will help them to advance to more responsible positions. While the school has been in operation but a few months, those in charge of it have had long experience in somewhat similar schools, so that the plans and methods of instruction may be considered in no way experimental. The following facts dealing with the organization of the school and the results thus far accomplished will, therefore, be of interest.

Trades Taught. After a study of the probable demand for instruction the faculty of the Institute selected the following trades for the day courses. In the building trades—carpentry, plumbing, and electric wiring; in the manufacturing trades—machine work, foundry practise, and pattern-making; also, electrical construction for those who wish to become foremen in electrical industries, and machine construction for those who wish to become foremen in mechanical industries. While in the case of foundry practise, especially, great doubt was felt as to whether American boys could be made to see its scope, the possibilities of future development in the industry made this trade of importance. The class in foundry practise has proved one of the most successful of the day courses.

For boys employed during the day, evening classes are provided. For those who wish to perfect themselves in mechanical skill and practical knowledge of their trade, courses are offered in carpentry, pattern-making, machine work, tool-making, foundry practise, electric wiring, and plumbing; and for those who wish to supplement their knowledge and prepare themselves for more responsible positions, there are courses in practical mathematics, mechanical drawing, machine design, practical mechanics, strength and properties of materials, the steam engine and the operation of power plants, applied electricity, and electrical machinery.

Selection of Students. Although the buildings and equipment of the Institute were hardly completed in September, 1911, more than three times as many applicants as could be accommodated appeared. In selecting from this large number, personal interview and oral questioning were the only practicable means. All academic standpoints of scholarship and skilled attainments were discarded and the attempt was made to measure the applicant's forcefulness, seriousness of purpose, and adaptability to the trade selected. In this way an earnest body of students was picked out.

Selection of Teachers. Of the 18 men who constitute the day school faculty, eight have charge of shop instruction. Six of the eight have special qualifications for this work, having occupied responsible industrial positions. The other teachers are school and college trained and they have had wide experience in industrial work. As the success of an institution like this depends largely on the teachers every effort has been made to get those properly equipped for this work.

Typical Curriculum. Following is a typical curriculum which shows clearly the scope of the work of this institution:

A typical curriculum for a one-year course is as follows:

	Hours per week		
	Fall term	Winter term	Spring term
Shop practise in machine-tool work, machine construction, bench work and tool-making, principles and practise of forging, tempering steel, foundry practise and pattern-making	20	20	20
Mechanical drafting and blue print reading	6	6	6
Practical mechanics, materials of construction, and power transmission, etc., (recitations and laboratory practise)	9	9	9
Practical mathematics, machine shop computations	5	5	5

A typical curriculum for two-year courses is as follows:

FIRST YEAR

	Hours per week		
	Fall term	Winter term	Spring term
Practical Mechanics:			
Recitations	5	5	5
Laboratory practise	8	8	
Electrical Motors and Appliances:			
Principles of construction and operation,			
Recitations			5
Laboratory			8
Mechanical Drafting:			
Shop drawing and machine details	8	8	8
Practical Mathematics:			
Shop computations and use of formulas	5	5	5
Shop Practise:			
Moulding and foundry work	8	4	
Pattern making		4	8
Forging and tempering	6		
Machine tool work		6	6

SECOND YEAR

	Hours per week Fall term	 Winter term	 Spring term
Applied Mechanics:			
Mechanism of machinery, materials of construction, transmission of power, plant care and operation, etc.			
Recitations	5	5	5
Laboratory	8	8	8
Machine Sketching:			
Tool and jig design	6	6	6
Advanced Practical Mathematics, including useful applications of algebra, geometry, and trigonometry	5	5	5
Advanced Shop Practise:			
Machine construction	10	4	4
Tool making		6	6
Optional			
Advanced jig and tool making	6	6	6
or			
Advanced machine construction	6	6	6

NOTE: In the two-year courses a considerable portion of the laboratory work is actual construction and for that reason the time spent in shop practise is somewhat reduced.

Vocational Instruction under the Direction of the New York State Department of Education. In 1908 a law was passed by the legislature of New York State (already referred to in Section II) providing for vocational and trade instruction in public schools. To put this law into effect the New York State Education Department organized a separate division of trade schools under the supervision of a chief. This division endeavors to keep in touch with the various labor organizations and with the manufacturers with a view to the promotion of education of such a nature that the young people of the state will be fitted to take up employment in the industries with the greatest possible efficiency.

The Department of Education recognizes two divisions of this field: (1) There are young people from 12 to 16 who need industrial education of a preliminary character. At this age young people are of little value in the industries, but they are of an age suitable for the acquirement of the fundamental principles of industry. Assuming that the ordinary school subjects of reading, spelling, writing, arithmetic, etc., have been fairly well mastered, the applications of these fundamental studies to shop work, shop accounts, business subjects, etc., may be profitably emphasized. It is not the aim in this part of the work to teach trades, but by means of manual training, drawing and other practical studies, the elements of all trades are taught.

Under the law of 1908 a number of vocational high schools have been organized, including a school at Albany near the headquarters of the State Department of Education. The Albany school is considered typical, and will be treated in more detail later.

(2) The second division of industrial training recognized by the Board of Education is instruction in the trades. New York State contains a large number of groups of industrial workers engaged in printing, textile industries, shoe manufacture, ready-made clothing manufacture, manufacture of electrical apparatus, iron working, paper manufacture, etc. These groups need recruits especially prepared for their specialties. In addition to the general preparation given by the vocational high school, which is supposed to prepare the way for all trades and business activities, there are many special subjects which should be studied in order to make intelligent workers in, say, the printing business, shoe manufacture, or electrical machinery manufacture.

The State Department of Education has made a real beginning in the first division of its field mentioned above. State aid is given to schools which qualify under the law. In the 8th annual report of the Department, Mr. A. D. Dean, Chief of the Division of Vocational Schools, states as follows:

" *The Intermediate Industrial School.* The plan as now operating provides that five-twelfths of the school program shall be given over to the shop, laboratory and drawing instruction and that the remaining seven-twelfths be devoted to " book studies," which practically amounts to saying that the pupils shall for the remainder of the time take the regular elementary school studies corresponding to the seventh and eighth grades. These studies are related to the industrial studies as far as is possible. Both boys and girls have similar work in English and history. The arithmetic course for boys differs from that for girls. The geography is viewed as an outgrowth of the life-long problem of providing food, clothing, and shelter. The physiology is studied from the view-point of hygiene and sanitation rather than the structural only. The shop, laboratory, and drawing work differs with the sex considered.

Vocational Courses in the High School. The Education Department proposes a plan by which an average high school now teaching college preparatory, commercial, industrial, and home-making subjects can economically and effectively develop courses of instruction which shall have a well-blended liberal and vocational training. Instead of these schools offering commercial, industrial, and home-making subjects it is arranged so that they offer well-defined courses for pupils who seek different destinations. A certain amount of the work is common to all these courses and consists of the prescribed studies which are deemed essential to a sound and symmetrical education and which, under normal conditions, should be prescribed for all pupils in a secondary school. These prescribed studies are English for four years, English history with civics, algebra, plane geometry, biology, and physics. Another division consists of such elective subjects as may be necessary for pupils seeking different destinations.

The " industrial and agricultural purpose " courses have intensive courses in the agricultural and manual arts and drawing. The " home-making purpose " course is rounded out with strong courses in domestic science and art, household decoration, sanitation, and personal hygiene. It cannot be emphasized too often that a vocational course does not consist merely of vocational subjects thrown at random into a high school system. The vocational purpose must be satisfied by a definite course.

The law states clearly certain conditions which a vocational school must meet in order to be considered as entitled to special State aid. (1) It must be independently organized— not necessarily a separate building but most assuredly established with a distinct vocational purpose in mind; (2) it must have an enrolment of at least 25; (3) it must employ the full time of a teacher and (4) it must have a course of study meeting the approval of the Commissioner of Education. The first three conditions admit of no changes and are to be enforced in all places without variation from the word of the law. The fourth condition allows for considerable latitude and discretion. The course of study is not defined by the law; it may vary in different localities and connect with the different local industries, which vary in different parts of a great State. The course of study in agriculture and related subjects may emphasize dairying in St. Lawrence county, and fruit growing in Ontario county. An industrial course may concern itself with the shoe industry of Rochester or the knitting mills of Utica; it may omit mechanical drawing in

Gloversville and emphasize it in Schenectady. The vocational training may be of rather the general industrial nature in Albany or have its specific trade aspects in Lackawanna. The only points that need to be considered in the establishment of such a school course in a high school system are: (1) Is it established to meet the vocational purposes in education? (2) Does it meet the requirements of the law?

The New York Department has ruled that five-twelfths of the weekly program of a vocational school department must be given over to the vocational studies chosen for the elective group. This particular ratio was settled upon after considering two propositions: (1) The present requirements for an academic diploma call for 41 counts in certain studies, primarily liberal. These counts closely approximate seven-twelfths of the total number, 72, required for a diploma. (2) Vocational training of high-school grade demands a certain amount of liberal training. Preparation for a vocation should have academic recognition through a diploma if the work is of high school grade. The placing of the ratio five-twelfths vocational to seven-twelfths liberal will satisfy the time elements of both divisions of the course of study. Consequently the pupils in the vocational school course have the same liberalizing studies, or their equivalent, as do pupils in other courses. They take the same department examinations in English, history, algebra, geometry, and biology when they follow the same syllabus as other pupils. When the school offers, as it should, special and practical courses in mathematics and science beyond, or in place of, those just mentioned, the work is inspected and if the definite outlines submitted to the Department are satisfactory, if the teacher is trained for his work, and if it is seen that he can make direct and useful applications of the abstract to the concrete shop, laboratory, or field work of the home and the school, then the Department grants credits without examination. No examinations are given in the vocational subjects proper.

There are now 35 industrial and trade schools, employing 145 teachers. These schools have a day enrolment of 3370 pupils and an evening enrolment of 2933 pupils, or a total enrolment of 6303 pupils. There are 527 other pupils using the equipment, but not enrolled in these schools.

The Albany Vocational School is one of the most advanced of these institutions. It was organized soon after the law of 1908 went into effect. It started with one hundred pupils selected from a large number of applicants prepared in the lower schools. The equipment of the school does not differ materially from that of manual training high schools, but very much greater prominence is given to the manual part of the course. This equipment comprises a wood shop with the necessary benches, bench tools, saw bench, band saw, speed lathes, and accessories, all electrically driven. A home-making department uses cooking tables, gas stoves, and other necessities of the home, for instruction in domestic arts.

Book-work is not neglected, but it has a practical aspect. For example, in the study of algebra the formulas are stated in terms of the workshop and complicated equations are solved graphically. The formulas studied deal with such applications as electricity, mechanics, and engine practise. In mensuration, areas are studied by reducing plane figures to equivalent triangles, by counting squares when figures are drawn on squared paper, by weighing similarly shaped areas cut from cardboard, sheet lead, or iron. In scientific subjects like physics everyday applications are studied. Among these may be mentioned the radiation from water supply pipes, practical use of exhaust steam, steam boilers, and heating and ventilating.

Industrial work in this school is not confined to boys, but the needs of girls are carefully considered. The work for girls comprises housekeeping, sewing and design. The fundamental scientific principles underlying the household arts are taken up. Girls are taught to use their hands as well as their heads.

While the Albany school has been in operation but a short time, it has apparently demonstrated the soundness of the principles upon which it is founded.

C. TYPICAL ELECTRICAL OPERATING CORPORATION SCHOOLS

New York Telephone Company. This company gives five courses of instruction to its employees, maintaining continuously (1) a school for operators, and (2) a school for instrument inspectors and installers; and offering periodically, as occasion may demand, (3) a course for cable splicers and wiremen, (4) a course for salesmen and employees of the Commercial Department, and (5) a course for college men employed in various capacities in the Plant, Traffic, and Engineering Departments.

The first three courses are directed towards the instruction of the employees in the performance of the specific duties for which they are employed. The other courses are directed toward extending the information of the employees so as to give them a perspective view of the policies and many correlated activities of the company.

The instruction in the operators' school consists of a series of lectures, each followed by practise at a special school switchboard of standard construction. The course lasts for four weeks; the first week is devoted to simple calls from one direct line to another; the second is devoted to more complicated calls, such as emergency, party line, official, and telegram calls, and those involving an understanding of the meanings of switchboard markings; the third is devoted to calls from automatic pay stations, to busy or unanswered calls and to trouble reports; and the fourth week is devoted to a review.

The instruction in the school for inspectors and installers comprises lectures, work with standard apparatus that has been specially modified for the introduction of troubles, and work as helpers in the field. There are six grades of instruction differentiated from each other by the greater or less complexity of the involved apparatus or circuits. Not all of the employees in this line are required to take all grades.

The course for salesmen and employees of the Commercial Department consists of lectures and observations. It is directed so as to give information concerning the organization of the company, its territory, the correlation of its departments, central office operation and traffic troubles, accounting, ledger routine, adjustments, advertising, rates, contracts, renewals, office practise, orders, collections, canvassing, and salesmanship.

College men are usually employed for engineering positions, for construction work, or as central office managers. Instruction is given to them through informal talks and through observation. They are required to make written reports upon their observations. They are also questioned so as to determine their understanding concerning the work. The following schedule, indicating the nature of the course which is taken by those who enter the Engineering Department, has been obtained through the courtesy of Mr. H. C. Carpenter:

NEW YORK TELEPHONE COMPANY

INSTRUCTION COURSE

Operating— 3 weeks

a. Course in the Operators' School, 2 weeks; the afternoon being spent in listening in for about 1 week at the " A " board and for 1 week at the " B " board at the Spring office.

b. Listening in at various toll board positions, information desks, and " A " and " B " boards at other offices, 1 week.

Maintenance of Common Battery Central Offices— 2 weeks

To gain a general knowledge of the wire chief's work and of the functions of the various pieces of apparatus.

Instrument Installation and Inspection— 2 weeks

To include a special course for one week in the Instrument Installer's School in New York and a week on installation and inspection work, including private branch exchange installations.

Pole Line Construction— 3 weeks

Placing new and replacing existing poles, crossarms and other fixtures, highway and interior block.

Making transpositions, including phantom circuit transpositions.

Stringing wire and removing dead wire.

Placing and splicing aerial cables and terminals.

Joint construction with electric light and power lines.

Protection against high-tension lines.

Loop Construction— ½ week

Special attention is given to the methods of distributing from crossarms, iron brackets, and from joint lines with an electric light company; distribution through trees.

Subway and Subsidiary Work— 1 week

To include, if possible, both light and heavy subway construction in city and country, special attention being given to the arrangement of manholes, duct formation, and the kinds of material used. (If no heavy subway construction in congested streets is under way while the student is taking the course, a day or two of this time may be spent with the Empire City Subway Company.)

Placing and Splicing Cable— 3 weeks

Placing cables in subways and subsidiaries.

Removing cables from subways.

Placing interior block cables.

Placing house cables.

Placing submarine cables.

Straight splicing.

Potheads of both okonite and switchboard cable (when made on the job).

Test of splicing, including throw and tap work, special attention being given to the methods of testing working and dead cables.

Block splicing.

Wiring Work— 1 week

Half tap.

Block rewiring and reconcentration.

Cutting in potheads in central offices and in buildings.

Galvanometer Work— ½ week

To gain a general knowledge of the tests made, and also the method of locating faults.

Outside Trouble Hunting— ½ week

To gain a general knowledge of the kind of troubles met with, and the methods of locating and clearing them.

Plant Engineering and General Office Work— 5 weeks

This is to gain a general knowledge of the work of the plant engineer, of the methods of accounting, and of the organization of the Plant and other departments. It is suggested that these five weeks be spent about as follows:

1 week in learning the nature of the plant engineer's work, the preparation of spider maps, character maps, and getting familiar with joint use agreements and division instructions.

1½ weeks working with an assistant to one of the district engineers on such jobs as may be under consideration, if possible letting the student do some small job himself so that he may become familiar with the methods of planning relief and reaching new territory.

1 week on block work—spending about a third of the time in inspecting block work, which should include both short pole line construction and fence runs so as to become familiar with the general layout of interior block cable. The remainder of the time may be spent with the block engineer in making new blocks and relief of existing blocks, in estimating the cost of the work, and finally in the making out the necessary permits for the Wayleaves Department.

½ week in learning how to overcome inductive disturbances on telephone lines, in studying exposures and methods of cutting in transpositions on ordinary circuits and for phantoms.

1 week with the Accounting Department—learning how the material is ordered from the storerooms and from the manufacturing company, and the accounting of the material and labor under estimates; also learning how records of the Plant Department are kept, such as attachments to foreign poles, card records, statistics, and records of trunks.

Traffic Department— 2½ weeks

Work of the traffic engineer.

Rainy Weather.

During rainy weather, the student goes to one or more repair shops to become familiar with the work done in them and to see the making up of cable forms, cable head boxes, repairing apparatus; also to gain a knowledge of the stock rooms and the methods of issuing and crediting material recovered.

New York Edison Company. Under the auspices of the Association of Employees of the New York Edison Company, there is offered free to any employee of the company a theoretical and practical course in electricity extending over three years and including fifteen two-hour weekly exercises each year. The upper portion of one of the company's substation buildings contains a fine auditorium, a well equipped laboratory, and a carefully selected and growing reference library. Members of the test department give instruction during every evening and on one afternoon during fifteen weeks of the year, commencing about the middle of November. There has been prepared a separate printed and illustrated instruction sheet for each exercise, the nature of which can be inferred from the titles given in the following table furnished by Mr. H. G. Stott.

Course 1

1. Uses and Properties of Electric Currents.
2. Measuring and Controlling Electric Currents.
3. Connections and Types of Circuits.
4. Magnetic Fields and Magnets.
5. Conductors and Resistors.
6. Voltmeter Adjustments and Calibration.
7. Ammeters and Shunts.
8. Measurements of Power and Electric Energy.
9. Magnetic Properties of Iron.
10. Generators.
11. Motors.
12. Storage Batteries.
13. Characteristics and Testing of Insulation.
14. Lamps and Photometry.
15. Alternating Currents.

Course 2

1. The Magnetic Circuit.
2. Direct-Current Armatures.
3. Separately Excited Generators.
4. Shunt Generators.
5. Shunt Generators (concluded).
6. Compound Generators.
7. Shunt Motors.
8. Shunt Motors (concluded).
9. Prony Brake Tests on Shunt Motors.
10. Prony Brake Tests on Series Motors.
11. Motor-Generator Heating Test.
12. Armature Reactions.

13. Shop Tests on Motors.
14. Boosters.
15. Balances.

COURSE 3

1. Alternators.
2. Characteristics of Alternating-Current Circuits.
3. Phase Measurements and Vector Diagrams.
4. Principles of the Transformer.
5. Constant Potential Transformers.
6. Instrument Transformers.
7. Polyphase Circuits.
8. Induction Motor Principles.
9. Induction Motor Operating Characteristics.
10. Induction Regulators.
11. Polyphase Transformations.
12. Alternators in Parallel.
13. Synchronous Motors.
14. Converters.
15. Wave Forms.

Of some 4500 employees, the initial enrolments for 1910-1911 in these three courses were respectively 60, 180, and 60. Of those there were respectively 5, 9, and 5 who attended every exercise and prepared the corresponding reports. The average weekly attendance was initially 100 and dropped to 70 at the conclusion of the season. Decrease in attendance after the novelty had worn off also characterized a course of free lectures by electrical specialists, given previously in connection with the educational work of this company. To prevent falling off in attendance, one department of this company is at present compelling attendance on the time of the company.

D. DATA CONCERNING RAILROAD CORPORATION SCHOOLS.

New York Central Lines Apprentice School System. As the New York Central plan has been worked out in great detail and as it comprises most of the features found satisfactory in other systems it may be considered as typical of the best practise in its line. Six years ago the New York Central lines put into operation at the larger shops a school system for the benefit of shop apprentices, in various trades. The purposes of these schools are:

1. To improve the quality of mechanical skill available in shop work.

2. To make apprenticeship attractive to intelligent boys.
3. To make it possible for the right kind of boys to rise from the ranks to positions as foremen and master mechanics.

School work is done in regular shop time under pay, and in the morning when the boys are at their best. The work is done under drawing and shop instructors appointed from the local shops, these instructors being under the direction of the officers of the company in charge of the local shop operations. The whole work is under the supervision of a superintendent of apprentices who in turn reports directly to the general superintendent of motive power.

The boys who apply for apprenticeships in the shops of the company are of various grades of education, some having practically no schooling, while others are high school graduates. The instruction is therefore somewhat varied in character, but is mainly of two general types: drawing and numerical calculations, and shop work. The drawing instruction is given in the rooms or small buildings especially devoted to this work. These rooms are fitted up in a simple style with drafting tables, blackboards, cabinets for storing boards and supplies, models, etc. The courses, which are laid out for all shops by the superintendent of apprentices, are of a nature to appeal to apprentice boys.

The objects which he is expected to draw are the familiar things with which he works in the shops. Small locomotive parts, parts of shop tools, wrenches, nuts, etc., form the drawing exercises. Very simple subjects are assigned at the start, leading up to rather complicated ones toward the close of the four-year course. The work includes tracing so that the student finally leaves his work as if for use in actual construction. In many cases the apprentices actually prepare drawings for foremen, supplementing the work of the regular draftsmen.

The drafting room periods afford an opportunity also for testing the ability of the students to think for themselves. A large number of problems are assigned for home work, these problems being all of a simple and practical character. Solutions to the problems are handed in from time to time, and by means of blackboard exercises the real ability of the pupils in solving problems is tested.

Most of the time of the apprentices is put in at actual shop work under the direction of the shop instructor. This instructor is a practical mechanic who is familiar with all branches of shop work. His duty is to see that the pupil is taught thoroughly all branches of the selected trade. The instructor shifts the pupil from one line of work to another, giving him sufficient time to obtain a thorough mastery of each part. For example, if a boy elects to learn the trade of machinist, which requires four years, his time will be divided up roughly as follows: helping in shop, 0-3 months; bench work, 6-12 months; light tool work, 3-6 months; heavy tool work, 3-12 months; in air brake department, tool room or brass tool, 3-6 months; in erecting shop, 16-24 months. The instructor shows the apprentice how to perform each operation assigned to him and sees that the work is done thoroughly. He thus relieves the foreman of the necessity of instructing apprentices, and as he is a specialist in this line, the work is much better done than formerly. It is understood that while the shop course is going on the apprentice is also working in the drafting room, as explained earlier.

The instruction of apprentices is very similar to the best type of school work of any kind, as will be evident from the description given. The primary function of the course, as should be that of the courses of all schools, is to teach the apprentice to apply skill and knowledge efficiently in his vocation. Mental development is, of course a vital necessity; but this mental development comes as a result of the continual exercise of the constructive and reasoning faculties. Practically no text-books are used in the course. Lectures, examinations, and recitations, as used in school, have little place.

The results of the system have been highly gratifying to the company, and although the experiment has been in operation but a few years, the benefits have been evident in an increase in shop output, a reduction in the amount of spoiled work, and increased desire on the part of the boys to prepare themselves for trades (including even some trades which a few years ago did not attract boys at all) and a general improvement of the spirit in the shops. The shop instructors meet from time to time to discuss their problems, and as they work through a central organization, their efforts are marked by unity of plan and purpose.

The Pennsylvania Railroad Apprentice School. An instance of a continuation school, doing a large amount of good in its community, is the one maintained by the Pennsylvania Railroad Company in Altoona, Pa., which was inaugurated under the direction of General Superintendent George W. Creighton and his staff, of the company, and the Chairman of the Committee making this report, representing The Pennsylvania State College. (The latter institution holds an advisory position in the organization of the school and receives full weekly reports from the head instructor.) In this school something over 250 apprentices spend one-half a day a week in a specially prepared building, which, with its equipments, was comparatively inexpensive. Three instructors are required. The curriculum consists largely of practical drawing, English, natural science, and mathematics. The weekly time spent by each apprentice in the school is divided into two periods scheduled for different days.

The English is taught in a manner best adapted, in the opinion of the instructors, to improve the pupils' ability readily to understand shop or similar orders and to make verbal or written reports in clear language. The natural science studies take up elementary functions having to do with features of combustion in the firing of boilers, the simple principles underlying machine mechanisms, the qualities and characteristics of materials used in machine construction, and similar practical information which should add to the intelligent performance of the workman's duties. The mathematics taught is a study of the fundamental principles of arithmetic, algebra, geometry, etc., as they apply to the ordinary simple mental or written computations which are demanded of the skilled mechanic in the course of his labor. The drawing is of a practical sort, such as to give the mechanic keener appreciation of working drawings required in construction, and to enable the management to select men of suitable caliber for their drafting rooms as needed. The instruction in English and natural science, of the nature indicated, seemed at the outset of the work to be desirable; and the experience thus far obtained indicates its material value in improving the quickness and intelligence of the young men pursuing the work.

While in the shops the apprentices are under the supervision of the foremen, who in turn are in close touch with the school instructors. The use of the foremen, instead of the special shop instructors employed in some other corporation schools, has much to commend it. The foreman of sufficient intelligence to carry on the industrial operations of his department should have ability, if he is the proper man for his place, to direct the apprentices to proper advantage. Further, adding this special supervision and instructional function to the responsibilities of the foreman seems rather to add to his effectiveness and interest in his work than otherwise. And still further, by using the foreman the schools are tied up more closely and correlated to better advantage with the industrial organization as a whole than is otherwise possible. The apprentice courses are four years in length. During this time the young men are given a well rounded and broad shop training. They attend the school classes regularly during the first three years.

The school instructors and foremen are required to submit exhaustive weekly, monthly, semi-annual, and annual reports to the organization management. These reports have apparently proved of value in enabling the management to weed out apprentices who are unworthy and to place into line of promotion young men who are of noteworthy merit. This latter function is in itself of sufficient worth to warrant the expense of the school.

The success of the school, though in operation but slightly over two years, has been marked; and the pupils themselves have been enthusiastic over this work. Those completing the course have, in many cases, petitioned to be allowed to continue further. That the management believes the expense of the school to be warranted by the results, is indicated by the fact that it has recently extended the system to other divisions of the railroad.

Tabulation of Data Concerning Instruction by Certain Steam Railroads. A number of important railroads have well-organized systems of instruction of apprentices. Mr. J. W. L. Hale, Head Instructor in the Pennsylvania Railroad Apprentice School, just referred to, recently made a careful study of the instructional work of a number of systems. His findings are summarized in the following tables:

1. EXTENT OF INDUSTRIAL EDUCATIONAL WORK.

Name of road	Where applied	How applied	No. of points where instruction is provided	Headquarters for the Educational Department
Atchison, Topeka & Santa Fe Ry.	To apprentices in the Mechanical Dep't. over the entire system.	Through an organized apprenticeship system extending over entire railway and providing both shop and school instruction.	29 (2-31-11)	Topeka, Kansas.
Canadian Pacific Railway.	To apprentices in the Mechanical Dep't. at the Montreal, Toronto and Winnipeg shops.	Through apprenticeship operated independently at the several shops and providing both school and shop instruction.	3	No central organization for the apprentice work of the system. Each shop operated independently as regards apprentice training.
Delaware & Hudson Company.	To apprentices in the Mechanical Dep't. over entire system.	Through an organized apprenticeship system providing both shop and school instruction.	3	Green Island (Albany, N. Y.).
Erie Railroad.	To apprentices in the Mechanical Dep't.	Through an organized apprenticeship system providing both shop and school instruction.	5	Meadville, Penn.
Grand Trunk Ry.	To apprentices in the Mechanical Dep't.	Through an organized apprentice system providing compulsory evening school instruction and a system of examination for promotion in the shops.	7	Montreal, Quebec.
N. Y. Central Lines.	Same as above.	Through an organized apprentice system providing both shop and school instruction.	12	Grand Central Terminal, New York City.
Union Pacific R. R. Company.	Open to all employees of the railroad. Evening apprentice school at Omaha, Neb.	Through correspondence courses conducted by an Educational Bureau of Information. Apprentice evening school at Omaha.	Reaches all employees who voluntarily apply for instruction.	Omaha, Nebraska.

2. ORGANIZATION EMPLOYED.

Name of Road	Higher Officer in Charge	Officer in Direct Charge	Assistant Officer in Direct Charge	Officer in Charge at Local Shops	Instructors at the Local Shops
Atchinson, Topeka & Santa Fe.	General Supt. Motive Power.	Supervisor of Apprentices.	School Instructor at Topeka, Kansas.	Master Mechanic or Superintendent of Shops.	School and Shop.
Canadian Pacific Ry.	Superintendent Motive Power.	Senior School Instructor.	—	Local Shop Head.	School and Shop.
Delaware & Hudson Company.	Superintendent Motive Power at Albany.	General Efficiency Engineer.	Traveling School Instructor.	Local Shop Head.	School and Shop.
Erie R. R. Company.	General Mechanical Superintendent.	Shop Specialist or Supervisor.	Assistant Supervisor.	Local Shop Head.	School and Shop.
Grand Trunk Railway System.	Superintendent Motive Power.	Chief Draughtsman at Montreal.	—	Local Shop Head	School
New York Central Lines.	General Superintendent Motive Power.	Superintendent of Apprentices.	Asst. Supt. of Apprentices.	Master Mechanic or Local Shop Head.	School and Shop.
Union Pacific R. R. Company.	Vice-President.	Chief of Educational Bureau.	Asst. Chief of Educational Bureau.	—	Apprentice evening school instructor at Omaha only.

4. NUMBER OF INSTRUCTORS AND PUPILS

Name of road	No. of points reached	Total No. of apprs. instructed on system	Total No. of instructors
A. T. & Santa Fe Railway.........	29	645	40
Canadian Pacific Ry..............	3	353 of whom 223 are at Montreal.	School 5 Shop 6
D. & H. Co.....................	3	95	School 2 Shop
Erie R. R. Co....................	5	253	School 3 Shop 3 (?)
Grand Trunk Ry. System.........	7	329	——
N. Y. Central Lines..............	12	690	School 12 Shop 12
Union Pacific.....................	2700 from all branches of service. Approx. 175 apprentices included on entire system not all taking course		——

DISCUSSION ON "INDUSTRIAL EDUCATION" (COMMITTEE REPORT), BOSTON, MASS., JUNE 27, 1912.

Henry G. Stott: The work that we are doing in New York in connection with the companies which I represent, is a very modest one, but one which was forced upon us by very peculiar circumstances. We have men who are trained for switchboard operators in railroad work, who handle a large amount of power, and these men are brought in with practically only a common school education and are taught the ordinary methods of operation of switchboard apparatus, taking care of the apparatus, etc. We found after training up men in this way that they became highly expert, although they had apparently no theoretical knowledge of what they were doing. However, a day of reckoning came to us when something went wrong with the operation or some trifling connection was broken, and these men failed lamentably. After a few experiences of that kind we discovered that no matter how well a man was able to carry on his routine duties, assuming everything was in first-class order, the least disturbance of that routine upset his whole idea. He was only an automaton. He could not think for himself. We thought we were using, perhaps, too poor a class of men. We tried a number of men trained at technical schools but it became very manifest that men who had received technical school education, while they met all the requirements of the case, could not be held there and we could not expect to hold them in work which soon becomes monotonous. We finally came to the conclusion that it would be necessary to establish a class to find out whether a man was an automaton or whether he had been really thinking and reading.

The work started in this way, but we went on with it as we found there was some very good material in the men and it gave us an insight into men's characters which we could not get in any other way. We started in the school by putting in the same kind of apparatus which men had to handle in their every-day work, with all the wiring and apparatus exposed. One of my assistants gave the instruction and began at the beginning of the electrical work, and found that the men took great interest in it.

After trying this out for about a year we found that we were getting inside information in regard to the men's characters, and their way of thinking, which was extremely valuable to us in promoting them. Promotions are now made from the bottom up. We then established the rule that unless a man took this course and passed the examination he could not be promoted. Nothing would be done to interfere with his present position, we announced, but he could not hope for promotion unless he took this course and passed the final examination. This immediately segregated these men into two classes; those who had no hope of promotion, who were indifferent, and those who were ambitious and wanted to get along. It has thus been the means of telling us which men were best fitted for promotion.

The course is a simple one, a rudimentary course in mechanics and physics, then going on to show how current is generated, etc. We have a good laboratory there, showing how measurements are made, and calculations of various simple problems are made. In other words, a man is being taught to think and reason for himself, not simply to obey rules because he is told to do so. The whole endeavor in the department which I control is to avoid arbitrary rules, to encourage a man to act on his own judgment as far as possible. In this way we have achieved results by this simple course which I don't think we could have reached in any other way. By encouraging these men to take courses more advanced in other institutions, we got a few into college, and I think they will make their mark in life.

It has been the purpose of the company to find out the point of view of the man, whether he was simply there to get his pay at the end of the week, or whether he was ambitious enough to study and devote his time to progress. That has gone through a process of evolution, as I have said, so that it is a fairly good course of instruction now, and any man who leaves us is capable of performing good service in any company.

J. P. Jackson: May I ask Mr. Stott where his school gets the men—what the class of men is that he gets?

Henry G. Stott: The majority of men that we get have simply been through part of the grammar school; a few through high school, but as a rule with only grammar school education. We started in at one time to get men educated in technical schools, but naturally the monotony of the work, eight hours' work, seven days in a week, with of course a day off now and then, was too great to expect a man to remain there who had spent time in getting a scientific education. They would stay a year or less and then leave us. So that practically all the men whom we put into these positions for operators are those who have had only grammar school educations.

A. L. Williston: A great deal has been written or spoken from the public platform regarding the pressing necessity for industrial education, until it seems as though every thoughtful person must understand. And yet, as I work in this field, I find that we have not yet begun to make an impression on most persons of the seriousness of the need for this kind of work. As engineers, we are all interested in efficiency; and we are interested in the conservation of natural resources; and we are interested in all things that tend toward the greater economy in the utilization of all forces. As we commence to study actual conditions in almost all our large industries, we find waste of material, we find loss due to inefficiency in the use of power and machinery; but, gentlemen, as we study the conditions more closely we find that these losses are almost insignificant compared with the greater human losses in almost all organizations and in all the industries.

These human losses are of two kinds; first, those losses that arise from the mistakes, the errors, the blunders, the waste of time from not knowing what to do, or from not knowing how to do the work in hand in the right way. Such losses, as we all know, are great enough; but a second type of human losses is, I believe, still greater. This includes the waste of human energy that comes from having so often the wrong man in any particular job, having no natural aptitude or taste for it; and the waste that comes from having the great majority of men without any real vision of future possibilities that lie ahead of them, and, therefore, without ambition to do their work with the same spirit of energy and excellence as, when youths, they put into their play. It is the lack of ability to see and understand what is ahead, the lack of vision of the possibilities beyond the present that, more than all else, makes work uninteresting and makes workmen feel that it is not worth their while to do their best or cooperate cheerfully and loyally either with individual employers or with the corporations that are furnishing them the opportunities for work.

If we could only estimate the value to society of having all the young people of the rising generation selected, or sorted in some way, so that the right persons would get into jobs for which they are fitted and for which they have some particular ability and taste; and also could estimate the value of having all of these persons given the spirit that would make them feel that their work was worth putting their hearts into, and could add to this the value of special training that would enable them to do their work with skill instead of with indifference, I think we all would appreciate that, in comparison, all the other efforts that we have been making in the past toward increased efficiency would seem small.

In discussing types of vocational schools and what vocational schools may accomplish, emphasis is too frequently placed upon the curriculum and upon details of methods of instruction. To my mind these are important, but there are at least two other things that are more fundamental and important. First, it is absolutely essential at the beginning to get the right boys to work on. If you are going to train young persons for a given industry, for example, to train them to be machinists or to be switchboard operators, or what not, it is of the utmost importance to select persons not only adapted to this kind of work, but also to select persons who, because of their natural environment, their previous life experience, their home traditions and surroundings, will look forward to the kind of life and future to which the particular vocation will probably lead with enthusiasm, eagerness and interest. The first and all-important problem, therefore, for the vocational school to solve is to get the right fellow into the school at the beginning. This is not easy, in fact it is extremely difficult; and there are very few precedents or guides to go by. It is possible, however, as there are men who have had experience in selecting from the great mass of untrained people who are coming out of the elementary schools every year, those who will be, with training and experience, well adapted to different lines of work. Every capable factory superintendent employing a large number of young persons and every experienced employment director has some skill in this kind of selection. Men with such experience are needed in vocational schools to advise boys and girls regarding the future possibilities that are open to them, and to select from the applicants for admission those who by natural ability, home environment, etc., are well fitted to succeed in the several lines of work for which the school offers courses of instruction.

The thing of next importance is that during the period when the boys and girls are in vocational schools, they should, in addition to the manual skill that is needed and the elementary technical knowledge that is necessary to enable them effectually to use such skill in their chosen vocation, receive the kind of industrial discipline that will enable them to fit into their life work as efficiently as possible, and also that they should have their ambition stimulated by accurate and intelligent appreciation of the opportunities that will be likely to be open to them later. It is entirely possible to develop in school an atmosphere which will give just as good industrial discipline as any shop. It is possible to select tasks and occupations in the school which will cultivate a right attitude toward work, a spirit of co-operation with one's employer and those other qualities of character which are essential for the best success in after life. And these things are more important, in my judgment, than are the questions of how to teach practical mathematics or elementary applied science, or of how many hours of shop practise of one kind or another to include in the curriculum. Yet, when we get together to discuss matters of industrial education, I find, too often, we spend our time on the latter questions of details regarding the curriculum and too seldom on the correct methods of getting the right boy to work with, or the best ways of developing in him the particular qualities of character and manhood that his chosen vocation requires.

To some persons what I have just said may sound as if I were repeating what has always been the aim of all good schools. This, however, is far from the fact. Until very recently, and with very few exceptions, no schools have made a serious attempt to analyze the different vocations and to find out what particular qualities of character are essential to each, and no schools have seriously endeavored to develop the particular qualities that a chosen calling requires. It is this specialized kind of character-building which is the important function of the vocational school. There is in this country and abroad experience enough to prove beyond a possible doubt that this is not a visionary idea but is entirely practical if we set ourselves seriously to the task.

It is not necessary for me to take time to tell you gentlemen of the American Institute of Electrical Engineers or of the teaching profession—all of you earnest advocates of engineering education and of all the higher types of industrial schools—that mechanical skill is a good thing, or that technical training is a good thing, or that the spirit of open-mindedness, which makes one always eager to search for truth and a better way, is a good thing. To you I have only to suggest that in the field of trade teaching, mechanical skill and elementary technical training adapted to the needs of the boys who may not have even a complete grammar school education, and the spirit of open-mindedness to new methods and new ideas, are as useful, in relative measure, as we ourselves have found them in our own particular field in the higher departments of education.

Albert L. Rohrer: Tolstoi was very fond of describing labor as being under four heads, the first being that of muscular labor such as the ordinary laborer does, building roads and carrying the hod; the second class is that of the hand and wrist, done principally in factories; the third is that of the mind as shown by the work of the engineer; and the fourth is the labor of co-operation, that is, of all classes of labor working together, team work, as we are pleased to call it now. Until now both societies have been concerned from time to time in discussing the third class, the work of the engineer, the training of his mind, and the result of his work. Both societies, I say, because one society has discussed the education of the engineer, the man who is to do the thinking, while the other society has discussed his work; but it seems to me that the second class of labor, that of the hand and wrist, is of equal importance, and I am very glad indeed to see it given such an important part in the program. It well deserves and merits the joint session which is being held to consider it.

Now the problem of training the hand and wrist has been attacked from a great many view-points. A great deal of good work is being done. The report of the committee just made indicates to you what has been accomplished, and I believe and agree with Professor Slichter that any man who takes the time to inquire into the topic at all will become enthusiastic. And I think it is the duty of every engineer to get interested in this problem. He can serve his locality and his country to very great advantage by getting interested in the situation and assisting with his good judgment.

Professor Jackson has asked me to describe briefly the work at Bridgeport which was referred to in the report of the committee. I spent a very interesting day there some time ago, and to any of you who are interested I think a few hours, even, spent in inspecting that school will serve to fill you with enthusiasm.

The peculiarity about the Bridgeport school and the school at New Britain is that the two schools were started and are conducted by the state of Connecticut. The state alone is doing it, and the schools are doing some real constructive work. For instance, the school at Bridgeport, which I inspected, is located in a factory building. That gave me a very good impression at first sight. There is a certain atmosphere that prevails there which you could not possibly get in a school building. Four different branches have been taken up: that of metal working, or machinist; of carpentry and pattern making; of printing, and that of sewing. They have been particularly fortunate, I think, in selecting their teachers. They are all journeymen. They have attacked the problem, you see, from the standpoint of the practical man, and not from the schoolmaster's idea, and I think in some cases where the problem has been attempted by schoolmasters alone that it has not worked out so satisfactorily. These men at Bridgeport are all enthusiastic. They also have two ladies who are in charge of the sewing division and they are really accomplishing things too.

One feature impressed me very favorably in talking with the boys, and inquiring into what they had been doing.

The boy does not usually know what he wants to do. Mr. Williston has referred to that. They are given an opportunity there to try themselves out, which is a very important thing. Several of the boys had tried two or three different trades. One boy thought he wanted to learn the printing trade. He did not work out well at that; he then thought perhaps he might want to be a carpenter. He entered that division for a time, but did not work out very satisfactorily there, and finally he landed in the machine shop, where he is doing very good work indeed.

The work is all practical. They don't do any show pieces which are put in a case or laid on a table. Everything that the boy does is put to practical use. The city of Bridgeport offers some very good opportunities for that work. The business of Bridgeport is very largely the metal trades, and it comprises a large number of small factories. Everything that they do in the way of carpentry and printing and sewing can be carried into any city in this country. The carpentry division took a contract a few months ago for building a $5,500 house. These boys, fourteen years or over, made their designs and have done all of the work. It seems to me a great inspiration for the boy because he sees that he is accomplishing things, and that is far better than making up forms and things of that sort.

I don't know that we can say that this Connecticut plant is the only solution of the problem, but it seems to me that they are working along the right lines and I was greatly impressed with the character of the work that they are doing. They are doing a great many interesting things. It is practical, every bit of it.

Another feature that I should have mentioned earlier—any boy fourteen years or older can attend that school. I saw one man there of some twenty-five or twenty-six years. And a great many boys go from the sixth grade into the school and are doing very good work. It is possible that there should be a little closer affiliation between the school and the municipality in which it is located, but I like the spirit they show. They don't ask the boy if he comes from Bridgeport, or where he comes from. A great many boys come there from the farms outside, and they belong there as well as the boy from the city. It is certainly interesting, the way the plant has worked out, and I am very glad to call it to your attention this morning. If any of you can find time to stop off there I am sure you will be very much interested.

J. P. Jackson: May I ask Mr. Rohrer whether, in the large number of young men that he employs, he has noticed any distinct differences in the kind of men they are on account of the different kinds of education that they have?

Albert L. Rohrer: I don't know that I can answer that question. A great deal depends on the characteristics of the boy, how industrious he is and how anxious he is to get on. We of course prefer boys—I am speaking now of the apprenticeship work—we prefer boys who have been through the eighth grade. But we have found boys who had dropped out before they were fairly started in the seventh grade and they got along just as well. It all depends on the characteristics.

W. S. Franklin: I would like to ask whether the school is run the year round, or whether they have a vacation in the summer?

Albert L. Rohrer: Fifty-two weeks in the year. And may I say a word more? Mixed up with this, they are doing several other things. They maintain a night school carrying along the same lines so that boys who are working in the city or elsewhere can come into the night school. They also have the continuation idea. A number of the small manufacturers in the city who have apprenticeship boys, but not in sufficient number to maintain a school for them, send their boys a half day each week and they receive instruction in shop work and mechanical work there. You can see that they have a combination there where nothing stands in the way of the boy or man who really wants to improve his condition.

W. S. Franklin: I would like to know whether the Bridgeport school attempts to reproduce the shop equipment in detail of the various industries for which they attempt to train the young man; or do they give the more elementary and fundamental phases of all industrial work? I ask that for a very practical reason. A number of us have been discussing in Bethlehem the question of starting a school of this kind, and the problem we are faced with at once is whether it is justifiable to reproduce at a large expense the machinery equipment in the existing shops, or whether we ought not to try to give the boy a beginning in his apprenticeship work so that he can afterward get the more detailed training in actual shops. I want to know simply, does the Bridgeport school have a complete shop equipment in the metal working industries?

Albert L. Rohrer: Very complete, including an assortment of lathes, milling machines, and one or two planers. Of course a boy fourteen years old has got to begin with fundamentals. But it is worked out in a very practical way. If they take, for instance, a repair job, a boy is sent to the place where the piece of machinery is located and he makes a pencil sketch. He comes back and makes a drawing of the part. Then a pattern is made and when the casting comes in the boy machines it and he is sent out to put the piece in position.

Henry H. Norris: In a recent letter, Mr. Glenn, the superintendent of the Bridgeport Trade School, states that the " day school runs nine hours a day, five days a week, four hours Saturday, fifty-two weeks a year, and that the length of course is 4800 hours, approximately two years, for boys." He also states that the manufacturers' association has allowed two years on commercial apprenticeship for graduate machinists, exactly the time spent in school, so that the boys enter the trade of machinist with full credit for the time spent in this school applied to their period of apprenticeship. I also want to call attention to the " Artisan," a monthly publication of this school, entirely the work of the boys of the school. It gives a delightful picture of the school from the standpoint of the student.

J. W. L. Hale: I think it is evident to you that within the last decade the subject of corporation industrial education has become significant. It is a matter generally of the conservation of mental as well as physical resources. As has been well said this morning, when the country's resources become reduced it is necessary to turn more strongly toward development on the mental side. You can cite the example of Germany in this connection. Germany's resources, compared with those of the United States, are poor, but particularly in the mechanical line Germany has endeavored to, and is, conserving mental resources. In the United States, within the last few years, considerable attention has been directed toward the subject of physical conservation, and now we are discussing the question of mental conservation. One agency for mental conservation is the corporation school. The railroad school is one which I want to discuss for a few moments.

The functions of this class of school are given in the Report as follows:

" 1. To improve the quality of mechanical skill available in shop work.

" 2. To make apprenticeship attractive to intelligent boys.

" 3. To make it possible for the right kind of boys to rise from the ranks to positions as foremen and master mechanics."

As far as the speaker's experience goes it seem that the third function is perhaps the most important. In order to make the third possible, the second must be carried out. That is, apprenticeship must be made attractive to intelligent boys. In the case of the Pennyslvania Railroad, which has recently taken up the question of industrial training in shops, in the present stage of the work, it is impossible to hope to recruit the mechanical force in the shops entirely from apprentices. In Altoona alone there are approximately at the present time 12,000 employees of the railroad. The apprentices number approximately three hundred. Therefore, my former statement, I think, is evident. However, it is highly desirable to develop the three hundred for positions of responsibility in connection with the shop management.

The growth of the railroad school in the last five years has been remarkable. There are at least eight representative roads through the Eastern and Middle States which are giving apprentices well organized courses of instruction—I don't like to say theoretical—but in underlying principles and in shop work as well, and they are getting results. The tables which are shown in the Report, given by permission of the Pennsylvania Railroad officials, are made up from data obtained in the spring of last year. However, they represent conditions at the present time. If we refer to these for a moment it might be well to note that the development thus far along the line of railroad schools has been confined to apprentices in mechanical departments, except in the case of the Union Pacific Railroad which is doing a general educational work by correspondence. They have an evening school at Omaha for apprentices, of the Omaha shops only. They are doing a good work generally, but since the instruction is conducted by correspondence it has some disadvantages which are inherent in that method.

So far as the organization is concerned, the shools giving instruction to apprentices in the mechanical department are managed by the motive power officials. Instruction is given in both shop and school and includes elementary subjects from arithmetic to mechanics, and is presented in a severely practical way. The work of these schools is distinctly different from that of a good many other types of school from the fact that we have to change over the courses of the common school for specific trade purposes. This work opens up a new field in changing over from the general into more practical and definite subjects. The preparation of the boys that we get varies all the way from the sixth or seventh grade grammar to high school graduates.

As has been well said, what we have to do, is to give the boys the proper degree of ambition, enthusiasm and interest. There is only one more point for which I will take your time, and that is to repeat the statement I made first, that we must conserve mental as well as physical energy and give attention to development and increase of efficiency on the educational as well as on the mechanical side. It is necessary to develop the human unit as well as the mechanical unit.

W. S. Franklin: I happen to be quite familiar with a recent educational movement in the Pennsylvania Railroad in the telegraph department, which is superintended by

Mr. Johnson, and the work that he is doing illustrates a matter which has been in my mind for a long time and which I had in mind when I asked the question of Mr. Rohrer as to the duplication of existing industrial equipment for educational purposes for schools.

It seems to me, if I may preface what I want to say by a general statement, that one of the greatest problems we have in education at the present time is to make use of industrial and commercial establishments as schools to the extent that they *are* schools, and I think that they are schools to an extent which we scarcely realize. We have been going on for many years, detaching school work from practical work. And I think that one of the most serious faults of our present educational system is its detached character. We place a boy or girl in a seat, at a desk, with a book to study, requiring power of application they have not got and ideas that they have not got to understand. This seems to me to be the most unfortunate thing that can possibly be imagined.

Now, what I want to say is this: if boys of fourteen years and older are able to earn money in industrial establishments by going in there against the law, or on the basis of perjury of their parents, why is it not possible to place them there under the supervision of the public school officer to see that they get a proper variety of work and to see that they work not to exceed a certain maximum number of hours? Why isn't it possible to make use of the industrial value of that youngster at the same time that we are training him?

Now what Mr. Johnson is doing is this: Mr. Johnson's department in the Pennyslvania Railroad is the telegraph system, and his equipment, of course, is spread over the whole United States, pretty nearly; it is a distributed equipment which cannot be made use of for school purposes except it be organized as a part of a correspondence system, and Mr. Johnson is now establishing a correspondence school for all of the employees of this department.

As I said a while ago a number of us in Bethlehem have been discussing this question and the one thing that stares us in the face is this—what is the use of the town of Bethlehem buying a new lathe when there are about a million lathes in that town already? And what is the use of the town of Bethlehem doing a great many other things in useless duplication of existing devices which are already crying out for somebody to use them? We must study to some extent how to make use of existing commercial and industrial establishments as schools to the extent that they are schools.

And just one other thing I want to say: In order to realize my idea, let us devise, let us plan detached schools for babies, so that by the time our youngsters are fourteen years old they can do something that is commercially worth while in an actual establishment, instead of in detached establishments.

I am very glad to know, from what Mr. Rohrer says, that a nine-hour day with six days a week, or nine hours for five days and five hours on Saturday, is the rule in the Bridgeport school; for that means an approach to real discipline which is good to see.

A. L. Williston: I am somewhat familiar with the plan of the Fitchburg School. It is an adaptation to high-school conditions of the plan which Dean Snyder has worked out for university conditions in the city of Cincinnati. The boys enter the Fitchburg high school on very much the same terms as any other boys enter other high schools. They spend the first year in the high school giving their whole time to the school work inside the school building. During the second, third and fourth years, however, an arrangement is made with local manufacturers in Fitchburg by means of which the boys spend alternate weeks, one week in school and the next week in some shop in the city.

There is an effort made to distribute the boys around in different shops during the different years of their four years' course, so that each boy will get some experience in wood-working, some experience in foundry-work, and a larger amount of experience in machine shop practise. For some boys the plan is working admirably, especially for those who are fortunate in getting into shops where the conditions are such that they have a chance to work on a variety of tools and to get intelligent answers to questions regarding how this work should be done or how that machine should be operated.

Without doubt, there is in all the shops the endeavor to treat the boys as well as possible; and the school authorities endeavor to carefully supervise them in the commercial shops, so that all is being done in that direction that can be done. But nevertheless, I think this statement is entirely fair: Many of the persons who provide places in their works for these " part-time " boys find it extremely difficult so to organize their shops as to make it possible for each boy to get the variety of work and the change of occupation that he ought to have for his most rapid advancement. The conditions in some of the shops make it necessary for a boy to do things which he already knows how to do, and to continue to do this week after week, wasting a good deal of his time. In other shops the atmosphere is not stimulating either to the boy's intelligence or his ambition, and he does not learn from the workmen around him the spirit of co-operation.

On the whole, however, I think the plan is working well, and I believe that the boys who are taking the part-time course are getting a far better industrial training than they could get with the facilities in Fitchburg in any other way; but I don't think that it is by any means demonstrated that this is for all places the best way. The State Board of Education in Massachusetts recognizes the Fitchburg plan as one of the ways to give industrial education, but it has also encouraged in other cities, in Worcester, New Bedford and elsewhere, the establishment of schools of very much the type of the Bridgeport school which Mr. Rohrer described, in which the boys are kept all of the time in an atmosphere that is, I believe, just as honestly industrial as is the atmosphere that the apprentice boy finds in the average commercial shop. This enables the school to keep complete control over the situation at all times, and the boy to be transferred from machine to machine, or from department to department, as is necessary for his best advancement.

The course of school instruction in the part-time school at Fitchburg is modified somewhat from the usual high school course in order to make it better fit the needs of these boys who are spending one-half of their time in commercial shops. This modification or adaptation of the school instruction to make it dovetail in with the shop practise and fit the special needs of these boys, is growing, but as yet it has not been developed as far as I believe the authorities in charge of that school feel is desirable. If further information is desired, I shall be glad to answer any questions which you gentlemen may desire to ask.

W. I. Slichter: The states of Massachusetts, Maine and Wisconsin provide that this arrangement may be carried out and it is carried out in a number of instances, particularly in Massachusetts. In the report of your committee you will find a definition of the " part-time school " and this statement in the body of the recommendations:

" In the opinion of this committee, the feature of the Massachusetts and Wisconsin laws which causes them to excel those of all other states, is the provision that in order for a vocational school to receive state aid it must receive the state's approval of many of its important features, such as courses, teachers, buildings, methods, time and accounts. This clause is used as an inducement to encourage the local boards to consult with the proper representative of the state board from the beginning of the organization of the school, rather than await the exact period when money is requested of the State. The State board includes an assistant superintendent who has made a special study of the subject of vocational training, and, as members of the board, are private citizens representing the points of view of employers and employees."

William McClellan: It was my privilege for several years to be in manual training school work as a teacher, and later to be connected with engineering education in one of our larger institutions. With all due respect to those who favor industrial education, it ought to be recognized that, so far, it has been framed and worked out rather from the standpoint of the corporation than from the standpoint of the individual.

Proof of this has been given this morning. For example, Mr. Stott said that he was forced into it, and yet Mr. Stott has proved that his thought and aim in every respect are philanthropic. The apprentice system has failed and corporations have been driven to take up some other means for getting their industrial workers.

Again, when Mr. Williston spoke this morning of ambition, and the cultivation of it, it occurred to me that the necessary condition to cultivate it and to have it grow and accumulate is that in which there shall be not only an inlet but also an outlet.

The man whom you expect to be an ambitious man should never find himself or be set in a blind alley. I am impressed in this discussion today with the distinction which is apparently made between the so-called vocational school and the so-called professional school. At the beginning we seem to be dividing men arbitrarily between those who must go into vocations and those who must go into professions. This leads me to think that correlation is really what we must strive for.

Those of you who remember Plato's " Republic " recall that a scheme was laid out by him in which men dropped out along the road. As their mental abilities were discovered by the state, they were arbitrarily side-tracked here and there, and there was a gradation of activities until, at the top, was government in its noblest sense.

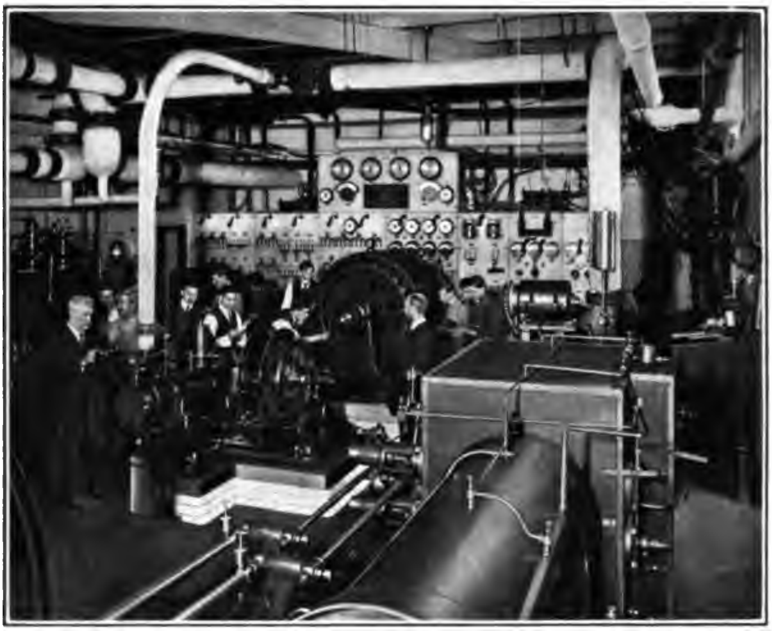
I have never framed a definition of the word " professional " as applied to professional schools, but it has seemed to me that the difference between a profession and a vocation is that as you deal more with the human element you get into what we designate " professional work." That is the reason today, I think, that the occupations of the clergyman, the lawyer, and the physician are regarded as professions. We hear so many ask why engineering does not stand with the professions, and I believe that the answer is that we have not yet begun to deal sufficiently with the human element.

I find, however, in our professional schools, so-called, that we are turning out four or five classes of men. We turn out the mere operative, the man who for all his life must stand at the drawing board, machine, or instrument and this is as far as he can get. Then we have the engineer business man. He is not an engineer in the true sense. Then we have the genuine engineer who really designs and constructs on original lines. And, finally, we have, from the same course of study, a type of man—for which I am really indebted to Professor Bedell for a name—the " industrial physicist " who does not actively get into engineering but who applies science.

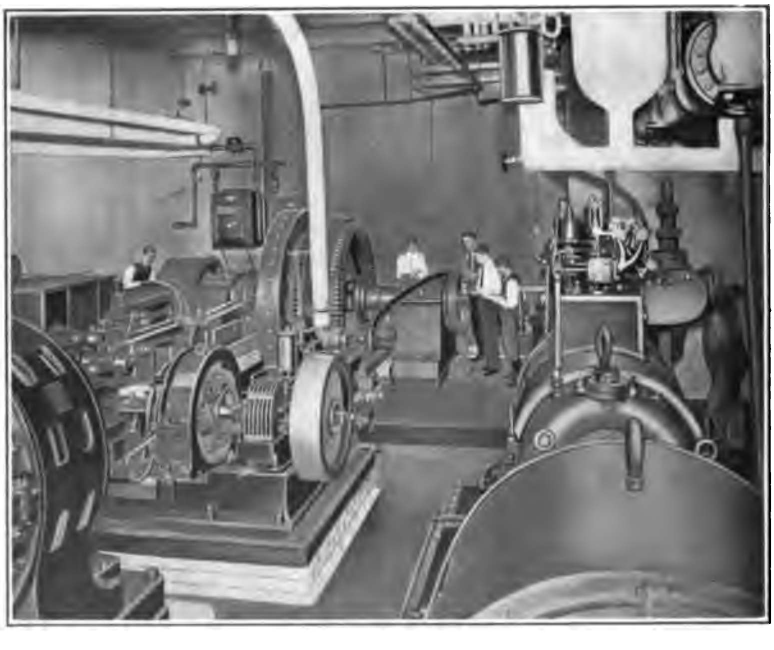
Now, gentlemen, these classes are needed and we must arrange for their development. We must start with the boys and correlate all these agencies for education in such a way that men will find themselves by natural selection. We cannot select them at the beginning. We have no business to assume that there is a certain class of vocationalists here and a certain class of professionals there when they are thirteen or fourteen years of age. We must provide means in our system for professional, industrial, vocational and what-not education in proper relation, so that the workers will drop into vocations and professions for which they are particularly adapted.

Class in Carpentry at Pratt Institute [SHELDON]

Tanning Leather at Pratt Institute [SHELDON]



ENGINE ROOM AT STUYVESANT HIGH SCHOOL [SHELDON]



ENGINE ROOM AT STUYVESANT HIGH SCHOOL [SHELDON]

In line with that, let me make one suggestion which I think I have made several times before, and that is, that as an engineer I do wish that, as far as professional and educational interests are concerned, we could get rid of the use of adjectives.

Yesterday President Dunn spoke, I think, of some thirty-four different kinds of engineers and of the fact that when we want to do anything in this country for engineers, we have to get joint committees for pretty nearly every one of the thirty-four organizations. Is it any wonder that we do not make more progress? I wish that the colleges would stop using the adjectives for the mere graduates, or bachelors, and call them graduates in engineering. Later, let them grow into engineers—civil, sanitary, mechanical, electrical, bridge, industrial, and so on.

Professor Diemer: Right in line with what the previous speaker has said I would like to call attention to a charting of industrial education along Plato's line, only modernized, by Dean Pearson of the Tuck School of Finance in Dartmouth College. In a little book entitled " Industrial Education " he has outlined a chart in which the central path shows the continuous flow of the common school education, and he recommends there a branching off on one side or another, particularly the establishment of such systems of education in which a child can be branched off at any stage, we will say, after the seventh or eighth grade, and made to receive certain lines of education which will insure his becoming a better citizen in the line in which he is forced to go.

For instance, we have here the continuation school after the seventh and eighth grade, and we advocate that the common school system should include constantly certain principles of fundamental work, we will say, in science or mechanics, simplifying those terms as will best suit, or manual arts, arts and crafts, which are not intended to be in any sense of the word educational, but general culture. Now we should supplement that common school, Dean Pearson says, by certain systems of education on the one side branching off for the men who have more ability with handicraft, and on the other side for those who have ability in accounting and clerical work. So that we branch off on the seventh or eighth year to provide a system of education which will better them in their lives. Then we must provide for trade schools or for industrial schools which will take the place of high schools which are intended as a system flowing into the college. Then he advocates in the college, also, a certain differentiated technical college course. He would have this college course divided, each side containing a predominancy of management, but the one side of a predominancy of the scientific technique and the other of instruction in accounting and financial technique. I simply call attention to that suggestion of Dean Pearson as carrying out a little further the idea of the previous speaker.

Comfort A. Adams: I wish to endorse most heartily what Mr. McClellan has said, since it strikes at the very root of the problem. This problem is not solved when we have provided industrial education for those who, by accident of birth, cannot afford anything else, although that is doubtless a step in the right direction; the problem is not solved when we say to at least 80 per cent of our boys—" You may attain to the position of high grade mechanic but may never gain admission to the professional fields, no matter how much better your native talents may be adapted to professional work."

At the same time, we are forcing through our technical professional schools many young men who are there chiefly because their parents can afford to give them the higher education and not because they are able to profit by it in any marked degree. I am not forgetting the numerous scholarships, evening schools, and other aids to bright boys of slender purse, but I think you will find on closer scrutiny that the beneficiaries of these various aids come in large part from the financial upper 10, or at outside, 20 per cent of the population. Neither am I overlooking the very exceptional men who cannot be kept down by any lack of opportunity; they make their own opportunities. If we were to base our educational system solely on the needs of this exceedingly small group, our problem would disappear.

We thus have a social order in which education beyond the rudiments is so restricted that we are practically wasting a large part of our raw material, in so far as the assorting of the men for the various occupations and professions is based largely upon accident of birth rather than upon real fitness; upon the extent of the parent's pocketbook rather than that of the child's intellect.

The only factor which should control the opportunity for an education is the relative ability to profit by it, and while this may seem a millenial ideal to many, our talk of " equal opportunity " is hypocritical until we have definitely set ourselves the task of realizing that ideal.

We talk much of efficiency in our engineering work, but we are apt to overlook these very vital considerations which affect so tremendously the efficiency of the whole social organism of which we, as individuals, are very small parts.

I realize fully how far such questions reach, and that they involve the consideration of many subjects and problems neither primarily educational nor engineering in their nature, but they are problems which we as citizens must face, and many of which would be vastly simplified by the application of engineering methods.

Therefore, while we are lending our cordial assistance to the promotion of the numerous extensions of our educational system, let us not lose sight of the ideal of " equal opportunity "; let us work towards that ideal, first, as " citizens of no mean country " and second, as members of no mean profession.

F. C. Caldwell: I am glad to say that in Ohio we are making a good start along this line of industrial education. Besides the general application of manual training to the grammar schools, we have manual training high schools in the larger towns and in Columbus, at least, they are also experimenting with the alternate week cooperative plan in connection with manufacturing companies. I agree with Professor Williston that this is something which should be regarded as an experiment. It is certainly a good thing for some cases and always much better than nothing. But that it is better in the case where a man is able to put all his time into his school work is by no means demonstrated.

This educational attitude, which the employers of labor forming the manufacturing companies are coming to adopt toward their employees, is exceedingly promising in one direction which has not been mentioned. When the personal employer was superseded by the corporation with its officers there was a great loss in the personal and friendly relationship with the employee. I suppose a good many here, like myself, have been through the shops and they probably found, unless under unusually favorable conditions, that the employees felt they were simply parts of a big machine, that their personality was of no consequence; that the corporation employed them to do a job and that it was a matter of absolute indifference to the employer whether they stayed or went, whether they advanced or not. That there has often been some justification for this feeling cannot be questioned. It seems to me that what you might call the " educational attitude " of the corporation toward the employee may do something to fill the place of the old friendly relationship between the personal employer and the employee.

One other point that one of the recent speakers brought out ought to be emphasized, and that is, that whatever we do in the way of industrial education for the masses should always have in view the possibility of carrying a man further, of giving him the very best education that any one can have. I do not like the idea that when a man selects the manual training high school or vocational school, he is thereby shunted off from the natural course of advancement into the university. We must find some way by which a man who comes to the vocational school and thereby develops and shows the qualities which will fit him for a position as an engineer should have the opportunity to go right on up to the top.

M. J. McGowan, Jr: I would like to ask a question with reference to the relation of the engineering society to the state boards of education in the different states of the United States. Does this society cooperate in every state with the state board of education, to teach particularly the line of electricity? I ask it for this reason. In the state where I come from, New Jersey, the doctors are interested in the advancement of instruction in their line, the agriculturist is the same way, and all the different professions have colleges which teach their particular work. But I have never heard of anybody being interested through the state board of education to take up the technical courses in the schools of the state as to this line. Now having been connected with the state government, I took great interest in watching the different schools, the different societies and professions which are interested, but at no time in the state of New Jersey have I seen anybody in the electrical line interested to see that the scholar or student should get the preliminary education which would bring him in touch with this particular line or profession. I think this is a very important point and I think this society, in this joint session, should arrange, in all states, committees who would wait on the state boards of education and show them that the electrical field today is one of the greatest and most promising of any profession that has ever been known. In the city from which I come, Newark, New Jersey, I have installed in one school a switchboard apparatus, for technical training in the electrical field. It was the first time it had ever been done in this twentieth century. That is due to lack of encouragement to the state board to show that this particular line needs taking care of. You will notice that all these technical schools are situated nearby the different electrical industries. That shows, in my mind, that those industries are greatly interested in the particular schools for their own convenience, for which I do not blame any man or any corporation. They further their own interests. We must try to eliminate if we possibly can any stated line of study being taught or the following of any particular line of material or peculiar workmanship. Let the teacher be interested generally and go through it all from a to z. Don't lay any stress on any company's manufacture in any school. And I trust that in this way we shall undertake to cooperate with the heads of education in the different states. Go to the governor and ask him if he will appoint some representative from the engineering society or from this joint convention to attend to that matter, and by doing that you will put the responsibility for the teaching of electrical science in the public schools of the different states up to the A. I. E. E. to see that the teaching will be right.

W. G. Raymond: The time has almost arrived when we shall have to ask Professor Jackson to close the discussion, but the chair cannot forego this opportunity of relieving his mind of something which, perhaps, you will consider a heresy. You have been discussing principally this morning the details of industrial education, and sometimes it is necessary to plan the details before we plan the general structure, but it is always necessary to provide the means before the general structure can be built. I do not know whether you all realize it, although you all doubtless know, that as far back as 1862, a plan was outlined and provision was made by the Federal Congress for putting us in a position that we are not now in. This committee says that we rank behind European nations in this matter of industrial education, but if it had not been that the funds derived from the act of 1862 have been almost universally misapplied this country would not now be in that position. It makes no difference whether the colleges of mechanic arts established under that act were separate institutions or combined with state universities, the money has never been used for the development of mechanic arts. I think without exception there has been no school of mechanic arts created in any state under that act which provided distinctly for schools of agriculture and schools of mechanic arts. Dean Jackson will now close.

J. P. Jackson: I suppose from the remarks made by Professor Raymond that he is not familiar with the basis of organization of the Land Grant Colleges. The measure passed by Congress in 1862, in regard to the establishment of these useful institutions, is as follows:

" The leading object shall be, without excluding other scientific and classical studies, and including military tactics, to teach such branches of learning as are related to agriculture and the mechanic arts, in such a manner as the Legislatures of the States may prescribe, in order to promote the liberal and practical education of the industrial classes in the several pursuits and professions of life." This includes everything, I believe, that is being taught by the great bulk of our State and United States supported, or, to use the official title, Land Grant institutions. These institutions have always been alive and vigorous, have been leaders of educational thought along the applications of science, and have proved of prime usefulness to the nation.

W. G. Raymond: I agree with you.

J. P. Jackson: If that is the case, I need say no more on that subject. I think there is a great deal in what Mr. McGowan said; his plea is similar to that contained in this morning's report by the educational committee. It is a necessary preliminary to have such discussion as we have had among engineers, in order to arouse sufficient interest to do what Mr. McGowan has asked. His plea was made with reference to a specific act. Let me broaden it. If each one of the eleven thousand members of these two societies will use his influence in his local community, to get in touch with the school authorities—get himself appointed to some committee or otherwise place himself where he can be of service—he can, or the eleven thousand members can, do much to raise the efficiency, improve the happiness, and remove the discontent that seems to be growing among the hand laborers of this nation. If the TRANSACTIONS containing the discussion of this morning persuade only five hundred of the eleven thousand members scattered out over the country, who are now inactive in educational matters, to engage in the movement under discussion, this meeting will have been well worth while. It will have been the incentive to cause men of intelligence in our industries to become more active in doing what Mr. McGowan suggests; that is, going actively and practically into the machinery of the state to help develop our people in a proper manner. I say to the electrical convention here assembled and to the American Institute as a whole, that I believe there is no other way in which the electrical industries can be so rapidly improved, as by properly solving this very question, which we are discussing this morning, with reference to producing the greatest efficiency in our young people. There is apparently no specific answer required to any of the other discussions of this morning, as the papers presented were really not under discussion, but rather the general problem.

Harry Barker (communicated after adjournment): Professor Williston has pointed out the vital necessity of securing the proper boys for the various vocational school courses and the difficulty that such schools have in selecting from the candidates presented.

It ought not to be necessary for the vocational school instructors to have to step out of their true sphere to do this work. They cannot hope to have the available time or the data and information at hand to make the wisest selections. They need not perform this unwilling function if the cooperation which Mr. McClellan and others have spoken of, is secured with the present public school systems. The organization of vocational guidance based on the boy's manifest aptitude, on his environment and heredity, and based somewhat on a psychological study also, has advanced to such a stage that it is a necessary link between the existing graded schools and vocational courses. The work has risen to its highest development, so far, in vocational bureas such as found in Boston. Trained and experienced men now find out what work or study the various pupils seem best fitted for and how far they seem capable of progressing; the counselors advise what paths pupils may well follow and what ends they should aspire to, and finally keep track of them for a greater or less number of years, to see that they do not stagnate either from inherent tendency or outside influence.

While this work has been carried out to the greatest extent with bureau organization, there is much of the work within the ability of the grammar and high-school teachers and even such modest beginnings are better than waiting for the organization of a completely equipped bureau. Indeed the largest success will be greatly hastened by an early start. This function, moreover, is one very properly tied in with the work of the local superintendent of schools, acting as the general adviser of other teachers who are striving to make some safe beginnings at vocational guidance, and as the collector of information about local industries and opportunities.

There is not time here to describe the work in detail; it can be studied, however, by those interested. In reaching out for cooperation with state boards and local educational authorities, this is a chance for immediate effort and practical benefits, not to be neglected. Where there is a vocational school, it is a necessity for efficient work; where there are no vocational courses, it is of the greatest possible good in preventing misfits. Once undertaken, it will lead logically to such vocational courses as are best suited to the local situation.

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 27, 1912.

THE WIRING OF LARGE BUILDINGS FOR TELEPHONE SERVICE

BY FREDERICK L. RHODES

In modern office buildings, hotels and apartment houses large numbers of telephones are required. It would be inconvenient and impracticable to run a pair of wires through one of these large buildings each time a telephone is installed, in order to establish connection with the outside wire plant of the telephone system, as is ordinarily done when telephones are installed in residences or small business buildings. To overcome this difficulty, when the plans are prepared for an office building, hotel or apartment house, a forecast should be made of the probable future requirements of the building as a whole for telephone service, and facilities provided for a certain amount of cabling with the necessary terminals and subsidiary wiring. All large cities contain many buildings that are cabled and wired for telephone service according to a comprehensive plan, and, of the smaller places, there are few that do not have some buildings of a character requiring more or less provision of this kind.

Building Plans Should Include Provision for Telephone Wiring. Owing to the type of building construction generally employed, and the large number of telephones to be served, unless suitable facilities are provided in advance for accommodating the cables and wires, and for running them through the walls and floors, the work will either be unsightly in spite of all precautions to the contrary, or expensive and costly alterations will be required after the completion of the building to enable the wires to be effectively concealed.

It is therefore of prime importance to owners and architects that, in preparing plans and specifications for office buildings, hotels or apartment houses, suitable arrangements should be made for such telephone wiring and terminal boxes as the character and use of the building will demand. As every large building to a certain extent presents problems of its own, advantageous and economical arrangements can frequently be suggested by those who are specially familiar with work of this kind. It is to the advantage of telephone companies as well as building owners to have adequate facilities provided for the cables and wires, and telephone companies are glad to place their experience freely at the disposal of those who are planning the erection of buildings that require special provisions to be made. It is now the general custom to architects to send for the telephone company's experts in these matters to give them such information as they need to plan this work in the best way.

Classification of Buildings. In the following pages are described the general methods that have proved satisfactory for wiring buildings for telephone service. From this standpoint buildings may be divided into two classes:

1. Office and loft buildings.
2. Hotels and apartment houses.

The conditions that make a broad distinction between the two classes are these: In office and loft buildings the telephones do not remain fixed either in number or location for any extended period, varying with the requirements of the individual tenants, who will use more or less of the telephone service according to their respective kinds of business. In hotels and apartment houses the number of telephones is fairly definitely fixed, being almost invariably one for each room in a hotel and one or two for each apartment in an apartment house.

The office or loft building requires a permanent cable system supplemented by a multitude of branches consisting of pairs of wires whose function it is to connect the individual telephones or private branch exchange switchboards with the permanent cable system. This permanent backbone of cable extends upward from the basement, branching out and terminating at suitable distributing points on the several floors. These distributing points or cable terminals must be sufficiently numerous and so located that the changing requirements of the tenants can readily be met by running individual pairs of wires as needed to connect the telephones with these terminals.

It is, therefore, apparent that an office building must have a more comprehensive and flexible system of wiring than a hotel or apartment house on account of the different character of the telephone service required. In the office building only a portion of the wiring system is permanent. In a hotel or apartment house practically all of the wiring is permanent.

OFFICE BUILDINGS

General Scheme of Wiring. In large office buildings one or more cables from the nearest telephone central office are brought to some convenient point, usually in the basement of the building. At this point the house cable system begins. A main terminal box (Fig. 1) is furnished and placed by the telephone company at this point so that cross-connections can be made as required between pairs in the house cables and pairs in the central office cables.

These main terminal boxes in the case of large buildings are necessarily somewhat bulky and the question of the size of the box that will be needed in any particular case may well be taken up with the telephone company by the architect or builder in order that sufficient space for it can be provided in a convenient and appropriate location at the foot of the riser shaft or conduit, as the case may be. A dry, clean and accessible place should be selected. In some sections of the country, where buildings are in localities subject to floods, it will be well to provide space above the basement so that the telephone service will not be interrupted due to water getting into the basement.

From the main terminal box one or more riser cables are run to the top of the building. The riser cables gradually diminish in size as they extend up through the building. From the riser cables, subsidiary or branch cables of proper size are taken to distributing centers on the several floors. The locations of these centers should be chosen so as to admit of the shortest practicable wire runs to the offices, without making objectionable work necessary to conceal the wires.

Each subsidiary cable ends in a subsidiary terminal box, the purpose of which is to enable connections to be made readily between the cable and the individual pairs of wires that are run to each telephone. These subsidiary terminal boxes, when placed by the telephone company, are fastened against the walls of corridors near the ceiling and constitute the ends of the permanent wire system. Not infrequently the owner of the building desires to own the subsidiary terminal boxes in order that he may provide recesses for these boxes, and small doors to match the trim of the building so that the boxes will be concealed from view. Where the boxes are built into the walls it is important that they should be of ample capacity, on account of the trouble and expense that would result if they should prove inadequate and have to be replaced. It is customary to allow a greater margin for growth where the boxes are built in than where they are merely fastened against the wall. Where a conduit system has been installed on the various floors for the purpose of distributing wires to each office, the subsidiary terminals are located at the centers of the conduit system. Fig. 2 shows a subsidiary terminal box, recessed in a corridor wall, under the molding, and also a subsidiary box placed against the wall under the molding.

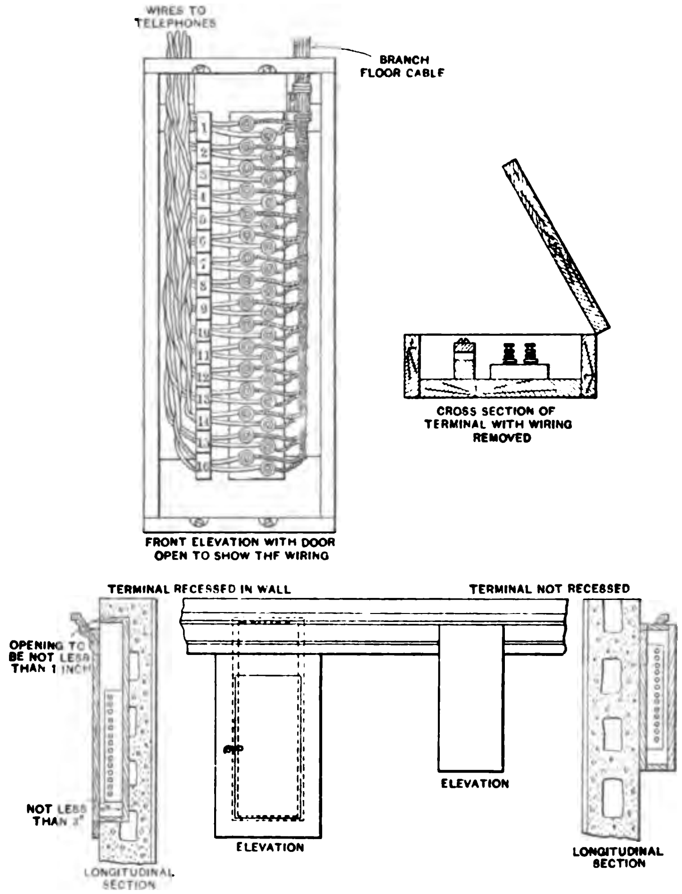


FIG. 2—SUBSIDIARY TERMINAL BOX—15 PAIRS.

FIG. 1—MAIN TERMINAL BOX, CAPACITY FOR TERMINATING 312 PAIRS OF WIRES. [RHODES]

The sliding door is removed to show the cross-connecting wires between pairs in the feeder cable and the house cable.

FIG. 5—PERSPECTIVE VIEW OF TERMINAL BUILDINGS, NEW YORK CITY. [RHODES

Forecasting the Number of Telephones. In forecasting the number of telephones that will probably be required in an office or loft building, the principal factors to be taken into account are the " renting floor area " of the building and the character of the business district in which it is situated, with special reference to its proximity to railway terminals, important streets and business centers.

Buildings in the financial district of a city ordinarily demand more telephones per unit of floor area than do buildings located in the commercial districts. In computing the " renting floor area, " only the office floor space is considered; hallways, elevator shafts and light wells are omitted. In all cases a safe margin for growth must be allowed. The following table shows rough average figures for telephonic density in office and loft buildings, based on a large number of cases:

Kind of building	Character of district	Pairs of telephone wires per 1000 sq. ft. of renting area
Office	Financial	4 to 5
Office	Commercial	2½ to 3½
Loft	Commercial	1 to 2

Size of Riser Cables. By basing the size of the riser cables on the renting area and the expected telephonic density as influenced by the character of the locality (checking this by a study of the probable number of offices and the requirements of prospective tenants), the cable system for any office or loft building may be planned with reasonable assurance that provision will be made for the maximum service required. On account of the requirements for battery feed wires and ringing current for private branch exchanges, the riser cables necessarily contain more pairs than do the cables that run from the building to the telephone central office.

Shafts or Conduits for Riser Cables. In buildings over 12 stories in height or in buildings of less height, where large riser cables are required, it is preferable to place the riser cables in suitable shafts rather than in conduits, as the advantage of having the cable protected by conduits is offset by the difficulty of installing and properly fastening the large cables in the conduits and making large complicated splices in the junction boxes that are required with a conduit system.

If properly installed, a conduit system is the best equipment for buildings less than 12 stories in height where small cables are to be placed, as the cables are effectually protected against injury. It is important, however, to remember that the success of a conduit system for installing vertical cables depends entirely on a perfect installation. The conduits must be of proper size and if possible free from bends. If bends are absolutely necessary, they should be made with a radius not less than three feet. The junction boxes at splicing points must be at least two feet square and the conduits must enter the boxes adjacent to a side in order that the cable may be bent and placed in a horizontal position for splicing.

Cable Shafts. Cable shafts should extend from the basement of the building to the top floor and should be easily accessible at each floor for the placing and splicing of the cables. Usually the shaft can best be located in a corridor partition, or in the wall of some public space leading out from the corridor, so that an opening can be made into the shaft from the corridor and covered with removable paneling or doors.

It is desirable to have a separate shaft for telephone cables and wires, as the placing of steam, water or gas pipes and light and power wires in the same shaft with the telephone cables renders the latter liable to injuries that may result in interrupting the telephone service.

Underground Cable Entrance to Building. Repairing basement walls and their waterproofing, due to the necessity for cutting through them, can be avoided if architects will specify a three-inch iron pipe sleeve for each ultimate underground cable entering the building, these sleeves extending through the wall at the point of entrance. The location of the point of entrance should be taken up with the telephone company in order that it may suitably fit in with the underground conduit system outside the building.

Junction Boxes. Riser cables ordinarily diminish in size as they go up the building. When a building is provided with conduits for both riser and subsidiary cables the conduit may diminish in size in the vertical section in the same relative manner as it is proposed to diminish the riser cable. Where a separate conduit is installed for each subsidiary cable a splice is required between the subsidiary and the main cable and a junction box is required wherever one of these splices must occur. These boxes should be approximately 24 inches square by five inches deep (inside dimensions) in order to enable the splices to be properly made and stowed away. In a system of this kind the subsidiary cables and the sections of the riser cable between floors are run separately and spliced in the junction boxes.

Terminal Boxes. The terminal boxes in which the subsidiary cables end must be large enough to accommodate the necessary connecting blocks. In most cases, boxes 18 inches square by five inches deep (inside dimensions) are sufficiently large. These boxes are installed on each floor as near the wiring center as possible, and where there is a conduit system on the floor, they are connected with each office by a 5/8-inch or 3/4-inch conduit which ends in the office at an outlet located either at the baseboard or the molding. Outlets should be located at the baseboard when it is of wood. If the baseboard is of metal or marble the outlet should be located at the molding.

In many cases owners of buildings do not desire to install conduits from the subsidiary boxes on each floor to every office. By providing suitable moldings, properly arranged to carry the individual pairs between the subsidiary boxes and the offices, wiring that is practically concealed can be done without the expense of conduits, and as the wiring is permanent only as far as the subsidiary boxes, the system is flexible enough to allow a suitable distribution of cable wires among the various rooms on a floor.

Where this plan of wiring is employed the subsidiary boxes may be made smaller than where individual conduits to the rooms are installed. The following table shows the outside dimensions of the present standard sizes of subsidiary boxes:

Number of pairs of wires terminated in box		Height of box in inches	Width of box in inches	Depth of box in inches
Regular	Extra			
10	1	12⅛	6¼	2⅝
15	1	16	6⅛	2⅜
20	1	21	6⅜	2⅛
30	2	16	12	2⅜
40	2	21	12⅛	2⅞

Fig. 2 shows a front elevation and section of one of these boxes. The equipment consists of a connecting block strip and a form or fanning strip. The connecting block is of insulating material and carries a pair of binding posts for each pair of cable wires to be terminated in the box. The form strip is of wood and serves merely as a guide to preserve an orderly arrangement for the individual twisted pairs that run from the telephone to the box. These twisted pairs pass through holes in the form strip and are secured under the nuts and washers of the binding posts, as are also the wires of the cable.

Cross-Connecting Boxes. Where a private branch exchange switchboard is to be installed, a cross-connecting box will be required. The wiring center in a case of this kind is at the cross-connecting box and not at the private branch exchange switchboard.

Use of Moldings. As shown in Fig. 2, the subsidiary boxes

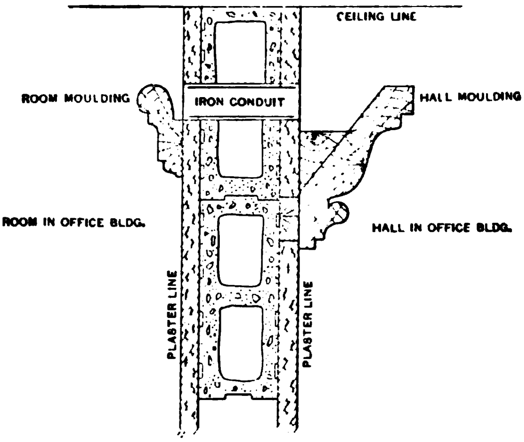


FIG. 3—CROSS-SECTION OF PARTITION SHOWING HALL MOLDING, ROOM MOLDING AND PARTITION CONDUIT.

are placed near the ceiling and wide shell molding, Fig. 3, should be provided in the halls for carrying the paired wires from the subsidiary boxes to the rooms. A smaller molding should also be provided in the individual rooms for carrying the wires to the particular locations desired. The space for the wires at the tops of these moldings should not be enclosed but should be left open. The object is to provide a continuous trough from each subsidiary box, reaching out to every room that is to be fed from it. Fig. 3 illustrates a section of one of these moldings.

Where it is necessary to make a concealed run across the ceiling of a hall, in order to avoid carrying exposed wires across the finished ceiling or to obviate making a circuitous run around the hall to reach rooms on the opposite side from the subsidiary box, conduit should be laid in the ceiling before the plastering is completed, to enable a small cable to be carried across the hall to provide for such lines. (Fig. 4.)

Where the wires enter a room from a hall molding, a piece of 3/4-inch conduit should be placed in the partition to enable the wires to be carried through it from the molding in the hall to the molding in the room. This avoids the necessity for drilling holes through the partition after the building is completed, which would be likely to result in damaging the finished wall. The conduit should either be lined with insulating material or the sharp edges around the inside of the pipe should be rounded off. (Fig. 3.)

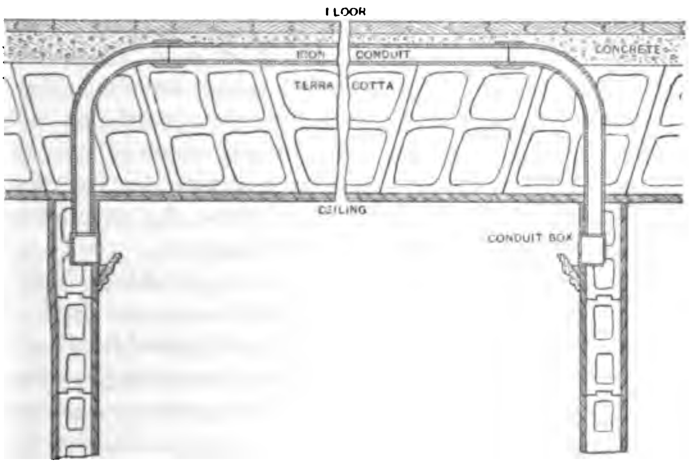


FIG. 4—METHOD OF PLACING IRON CONDUIT ACROSS CEILING OF HALL.

Kind of Cable. Paper-insulated lead-covered cables, such as are used by telephone companies in their outside plant, are the most desirable for use in building work. These cables are smaller and less costly for the same number of wires than cables of rubber-insulated wires. With this type of cable all of the terminals must be made with lead-covered silk and cotton-insulated cable, boiled out in beeswax or approved compound, and carefully shellaced, as the paper insulation will not stand handling if exposed, and moisture must be prevented from entering the paper-insulated cable. Should the terminal of necessity be in a particularly damp location it must be made with rubber-covered wires.

General Arrangement of Riser and Subsidiary Cables. From what has already been said it will be seen that the general arrangement of riser and subsidiary cables is practically the same, irrespective of whether conduits or shafts and moldings are provided.

The splicing of the subsidiary cables for each floor to the riser cable is usually done so that a given pair of wires in the riser cable is available for use on more than one floor. This is termed " bridging " the conductors and furnishes a multiple system of distribution. By this means the flexibility of the system is increased and fewer spare pairs need be provided in the riser cable than would be required if there were no " multipling."

From records of a large number of house cable systems it has been found that by bridging about two-thirds of the pairs in the riser cable at the subsidiary branches the most advantageous balancing of facilities is obtained. If less bridging is done it often happens that many of the subsidiary cables become congested before the riser cable. Owing to the use of standard size cable it is frequently necessary to make either risers or subsidiaries somewhat larger than the exact number indicated by the density study. The use of such cables may cause the proportion of bridging to vary from one-half to three-quarters.

In splicing the subsidiary cables to the riser cable in buildings of moderate size, it is not economical to open the large riser cable on each floor. In such cases, the plan followed is to take out from the riser cable at one floor the small subsidiary cables for several floors and to carry them from that point up or down to their respective floors.

Methods of Installation. If the riser cable is placed in a shaft the main cable and its subsidiary branches are often spliced together on the roof of the building or in some upper story and then lowered into place. In some cases the splicing is done in the telephone company's shop and the cable shipped to the building ready to be installed.

For supporting the cable a steel strand is used. Two or three wraps of iron wire are made about the cable at frequent intervals and these are attached to the strand by separating the individual wires of the latter and passing the tie wires through the interstices of the strand. If the subsidiary cables are more than about 30 feet in length only a short section of each is spliced to the riser cable before lowering. In this case the subsidiary branches are run and spliced to these stubs after the riser is put in place.

Special Conduit Work. In the methods above described the facilities provide for locating the telephones on or near walls or partitions, as this is the most common location. It can sometimes be foreseen by owners or architects that telephones will be required at some distance from a wall or partition, as would be the case with a desk placed in the center of the room. Where an arrangement of this kind is desired the owner should provide a duct in the floor extending from the location of the telephone to the picture molding on the wall or to some other place easily accessible for wiring. A duct of this kind should end at the floor in a floor box covered with a flush plate.

It sometimes happens, particularly in buildings used by large corporations or firms, that entire undivided floors are occupied by large numbers of desks. Telephone service is frequently required at all, or a large part of these desks, and the locations and arrangement of the desks on the floor may from time to time be changed. The floors of these buildings are often of fireproof construction. To meet a situation of this kind adequately it is necessary to be able to carry individual pairs of concealed wires to desks placed at any points on the floor, so that great difficulty and expense would be encountered in providing concealed wiring if suitable facilities admitting of the utmost flexibility were not provided in advance.

The best method of doing this is to carry branches from the riser cable in conduits to convenient building piers, placing subsidiary junction boxes at the bases of these piers. The entire floor is then provided with small floor outlets placed at the corners of squares about eight feet apart, each outlet being connected by conduit in the floor with the nearest subsidiary junction box at a building pier. Where the floors are not of fireproof construction, the individual pairs of wires are run in small channels grooved out of the floor beams on their upper surface. The locations of these channels should be accurately marked above the finished floors. Small brass nails are convenient for this purpose. When a telephone is required at a desk the flooring over the nearest channel is cut through, thus establishing a connection through the channel with a subsidiary terminal, conveniently placed, the wires being fished through the channel in the ordinary manner.

Arrangement of Conductors to Insure Flexibility in Operating the System. In order that the main terminal box may be as small as practicable the number of cross-connections to be made in it should be kept at a minimum. This is also important from maintenance considerations. To enable this to be done the method of distribution is arranged in a similar manner to that employed in other portions of the telephone plant. A certain number of pairs of wires in the riser cable are directly connected to the cable entering the building from the telephone exchange. These connections are made in a lead-covered splice and the pairs of wires thus spliced directly through do not appear in the main terminal box.

Certain other pairs in the riser cable are brought to terminals in the main terminal box. The remainder of the pairs in the riser cable are directly spliced to pairs in the exchange cable and these same pairs are also brought out by means of a branch splice to terminals in the main terminal box. If there are any extra pairs in the exchange cable that are not directly spliced to pairs in the riser cable they also are terminated in the main terminal box.

This arrangement, if the pairs have been skilfully distributed, permits of great flexibility and reduces to a minimum the number of cross-connections required in the main terminal box. The pairs that are connected straight through from the exchange cable to the riser cable without appearing in the main terminal box are used for the direct line telephones in the building and for private branch exchange trunk lines. The pairs of the exchange cable that appear in both the main terminal box and the riser may be used, first at the various floor boxes in the event of the congestion of the direct exchange pairs that appear in these boxes, and second in the main terminal box for battery and generator circuits and for overflow of business, due to erratic growth in lines on the various floors in the building, by cross-connecting to the house cable conductors extending to these floors. House cable pairs terminating in the main terminal box are used for private lines and miscellaneous circuits and for providing battery and generator circuits between the box and the various private branch exchanges by cross-connecting to the exchange cable in the main box.

EXAMPLES OF OFFICE BUILDING WIRING

The Hudson Terminal Buildings in New York City, extending from Cortlandt to Fulton Streets, one block west from Broadway, afford an example of the facilities required for telephone service in the case of office buildings of the largest size. The two Terminal buildings are treated as a unit so far as the telephone wiring is concerned. Together they contain nearly a million square feet of renting area and at the present time have about 3000 telephones. These data, with Fig. 5, Plate LXXIV, a perspective view of the buildings, will indicate the magnitude of the wiring problem.

The cabling and wiring of these buildings is illustrated by the following figures:

Fig. 6 is an elevation of the riser cables, showing the connections with the exchange cables and the general arrangement of the branch cables to each floor. Fig. 7 is a detail elevation showing typical "multipling" of the branches from the risers to the floors and of the subsidiary cables on the floor. Fig. 8 is a typical floor plan showing the locations of the riser cables, the floor cables, the floor terminals and the wire runs in the hall moldings to each office.

At the present time there are three 606-pair underground cables extending from the telephone central office to these buildings. The central office cables are spliced to the house cables near the main terminal. About 16 per cent of the pairs in the central office cables are connected directly to pairs in the riser cables that do not terminate at the main frame terminal of the buildings. The remaining 84 per cent of the pairs in the central office cables are bridged to pairs in the riser cables which also appear at the main frame terminal. All pairs from the central office cables that are directly connected to house cable pairs are marked *D F*. All pairs from the central office cables that are connected to house cable pairs that also appear at the main frame terminal are marked *F*. The balance of the pairs in the house cables (marked *H*) have no connection with pairs in the central office cables except by cross-connection at the main building terminal, where they may be connected as desired to pairs in the central office cables that are also bridged to riser cable pairs.

As new cables to the central office are added to meet the demand for additional telephone service in these buildings, the existing central office cable requiring relief will be left directly connected to the riser cable system and the bridged pairs will be transferred to the new cable.

The riser cables, of which there are five in all, are located in cable shafts beside the elevator shafts, Fig. 8. On each normal floor are provided conduits extending from the cable shaft to each of the five subsidiary terminals on that floor. In Fig. 8 these conduits and the subsidiary terminals are shown by solid lines. Broken lines represent the runs of individual twisted

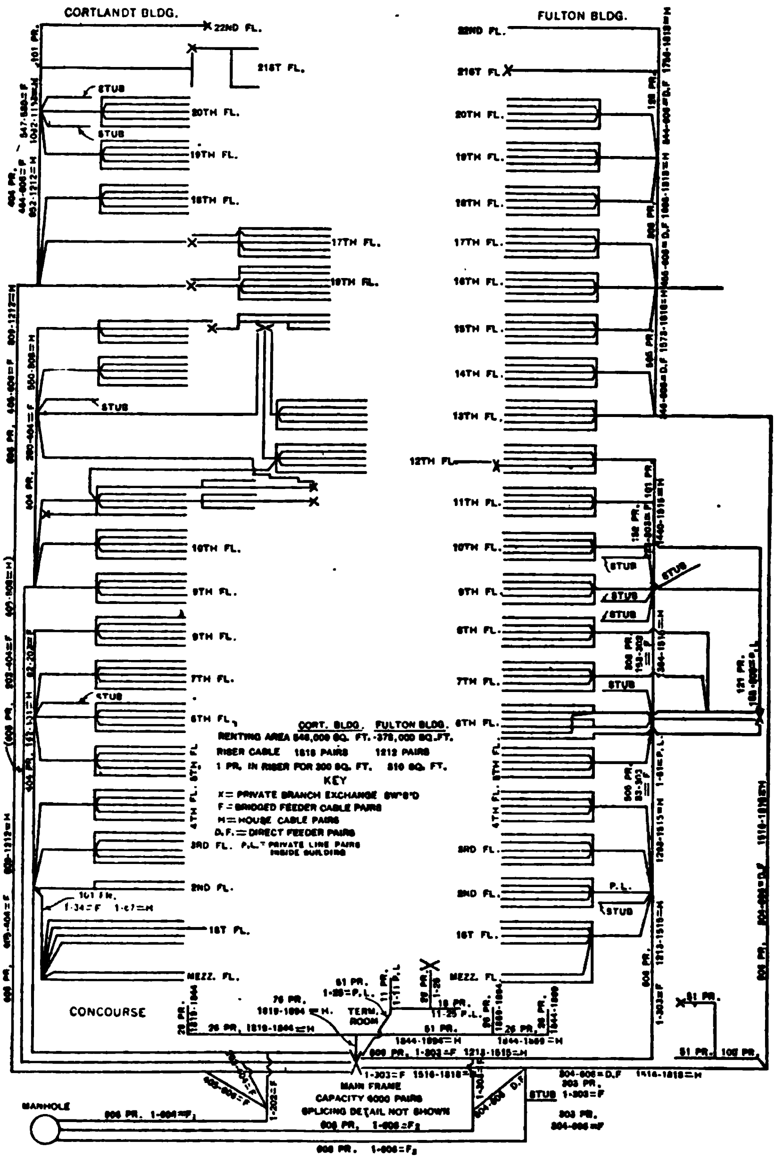


FIG. 6—TERMINAL BUILDINGS, HOUSE CABLE DISTRIBUTION.

pairs of wires in moldings from the subsidiary floor terminals to each office on the floor.

On account of its complexity, the entire scheme of multiple

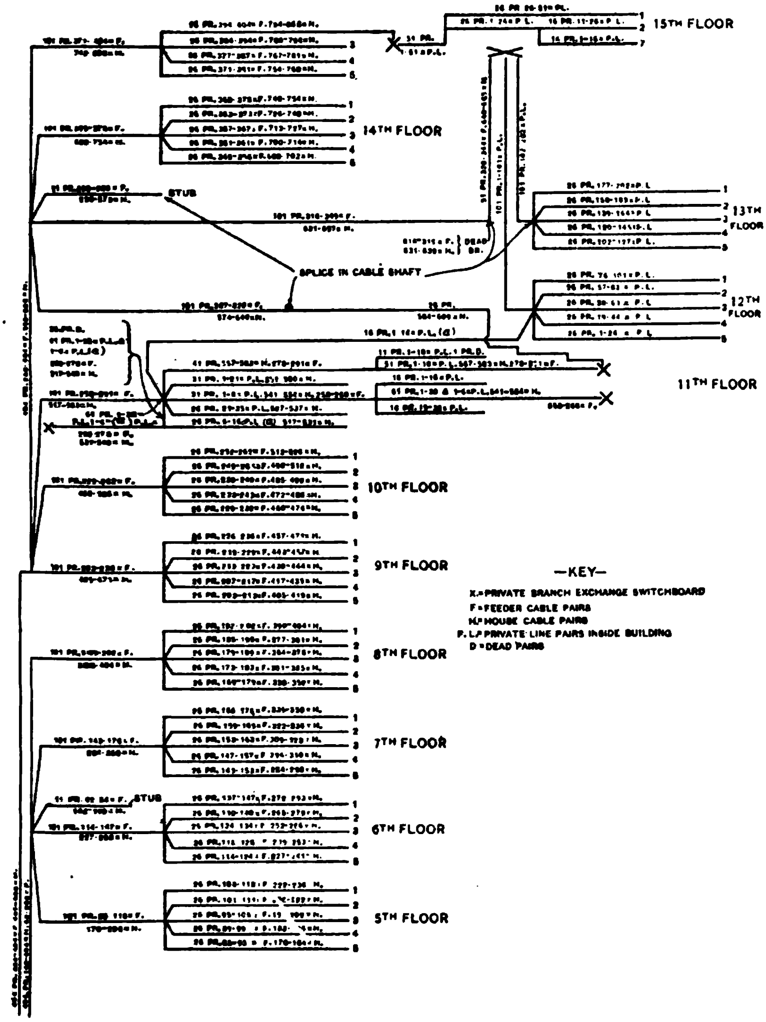


FIG. 7—HUDSON TERMINAL BUILDINGS.
Detailed distribution of cable pairs on the 5th to 15th floors, inclusive, in Cortlandt Street Building.

distribution for these buildings is not shown in full detail. The principles are, however, illustrated in Fig. 7, which shows the complete lay-out of the distributing cables branching from two points of the riser cable system of the southernmost (Cortlandt) building and feeding from the fifth to the fifteenth floors, inclusive. The distribution for the fifth to eighth floors inclusive represents one of the simplest cases in these buildings. That for the ninth to fifteenth floors is one of the most complicated, due to the special demands brought about by certain private branch exchange requirements.

In portions of these buildings, on account of private branch exchanges, some of the floor distributing branches from the riser cables that would be needed to supply individual tenants, are not required at the present time. Stubs containing the cable pairs that would normally appear on these floors are, however, provided and left in the cable shaft so that, merely by splicing subsidiary cables to these stubs, service on these floors of a different character could readily be established if changed office conditions should render this necessary.

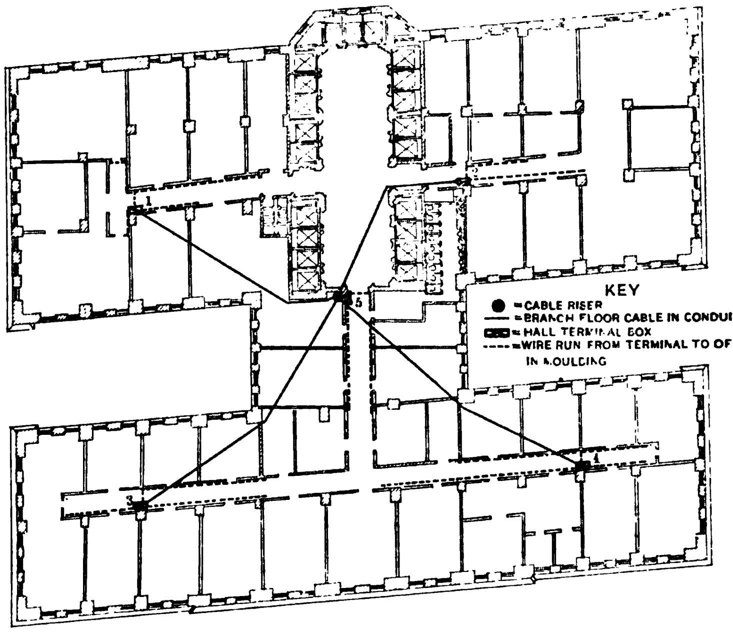


FIG. 8—TERMINAL BUILDINGS—TYPICAL FLOOR PLAN IN CORTLANDT BUILDING.

The requirements for telephone service in these buildings are so large that a main distributing frame is installed to act as the main building terminal. This frame serves the same purpose as the terminal box equipment shown in Fig. 1, namely to enable the pairs from the central office cables to end in a compact series of terminal lugs, and the pairs from the house cables in another series of terminal lugs; the lugs being so arranged that, by short lengths of twisted pair wire, cross connection can readily be made between any pair brought to the frame from the central office cables, and any pair brought from the house cables. This permits great flexibility of distribution. In the "multipling" diagrams, Figs. 6 and 7, the numbering of the pairs in the house cable system is on the basis of two groups. All feeder pairs in the house cable system, whether directly spliced to pairs in the central office cables and not appearing at the main terminal, or bridged to pairs in the central office cables and also appearing at the main terminal, are numbered from one up and designated either *DF* for direct feeder or *F* for bridged feeder pairs.

All pairs in the house cable system that terminate at the main terminal without being directly connected or bridged to the central office cables are numbered as a separate group from one up and are designated *H* for house pairs.

Eleven-Story Store and Office Building. This building is chosen as an example of a complete conduit installation. Fig. 9 is a plan of one of the office floors and Fig. 10 shows elevations of the conduit system and the cable system. The diameters of the conduits are indicated in order to show how the conduits decrease in size with the cables as they rise up through the building.

Owing to the lower portion of this building being arranged for stores, the office distribution on certain of the riser cables does not begin until the sixth floor is reached.

LOFT BUILDINGS

Conduits for wires or cables are rarely provided in loft buildings. The riser cables are placed in shafts and the wires are distributed on each floor along the baseboards. The wire center on each floor is usually at the baseboard near the passenger elevator shaft. Although this arrangement is undesirable in many cases, it is difficult, on account of the floors being undivided and the locations of the telephones not being known until the premises are occupied, to make any provision in advance for distributing the wires. A system of conduits and floor boxes would be expensive and is not considered necessary.

Where one firm occupies the entire loft building, the size of the riser cable is determined entirely by the equipment of the private branch exchange switchboard and the probable future requirements of the firm as to telephone service. In a case of this kind the center of the wire system is at a cross-connecting box located close to the private branch exchange switchboard.

A modification of the method of distribution already described for office buildings is usually employed in loft buildings. The riser cable is divided into two parts termed "bridged feeder" and "house cable." The house cable pairs are terminated in the main terminal box near the foot of the riser, and the bridged feeder pairs are directly connected to pairs in the exchange cable and also by a branch splice are terminated in the main terminal box.

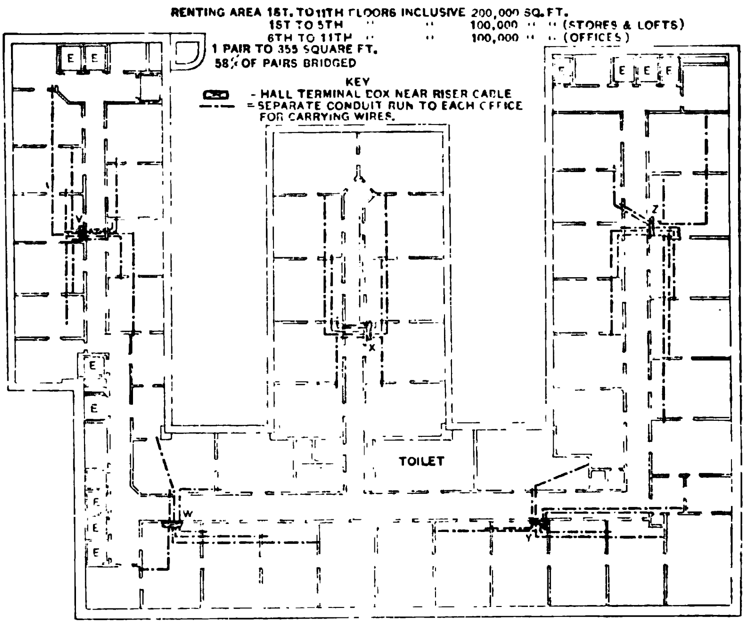


FIG. 9—11-STORY OFFICE BUILDING, TYPICAL FLOOR PLAN.

Example of Loft Building Wiring. Fig. 11 shows the floor plan and cable distribution of a twelve-story loft building. It will be noted that the arrangement of pairs does not agree with the preceding statement that in loft buildings the riser cable is divided only into bridged feeder and house cable groups. This

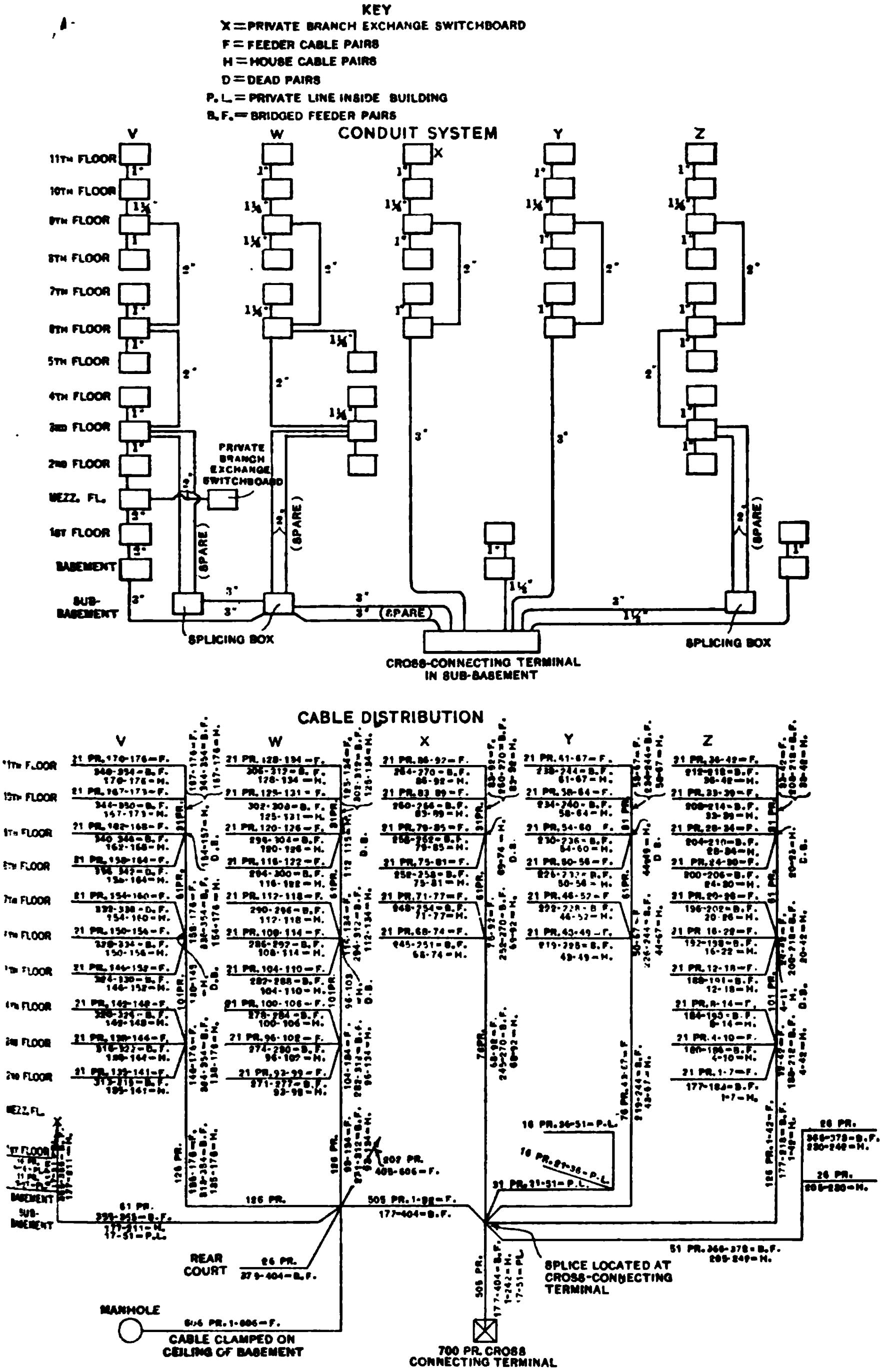


Fig. 10—11-Story Office Building, Conduit System and Cable Distribution.

diagram shows, in addition to these groups, certain direct feeder pairs. The reason is that it is expected that this particular loft building will sooner or later be partitioned off for office use, and this condition has been anticipated in planning the cable distribution.

Hotels and Apartment Buildings

General Scheme of Wiring. The telephone systems for hotels and apartment buildings differ from those for office and loft buildings in one important respect. Hotels and apartment buildings can be wired in advance on a permanent basis on account of the probability that there will be no essential change in the number of wires needed, the ultimate requirements being closely determined by the number of rooms or apartments. The locations for the telephones in the various apartments or rooms are also generally permanent and the relative locations of the telephones are the same on each floor.

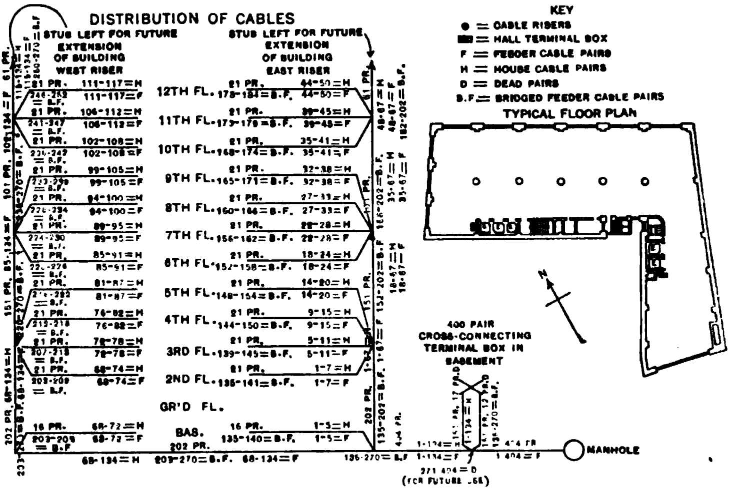


Fig 11—12-Story Loft Building.

The telephone system installed in these buildings consists of a private branch exchange switchboard located at some convenient point, usually on the ground floor. In hotels this private branch exchange switchboard is placed in or near the office. Telephones are installed in each room or apartment and wired to this switchboard. The latter is connected by the necessary number of trunk lines with the nearest central office of the telephone company.

The wiring problem is simple in comparison with that in office buildings. It consists of running a pair of wires from the telephone location in each room or apartment to a common center in the cross-connecting box near the private branch exchange switchboard. It is important to make provision so that the telephone company can run its wires from the cross-connecting box of the private branch exchange switchboard to some point in the basement where connection can be made to the central office cable. The latter cable is generally not run in conduit but is clamped to the ceiling of the basement.

Subsidiary Conduit. Conduits for distributing wires on floors in hotels or apartment buildings should not ordinarily be over 50 feet in length nor should they have more than three bends with a minimum radius of five inches. Any conduit 100 feet in length should not be less than one inch in diameter: 5/8-inch conduit should be provided for a maximum of two pairs of wires and 3/4-inch conduit should be provided for a maximum of four pairs of wires. For more than four pairs of wires it is preferable to run cable.

Hotels. In laying out the wiring system for hotels, in addition to one pair of wires for each room, as mentioned above, provision has ordinarily to be made for a small percentage of spares to provide for defective pairs and for a few direct lines.

From the wire center at the cross-connecting box near the private branch exchange switchboard a cable is extended through the basement or sub-basement to the foot of the riser shaft. The riser cable extends up this shaft as a diminishing cable with subsidiary terminals located at convenient points on each floor for reaching the various rooms. The wires are distributed on the floors either by molding or through conduits, as the case may be. In many of the modern hotel buildings complete conduit systems are provided for concealing the telephone wires and cables. In such cases the vertical conduits are installed at some central point and junction boxes are provided on each floor for splicing and terminating cables. From the junction boxes separate 5/8-inch conduits are extended to each room. The outlets in the rooms should be located four feet 10 inches above the finished floor for wall sets, this having been found by wide experience to be the most satisfactory height at which to place the telephone. For desk stands the outlets should be at the baseboard near the proposed location of the telephone. Where the floor area and the number of rooms are large it is often economical to have more than one terminal box on a floor.

EXAMPLES OF HOTEL WIRING

18-*Story Hotel.* Fig. 12 shows the floor plan of this hotel with the locations of the riser cables and the individual telephones in each room. The separate conduit runs from the riser terminals to the rooms are not shown in order to avoid confusion on the drawing. Fig. 13 shows elevations of the riser cables with the branches at each floor.

In this installation the riser cables (five in number) are placed in shafts and the wire distribution on each floor is in separate conduits to each room. It will be noted that no feeder pairs are provided in the riser cables.

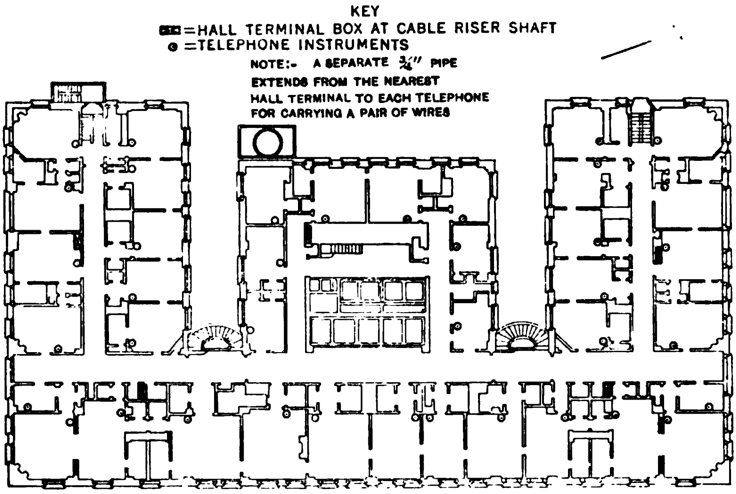


FIG. 12—18-STORY HOTEL, TYPICAL FLOOR PLAN.

17-*Story Hotel.* This is a complete conduit installation. Fig. 14 shows the riser cable terminal boxes and individual telephone locations on a typical floor. Fig. 15 gives the elevation of the house cable system. This hotel has an apartment section which is cared for by the north riser cable. This section of the house has its separate switchboard. The other two riser cables feed the hotel portion of the house.

ELEVATOR APARTMENTS

Elevator apartment buildings are generally wired on the basis of two telephones to an apartment, one connecting to the private branch exchange switchboard and the other, when desired, directly to the central office of the telephone company.

In most of the high-class elevator apartment buildings it is the practise of owners and architects to provide conduits for concealing the telephone wires and cables. In some cases a vertical shaft is provided instead of vertical conduit.

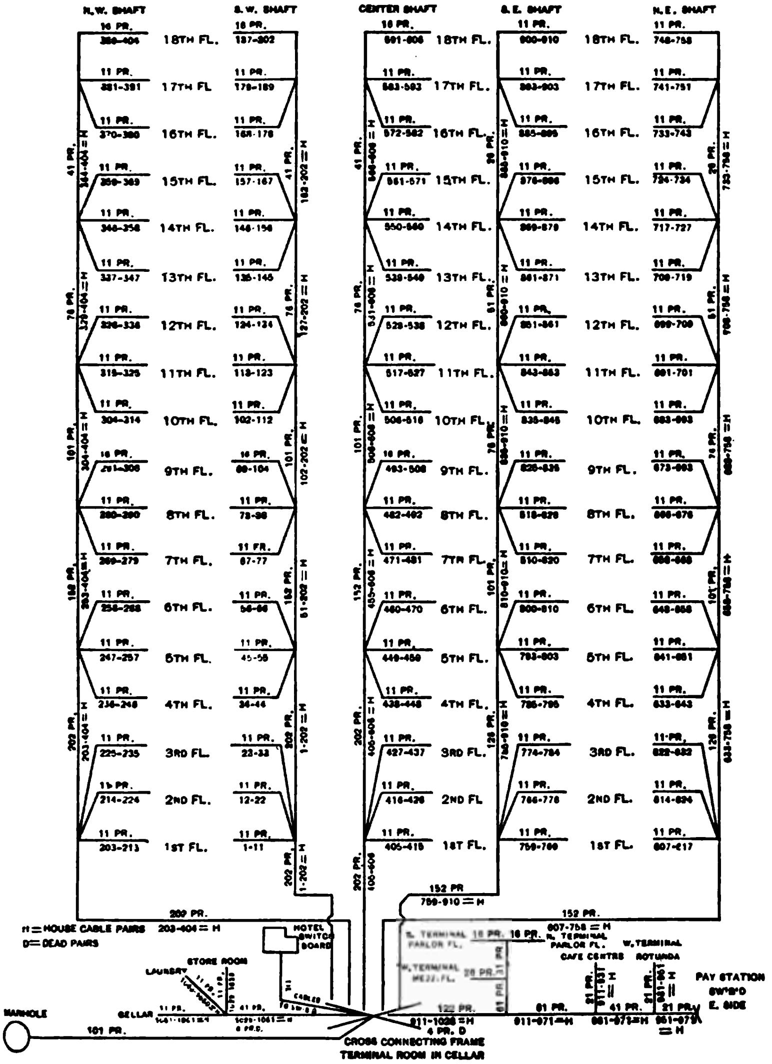


FIG. 13—18-STORY HOTEL, HOUSE CABLE DISTRIBUTION.

Where the floor space occupied by each apartment is small and the horizontal runs on each floor are short a riser or diminishing house cable is placed. This cable is extended up through the building in a conduit or a shaft, as the case may be, and branches containing a sufficient number of wires to provide two pairs for each apartment are terminated in junction boxes located at central points on each of the floors. From each junction box 5/8-inch or 3/4-inch conduits are extended to the location of the telephone in each apartment, the outlets being located, as in hotels, at the baseboards for desk telephones, and in the wall, four feet 10 inches above the finished floor, for wall telephones. This arrangement provides a flexible system, as the wires between the apartments and the subsidiary branches may be drawn in whenever service is required. As the horizontal run of conduit on each floor is comparatively short, the cost of the conduit installation is minimized. There is a further opportunity for economy in installing conduits from the junction box to the apartments, as it is frequently possible to use a single run of conduit for two apartments instead of a separate conduit to each.

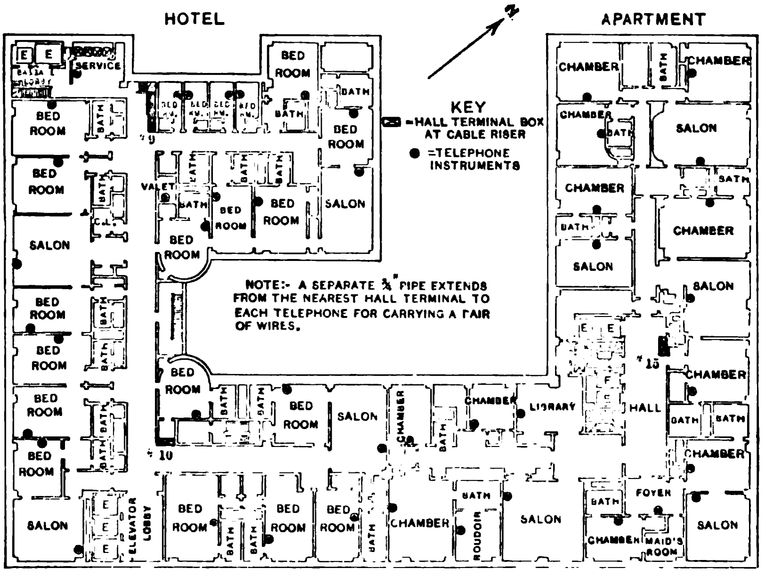


FIG. 14—17-STORY COMBINATION HOTEL AND APARTMENT BUILDING, TYPICAL FLOOR PLAN.

In apartment buildings where the floor space occupied by each apartment is large, the above arrangement would necessitate long runs of small-size conduit on each floor. In such cases, to avoid the excessive cost of this conduit, the wires are usually distributed to the apartments by a vertical system of conduits extending from the basement up through each tier of apartments.

These vertical conduits diminish in size as they approach the upper portion of the building, and the outlets in the apartments are located in the walls at the points where the telephones are to be placed.

In the basement, cables are extended from the cross-connecting box near the private branch exchange switchboard along walls and ceilings to the foot of each line of vertical conduits. At these points terminals are established with sufficient conductors to provide two pairs of wires for each apartment to be cared for by the riser. The pairs of wires between these terminals and the apartments are pulled into the conduits as the service is required.

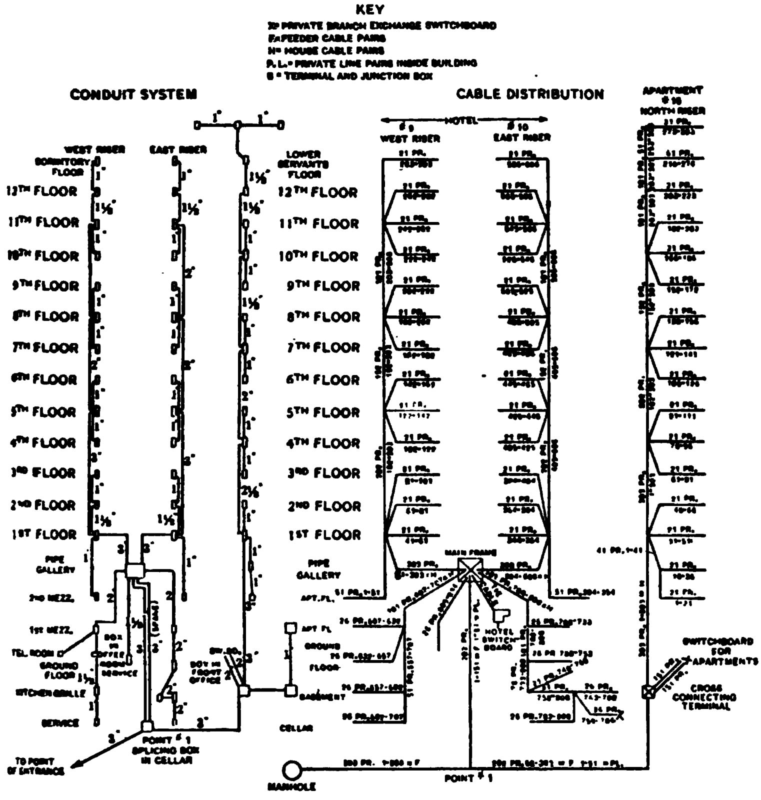
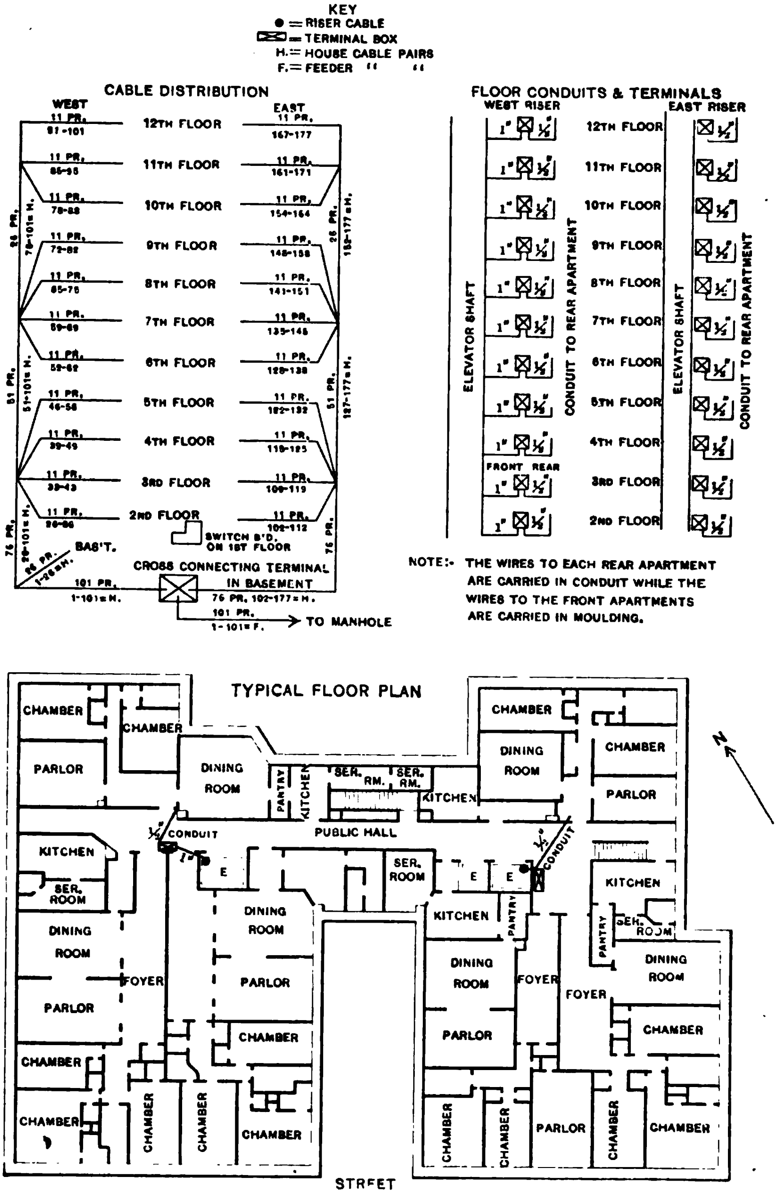


Fig. 15—17-Story Combination Hotel and Apartment Building, Conduit System and Cable Distribution.

The size of the vertical conduit varies with the number of apartments to be served. Generally a conduit two inches in diameter in the basement diminishing gradually to 3/4 of an

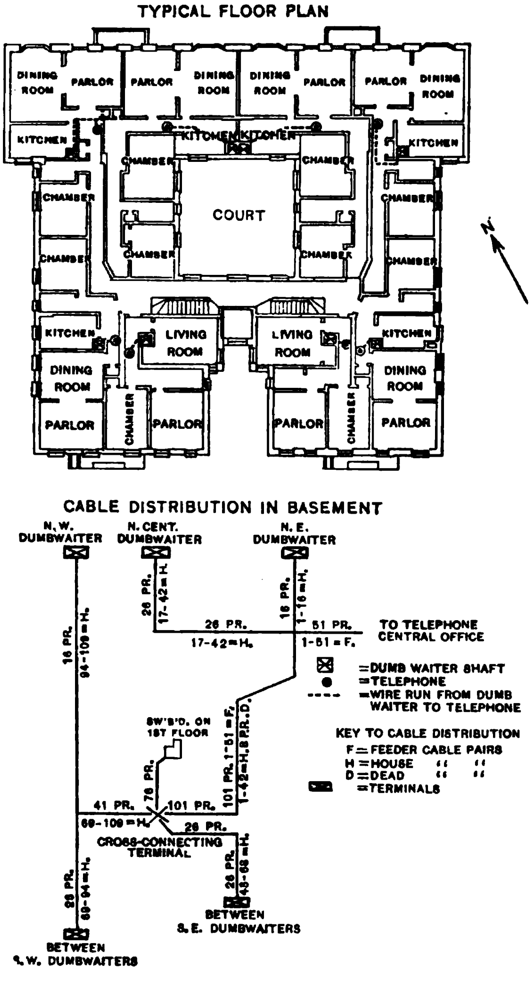


NOTE:- THE WIRES TO EACH REAR APARTMENT ARE CARRIED IN CONDUIT WHILE THE WIRES TO THE FRONT APARTMENTS ARE CARRIED IN MOULDING.

FIG. 16—12-STORY ELEVATOR APARTMENT HOUSE.

inch at the upper floor is sufficient to care for buildings 10 to 12 stories in height, and a conduit 1¼ inches in diameter in the basement diminishing to 3/4 of an inch at the top for buildings from six to 10 stories high.

The number of vertical lines of conduit depends on the number of apartments on each floor. Usually a separate line of conduits is required for each tier of apartments, but it is often possible to care for two adjacent apartments on each floor by a single line of conduit when the telephones in both apartments are to be placed on the dividing wall between them. This arrange-


TYPICAL FLOOR PLAN

CABLE DISTRIBUTION IN BASEMENT

Fig. 17—6-Story Non-Elevator Apartment House.

ment is, however, open to the objection that installers must gain access to one apartment for the purpose of installing the telephone in another. In spite of this objection, from the standpoint of the owner this method is probably the best for buildings of this class as it minimizes the cost of installation of conduits and is flexible enough to admit of direct lines being installed when such service is required.

Example of Elevator Apartment Building Wiring. Fig. 16 shows a 12-story elevator apartment building with six apartments to a floor and stores on the front of the first floor. The two riser cables are run in the elevator shafts.

A diagram is given showing the junction boxes on each floor and the sizes of the conduits used for distributing the wires on each floor.

NON-ELEVATOR APARTMENTS

Apartment buildings of the non-elevator class do not as a rule exceed five or six stories in height and frequently have as many as 10 apartments on each floor. Buildings of this class are wired by extending lead-covered cables from the cross-connecting box near the private branch exchange switchboard through the basement to the foot of each dumb-waiter shaft where terminals are established. The terminals are made large enough to provide approximately for a direct line and an extension telephone for each apartment cared for by the dumb-waiter shaft, when it is thought that direct service will be required. The allowance made for direct line service depends upon the neighborhood. The wires to the various apartments are extended up through the dumb-waiter shafts from the terminals in the basement as service is required.

In some cases these buildings are wired in advance by forming the wires into a cable and taping the cable to protect it against mechanical injury, one or two pairs being brought out at each apartment.

Example of Non-Elevator Apartment Building Wiring. Fig. 17 illustrates the case of a six-story apartment building having eight apartments to a floor. The wiring diagram shows the cable distribution in the basement to terminals at the foot of the dumb-waiter shafts.

The author wishes to acknowledge the valuable assistance of Mr. E. S. Worden and Mr. W. A. Taylor in preparing the illustrative examples of this paper.

DISCUSSION ON " THE WIRING OF LARGE BUILDINGS FOR TELEPHONE SERVICE" (RHODES). BOSTON, MASS., JUNE 27, 1912.

Edwin M. Surprise: I noted in reading Mr. Rhodes's paper, that in New York City, at least, and probably in other places where very large and tall office buildings are under consideration, the scheme of attenuation is employed; that is, a large cable is brought in at the basement and branches taken off from that cable at necessary intervals. In our New England territory we have leaned a good deal toward the extension of small risers, one, two, or more, as may be required, to each floor, with the idea that it would result in economy, not only on account of the first cost of extending the cables, but also by reason of flexibility.

I am very much interested to get Mr. Rhodes's opinion regarding one method as against the other, of the advantages, if there are any, of small risers, and the exact point, if it is possible to give it, where perhaps small risers would prove best and where the large riser would not.

George K. Manson: Mr. Surprise referred to the question of comparative costs, or comparative conditions when the attenuation system proves economical as compared with the small riser system, and to supplement Mr. Surprise's remarks, before Mr. Rhodes gives us that information, it may be proper to say a little something about the building conditions in Boston that have led to the very general adoption of the small riser system in preference to the attenuation system.

Mr. Rhodes stated, I think, that twelve years ago there were very few buildings in New York City which were over twelve stories in height, and, to-day, I believe, he said there were 1500 or more. I believe somewhere in his paper, in reference, perhaps to the Hudson Terminal buildings, he has spoken of a floor space of nearly 2,000,000 sq. ft. Now, we have in Boston, we think, a fairly large city, especially if we are allowed to take in the suburbs which properly belong to it. In Boston today I think I am not mistaken in saying that there is only one building which is over twelve stories in height, and that was built before the present building laws were in existence. If there are more than that, they also were built before the present building ordinance. As to the area, I presume it is very doubtful if there are half a dozen buildings in Boston that have, we will say, over ten per cent of the total rentable floor space referred to in Mr. Rhodes's paper in connection with the Hudson Terminal buildings.

The building law in Boston, briefly, is that no building in the city shall exceed 125 feet from the average sidewalk height to the roof line. If the width of the abutting street is so narrow that two and one-half times the width of the abutting street is less than 125 feet, then the building must be correspondingly less in height, and must not exceed two and a half times the width of the abutting street, and is not to exceed 125 feet as a maximum, and in some parts of Boston there are special ordinances that restrict the height to even less than that.

You will see, therefore, that our problem of providing wiring for office buildings is a little different from that in New York and other cities where the development in terms of lines and perhaps subscribers may be no greater than the development in many of our medium-sized New England cities. It is by reason of that fact that in office building wiring we have found it is expedient, to a very large extent, to use the single riser system, perhaps one cable feeding a single floor, a 30-pair, or a 60-cable, or, perhaps, initially, one cable feeding two floors, and later to be tapped in such a manner as to supply a cable for each individual floor. I cannot quote figures at this moment, and possibly we could not back up our position, but I think under these conditions the single riser cable has proved economical; at least it is very convenient to install, and leads to very efficient results in the use of the main cables and in the use of the office cables. I trust Mr. Surprise will pardon me for enlarging on his question to that extent.

There is one other point that I will mention, and that is the vast reduction of the fire hazard that has been brought about by the modern methods of wiring buildings as compared with the older methods.

F. L. Rhodes: I think that Mr. Manson has, in supplementing what Mr. Surprise said, very well pointed out the wide range of conditions to be met in work of this kind. In building wiring, the reason why it is not the best practise to run separate cables to separate floors is principally a matter of economy, both as regards the cable itself and the space occupied. For a given number of pairs of wires, the most economical cable is secured by placing these all in one sheath. This is true, not only as regards the cost of the cable itself, but also true as regards the space occupied. One cable of 600 pairs occupies less section, and has less cost per pair than 10 cables of 60 pairs each, and these conditions of economy, both of cost and space, are intensified in the case of tall buildings as compared with the conditions that prevail in the case of buildings of comparatively few stories.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 27, 1912.

THE VIBRATIONS OF TELEPHONE DIAPHRAGMS

BY CHARLES F. MEYER AND J. B. WHITEHEAD

HISTORY

Investigations of the vibrations of telephone diaphragms have been published by Rayleigh,[1] Wien,[2] Kempf-Hartmann,[3] Taylor,[4] Gati[5] and others. Rayleigh and Wien measured the value of the simple harmonic current which would just produce an audible tone in the receiver at different frequencies. They found that at certain frequencies the current required was a minimum, and Wien concluded that these minima showed the existence of natural vibrations of the diaphragm, but realized that the variation in sensibility of the ear with pitch played possibly a larger part in the difference of current required at different frequencies than the natural vibrations themselves.

Kempf-Hartmann fastened a mirror on the diaphragm of a receiver and photographed on a moving film the oscillations of a spot of light reflected from the mirror. By passing direct current interrupted about 100 times per second through the telephone he was able to photograph the natural oscillations of the diaphragm which were produced at each make and break, and showed also that when the diaphragm had been given an impulse its reaction could be detected after about 1/2000 of a second.

Taylor has plotted curves showing the connection between the least current producing an audible tone and the frequency, his work being similar to that of Rayleigh and Wien. He noticed

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[1] Rayleigh. "Theory of Sound," I, p. 473.

[2] Wien. *Annalen d. Phys*, IV, p. 450, 1901.

[3] Kempf-Hartmann. *Annalen d. Phys.*, VIII, p. 481, 1902.

[4] Taylor. TRANSACTIONS A. I. E. E., 1909, XXVIII, II, page 1184.

[5] Gati. *Electrician*, LXVI, p. 456, 1910.

that as the alternating-current generator from which he obtained his current accelerated or slowed down there were certain frequencies at which the sound from the receiver was very much increased, and he plotted rough curves showing this.

Gati has worked with transmitters. He produced before the diaphragm a sound of which the frequency was varied, but the amplitude was kept as constant as possible. The transmitter was in circuit with a battery and the primary of a transforming coil. To the secondary of the coil he connected the capacity required to produce electric resonance at each frequency and measured the current in the secondary circuit. Plotting curves between frequency and current a decided maximum is obtained showing resonance at about 700 vibrations per second.

The mathematical theory of the free oscillations of circular membranes and plates has been developed. It shows that the nodes are either circles about the centre, or diameters symmetrically distributed[6], this holding true for plates with either a free or a clamped boundary; the boundary of membranes is, of course, necessarily fixed. Rayleigh gives the following formula for the frequency of the lowest natural vibration of a clamped plate.

$$n = \frac{3.2^2 \sqrt{q}\, h}{2\pi a^2 \sqrt{3\rho(1-\mu^2)}} \tag{1}$$

where q = Young's modulus.
μ = Poisson's ratio.
ρ = volume density.
$2h$ = thickness of plate
a = radius of plate.

He applied the formula to the case of a receiver diaphragm which he measured, and found 991 as the fundamental frequency. No experimental verification of this seems to have been attempted.

OBJECT

The present work was undertaken to obtain further and more accurate information concerning the way in which the diaphragms in the transmitter and receiver vibrate when acted on by periodic forces of simple wave form of different frequencies. Also to obtain quantitative data on the influence of the free periods, and to determine to what degree of approximation the

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[6] Rayleigh. "Theory of Sound," Vol. I, pp. 331, 366.

form of the vibration of the diaphragm follows that of the impressed force. The question of the localization of the nodes and loops at the higher resonance frequencies is also interesting, but it has thus far evaded solution.

WORK ON THE RECEIVER

Arrangements and Apparatus. The receiver is simpler in construction than the transmitter and is therefore more easily investigated. With the receiver the problem is to pass through it an alternating current of simple wave form, as nearly simple harmonic as obtainable, and to record the form of the current, and the corresponding oscillation of the diaphragm. The amplitude of the oscillation of the diaphragm for the same current at different frequencies, plotted against frequency, would then give the resonance curve for the diaphragm. For producing the alternating currents two special generators with smooth body armatures were used for low frequencies. For the principal range a third generator was used. With these three machines frequencies from 16∼ to 3000 ∼ could be attained. The current wave form was recorded by a Duddell double high-frequency oscillograph, used simultaneously as oscillograph and ammeter. An oscillograph of this type has a free period of from 8000 to 10,000. It may hardly be relied upon to record with any accuracy a wave of over three or four hundred cycles. In the present case, however, the current wave is, with a few exceptions, very nearly pure, and the question of wave form does not enter markedly into the results of the work.

The method adopted for recording the oscillations of the diaphragm was as follows: A small fragment of mirror was mounted directly on the diaphragm by means of wax or cement, and its vibrations recorded by a spot of light reflected upon a photographic plate. It is easy to mount the mirror rigidly, and its mass, which may be 0.007 of a gram or under, is too small to influence the motion of the diaphragm greatly. There can further be no doubt that the angular deviation of the mirror is the angular deviation of the diaphragm at the point where it is mounted.

DIAPHRAGM A

The first receiver worked with was one of the ordinary bipolar type. Its characteristics were: Total diameter of diaphragm 5.42 cm. (2.14 in.). Inside diameter of clamping ring in cap 4.98 cm. (1.96 in.), this being the effective diameter of the diaphragm. Thickness of diaphragm with enamel on front face 0.03 cm. (0.012 in.). Thickness bare at edge 0.023 cm. (0.009 in.). Distance between pole pieces and plane of clamping ring of diaphragm 0.05 cm. (0.02 in.). The air gap between pole pieces and diaphragm is less than this as the diaphragm is permanently bent inwards by the attraction of the magnet. The part of the cap extending over the diaphragm was cut out in order to make room for the small mirror which was fastened on. See Fig. 1. The mirror was placed about half way between the center and edge. The diaphragm was so oriented over the pole pieces that the mirror came on the perpendicular bisector as shown in Fig. 2. The receiver was then set up so that the mirror came on a horizontal diameter. Pulling in of the diaphragm corresponded to a motion to the right of the light spot on the photographic plate.

Some of the photographs obtained for this diaphragm are

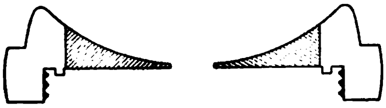


FIG. 1—CAP OF RECEIVER—THE SHADED PORTION WAS CUT AWAY.

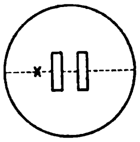
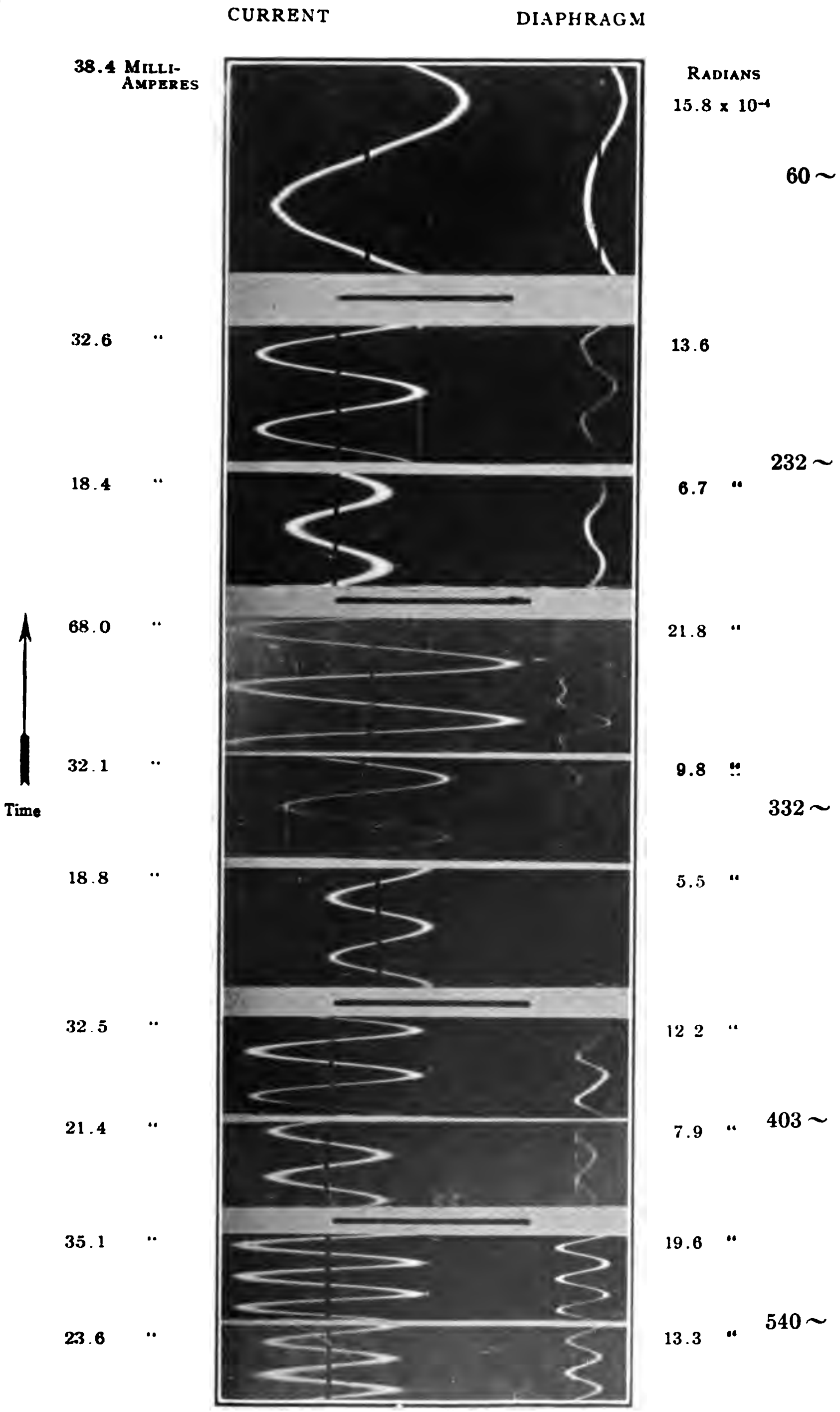


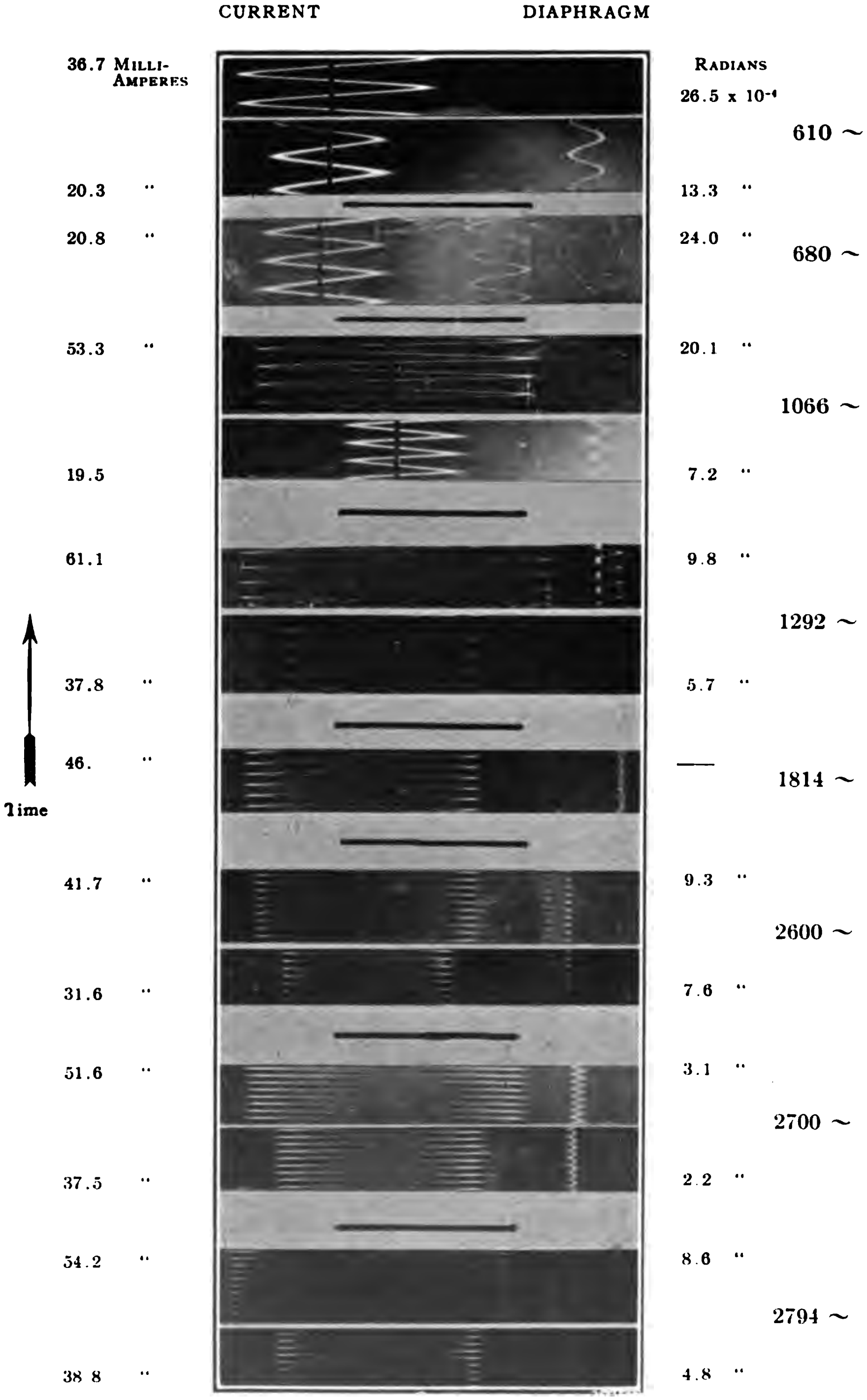
FIG. 2—THE *X* MARKS THE POSITION OF THE MIRROR ON THE DIAPHRAGM

shown in Figs. 3 and 4, with frequencies noted for each set. The curves on the left are the oscillograph records of the current through the receiver, the number at the side giving its value in milliamperes (effective), calculated from a knowledge of the sensibility of the oscillograph. The curves on the right are the traces from the diaphragm, the accompanying figures giving the value of the angular deflection in radians $\times 10^{-4}$, calculated from the dimensions of the optical system. As these latter curves are unsymmetrical it is impossible to speak of their amplitudes, so the total deflection from one extremity of swing to the other is given; this quantity will henceforth be referred to as the "range" of the oscillation. The numbers on the extreme right-hand side of the figure give the frequencies of the vibration in cycles per second. In all of the photographs time proceeds upwards, as shown by the arrow. In the first traces a break is noticeable about the middle of the vibration, which indicates the rest positions of the spots of light. This break was produced by



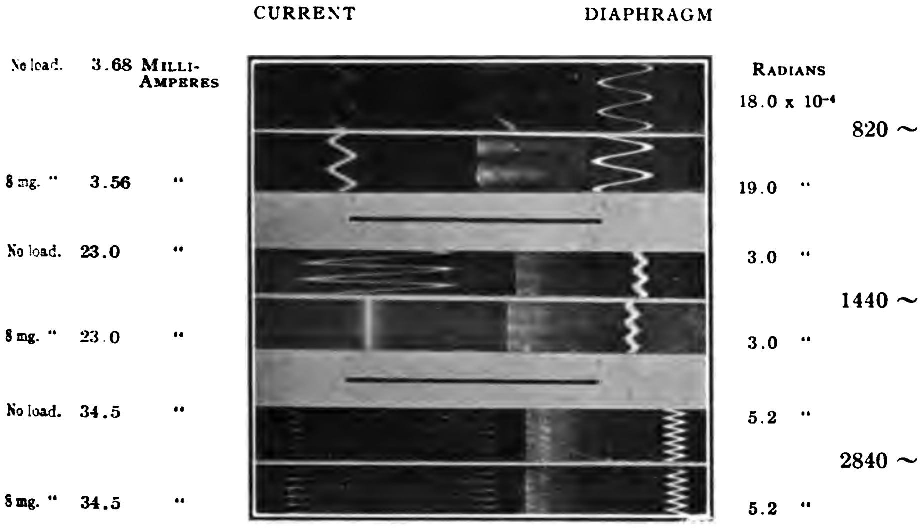
[MEYER AND WHITEHEAD]

FIG. 3—RECEIVER DIAPHRAGM A



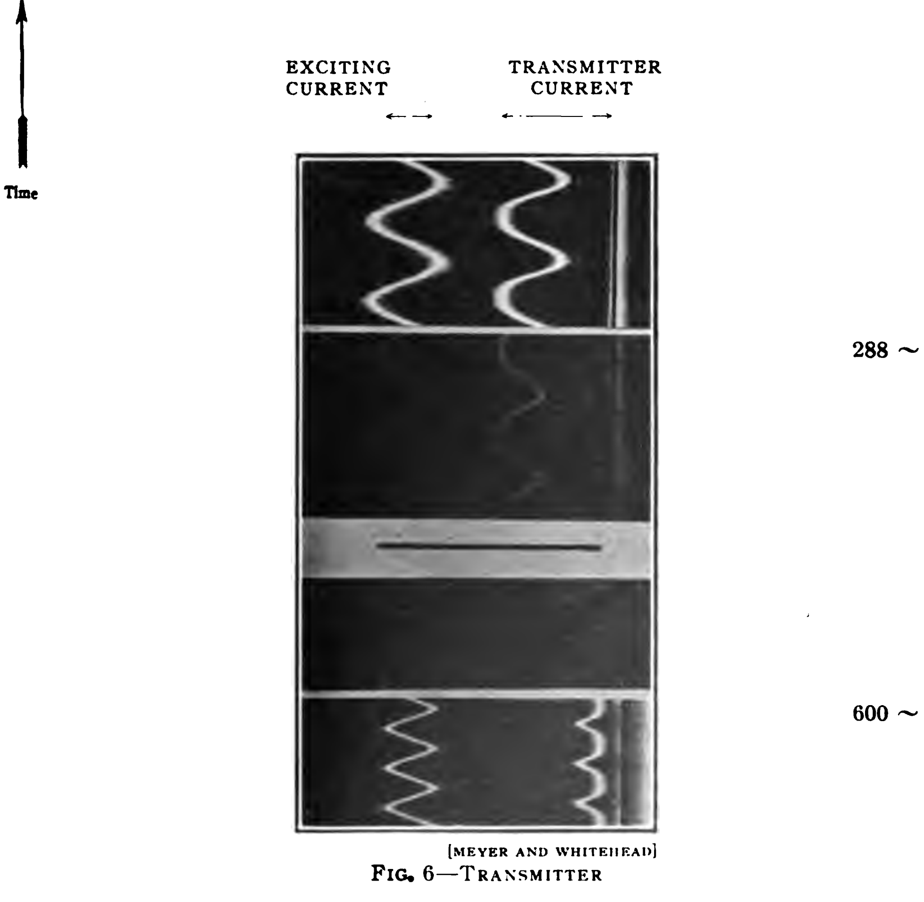
[Meyer and Whitehead]

Fig. 4—Receiver Diaphragm A



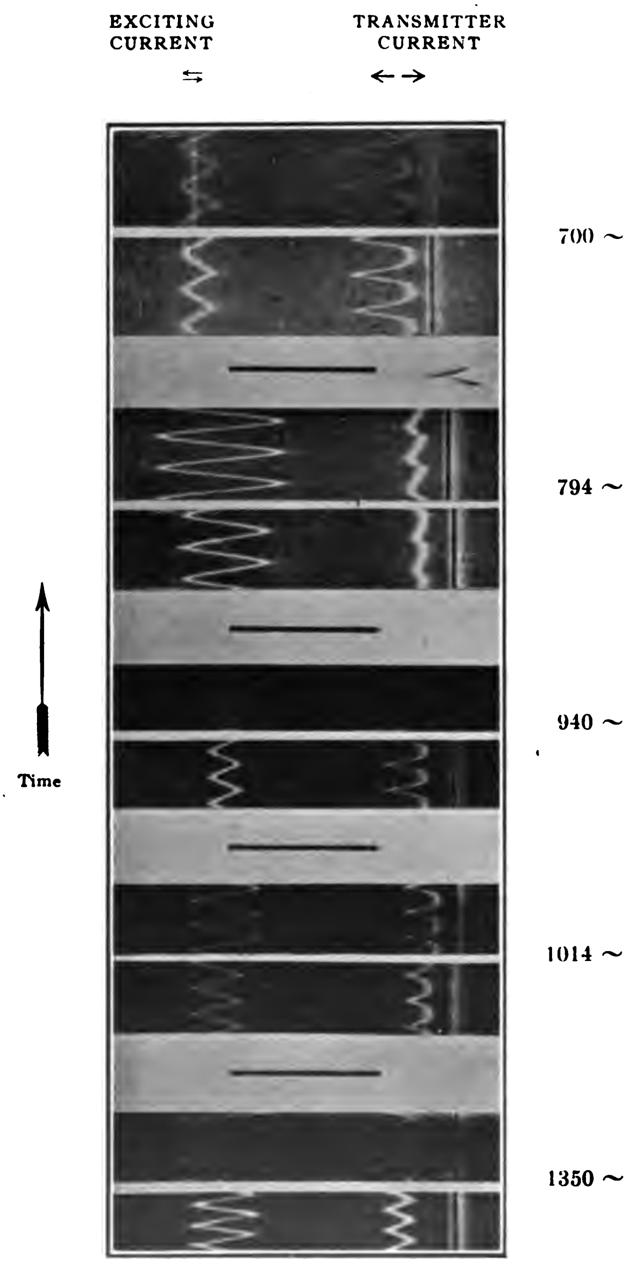
[MEYER AND WHITEHEAD]

FIG. 5—RECEIVER DIAPHRAGM B



[MEYER AND WHITEHEAD]

FIG. 6—TRANSMITTER



[MEYER AND WHITEHEAD]

FIG. 7—TRANSMITTER

placing a fine wire in the path of the beam of light when there was no current, but the wire was soon abolished as it introduced unnecessary complications.

The diaphragm trace for 60 cycles is seen to be somewhat unsymmetrical, the curve being pointed on the right, that is, when the diaphragm is nearest the pole pieces. At 232 cycles for a range of 13.6 the curve is rather unsymmetrical, but for a range of 6.7 the irregularity is less marked. At 332∼, and 1292∼ also, the irregularities are seen to be greater for greater ranges while for most of the other curves this is not noticeable. The development of the dimple in the curve for 332 and 1292 ∼ at the point where the diaphragm is furthest from the poles is rather surprising; it will be seen later that 332 ∼ shows a peculiarity in another respect. It might be expected from the following considerations to find greater regularity in the photographs for small ranges.

The force on the diaphragm is proportional to the square of the induction. If we consider the induction B as made up of a constant part B_0 due to the permanent magnetism, and a variable part B_1, due to the current, we have for the original force

$$F_0 = c\,B_0^2$$

and for the variable force

$$F = c\,B^2 = c\,[B_0^2 + 2B_0\,B_1 + B_1^2] \qquad (2)$$

The increment of the variable force over the original force determines the motion of the diaphragm. Its value is

$$\triangle\,F = F - F_0 = c\,[2B_0\,B_1 + B_1^2]$$

If B_1 is sufficiently small we may neglect its square and write

$$\triangle\,F = 2c\,B_0\;B_1 \qquad (3)$$

So that, if B_1 is made to vary harmonically, $\triangle\,F$ will do so. In the present work the currents have been kept nearly harmonic in all cases. The variation in the air gap between the pole pieces and the diaphragm would prevent B_1 from being strictly proportional to the current, but for sufficiently small vibrations the influence of the variation in the air gap may be neglected.

The ranges of all the traces were carefully measured. The results obtained for the first diaphragm are plotted in the curves of Figs. 8, 9, and 10. The abscissas are current through the receiver, expressed in milliamperes (effective). The ordinates are the angular range of oscillation of the diaphragm, expressed in radians $\times 10^{-4}$. Each curve gives the relation between current through the receiver and oscillation of the diaphragm at a given frequency which is marked beside it. The curves are all plotted to the same scale and put in separate figures to avoid crowding. They show that an approximately linear relation exists between the current and deflection of the diaphragm, even to the large values of current here used. The sound of the telephone for the greater currents was sufficient to be heard all over the room.

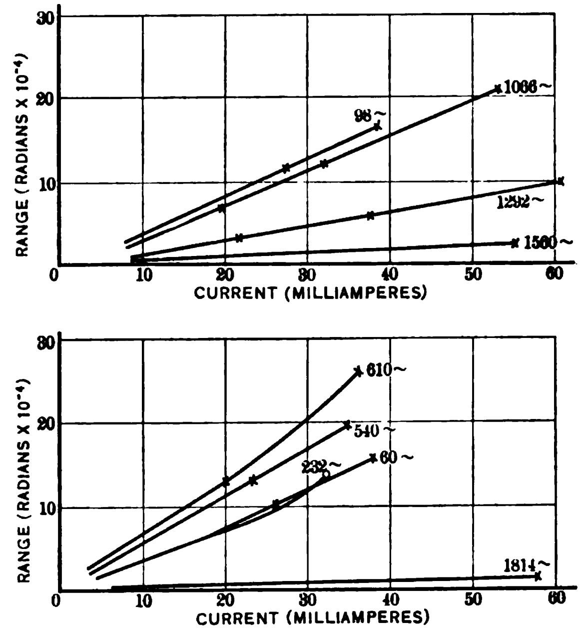


FIG. 8—RELATION BETWEEN CURRENT THROUGH THE RECEIVER, AND RANGE OF OSCILLATIONS OF THE DIAPHRAGM AT DIFFERENT FREQUENCIES.

From each of the curves of Figs. 8, 9, and 10, the angular oscillation corresponding to a current of twenty milliamperes, at the frequency for which the curve is taken, can be read off. In Fig. 11 a curve is plotted between the frequency as abscissa, and the angular oscillation as ordinate, showing the effect of change of frequency on the angle of oscillation, this being the so-called resonance curve for the diaphragm. It will be noticed that the curve starts out horizontally, then drops to a minimum at 300 ~ from which it rises and reaches a maximum at 720 ~, at which the range of oscillations is about five times that of the minimum, and about four times that at the lowest frequency. After 720 ~ there is no other maximum until 2600 ~, and then shortly after this there appears to be another, but this was not

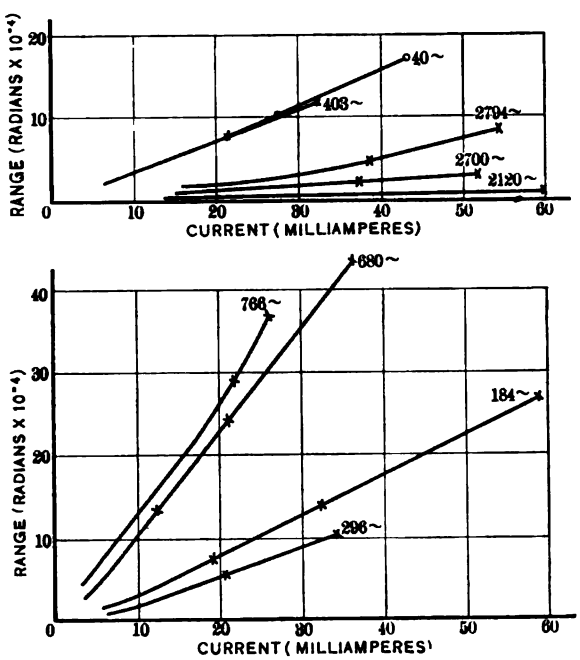


FIG. 9—RELATION BETWEEN CURRENT THROUGH THE RECEIVER, AND RANGE OF OSCILLATION OF THE DIAPHRAGM AT DIFFERENT FREQUENCIES.

quite reached as it was not desired to overspeed the machine at the time these records were obtained. It is rather surprising to find the minimum at 300, before the first maximum. At first its real existence was doubted but the appearance of a similar dip in the curve for the next diaphragm, with an entirely different make of receiver, seems to indicate a real effect. It should be remembered that the damping of the diaphragm in a receiver is not purely mechanical, but is partly electromagnetic and this may have a bearing here. The mechanical effect can be expressed by a term of the usual form $k\,\frac{dx}{dt}$ in the differential equation of motion of the diaphragm. The electromagnetic damping we may consider to be made up of two parts. One of these is due to eddy currents set up by the motion of the diaphragm in the permanent magnetic field. It would be present if the diaphragm were executing free vibrations. This also could be expressed by a term of the form $k\,\frac{dx}{dt}$. The other part is due to hysteresis and eddy currents caused by the current in the receiver. This would increase with the frequency, so that we are dealing here not with a constant damping coefficient, as is usually supposed in the treatment of forced oscillations, but with one that increases with frequency. The minimum in the resonance curve appears at about 300 ~ and it is the trace at 332 ~ to which attention was called above, which shows the dimple. The plate

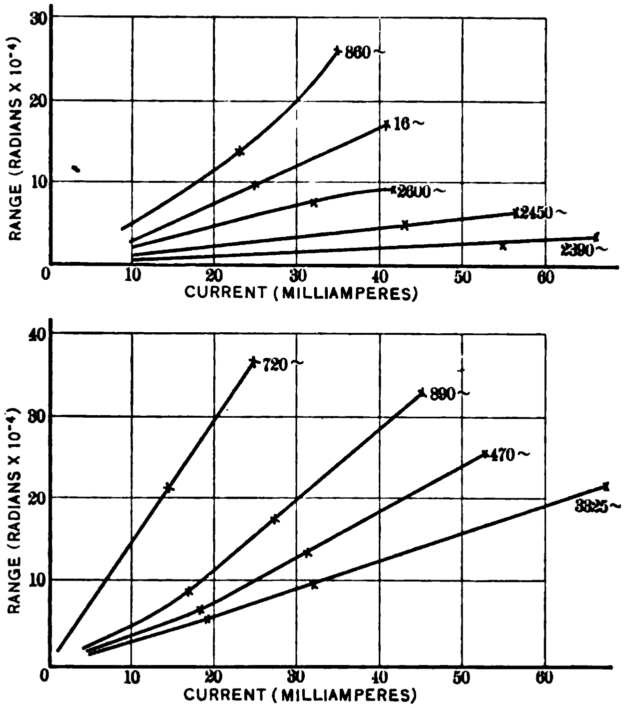


FIG. 10—RELATION BETWEEN CURRENT THROUGH THE RECEIVER, AND RANGE OF OSCILLATION OF THE DIAPHRAGM AT DIFFERENT FREQUENCIES

for 296 ~ (not reproduced) was exposed in two sections, giving traces very similar to the lower two of 332 ~. This plate was obtained before the one for 332 ~ and the range was not carried high enough to get the dimple. It cannot be definitely said that the minimum of the curve and the dimple in the trace are causally connected, but the coincidence is rather striking.

The resonance curve Fig. 11 covers the range of the important frequencies existing in the human voice. The lowest tone reached by man in singing is about 65 vibrations per second. The highest reached by a woman is 1036, but this tone contains harmonics of higher frequencies. A number of investigations have been performed on the vibrations contained in vowel sounds. According to results obtained by Bevier[7] the prominent frequencies are:

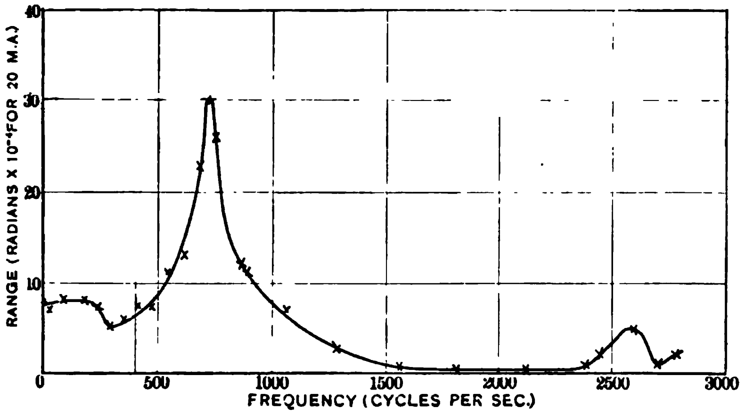


FIG. 11—RESONANCE CURVE FOR DIAPHRAGM A. GIVING THE RELATION BETWEEN FREQUENCY AND RANGE OF OSCILLATION FOR A CONSTANT CURRENT.

For *a* as in *hat*	650	1050	1550
" *e* " " *pet*	620	1050	1800
" *i* " " *pit*	575	1850	
" *i* " " *pique*			2050

In the consonants, especially those of the hissing type, very much higher frequencies exist, going in some cases as high as 10,000. These consonants have not the importance in speech that the vowels have, and it may well be said that the prominent

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[7] *Phys. Rev.*, 1901, 1902, 1903. Quoted by Barton " Text-Book of Sound," p. 672.

vibrations are included between 300 and 3000, probably not many lying above 2000.

We may obtain a comparison between the fundamental frequency of the diaphragm determined experimentally, with that to be expected from Rayleigh's formula. The greatest ordinate of the resonance curve comes at 720. This ordinate for any system lies at a somewhat less frequency than its free vibration. Further, the actual frequency is somewhat less than it would be if there were no damping. It is this last value which is given by Rayleigh's formula. By applying the theory of a system with one degree of freedom to the resonance curve of Fig. 11, a simple calculation shows that if there were no damping the free frequency of diaphragm " *A* " would be 732. This is 12 vibrations a second higher than the point for the maximum ordinate of the curve. The difference is not greater than the error in measuring the frequency. Let us now substitute in equation (**1**). We may take

$$q = 2.0 \times 10^{12}$$
$$\mu = \tfrac{1}{4}$$
$$\rho = 7.7$$

which gives

$$n = 2.41 \times 10^{5} \times \frac{2h}{a^2};$$

from the measurements of the present diaphragm,

$$2h = 0.023 \text{ cm.}$$
$$a = 2.5 \text{ "}$$

Hence

$$n = 890$$

this being the value required by Rayleigh's formula, whereas the value obtained experimentally is 732. The agreement is not very good but a better result is hardly to be expected. The diaphragm has 0.007 cm. (0.003 in.) of enamel on its front face, which probably loads it down without adding much to its stiffness, thus causing the actual value of the free frequency to be lower than the calculated one. The measurement of the thickness of the diaphragm is not very accurate, only a small spot at the edge being available for this, and moreover the value of Young's modulus substituted in the equation may not be the correct one for the iron of the diaphragm. It cannot be told in what direction more accurate values for these last two quantities would change the result.

DIAPHRAGM B

Another receiver designated as No. 122 *W*, also of the bipolar type, was next investigated. Its characteristics were: Total diameter of diaphragm 5.51 cm. (2.17 in.). Inside diameter of clamping ring 5 cm. (1.97 in.). Thickness of diaphragm over enamel and varnish 0.028 cm. (0.011 in.). Thickness bare at edge 0.023 cm. (0.009 in.). Distance between pole pieces and plane of clamping ring of diaphragm about 0.03 cm. (0.012 in.).

It seemed desirable to ascertain whether the mirror had any noticeable effect on the form or range of the oscillation, so in this set of exposures the current was kept as nearly constant as possible for each plate. One section was exposed with a load of 8 mg. wax placed on the diaphragm as near to the mirror as possible, and the other section was exposed without the load. Some of the photographs are reproduced in Fig. 5. In none of these is there any noticeable difference in wave form when the load is on and off, nor is any difference shown in the other photographs which are not reproduced. The traces were all carefully measured. The differences in width are of the order of the errors of measurement, which range from, say, 5 per cent when the traces are as wide as those for 820 ~ to 15 or 20 per cent for narrow traces, as for 1440 ~. The measurements on the same trace usually check up to one or two per cent if the range of the trace is a centimeter or more, but in measuring traces of different photographic intensity the accuracy is probably not so great. The figures for 820 ~ show an increase of 8 per cent for the loaded case over that for no load; this may be a real effect.

Fig. 12 gives the resonance curve as nearly as it can be plotted from the scant data obtained for this diaphragm. Frequency is plotted as abscissa, and the ratio of diaphragm oscillation to current as ordinate. If we assume the linear relation of current and diaphragm oscillation for a fixed frequency this gives the same curve as Fig. 11 to within a constant factor. We see that the minimum before the first maximum is again present, and in a more marked degree than for the first diaphragm. The maximum ordinate is about five times that at the minimum as before, but only three times that at the lowest frequency. However, it is not entirely certain that the maximum comes at 820 ~ as drawn. When watching the light spots this appeared to the eye to be about the maximum and so the photograph was made at this frequency. If more points had been obtained they might have shown that the maximum really lies at a somewhat different frequency, and has a 10 or 20 per cent greater value. The curve shows no further resonance points up to the highest speed the machine attained, but they doubtless would have been found if it had been possible to go high enough. This diaphragm had approximately the same characteristics as the first, so if we apply Rayleigh's formula we again get 890 as the natural frequency, the agreement with the experimental value being somewhat better this time.

General Observations

More diaphragms, and diaphragms of different characteristics, might have been examined by the method here used, but it was thought that before the investigation was extended in this direction further knowledge should be obtained about the motion of some one diaphragm. It was pointed out above that when a circular plate is vibrating freely, the nodes are circles and diameters.[8] In the case of a clamped diaphragm this means that the nodes may be located as shown in Fig. 13. These drawings are for the five lowest modes of vibration and are given in the order of ascending frequency. We may expect that in the case of a telephone diaphragm some of these types of vibration will be present. It cannot be said in advance which ones will occur nor to what extent they will do so. This depends on the frequency of the impressed force and on the way in which it is applied, and can only be found by experiment. Hence we may suppose that

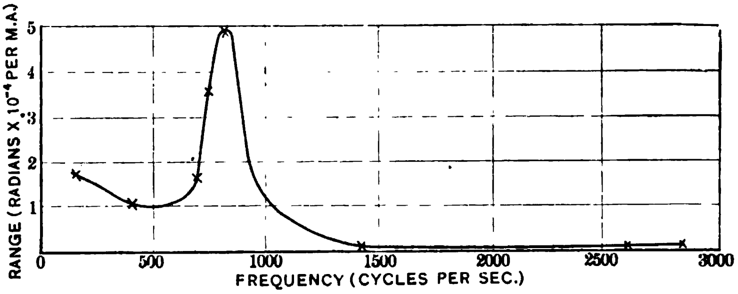

FIG. 12—RESONANCE CURVE FOR DIAPHRAGM B.

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[8] Winkelmann's "Handbuch der Physik, II," p. 372, ed. 1909. Rayleigh, "Sound," Vol. I, p. 331.

by fixing a mirror in one spot (*e.g.*, over the perpendicular bisector of the pole pieces), we cannot learn all that should be known about the motion of the diaphragm, and this is borne out, even to a more marked degree than was expected, by visual observation of the spot of light at certain frequencies. The spot ordinarily vibrated in a horizontal direction. This is what would be expected if the vibration consisted of a motion of the diaphragm as a whole (Fig. 13*a*,) or if there existed an internal circular node (Fig. 13*d*). We may refer to this as a " circular " vibration. At certain frequencies the spot of light vibrated, not horizontally, but obliquely. An oblique motion would be produced

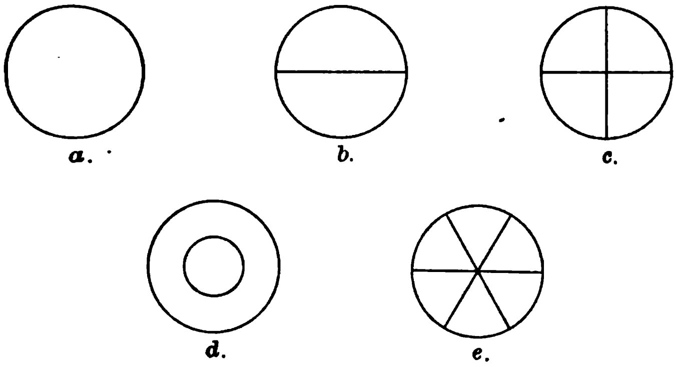

FIG. 13—REPRESENTING THE FIVE LOWEST MODES OF FREE VIBRATION OF A CIRCULAR DIAPHRAGM.

a.—The boundary as the only node—diaphragm vibrating as a whole.
b.—One diameter as node—the two halves of the diaphragm vibrating in opposite phase.
c.—Two diameters as nodes—adjacent quadrants are in opposite phase.
d.—Two circles as nodes—the inner and outer areas are in opposite phase.
e.—Three diameters as nodes—adjacent sectors are in opposite phase.

if there were superimposed on the circular vibration a vibration having one or more diameters as nodes, as in Fig. 13 *b*, *c*, or *e*. We may speak of this motion as a " diametral " one. The mirror need not be located on a node to show this component, but would do so to some extent if it were located anywhere except on a loop. This component cannot be symmetrical about the center of the diaphragm.

It is not at once evident why the diametral vibration should be introduced at all. If we assume the complete symmetry of the diaphragm about its center, and of the pole pieces about the diameter bisecting them perpendicularly, there is no reason to expect it. We must look for a lack of symmetry somewhere. The mirror on the diaphragm suggests itself, but the weight of the mirror was only 4 mg. and it seems improbable that so small a load could be responsible for the vibration. It was thought that some sort of asymmetry must exist in the poles, and if this were the case then a rotation of these behind the diaphragm ought to make the nodal diameter rotate in the diaphragm, keeping a fixed position with reference to the poles. This would allow an exploration of the motion, so to speak, around the diaphragm without moving the mirror or the diaphragm itself. A receiver (122 *W*) exactly like the one used with diaphragm "*B*" was fitted up to allow the rotation of the poles. With this instrument it was found that the diametral component recorded by the spot of light changed markedly as the pole pieces were rotated; it passed from zero through a maximum and back to zero in about half a revolution. But it was also noticed that there was a decided change in the intensity of the sound as the rotation took place, which, of course, should not exist if the diaphragm were symmetrical and the nodal diameter were merely being turned therein. Moreover the maximum diametral components recorded by the image coincided with the maximum sound, so that possibly the main thing shown was that the amplitude of the diametral vibration of the whole diaphragm depended on the orientation of the diaphragm over the poles. Three things presented themselves in explanation of this fact: First, mechanical imperfections in the rotating part might cause the poles to approach the diaphragm in certain positions and recede at others. Second, the influence of the weight of the mirror might make one direction in the diaphragm different from another. Third, the grain of the diaphragm may be the cause. This was suggested by Kempf-Hartmann[9] as a possible cause of asymmetry. Some rough experiments were at once instituted to decide between these three possibilities, and it is certain that mechanical imperfections play only a small part if any at all. No decision could be made between the influence of the mirror and grain, but it is thought that this can be done in the future. If it develops that the orientation of the grain in the diaphragm over the poles plays an important part in determining to what extent the diametral vibrations are introduced, it would appear to be a matter of some importance.

Whether these vibrations are a help or a hindrance in the

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9. Kempf-Hartmann. *Annalen*, VIII, p. 492 1902.

transmission of speech it is difficult to say. It is generally considered that the fundamental tone of the diaphragm falls within the range of the principal frequencies of the voice, and this is borne out by comparison of the curves of Figs. 11 and 12 with the data given on the frequencies for different sounds. The amplitude of the circular vibration is small between the fundamental and the next higher resonance tone. Sounds of certain pitch are therefore very much magnified in relation to others. The frequencies of the vibrations with one diameter and two diameters as nodes lie below the frequency for the second circular vibration. From the observations discussed above it appears that a telephone diaphragm may be made to take up these modes of vibration by properly orienting it over the pole pieces or by properly loading it. Now, might it not be possible by deliberately introducing the diametral vibrations, both in transmitter and receiver, and choosing the sizes of the diaphragm in such a manner that the maxima of the resonance for the one diaphragm coincide with the minima of the resonance for the other, to maintain more nearly the relation between the amplitudes of sounds of different frequencies?

WORK ON THE TRANSMITTER

Arrangements and Apparatus. For the transmitter the general problem is similar to that for the receiver, namely, to exert an oscillating force of known form on the diaphragm and record the vibration produced by it. As in actual use the transmitter is acted on by sound waves, the most natural thing would be to use these for the impressed force, but experimental difficulties arise which make this impracticable. It is difficult, if not impossible, to get a source of sound which is sufficiently loud, and at the same time gives a pure tone of which the pitch and intensity may be easily varied and measured over a wide range. Moreover when working with sound sources in an enclosed space, such as the room of a laboratory, there are always standing waves set up between the walls of the enclosure which would introduce a further uncertainty in determining the intensity of the sound which is incident upon the transmitter diaphragm. For these reasons no attempt was made to use a sound source. From the work on the receiver the conclusion seemed justified that the pull produced on the diaphragm by the receiver magnet is nearly harmonic for a harmonic current, and the amplitudes of the force and current are proportional if the current is not too great. It was accordingly decided to use a receiver magnet for producing the force acting on the transmitter diaphragm, as this allows the frequency and amplitude to be easily varied and measured. The magnet of a receiver was mounted rigidly in front of the transmitter. A small iron disk was shellaced on to the diaphragm to have some magnetic material for the magnet to act on, as the transmitter diaphragms themselves are of aluminum. The necessity of using the disk and the fact that the magnet produces a central force instead of a distributed one, as does a sound wave, are disadvantages of this method. (The weight of the disk was 0.81 gram.)

The current from the alternating-current generator was passed through the coil of the receiver magnet, and the current wave recorded on the oscillograph. For recording the vibration of the diaphragm the mirror method would have had certain advantages, but with a system as stiff as the transmitter the amplitude would not be great enough. Current from a storage battery was passed through the transmitter and the second vibrator of the oscillograph in series, and the variation of current in the transmitter due to the vibration of the diaphragm was recorded on the same photographic plate on which the curve of the current through the magnet was recorded; the variation of current in the transmitter was taken as a measure of the oscillation of the diaphragm. The electrical connections are shown in Fig. 14. In one electrical circuit, which will hereafter be referred to as the "magnet circuit," the high-frequency generator *G*, the oscillograph O_1, the coil on the magnet *F* and the resistance *R* are in series. In the other circuit, which will be called the "transmitter circuit," the current flows from the storage battery *B* to the diaphragm *D*, through the carbon granules box of the transmitter *C* to the oscillograph O_2, and through the milliammeter *A* back to the battery. The battery consisted of three storage cells; the voltage remained constant at 2.9 volts throughout. The two circuits

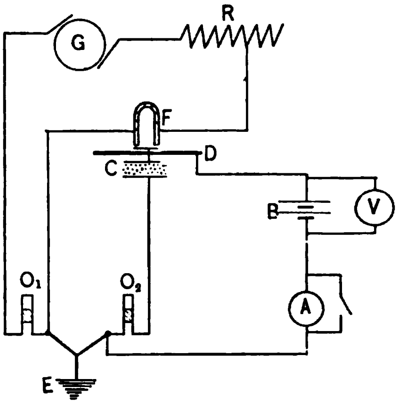

FIG. 14—ELECTRICAL CONNECTIONS IN WORKING WITH THE TRANSMITTER.

had the point E in common at which they were connected to earth. The action of the apparatus is simple. The alternating current in the coil of the magnet F causes the diaphragm D to vibrate. Before the beginning of the vibration the current in the transmitter is steady and can be read on the milliammeter A. This steady current causes a steady deflection of the oscillograph O_2. When the motion of the diaphragm begins the current undergoes variations which are recorded by O_2. During the time of making an exposure the milliammeter is shunted so as to do away with all possible self-induction in the transmitter circuit.

PHOTOGRAPHS AND MEASUREMENTS

Some reproductions of the photographs are shown in Figs. 6 and 7. The trace on the left shows the current in the magnet coil. The zero line is not shown but would traverse the middle of the trace, as this is due to a simple alternating current. The straight dark line on the right gives the line for zero current in the transmitter. The trace to its left gives the variation of current through the transmitter when the diaphragm is oscillating. That is, the distance from the zero line to the trace at any point gives the instantaneous value of the current, and the difference between the maximum and minimum distance gives the range of oscillation of the current. The frequencies are given to the right.

On the plates for 600, 700, 940 and 1014 cycles, and on most of the plates not reproduced, the traces are pointed for maximum current (granules compressed) and flat for minimum current. In these cases the steady current line runs nearer the minimum than the maximum. This was shown by an asymmetrical broadening of the light spot toward the left when the exciting current was turned on, and also by a rise in the reading of the milliammeter A. In the first plate shown, namely for 288 cycles, this is reversed. The points are for minimum current and the flat side for maximum. In this case the steady current line runs nearer the maximum, the broadening being asymmetrical to the right, and correspondingly, the milliammeter fell on making the exciting current. The plate for 1350 cycles gives a more symmetrical trace than 288 $\sim$, but showed the same anomalous behavior in the broadening of the light spot toward less current, and the dropping of the milliammeter. These two plates were taken one after the other. This anomalous condition had been observed visually on one occasion when observing the oscillations by means of a ground glass and a rocking mirror, but the transmitter had gone back to its normal condition before a photograph was obtained. After this no amount of tapping and exciting would bring it back. The plates in question were obtained when at the end of a series of exposures this condition was found to exist accidentally. After these two plates the transmitter returned to

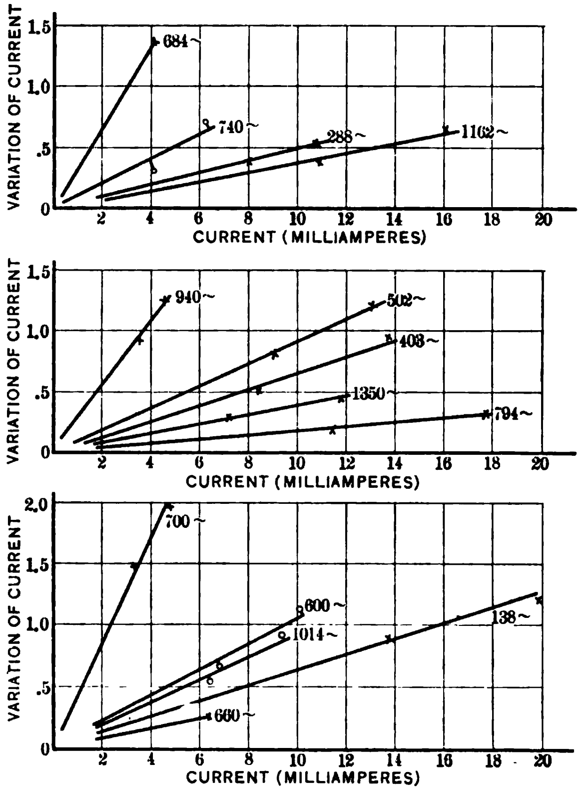

FIG. 15—RELATION BETWEEN CURRENT THROUGH THE COIL OF THE MAGNET, AND THE VARIATION OF THE CURRENT THROUGH THE TRANSMITTER.

its normal state. Later one more anomalous trace was obtained at 660 but this does not fit in well with the others. The peculiarity did not seem to occur at any definite frequency, but seemed to depend entirely on the arrangement of the granules, for when once present it showed over a wide range of frequency, and when absent the same frequency could be gone over with normal results. It is not to be confused with ordinary "packing" but may be closely allied to it. The traces for the transmitter in general show a great deal more distortion than do those for the receiver. The actual range of force on the diaphragm is considerably less for the transmitter, as the air gap between the magnet and disk is greater, and the amplitude of the current in the magnet is less.

Plotting for each frequency the current in the magnet as abscissa, and the variation of current in the transmitter, per milliampere of steady current, as ordinate, we get the curves of Fig. 15. This relation between the two is seen to be approximately linear. The point farthest out usually shows a somewhat steeper slope, but in several cases the reverse is true. The accidental errors due to changes in the transmitter are, of course, great, so a straight line running between the two points was considered a fair locus for the curve. In Fig. 16 a curve is plotted having frequencies as abscissas, and as ordinates the variation of current in the transmitter per milliampere of steady current, when the current in the magnet has a constant value of four milliamperes. This is the resonance curve for the diaphragm. The points all fall fairly well into line except the one for 660 ∼, which is the one exposure made when the transmitter was for the second time in the anomalous state. The two plates obtained when it was for the first time in this state fall into line very well. The resonance curve certainly does not include the point at 660 ∼, as the light spots were watched vis-

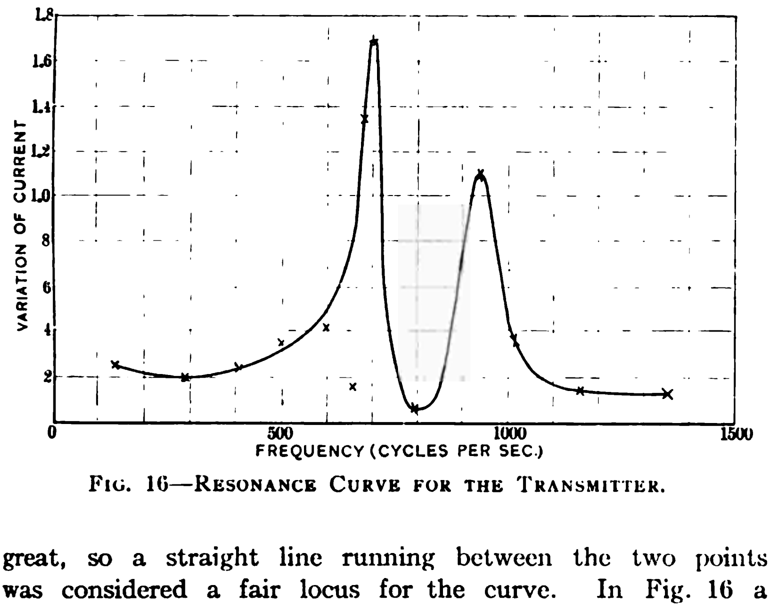

FIG. 16—RESONANCE CURVE FOR THE TRANSMITTER.

ually, when the granules were in normal condition, and no drop in amplitude at that frequency was ever noticed. The light spots were watched time and again as the generator accelerated or came to rest; and it was easy to see the marked continuous rise and fall in the width of the oscillation. Whatever errors may have crept into the determination of one or two of the points, the general nature of the resonance is certainly that of Fig. 16.

We notice in the curve the slight fall before the first maximum which was present in the receiver diaphragm curves, and is probably due to the losses in the magnet. Next the sharp maximum at 700, the minimum at 800, the second maximum at 940, and after this the drop to a fairly constant value. It is regretted that the investigation could not be pushed above 1350, but at higher frequencies conditions became very unsteady; especially is this true of the average current through the transmitter. It is a great surprise to find such sharp maxima in the curve, and two so close together. The ordinate of the first maximum is seen to be about eight and a half times that at the minimum, and six and a half times that at the lowest frequency; at the second maximum about eighteen times that at the minimum just before it, and about four times that at the lowest frequency. The location of the fundamental vibration at 700 cycles is in good agreement with Gati's work. It is to be regretted that no data can be obtained from his results regarding the sharpness of the resonance. His curves having as ordinate the current in a secondary circuit have a zero ordinate for zero frequency, *i.e.*, they start from the origin. Hence no comparison between the amplitude at resonance with that at zero frequency can be made.

The first resonance of the diaphragm we would naturally suppose to be due to its vibration as a whole. The second may be introduced by one of the so-called damping springs. The diaphragm in most modern transmitters, and in the one here worked with, is held in place by two pieces of spring steel about ⅜ in. wide, 1½ in. long and 0.01 in. thick. These have rubber tips on the ends. One presses against the diaphragm at the edge; and the other one, some distance in towards the center. Now the point where the second one presses is more firmly supported than the points in its vicinity, so the second resonance may be due to a vibration of irregular configuration with this point lying on a nodal line. If this is the case one of the actions of the damping springs is just the opposite to that commonly supposed. According to Kempster B. Miller:[10] "The object of these damping springs is to prevent too great an amplitude of vibration of the diaphragm, and also to keep it from vibrating in separate parts instead of as a unit." The inside damping spring may also have considerable influence in raising the fundamental period of the diaphragm as it adds to its stiffness. It should be possible to settle these questions by placing both springs on the edge and taking another resonance curve. It is hoped to do this in the near future.

SUMMARY OF RESULTS

Photographs have been obtained showing the vibration of receiver diaphragms when approximately harmonic currents are passed through the receiver. These show considerable distortion at some frequencies and very little at others. At any one frequency the distortion is less for smaller currents. This is what would be expected from *a priori* consideration.

An approximately linear relation has been shown to exist between current and amplitude of oscillation of the diaphragm over the range of work, which extends well beyond that of practise. Resonance curves for two receiver diaphragms have been plotted giving quantitative data of the influence of the natural period of the diaphragm.

The effect of a small load on the form and range of the oscillation was examined. Its influence could not be detected except in one instance in which there was possibly a slight effect on the range of oscillation.

Diametral vibrations of the diaphragm were observed in cases in which they would not have been expected from the apparent symmetry of the instrument. The orientation of the diaphragm over the pole pieces was observed to have a marked effect. It has not been experimentally settled whether this is due to the mirror or the grain of the plate, but it is difficult to see how a mirror weighing only 4 mg. could cause the vibrations. It is suggested that by properly introducing " diametral " vibrations the transmission of speech might be improved.

Photographs have been obtained showing the variation of current in the transmitter when an approximately harmonic force acts on the diaphragm. These show a rather marked distortion even for the lowest exciting force used, which was very much lower than the lowest force used on the receiver diaphragm.

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[10] "American Telephone Practice." 4th edition, p. 56.

These distorted curves may be just reversed from their normal form when the microphone is in a certain abnormal state.

An approximately linear relation exists over the range examined between the variation in current and the exciting force. The resonance curve of the transmitter is given, showing very marked maxima and minima. The first maximum is attributed to the fundamental period of the diaphragm vibrating as a whole. The second maximum is attributed to the diaphragm vibrating in an irregular configuration on account of the damping springs.

DISCUSSION ON "THE VIBRATION OF TELEPHONE DIAPHRAGMS" (MEYER AND WHITEHEAD), BOSTON, MASS., JUNE 27, 1912.

George D. Shepardson: Attention is called in the paper to the irregularities in the oscillograph curves at the values 332 cycles and 1292 cycles. I examined that "dimple," as it is called, with considerable interest, and found two possible explanations for it. In both cases the dimple occurs where the diaphragm is at the greatest distance from the magnet. The first explanation which occurs is that the diaphragm is there in a comparatively weak field where the diaphragm is more free to vibrate in its own natural periods. Another more plausible explanation is that the actuating current in this case is several hundred times greater than the normal current. Now, that means, if we refer to the equation which is given here for the performance of the diaphragm, a very strong m.m.f., due to the current in the coil. At the "dimple," the current in the negative or demagnetizing direction becomes dominant and neutralizes the m.m.f. due to the permanent magnet; as the current passes the critical value, its pull becomes positive, being proportional to the square of the current, and thus causes the "dimple" at the extreme value. I think this second reason is much more plausible than the first, that is, that it is the m.m.f. of the current overcoming and reversing the permanent field.

That suggests a point in connection with the equations (2) and (3). You will find that all of the discussions of the theory of the telephone transmitter are based on the assumption that the current in the coil actually changes the value of the permanent field. I think that is entirely erroneous. If you place a coil about the heel of the magnet, at the most remote distance from the coils, you will find that the variation in the permanent flux is almost nil; it amounts to from 1 to 10 per cent with the greatest possible variation in the inductance you can get, by removing the armature entirely away from the soft iron pole pieces. It seems to me, the real action of the current in the coil on a telephone receiver is not to change the total amount of flux but simply to change the distribution of it. I doubt very much whether the total flux passing through the diaphragm is even changed, but the action of the coil is to concentrate that force.

Inquiry is made about the discrepancy between the natural period as observed and that as calculated, 890 in one case and 732 in the other. I suggest that that discrepancy may be due to the fact that Rayleigh's formula does not take very much account of the temperature effect. The temperature acts very much like the cords of a drum. You tighten up the cords on the drum and the tone of the drum rises, and so in the case of the telephone receiver, as the temperature rises it strains the diaphragm and raises its natural period of vibration. Rayleigh's formula does not specifically cover that point. In the case of the transmitter diaphragm, clamped only at one or two points, and if there are other points these are usually in a straight line, the temperature effect is almost nil. I have applied temperature variation of 100 deg. fahr. to a transmitter diaphragm and found no appreciable difference in the sensitiveness to sounds of varying pitch.

Mention is made of the effect of the damping spring. I have experimented recently upon a transmitter where the source of sound was a siren whose speed and whose pressure were separately controllable, and I found in almost every case a curve of sensibility which bears a general family resemblance to Fig. 16 of the paper. The effect of the damping spring upon the natural period does not seem to be as great as one might expect, although it does seem to have some influence. In one case I found a minimum sensitiveness at 1115 vibrations, with the damping spring removed clear off to one side. With the damping spring shifted back to its ordinary position, and with the ordinary tension, the maximum point was at 1070 vibrations. By tightening the damping spring, moving the screw in about one-quarter turn, the maximum point was shifted over to 975, so that the presence of the damping spring seems to affect the pitch for maximum sensitiveness. These results were not repeated, and I do not attach great importance to them.

Regarding the positions of maximum sensitiveness in the curve of Fig. 16, experimental work shows that these positions vary according to the construction of the transmitter; that is, transmitters of different manufacture will show these points of maximum sensitiveness coming at varying positions. Different transmitters from the same factory will show marked differences in the positions of the peaks. For example, one transmitter showed minor peaks at about 500 cycles per second, and major peaks at some 925 cycles per second, another at 1065, another at 1655, and another at 2100, so you may expect a series of peaks of maximum sensitiveness. In another case the peaks came at 1600, 900, 1065, and 1640, and this case of 1640 was what I would call the *summum maximum*, that is the highest, higher than any of the other peaks. Another transmitter had equal maxima at 1050 and 1700.

I would say that these experiments were made with sound as the source of the disturbance, and there was considerable difficulty experienced in getting rid of reflections from the walls. In some cases these brought in phenomena that were very puzzling until means were found to eliminate them.

George W. Pierce: I have been very much interested in this paper, particularly as Professor Kennelly and I have recently been making some experiments[1] which include as a part of the work the determination of the period of vibration of the telephone diaphragm. First, as to temperature. One of our

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[1] Published in full in *Proc.* Am. Acad. (Boston), Vol. 48, No. 6, 1912.

laboratory mechanics, Mr. Greaves, who was trying to make a telephone of particular pitch, found when he breathed on the diaphragm he changed the period perhaps fifty per cent. The period changes enormously if the diaphragm is rigidly clamped into a metallic frame, but if the diaphragm is loosely clamped, as in the case of the ordinary telephone receiver, with washers or gaskets, the temperature does not have so great an effect.

In regard to the occurrence of the dimple in two or three of Meyer's and Whitehead's oscillograms, also with some oscillograms similar to these, I found that the dimple occurred when the current was large, independent of the pitch, and it seems to me to be the phenomenon that Professor Shepardson has mentioned, of the preponderance of impressed force over the directing force of the permanent magnet. To avoid that effect I found that, if you use a permanent magnet for the field and attach a coil to the diaphragm, so as to link with the magnetic flux of the field magnet, and send alternating current through the coil, you can vary the pull on the diaphragm to any extent, yet get no dimple at all, because there was no change in the B_0 magnetic field by the effect of the impressed current.

In regard to the period of the diaphragm, Professor Kennelly and I have been measuring resistance and inductance of the telephone receiver at different frequencies, and the result is very interesting and indicates the marked effect of periodicity of the diaphragms as Messrs. Meyer and Whitehead have found. If you measure the resistance and the inductance with the telephone diaphragms damped you get one value, and then, if you take your finger off the diaphragm, and allow it to vibrate, you get a different value of inductance and resistance.

With the diaphragm vibrating, the inductance and resistance may differ by 50 per cent from the inductance and resistance with the diaphragm damped. Let us call the excess of the inductance or resistance when the diaphragm is free over the inductance or resistance when the diaphragm is damped *the motional inductance or resistance* of the receiver. The motional inductance multiplied by the angular velocity we shall call the *motional reactance.* If now we plot motional resistance and motional reactance against the angular velocity of impressed e.m.f. we get —for a particular receiver—the curves "reactance" and "resistance" in Fig. 1 herewith. At the pitch of 5700 radians per sec. the vibration of the diaphragm increases the resistance by a large amount (22 ohms). At a slightly different pitch—5900—the vibration of the diaphragm decreases the resistance by 45 ohms. The reactance may follow a curve somewhat like the resistance curve, but in general, with the change of pitch, the vibration of the diaphragm causes the reactance to decrease to a minimum and then to go up again, as shown by the curve marked "reactance."

Now, if we measured the inductance, calculated the reactance and measured the resistance, we had the impedance, we also knew the current—and, multiplying the square of the current by the resistance, we get the power, and taking the difference between the power when the telephone is free and vibrating, and the power when the telephone is damped, we get the curve marked "power" of Fig. 1. The change-of-power curve, the amount of power supplied to the telephone when free in excess of the amount when damped, is very large when you approach the resonant period of the diaphragm, and attains its maximum in the neighborhood of natural period of the diaphragm, which in the case of Fig. 1 was 5820 radians per second. This change of power amounted to as much as 68 per cent, when the telephone was making a pretty good noise. That is, if you put your finger on

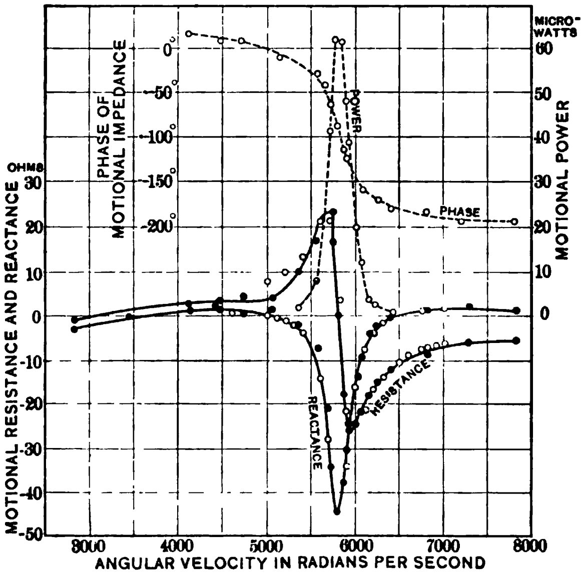

FIG. 1

the diaphragm and measure the power input at constant voltage, and take your finger off the diaphragm, and then measure the power input, you will find that the power input has increased by 68 per cent.

The telephone was free in a room, and the room was full of sound, when we were using current of frequency near the resonance point, and the sound interfered by reflection, producing stationary waves in the room. If an assistant walked through the room, so as to go through the different points of maxima and minima of sound, the effect was a reaction on the telephone, so that its inductance and resistance changes with the position of the assistant in the room, and if you had a bridge balance for inductance and resistance and allowed a man to walk through the room, the bridge would be variously thrown in and out of balance. The reflected sound, coming back and striking the diaphragm, determines in part the work by the diaphragm, so that a shift of the stationary wave system in the room affected inductance, resistance and power. With a given e.m.f. the resistance of the diaphragm would usually increase with the amount of work done by the diaphragm, and that would depend upon the stationary wave system.

If you plot the motional reactance against the motional resistance—meaning by the motional values the excess of reactance or resistance when the diaphragm is free over the corresponding value when it is damped—if you plot one of these quantities against the other, *R* being plotted horizontally and *L* being vertical, you get a circular locus, as in Fig. 2. The resistance and inductance change in relation to each other. The position of the center of the circle is determined by the mechanical and electrical constant of the diaphragm, and if you plot angular velocities of impressed e.m.f. around the circle, you begin at the origin with angular velocity zero, and as the angular velocity increases to infinity the vector "motional" impedance goes once around the circle in a negative direction. The frequency of e.m.f. which gives this point of the impedance circle diametrically opposite to origin is the natural frequency of the diaphragm; and the periods of the diaphragm differ in different instruments and also the sharpness of these resonance curves differs in different instruments. If you take a curve like that which Messrs. Meyer and Whitehead have in their paper—or the resonance curve of the excess power put into the telephone when the diaphragm is free, you find that with an ordinary Bell receiver, the change of frequency to throw the diaphragms well out of resonance may be as much as 100 radians per second, but if you take a diaphragm rigidly clamped around the periphery by a heavy metallic clamp a change of period of 10 radians per second in five thousand would throw it completely out of resonance and reduce the amplitude of vibration so as to give almost complete silence. If you breathe on the rigidly-clamped diaphragm when it is actuated by a resonant current, the heat of the breath may so change the natural mechanical period of the diaphragm as to produce complete silence.

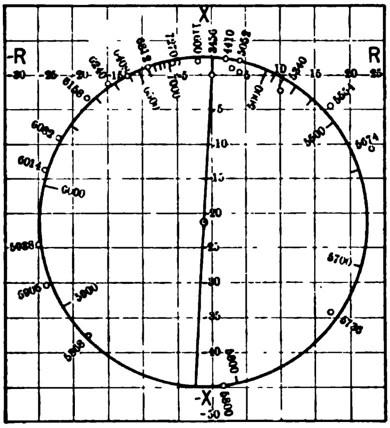

FIG. 2

Professor Kennelly and I find that the curves that I have shown agree closely with theoretical values obtained by considering the reaction of the moving membrane on the magnetic circuit. The theoretical treatment resembles the theoretical discussion of refraction and absorption in the neighborhood of the absorptive band in optics, except that in the telephone diaphragm problem account had to be taken of the fact that the magnetization of the iron lags behind the magnetizing forces, consequently the shift in phase in the telephone problem differs from that in the optical problem. We determined experimentally the shift of phase, and found that it was equal to twice the angle of lag of the magnetization behind the magnetizing force as was demanded by the theory.

Alan E. Flowers: I ask what bearing your results have on the values that have been given for the principal frequencies in telephone currents; and also, if it is possible in further experiments to use a diaphragm which would be free from enamel or other non-elastic substances, so that the period could be calculated more accurately, and if possible have the surfaces polished so that you would get the reflection from different portions at will without loading any particular spot. The very small mirror may or may not have some effect upon some particular laws of diametral vibration, depending, of course, on the relation of the weight of the mirror per unit area and the weight of the diaphragm itself per unit area; and, further, I ask if it would be possible to carry out further experiments with different diaphragm thicknesses.

A. E. Kennelly: There seems to be a difference of phase indicated in some of the oscillograms, judging from a merely random examination, between the currents and the motions, and we should be glad to know whether that difference actually exists or not.

John B. Taylor: Dr. Kennelly asked the question I was about to ask; that is, whether the apparatus is set up with sufficient exactness so that measurements made from the current to the diaphragm displacement line can be taken as indicating the relative phase between the two. Some of the records at low frequency seem to show more pronounced lags than those at higher frequency, and one of the records, in Fig. 4, seems to show almost a reversal. It is possible in this case they may have taken their apparatus down and set it up again with connections reversed.

John B. Whitehead: Which one?

John B. Taylor: The one I call a reversal, as it appears so to me, is 9.8 radians.

John B. Whitehead: What is the frequency?

John B. Taylor: It is 1066, as given on Plate LXXVI.

John B. Whitehead: There are some of these which are quite extreme.

John B. Taylor: 9.8×10^{-4} radians deflection under 1066 cycles seems to show a distinct reversal. Some appear to lag and others to lead.

Another point is, whether the natural period has not been modified by cutting out so much of the receiver cap. I should think that the records might have been taken by boring a small hole in it. The air cavity is likely to have some effect on the period. When sound is produced, energy must come from somewhere, but, as a rule, the efficiency of sound production is considered to be so low that the energy consumed is not given much attention. Just as an induction motor, clamped and at a standstill, will show different characteristics from a motor running, whether lightly loaded or heavily loaded, so will a telephone receiver show different electrical properties if the diaphragm is not allowed to move. It would be interesting to compare these records with others taken with the receiver held against the ear, in which case the " load " conditions would be those for which the apparatus is designed.

George D. Shepardson: There is one further point I want to call attention to in connection with the performance of the transmitters. In Fig. 6 the curve for the transmitter current is considerably flattened on one side; that is just what we should get if we had superimposed upon the fundamental wave a second wave having twice the frequency, but with the zero corresponding with the zero of the fundamental wave. That is just what is demanded in what is sometimes called the inverse theory of the transmitter, that is, the motion of the transmitter diaphragm which would be required in order to give a sine wave. That theory calls for a strong component of double frequency, and that is exactly what is shown in this experimental investigation, coming about from an entirely opposite direction. I think Mr. Anderegg was the first one who called attention to this in an article which appeared in *Telephony* in January, 1909, and his double frequency component, which he obtained mathematically, is exactly what is brought out in this oscillogram of the transmitter.

Frank Wenner: There is one point which I should like to call attention to, and that is that the motion of the diaphragm produces an e.m.f. in the circuit just as in any other dynamo-electric machine the relative motion of a part of the magnetic field and the winding results in an induced or generated e.m.f. This e.m.f. is a back e.m.f. and at the resonating frequency of the diaphragm may amount to as much as 90 per cent of the impressed e.m.f.

This is a matter to which I wish merely to call your attention now, as I expect to take it up in the discussion of the vibration galvanometer, the telephone receiver being one form of vibration galvanometer.

George W. Pierce: This whole effect of the shifting of reactance and inductance is the reaction of the diaphragm on the coils and that is taken account of in our theoretical treatment.

I have no doubt the treatment is the same as for the vibration galvanometer, except for the lag in the iron, which will shift our change of resistance curve to where our change of induction curve ought to be if there were no magnetic lag; that is, the double angle of lag amounts to enough to almost interchange these two curves.

As to this amount of power, perhaps my illustrations were not clearly explained. I said that this 68 per cent increase of power occurred when we got at the resonant point of the diaphragm. That does not mean that we have the measure there of the energy of the moving diaphragm; it merely means that with a given e.m.f. we draw more power under one condition than under another condition. The excess of power drawn amounted to a considerable quantity, and no doubt a good deal of it went into sound and energy radiation from the diaphragm, a part of which is not sound. The experiments were made with 0.3 of a volt in the telephone circuit, *i. e.*, under conditions which were somewhere near normal. The strength of the current in the telephone varies with the frequency, but it is in the neighborhood of one milliampere.

This reaction of the absorption of the sound upon the sounding body is a matter that Professor Sabine, at the physical laboratory, of Harvard, has emphasized and pointed out to me by means of an experiment of that kind. He had a tuning fork electrically driven in a room and measured the energy of sound all over the room, everywhere, and integrated it so that he got the total amount of energy in the room. He then put felt, which is an absorber of sound, in the room, with the intention of reducing the sound and measuring it again. He measured it again, and he had more energy than before. Although the felt absorbed a lot of energy, there was more energy than before. The explanation was that, putting the felt in the room shifted the wave zones in the room. He set his tuning fork at a constant amplitude, but the power drawn electrically happened to be increased by the shift of waves due to the introduction of the felt.

On the question of the absorption of energy by an observer, Professor Sabine has measured the absorption of energy by a person—that is, he got the energy in the room, and measured it, and then got the energy absorbed per person. It is interesting that he found that a woman absorbs more sound than a man, the difference being due to the difference in the character and amount of clothing of the woman and the man.

John B. Whitehead: Referring to the explanation for the "dimple" in the diaphragm curves—although I could not follow the first speaker very closely, I understand his suggestion is that the dimple was caused by the actual killing of the flux of the magnet itself, yet in the further progress of his remarks, he says that so far as he has been able to observe the total flux of the exciting magnet of the diaphragm changes very little throughout the range of operation due to the first current in any event.

George D. Shepardson: I distinguished between the ordinary operation of the receiver and that with a current some hundred times greater than the ordinary; in this case the current was unusually large.

John B. Whitehead: That may be true, and is certainly a very interesting suggestion.

As to the relation of frequency to pitch, Mr. Flowers explained that, I believe. It is quite obvious that if we depend upon the natural frequency of vibration of the diaphragm for telephonic communication it is, therefore, desirable to have the peak spread out as far as it possibly can be, and as high up as possible toward the peak of the curve itself. So that, if I understand the question correctly, I should think we would aim to get a diaphragm with resonance curve broad at its base, rather than extremely narrow, such as the one that Professor Pierce has described.

I think that great difficulty would be met with in attempting to polish the surface of the diaphragm itself in order to use it as a mirror for reflecting spots of light. The definition on the plate resulting from a reflection from the tiny mirror is really got by the size of the mirror itself. All the light reflected from the mirror itself goes to the plate, and the polishing of the whole surface would lead to a good deal of difficulty, diffused light spoiling the definition.

As to the thickness of the diaphragm, that would be an interesting line of investigation. Doubtless something has been done in this direction but so far as we know no results have been published.

As to the cutting out of the receiver cap, it is practically impossible to carry out any very extensive investigation of this kind without removing the receiver cap. We did nothing to check the influence upon the vibrations of the removal of the cap, but I do not believe, from the progress of the experiments, and from the absence of any evidence of an upsetting of any of the results, that it is an important factor.

It is proper in closing to state that the bulk of the work involved in the preparation of this paper was done by Dr. Meyer, in our laboratory, at Johns Hopkins University.

Charles F. Meyer: The explanation of Mr. Shepardson regarding the " dimple " in the curve obtained at 232∼, for a range of 21.8×10^{-4} radians, seems very plausible. His explanation is corroborated by an examination of the curve at 1292∼, for a range of 9.8×10^{-4} radians, which also shows a slight dimple. It will be observed that the values of the current corresponding to these two photographs were 68.0 and 61.1 milliamperes, and for no other records did the current have such high values. It would therefore seem as though the " dimple " were due to the high value of the current.

In setting down the equations (2) and (3), page 1401, it was not desired to convey the idea that the current in the coils of the receiver actually changes the induction in the permanent magnet, for there is no reason to believe this. There is a certain amount of induction present due to the permanent magnet, and there is a variable induction, due to the current, superimposed on this. Equations (2) and (3) hold good independently of how far back into the pole pieces the variation in the induction extends.

The observation of Mr. Pierce upon the variation of power consumed by the telephone, accompanying a variation of the system of standing waves in the room, is very interesting. He did not state the proportionate magnitude of the change in power. In the present investigation no effect of the standing waves upon the amplitude was observed. The photographs were all obtained with the experimenter in one position, which was necessary for manipulating the apparatus, but no variation in amplitude due to walking around the room was visually observed. It is thought that a variation of ten per cent could not have escaped detection.

It was questioned as to how far the photographs might be relied upon to give the phase relation existing between the exciting current and the motion of the diaphragm. There was no attempt made to adjust the apparatus so that reliable measurements might be made, but the photographs give a general idea of the phase relation. According to the ordinary mechanical theory of forced vibrations the force and the vibration ought to be in phase when the frequency is low compared to the natural frequency of the system. As resonance is approached the phase of the vibration begins to fall behind and when the resonance has been well passed the vibration lags half a period behind the impressed force. In the present case the impressed force is that due to the magnetization, which lags somewhat behind the current, the amount of lag being small for low frequencies and increasing with the frequency. The vibration of the diaphragm ought, therefore, to be practically in phase with the current at the very low frequencies, then fall gradually behind as the frequency is raised, and when the resonance point has been well passed it ought to lag over half a period behind the current. Close scrutiny of the photographic reproductions of Figs. 3 and 4 will show that the vibrations are in phase for the low frequencies, and that the vibration falls behind as resonance is approached. The curve for 1292~, to which attention was called by Mr. Taylor, is beyond the resonance point. It seems to lag about half a period behind the current. The lag between the magnetization and the motion should, at this frequency, be almost half a period, and the real lag between current and vibration is probably more than half a period. The fact that the photograph shows only half a period may be due to lack of adjustment. The adjustment would have to be quite good in order to record the phases for the high frequencies with accuracy.

In answer to the question of Mr. Flowers it may be said that, before the small mirror was resorted to, attempts were made to reflect the light directly from portions of the diaphragm by silvering them, but even very small areas of the diaphragm are not optically true, and will not give a good image.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 27, 1912.

MILITARY TELEGRAPH LINES USING THE POLARIZED SOUNDER AS RECEIVING INSTRUMENT

BY GEORGE R. GUILD

It is well known that, in time of war, the army has considerable difficulty in keeping up its overland telegraph lines, and especially so if these lines are operated on the ordinary Morse system and with wet cells. In actual warfare, in the field, all impedimenta must be reduced to a minimum, and consist of as little perishable material as possible. If, for example, it is desired to operate a closed-circuit line of say 300 miles in length about 150 gravity cells would be required, and if the line were to be operated on open circuit it would require about 100 dry cells per station. On the other hand, induction telegraphy, so-called, allows such a line to be successfully operated with from four to six dry cells per station. This fact and other features of simplicity which it possesses explain the existence of army field induction telegraphy.

Ordinarily the United States Army induction telegraph kit consists of a polarized relay, a four-ohm sounder, key, induction coil, and four dry cells. These instruments are installed in a portable box weighing about 12 pounds. The induction coil is small and the ratio of the winding of its coils is as one is to one hundred, the primary coil consuming about 12 watts at four volts. New sets are being experimented with by the United States Signal Corps with a view of simplifying the present set by replacing the polarized relay and the four-ohm sounder by a polarized sounder, and as the results obtained so far have been very successful it is believed that a new type of kit will soon be adopted somewhat along the lines described in this paper. The writer has conducted a series of tests with induction telegraph circuits with the object in view of obtaining suitable kits and circuits in order that induction telegraphy may be used more extensively in the field than heretofore, to displace some, or many, of the closed-circuit lines which must now be used.

This paper will describe some of the important phases of single-impulse induced current circuits, and at the same time will also indicate the instruments which the writer has found to be best adapted to these circuits. In some cases these instruments may be advantageously used with other than induction circuits, and instances of these circuits are included in this paper.

It has been deemed advisable first to outline briefly the operation of an induction telegraph circuit. For the sake of illustration only, suppose that it is possible to construct an induction coil having an efficiency of 100 per cent. With such a coil as many watts could be obtained from the secondary coil as are expended in the primary. As watts are the product of volts and amperes, and as the voltage of the secondary coil to that applied to the primary coil is in direct ratio to the number of turns in each, it will be evident that it is possible to obtain a small current in the secondary circuit at high voltage, sufficient to operate a line, and still do this by drawing only a moderate amperage from the battery in the primary circuit at low voltage.

Of course it is known that current in the secondary circuit exists only while there is an increase or decrease of intensity of current in the primary coil, and further, that the direction in which the current flows in the secondary at the closing of the primary circuit is opposite to that at the opening or breaking of the primary circuit. Consequently, in order to operate a telegraph relay or sounder by a momentary induced or secondary current of reversed polarity, it is necessary that the armature of the instrument respond to direction of current flow, and the armature having thus responded it must remain at rest until a current in the opposite direction passes through the instrument and causes the armature to reverse its position. In other words, the relay or sounder must be a polarized instrument.

To overcome resistance of any considerable amount and yet have sufficient current on a line to operate relays, a comparatively high electromotive force is necessary. One way to obtain this electromotive force is to use sufficient cells in series with the line. Another way is to use an induction coil and a few cells with more frequent renewals, drawing a heavy current from these cells at low voltage and increasing the voltage and decreasing the current in the secondary circuit, thus obtaining enough voltage to overcome the considerable resistance of the line and sufficient current to operate polarized relays. For example, the army field kit previously referred to will operate well through a non-inductive resistance of 50,000 ohms with three dry cells, and can even be made to operate, under favorable conditions, through 100,000 ohms.

A type of telegraph sounder employing the well-known principles of the Hughes* relay lends itself so readily to induction telegraph circuits that the writer has used it exclusively in his experiments, either as a sounder, main-line or local, or as a relay. An illustration of this instrument (in this case a relaying sounder) is shown on Plate LXXIX.

Referring to this illustration it will be noticed that the instrument is in appearance very similar to the standard American sounders, except that a permanent horseshoe magnet of considerable strength is bolted at right angles to the lower cores of the electromagnets, one leg of the magnet to each core. The armature is a piece of soft iron. It follows that this use of the horseshoe magnet normally gives a certain polarity to the poles of the electromagnet cores. When a current is passed through the electromagnet coils it will either increase or lessen the strength of this induced magnetic polarity, and will cause the electromagnet cores to attract their armature more strongly if the current through the coils is in such direction as to work in conjunction with the magnetism of the cores due to the horseshoe magnet, or, if the current be in opposite direction, the magnetic effect on the armature may be neutralized, or at least nearly so, allowing the spring to raise the lever.

The sounder is made adjustable so that the lever will remain up until pulled down, and vice versa. This is termed " adjusting the sounder to its neutral position." Or a bias can be given to the lever so that it can be pulled down, but when released will return to the " up " position (and conversely). This latter adjustment enables the sounder to be used as an ordinary main line (or local) instrument.

There appears to be nothing that the ordinary sounder will accomplish that cannot be equally well accomplished with the polarized sounder, while on the other hand the position of the

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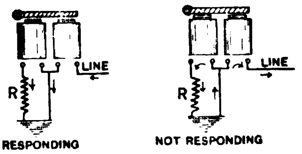
*Maver's " American Telegraphy," p. 240, edition 1912.

lever of the latter will be reversed by reversals of current flow, which is not the case with the ordinary sounder. This feature makes the polarized sounder desirable for the following reasons.

Due to the fact that the sounder is polarized and may be differentially wound, the instrument can be readily duplexed, responding (Fig. 1) to a current flowing into it from the line, but not responding (Fig. 2) to a current flowing through it from its own station, provided *R* (non-inductive resistance) equals the resistance of the line and that the capacity of the line is also balanced in accordance with the usual arrangement of duplex circuits.

It will respond to a current flowing for an instant in one direction, and its armature will remain attracted (or repelled) until acted upon by an instantaneous current in the opposite direction. Such a current would be produced by the secondary coil of an induction coil when the primary circuit is made or broken.



FIGS. 1 AND 2

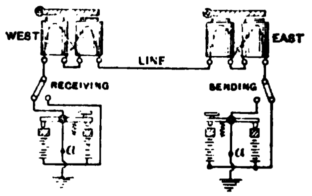


FIG. 3

It will operate in the same manner on certain lines in series with a condenser, as shown in this paper.

It can be placed directly in the line circuit without a relay or a local battery, and will give firm, readable signals similar to those obtained in a local circuit, with line currents of the ordinary strength used for operating ordinary relays. It gives excellent results on underground lines. As it can be adjusted to operate perfectly through a condenser it is a valuable instrument on lines subject to disturbances by earth currents.

Tests of this sounder seem to show that it is superior in action to an ordinary main-line sounder; that it can be used as a local sounder with good results; that it can be operated equally well on closed or open circuit lines, condenser lines, and induction lines; that used as a polarized relay it is very sensitive.

The following are a few circuits with which the sounder can be advantageously used.

Fig. 3 shows the method of connecting the sounders on simplex

PLATE LXXIX
A. I. E. E.
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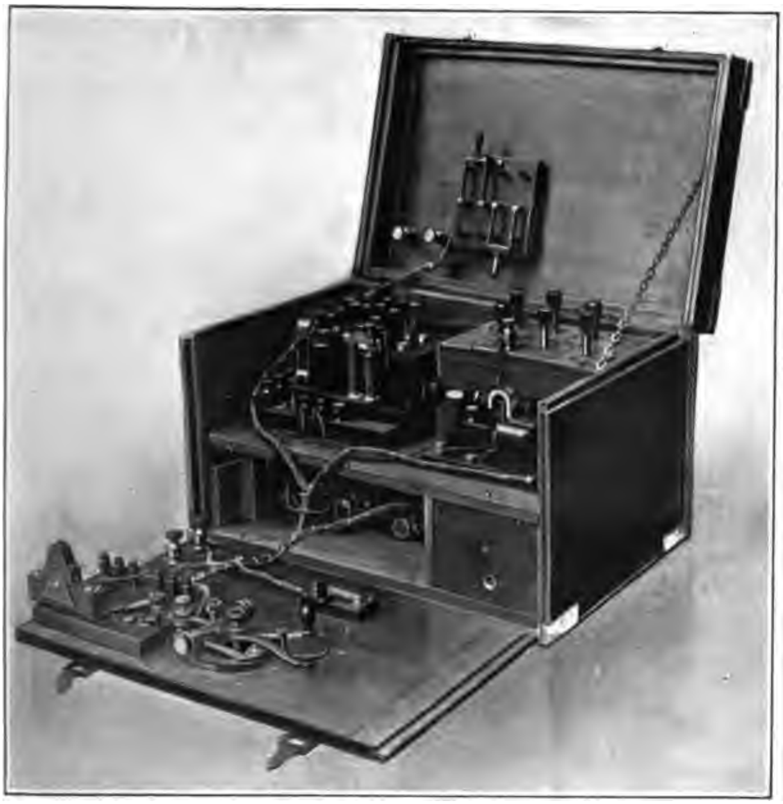
[GUILD]
INDUCTION REPEATER SET


[GUILD]
RELAYING SOUNDER


[GUILD]
SIMPLEX INDUCTION SET

double-current split battery open-circuit working. The sounders are adjusted to the neutral position, and a double contact key is used. Ten milliamperes are required to operate the instruments. A switch to throw from sending to receiving is shown. Condensers may be placed in series with the line at *a* if desired. In this figure East is sending and West is receiving.

Fig. 4 represents a central battery system; the battery *C B* is located at the central station. The line is taken from the point *0* through a resistance of some two thousand ohms, and the first set is at the central station. Other lines may be connected at *0* as shown, each one of them being first carried through two thousand ohms of resistance. Polarized sounders are used at the central and at the way stations, and a two-microfarad condenser is in series with each sounder as shown, the sounders, condensers, and keys being bridged between the line and ground.

The action of this current is as follows. When the line is at rest the battery *C B* charges all of the condensers on the line, then when any one station, Station *A* for example, depresses the key a short path to ground is furnished through Station *A* for the discharge of all the other condensers on the line, which actuates their polarized sounders. A path to ground for battery *C B* is likewise furnished through Station *A* when this station depresses its key, hence the necessity for the resistance of about two thousand ohms in order that the battery be not short-circuited. The sounder at Station *A* is not affected by the depressing of the key at this station because its condenser is not discharged. When the key at Station *A* is raised all the condensers on the line are again charged, due to the fact that the path to the ground is now interrupted.

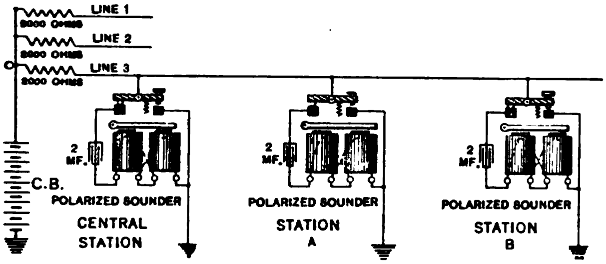

FIG. 4

This circuit operates nicely, an objection to it being, however, that the sender does not hear his own instrument while sending, unless another sounder is added.

The use of the sounder with closed or open circuit lines is identical with that of the ordinary sounder. The use of the sounder as a repeating relay for repeater stations is shown later. It is admirably suited to this use, due to the particular manner in which it is made and to its sensitiveness. Most of the circuits due to the writer that appear in this paper are based upon this use of the sounder.

Although the use of this sounder with closed, open, and condenser circuits has been briefly mentioned in preceding pages, the real purpose of this paper is to deal with this instrument particularly with reference to its use with induced currents, for it is in the field in time of war that this sounder excels, due to the fact that ideal conditions of line cannot be maintained and that the transportation of means for development of electrical energy is a difficult problem. The ordinary semi-permanent lines and field lines will seldom be over 300 miles in length, and, as will be subsequently shown, the induction field set now in use, or one of improved type, will operate over this distance on three dry cells without difficulty. If greater distance is required, the new sets devised by the writer can be employed as induction repeaters, allowing induction telegraphy to be used over any reasonable length of line on three dry cells per set.

The writer has devised two induction telegraph sets designed to displace the induction telegraph set now used by the Signal Corps. One of these sets is intended for simplex working only, and is composed of the least number of instruments possible for efficient working. The other set is more complicated and is intended as a general repeater and also as an induction telegraph duplex set. Both of these sets will now be described.

The simple set consists of one polarized sounder, one key, one induction coil and three dry cells, all suitably and compactly boxed. This set will operate on simplex only, and has a range of about 300 miles on a line strung on poles, and will operate a few miles over a line of bare wire laid on the ground.

Fig. 5 shows the circuits of this set.

B, battery, three dry cells connected in series.

K, closed-circuit key with switch removed.

P, primary winding of induction coil, 2-ohm resistance.

S, secondary winding of induction coil, 200-ohm resistance.

P S, polarized sounder, 200 ohms per coil.

The ratio of winding of the induction coil is 1 to 100. The illustration on Plate LXXIX shows this simplex induction set.

The action of the polarized sounder (simplex circuit) in either of the induction sets just mentioned is as follows, reference being made to Fig. 6.

This figure represents a battery *B*, key *K*, an induction coil with primary *P* and secondary *S*, and a polarized sounder *P S* adjusted to the neutral position.

When the key *K* is depressed the current will flow through the primary coil in the direction *a* to *b* and will continue to flow until *K* is released. While this current is building up in the primary coil an induced current will flow in the secondary coil from, say, *a′* to *b′* to *d* through polarized sounder coils in series to *e* and back to *a′*, and will continue to flow until the current in the primary coil has reached a maximum, when the current in the secondary will cease, and the secondary coil then becomes, for the time being, totally independent of whether current is or is not flowing in the primary. Hence with the key depressed current may be sent from the distant station through the sounder in the same manner as could be done were the key not depressed. This shows that the key *K* may be either a closed or an open circuit key, and battery *B* may be either wet cells or dry cells, that is, a current may or may not be flowing through the primary coil continuously, and the only effect on the polarized sounder in the two cases is that if the primary circuit is a closed circuit the armature of the sounder will be left at rest on reverse contact to that when the primary circuit is an open circuit. Bearing this in mind it is evident that in all of the induction circuits herein shown the primary circuit may be a closed circuit if desired, care merely being taken to see thatt he battery is connected to the primary coil with the correct polarity, and no further remark concerning this point need be made. For the sake of uniformity and brevity, however, all induction circuits herein are shown as operated on open primary circuit.

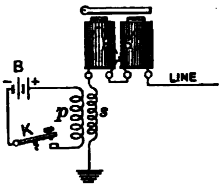

FIG. 5

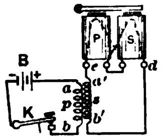

FIG. 6

Now, returning to the action of the sounder; it will be recalled that when the key *K* is depressed, an instantaneous induced current passes through the sounder from a' to b'. This current, though brief as to length of its duration, is sufficient to give enough electromagnetism to the sounder's coils to attract the armature,

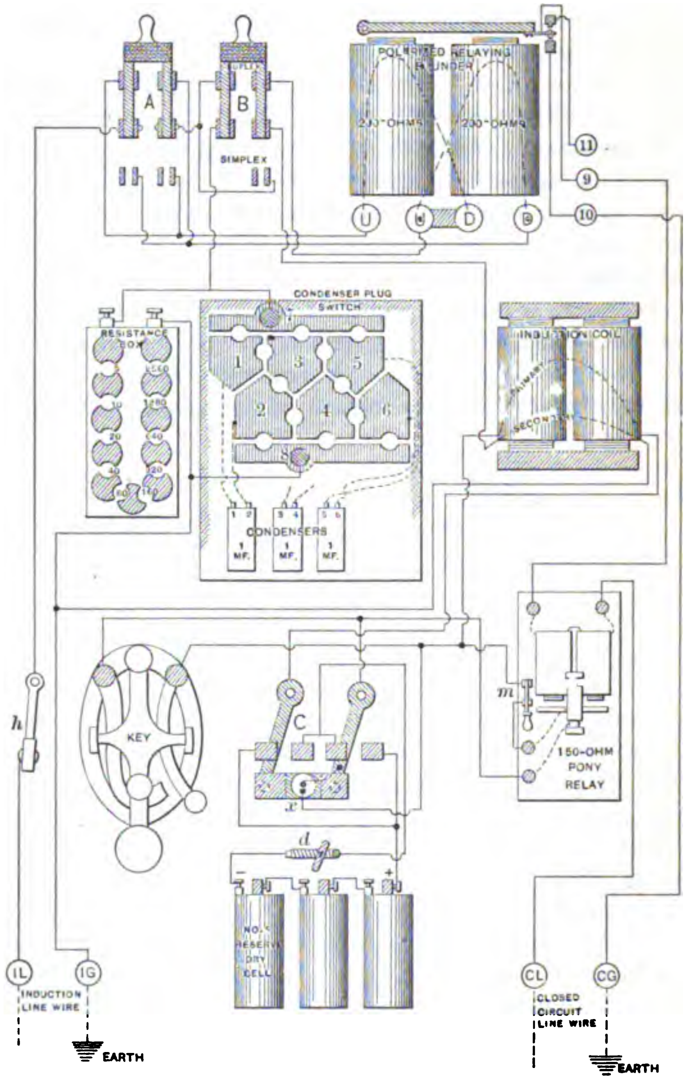

FIG. 7—FIELD INDUCTION TELEGRAPH REPEATER SET

which is held attracted upon the disappearance of the secondary current by the permanent magnetism of the sounder's cores.

Upon releasing the key *K* the primary current rapidly falls off to zero, and while doing so induces another momentary current in the secondary coil and circuit. This second induced current is now in the direction opposite to that caused by the closing of key *K*, and passes through the sounder coils in an opposite direction to the former induced current. Depending on its direction, the electromagnetic effect of this current in the coils of the sounder is either totally or partially to neutralize the effect of the permanent magnetism of the cores, leaving little or no induced magnetism to act upon the armature, and consequently the spring on the lever has time to raise the lever and its armature to the " up " position. In the " up " position the armature is too far away from the cores of the coils to be affected much by the permanent magnetism in them, and hence when the lever is allowed to go up it remains there. Thus by closing and opening the primary circuit by means of the key *K* the armature is made to respond to these actions and the sounder gives the desired reading.

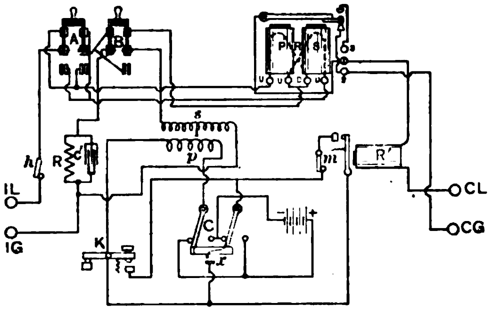

Fig. 8

As the sounder operates on direction of current, it will be noticed that connecting the battery to primary coils with reversed polarity or reversing the terminals of the secondary coil will have the effect of causing the induced current to pass through and operate the sounder reversely.

In using the sounder as a repeating relay on certain circuits use is made of the fact that current may be passed through each coil separately, the lever being so adjusted that the armature will be held by the current in but one coil.

The illustration on Plate LXXIX shows the induction repeater set.

In discussing the operation of the induction repeater set shown in the illustration reference will be made to Figs. 7 and 8.

Fig. 7 shows the actual wiring and apparatus of this repeater set and Fig. 8 shows the wiring diagrammatically.

PRS, polarized relaying sounder, 200 ohms per coil.

I, induction coil:

- *p*, primary of induction coil.
- *s*, secondary of induction coil.

R, resistance box.

C′, condenser.

R′, 150-ohm pony relay wound with No. 34 enameled wire.

b, battery, consisting of three No. 6 dry cells.

A, double-throw double-pole switch for reversing the direction of the secondary current through the polarized sounder.

B, double-pole double-throw switch for throwing from simplex to duplex, as desired.

C, double-pole double-throw switch for reversing the direction of the primary current through the primary of the induction coil. The handle of the switch has a slight lateral motion on a horizontal axis so that as the switch is being thrown by hand a contact is maintained by this handle in order to keep the primary circuit closed while the switch is being reversed. This action of the switch is necessary only when the set is used as the terminal station of a simplex induction line which is repeating into a closed-circuit line. The switch thus serves to leave the distant polarized relaying sounder on proper contact when the induction line is finished working, in order that the closed-circuit line will not be left open at the repeater station.

IL, binding post for induction line wire.

IG, binding post for induction ground wire.

CL, binding post for closed-circuit line wire.

CG, binding post for closed-circuit ground wire.

x, contact point on under side of handle of switch *C*.

h, single-pole single-throw switch for opening the line.

m, single-pole single-throw switch for opening the primary circuit of battery *b* to prevent its being closed by relay armature when relay is not in use.

The induction repeater set just referred to is so constructed that it may always be ready for use on the following circuits, by merely throwing certain switches:

As the terminal station of a simplex induction line.

As the terminal station of a duplex induction line.

As the repeater station of a simplex induction line repeating into a simplex closed-circuit line, one set used at the repeater station.

As the repeater station of a simplex induction line repeating into an open-circuit line, one set used at the repeater station.

As the repeater station of a simplex induction line repeating into another simplex induction line, two sets being used at the repeater station.

By using the instruments of the set and slightly altering the wiring these sets may be used as follows:

As the terminal or intermediate station of a closed-circuit line, simplex.

As the repeater station of a simplex closed-circuit line repeating into another simplex closed-circuit line, two sets used as repeater.

As the repeater station of a simplex closed-circuit line repeating into a simplex open-circuit line, two sets used as repeater.

As the repeater station of a simplex open-circuit line repeating into another simplex open-circuit line, two sets used as repeater.

The following is a brief description of the various circuits included in the repeater induction kit to which reference has just been made.

Fig. 9 illustrates the operation of a simplex induction circuit using a polarized sounder.

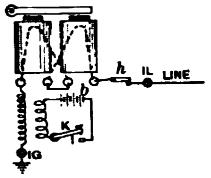

Fig. 9

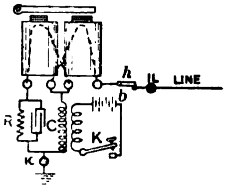

Fig. 10

This figure is the terminal station of a simplex induction line. On depressing the key *K* of this station a secondary current is caused to flow through the polarized sounders of this and the distant station, causing the armatures of these sounders to be actuated. As these sounders have been adjusted to the neutral position the armatures remain attracted at the cessation of the secondary current. On opening the primary circuit by means of the key *K* another secondary current in the opposite direction is caused to flow through both sounders, allowing them to release their armatures, which armatures remain released at the cessation of this secondary current. Either station may break by opening the switch *h*.

Fig. 10 illustrates the theory of one terminal station of a duplex induction line, using a polarized sounder.

R and *C* are artificial line resistance and capacity respectively, and the secondary current induced by the closing of the key

K divides equally through the differentially wound coils of the sounder and does not actuate its armature, but the portion of this induced current that goes out on the line does actuate the distant sounder as it does not divide through the coils of that sounder. In the same manner the distant station may operate this station's sounder without interfering with its own, and the line becomes an induction duplex. One feature of this duplex circuit that should commend it is the fact that the resistance and capacity of the artificial line need only approximate that of the line; the instruments will operate perfectly on a considerable discrepancy between the two lines, the real and the artificial. The experiments that the writer has had an opportunity to conduct with this circuit seemed to show that it makes little or no difference whether the resistance of the line is increased or decreased within reasonable limits, limits such as would ordinarily affect the closed-circuit duplex quite seriously.

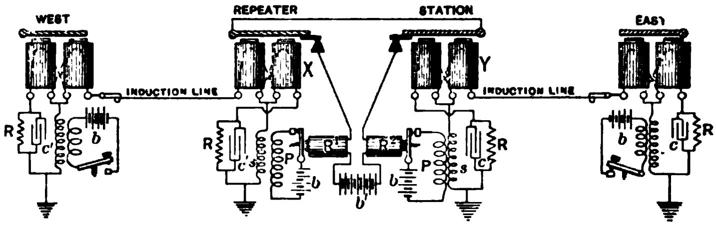

FIG. 11

Figs. 11 and 12 illustrate the theory of an induction to an induction repeater.

The repeater station is composed of two induction repeater sets, *X* and *Y*, battery *b'* being of the closed circuit type. The terminal stations are each composed of one of these repeater sets, with switches thrown to " duplex " but in reality operating as simplex sets. This is accomplished as follows.

West is sending—the make and break of the primary current at West's station induces a secondary current through West's polarized sounder, and this current divides through the coils of this sounder, thus not operating it. The portion of the induced current that goes to line passes through the coils of the polarized relaying sounder *X* in multiple and operates *X*, causing the lever of *X* to rise when West's key is depressed. The rising of the lever of *X* opens the circuit of battery *b'* and causes pony relay

R' to release its armature. This causes current to flow through the primary of X's induction coil and sends an induced current through the polarized sounder of X dividedly, not operating this sounder, but the portion that passes to line does operate the distant West sounder. Hence as West sends he hears his own sounder operate, with perhaps a very slight drag, but not enough to be bothersome.

Returning now to the repeater station—the raising of the lever of X's sounder, as has been stated, breaks the circuit from battery b'. This causes R_2 to release its armature and the operation just described for X occurs with Y, and the distant East sounder is operated, the contact of Y being closed all of the time due to the dividing of the current through Y's coils equally. East may break by closing his key. This causes the induced current from East's station to release Y's lever and open the battery of battery b' at Y's contact, and the armatures of both pony relays, R_1 and R_2, close the circuits for batteries b. These contacts remain closed as long as East's key is closed, and West's sounder becomes and remains silent. Before West can read East he must close the contact on the polarized relaying sounder X. This is done by means of the switch C described in the discussion of Fig. 8.

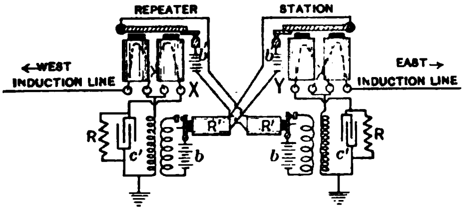

FIG. 12

It is not necessary that the West and East stations be wired as for duplex as shown in Fig. 11, but if open-circuit cells are used, as they would be in army field kits, this manner of wiring is necessary. If, however, closed-circuit cells are used at these terminal stations, the simplex wiring shown in Fig. 9 will suffice, a closed primary circuit being used. Of course the latter would be much the simpler method.

Fig. 12 differs from Fig. 11 only in the manner in which the pony relays of the repeater sets are connected to their closed-circuit batteries. Only the wiring of the repeater station is here given, the wiring of the terminal West and East stations being the same as that given in Fig. 11.

Fig. 12 operates in much the same manner as just described for Fig. 11 except that when West is sending, his own sounder remains silent and operates when East breaks, for in this case West's sounder can be operated only by the contact of Y being opened and closed. East may break in either of these two methods of wiring by merely opening his line switch. This destroys the balance of the line for the *Y* set of the repeater station, and in the first case West fails to hear his own sounder when he should hear it if East had not broken, and in the second case the opposite obtains.

The choice of these two circuits depends on what is desired. For instance, Fig. 11 is the better circuit if the terminal stations are to be wired for duplex operation (using dry batteries) and if there is only one repeater station on the line. Fig. 12 must be used if there is more than one repeater station on the line.

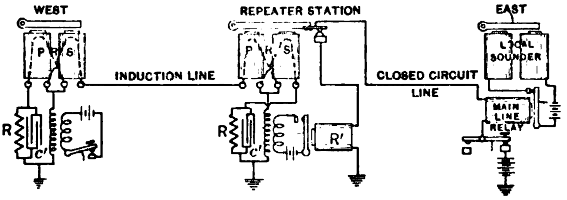

Fig. 13

Fig. 13 illustrates the theory of an induction to closed circuit repeater.

As described for Fig. 11, the polarized relaying sounder of the repeating set does not operate when East is sending. When West closes his key he causes the polarized relaying sounder of the repeater station to operate, thus breaking and closing East's closed-circuit line at the contact point on the polarized relaying sounder of the repeater set. This has exactly the same effect on West's sounder as described for the operation of Fig. 11, and West hears his sounder as long as East does not break. When East sends to West the former opens his closed-circuit line at his key and consequently allows the pony relay *R'* of the repeater station to release its armature and send an induced current over the line to operate West's sounder, at the same time not interfering with the position of the lever of the polarized relaying sounder of the repeater station. West may break East by depressing his key or by opening the line. West must leave the lever of the polarized relaying sounder of the repeater station on ***down*** contact when through working. This is accomplished by means of the switch *C* previously referred to. As in Fig. 11, it is the "back kick" of the repeater station that operates West's sounder.

The arrangement of circuits and apparatus shown in Fig. 13 is operative on a line where there is only one repeater station on the line, but where a closed-circuit line repeats into an induction line and this line in turn repeats into another induction line the wiring given in Fig. 13 will not operate, and the repeater station must be wired in accordance with the arrangement shown in Fig. 14.

Fig. 14 illustrates the theory of an induction to closed circuit repeater, the repeater station only being given. The terminal stations are shown in Fig. 13. It will be noticed that a 150-ohm pony relay is employed in this circuit as in the others, but that it is shunted with 40 ohms resistance. This is done merely to retain the instruments composing the induction repeater set. This relay might be a 20-ohm relay and in this case it would not be shunted, and the battery *b* might be reduced in voltage.

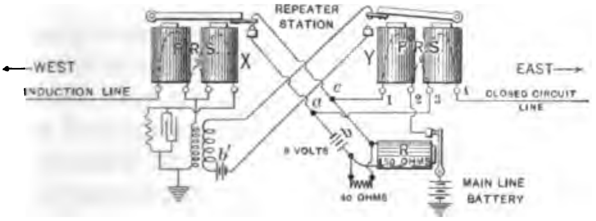

FIG. 14

This circuit, Fig. 14, is composed of the induction wiring for duplex for the left half of the repeater set, while the right half utilizes the individual coils of the polarized sounder separately. The battery *b'* may be either of the closed or open circuit type. In this circuit it is supposed to be the latter, consequently the armature of *Y* is given a natural bias that will cause it to remain normally on down contact but the presence of a current in either one of its coils will allow the spring to draw it upward.

If battery *b'* were a closed-circuit battery the armature of *Y* would be adjusted reversely. The operation of this repeater requires that *X* shall remain unaffected while East is sending and that *Y* shall remain unaffected while West is sending. The method whereby the former is accomplished has already been discussed for other repeaters, and it remains only to show how *Y* remains silent when West sends. The closed-circuit line is brought into *Y* at post 4 and passes through one coil of the polarized relaying sounder, leaving that coil at post 2 and passing to ground through the armature of the pony relay *R'*. As long as the armature of *X* is closed battery *b* discharges current through the pony relay *R'*, and holds the armature of this relay closed, and as the circuit from *a* through the contact points of *X* to *c* is practically short-circuited no appreciable current will flow through the left coil of *Y* as long as contact at *X* remains closed; hence the armature of *Y* will be affected by the presence or absence of current in the right coil of *Y* only.

As East opens the closed-circuit line he removes current from this right coil, and the armature of *Y* being no longer drawn up by current in *Y*, as stated, this armature goes to down position and closes the circuit of *b'* and causes an induced current to flow over the West induction line and throws West's sounder to up contact. Therefore as East closes and opens his key he causes West's sounder to respond. On the other hand when West sends he causes the left polarized relaying sounder *X* to operate and when *X* releases its armature it removes the low-resistance shunt from around the left coil of the polarized relaying sounder *Y* and battery *b* now discharges current into this left coil which keeps the armature of *Y* up. At the same time the armature of the pony relay *R'* is released, due to the fact that its spring is so adjusted that when the contract of *X* is closed the battery *b* gives *R'* sufficient current to attract its armature, but when the contact of *X* is open and the resistance of the 200-ohm coil of *Y* is added to that of *R'* the current from battery *b* is not sufficient to hold the armature of *R'*. The opening of *R'* opens the closed-circuit line at this point and consequently operates East's sounder accordingly. It will be evident that care must be exercised to see that the main line battery of the closed-circuit line and the local battery *b* are connected to *Y* with the correct polarity to cause *Y*'s armature properly to respond to current in either of the coils of *Y*. The spring of *R'* must be so adjusted that the armature of *R'* will remain closed on the strong current but will be released on the weak current passing through the relay *R′*. This is amply sufficient to eliminate the necessity for a fine adjustment of relay *R′*.

Fig. 15 illustrates the theory of the induction to open circuit repeater.

As this circuit differs very little from the theory of the induction to closed circuit repeater given in Fig. 13 it is not considered necessary to discuss its operation.

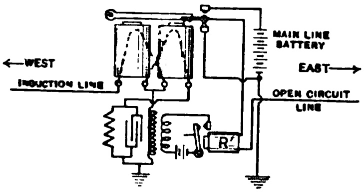

FIG. 15

Fig. 16 illustrates the theory of the open circuit to open circuit repeater.

This is the theory of an open circuit to open circuit repeater given in Maver's "American Telegraphy," except that polarized relaying sounders are used in place of ordinary relays. When West puts battery to line he causes the right pony relay R^2 to close its armature. This closes the local battery circuit of *b′* and closes the armature of *Y*, which in turn puts battery to the East line and operates East's sounder. East may break only by operating his key and interfering with West's sending.

Fig. 17 illustrates the theory of the closed circuit to open circuit repeater that depends for its action on the employment of a polarized relaying sounder.

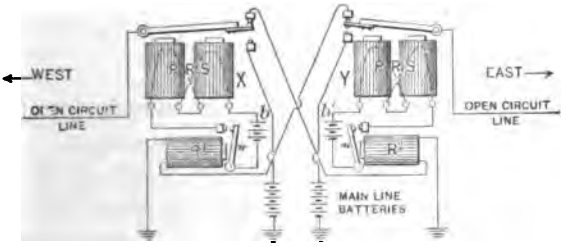

FIG. 16

The instruments composing this repeater are one polarized relaying sounder, one 150-ohm relay and one 20-ohm relay.

The closed-circuit main line battery *C B* normally holds the armature of the polarized relaying sounder on down contact. The breaking of this circuit throws this armature to up contact (by means of the upward bias previously given to the lever) and puts the open-circuit main line battery *O B* to the open-circuit line unless the contact of relay R^2 has been broken, as would be the case if West were sending to East, for then the short circuit (the armature of R^2) has been removed from the local battery *b* and this battery now furnishes current to the polarized relaying sounder as well as to R^1 and holds the polarized relaying sounder's armature down, but releases the armature of R^1, due to the fact that R^1 will hold its armature only when battery *L B* has been short-circuited by means of the armature of R^2; the releasing of armature R^1 opens East's line. It must be remembered that the West line normally has no current in it, hence the armature of R^2 is normally on released contact as shown. The only way East may break West is to interfere with West's sending, but West may break East in the ordinary manner. This repeater may be quite coarsely adjusted and yet give excellent results.

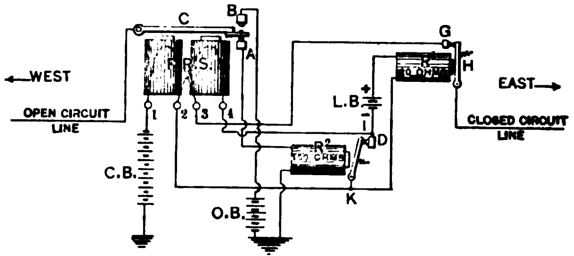

Fig. 17

Fig. 18 illustrates the theory of the closed circuit to closed circuit repeater using polarized relaying sounders.

It will be noticed that two 150-ohm relays shunted with 40 ohms resistance are used. This is only to allow the instruments in the writer's induction repeater set to be employed; in practise it would be better to employ two 20-ohm relays in place of the 150-ohm instruments.

It will also be noticed that the armature of *X* is a shunt to relay *Y* and likewise the armature of *X'* is a shunt to *Y'*. This repeater operates on the principle described for the one half of Fig. 14 and it is therefore not deemed necessary to describe its action more fully. However, as the setting up of this repeater is apt to give trouble to one not familiar with its operation, the method of doing so is here given.

Adjust the armatures of *X* and *X'* so that they will normally remain on up contact, or stop, when no current is in either coil, but will be readily attracted by a current of from 20 to 40 milliamperes flowing in one coil. Bring West line to post 1, connect post 3 with *b′*, *g′*, and battery *h′*, to ground. This should cause the armature of *X* to be attracted or released as contact is made or broken at *b*; if *X* acts reversely transfer wires at posts 3 and 1 or change the polarity of the main line battery *h′*.

Do the same with *X′* if necessary. Assuming the proper connections to be as in the figure, temporarily disconnect West and East lines from posts 1 and 4 respectively. Wire in relay *Y* as follows: relay to *d*, to *a*, to *f*, *c* to 1, and to relay. If a 150-ohm relay is used, shunt with 40 ohms as shown. Now close and open armature *X* contact at *f* and adjust relay *Y* armature so that it will just respond to the closing and opening of *f*. Do the same with relay *Y′*. Now see that contacts at *f* and *f′* are broken and kept broken temporarily and wire *a* to 3′. This connection should cause armature of *X′* to close and remain closed but should not close relay *Y* armature. If *X′* armature is repelled instead of attracted reverse the polarity of battery *d*. Close and open armature of *X*. This should cause the armature of *X′* to open and close, and the armature of *Y* to close and open. Now disconnect wire at 3′ for a moment and see that armature of *X′* is up. Wire *a′* to 2. This should attract armature of *X* but not that of relay *Y′*. If it repels, reverse the polarity of battery *d′*. Now close and open the armature of *X′*. This should open and close the armature of *X*, and close and open the armature of relay *Y′*. Now connect all disconnected wires (at 1, 4′, and 3′) and repeater should operate.

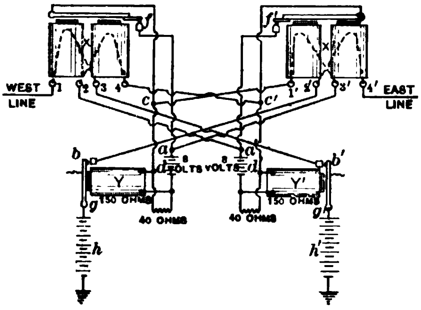

FIG. 18

The writer advocates the use of the polarized sounder exclusively on all Army Signal Corps land lines in time of war, and believes that this sounder has widened the possible scope of induction telegraph circuits for the more advanced lines in the presence of the enemy, the closed-circuit system being used on only such lines as may be considered permanent lines. Consequently the writer has endeavored to produce a telegraph field set that will meet every possible telegraphic condition likely to be encountered by troops in the field. This set must be compact in size, contain few instruments, be simple in operative principle and easy and ready of adjustment.

It follows that such a set must combine the closed circuit and induction telegraph features. It must, either alone or in conjunction with a duplicate set, be able to repeat from any one kind of a simplex line into another kind, in order that a partially destroyed line can be hastily "patched" or extended. It is not necessary, however, that such a set be used on duplex or quadruplex, as such lines cannot, as field lines, be well maintained in time of war. On the other hand, an induction telegraph line of this type may be easily duplexed, consequently it would be advantageous to have such a set capable of being used as a terminal station of a duplex induction line.

Hence it will be seen from the foregoing that the set fulfills practically all the requirements of a station set for virtually any kind of a military telegraph line that might be employed by armies in time of war.

In order to accomplish these results the writer determined upon the necessary instruments to use with such a set, then he adapted well-known circuits to these instruments wherever this was possible, and where not possible he either altered these circuits to fit the instruments used, or devised new circuits to accomplish the desired results.

Acknowledgment is therefore due the British Insulated and Helsby Cable Company for the circuit shown in Fig. 3; to Mr. Stephen Dudley Field for the circuit shown in Fig. 4; to Mr. William Maver, Jr., in his "American Telegraphy," for the circuit shown in Fig. 16, which has been slightly altered by the writer; and to Major Edgar Russel, U. S. Signal Corps, for valuable assistance given the writer in some of his experiments with these circuits. The other circuits in this paper are believed to be original circuits. Of course no originality is claimed for the principle of operation of an induction telegraph circuit.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

MEASURING STRAY CURRENTS IN UNDERGROUND PIPES

BY CARL HERING

The measurement of stray electric currents flowing through buried conductors, such as pipes, and generally originating from an electric railroad or other grounded system of electric distribution, is attended with various difficulties, particularly in the determination of the current which enters or leaves the underground pipe through the surrounding earth, and as it is the current which leaves a pipe in this way that corrodes it electrolytically it becomes important to be able to locate and measure that current. Another important measurement is to identify the original source of the stray current.

The purpose of the present paper is to describe several methods which the writer devised some years ago, for making these measurements, and which he used with success at that time in a practical case. The present description is published with the permission of the party for whom the measurements were made.

One of the problems given to the writer was to measure the currents in a pipe and to locate and measure the currents leaving it through the earth, by methods which were positive and not based on any questionable assumptions, and the results of which could be used as reliable evidence in court. Another was to identify the source of the stray currents flowing in pipes so as to establish the responsibility for them in legal proceedings. The methods therefore had to be unquestionably correct, and free from any questionable assumptions.

The usual method which consists in measuring the drop of potential in millivolts between two fixed points on one length of pipe exposed for that purpose, and then calculating the current from an assumed resistance of the pipe, would not answer the requirements, as the resistance of the pipe is a mere assumption which may be far wrong, even when based on measurements of other presumably similar pipes before they are laid. A little thought will show that such a test at best is only a crude one and the results would not be likely to stand the usual attacks in court proceedings. Even though many pipes may have been measured before laying and found to agree fairly well, there is always the uncertain factor of the wall thickness of that particular piece of pipe in service on which the drop of potential was taken. It is customary for instance in laying water pipes over a rolling country to use varying thicknesses as the pipe crosses a valley or a hill, and it is of course impossible for the one making the electric tests to measure this thickness himself. Drilling through or cutting the pipe was not permitted, as it was in service.

The method of using the academically interesting ground current detector, for measuring the current passing through a definite cross-section of the ground near the pipe, was also excluded, as it involves disturbing the very conductor through which the current had been flowing, as also the assumption that the distribution of this current in the ground is uniform, which is not only not likely but highly improbable; in any case it is based on mere assumptions, and is therefore not positive and direct.

A magnetometer method was tried by suspending over the top of the exposed pipe an astatic couple having a long distance between the two needles; the lower needle was brought to a fixed distance from the outside of the pipe, hence within the field produced by the current in the pipe, while the other was far enough away to be practically outside of that field. The system will then tend to place itself perpendicular to the pipe, hence by bringing it parallel to the pipe by means of a torsion wire or a current in a neighboring coil, a measure of the external magnetic field and therefore of the internal current is obtained. This would be an extremely simple method, but it was found that the magnetic field around such a pipe was extremely irregular, the surface of the pipe showing numerous irregularly distributed poles; it was therefore also abandoned.

After trying out numerous other methods the following were found to be the best and were the ones actually used.

The fundamental principle is as follows. Let *P*, Fig. 1, be a part of an underground pipe which has been uncovered and through which an unkown current *I* is flowing as shown; at first let it be supposed that this current is steady, and of course a direct current. Let *D* be a sensitive galvanometer, millivoltmeter or any other form of detector of small differences of potential, connected as shown; there should preferably be no variable resistance like an unbonded pipe joint between the two contact points. Let *A* be an ammeter, *B* a few cells of accumulators and *R* an adjustable resistance; the shunt circuit containing them is connected, as shown, anywhere outside of the points of application of the voltage detector, the farther away the better—they may even be on the other side of a joint.

To find the current flowing in the pipe adjust the resistance *R* until *D* reads zero; then there will no longer be any current flowing in the shunted part of the pipe, hence the reading of the ammeter will give the current *I* in the pipe. The current may be said to have been sucked out of the pipe by the battery, and made to flow through the ammeter, where it can be measured; as far as the current in that short section is concerned the pipe circuit has in effect been electrically cut in two as though an insulating joint had been introduced.

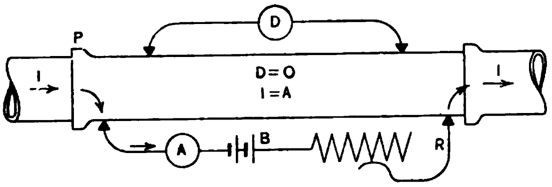

FIG. 1

If *D* is a galvanometer with proportionate deflections, instead of a mere detector, then by taking a deflection immediately after the shunt circuit has been opened a reading proportionate to the drop of voltage for that current will be obtained. The instrument *D* is thereby calibrated to read the pipe currents directly and can be used for this purpose thereafter; the test with the battery current is therefore merely of the nature of a preliminary calibration, and need be carried out only once for each station.

If in addition this voltage instrument is calibrated to read directly in volts (usually in terms of milli- or microvolts as for instance a millivoltmeter,) then if the deflection reduced to millivolts is divided by the current it will give the resistance of the pipe in milliohms between the two points of application of the voltmeter; hence it enables the true resistance of the pipe to be measured. The distance between the two contact points is best made an exact number of feet, which standard length is then preferably kept the same for the whole series of tests on that line of pipes. From the resistance per foot obtained from tables a rough check of the measured result may be obtained.

In most cases it is advisable to make these connections for the voltmeter permanent and to bring wires from them to the surface before filling in the hole (being careful to mark one of them with a knot), for having once obtained the constant from this test with care, the current in the pipe can be measured any time thereafter, correctly and very simply with a mere millivoltmeter. The most convenient form of this constant is the amperes per millivolt, which is numerically equal to the conductance in kilomhos.

The current which leaves or enters a pipe between any two points or stations can then be determined by making this calibration at each of the two stations and then taking simultaneous readings of the currents in the pipe at the two stations with two millivoltmeters or calibrated galvanometers; the difference between these currents will then show the amount of this current, and whether it is leaving or entering.

This becomes possible by this method because it is a positive one, involving no questionable assumption, and because the measurements can be made with all necessary accuracy, if one has sufficiently sensitive and reliable instruments; it can therefore be depended upon to measure the current with sufficient accuracy at two neighboring stations so that the difference between the readings gives a reliable measurement of the entering or leaving current. If the pipe current measurements were dependent, as they often are by the older method, on an assumed pipe resistance, such a measurement based on taking the difference between two currents would not be permissible, as the probable error would be so great that the results might even make it appear that the current was entering when it was in fact leaving the pipe.

In this method shown in Fig. 1 there should be no current leaving or entering the pipe between the points of application of the shunt, hence the hole should be free from water and there should be no moist earth in contact with that part of the pipe.

It is assumed in this method that the short length of pipe between the shunt contacts is too small a fraction of the whole circuit of the pipe line currents to alter these currents when that section is practically cut out of circuit, as it is when the current flows through the shunt. This assumption is probably absolutely safe in all cases in practise.

As this method is not in any way concerned with the nature of the circuit beyond the single pipe length under test, nor with the rest of the path of the current, it can be applied to the most complex network of pipes, even when the pipes are interconnected together elsewhere or bonded to the track.

In measuring the pipe resistance by this method, or in general when the voltage drop is measured, it is of course assumed that the current is constant while the two successive readings are taken, hence it is recommended to repeat the two readings a number of times. When this constancy of current cannot be assumed, one of the modifications of this method described below may be used.

A portable millivoltmeter with a full scale deflection of 10 millivolts has divisions of 0.1 millivolt, hence can be estimated to 0.01 millivolt. If a 16-in. (40.6-cm.) cast iron pipe has a resistance of about 0.00001 ohm per foot (30.5 cm.), then say 5 feet (1.5 m.) will give a drop of half a division per ampere. This will give a rough idea of the range of measurements that can be made with a millivoltmeter. Improvements may perhaps also be made in these instruments to make them still more sensitive.

When a portable galvanometer is used instead of a millivoltmeter in order to get greater sensitiveness, like the mirror and telescope galvanometers that were used in these tests by the writer, it is necessary to calibrate it for volts while in place before each test, hence a convenient way of doing so should be provided. With the accumulator, ammeter and rheostat available in this test, this is easily done by passing a known current through a known low resistance, giving a known drop which is then used to calibrate the instrument. Such a galvanometer should be provided with the usual shunts, and if so it can also be calibrated with a millivoltmeter which is always at hand for such tests.

When such galvanometers are made extremely sensitive, as would be desired for instance when the pipes are very large and thick or the current very small, they are apt to have a loose zero or give somewhat indefinite deflections. Attention is therefore called to the fact that small deflections, when they are very definite and when the instrument has a rigid zero, as in a good portable millivoltmeter, may be more accurate and reliable than larger deflections in a galvanometer that is more sensitive but has a loose and unreliable zero and less definite or not strictly proportional deflections. Instead of using exceedingly sensitive instruments it may be better to use greater lengths of the pipe, even to the extent of including a joint, which in that case should preferably be bonded so that it is not variable.

In practise there are various very desirable modifications of the method which is shown only in its simplest form in Fig. 1.

Instead of attempting to adjust the current in the shunt to bring the voltage *D* to zero, it is far more convenient to use a regular measuring instrument for *D* instead of a mere zero detector, and then to pass a definite current through the shunt, say 10, 50 or 100 amperes, and read the two deflections of *D* when this current is on and off; this had best be repeated several times. The difference between these two readings then corresponds to that current, from which data the instrument can be calibrated to read in amperes. The best current to use is that which will reduce the original deflection as much as possible. By thus using the difference between a large and a small deflection the errors due to a loose zero, which are so common with highly sensitive instruments, are reduced.

This method also has the advantage that an observer can read both *A* and *D*, as he first adjusts the rheostat to give the exact predetermined current and after that can open and close the switch to throw this current on or off, without having to read the ammeter, this current being absolutely constant. He need, therefore, read only *D*.

All the above applies to steady currents or to such as are steady long enough (a few seconds) to take two successive readings, as the voltage drop and the current cannot be measured simultaneously in the form shown in Fig. 1. In practise such stray currents are likely to vary continuously and often very rapidly. By waiting for a suitable opportunity when the current is practically constant for a short time, measurements of sufficient accuracy can often be made, and as this part of the test is only for the calibration, hence of a preliminary nature and needing to be made only once for each station, one is justified in taking more time for it. It may be facilitated by using an extra voltage detector applied somewhere outside of the shunted part (as in Fig. 3) and having an additional observer to call out when it is steady or to note whether or not it had been steady while the other pair of readings was taken.

When, however, the fluctuations are too rapid, the following modification can be used; it proved to be very satisfactory in practise, although somewhat more cumbersome, and requiring additional apparatus, though no more observers.

Let the left-hand side of Fig. 2 represent the same arrangement as in Fig. 1. A second voltage detector *D* is then added as shown; it may be a sensitive galvanometer and need not be calibrated. *S* is a second shunt circuit containing a battery and an adjustable resistance which is operated by the observer of *D*, who keeps adjusting it continuously so as to maintain the deflection in *D* constant. During that time the current will be steady for the other observer, who then completes a set of readings with the other instrument *V* according to the method shown in Fig. 1.

The purpose of the additional shunt *S* is to take up all the excess of the pipe current above a certain amount, thus acting as a sort of overflow, taking care of the peaks only. The observer of *D* must, therefore, use some judgment in selecting the deflection at which the current is to be held constant; it should be kept at about the base of the average peaks, but should not be too low for the other observer to get good readings for his calibration. It may be a different deflection for each set of readings of the other observer; the only important point is that the current should be held constant in that length of pipe for a long enough time to take two successive readings, requiring only a few seconds.

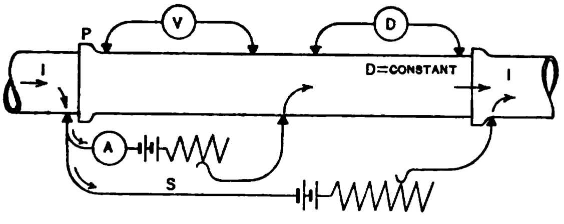

FIG. 2

Or, if practicable, the observer of *D* could shunt off the whole pipe current, thus making *D* read zero, and leaving the pipe entirely free from current for the other observer to make his calibration or any other test for which it is required to have the pipe free from current.

The adjustable resistance for this extra shunt *S* should be made of a pile of carbon plates which are compressed by means of a lever so that the observer of *D* may quickly follow the variations of the current with it. Very good results were obtained with such an arrangement after a little practise. As the observer of *D* knows whether or not the current has been successfully kept constant he can discard the readings of the other observer for which the current had not been constant. By taking the mean of a number of good readings, very satisfactory results were obtained.

Having thus calibrated the voltmeter *V* at each of two neighboring stations, the currents which enter or leave the pipe between them may be determined, with the fluctuating currents, by taking the readings of the two instruments simultaneously by means of visual or telephonic signals, preferably at times when the currents are momentarily steady.

It may be of interest to state here that after making the calibrations in this way over miles of the same line of pipe, at numerous stations, to determine the places where the current enters or leaves, and its amount, and also to measure the current in the pipe itself, the results were finally all reduced to the resistances in milliohms per foot of pipe, in order to see how they agreed, as the pipe had nominally the same outside diameter throughout the entire length. They were found, however, to differ very greatly, far too much to be due to errors of measurement. The writer, therefore, concluded that the pipes in different parts of the line must have different thicknesses, and upon examining the specifications according to which the pipe line was laid, this was found to be true, thicker pipes having been used in the valleys and thinner ones over the hills. Upon making comparisons with the specified thicknesses the results agreed very well with the measured resistances, showing the reliability of the method of measurement.

Incidentally this also showed the serious errors which might arise by using the older method based on the assumed resistance of the pipe, it being often impossible to state, after the pipe had been laid and was in service, what thickness the particular piece under test had. In the present case those who made the electrical tests of this pipe line had not been informed that the pipe varied greatly in thickness.

Another modification of the method for use when the currents are very unsteady is shown in Fig. 3. The apparatus is similar to that in Fig. 2, except that the additional shunt with its battery and rheostat is not required, but on the other hand three observers are required instead of two. The positions of *D* and *V* are now reversed, the important instrument *V*, to be calibrated, being now placed beyond the shunt, while *D*, which may be a mere detector or galvanometer, is connected to the points within the shunted part. The resistances *R* and *R* need not now be equal as marked on the diagram.

The shunt current is first adjusted to some convenient average value of that flowing in the pipe, then as the latter fluctuates on both sides of this value there will be times when it is exactly equal to it; this is indicated by *D* reading zero, and at that moment the observers of *A* and *V* take their readings. This can be repeated for different currents. The quotient of *A* divided by *V* should then be a constant for all the readings; this calibrates the instrument *V* as it gives the amperes per division, and it can therefore be used as a pipe current ammeter thereafter.

This method was not tried. It requires a battery, leads and connections large enough for the whole pipe current, and a constant flow of the current for a long enough time to get a number of good readings; this may sometimes require rather large battery and leads. But if the observer of *D* manipulates a carbon plate rheostat rapidly to keep his instrument at zero, it ought not to take long to get a group of good readings.

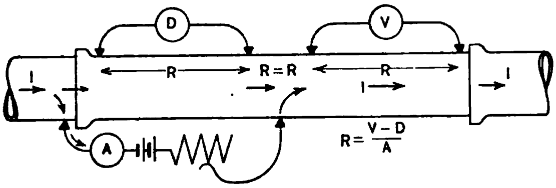

FIG. 3

If in this method shown in Fig. 3, the instrument *D* is also a measuring instrument instead of a mere zero detector, then the following modifications can be used. The two instruments *D* and *V* need not then be calibrated in volts, hence they can be two uncalibrated galvanometers, provided only that they are exactly alike in giving the same deflections when connected in multiple; they may be adjusted to do so by a series resistance. Two good millivoltmeters would do in cases in which the deflections are large enough and accurate enough so that their *difference* may be relied upon as being an accurately measured quantity, for the present modification of the method is based on measuring this difference.

Having two such instruments, adjust the points of contact for either *D* or *V* so that the two instruments always read alike for the pipe current alone, however fluctuating that current may be. This, of course, must not be done by an adjustable resistance in the circuit of the instrument, but by moving the contacts on the pipe, hence this method cannot be used directly when all four of these contacts are drilled or soldered, although it may then be used indirectly, as shown later. Three of them may be permanent and the adjustment made with the fourth.

Such connections mean that the two pipe resistances shunting these instruments are equal, as any current then gives the same drop in both. If now any known part of the current be sucked out of the pipe by the battery shunt as before, then, as the two resistances are equal, the difference between the readings *D* and *V* must correspond with the difference between the two currents in these two parts of the pipe, and this difference between the currents is of course equal to the known battery curent *A*. Hence, dividing this known battery current by the difference between the two deflections calibrates both of the instruments for reading pipe currents thereafter, that is, either of them will then give the amperes per unit deflection. It is precisely like the method described above, except that the two readings which then were necessarily successive are now simultaneous.

It will be noticed that as only the difference between the two currents is now involved, and as this difference is always constant, the method does not assume even a momentary constancy of the pipe current, being entirely independent of it; this current in the pipe may therefore fluctuate over wide ranges, the only important point being that with such fluctuating currents the two readings must be taken simultaneously. And as the calibration depends on the difference between two readings, the larger one should be as large as possible and the smaller one as small as possible, hence the battery current should be made as nearly equal to the pipe current as practicable.

As the battery current in the shunt is in practise governed entirely by the adjustable resistance in that shunt circuit, this local current will remain constant no matter how much the pipe current varies. Hence it can be adjusted and noted prior to the taking of the two simultaneous readings, thus saving one observer. Moreover, this shunt current can be adjusted to any convenient number of amperes, 10, 20, 50, etc., so as to simplify subsequent calculations.

As before, the above measurements will also enable one to calculate the resistance of those parts of the pipe which are embraced by these two instruments, provided the latter are calibrated to read in volts, and are not merely deflection instruments. The readings in millivolts, divided by the now known currents in amperes, give the pipe resistances in milliohms.

If it is not convenient to adjust the contacts on the pipe so that the readings of the two instruments are alike, the inequality of these readings may be allowed for by calculation. For simplifying the rough mental calculations which a careful testing engineer should always make during a test to see that there are no grave errors, wrong connections or inconsistencies, it is advisable to make the two distances between the pairs of contacts approximately equal, so that the ratios between the deflections will be approximately unity.

A preliminary test is then made to determine this correction factor accurately. This is done by taking a series of simultaneous readings on the pipe current only, or if too small, then supplemented by the battery current, which should then be reversed, so as to add to instead of deducting from the pipe current, and it must of course now flow through both pieces of pipe, and not as shown in the figure.

From this preliminary series of readings a good average value can be obtained for the ratio of the readings of D divided by the corresponding ones of V. Call this n. Then all subsequent readings of the instrument V in the main test must be multiplied by this correction factor n, to reduce them to what they would be if the two pipe resistances had been equal as at first described.

In general, the modifications shown in Figs. 2 and 3 have the disadvantage, as compared with that in Fig. 1, that they require an exposure of a larger part of the pipe; the alternative of using shorter lengths for each instrument is not recommended—these lengths should be as great as conditions permit, preferably each a whole pipe length.

In the writer's tests the galvanometers had been designed for different conditions and were therefore somewhat oversensitive; the zero was too loose and the deflections were not as definite and accurate as desired to give the best results which these methods could give. The deflections of millivoltmeters under the existing conditions were considered to be too small and therefore too unreliable for methods depending on calculations involving the relations of quotients and differences. The galvanometers should have had stiffer suspensions, giving them more rigid zeros and more definite deflections, at a sacrifice of some of their sensitiveness.

The present modification of the method was tried out with millivoltmeters in a single one of the tests of the above-mentioned series where the pipe current was greatest, and although the deflections were small, the calculated results seemed to be concordant, although there was no way of checking them with results from other observations or with repetitions under different conditions. In the laboratory this latter method may be a very satisfactory one, but whether it will be so on a series of outdoor road tests should be determined by the testing engineer when he knows the particular conditions of the test and the characteristics and reliability of his instruments. It has several very good features and might in some cases give very good results.

Attention is here called to the great importance of having the directions of the currents correct in all these tests.

In general, methods which give the final results as directly as possible and in intelligible form, are to be preferred to those of the indirect kind in which the readings themselves convey no meaning and in which the final results must be calculated from more or less involved mathematical relations, which it may not be convenient to work out during the test itself to see whether there are any grave errors, wrong connections, or inconsistencies. This is particularly true of road tests in which the apparatus is moved rapidly from station to station and in which holes are dug which must be filled in again as soon as possible; in such tests it would be awkward to find later, when the calculations have been made in the office, that there had been something wrong, requiring a repetition of an expensive test.

Another objection to the indirect kind of tests, in which the final results are calculated from formulas, is that such formulas may involve quotients, differences and relations between them, and in such cases it may be the case that small inaccuracies in the readings mean very large ones in the final results, as for instance in taking the difference between two small and nearly equal readings. And such inaccuracies may not be included in the academician's calculated " probable error," as they may lie back of the readings. A rigid zero, definite and strictly proportionate deflections, accurate and strictly simultaneous readings, etc., may be necessary for such calculated results. The indirect methods may be quite correct in theory and may give very good results in laboratories where one may work out the best possible conditions, instead of having to take them as one finds them, as in road tests.

The other test referred to in the introduction concerns the identification of the source of the stray currents in the pipes. This is often important in legal proceedings, for even if currents are shown to be flowing in pipes the question of where they come from still remains.

The method devised by the writer, and used very successfully in a large number of tests, consists in taking a series of many simultaneous readings of the drop of potential or the current, in the pipe and in the track of the supposed source, especially the extreme high and low readings of the fluctuations, and plotting them together on the same sheet of cross-section paper, using different scales if necessary to make the average ordinates nearly equal. If the prominent peaks and troughs of these two saw-tooth curves then correspond approximately with each other, there is no doubt that both the currents originate from the same source. If the curves are radically different then that track is either not the right source or at least is not the only one.

In the tests referred to, these identification measurements were made over long stretches of several miles, with the aid of telegraph wires, but it is possible that good results could also be obtained in certain cases with millivoltmeters applied to stretches short enough not to require the use of long telegraph wires. The readings need not be in volts or amperes. They merely need to be proportional to them; hence the instruments need not be accurately calibrated, but should give correct proportional deflections. Nor need the resistance of the telegraph wire leads be taken into account.

Numerous other tests concerning such stray currents were devised by the writer which may be new, but those described above were considered to be the best. There were also a number of other tests proposed and in part used in this series, but as they were devised in conjunction with others the writer does not feel at liberty to describe them here.

As the above-described methods for measuring the pipe currents and resistances are entirely independent of the rest of the pipe circuit or the rest of the path of the current, they may also be applied to other tests than those of underground pipes, in which the rest of the circuit is also unknown or inaccessible, as for instance in measuring the resistance of a part of a circuit such as a busbar, a permanently connected shunt, etc., through which current is flowing and which is in service and can therefore not be cut or have its current interfered with. Or the current may be alternating. There are of course numerous other modifications of the same general principle, which may be made in special cases.

The apparatus used for the pipe current tests consisted of two portable, low-resistance, suspension coil, mirror and telescope galvanometers on tripods, of the type used for outdoor insulation tests, with the usual set of shunts, but made very sensitive, as the original requirements were to include measurements of even relatively very small currents in rather large pipes. Their constants were about 0.001 millivolt per mm. For ordinary work they would not need to be so sensitive. Probably in many cases two sensitive but reliable millivoltmeters would be sufficient to carry out the above-mentioned tests; if so, they are of course decidedly preferable on account of their portability, especially when high-speed automobiles are incessantly passing along the road uncomfortably close to the instrument and observer.

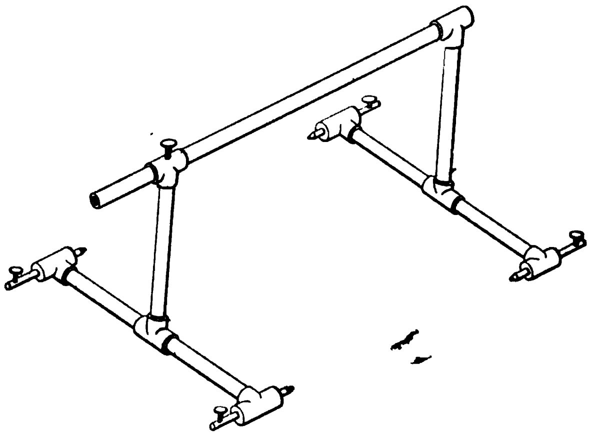

FIG. 4

The rest of the apparatus consisted of a wire rheostat, a reversing switch, a small portable two-cell accumulator capable of giving about 100 amperes, and a millivoltmeter with several shunts to be used as an ammeter also, all conveniently mounted in a portable box serviceable also as a writing table. A single cell would probably have answered nearly as well. For the preferred form of test shown in Fig. 2 there was in addition a carbon plate resistance with a lever for quick and strong compression, a second set of two cells of accumulators and a sensitive millivoltmeter.

The form of the universal clamps finally adopted for making the contacts with the pipes is shown in outline in Fig. 4; these clamps proved to be very convenient. They spanned the pipe, making contacts for the same lead at two diametrically opposite points. The contact pins were made with hardened points which with a light hammer blow entered the pipe slightly and made serviceable contacts even for currents of 100 amperes. These pins were insulated from the frame so that they could be used for different circuits if desired. The clamps were made of light bicycle tubing and ordinary T-joints.

DISCUSSION ON "MEASURING STRAY CURRENTS IN UNDERGROUND PIPES" (HERING), BOSTON, MASS., JUNE 28, 1912.

Albert F. Ganz: In electrolysis surveys it is important to measure the currents flowing on pipes. The most common method used for this measurement is to treat part of the pipe length as a shunt, and to measure the drop across this shunt with a sensitive millivoltmeter, and then to compute the current from the measured drop and from an *assumed* resistance of the included pipe length. The methods which Dr. Hering gives in his paper for measuring pipe currents involve essentially the *actual measurement* of the resistance of a length of pipe, which is part of a piping system. These methods are in fact special cases of a general method based on Kirchhoff's first law, namely, that the sum of the currents flowing towards a junction point is equal to those flowing away from the point. This principle has been used before for measuring pipe resistances, and is mentioned on page 67 of the American edition of Dr. Michalke's book on "Stray Currents from Electric Railways" published in 1906. For a number of years I have also used in special cases what is practically the last modification of the method described by Dr. Hering in the second paragraph of page 1458. In carrying out the method I have used the connections shown in Fig. 1 of this discussion.

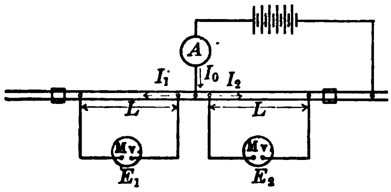

FIG. 1

The two millivoltmeters are similar and highly sensitive instruments, one scale division representing 0.1 millivolt. They are shunted across equal lengths of pipe, and a battery current is introduced in the middle, as shown in the diagram. I have found it convenient to use a battery current larger than the pipe current, so that the currents I_1 and I_2 flow in opposite directions. The two instruments are first read simultaneously with the battery circuit open, in which case the readings are due to the stray current on the pipe. If the readings are alike, which is generally the case, the two included shunts have the same resistance; if the readings are not alike, the two included shunts have resistances proportional to the readings. The battery circuit is then closed, and the ammeter and the two millivoltmeters are read simultaneously. If the two millivoltmeters previously read alike, the resistance of the pipe between contacts is

$$R = \frac{E_1 + E_2}{I_0}$$

Where trolley rails are accessible I have frequently dispensed with the battery, and have connected from the middle of the pipe through an ammeter directly to the rails, thus drawing current from or to the pipe. The use of battery current has, however, the advantage of giving steadier readings.

I have used the above method for measuring the resistances of pipes and of lead cable sheaths in special cases. Such cases arise, for example, in long cable sheaths or in long individual pipe lines, where it is desirable to measure current flow simultaneously at two or more points for the purpose of determining the change of current between the points; where the changes are small the individual readings must be taken with considerable accuracy.

Stray currents on pipes fluctuate violently from moment to moment and also vary greatly during different periods of the day. Great accuracy in measuring stray currents is therefore generally unnecessary. This is particularly true in the case of pipes forming parts of interconnected networks, where the method of determining the flow to or from a pipe from simultaneous readings is not generally applicable, and where variations of 10 per cent or even 20 per cent would not be serious. For such cases it is abundantly accurate to measure the millivolt drop in a measured length of pipe, and divide this by the resistance of the included length of pipe, estimated from its known size and material.

I have found in the case of long individual pipe lines or long cable lines, that a fair estimate of stray current leaving or flowing to the pipe or cable sheath can only be obtained from a comparison of simultaneous 24-hour records of the current flow at successive points. These records can be obtained by means of suitable recording millivoltmeters.

Dr. Hering states, in the third paragraph of page 1456, that after he had completed a series of resistance measurements at many points over miles of a pipe line, he had found that the computed resistances per foot of pipe differed very greatly from each other. Upon examination, however, it was found that some portions of the pipe line had been laid with heavier pipe than others, and when a correction was made for this the results agreed very well. He concludes that this is a proof of the reliability of his method of measuring resistance. It seems to me, however, that it really proves that the method of estimating the resistance of a pipe from its dimensions is reasonably accurate.

I am convinced from my experience that in about 95 per cent of the cases met in practise, the method of measuring drop between two contacts on a pipe, and dividing this by the resistance of the included length of pipe estimated from its dimensions, is sufficiently accurate for practical purposes, and on account of its great simplicity it is to be preferred. I am prepared to admit that I have used, and am still using, this method for a great many pipe current measurements, and believe it is a perfectly satisfactory and practical method.

Where current flowing from or to a pipe is obtained from simultaneous current measurements at two points, I have found it very necessary that the two instruments have the same period of vibration, as otherwise they will not fluctuate together, and the instantaneous readings cannot properly be compared.

Dr. Hering also states that he has devised a method of identifying pipe currents, consisting of simultaneously measuring drop along a pipe and drop along rails, and comparing the fluctuations in these curves of drop. I would like to say that I have used this method, but find it better to obtain simultaneous 24-hour records of the drop on a pipe and on the rails, and then to compare the characteristic variations of these drops. I have found it satisfactory to use a few feet of pipe and of rail for this purpose. I have also found, where there is an extensive piping network, and where there are several individual rail lines, that the current on any one pipe may not fluctuate with the current in the neighboring rail, because the pipe is receiving current from a number of rail lines. The method of comparing the twenty-four-hour records of drop on the pipe with the rail drop is therefore safer in such cases.

Dr. Hering also states that the ground current detector is academically interesting but could not be used because it disturbs the very conductor through which the current to be measured is flowing. I presume that he refers to the Haber earth ammeter. It is true that this earth ammeter is not satisfactory as a means of measuring the total current leaving a pipe. I have, however, found it exceedingly useful as a means of proving that stray current is actually leaving a pipe which is found corroded, and by using the earth ammeter with a recording instrument for identifying the source of the current leaving the pipe.

Edwin F. Northrup (by letter): In this paper Dr. Hering has made a valuable contribution to the literature of a class of electrical measurements which is commercially important. A word on the history of the development of these methods is not out of place. According to the writer's best knowledge (and he has informed himself with considerable pains), the original conception and original execution of the methods of measuring currents in underground pipes and the resistance of sections of such pipes as Dr. Hering describes in connection with Figs. 1 and 2 of the paper, belongs wholly to the author of the paper. The method, rather vaguely described on page 1459, intended as a modification for avoiding the difficulties which arise from the fluctuations of the currents in the pipes, was quite independently devised, fully worked out, generalized, and tested in the laboratory and in the field, by the writer of this communication. The present writer has tried no other method, as he believes thoroughly, both from theory and tests in laboratory and field, that it is the best method for the purpose, that it is quite general in application and is not at all deserving of the criticisms made in the paper, beginning with the third paragraph of page 1460.

Its independent conception was undoubtedly stimulated by a full knowledge of what Dr. Hering had accomplished by the method described and shown in Fig. 1 of his paper. But the writer of this communication feels that he has added precision and generality to the methods which Dr. Hering has described. The importance of the subject is such that the writer thinks his viewpoint and additional contributions should be presented to the Institute for permanent record in full. What follows is taken from the writer's notes, which were prepared over one year ago.

Resistance Measurement of Closed Circuits. The problem is often presented in commercial practise of obtaining the resistance of a portion of a circuit which is closed upon itself and which may contain a source of current, either alternating or direct. If the circuit could be opened even momentarily the problem could be solved by well-known methods. But if the circuit cannot be opened, the problem is still solvable in more than one way. The following methods have been carefully tested out by the writer in practical cases, and have been found to give such satisfactory results as to warrant a detailed description.

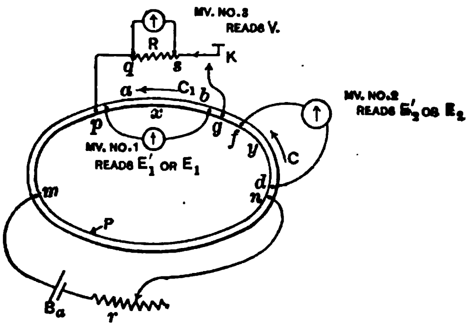

FIG. 2

We shall first consider a general method applicable to measuring the resistance of a section of a closed conductor loop, such as the rim of a cart-wheel, which may be assumed to have a cross-section which varies in an unknown way from one portion of its circumference to another. Referring to Fig. 2, we have the following dispositions of circuits and instruments.

P is a closed metallic circuit of medium or very low resistance which ***cannot be opened.*** It is required to determine the resistance *x* of a definite length of this closed circuit, as between two points *a* and *b*. For this there are required three deflection instruments which deflect proportionally to the current through them. The constants of these instruments need not be known but must be the ***same*** for all three. In the present application of the method there is required one known resistance R provided with potential terminals. This resistance R should be chosen, for the best accuracy, of the same order of magnitude as the resistance x which is to be determined. A cell of storage battery and a rheostat r to adjust the current from the battery to a suitable value, are required, also a key K. The deflection instruments would ordinarily be millivoltmeters, though three galvanometers having the same constant could be used. Millivoltmeter No. 1 is joined to the potential terminals a, b, between which the resistance is x. Millivoltmeter No. 2 is joined to the potential terminals f, d, between which the resistance is y, and the terminals of millivoltmeter No. 3 are joined to the potential terminals q, s, between which the resistance is R, which is known. The current terminals of R are joined to the points p, g, of the loop, and in circuit with R is the key K. The cell of storage battery $B\,a$, which includes in its circuit the rheostat r, is joined to two points, such as m and n, of the closed metallic circuit. This supplies to the system the current required for the measurement.

The procedure in making a measurement is as follows:

a. With the key K open, *read at the same moment* millivoltmeter No. 1 and call its deflection d_1' and millivoltmeter No. 2 and call its deflection d_2'.

b. With the key K closed *read simultaneously* the three deflection instruments. Call the deflection of millivoltmeter No. 1, d_1, of millivoltmeter No. 2, d_2, and of millivoltmeter No. 3, D.

Then, in case (a),

$$\frac{x}{y} = \frac{d_1'}{d_2'}, \text{ which call } N; \text{ then } x = Ny \qquad (1)$$

In case (b), since the deflections D, d_1 and d_2 are proportional respectively to e.m.fs. V, E_1, and E_2, we have

$$E_1 = K\,d_1 = C_1\,x \qquad (2)$$

and

$$E_2 = K\,d_2 = C\,y \qquad (3)$$

Here K is a constant and C is the current through y, and C_1 is the current through x. We also have

$$C = C_1 + I, \text{ where } I \text{ is the current through } R.$$

But

$$I = \frac{V}{R} = \frac{KD}{R}, \text{ whence } C = C_1 + \frac{KD}{R} \qquad (4)$$

In the relations (1), (2), (3) and (4) we have the unknown quantities x, y, C and C_1 and hence, there being but four unknown and four equations, both x and y can be determined.

We finally derive $x = \dfrac{d_2 N - d_1}{D} R$ **(5)**

and

$$y = \frac{d_2'}{d_1'} x \qquad (6)$$

Equation (5) is obtained as follows:
From (3) and (4)

$$\frac{K d_2}{y} = C_1 + \frac{K D}{R} \qquad (7)$$

From (2) and (7)

$$\frac{K d_1}{x} = \frac{K d_2}{y} - \frac{K D}{R}$$

or

$$\frac{d_1}{x} = \frac{d_2}{y} - \frac{D}{R} \qquad (8)$$

Putting in (8) the value of y from (1), we obtain

$$\frac{d_1}{x} = \frac{d_2 N}{x} - \frac{D}{R} \qquad (9)$$

and from (9) we find the value of x to be that given in (5).

The above method possesses four special merits: The circuit of the resistance being measured does not have to be opened; the resistance of no contact enters, and hence the contacts at points p, g, m, n and k need not be made with any special care, while the points a, b, f, d, q and s are merely potential points and contact at these places may be made with a sharp point or knife-edge pressed against the conductor; the constant of the deflection instruments need not be known, it being only necessary that all three instruments have the same constant; two instruments are read simultaneously in case (a) and the three instruments are read simultaneously in case (b), hence the current in the loop P may be very variable, and accurate results still be obtained.

This method was tried by the writer, using a brass ring a little over one meter in circumference and of No. 0 B. and S. wire. The ring was placed over an open-core alternating-current electromagnet of very great size. By exciting the alternating-current magnet induced alternating currents were sent through the ring. It was found that the readings of the three instruments, and hence the resistances measured, were in no wise affected by the presence of the alternating current induced in the ring, hence the method applies whether the closed loop is or is not carrying an alternating current.

In the above trial the actual readings observed and the results obtained were as follows:

$d_1 = 20.54$; $d_2 = 25.18$; $D = 18.51$; $R = 0.01$ ohm. The ratio of d_1' to d_2', or N, was 0.9940. From these readings the value obtained for x was, by equation (5),

$$x = \frac{25.18\,(0.994 - 20.54)}{18.51}\,0.01 = 0.002425 \text{ ohm.}$$

The ring was afterward cut open and the resistance x was determined by an ordinary method, and found to be 0.002439 ohm. Hence the error in the measurement of the closed ring was 0.57 of 1 per cent.

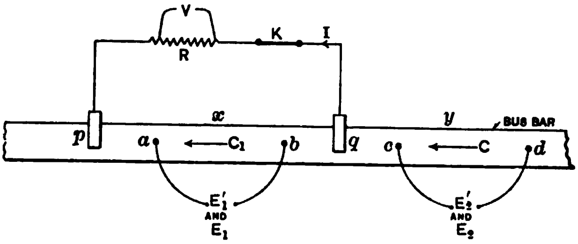

FIG. 3

This method has a useful application when applied to the determination of the resistance between two points in a d-c. busbar while this is carrying its current.

To Measure the Resistance between Two Points on a Busbar. The arrangement to emplcy is represented in Fig. 3. The potential points *a*, *b*, and *c*, *d*, may be obtained by drilling and tapping small holes in the busbar and inserting in these holes small screws to which the terminals of the millivoltmeters may be secured. The terminals of the resistance *R* may be attached to the busbar at *p* and *q* by means of iron clamps, as the precision of the method is not affected by contact resistances at these places. The distances between the point *a* and the clamp *p*, and the point *b* and the clamp *q*, should be at least three times the width of the busbar. It is also desirable to have the clamps *p* and *q* make contact with the busbar across its entire width. The purpose of these two precautions is to insure that the stream lines of current are parallel with the busbar at the potenial points *a* and *b*. For the same reason the potential point *c* should be as far to the right of q as the potential point b is to the left. The distance from c to d should be chosen about equal to the distance from a to b in order to bring the ratio N near unity.

If there is direct current in the busbar, supplied by the generator, then there is no necessity of introducing additional current from storage cells, as is required when measuring the resistance of a section of a loop as in the example above.

The standard resistance R should be supplied with potential points and should be not over ten times the resistance of the busbar between the clamps p and q. Greater accuracy will be obtained if this resistance is about equal to the resistance of the busbar between the clamps. Since the drop of potential over the resistance R is read to give the value of the current I, which flows in the branch circuit, one may substitute an ammeter for the resistance R and the millivoltmeter which reads the drop over this resistance. In this case, however, the other two deflection instruments must read, not in arbitrary units, but in volts or millivolts.

The procedure is the same as in the case of the ring, described above. Giving the symbols the meanings designated in Fig. 3, we have:

With the key K open,

$$\frac{x}{y} = \frac{E_1'}{E_2'} = N \tag{1}$$

With the key K closed, we have, from readings taken simultaneously by three observers,

$$E_1 = C_1 x \tag{2}$$

and

$$E_2 = C y \tag{3}$$

We also have the relation

$$C = I + C_1 = \frac{V}{R} + C_1 \tag{4}$$

From (1), (2), (3) and (4) we deduce, as in the case of the measurement of the resistance of a ring,

$$x = \frac{E_2 N - E_1}{I} \tag{5}$$

or

$$x = \frac{E_2 N - E_1}{V} R \tag{6}$$

If equation (6) is used, E_1, E_2 and V can be multipled by the same constant, a, and hence the deflection instruments may be calibrated in arbitary units, provided the same arbitrary units are used for all three instruments.

The purpose to be fulfilled in finding the resistance between two points in the busbar is to enable the current in the busbar to be measured at any time by reading the drop of potential between the points with a millivoltmeter. A portion of the busbar is made in this manner to serve as a shunt for a millivoltmeter, which thus becomes an ammeter for reading the current in the busbar. As busbars are made of copper or aluminum, which have a large temperature coefficient, we have to consider to what extent, if any, their change in resistance with temperature will affect the precision with which the current may be read. Let Fig. 4 represent an arrangement to be employed.

Here, $B - B_1$ is a section of a busbar. We shall suppose that the resistance R_{20} has been accurately obtained at 20 deg. cent., between the two points a and b, by the above method. The millivoltmeter MV is joined to the points a and b.

Let
$$r_T = r_{20}(1 + \alpha T) \qquad (1)$$

be the resistance of the millivoltmeter at T deg. cent. above 20 deg. cent. when r_{20} is its resistance at 20 deg. cent. and α is the temperature coefficient of its winding.

Let
$$R_t = R_{20}(1 + \beta t) \qquad (2)$$

be the resistance between points a and b of the busbar at t deg. cent. above 20 deg. cent. when R_{20} is its resistance at 20 deg. cent. and β is the temperature coefficient of the material of the busbar.

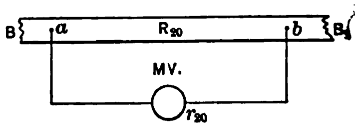

Fig. 4

The busbar may change in temperature both from changes in the temperature of the room and from the heating due to the current which it carries. The millivoltmeter MV can only change in temperature from changes in the temperature of the room. Hence, in general, the temperature T of the millivoltmeter will not be the same as the temperature t of the busbar.

We wish to determine the nature and magnitude of the errors produced by these temperature changes in reading the current. If I is the current in the busbar, the fall of potential from a to b, when the temperature of busbar is t, will be

$$E_t = I R_t \qquad (3)$$

The current through the millivoltmeter will be

$$C = \frac{E_t}{r_T} = K D \qquad (4)$$

where D is the deflection of the millivoltmeter and K is a constant. Hence

$$E_t = K\,D\,r_T \tag{5}$$

By equations (3) and (5),

$$I = K\,D\,\frac{r_T}{R_t} = K\,D\,\frac{r_{20}\,(1 + \alpha\,T)}{R_{20}\,(1 + \beta\,t)} \tag{6}$$

Since the busbar and the winding of the millivoltmeter are both of pure metal, as copper or aluminum, the temperature coefficients α and β would be practically the same and may be taken, approximately, as 0.004. Equation (6) can therefore be written:

$$I = \frac{K\,D\,r_{20}}{R_{20}} \times \frac{1 + 0.004\,T}{1 + 0.004\,t} \tag{7}$$

The error in the measurement of I is now seen to depend directly upon the amount by which the last term of equation (7) departs from unity. In the case of no heating, by the current, of the busbar above room temperature, (as would be very approximately realized for a loading of the busbar of 50 per cent full load or less) $t = T$, and there is no error, whatever the room temperature becomes. Now t can never be less than T, but may assume a value $T + \delta\,T$, where $\delta\,T$ represents the temperature of the busbar above the temperature of the air. In this case equation (7) becomes

$$I = \frac{K\,D r_{20}}{R_{20}} \times \frac{1 + 0.004\,T}{1 + 0.004\,T + 0.004\,\delta\,T} \tag{8}$$

As a rather extreme case we may take $T = 10$ deg. cent. above 20 deg. cent., and $\delta\,T = 5$ deg. cent. Then

$$\frac{1 + 0.004 \times 10}{1 + 0.004 \times 10 + 0.004 \times 5} = \frac{1.04}{1.06} = 0.981 + .$$

Thus the true value of the current would be, in this case, about two per cent less than one would read it upon the millivoltmeter.

The following estimate shows that the fall of potential in a busbar is large enough to apply the above method of measuring the current in it; though the writer has not had an opportunity of putting the method into practise as was done in the other cases here described. The resistance of 100 per cent conductivity copper at 20 deg. cent is 67.7×10^{-8} ohm per linear inch

(25.4 mm.) per sq. in. (6.45 sq. cm.) of cross-section. It is good practise to allow 1000 amperes per sq. in. of cross-section of copper conductor. Then, with 1000 amperes to the sq. in. of cross-section, the drop of potential per linear in. becomes $10^3 \times 67.7 \times 10^{-8} = 0.677 \times 10^{-3}$ volt, or 0.677 millivolt per linear inch. If the full scale reading of the millivoltmeter is 20 millivolts, the distance between the potential points *a* and *b* (Fig. 4) would need to be $\frac{20}{0.677} = 29.2 +$ in.

This length of busbar, to be used for the purpose of a shunt, could be obtained behind most any switchboard, and it is probable that a shunt for the millivoltmeter of this character would serve quite as well and perhaps be superior to the shunts ordinarily used. For these latter have a very low temperature coefficient and changes in the temperature of the room will increase the resistance of the millivoltmeter without increasing in like degree the resistance of the shunt, and hence there is no automatic compensation, as in the case discussed above, where the busbar itself serves as a shunt.

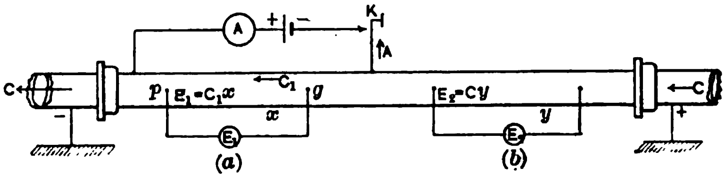

FIG. 5

To make the millivoltmeter read directly in amperes requires, of course, that the constant *K*, in equation (8), be correctly chosen. As we are at liberty to give any value to the resistance, r_{20}, it will always be possible to do this.

Measurement of the Resistance of Underground Mains. An important application of the methods above described for measuring the resistance of a portion of a closed circuit is the determination of the resistance between two selected potential points upon an underground gas or water main. Underground pipes are subject to deterioration from electrolysis, caused by " tramp " currents which get into the pipe line from neighboring electric trolley roads. The electrolysis occurs when current *leaves* the pipes. It becomes important, at times, to be able to measure quickly and accurately the *current* which flows in some selected section of a pipe line. It is evident that this can be easily accomplished by measuring at any time, with a millivoltmeter, the potential drop between the points on a section of pipe, provided the *resistance* between these two points has been previously determined. The method shown in Fig. 5, which is a slight modification of those described above, enables this resistance to be measured with considerable precision while the section of pipe is in place in the pipe line.

The measurement is made with two millivoltmeters and an ammeter. One or two cells of storage battery are also required. The cells of storage battery, a key *K* (Fig. 5) and the ammeter *A* are joined in series and connected at two places, as shown in the diagram, to a section of pipe. These connections are best made by drilling ¼-in. (6.3-mm.) holes about half way through the pipe wall, and driving brass plugs into them. Heavy copper wire connections may then be soldered to the brass plugs. The other connections, which serve as potential points, may be made in a similar manner, but smaller holes and plugs will serve. There should be as much separation as possible between a potential point and the place of connection of a current lead, and these should, preferably, be located at the ends of diameters of the pipe which form with each other an angle of 90 deg.

It is well to take one set of readings and calculate the resistance with the polarity of the storage cell in one direction and then take a second set with the polarity of this cell reversed. In the mean of the two resistances thus obtained, the error, which results from the flow lines of current from the storage cell not being parallel with the section of pipe between the potential points, is largely eliminated. This is specially the case when there is considerable current flowing in the pipe from other sources than the storage cell.

This error will be small, however, in any case, if the distance between a potential point and the point of connection of a current lead is, say, twice the diameter of the pipe and these terminals are located as above suggested. Referring to Fig. 5 for the meaning of the symbols, we have, as in the cases given above:

With the key *K* open,

$$\frac{x}{y} = \frac{E_1'}{E_2'} = N \tag{1}$$

and with the key *K* closed,

$$E_1 = C_1 x \tag{2}$$

$$E_2 = C y \tag{3}$$

and

$$C = C_1 + A, \tag{4}$$

from which we find

$$x = \frac{E_2 N - E_1}{A} \tag{5}$$

Also
$$y = \frac{E_2 - E_1 \frac{1}{N}}{A} \tag{6}$$

or
$$y = \frac{x}{N} \tag{7}$$

In applying the method, one is not in the least troubled by the sudden variations of the current in the pipe which constantly occur, because E_1' and E_2' are read *simultaneously* to obtain the ratio N and then, again, E_1, E_2 and A are read simultaneously to obtain the other necessary values. Three observers, reading at the same moment, obtain correct values; for when the current varies, a variation occurs in all three instruments at the same time, the proper *relation* between the readings of the three instruments being always maintained.

This method was carefully tested by the writer upon an actual pipe line with excellent results. The essential features of the test are given to show how the measurement works practically, and are recorded below:

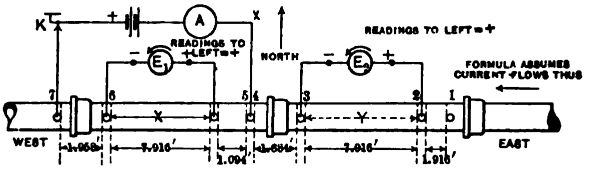

FIG. 6

The diameter of the pipe was 15 in. (38 cm.). Two pipe lengths were uncovered and the connections to the pipe sections were made at distances and in the manner shown in Fig. 6. The method embodied the use of two cells of storage battery, which would yield on short circuit, when joined in parallel, 125 to 150 amperes, and also one ammeter reading to 200 amperes and two millivoltmeters giving a full scale deflection with 20 millivolts. In circuit with the ammeter and storage cell a single-pole current switch K was used. The following readings were taken:

E'_1 and E'_2 were read simultaneously. The current in the pipe was sufficient for the purpose. The mean of nine readings of E_1' was 7.511 millivolts and the mean of nine readings of E_2' was 7.122 millivolts. Hence the value of the ratio $\frac{x}{y}$ was

$$N = \frac{7.511}{7.122} = 1.055$$

There were then taken seventeen sets of readings of E_1, E_2 and A with the positive pole of the battery cell joined to No.7 terminal (Fig. 6), and a like number with the negative pole to this terminal.

The following table exhibits a few sample readings.

Current + to No. 7 Terminal				Current – to No. 7 Terminal			
E_1 millivolts	E_2 millivolts	A amperes	X = ohms for 7.916 ft.	E_1 millivolts	E_2 millivolts	A amperes	X = ohms for 7.916 ft.
—6.8	1.6	116	0.0000731	7.60	0.4	—102	0.0000703
—6.2	1.8	110	0.0000736	7.8	0.8	— 98	0.0000709
—8.3	0.9	127	0.0000728	8.2	1.0	—101	0.0000707

The mean value deduced for X with the current from the storage cell positive to terminal No. 7 was 0.00007315 ohm, and with the current from the storage cell negative to terminal No. 7, it was 0.00007077 ohm. The mean of these two results was 0.00007196 ohm for a length of the pipe of 7.916 ft. There were 40 ft. (12.2 m.) of No. 14 wire used, as potential leads, to each millivoltmeter. Calculation showed that to correct for the resistance of these leads the final value of X should be multiplied by 1.088. Doing this and reducing the resistance to a length of one foot (304.8 mm.) of pipe, the final value found was: 9.91 microhms per foot, at 65 deg. fahr.

The test was defective in that the distances between potential points and points of attachment of current leads were not chosen as great as they should have been and were all made on the top side of the pipe. The " tramp " currents in the pipe were large and very variable at the time of the test. In spite of this the resistance measurement is probably correct within 1.5 or 2 per cent, and should have been better.

It was found in this test that care had to be exercised to give the readings of the three instruments the proper algebraic signs. By making a diagram, like Fig. 6, before beginning the test, errors of this character may be avoided.

George F. Sever: Assuming that this method of Dr. Hering's is correct, which it undoubtedly is, and perfectly available for measuring current in pipes, what are we going to say in court to the jury, or to the judge, when we do find current in the pipe, and it is recognized that current, when leaving a pipe, under most circumstances, causes corrosion? A cooperative test by the parties in interest will undoubtedly show current on the pipe, and if both parties in interest go into court with this statement, it becomes a very difficult matter, at least for the railroad company, to defend the presence of current on these pipes.

If we agree that one ampere on a pipe causes a certain amount of electrolytic effect when leaving it, and then find 100 or 200 or even 500 amperes on a pipe, it becomes a very difficult matter for the railroad company to say that there is no damage. In other words, if there is found any current on the pipe, might it not cause damage at all sorts of places, and can the railroad company, which is alleged to put the current on the pipe, defend its position?

All of these measurements lead up to interesting technical conclusions, but the real common sense question is, how are we going to interpret the results?

Edward B. Rosa: We have been making some study of this subject at the Bureau of Standards. Several years ago we tried the method Dr. Hering has outlined, before we knew that it had been used by him, but we believe that it is not generally necessary to determine the resistance of the pipe. You cannot determine the current, with precision, as has been said, as it is so variable, and therefore, it is not necessary to determine the resistance with precision. We have found that the resistances of different kinds of pipe are sufficiently near together, so that we believe it is practicable to prepare a table of resistances for different sizes and different kinds of pipe. We have obtained samples of different kinds of pipe used for gas and water, and have measured the resistance, and will shortly have a table prepared, which will be in practical form for the use of engineers, so that they may be required only to measure the drop in potential and take the resistances out of the table. That is not expected to be accurate, as the pipes may have corroded to some extent, but it may be used for approximate purposes, where approximate determinations will be satisfactory, and the table will, undoubtedly, be of very considerable value.

Alexander Maxwell: I do not think that Dr. Hering does entire justice to Haber's earth ammeter, in describing it as merely of academic interest, or in stating that its use involves many assumptions. I have used it extensively, and with very good results.

By means of this instrument, earth currents are intercepted and measured; and while it is true that the soil conditions are somewhat altered, that is of little importance if the path of the current through the soil is of any considerable length, which is nearly always the case. However, it is generally not of the first importance exactly to reproduce the normal conditions quantitatively. It is of much greater importance to determine whether current does flow or not, and to determine its direction and its source. The actual normal value of the current is only a matter of secondary importance, since the total amount of current lost from an entire pipe line may be quite accurately determined by other means, where it is necessary to determine it at all.

In my opinion, too much stress is sometimes laid upon the total amount of current lost from a particular pipe, or from a system of pipes, since this is often a matter of no particular importance. A comparatively small amount of current escaping from a pipe may produce corrosion over a limited area, and yet the whole pipe will be made useless, just as though it had been corroded over its entire surface.

The earth ammeter is actually a very useful instrument, and when properly used it is capable of indicating conditions which are otherwise obscure. Moreover, when its indications are observed simultaneously with other quantities, such as potential difference, or the main current flowing in the pipe, the source of stray current may be identified by means which involve no questionable assumptions. Thus, as in Fig. 7, where it is suspected that current is escaping from a pipe and flowing to a street railway rail, the earth ammeter may be placed in the earth between the two structures, and by setting it successively in three planes the direction of the stray current may be quite definitely determined. A still better way to do this is to employ three instruments, set as above, and read them simultaneously.

Measurements such as these, taken simultaneously with measurements of potential difference between the two structures, constitute good evidence of the existence of the suspected stray current, and good evidence of its identity. It is even better to obtain 24-hr. records of the quantities, by means of recording instruments.

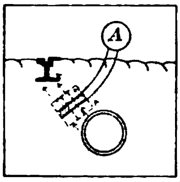

FIG. 7

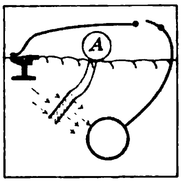

FIG. 8

The main object of tests of this character is to prove that stray currents from some suspected source do actually escape from the pipe being tested. The earth ammeter can be used to indicate the escape of currents much smaller than those which could possibly be determined with any accuracy by even the most refined methods for measuring the total current in the pipe. The loss may be even less than one per cent of the total current in the pipe, and still produce measurable indications in the earth ammeter. It is well understood that even such small currents may produce serious corrosion, and, in fact, it is the usual condition that stray currents flow on to pipes, and escape from them, in very small amounts, as reckoned for units of pipe surface.

Another useful application of the earth ammeter for the identification of stray currents consists in shunting the conducting path through the soil, by means of a heavy bond connection between the two structures which, with the soil, constitute the circuit for the stray current. This general arrangement is shown in Fig. 8. In this case, if the earth ammeter shows a certain current flowing between the pipe and the rail with the shunt circuit open, and this earth current is reduced in value when the shunt circuit is closed, excellent evidence is obtained of the actual flow of stray current through the earth.

I am of the opinion that stray earth currents can be detected, measured and identified by means of the earth ammeter, in cases where a survey based merely on measurements of total current in the pipes would not adequately indicate all of the places where current enters or escapes from the undergound structure being investigated.

With regard to the main feature of Dr. Hering's paper, namely, the methods of calibrating the pipe resistances, I have employed the last method described in the paper since 1908, generally utilizing the stray current itself, by means of a temporary bond connection to the street railway rails. I have, however, only found it necessary to calibrate pipes in this manner for very special cases, generally finding the calculated resistance amply accurate, since measurements of such fluctuating quantities as stray railway currents cannot be even observed with great accuracy.

This same consideration of accuracy affects the choice of instruments, and I have found that portable pivoted instruments of relatively high sensibility for their class are decidedly preferable to reflecting instruments as used by Dr. Hering. In short, a large number of significant readings of moderate accuracy provides a better basis for preparing a case than a few observations of wholly unnecessary precision.

Frank Wenner: This method that Dr. Hering has described for measuring currents in pipes seems to be a perfectly obvious method. I personally know of a number of persons who have thought of the method, and I should like to point out that it was used by Professor Adams in Columbus about fifteen years ago, and in that particular case—it was a court case in which the matter of resistance of the pipe was brought into question—he used the method for measuring the resistance as well as measuring the current.

In this particular method, a high degree of accuracy cannot always be obtained, especially in large gas pipes if the current to be measured is comparatively small. The difference in temperature between the two points of the pipe to which the potential connectors are attached may amount to a degree or even to two degrees. Since the thermo-electromotive force amounts to about fifteen microvolts per degree difference in temperature, if the potential connections are copper, serious errors may be introduced where the currents are small and the pipes large and of low resistance. The thermo-electromotive force may cause errors either when the method described by Dr. Hering is used or when the ordinary method, using a sensitive millivoltmeter, is used.

Clayton H. Sharp: In electrolytic surveys and studies all methods are useful, at some times. Conditions are varied, and while in general the method of estimating the resistance of the pipe is sufficient, yet there are times when a method like the one which has been presented to us in this paper is bound to be useful. I think that we are indebted to Dr. Hering for bringing it to our attention, and for smoking out a whole lot of people who have been using it and saying nothing about it.

Carl Hering: Dr. Sharp has already answered one point which came out in the discussion; when members of a profession like ours keep their methods of measurement secret, they are not doing their duty to their colleagues and it is not creditable to them to come out afterwards with claims of priority when someone takes the trouble to publish a description. Moreover I do not admit that the alleged prior methods described in the discussion were really the same; Professor Ganz's certainly was not.

It has been said in the discussion that such precision as is indicated in this paper is not necessary; in most of the ordinary cases it is not, but in a legal case, in a suit in court, it is necessary or else the results will not be sound legal evidence. Furthermore, one of the principal points in this case was to find the current entering or leaving the pipe, and unless the original currents are measured accurately, you cannot depend on their differences. If, for instance, one is 100, and the other 98, an error of only 3 per cent in these measurements may even change the sign of the result.

Professor Ganz upheld the method of *assuming* the resistance and then measuring the current with a millivoltmeter. I do not believe in virtually assuming the thing you are going to measure; it is a very easy way to get results, but I do not approve it. It is moreover dangerous to assume a resistance for a pipe, for the reason that pipes are laid much thicker in the valleys than at the tops of hills, and the gradations are rather small; for that reason alone it is unsafe to assume that any particular length of pipe has any particular thickness, unless you have laid the pipe yourself and know just what the thickness is.

As to the 24-hour measurement that Professor Ganz spoke of, it is hardly necessary, in most cases, to run such identification tests for 24 hours. In fact, a measurement continued over a period of one hour will generally give you two saw-tooth curves that are so nearly alike that you have enough evidence to show the court that the street railway is the offending party.

I do not wish to say anything against Haber's earth ammeter, as it is very ingenious and undoubtedly very useful for certain purposes, but it will not do for the purpose for which I wanted these measurements.

As to who originated the system, that is of little general interest. I agree with Dr. Sharp that a person who has used some system which is valuable to others and does not make it public in a paper or some other form of announcement, has no moral right to come out afterwards and claim originality.

Carl Hering (communicated after adjournment): In examining more carefully such broad, vague, general and sweeping claims of priority as those made in this discussion, I have often found, in other cases, that the alleged prior method was not the same one at all, but that it lacked the very elements which characterize the method whose originality is disputed. Several of the speakers evidently overlooked the important statement that this method was devised specifically to determine the current which enters or leaves a pipe, as distinguished from the current flowing in the pipe; for the latter purpose I admit that the very simple method of *assuming* the pipe resistance would be good enough for many purposes, and perhaps even for some legal cases; but I do not believe that any of those speakers will claim that a method based on assumed resistances would be satisfactory or reliable when the result sought is a *difference* between two readings which may at times be nearly equal, and when a lawyer attempts to discredit it to the court.

I grant that Dr. Northrup devised the particular modification described on page 1459 without knowing that I had devised exactly the same one a year or two earlier; I preferred to use the others in most of the tests because the instruments I had to use were not considered to be sufficiently reliable for this method. I cannot grant him, however, that any " precision and generality " was " added " when he devised it independently; as they are identical, one cannot be more precise or more general than the other. Whether my description of it in this paper was " vague," as he claims, I am willing to leave to others to judge.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

A TUBULAR ELECTRODYNAMOMETER FOR HEAVY CURRENTS

BY P. G. AGNEW

Theory of Instrument

To obtain the same current distribution for both alternating and direct current it is usual to strand the windings of the field coils of electrodynamometers, and the strands should also be thoroughly mixed so that all shall have the same effective resistance and inductance. For very heavy currents this becomes a matter of extreme difficulty.

In the present instrument an entirely different means of obtaining the same end is employed. Evidently the ultimate requisite in an instrument for transferring from alternating to direct current is that the torque shall be the same, and it is immaterial whether we make the current distribution the same, or the field due to the current the same. The latter is the method adopted. There is no theoretical reason why the current distribution and the magnetic field could not both be allowed to vary if it could be shown that the torque did not change.

The field " coil " of the instrument consists of two coaxial copper tubes, thus giving a circular magnetic field in the space between the tubes. On direct current the distribution may be assumed to be uniform over the cross-section of the tubes, but on alternating current, as is well known, the stream lines are crowded toward the outside of the inside tube and toward the inside of the outside tube, and the amount of this change depends upon the frequency. But it may easily be shown that if we have axial symmetry the magnetic field at any point is independent of the current distribution. Expressed in the usual terms, there is no magnetic field between the tubes due to the outside tube, and that due to the inside tube is independent of the skin effect, but it is better to consider the arrangement as a special case of a more general principle.

Let us consider a generalized toroid such as would be formed by rotating any closed circuit such as *A* (Fig. 1) about an axis. We may think of the circuit *A* as consisting of a wire carrying a current, and similarly of the surface of revolution as being a current sheet. Or we may think of the surface as being wound with a layer of wire with no space between turns and thus becoming an endless solenoid.

It has been shown by Maxwell[1] and by Gray[2] that the field at any point, as at *O*, is independent of the size, shape and thickness of the conductor and depends only on the total current and the distance of the point from the axis. This may be shown by a very simple process of reasoning. The all-important condition is axial symmetry.

Consider a circle perpendicular to the plane of the paper, and cutting it in the points *O* and *O′*. This circle links once with the current. Hence the line integral of the magnetic field around this circle, or the work required to carry a unit pole around it, is 4 π times the total current, or, if we remember that *H* is uniform around the circle,

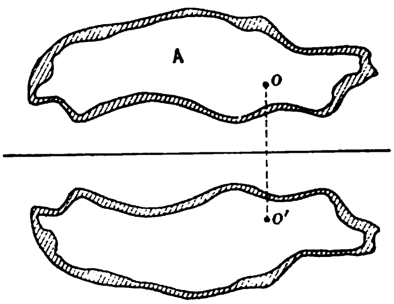

FIG. 1—THE GENERALIZED TOROID.

$$2\pi R H = 4\pi I$$
$$H = 2I/R$$

The value of *H* at any point within is thus entirely independent of the dimensions of the conductor, provided there is axial symmetry. Hence an approximation to such a form for the current coils is admirably adapted for alternating-direct-current transfer dynamometers, since it is independent of the current distribution.[3]

It will be seen that the concentric tubes form an approximation

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[1] "Electricity and Magnetism," Vol. II, Art. 681.

[2] "Absolute Measurements," Vol. II, page 278.

[3] For a detailed discussion of this principle and its application to electrodynamometers, see Agnew and Fitch, *Elec. Rev.* (Chicago), **60**, p. 767, **1912.**

to a toroid or an endless solenoid of one turn. It can only be an approximation since it must be open at one end in order to introduce the current.

CONSTRUCTION

Fig. 2, which is a vertical longitudinal section through the instrument, shows the general arrangement. The tubes are horizontal in order to allow a vertical suspension, and the moving coils are placed astatically, one above and one below the inner tube. These are shown in the plane of the section instead of in the mean working position, which is nearly perpendicular to the plane of the paper. This is done in order to show the shape of the coils, which are wound on ivory frames. They are held together by fine silver wires, one on either side of the inner tube, as indicated in the figure.

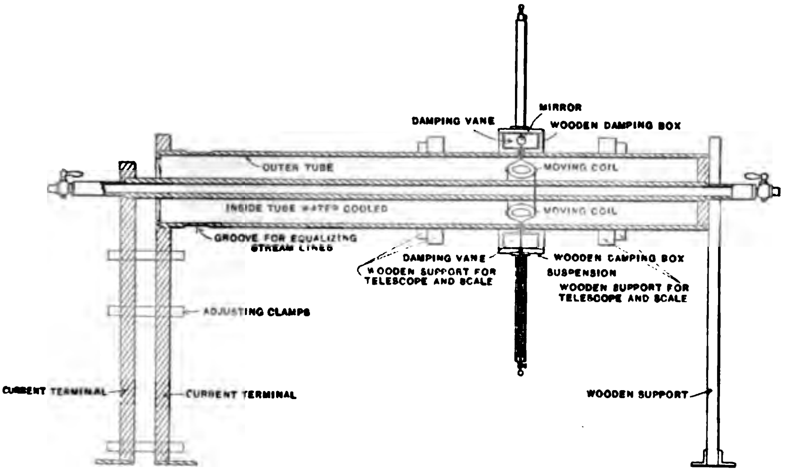

FIG. 2—TUBULAR DYNAMOMETER.

Phosphor bronze strip suspensions are used, and two air damping vanes are provided. The damping boxes are of wood and are mounted directly on the outside copper tube. The instrument is read by telescope and scale.

Massive copper slabs placed parallel and 4 cm. apart serve as current terminals. They are provided with 5 bolts so arranged that any number of parallel leads up to 5 may be connected symmetrically. These at the same time serve as supports for one end of the instrument, and the closed end is supported by an oak upright.

Water cooling is provided for the inside tube by passing water through it, but no special means are provided for cooling the outside tube.

While the very heavy copper slabs used for current terminals tend to equalize the stream lines in the larger tube about the axis as a line of symmetry, this was deemed insufficient for the most precise work. Accordingly a groove 5 cm. wide was turned eccentrically in the large tube near the open end, so that the groove was 2 mm. deep on the top of the tube and 3 mm. deep on the bottom. When finally mounted a current was passed through the instrument and equipotential surfaces laid off on the tube. By a small amount of filing the eccentricity of the groove was adjusted so that the equipotential surface was a plane perpendicular to the axis. It was found that the relation held very accurately throughout the length of the tube—the distances between equipotential surfaces measured at different points on the circumference differed but one millimeter in 800.

From the principle of axial symmetry outlined above, it may easily be seen that no error due to skin effect in the closed end will enter. For this reason the moving coils were placed one third of the length from this end so as to minimize the effect of the leading-in cables, etc. Perhaps a fourth or even a fifth would have been better.

PERFORMANCE

It is of first importance to determine whether the instrument is affected by distribution errors. Rosa has described an indirect method[4] for making this determination by the use of capacity in the moving coil circuit. If the moving coil circuit be short-circuited on a resistance shunted by a condenser having such a value that

$$L = C R^2$$

where L is the self-inductance, R the external resistance and C the capacity shunted around it, then there should be no deflection on closing the circuit, no matter what the position of the coil. But if there is such an error then there will be a residual deflection.

When the instrument was first set up it showed no such error up to 300 cycles. But after it had been in service some time

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[4] *Bulletin of the Bureau of Standards*, 3, p. 43, 1907. *Reprint* No. 48.

this same test showed a slight error. This was found to be due to an extremely slight flexure of the inner tube brought about by clamping heavy cables and lugs to the massive terminals, although considerable care had been taken to obtain a secure mounting. The trouble could be removed by springing the tubes by means of clamps placed on the copper slabs which serve as terminals. In other words a slight departure from the, condition of axial symmetry introduces a distribution error, and this can easily be detected and corrected by a purely electrical test. Strong clamps and struts (shown in dotted lines in the figure) have been arranged to hold the copper slabs in proper position.

Measurements of large currents by means of a current transformer whose ratio had been carefully determined were in substantial agreement with the indications of the tubular dynamometer. It is believed that the instrument is accurate to 0.05 per cent.

It was found necessary to put loose-fitting diaphragms across the tube on each side of the moving coils to prevent air currents, for such currents of air caused considerable unsteadiness of the reading, even for comparatively small temperature differences in the mass of copper composing the instrument. The diaphragms effectually removed the trouble.

A more serious difficulty was encountered with magnetic impurities in the moving coil. The requirements here are even more exacting than in the sensitive moving coil galvanometer, for the parts of the moving coils nearest the inside tube are in a field comparable in magnitude to the flux in the air gap in the permanent magnets of such galvanometers. The whole directive magnetic force exerted on the coil must be vanishingly small or the zero of the instrument will not be the same with current on that it is with current off. In the galvanometer, on the other hand, the requirement is merely that the magnetic force on the coil shall not vary appreciably through comparatively small angles.

Finally special coils were wound which were entirely satisfactory. These were of silver wire 0.2 mm. in diameter, silk-covered, and were stated by Mr. W. N. Goodwin, Jr., of the company which made the coils, to be actually diamagnetic.[5]

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[5] Mr. Goodwin found the torque acting on the coils and tending to maintain them at right angles to a magnetic field having a strength of 1175 gausses to be 0.286 and 0.238 dyne-centimeters per radian, respectively.

They were mounted with great care to prevent magnetic contamination from dust. The zero is precisely the same with current on or off.

It might have been better to have made the instrument with two independent sets of moving coils, one set for the smaller currents, placed very close to the inside tube where the field is strongest, perhaps even decreasing the diameter of the tube for the purpose, and a second set for heavier currents, placed near the outer tube. This would extend the range of the instrument. In addition, current and power could be measured simultaneously.

CONSTANTS AND DIMENSIONS

Copper slabs for current terminals:		
Thickness	2.5	cm.
Width	20	"
Outer tube:		
Length	101	cm.
Radii	6.41 and 7.07	"
Inner tube:		
Length	126	cm.
Radii	1.03 and 1.66	"
Total weight of instrument (approximately)	80	kg.
Moving coils:		
Diameters (approximately)	2.5 and 5	cm.
116 turns of 0.2 mm. silver wire		
Weight of each coil	7.3	g.
Moment of inertia, each	12	g-cm.^{2}
Resistance:		
Coils alone	12.2	ohms.
Total for system	14.4	"
Self-inductance	1.4	mh.
Resistance:		
Outer tube	8	microhms.
Inner tube	42	"
Complete instrument	53	"
Power consumed (at 5000 amperes):		
Outer tube	200	watts
Inner tube	1050	"
Complete instrument	1325	"
Magnetic field at center of coils (approximately)	300	gausses
Sensitivity:		
100 cm. deflection at 86 cm. scale distance requires 100 amperes with 0.06 amperes in the moving coil.		
Capacity:		
With water cooling	5000	amperes
Without water cooling	1200	"
Of moving coil circuit	0.06	"

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

MEASUREMENT OF ALTERNATING CURRENT OF LOW VALUE

BY M. G. NEWMAN

Alternating-current ammeters of the dynamometer type when used for measuring small currents are usually connected so that the moving coil is in series with the stationary or field coils.

As the instrument has no iron in its magnetic field, the instantaneous values of the flux densities in the moving and fixed coils will be proportional to the current. The torque will, therefore, be proportional to the square of the current and the instrument will indicate the effective value of the current.

In order to increase the sensibility of the ammeter, suspensions are used in place of pivot and jewel bearings. The weight of the moving parts and the size of the suspension are made as small as possible without having the period too long or the instrument too much affected by external disturbances.

The determination of small alternating currents is usually required in circuits of low voltage. It is, therefore, necessary that the impedance of the ammeter shall be small, as the voltmeter reading must include the potential drop in the ammeter,

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REFERENCES

"Study of the Current Transformer with Particular Reference to Iron Loss," by P. G. Agnew; National Bureau of Standards, Reprint No. 164.

Electrical Measurements on Circuits Requiring Current and Potential Transformers, by L. T. Robinson, TRANSACTIONS A. I. E. E., 1909, XXVIII, II, p. 1005.

National Bureau of Standards, Reprint No. 130, "The Determination of the Constants of Instrument Transformers," by P. G. Agnew and T. T. Fitch.

and this should be negligible within the limits of accuracy required by the test.

In examining an ammeter for sensibility, two things should be considered, the ampere sensibility and the impedance.

The square of the current multiplied by the impedance of the instrument gives the volt-amperes. If the weight of the moving coil and size of the suspension have been reduced to the minimum limit, the ampere sensibility can only be increased by increasing the number of turns in the coils; but if the size and weight of the coils are kept the same, the resistance and inductance of the instrument will increase approximately with the square of the number of turns.

The voltage necessary to give a deflection of a certain amount, therefore, will increase as the current sensibility is increased. Thus for very low reading ammeters the impedance is high, and if measurements are to be made in a circuit of low electromotive force the error in the voltmeter reading, due to the potential drop in the ammeter, will be considerable.

Separately Excited Dynamometers. By separately exciting one of the elements of the ammeter by current from a phase-shifting transformer, the sensibility of the instrument is very much increased. Its deflection then is proportional to the product of the amperes in the moving and fixed coils times the cosine of the phase angle between them.

The instrument is calibrated as a wattmeter.

$W = k\,r\,d$, where (1)

W = watts
r = total resistance in the potential circuit
d = the deflection
k = constant of the instrument

The phase position of the current in the separately excited element is changed by the phase shifting transformer until the reading of the instrument is a maximum.

In the equation: $W = E\,I$ cosine θ, (2)
if θ is zero, $W = E\,I$

Wave Distortion by Phase-Shifting Transformer. The angle of shift of the secondary potential of the phase-shifting transformer is determined by the position of the secondary winding relative to its primary winding, and is independent of the frequency. If the impressed wave is not sinusoidal, there will be a distortion due to the fact that each harmonic wave which makes up the complex wave is shifted the same number of degrees; but each with reference to its own length and not to that of the fundamental. For this reason it is better, in general, to use an approximate sine-wave generator.

There may also be present a small wave distortion due to the leakage reactance of the phase-shifting transformer. This, however, is very small and in general may be neglected.

Errors Due to Wave Form. If the wave form of the currents in the two elements of the dynamometer is the same, the above equation (2) is strictly correct, but this is seldom the case. A brief discussion of the errors of the method is necessary.

Harmonics of current present in only one element of the instrument produce no torque. Taking an example: consider a sine current wave in the potential circuit of the dynamometer, and in the current coil, a current wave with a fundamental, the effective value of which is 10 amperes, and a third harmonic with an effective value of 1 ampere: the effective value of the complex wave will be $\sqrt{10^2 + 1^2} = 10.05$ amperes, but the dynamometer will measure only the fundamental and the error will be 0.5 per cent.

If harmonics other than the fundamental are present in both elements, torque will be produced by those of the same frequency which may be either negative or positive, the sign and magnitude depending upon the phase position of the harmonics.

As the errors pointed out above depend upon the wave shapes of the current in the two circuits of the dynamometers, it is impossible to make corrections without knowing the wave forms.

The following current measurements were made to investigate the errors of the method and a comparison was made with the readings of a dynamometer ammeter which was used as a standard.

TESTS

Exciting current tests were made on a telephone transformer at 60 cycles:

(a) Using the separately excited dynamometer as an ammeter. The diagram of connections is shown in Fig. 1.

(b) Using the dynamometer ammeter with connections as shown in Fig. 2.

Power was supplied from a three-phase Thomson-Houston smooth-core alternator. The potential waves are given in Curve 1.

The voltage of the generator is 575 at 60 cycles, and was stepped down through 5:1 step transformers with their primaries and secondaries connected in delta.

With the amplitude of the complex wave taken as 100, the following amplitudes of the harmonics were obtained by analysis:

Amplitude of the fundamental	99.34
" " " 3rd harmonic	0.25
" " " 5th "	1.44
" " " 7th "	0.71
" " " 9th "	0.44
" " " 11th "	0.21

A one-ampere reflecting dynamometer wattmeter was used separately excited. The resistance of the current element of this instrument is 4.8 ohms. The resistance of the moving coils, including suspension and spiral, is about 30 ohms. The constant of the instrument when expressed by equation (1) is approximately 7×10^{-7}, where d is the deflection in mm. with the scale one meter distant from the mirror.

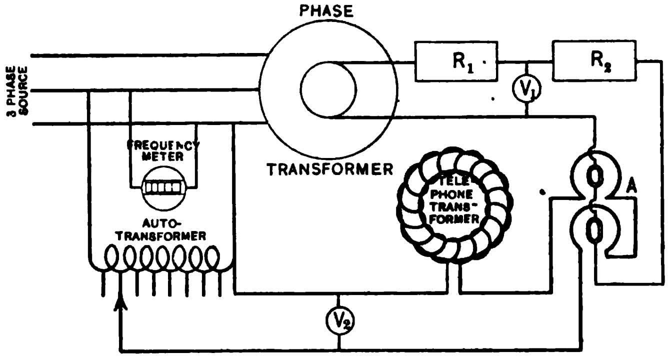


FIG. 1—DIAGRAM OF CONNECTIONS.

The moving element of the instrument was separately excited, as is shown in Fig. 1, and the current was maintained constant by means of an adjustable non-inductive resistance (R_1) and voltmeter (V_1).

The voltage on the telephone transformer was changed by changing the taps on the auto-transformer. The excitation of the generator was held constant. The voltage applied to the telephone transformer was measured by (V_2). This included the potential drop in the current coils of dynamometer, which was negligible.

The tests were repeated using a reflecting voltmeter as an ammeter, with connections as given in Fig. 2. The resistance of this instrument is 60 ohms with the stationary coils connected in parallel, and in series with the moving coil. The instruments were calibrated by potentiometer with direct current.

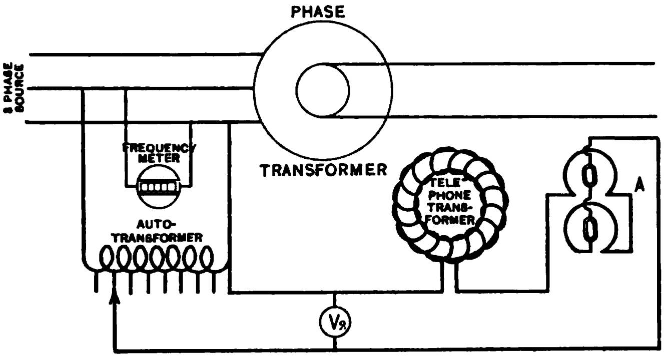


FIG. 2—DIAGRAM OF CONNECTIONS.

TABLE I

EXCITING CURRENT OF TELEPHONE TRANSFORMER AT 60 CYCLES

Ammeter method			Separately excited dynamometer method		
Flux density lines per sq. cm.	Volts	Amperes	Flux density lines per sq. cm	Volts	Amperes
328	22.2	0.00357	346.8	23.48	0.00382
406	27.5	0.00402	416.5	28.2	0.00400
488	33.05	0.004425	490.5	33.2	0.00442
569	38.5	0.00475	560	37.9	0.00469
650	44	0.00505	632	42.8	0.005015
730	49.4	0.00537	694	47	0.00525
811	54.9	0.00554	765	51.8	0.00547
892	60.4	0.00580	834.5	56.5	0.005612
961.5	65.1	0.00595	978	66.2	0.005932

The results of tests are given in Table I and Fig. 3.

On the average, the agreement of the two sets of readings is close, but variation in individual readings is considerable. It is believed that this trouble may have been due to the unstable magnetic properties of iron at low densities. It would have been better to have connected the instruments so that the measurements could have been made simultaneously.

The above tests cover a range of densities from 300 to 900 lines per sq. cm. In order to carry the measurements to higher densities and to obtain larger values of current so that oscillograph records could be taken, additional measurements were taken on a 20-lb. (9.07-kg.) core of high silicon steel made up of 7 by 10 by 0.014 in. ring punchings.

This core was wound with 140 turns of No. 12 B. and S. gage copper wire, the resistance of which was about 0.1 ohm.

A diagram of connections is given in Fig. 4. Portable instruments were used altogether in taking readings on the 20-lb. core.

A potential of 100 volts was impressed upon the potential coil of the wattmeter. The readings of the wattmeter were divided by 100 to obtain the current readings given in Table II, column 4.

It can be seen from Fig. 4 that the current in the voltmeter (V_2) was included in the reading of the ammeter, but as this was not a test on the iron, it was unimportant.

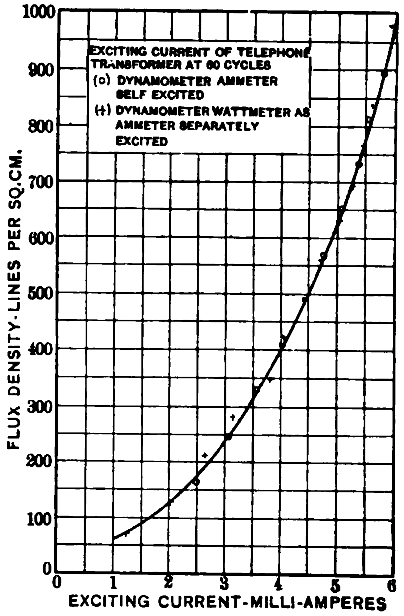
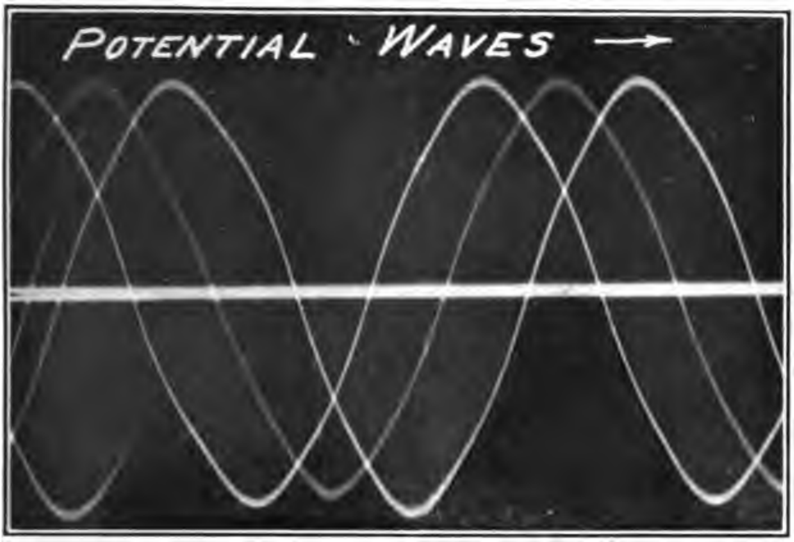


FIG. 3

The method of procedure was the same as before. The phase-shifting transformer was adjusted until the reading of the wattmeter was a maximum. The voltage on the potential coil was then adjusted to read 100 and A, V_2 and W were read.

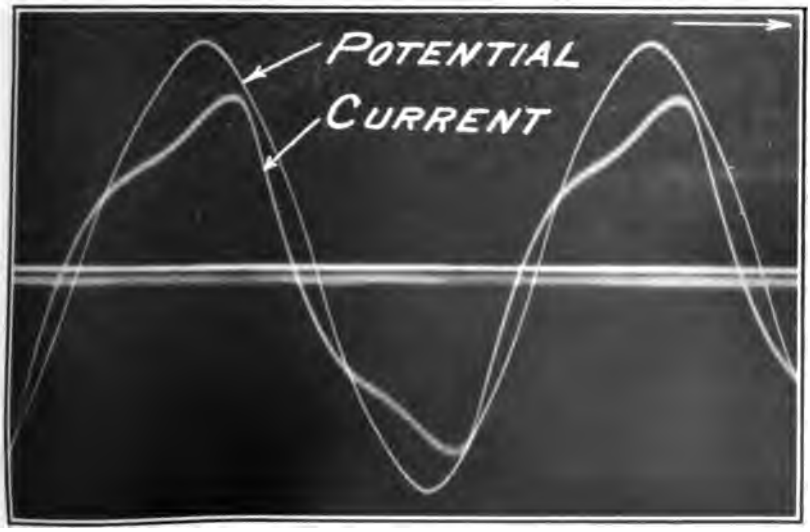
The results are given in Table II and Fig. 5.

From Fig. 5, it is seen that below a density of 6000 lines per sq. cm. the error is very small. Curves 2 and 3 show the exciting current, and the potential waves impressed upon the wattmeter from the phase-shifting transformer. Curve 2 was taken at 5090 lines per sq. cm. The effective value of the ex-



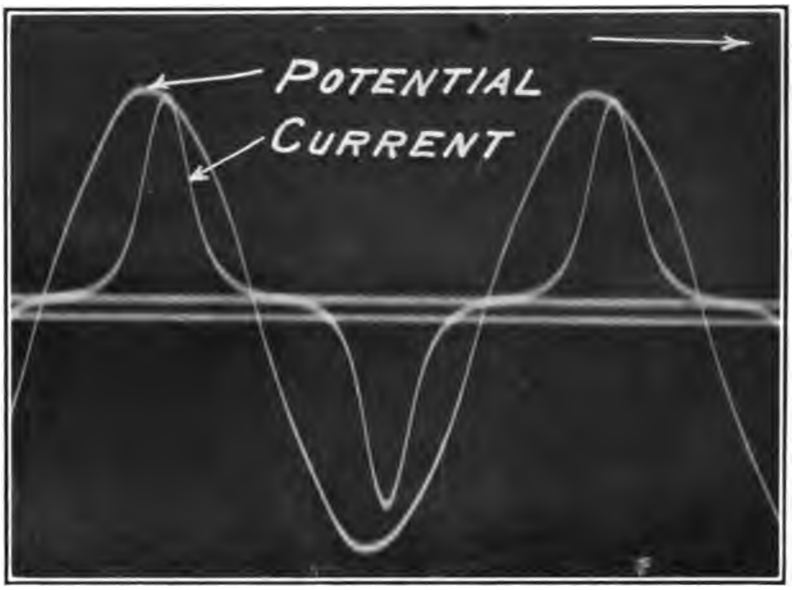
[NEWMAN]

CURVE 1—POTENTIAL WAVE OF THREE-PHASE THOMSON-HOUSTON GENERATOR AT NO LOAD—60 CYCLES.



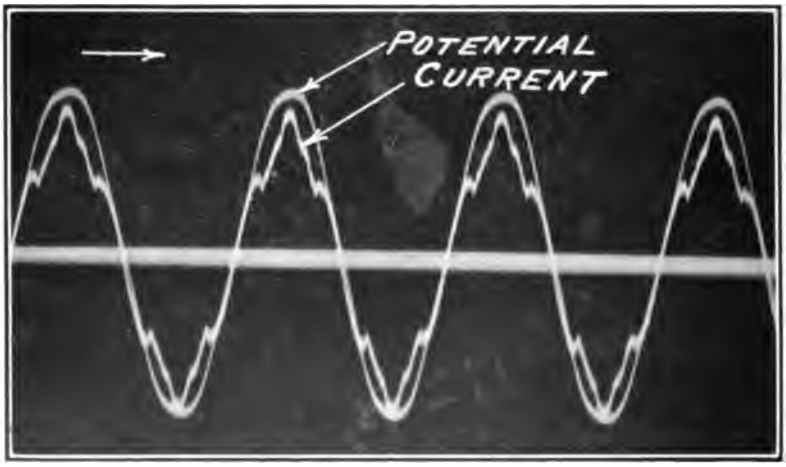
NEWMAN]

CURVE 2—POTENTIAL WAVE OF PHASE-SHIFTING TRANSFORMER AND CURRENT WAVE IN MAGNETIZING WINDING OF RING SAMPLE AT 5090 LINES PER SQ. CM.



[NEWMAN]

CURVE 3—POTENTIAL WAVE OF PHASE-SHIFTING TRANSFORMER AND CURRENT WAVE IN MAGNETIZING WINDING OF RING SAMPLE AT 15,400 LINES PER SQ. CM.



[NEWMAN]

CURVE 4—POTENTIAL WAVE OF PHASE-SHIFTING TRANSFORMER AND CHARGING CURRENT WAVE OF CONDENSERS.

citing current was 0.271 amperes. Analyses of the current and potential waves give the following results:

(The amplitude of the harmonics is expressed in percentages of the amplitude of the complex wave.)

	Current	Potential
Fundamental	94.1	98.0
3rd harmonic	17.1	0.9
5th "	3.82	2.0
7th "	1.77	negligible
9th "	1.58	0.4
11th "	0.88	0.4

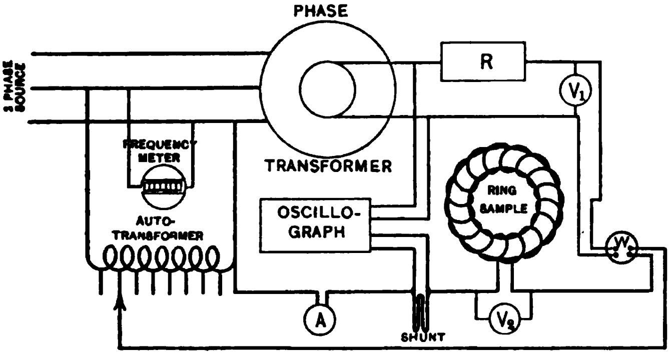


FIG. 4—DIAGRAM OF CONNECTIONS.

The effective values of the harmonics of the current are given below:

	Effective amperes
Complex wave	0.271
Fundamental	0.266
3rd harmonic	0.048
5th "	0.010
7th "	0.005
9th "	0.004
11th "	0.002

Assuming that no torque is produced by the harmonics in the current wave, an error of 1.8 per cent will be introduced. This agrees very closely with results obtained by tests.

Curve 3 was taken at a density of 15,400 lines per sq. cm. The effective value of the exciting current was 4.85 amperes.

The analysis of the current wave gives the following results:

TABLE II
EXCITING CURRENT OF RING SAMPLE OF HIGH SILICON STEEL AT 60 CYCLES

Flux density lines per sq. cm.	Volts	Exciting current—amperes		Error	Reading of phase-shifting transformer
		Ammeter	Separately excited dynamometer		
				Per cent	Degrees
812	5.39	0.0902	0.0885	1.9	45
2,542	16.88	0.1665	0.1642	1.4	45
3,300	21.9	0.1948	0.191	1.9	45
3,375	22.4	0.1975	0.197	0.25	45
4,200	27.9	0.232	0.2279	1.75	48
5,090	33.8	0.271	0.2667	1.5	48
6,070	40.3	0.321	0.3183	0.85	48
6,900	45.8	0.372	0.363	2.4	52
8,610	57.17	0.506	0.4895	3.2	52
9,520	63.2	0.614	0.589	4.0	53
10,120	67.2	0.692	0.659	4.7	53
10,950	72.66	0.851	0.794	6.7	55
11,930	79.16	1.086	1.019	6.2	58
12,780	84.85	1.396	1.257	10.0	58
13,950	92.6	2.2	1.88	14.5	60
14,800	98.3	3.49	2.815	19.3	60
15,400	102.2	4.85	3.91	19.4	64

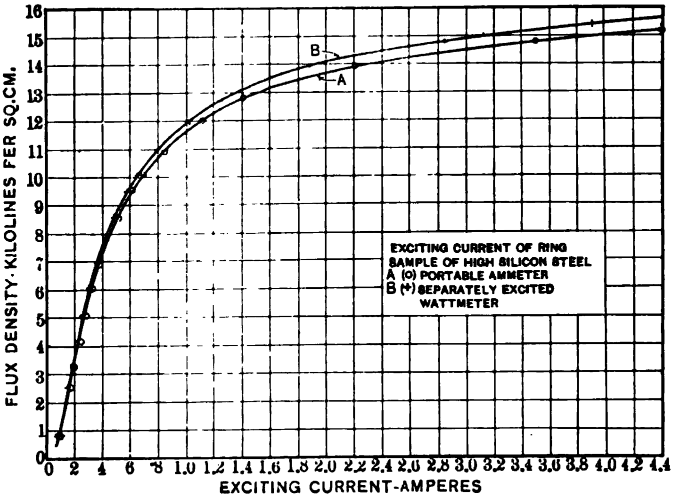


FIG. 5—EXCITING CURRENT OF RING SAMPLE OF HIGH SILICON STEEL AT 60 CYCLES.

(the amplitude of the harmonics is given in percentages of the amplitude of the complex wave)

	Current
Fundamental	49.6
3rd harmonic	23.9
5th "	10.9
7th "	4.5
9th "	1.6
11th "	0.2

The effective value of the fundamental in this case is 4.05 amperes, which would, if the potential wave from the phase-shifting transformer were sinusoidal, make an error of 16. 5 per cent in the results.

The actual tests gave 3.91 amperes, or an error of over 19 per cent.

Measurements of Capacity Current of 0.5-*Microfarad Condensers.* Readings given in Table III were made by the separately excited dynamometer and by the dynamometer-ammeter.

TABLE III

CAPACITY OF MICA CONDENSER AT 60 CYCLES BY SEPARATELY EXCITED DYNAMOMETER AND BY AMMETER METHODS

Volts	Amperes	Microfarads
	BY DYNAMOMETER	
100	0.0184	0.485
100	0.0183	0.485
100	0.01848	0.488
	BY AMMETER	
50.8	0.00946	0.493

The values of capacity were calculated from the current readings, using the following formula, which is for a sine wave:

$$C = \frac{I}{2\pi f E}$$

The difference in the results by the two methods is less than 2 per cent.

The condenser previously measured at 0.6 sec. charge and 1 sec. discharge by ballistic galvanometer gave a capacity of 0.4990 microfarad.

Sensibility of Separately Excited Ammeter. In order to obtain comparative measurements, it was necessary to use currents of comparatively large value. For this reason the one-ampere coils were used in the wattmeter dynamometer.

By varying the excitation of the moving coil, it is possible to make current measurements over an enormously large range without changing the current coils.

The sensibilities of the instrument with different field coils are given below:

Rated current-carrying capacity	Resistance	Amperes	Deflection
0.17 amperes	154.0 ohms	3×10^{-5}	10 mm.
1.0 "	4.8 "	2×10^{-4}	10 "
3.0 "	0.53 "	1×10^{-3}	10 "

By using the stationary coils as the separately excited element with full excitation, the following sensibilities may be obtained:

	Resistance	Amperes	Deflection
500-turn moving coil	400 ohms	3×10^{-7}	10 mm
65- " " "	65 "	3×10^{-6}	10 "

From the above values it is seen that an ammeter of very great sensibility is easily obtained. It has the advantage over a great many high-sensibility ammeters, in that the suspension and moving parts are comparatively rugged, and the instrument is not easily troubled by outside disturbances.

Discussion of Results

It has been shown by the above tests that comparatively large errors may occur if the separately excited ammeter is used to measure the exciting current of sheet steel at high densities.

The complex exciting current wave may be considered to be composed of a sinusoidal component and a distorting component. At high densities this distorting component is large and the sinusoidal component is small in comparison. This large distorting component is due to the rapid rate of change of reluctivity during the magnetic cycle. At extremely low magnetic densities the reluctivity may be even higher than that above the knee of the curve, but the distorting component is not great because the reluctivity remains more nearly constant. As the density is lowered the exciting current wave approaches the sinusoidal form.

The results of test indicate that below a density of 6000 lines per sq. cm., the errors obtained when using the separately excited dynamometer do not exceed 2 per cent. The results are always low since harmonics other than the fundamental produce no torque. The total range of measurements covered densities from 300 to 15,000 lines per sq. cm.

Of course, the wave distortion will vary with different samples of steel, depending upon the shape of the saturation curve.

CONCLUSIONS

The sensibility of a dynamometer-ammeter is greatly increased by separately exciting one element from the phase-shifting transformer.

Large errors are introduced when such an instrument is used to measure exciting current of sheet steel at high densities.

Measurements may be made of the exciting current of sheet steel at densities below 6000 lines per sq. cm. with very small error.

Because of the limited time available for making these tests several parts of the original outline had to be omitted, but although the investigation is limited and incomplete the usefulness of the method is apparent for measuring exciting current of sheet steel at low densities.

The writer wishes to acknowledge the great assistance rendered by Mr. F. Dakin in making the tests and preparing this paper.

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 28, 1912.

TO MEASURE AN ALTERNATING-CURRENT RESISTANCE AND COMPARE IT WITH THE DIRECT-CURRENT RESISTANCE—ELECTRODYNAMOMETER METHOD

BY EDWIN F. NORTHRUP

For comparing an alternating-current and a direct-current resistance by the electrodynamometer method in a precise manner, the apparatus required is a frequency meter to measure the frequency of the current used (which must be known, as the quantity being measured will vary with frequency), an alternating-current ammeter to give roughly the value of the current (for the alternating-current resistance will also, in general, depend upon the value of the current), a three-point double-throw switch for quickly changing connections, resistances, and an electrodynamometer. This last piece of apparatus should have sufficient capacity in its current coils to carry, without heating, the full current. Its hanging or potential coils should be two in number, and so arranged as to form a system which is perfectly astatic in respect to the earth's field. The constant of the instrument will then be the same for direct and alternating currents. All good electrodynamometers are constructed in this way. Either the Rowland deflection type or Siemens type, constructed to be astatic, may be used. The method to be described was tested with a Rowland deflection type electrodynamometer.

DESCRIPTION OF CIRCUITS AND THEORY OF METHOD

In I and II, Fig. 1, G, G, are the fixed coils and h, h, the hanging astatic system of the electrodynamometer. The hanging system has an ohmic resistance, α, and there is joined in series with this a non-inductive resistance, ρ'. Let $\rho' + \alpha = \rho$, the entire resistance of the hanging coil system. In the instrument referred to, the resistance α is about 18 ohms. It has a minute inductance, which is approximately 0.00045 henry. When ρ' is moderately large and non-inductive, we may consider, without sensible error, that the alternating current through the hanging system is in phase with its e.m.f. even when the frequency is high. We shall so consider it in all that follows.

A represents a coil which contains iron. It is assumed that this coil has a certain ohmic resistance, R_{dc}, as measured by direct current, and a different resistance, R, as measured by an alternating current of a given value, wave form, and frequency. It is this latter resistance (not the impedance or inductance of A) which the method will enable us to determine. The resistance, r, is any resistance capable of carrying the full current. It may be a coil inductively wound but it must *not* contain iron or have such a section and resistivity that its resistance on alternating current will be different from its resistance on direct current, due to hysteresis, skin effect, or other cause. By a sliding contact, p, means must be provided for tapping this resistance at any point along its length, as the diagram illustrates. ρ is a non-inductive resistance, which is equal to $\alpha + \rho'$, the resistance of the hanging coil circuit. As will be shown later, the connections can instantly be changed from the arrangement shown in I to that shown in II and vice versa.

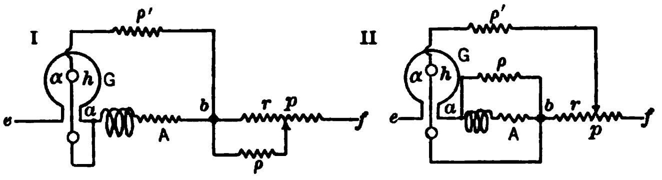


FIG. 1

We wish first to find the general expression for the power which the wattmeter measures when the connections are those shown in I, Fig. 1. Call I the current in the fixed coils of the dynamometer. Call i the current in the hanging coil circuit. Call φ the phase angle between the currents i and I. Then the deflection of the dynamometer is

$$D = K_1 I i \cos \varphi \qquad (1)$$

where K_1 is the instrumental constant of the dynamometer. This constant in the case of a deflection instrument of the Rowland type will change slightly with the magnitude of the deflection. There is also an inductive action of the current in the fixed coil which tends to induce a current in the hanging coil circuit when the plane of the movable system is not vertical to the plane of the fixed coils. This inductive action may vary in a complicated way, so equation (1) cannot be taken as strictly true. If, however, the system is deflected by means of the torsion head when there is no current through the instrument, so that when current is introduced the system is brought back to the position where its plane is vertical to the plane of the fixed coils, then the inductive action is null and the relation given by equation (1) may be considered to hold very exactly. In the use of the dynamometer which follows, the system should be deflected by means of the torsion head when there is no current flowing, to such an extent that, on introducing current, the instrument reads roughly at the zero of the scale. With this precaution observed, the theoretical relations will be found to hold very exactly.

If we call V the impressed e.m.f. between the points a and b, I, Fig. 1, then the current through the hanging coil circuit will be

$$i = \frac{V}{\alpha + \rho'} = \frac{V}{\rho} \tag{2}$$

As above stated, the current i will be approximately in phase with the e.m.f., V, because the inductance of the hanging coils is very minute.

By equations (1) and (2) we have

$$D = \frac{K_1}{\rho} I \, V \cos \varphi \tag{3}$$

But $I \, V \cos \varphi$ is the entire power, W_t. This power is the sum of two parts, W, the power consumed in A (I, Fig. 1) between the points a and b, and W', the power consumed in the hanging coil circuit. The value of this latter is

$$W' = \frac{V^2}{\rho} \tag{4}$$

Thus we have

$$D = \frac{K_1}{\rho} W_t \tag{5}$$

or

$$D = \frac{K_1}{\rho}\left(W + \frac{V^2}{\rho}\right) \tag{6}$$

From equation (6)

$$W = \frac{\rho}{K_1} D - \frac{V^2}{\rho} \tag{7}$$

and from equation (5)

$$W_t = \frac{\rho}{K_1} D \tag{8}$$

$\frac{V^2}{\rho}$ is generally a small quantity. ρ is known very precisely and V can be obtained with a voltmeter, hence equation (7) enables the true power spent in A to be accurately obtained. It is equation (8), however, which we wish to use in measuring the alternating-current resistance of A.

With the connections as shown in I, Fig. 1, the torsion head is turned, so that, with the current (as steady as possible) which is flowing, the deflection reads near the zero of the scale. The total power then being registered is given by equation (8).

The connections are now quickly changed to those shown in II. The main current will not be altered by this change in connections, for the resistance ρ is simply made to change places with an equal resistance. The total power which is registered, however, will now be

$$W_t' = \frac{\rho D'}{K_1} \tag{9}$$

when D' is the deflection which the dynamometer now gives. The contact, p, is moved along the resistance, r, until the deflection D' is made equal to the deflection D, then W_t' will be equal to W_t.

Since the main current, I, is the same for the connections I and II, we have

$$W_t = I^2 R' = I^2 r' \tag{10}$$

or

$$R' = r' \tag{11}$$

Here the quantity R' is not the alternating-current resistance of the coil A but it is the alternating-current resistance of this coil when shunted with the non-inductive resistance ρ. Similarly r' is the alternating-current resistance of r when shunted with the non-inductive resistance ρ.

We can write

$$R' = \frac{\rho R}{\rho + R} K \qquad \text{and } r' = \frac{\rho r}{\rho + r} k$$

The alternating-current resistance of two parallel circuits when one or both of the branches contain reactance is not given by the same expression as applies when the branch circuits are without reactance; hence the ordinary expression for branch circuits without reactance, namely $\frac{\rho R}{\rho + R}$, must be multiplied by some factor K the value of which we now have to determine: also the factor k. It is shown in " Alternating Currents " by Bedell and Crehore, pages 238 to 241, how the alternating-current resistance, or, as they call it, the equivalent resistance of any number of parallel circuits having self-induction and carrying alternating current, may be expressed. It is there shown that in general

$$R' = \frac{A}{A^2 + B^2 \omega^2} \text{ where}$$

$$A = \frac{R_1}{R_1^2 + x_1^2} + \frac{R_2}{R_2^2 + x_2^2} + \quad . \quad . \quad . \quad = \sum \frac{R}{R^2 + x^2}$$

and

$$B\omega = \frac{x_1}{R_1^2 + x_1^2} + \frac{x_2}{R_2^2 + x_2^2} + \quad . \quad . \quad . \quad = \sum \frac{x}{R^2 + x^2}$$

in which expressions R_1, R_2, etc., are ohmic resistances and x_1, x_2, etc., are reactances of the several branches.

We can now find expressions which will give the values of K and k.

Here we have

$$A = \frac{1}{\rho} + \frac{R}{R^2 + x^2}$$

and

$$B\,\omega = \frac{x}{R^2 + x^2}$$

We cannot, because of the necessity of brevity, give here the purely algebraic processes required for obtaining the final expressions, so we shall present only the final results, which are as follows:

$$K = 1 + \frac{\rho\, x^2}{[(R+\rho)^2 + x^2]\, R}$$

$$k = 1 + \frac{\rho\, x_1^2}{[(r+\rho)^2 + x_1^2]\, r}$$

Call the fractional expressions α and α_1 respectively, then $K = 1 + \alpha$ and $k = 1 + \alpha_1$.
This gives

$$\frac{R}{\rho + R}(1+\alpha) = \frac{r}{\rho + r}(1 + \alpha_1).$$

It will be shown that, in general, when a sensitive electrodynamometer is used, α and α_1 are very small quantities which in most cases can be neglected.

We have the following cases:

1. α and α_1 are negligible. Then

$$R = r \tag{12}$$

2. α and α_1 are not negligible but are very nearly equal. Then again $R = r$

In these two cases the alternating-current resistance sought may be taken as numerically equal to the resistance r.

3. $\alpha_1 = o$ but α is not negligible. In this case

$$R = r\,\frac{1}{1 + \alpha\,\dfrac{\rho + r}{\rho}} \tag{13}$$

4. α and α_1 are not negligible and are unequal, but ρ is very large. Then again we can take $R = r$.

Consideration of a single example of the third case will suffice to show the magnitude of the error which may be introduced by omitting the correction. The example chosen is from an actual measurement. With the electrodynamometer available, only 1/10 ampere could be passed through the fixed coil and hence, the potential drop over the coil A and over the resistance r being small, the resistance ρ had necessarily to be taken very small to give the requisite sensibility. If the dynamometer coils could have carried (as is ordinarily the case) several amperes, ρ would have been much larger and the error would be much less. In the example $\alpha_1 = o$, and

$$\alpha = \frac{\rho\,(2\,\pi\,N\,L)^2}{[(R+\rho)^2 + (2\,\pi\,N\,L)^2]\,R}$$

$$= \frac{300\,(2 \times 3.14 \times 60 \times 0.036)^2}{[(11 \times 300)^2 + (2 \times 3.14 \times 60 \times 0.036)^2]\;11}$$

or $\alpha = 0.052$ nearly.

Hence

$$R = r\,\frac{1}{1 + 0.052\,\frac{311}{300}} = 0.948\,r.$$

Thus if we had called $R = r$ the error would have been about 5.2 per cent, R being assumed too large. This conclusion was checked experimentally. Without changing the ohmic resistance of the coil A, its inductance, which was capable of variation, was varied from 0.003 to 0.036 henry, and in the first case, using the uncorrected formula, $R = 10.94$ ohms, and in the second case, using the same formula, $R = 11.62$ ohms, or six per cent too large, which is in fairly close agreement with the calculated result of 5.2 per cent.

If the fixed coils of the dynamometer had been made to carry 10 amperes instead of 1/10 ampere ρ could have been 100 times as large, in which case the correction factor would reduce to about 0.05 per cent.

The above adjustments having been made, direct current can be made to replace the alternating current and in the same way we find the direct-current resistance of A. It will be

$$R_{dc} = r_1 \qquad (14)$$

Hence

$$\frac{R}{R_{dc}} = \frac{r}{r_1} \qquad (15)$$

is the ratio of the alternating-current to the direct-current resistance of the circuit A. This ratio may take a value of two or more.

It should be clearly understood just what is meant by the quantity *R* which this method measures. It is a quantity which, expressed in ohms and multiplied by the square root of the mean square value of the alternating current through the circuit, expressed in amperes, will give the square root of the mean square value of that component of the impressed e.m.f. expressed in volts which is in phase with the current. Or, it is the quantity which, when multiplied by the mean square value of the current, will give the power in watts which is being dissipated in the circuit. In drawing the triangle of e.m.fs. of an inductive circuit one sometimes represents the component of the e.m.f. which is phase with the current by the product of the current and the direct-current resistance, R_{dc}. This procedure may lead to considerable error in circuits in which there are other losses than the $I^2 R_{dc}$ losses. In such circuits the alternating-current resistance, *R*, should always be used.

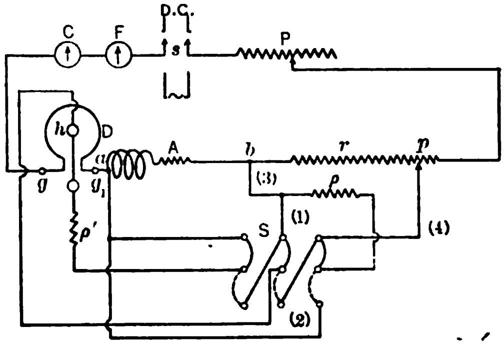


FIG. 2

METHOD OF EXECUTION

For making the above measurement the apparatus is assembled and connected as shown in Fig. 2.

D is the electrodynamometer with its hanging system *h*. The heavy or light wire fixed coils are used according to the magnitude of current with which the measurement is to be made. The light wire fixed coils will carry (in the Rowland instrument) 0.1 ampere and the heavy wire coils will carry 50 amperes.

C is the alternating-current ammeter and *F* the frequency meter. *P* is a rheostat to control the main current; *s* is a switch to shift from direct current to alternating current and vice versa. S is a three-point double-throw switch which in position (1) makes the connections shown in I and in position (2) makes the connections shown in II, Fig. 1. r is best obtained from a slide wire rheostat of considerable current capacity. It does not need to be non-inductive, but must contain no iron. If its reactance is just equal to that of the coil being measured, $\alpha = \alpha_1$ and $R = r$ exactly.

After the settings for p have been found, the connections are broken at (3) and (4) and the direct-current resistance value of r is measured with a Wheatstone bridge or by any other convenient means.

The resistances ρ and ρ' may be obtained best from plug or dial decade resistance boxes. These may be high, 10,000 ohms or so, depending entirely upon the current used, the magnitude of the resistance being measured, and upon the sensibility of the instrument.

The torsion head may be turned so that the no-current deflection is between 100 and 200 divisions of the scale. By then adjusting ρ the deflection with current on may be made to come near the zero of the scale.

It will be found, if A consists of an ironless variable standard of inductance, that the variable standard may be set to any inductance value without much altering the deflection. The change in the deflection will be less as ρ is made larger.

This method will be found useful in measuring the alternating-current resistance of steel-cored copper or aluminum cables, which differs considerably from their direct-current resistance.

The following test of this method was made for the purpose of showing how large a correction would be required when ρ was chosen only 300 ohms and L was varied between 0.003 and 0.036 henry.

The resistance measured was that of a variable standard of inductance, which should, of course, show the same value on direct and alternating current, at whatever value its inductance is set.

(a) $L = 0.003$ henry.

With alternating-current in circuit.

$D_t = 244$ (no current).

$D = D' = 0$ (current flowing).

$R = r = 10.94$ ohms.

$I = 0.08$ ampere.

$N = 60.2$ cycles.

$\rho = 300$ ohms.

(*b*) L = 0.036 henry.

With alternating-current in circuit.

D_t = 253 (no current).
D = D' = 0 (current flowing).
R = r = 11.62 ohms.
I = 0.08 ampere.
N = 60.2 cycles.
ρ = 300 ohms.

With direct-current in circuit.

D_t = 244 (no current).
D = D' = 0 (current flowing).
R_{dc} = r = 10.94 ohms.
I_{dc} = 0.08 ampere.
ρ = 300 ohms.

DISCUSSION on "A TUBULAR ELECTRODYNAMOMETER FOR HEAVY CURRENTS" (AGNEW), "MEASUREMENT OF ALTERNATING CURRENT OF LOW VALUE" (NEWMAN), "TO MEASURE AN ALTERNATING-CURRENT RESISTANCE AND COMPARE IT WITH THE DIRECT-CURRENT RESISTANCE—ELECTRODYNAMOMETER METHOD" (NORTHRUP), BOSTON, MASS., JUNE 28, 1912.

W. H. Pratt: Dr. Agnew's paper tells about the usual procedure in making a wattmeter for high current measurements, by stranding the conductor. Now, stranding the conductor must necessarily be done in a very careful manner, otherwise troubles will be encountered, but it performs two functions: it prevents the formation of eddy currents due to the field of the current coil itself, and it also prevents the formation of eddy currents due to induction from the moving coil. In an instrument in which you are going to get the highest possible sensibility it would seem that this should be taken account of. I see no reference to this in the paper.

In a discussion of the paper presented by Sharp and Crawford, at the Jefferson meeting of the Institute, in 1910, I gave a brief description of a reflecting dynamometer which we constructed some two and a half years ago for doing substantially the same work that the instrument described here is intended for. The two instruments differ in this way: The instrument described in Dr. Agnew's paper is evidently an attempt at making an instrument of which, from its geometrical constants, the accuracy characteristics can be determined. The instrument which we constructed was an instrument so designed that we were able to compare its performance directly with instruments of very small capacity in order to determine the limits of its accuracy. The instrument that we constructed, I think, is much more flexible than the one here described, because we can use it with the highest kind of accuracy in currents as low as 50 or 25, or even 10 amperes, and then can immediately go to 2000 amperes capacity. The heating of the conductor is negligible in any case.

The limits of accuracy of this type of instrument would seem to depend fully as much on the character of the suspension as on the other characteristics, and I am very much surprised at the statement that one-half of one-tenth per cent is thought possible, although one-tenth of one per cent certainly is definitely possible with the instrument that we worked with.

J. D. Ball: In reference to the paper *Measurement of Alternating Current of Low Value*, mention is made of the use of a portable wattmeter as an ammeter, by which Fig. 5 was derived.

This arrangement is of considerable value for measuring low currents, below the range of the portable alternating-current ammeters. An ordinary portable wattmeter with full field utilizes in the moving coil about 0.04 amperes for full scale deflection. Separately exciting the field coil to the full rating, and passing the current to be measured through the moving system, gives an ammeter scale of 0 to 0.04, which is considerably better than an ordinary alternating-current portable ammeter, having the advantage of a uniform scale, instead of a scale of squares. When the current is smaller than can readily be measured by this means, the reflecting dynamometer is, of course, the correct instrument to use.

It is often the case that measurements of this kind are desired, and there is no phase shifter convenient. In such an event, good results may be obtained by the use of resistance and reactance in series with the separately excited coils and "juggling" until maximum reading is obtained.

When using the phase shifter, instead of obtaining a maximum deflection, it is perhaps more satisfactory to obtain zero deflection and to read the ammeter after a phase shift of 90 degrees.

It also happens that small currents are to be measured when the circuit is non-inductive, or the phase relations are definitely known, in which cases the separately excited wattmeter may be used without phase shifter or resistance and reactance in circuit.

Small voltages may be measured by the same general method, by exciting the current coils of a reflecting dynamometer and connecting on the moving coils.

Frank Wenner: Dr. Agnew asked me to make a few remarks in regard to his paper, and particularly in reference to a change which has been made since the paper was sent in. In the paper mention is made of the fact that the clamping of heavy lugs in making connections with the instrument had sprung the inner tube in such a way as to throw the arrangement out of symmetry, and that later the end terminals were clamped to prevent this. It was found very difficult always to prevent a slight amount of springing in connecting very heavy leads, so a change has been made. A slight flexibility is secured by cutting a circle 10 cm. in diameter from the outside copper slab which serves as a current terminal. The inside tube passes centrally through this 10-cm. disk of copper, and the latter fits into the hole in the copper slab from which it was cut, the electrical connection being obtained by amalgamating the joint. This gives the desired flexibility.

M. G. Lloyd: In connection with the measurement of very small alternating currents, it may be of interest to mention another instrument for that purpose, known as the thermo-ammeter, which has some particular characteristics which make it valuable for that purpose. Besides being a very sensitive instrument, it can be constructed without appreciable inductance, if necessary, and that is particularly valuable in many classes of high-frequency work, such as wireless telegraphy. The thermo-ammeter has a heating element which is in the main circuit. The heat developed in this resistor is applied by radiation to a small thermocouple which is in the moving-coil circuit of an ordinary d'Arsonval movement. You consequently get the characteristics of the direct-current instrument in the indicating part and have all the advantages of the hot-wire instrument in the energy-producing or actuating part of the instrument. The great difficulty which I found with such an instrument, however, was the extreme slowness of the action. I think, perhaps, that could be improved by a better design; but it had that feature, which is to some extent common, perhaps, to all hot-wire or heating-element instruments.

In using a dynamometer, of course, great gain can be made by having an auxiliary current in the field, as the author has pointed out in this paper. The great disadvantage comes in in the case of wave distortion, which is always found, of course, in the use of coils containing iron. It occurs to me that the instrument might be used to great advantage in that case, by putting a similar coil in the field circuit. By using iron of about the same quality and saturated to about the same amount with flux, the wave distortion might be made approximately the same, and the instrument might then be used for that purpose. As the author has shown, it can hardly be so used under the conditions which he described.

It seems to me a word of appreciation of Dr. Agnew's work would be in order here. This dynamometer for heavy currents which he has designed seems to have eliminated all the ordinary sources of trouble in a dynamometer for such extremely high current. He has covered all the heretofore practical objections in the design and use of such an instrument, and it looks as though he had really solved the problem of the measuring of large currents.

Taylor Reed: With reference to Dr. Northrup's paper, he has indicated the measurement of alternating-current resistance, to use his term, to a considerable degree of refinement; in fact, to a greater degree of refinement than is necessary for most measures at commercial frequencies. Dr. Northrup speaks in particular of the unsteadiness of the circuit, and the difficulties arising from that, and he uses a very quick switch thrown back and forward, which, of course, eliminates nearly all of the error. In making similar measurements I have sometimes found it convenient, where two dynamometers are available, or where the measurements are being made with commercial instruments, like wattmeters, to use two, one connected to what you might call a self-calibrating resistance continually, and the other switching back and forward from the calibrating resistance to the unknown, or measured, resistance. Any violent fluctuation in the alternating-current source, to which the line may be very much subject, is readily shown, and in case the current is persistently unsteady can even be allowed for within moderate limits.

This subject of measuring conductors under alternating-current conditions is increasingly important. For instance, the old discussion has gone on for a long time between copper and aluminum until it has come to seem as though there were no other conductors; whereas if we run over the elements, one after the other, we come to the fact, which is a very true one, although very ludicrous in its impracticability, that metallic sodium is a great deal cheaper than either of them. But, of course, the use of steel has been made necessary on account of its strength for long spans, copper-clad steel, in particular, having become of practical value. Also, considering the whole range of measurements at high-frequency alternating-current, it does seem as if some better term for this quantity which is measured than " alternating-current resistance " or " effective resistance " should be provided for general use.

A. L. Ellis: I have been very much interested in the tubular electrodynamometer reported by Dr. Agnew for measuring heavy currents, as I have met the necessity for a dynamometer of this type very frequently in my work. I have also used the water-cooled dynamometer referred to by Mr. Pratt and can testify to its accuracy.

There is one point that seems difficult to overcome in the tubular dynamometer and that is the distribution of the current through the tubes and the location of the tubes to bring everything coaxial, and maintain this condition.

In case of the water-cooled dynamometer, such disturbances do not exist, because the current terminals, themselves, are two heavy copper bars that can be placed one directly over the other, with sufficient insulation between them, and securely bolted to the base, making a rigid construction. Attaching the leads does not disturb the location of any of the parts affecting constant of instrument to an observable extent. The tubes forming the field coils of the dynamometer are attached to the further ends of the heavy copper bars. The turns of the current coil can be so arranged that the astatic moving coils can be readily removed from the field without disassembling. The great difficulty with all of these instruments is the suspension. If we could only get rid of this suspension, we would get rid of practically all the trouble in connection with the water-cooled dynamometer. There is one other point in connection with the water-cooled dynamometer that must be borne in mind, and that is, you must be sure iron does not get into the pipe forming the current coils. Iron will sometimes get into the circulating water from the iron service pipes, but this is readily overcome by passing the water through a glass vessel, used as a settling chamber for the circulating water.

Edward B. Rosa: One very great advantage of the tubular dynamometer that has not been mentioned is the fact that there is such a small stray field. The magnetic field is between the tubes, and there will be absolutely no stray field, if the tubes are long enough. There is, of course, some around the end, but the stray field at those places is extremely small. With an electrodynamometer using coils of such character that the magnetic field extends a considerable distance from the instrument, errors may be introduced due to the presence of metallic masses in the neighborhood of the instrument or in the parts of the instrument. In the case of a dynamometer for measuring heavy currents, such as several thousand amperes, the stray field may be very considerable. In the tubular dynamometer, however, the magnetic field is almost completely included between the inner and outer tubes, and this is a very great practical advantage. This instrument has been thoroughly investigated, and there is no serious difficulty in respect to the centering of the tube. Fortunately, there is a definite test that can be applied to show that the current is symmetrically distributed.

L. T. Robinson: With regard to the measurement of small alternating currents, I think I might bring out one point quite clearly. We have three things which have been referred to in the discussion: the series-connected dynamometer, the thermal instrument in which substantially a D'Arsonval galvanometer is used on the thermocouple, and the separately excited dynamometer, which is, of course, as has been mentioned, subject to some errors. The conditions as to sensitiveness, etc., that can be met with these instruments do not conflict. The series dynamometer can be used up to a certain point. After that we can use the thermal instrument, and away beyond that in sensibility, as I have found it in my work, is the separately excited dynamometer.

P. G. Agnew: In regard to the tubular dynamometer, Dr. Wenner has already mentioned the fact that a somewhat flexible connection to the inside tube has been secured by cutting one of the heavy copper slabs serving as current terminals and using an amalgamated joint.

Mr. Pratt has raised the question whether there may not be errors due to eddy currents in the copper tubes caused by current in the moving coil. At commercial frequencies no error whatever could be detected due to this cause. Even at 900 cycles, with full rated current in the moving coil and the field system short-circuited, the deflection does not exceed 0.1 mm. at any part of the scale.

The point made by Mr. Ellis in regard to iron impurities settling in the copper tubes which form the field system of his instrument is a very interesting one. The only part of our instrument which needs water cooling is the inside tube, and as there is no magnetic field inside this tube there is not much chance of the sediment causing trouble by becoming magnetized. However, it may be well to adopt the suggestion as an added precaution.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

ELECTRICAL MEASUREMENTS WITH SPECIAL REFERENCE TO LAMP TESTING

BY EVAN J. EDWARDS

Perhaps there is no kind of testing for commercial results that requires more accurate electrical measurements than the testing of incandescent lamps. All incandescent lamps are very sensitive to changes in the electrical conditions of the circuit. A change of 1 per cent in pressure brings about a change of 5.7 per cent in luminous intensity for carbon lamps and 3.7 per cent for tungsten filament lamps. There is a corresponding change in the life, but of a magnitude four to five times as great.

An average deviation of luminous-intensity readings of 0.4 per cent from the arithmetical mean is obtainable with good photometric apparatus, calling for a voltage accuracy of 0.1 per cent in the same precision measure. 0.1 per cent is generally considered good enough for life testing also, even though the life is affected more than the luminous intensity by a given change in pressure, the justification being that the individual variation, inherent in a group of supposedly similar lamps, is considerable.

It seems safe to say that photometric and lamp testing laboratories should maintain an accuracy of 0.1 per cent in their electrical measurements, that is, the electrical measurements should furnish results which have little probability of being in error by more than 0.1 per cent. Not only should the instruments be capable of better than 0.1 per cent accuracy in reading, but also calibrations should be sufficiently accurate and frequent and with sufficiently well established standards to insure an accuracy of 0.1 per cent in the final result.

It may be of interest to consider the things upon which ultimate electrical accuracy depends and the methods made use of, in the engineering department of the company with which the writer is connected, for obtaining this desired degree of electrical accuracy.

The accuracy of electrical measurements may be said to depend first on the accuracy of the instrument, and second on the care and skill exercised by the observer.

An investigation of instrument accuracy involves first the testing of the mechanical characteristics. A voltmeter must have a friction drag of less than the accuracy desired in the result in order that it may be safe and convenient to use. The electrical and mechanical characteristics must be such that the reading corresponding to a given pressure is closely the same throughout a range of temperature and change in position such as will be encountered in use. Also, the process of calibration and the basic standard must be of sufficient precision. A careful comparison with a potentiometer, using standard cells of proved accuracy, taking readings up and down scale and for both directions of current, combined with a close inspection, furnishes a complete test of the instrument. Fig. 1 shows results from a test on an a-c. instrument.

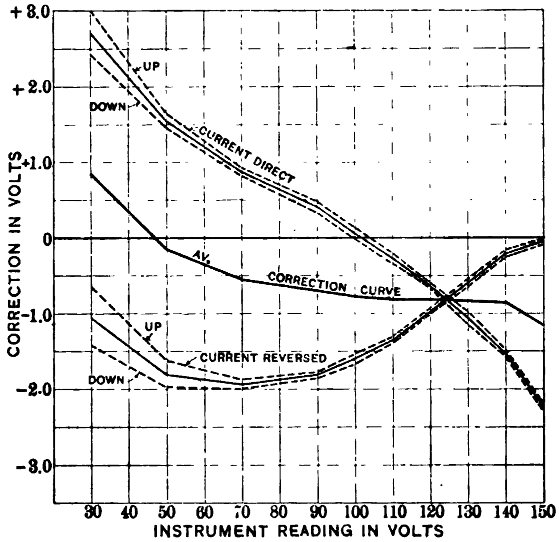


FIG. 1—CALIBRATION OF LABORATORY STANDARD ALTERNATING-CURRENT VOLTMETER NO. 33.

Surely all electrical instruments in a lamp testing laboratory should be tested periodically and, moreover, it is desirable that the results be recorded in chronological order. The advantages of maintaining a record are self-evident. All instruments in the engineering department are calibrated periodically according to a fixed schedule and the results are recorded in a graphical form which furnishes at a glance the past history of the instrument. The frequency of calibration depends upon the use to which the instrument is put; for example, a laboratory standard alternating-current voltmeter used for checking the voltage on the life test racks is checked with the potentiometer daily. The curve of Fig. 2 shows the record of this particular instrument, over the past six months. Since this instrument is maintained at nearly constant temperature, being in continuous service, and is undisturbed in position, it is interesting to note that the record is what may be termed a life curve of the dynamometer type of instrument. The change of calibration is no doubt due to the weakening of the spring.

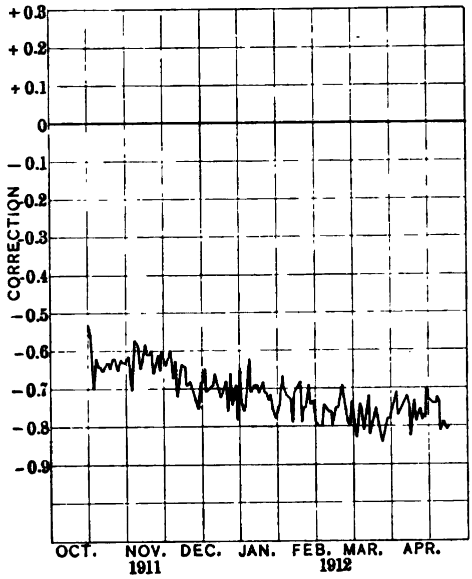


FIG 2—CALIBRATION OF LABORATORY STANDARD ALTERNATING-CURRENT VOLTMETER AT 120-VOLT POINT.
Voltmeter No. 33.

A new standard cell is obtained regularly twice per year, in addition to others obtained as needed. Two are kept apart at all times as reference standards and are used only for checking the cells used regularly on the potentiometers. This program in connection with the continuous graphic history in the calibration of a large number of instruments, practically eliminates all possibility of error or drift in the value of the unit used as a basis for the laboratory work.

The subjective factor which enters into meter reading is an important one and one seldom given sufficient attention. Aside from the ordinary care and judgment required in the use of electrical instruments, the accuracy depends on the skill of the observer in precise reading. The reading involves two kinds of subjective errors, the accidental or indeterminate such as occur in all measurements, and the error due to a mistaken idea as to the scale position corresponding to the various tenths between smallest division. Among untrained observers there is also a favoritism shown for certain digits as is shown by Fig. 3, which records the percentages of various digits representing the estimation of tenths for a large number of readings for one particular observer who has a preference for certain digits, especially zero.

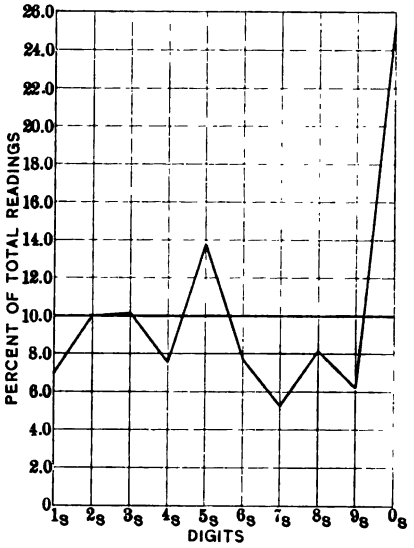


FIG. 3—ESTIMATION OF TENTHS.
Test A—600 readings.

Fig. 4 shows two meter setting curves which were obtained by averaging the curves for a large number of observers, and which are fairly typical. The deviation of the "setting" curve from the straight line is a measure of the error in the average observer's idea as to the position of the various tenths, and the deviation curve is a measure of the accuracy which the average observer can attain in the setting of the pointer in the position which he thinks is the correct one. No doubt the setting curve is what would be expected, the positions between five tenths and ten tenths being in error by about the same amount as those from zero to five tenths, but in the opposite direction, showing that the average observer obtains the upper values by subtracting a certain distance from the upper line, in the same manner that he obtains the lower ones by adding the same distance to the lower line. The five-tenths point is about right, as would be expected. Tests have shown that various observers show vastly different but reproducible characteristics both from the standpoint of error in idea as to position and of precision of setting. This is especially true of the precision of setting. Some have a low average deviation from the mean for the line and midway positions and others at the intermediate values. This test is valuable in that it furnishes a measure of both the directional and unavoidable errors to be expected; more than that, it allows the observer to correct his mistaken idea which previously was not known to exist.

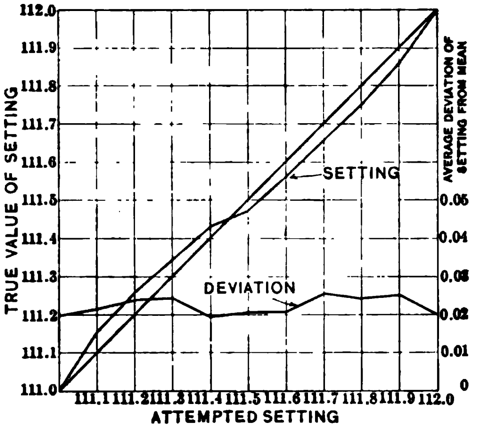


FIG. 4—PRECISION OF METER READING.
Estimation of tenths between smallest divisions.

It was found that for every-day use on photometric equipment, the precision attainable with portable instruments was not sufficient to furnish the desired accuracy, and as a result large laboratory standards and deflection potentiometers were substituted. The scales of these can be, in most cases, read to the nearest 0.1 per cent without estimation of tenths.

The indicating instrument used for the continuous observation of life test voltage, at the laboratory with which the writer is connected, is an interesting feature in itself, apart from the laboratory standard used for periodic comparisons. It is well known that a switchboard operator prefers an instrument to which no calibration correction need be applied, that is to say he prefers to adjust the voltage to a line which is labeled as the voltage at which he is instructed to run. This feature of the subjective problem finds no application in most laboratory precision work, but is worthy of consideration in this particular instance as in central station operation where a constant condition of operation is desired.

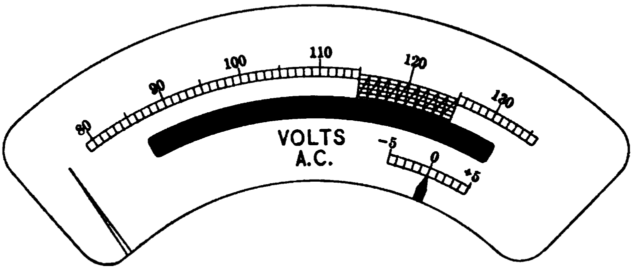


FIG. 5

It is well known that no instrument can be made which will maintain a zero correction, even though initially adjusted very carefully to that value. Many instruments on the market can be made to read correctly at one point on the scale by shifting the zero point by means of the adjustment of the spring. Such instruments are difficult of accurate adjustment, however, and moreover furnish no means of recording the calibration for a history of the performance of the instrument. Fig. 5 shows the scale of the instrument designed to overcome this difficulty. The scale can be shifted by means of a rack and pinion at the top (not shown) to the proper point to make the indication correct at the 120-volt point, the one used in this case. The calibration is indicated by the stationary pointer near the bottom of the scale. The instrument is calibrated daily and the correction recorded, and when the trend of the calibration curve shows a drift of more than 0.05 volts the scale is shifted and the new reading of the stationary point is made a new addition to the history of the instrument.

This instrument is of the dynamometer type, air-vane-damped and practically free from jewel friction. It has been in service only a short time, but promises to fulfil the requirements very well.

A graphic recording voltmeter is used in connection with the indicating instruments, but cannot be depended upon as a precision instrument, due to the comparatively large friction in the movement and the tendency to wear a rut, so to speak, in the movement, at the one point where it is constantly used. It is useful only in that it records any comparatively large change which may take place, and the time at which service is interrupted and resumed.

All must agree that in a photometric and lamp testing laboratory a great deal of thought and much time must be continually applied to the question of electrical measurements in order that those in charge may be assured that the desired accuracy is maintained at all times.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

INCANDESCENT LAMPS AS RESISTANCES

BY T. H. AMRINE

Incandescent lamps have long been used as resistances in electrical measurements, but they have not been used over nearly as wide a range and variety of work as they might be. The reason for this is probably that information as to the resistance values and characteristics is not generally available and for that reason the proper lamps can not be easily selected. It is the purpose of this paper to emphasize the value of incandescent lamps as resistances, to give some information regarding the resistance characteristics, ranges of resistance and current carrying capacities available, and such other information as will assist one in the selection of the proper lamps for any particular purpose.

The principal advantages of lamps as resistance are, of course, their general availability and their low cost. These are of especial importance in experimental work, where delays and expense under the best conditions often seriously impede progress. A wide range of lamps suitable for use as resistance can be kept in stock in a laboratory with a very small outlay of money and if properly selected and used will to a large extent take the place of a much more expensive equipment of rheostats, resistances, etc. The list price of a lamp which will carry 0.11 amperes and has a resistance of 2150 ohms is only 18 cents, which is probably less than the cost of an equal amount of resistance of like carrying capacity in any other form.

The fact that a very wide range of temperature coefficient of resistance is available in incandescent lamps is well known, perhaps, but is taken advantage of to a much less extent than is possible. Commercial lamps are now being made with un treated carbon, treated carbon, metallized carbon, tantalum and tungsten filaments. These materials range in temperature coefficient from a pronounced negative to a large positive value. In Figs. 1, 2 and 3 are given curves plotted between per cent normal current and per cent of cold resistance, for lamps with the various filament materials which are now in commerical use, and for a few forms of treated carbon (Fig. 3) that are not in commercial use but which have been made specially. These give an idea of the range in temperature coefficient available. It is seen from these curves that for limited ranges almost any desired change of resistance with change of current can be selected, ranging from a pronounced decrease to a very large increase, as well as a practically negligible change of resistance with current.

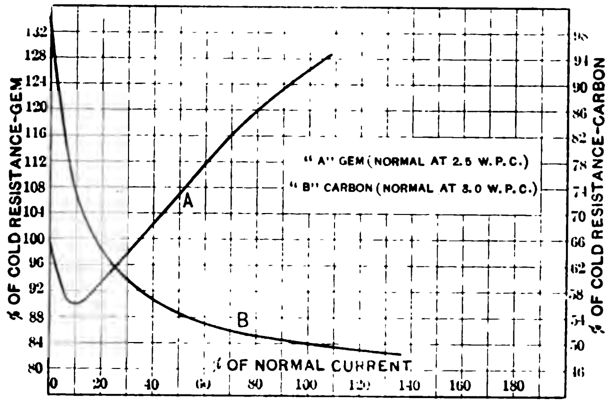


FIG. 1

In connection with these curves it may be necessary to explain that in undergoing the "flashing" or "treating" process carbon filaments decrease in resistance an amount depending upon the amount of treatment given. Hence, the curve marked "50 per cent treatment" would refer to a filament which had been treated until its resistance had decreased to 50 per cent of its initial resistance. Commercial carbon filaments are treated to approximately 60 per cent of their initial resistance.

Below is given, for the various commercial filaments, a table of exponents X in the equation $\frac{R_1}{R_2} = \left(\frac{F_1}{F_2}\right)^x$ which gives the change in resistance R with changes in F, where F represents the various quantities, candle power, efficiency, volts, watts and current.

TABLE I

F	Values of *X* for				
	Untreated carbon	Treated carbon	Metallized carbon	Tantalum	Tungsten
Candle power..............	—0.045	—0.015	0.050	0.060	0.115
Efficiency..................	0.070	0.020	—0.075	—0.100	—0.200
Volts......................	—0.310	—0.075	0.230	0.260	0.420
Watts......................	—0.135	—0.035	0.130	0.150	0.260
Current....................	—0.235	—0.070	0.300	0.350	0.720

These are average exponents which are approximately correct over a range of 20 per cent either side of the normal voltage of the lamps. By their use the resistance corresponding to any value of the function *F* can be determined, knowing the resistance at some other value, say normal, of the same function.

Below is given a table which shows the maximum resistance which is available in commercial lamps for various ampere capacities.

TABLE II

Type of filament	Amperes	Maximum resistance obtainable at given amperes	Commercial rating
Untreated carbon	0.077	1690	10-watt 130-volt
" "	0.110	2520	30 " 275 "
Treated carbon	0.154	845	20 " 130 "
" "	0.365	754	100 " 275 "
" "	0.920	141	120 " 130 "
" "	1.00	75	1-ampere resistance lamp
" "	2.00	13	2- " " "
" "	3.00	8	3 " " "
" "	3.85	36	500-watt, 130-volt heater lamp
Metallized carbon	0.231	563	30-watt, 130-volt " "
" "	0.462	282	60-watt 130- "
" "	0.77	169	100 " 130 "
Tungsten	0.077	1690	10 " 130 "
"	0.145	1900	40 " 275 "
"	0.218	1260	60 " 275 "
"	0.364	760	100 " 275 "
"	0.510	530	150 " 275 "
"	0.910	300	250 " 275 "
"	1.18	110	150 " 130 "
"	1.92	68	250 " 130 "
"	3.84	34	500 " 130 "
"	5.00	20	500 " 100 "

The resistances given above are "normal" resistances, that is, the resistances at the rated normal voltages of the various lamps. The resistances at other currents can be obtained by reference to the curves of Figs. 1, 2 and 3 or by use of the exponents given in Table I.

In almost all cases lamps of lower resistance, but having about the same ampere carrying capacity, can be obtained in regular commercial lamps.

In order to select the proper resistance lamps for any purpose it is necessary to have the following information:

1. Resistance.

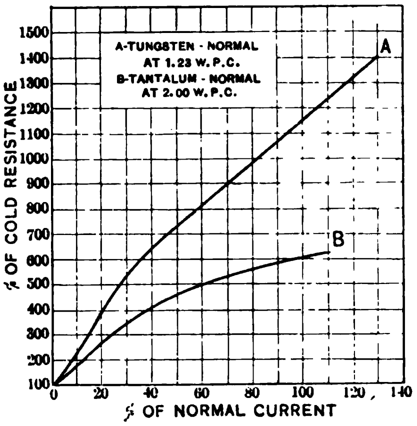


FIG. 2

2. Current carrying capacity.
3. Degree of incandescence permissible.
4. Change in resistance with change in current that is allowable.

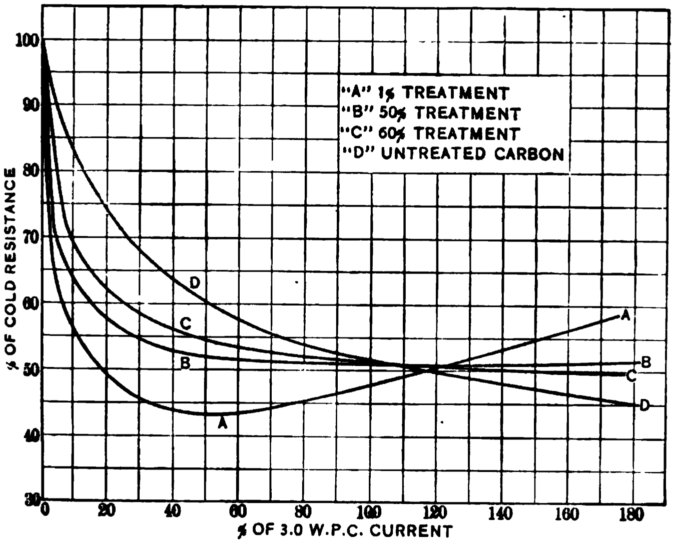
In selecting the lamp it is first necessary to know the per cent normal current at which the various types of lamps will give the desired degree of incandescence. Table III will enable one to choose these values.

The degree of incandescence permissible depends upon whether or not light is objectionable, upon the desirability of constancy over long periods of use and upon the necessity of long life of the lamps. The average total life of an incandescent lamp at the commercial efficiencies can be assumed at 1000 hours. A one per cent decrease in current below normal will increase the life from 11 to 24 per cent, depending upon the type of filament, so that if the lamps are operated a few per cent below normal they will give a very satisfactory life. Operation above normal will, of course, decrease the life in the same ratio.

TABLE III

	Per cent of normal current				
	Untreated carbon	Treated carbon	Metallised carbon	Tantalum	Tungsten
Dull red	12	14	17	20	23
Cherry red	18	20	24	26	28
Yellow red	28	30	33	35	38

From the curves of Figs. 1 and 2 one can select the type of lamp which will give most nearly the desired current-resistance change at the proper degree of incandescence. Knowing the per cent current at which the lamp is to be operated one can obtain from the curves the corresponding per cent resistance, and from this can be calculated the normal resistance of the proper lamp. From the normal resistance and normal current the voltage and wattage of the lamp can be determined. When



FIG, 3

possible, of course, it is very desirable to select a lamp which is a regular commercial product and so avoid the inevitable delay and increased cost of a special lamp.

As examples of uses to which incandescent lamp resistances have been put, other than the familiar laboratory use in lamp banks, etc., a brief description of some of the methods which have been utilized in the laboratory with which the writer is connected will be cited.

Carbon lamps seasoned at about 109 per cent of their normal voltage for a period of 12 hours* are carefully rated for volts at various ampere values and are used in the factories for checking ammeters. By this method, with a calibrated voltmeter and a few lamps one can check portable voltmeters and ammeters in as satisfactory a manner as with both standard voltmeter and ammeter.

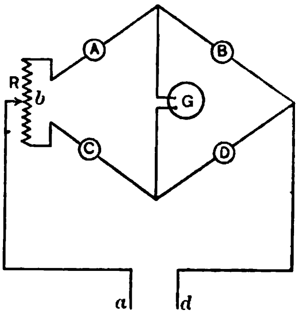


Fig. 4

Extensive use is made of a four-lamp bridge which is essentially the same as the old Howell indicator. In this bridge four lamps are arranged as shown in Fig. 4, in which *A* and *D* represent lamps having a different current-resistance relation from lamps *B* and *C*. For instance, *A* and *D* may be carbon lamps, and *B* and *C* metallized carbon lamps, the most sensitive combination which utilizes commercial lamps being with untreated carbon lamps for *A* and *D* and tungsten lamps for *B* and *C*. If, by means of the small adjustable resistance *R*, the galvanometer *G* is brought to zero for any current through *ABCD*, then any change from that current will produce a deflection of the galvanometer. This arrangement is used to enable one to hold the voltage on a given circuit constant by putting the terminals *a d* across the line, bringing the line to the desired voltage by the use of a voltmeter and then adjusting the galvanometer to zero by means of *R*. With a proper bridge and an ordinary portable galvanometer, a small change, say 0.1 per cent, in the voltage of the line is made evident by a considerable deflection

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*Before being used as resistances for any purpose which requires careful resistance adjustment, all incandescent lamps should be seasoned by burning for a period sufficiently long to bring them to a constant resistance value.

of the galvanometer. By placing a bridge arrangement such as this in series with a line the line current can be held to a constant value in a similar way.

A photographic recording alternating-current voltmeter of high sensibility which was developed by Mr. L. T. Robinson utilizes a four-lamp bridge similar to the one described, in connection with a reflecting dynamometer.

A temperature control device has also been made by using a small tungsten lamp as one arm of a bridge and placing it in the oven whose temperature was to be kept constant. The bridge is brought to a balance by adjustment of the other arms while the temperature is held constant at the correct value by means of a thermometer. After being set thus the oven can be readily held at the proper temperature by reference to the galvanometer.

DISCUSSION ON "ELECTRICAL MEASUREMENTS WITH SPECIAL REFERENCE TO LAMP TESTING" (EDWARDS), AND "INCANDESCENT LAMPS AS RESISTANCES" (AMRINE), BOSTON, MASS., JUNE 28, 1912.

Clayton H. Sharp: Speaking of the paper by Mr. Edwards, the author gives a curve of corrections for the alternating-current voltmeter as used in checking the voltages on the life testing rack. He emphasizes the importance of that correction curve. I do not think he emphasizes it quite enough and I doubt if a laboratory standard voltmeter alone, even though carefully checked, is quite sufficient to maintain the very high degree of accuracy which is called for in the measurement of life testing voltages. One-tenth of one per cent on the life testing voltage will make several per cent difference in the life of the lamp, and may have very serious commercial results under certain circumstances; so that in all lamp testing, the most important thing is the accurate determination and checking of these voltages. No single method is sufficient, but rather, various methods must be used and checked against each other. For instance, in our own laboratory, we use a multicellular electrostatic voltmeter with a mirror and scale, a method introduced by Dr. Kennelly some years ago. This is used as a transfer instrument to check directly against the potentiometer, so that the chances of errors of the instruments themselves are as nearly as possible eliminated. Other instruments are used in the same way.

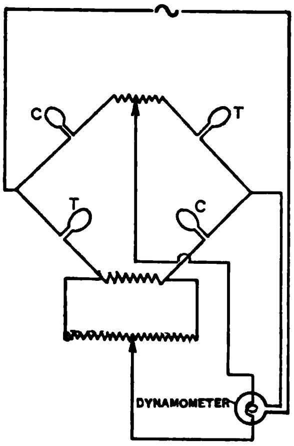


FIG. 1

More recently we have been trying the method suggested by Mr. Amrine, namely the use of the old Howell indicator. See Fig. 1.

The bridge which we have used is made up of tungsten and carbon lamps in opposite arms. At one diagonal of the bridge is placed a resistance of zero temperature coefficient. About this is looped a rheostat of high resistance with a rotating switch, making a very great many contacts.

The bridge is placed on the circuit the voltage of which is to be measured and in series with it is a fixed coil of a sensitive electrodynamometer. The moving coil, which is supported on a suspension wire and carries a mirror, is placed across the bridge in the usual connection for the galvanometer, excepting that one connection from it is made to the rotating switch of the rheostat. With this arrangement properly adjusted, the different positions of the rheostat arm correspond to different voltages on the bridge and the rheostat may be calibrated to read in volts. It is used as a transfer instrument, being calibrated on direct current. On account of the slight lead which the current has in a tungsten lamp on alternating current due to the considerable changes of temperature of the filament, the bridge does not give correct results as a transfer instrument if the lamp filaments are too fine. It is necessary therefore to use lamps of fairly high candle power in the construction of the bridge. The lamps must be of the same quality and character as are used for precise photometric standards; that is, all loose or variable contacts in the interior of the lamp must be eliminated and the lamps should be properly seasoned or aged before put into the bridge.

It should be noted that an arrangement of this kind is extremely sensitive to differences in voltage. Differences of 0.0001 of a volt in 100 volts, that is, differences of one part in 1,000,000, are shown by the deflection of the electrodynamometer.

Referring again to Mr. Edwards's paper, he says that in commercial testing the ordinary portable instruments are insufficient. That is quite true, and a larger type must be used. For more careful measurement it is better to use two potentiometers, one for measuring voltage and the other for measuring current.

As to the indicating instrument on the switchboard for the life test voltage, another possible modification of that scheme is to give the man who regulates a single positive mark to go by, so that he has not any chance to estimate or to do anything else. He merely holds his needle on that mark, which relieves him from a large amount of mental exertion.

A. E. Kennelly: This description which has been given us by Dr. Sharp is very interesting, in regard to that kind of voltmeter, and I quite agrée with the opinion he expressed, that no one particular instrument should be taken as the exclusive court of appeal in deciding the calibration of an alternating-current voltmeter. Checks should be obtained in all cases. We have found that the alternating-current potentiometer of Dr. Drysdale is a very useful and convenient check, which, by means of the vibration galvanometer, gives a high degree of sensibility, enabling a difference in voltage of one-twentieth of one per cent to be easily determined.

M. G. Lloyd: I should like to ask Mr. Edwards a few questions, and to have him elucidate Fig. 3 a little further. First, in regard to how the settings were made on which these readings were taken. There might be three ways of making these settings: In one way they would be evenly scattered across the entire scale; in the second way, they might be set on the exact tenths rigidly, and the same number of settings made on each tenth division; and in the third way they would be left to chance, and, on account of something in the set-up, they might fall more frequently in one region than in another; so I should like to know how the settings were made from which these readings were taken.

Secondly, I think the width of the space is a very important thing in a study of this kind, as it seems to me the tendency exhibited in these results would very largely depend on the ratio of the width of the pointer to the width of the space.

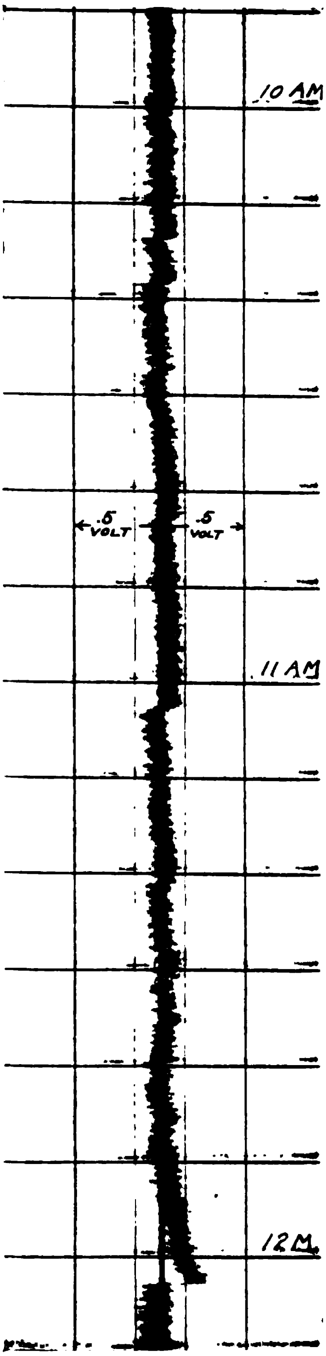
Paul MacGahan: I wish to point out an interesting application of the tungsten lamp used as a resistor. This is in connection with contact-making voltmeters, such as are often used for potential regulators, or in relay type graphic meters, in which the tungsten lamp is used as a resistance between the contact and the magnet or motor. The idea is to introduce a low resistance just when the contact is made, giving a good starting characteristic to the device, and improving the contact action. As soon as the contact is made, the lamp lights up and increases in resistance ten times, and thus greatly reduces the current and sparking when the contact is broken.

T. H. Amrine: In Mr. Edwards's paper, he mentions the use of graphic recording voltmeters on life testing lines. He is correct, of course, in his statement that the ordinary graphic voltmeter cannot be depended upon for anything more than to show very large changes in the voltage and to show interruptions in the service. The photographic recording voltmeter which is mentioned in my paper is being developed for this service and the indications are that it will serve the purpose well. It is sufficiently sensitive and has a sufficiently wide scale so that variations of one to two-tenths per cent in voltage are plainly indicated on the chart.

A couple of records from this photographic recording voltmeter are presented herewith, which show what can be done by the instrument. They also serve to show the sort of voltage regulation that can be obtained on alternating-current lines by means of the automatic voltage regulator under the best conditions. The original of chart No. 1 was taken with the voltmeter adjusted to give a scale of 1.8 in. (45.7 mm.) per volt. The original of chart No. 2 has a scale of 1.5 in. (38.1 mm.) per volt.

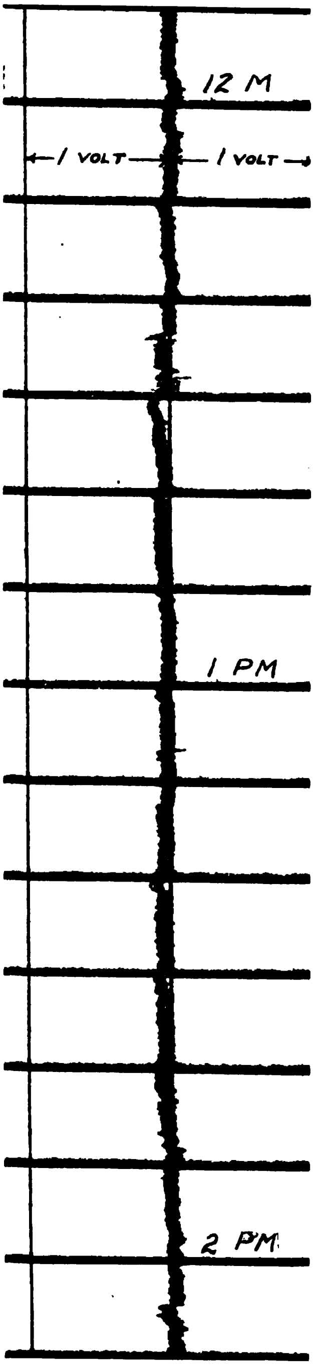
Evan J. Edwards: Referring to Dr. Lloyd's question as to the method used in obtaining the readings of Fig. 3, I would say that these figures were taken from old photometric data which were obtained with no thought that they might be used for the purpose of this investigation. Only such readings as were obtained in a straight estimation of tenths between smallest divisions, were selected; that is to say, only such groups of data as could be expected to show a nearly equal number of occurrences of each digit for a large number of readings were included.

The width between smallest divisions used in obtaining the curves of Fig. 4 was that of a standard portable voltmeter having 150 scale divisions. The ratio of width between divisions to the width of pointer was probably about 10. Dr.



[AMRINE]

CHART No. 1



[AMRINE]

CHART No. 2

[Reproduced one-half size of original]

Lloyd is, of course, right in saying that the results depend on this ratio. They probably also depend on the actual length as well as the ratio. The curves were intended as illustrative in the analysis of the various errors involved in meter reading.

Dr. Sharp has expressed the opinion that no single method of connecting alternating-current measurements with standard cell values is sufficient. Dr. Kennelly states that he concurs in that opinion. The author did not intend to give the impression that one single method or one single criterion was in use. It is true that only one method, the dynamometer method, is used as an everyday means of calibration. But before adopting this method, a careful comparison was made with a hot-wire instrument. Having proved the results to be the same by two very different methods and knowing that the wave form must remain unchanged, it seems justifiable to adopt as an everyday method the more convenient and sensitive one. Making measurements by using many instruments and many methods, of course, should give added assurance in the result, always, but it is possible to reach the point where additional measurements are not worth what they cost.

The modification of the special indicating voltmeter suggested by Dr. Kennelly was considered when designing the instrument. It was decided to add the divisions in order to enable the operator to make exact readings on the even hour when the regular log readings are taken.

It is my understanding that the photographic instrument mentioned by Mr. Amrine consists of a dynamometer movement carrying a small mirror which reflects a beam of light with a long throw, to a sensitized paper driven by a clock mechanism. Such an instrument should, of course, be as reliable as the indicating instrument described in the above paper. The records show it to be very sensitive and free from friction.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

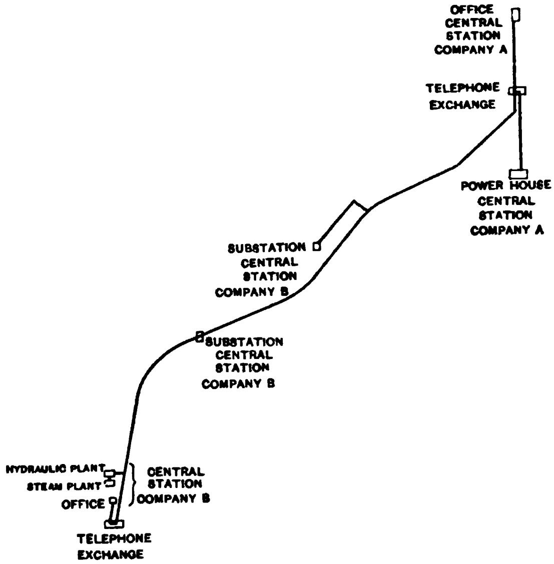
ELECTRICAL TRANSMISSION OF ELECTRICAL MEASUREMENTS

BY O. J. BLISS

The unique arrangement of standard instruments described in this paper was made for the purpose of transmitting and reproducing at a distance a direct electrical measurement, the distance in point being 35 miles (56 km.), the measurement the indicated kilowatts input to a 12,000-volt, 60-cycle, three-phase transmission line, and the medium of transmission a telephone line owned by the local telephone company but used as a private line by the central station companies.

The conditions which led to the necessity for the arrangement were these: First, a contract for power to be furnished by a large central station company which we will call *A*, to a smaller central station company called *B*, over a 35-mile (56-km.) three-phase transmission line, the smaller company being a customer of the larger and having substations of its own tapped off the connecting line. Second, a form of contract requiring that billing be done from the readings of a polyphase watt-hour meter installed in central station *A*, equipped with a printing device adjusted to print automatically the dial readings on a paper ribbon at intervals of 15 minutes, the charges to include a certain rate per kilowatt-hour for all energy delivered, a kilowatt-year charge based on the average of the three highest one-half hour peaks occurring during the year and a guarantee of a certain load factor.

With a contract of this kind it is evidently very much to the advantage of the customer to keep the load curve free from any peaks which would increase the kilowatt-year charge. But as the customer can only regulate at his own station and in the case in question the operators at *B* had no means of knowing what the input to the line was by central station company *A*, it became apparent that instruments must be installed in the stations of the smaller company which would indicate this input. Considerable advantage would also result if some permanent record could be obtained in order to check the watchfulness of switchboard operators, and as a comparison with the printed registration of the polyphase watt-hour meter instation *A*. It was desirable therefore to install a curve-drawing as well as an indicating instrument.



Map Showing Location of Telephone Stations.

In developing a scheme permission was first obtained from the telephone company to use the private line for the transmission of signals between the stations, it being understood that any arrangement installed for that purpose should in no way interfere with the telephone service nor should an e.m.f. of over 50 volts be put on the line.

Standard types of meters were then modified and installed as follows. On the switchboard of central station *A* was mounted a graphic recording wattmeter, with relay type of movement, connected through the regular equipment of current and potential transformers to the transmission line. Alongside the wattmeter a small special variable rheostat was installed, the movable contact of which was connected, by a brass rod provided with an insulating joint, to the recording mechanism of the graphic meter so that the position of this contact at all times corresponded exactly to the deflection of the meter.

If now a direct-current source is connected across the rheostat terminals, and one terminal and the movable contact connected to the telephone line, the e.m.f. across the line has a fixed relation to the deflection of the graphic meter, or the input to the transmission line, and the reading of a direct-current instrument connected in the telephone line may therefore be made to indicate this input.

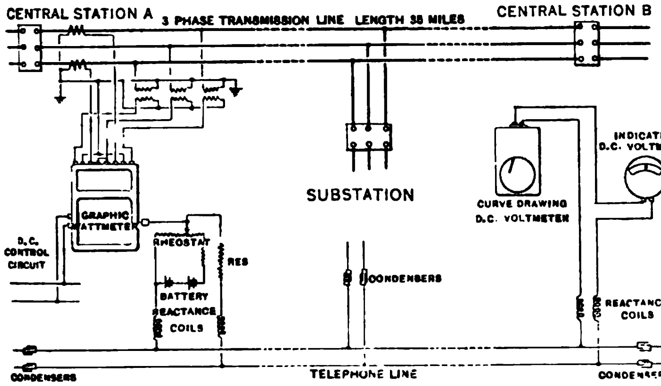


Diagram of Connections for Transmission of Electrical Measurements over Telephone Line.

The rheostat as made up has uniform resistance per unit of length and does not therefore give uniform increments of e.m.f. for equal distances of travel of the movable contact. By making the current through the resistance large as compared to the instrument current the error is, however, negligible, and the e.m.f. is considered directly proportional to the deflection of the graphic meter.

The source of direct current is a 36-volt storage battery of small capacity located near the switchboard. The continuous discharge rate through the rheostat is about 150 milliamperes. The direct-current instruments, one an indicating voltmeter installed in the steam plant of central station company *B*, the other a curve-drawing voltmeter with smoke chart recorder installed in the waterpower plant of central station company *B*, are in series, are adjusted to the same full scale current, about 7 milliamperes, have scales marked in kilowatts and have series resistances adjusted to give full scale deflection corresponding to the graphic meter in central station *A*.

One-half of this resistance is in one of the meters in central station *B*, and one-half is mounted on the rheostat in central station *A*. This is necessary because the signaling system forms at both ends of the telephone line a shunt across the line, which must be of at least 1000 ohms resistance in order not to interfere with the telephone service.

Interference with the telephone by the direct current of the transmitting system is prevented by the installation of condensers in the line at each telephone station, and interference with the meters by the telephone ringing current is prevented by the installation of reactance coils in the instrument leads.

The operation of this system has been so satisfactory, is so simple in its various parts, and has given such a small amount of trouble, that it leads one to believe the scheme practicable for many other applications. For instance, any two stations, whether belonging to the same company or not, if feeding into the same load, might use a system of this kind to advantage. A central office could have a continuous record of total output or that of any more important line or machine. Regulation of machines for synchronizing operations where the switch to be closed is in a station remote from that in which generators are located, as is sometimes the case in interconnected systems, could be easily arranged, or the more important positions on the load dispatcher's board might be made automatic, showing switching operations without waiting for the telephone call and the subsequent plugging or marking of the board.

In short, the installation here described seems to show that any points connected by telephone lines may be equipped for the transmission of measurements or direct-current signals at a low cost, without interference with the telephone system.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

METERING LARGE DIRECT-CURRENT INSTALLATIONS

BY F. V. MAGALHAES

The question of properly metering electrical energy when it is used in the form of high values of direct current is one that can profitably be discussed at this meeting. The following brief paper is intended as a summary, for the purpose of discussion, of various methods now being used, with suggestions for the development of apparatus that would eliminate certain disadvantages and errors now encountered.

We will consider the methods of metering currents of 1000 to 10,000 amperes at 100 to 600 volts. These limits are arbitrary but they cover a great many conditions which are comparable in metering both the energy for light and power from central stations and the energy from electric railway substations.

Below is given a list of four headings which will in turn be dealt with in detail.

Method 1. Install a single watt-hour meter between the source of supply and the distributing switchboard.

Method 2. Install in parallel in the main source of supply several watt-hour meters with an aggregate capacity sufficient for the total load.

Method 3. Divide the main service supply and meter separately any natural component parts of the total load.

Method 4. The development and the use of the shunt type of watt-hour meter both for the metering itself and for test purposes in connection with any of the three foregoing methods.

METHOD 1

The practise of installing only a single watt-hour meter is the easiest, best appearing and cheapest from the standpoint of switchboard design, and the cheapest from the standpoint of initial meter cost. The method, however, has the least to recommend it from the standpoint of meter accuracy, and is the most difficult and expensive to maintain after installation.

The advantages that may be claimed for this method are the registration on one set of dials of the total energy for the installation; also, as indicated above, the low initial meter cost as compared with other methods. This latter condition, however, is open to argument if careful consideration is given to the fact that a system of using several small meters permits more flexibility from the standpoint of exact assignment, as the rated ampere capacities of large meters are, from the manufacturing standpoint, necessarily arbitrary and in large steps.

The disadvantages that may be listed are: the possibility of complete interruption of registration or inaccurate registration due to a defect or to poor performance of the meter, such interruption or inaccuracy of registration applying over the energy for the total installation; extreme difficulty of proper testing, involving the insertion of instruments in the main circuit, the possible shunting of the customer's load and handling of an artificial load; the expense of owning and calibrating standards of very high current capacity; and the loss of registration due to the shunted load during the time of test.

METHOD 2

The practise of installing several meters in parallel, while increasing somewhat the initial meter cost and possibly the switchboard cost, tends to eliminate or improve several of the disadvantages of Method 1.

In case of defect or inaccuracy in a meter only part of the total registration is affected.

Testing is greatly simplified over Method 1, as the meters may in turn be disconnected on the house side for test and the remaining meters allowed to carry the load. The test connections, artificial load and capacity of the standard instruments will all be of smaller ampere capacity than in Method 1, with a corresponding decrease in initial cost and cost of maintenance.

This method is subject to one disadvantage in common with Method 1, namely, the poor performance of the aggregate meters at very light loads. A light load may exist for several hours which would be of considerable significance from the standpoint of energy, but which might be inaccurately metered, as it would be only a small percentage of the total meter capacity.

One disadvantage peculiar to this method is that the separate meters, due to differences in the resistance of the connections, may not register their proportionate part of the total energy. Such difference in registration, even when the meters are entirely accurate, can give rise to unnecessary question or criticism of meter accuracy.

METHOD 3

The practise of installing individual meters for the natural component parts of an installation, such as separate floors in a building, separate buildings in a group, separate motors in a large power installation or separate synchronous converters in a substation, is, if the meter sizes are carefully assigned and the meters properly maintained, the best method for most conditions.

This method is open to the same objections that may be advanced against Method 2 as to the increased installation and meter cost.

Method 3 has a distinct advantage over the first two methods in that the assignment of each meter may be made very closely by considering the performance of its particular installation. The aggregate light load and overload performance of the individual meters will then be better than the performance of a single large meter or group of parallel meters on the total load.

The development of a mechanical or electrical totalizing dial of some description would, in connection with Methods 2 and 3, provide a single totalized record of registration of the various meters. Such a record might be desirable or even essential in the case of a synchronous converter substation, with the individual converter meters installed near the converters and a totalizing dial located on the switchboard.

METHOD 4

Method 4 is a proposed practise based on the development of an accurate shunt type of watt-hour meter.

Assuming the availability of such a shunt type of watt-hour meter for service purposes and a carefully designed shunt type of portable watt-hour meter for test purposes, the metering of large direct-current installations would at once present other possibilities. It would be possible to meter a large power installation, consisting of a few units, with a single meter. This meter could at frequent intervals be compared quickly and accurately with the rotating standard. The service meter and the standard being of similar types and characteristics would permit the use, for test purposes, of the regular service load, even if of a very fluctuating character.

One marked advantage of the shunt type of meter in the large capacities would be its flexibility from the stock standpoint. The meters themselves could be all of five or ten amperes capacity and the range for the large capacities maintained by a stock of shunts. This feature is comparable with the flexibility which is possible with the standard five-ampere induction meter in connection with any ratio of current transformer.

For an installation of small power units or a large lighting installation, Method 3, namely, metering separate parts of the installation, would still be desirable even with the availability of the shunt type of meter. Such a type of meter would, however, increase the ease of testing and thus indirectly increase the accuracy of registration.

In conclusion it can be stated that the requirement of a brief paper has necessarily resulted in the discussion of only one narrow phase of the general subject of metering. The possibilities of the shunt type of meter have by no means been completely covered. No mention has been made of the proper assignment of the present type of astatic and four-pole meters for different installations and switchboard designs. Nor has the subject of proper instruments and artificial loads for test purposes been dealt with, although all of these points are related and essential to the proper metering of large direct-current installations.

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MEASUREMENT OF ENERGY WITH INSTRUMENT TRANSFORMERS

BY ALEXANDER MAXWELL

A good deal has been written concerning the determination of the ratio and phase angle of instrument transformers, and several methods are now available which are of good accuracy. Also, there is considerable matter available regarding the design of such transformers, with reference to the production of satisfactory ratio and phase angle characteristics. Comparatively little has appeared, however, concerning the effect of ratio and phase angle upon the accuracy of watt-hour meters.

The effects of ratio and phase angle upon the indications of switchboard instruments can generally be provided for without much difficulty, and where these effects become important in connection with special measurements made with portable instruments, such as precise measurements over a wide range of currents or voltages, or at low power factors, correction may readily be made for them, the only requirements being a knowledge of the ratio and phase angle characteristics of the particular transformers used, and some rather tedious calculations.

With watt-hour meters, however, the problem is more difficult. It is not possible to adjust such meters to compensate automatically for changes in ratio and phase angle for different loads and different power factors within the range of the meter. Legal and commercial considerations require that such meters be maintained within certain specified limits of accuracy. It is the purpose of this paper to consider, briefly, some aspects of the problem presented by the use of instrument transformers in connection with watt-hour meters.

POTENTIAL TRANSFORMERS

Deviations from stated ratio and ideal phase relation are small in potential transformers, as compared with current transformers. Furthermore, in a large majority of cases, potential transformers are used in connection with constant potential systems, and at constant secondary load, and therefore the determined values of ratio and phase angle for that particular load remain unchanged. Ratio may be taken into account once for all in the calibration of the meter. Phase angle may not be compensated, except for a particular value of load power factor, as shown later, but in most cases the error due to this deviation from the ideal phase relation will be negligibly small.

CURRENT TRANSFORMERS

Generally speaking, modern current transformers of the best design, under favorable conditions of use, show quite satisfactory ratio curves for secondary currents down to 10 per cent of rated current. Similarly, the angle by which the secondary current differs from the ideal 180-deg. relation with the primary current is small over a quite wide range, but may still introduce serious errors at low loads.

Current transformers of special design, such as those intended for portable use, or in other cases where special efforts are made to reduce the weight of the transformer, generally have ratio and phase angle characteristics which render them quite unsuitable for use in connection with watt-hour meters.

Ratio. Where current transformer ratios have the same value from full secondary load to a small secondary load such as 5 or 10 per cent, the meter accuracy is not affected, since this ratio, whatever its value, is accounted for in the calibrating constant of the meter.

Where the ratio curve bends upward at low loads, or in the occasional cases where it bends downward, as shown in Fig. 1, the meter accuracy is affected if some compensation is not provided.

It is possible to compensate within somewhat narrow limits for this variation in ratio, by utilizing the light load adjustment of the meter; that is, for the commonest case (ratio increasing with decreasing current) causing the meter to run slightly fast at light load, to compensate for the increase in ratio, which tends to make the meter under-record.

The obvious objection to this procedure is that it may cause the meter to creep. A number of experiments made on many different types of induction watt-hour meters indicated that such over-compensation might be carried out without any tendency toward creeping, up to amounts corresponding to 101 to 103 per cent of " normal " speed, and at 5 per cent load. Some results of such tests are shown in Fig. 2. It is true that these tests refer to rated voltages and frequency, but since the permissible range of compensation seems to be considerably greater than that required to correct for transformer ratio errors such as those shown in Figs. 2 and 3, it is possible that this method of compensation may be applied without disturbing the stability of the meter with respect to creeping. In cases where the transformer ratio curve bends downward at low load, it is of course very easy to adjust the meter to accommodate the ratio.

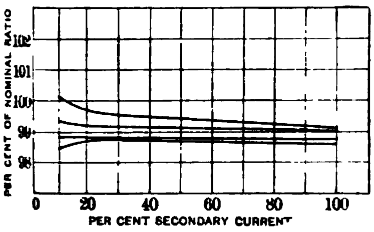

Fig. 1—Ratio Curves of Current Transformers, all with Minimum Secondary Load.

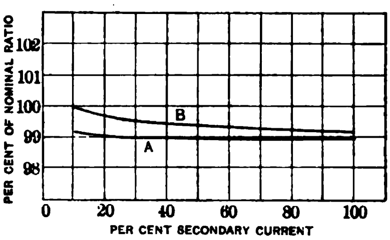

Fig. 2—Effect of Loading Current Transformer.
A—Watt-hour meter series coil only.
B—*A* plus ammeter and relay coil (about 60 per cent of rated volt-amperes.)

Another limitation of this method lies in the fact that transformer ratio curves are not always of the same form as the accuracy curve of the meter, and in this case, of course, complete compensation cannot be obtained. However, the most satisfactory current transformers have, when lightly loaded, ratio curves of the form shown by curve *A* in Fig. 3. The form of this curve reasonably approximates the form of the meter curves shown in Fig. 2. Curve *B* in Fig. 3, which is fairly typical of the change produced by loading the transformer, is of a form unsuitable for compensation. This indicates the desirability of restricting the load upon the secondary of the current transformer to a minimum, preferably the meter series coil and short leads only.

Phase Angle. Phase angle cannot be compensated by any means which will operate automatically. Since the meter torque depends upon $E\,I\cos(\theta + \phi)$ where ϕ is the transformer phase angle, the error will vary with the line power-factor, and since the transformer phase angle will vary with the current the error will also vary with the line current.

A few curves showing typical phase angle characteristics of modern current transformers of various types are given in Fig. 4. Fig. 5 shows the errors of measurement produced for various values of transformer phase angle, for different line power factors. These curves are computed for the condition where the secondary current leads the primary current in phase.

From Figs. 4 and 5 it will be seen that for ordinary commercial range of line power factors, the errors produced by transformer phase angle are comparatively small with transformers of good design. Where great accuracy is required, or where loads having low power factor are to be measured, errors due to this cause become troublesome. Apparently the remedy for this (besides selecting transformers having minimum phase angle) is to load the transformer as little as possible. Reactance may be added in the secondary circuit, to correct for phase angle, but only at the expense of the ratio. The writer's experience has been that with several different types, the ratio errors have increased faster than the phase angle errors diminished, and the former finally became unmanageable. On the whole, it seems best to reduce phase angle as much as possible, by reducing the load upon the transformer.

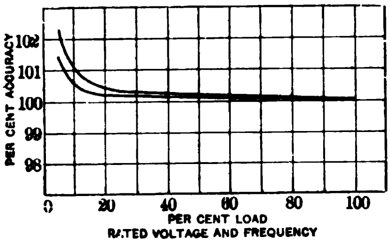

FIG. 3—WATT-HOUR METER OVER-COMPENSATED BY MEANS OF LIGHT LOAD ADJUSTMENT.

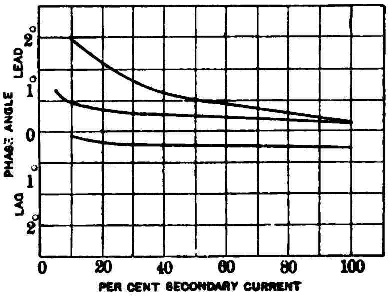

FIG. 4—PHASE ANGLE, CURRENT TRANSFORMERS, ALL WITH MINIMUM SECONDARY LOAD.

A common difficulty, which constitutes another reason for supplying watt-hour meters from separate transformers, lies in the practise of assigning over-size transformers for relay work. This over-size assignment is desirable, or necessary, for the relay, since the only function of the latter is to operate at overloads generally much greater than the normal load of the circuit, and it is important that the actual secondary current in the relay windings shall not attain excessive values. The result, however, where a meter is in series with the relay, is that the meter may actually be assigned at from one-half to two-thirds of its rated current and load; at very low loads on the circuit, corresponding to 5 or 10 per cent of rated circuit full load, the meter may actually be operating at 2 to 7 per cent of its rating, with all the attendant exaggeration of ratio, phase angle and meter errors.

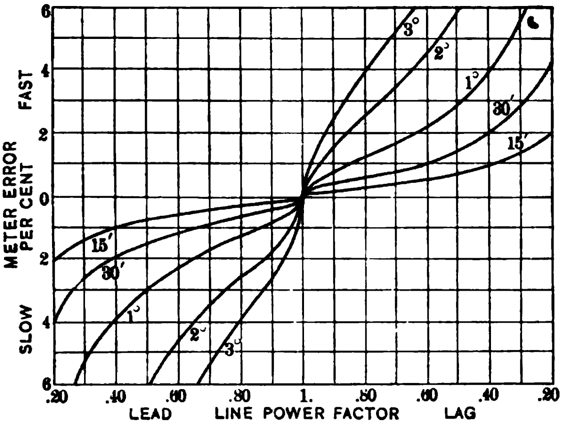

FIG. 5—ERROR PRODUCED BY TRANSFORMER PHASE ANGLE, FOR VARIOUS LINE POWER FACTORS, SINGLE-PHASE OR POLYPHASE WATT-HOUR METERS.

A question of design arises in connection with transformers for use in power supply systems of great magnitude. Here it has been found that transformers of small primary capacity are unable to withstand the enormous mechanical forces produced on short circuit, and under these conditions they have been destroyed. This condition has called for the development of special types of transformers, and in these the necessity for preserving the desirable ratio and phase angle characteristics of normal designs results in a great increase in weight.

In conclusion, it may be said that the best commercial types of current and potential transformers show characteristics which make them satisfactory for service in connection with watt-hour meters, under ordinary conditions of use. It appears further that some sources of error may be at least partially compensated, and that the more serious errors may be largely avoided by loading transformers only with the meter which they supply. It is also true that very serious errors may be produced by the use of transformers having poor ratio and phase angle characteristics, and that such transformers should therefore not be used for energy measurements, however satisfactory they may be for less exacting service, such as the operation of trip coils or relays

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WHEATSTONE BRIDGE-ROTATING STANDARD METHOD OF TESTING LARGE CAPACITY WATT-HOUR METERS

BY C. H. INGALLS AND J. W. COWLES

There are two general classes of large capacity watt-hour meters, alternating-current and direct-current. The meters used for alternating current are almost invariably of the induction type, generally five-ampere meters used in conjunction with current transformers, or both current and potential transformers. A facile and accurate method of testing these meters is by means of an induction type of rotating standard which by means of standard instrument transformers may be made available for testing any alternating-current meter of any capacity, with a precision well within commercial limits.

Where large capacity direct-current meters are to be tested, however, the problem is somewhat more difficult. The method usually chosen is the indicating instrument-stop-watch method, by which method the energy delivered to the meter under test is measured by indicating instruments (voltmeter, millivoltmeter and shunt) and the speed of the meter determined by a stop-watch. Where the load is constant, this method is satisfactory, but for power circuits similar to street railways, where there are rapid fluctuations of considerable magnitude, this method is not desirable.

The rotating standards have many advantages when used on loads of this character, but unfortunately they are not made commercially of a capacity exceeding 150 amperes and, unlike millivoltmeters, it is not advisable to use them directly with shunts, with the possible exception of the mercury flotation type of standard.

In order to adapt the rotating standard to the testing of meters of 1000 or 2000 amperes capacity a differential galvanometer was devised by Prof. F. A. Laws, of the Massachusetts Institute of Technology, which was so arranged that a standard of moderate capacity could be used. It consisted essentially of two current coils wound in opposition, having between them a pivoted coil of fine wire. The apparatus and connections are shown diagrammatically in Fig. 1. The coil *a* is of few turns (actually a straight copper bar) but of sufficient capacity to carry the full line current. Coil *b* has the same current capacity as the rotating standard and with such a number of turns that by adjusting the resistance *d* the effect of the current in *b* will counterbalance the effect of the current in *a* on the coil *c*.

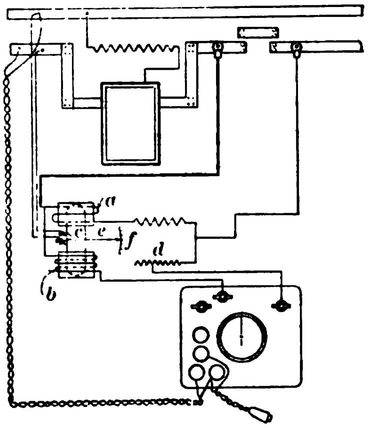


FIG. 1

With this condition of balance, which is indicated by the pointer *e*, the ratio of the two currents $\frac{Ia}{Ib}$, also $\frac{Ia + Ib}{Ib}$, is a constant, and the rotating standard will measure a definite percentage of the total energy delivered to the meter under test. This ratio and percentage are determined in the laboratory by actual measurements. The differential galvanometer as described above is subject to the influence of external fields, and a modification of this method was devised by the writer, based on the general principle of a Wheatstone bridge. The arrangement of the resistances and the rotating standard is shown diagrammatically in Fig. 2, where *a*, *b*, and *c* are fixed resistances forming three arms of the bridge, the rotating standard and the adjustable resistances *d* and *e* forming the fourth arm. When the potential differences between the terminals of the two resistances *a* and *b* are the same (and since they have one terminal in common, this is indicated by the galvanometer reading zero), the current in *a* is to the current in *b* as the resistance of *b* is to the resistance of *a*, or

$$\frac{Ia}{Ib} = \frac{Rb}{Ra} \text{ or } \frac{Ia + Ib}{Ib} = \frac{Ra + Rb}{Rb}$$

Ra and *Rb* are constant, therefore $\frac{Ia + Ib}{Ib}$ is a constant as long as the galvanometer indicates a zero reading. $Ia + Ib$ is the current measured by the meter under test and *Ib* is the current measured by the rotating standard, therefore the rotating standard measures a certain definite percentage of the current supplied to the service meter. This percentage may be computed from known values of *Ra* and *Rb* or preferably by actually measuring the values of *Ia* and *Ib*. The condition of balance between *a* and *b* is obtained by adjusting the resistances *d* and *e*, *d* being a strip of resistance metal used for coarse adjustments and *e* a carbon compression rheostat used for the fine adjustment. The three resistances *a*, *b*, and *c* are preferably made of manganin in the same form as instrument shunts, as manganin has a negligible temperature coefficient and low thermal effect. *a* and *c* should be of a current capacity sufficient to carry the full line current and *b*. approximately 40 to 50 amperes. The full load drop in potential is 100 millivolts each for *a* and *b* and 400 millivolts for *c*. Any change in the resistance of the rotating standard due to the temperature coefficient of the copper current windings or change in the contact resistance is readily compensated for by the rheostat *e*, but in practise it is found that after the preliminary adjustment very little further change is required. It is quite necessary for accurate work, however, to use materials that have very small thermoelectric effect upon each other, as

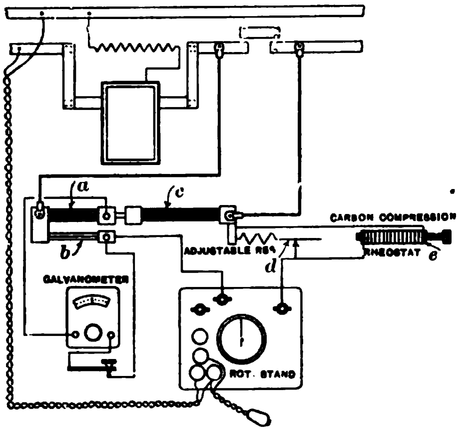
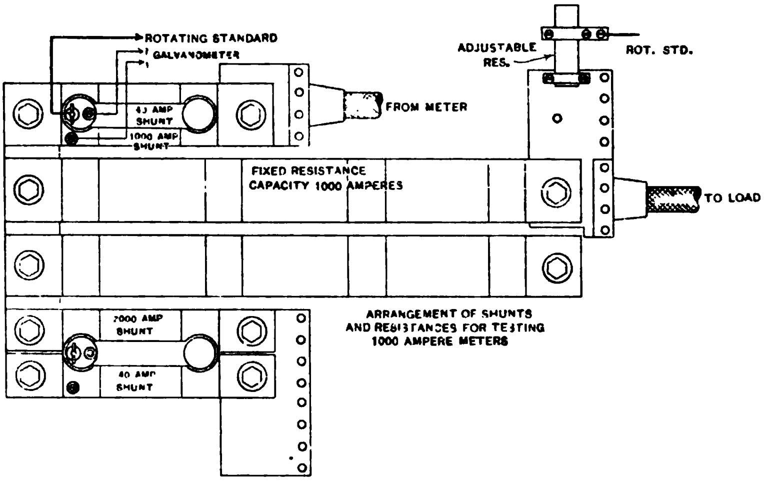


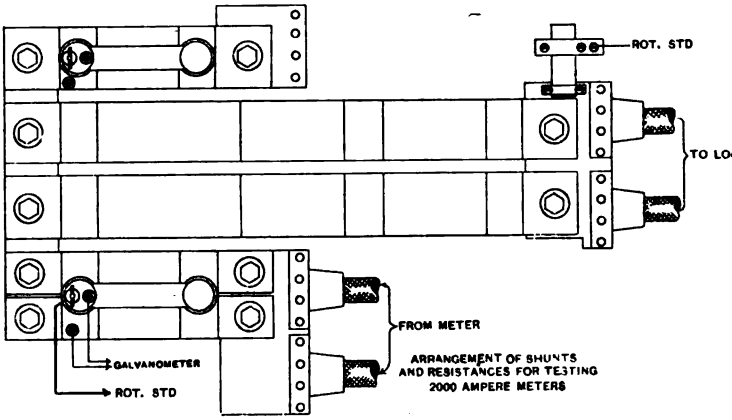
FIG. 2

in the first apparatus made up for trial more trouble was experienced from this source than any other. By using manganin for the resistances no difficulty from this source will be experienced.



ARRANGEMENT OF SHUNTS AND RESISTANCES FOR TESTING 1000 AMPERE METERS

FIG. 4



ARRANGEMENT OF SHUNTS AND RESISTANCES FOR TESTING 2000 AMPERE METERS

FIG. 5

Fig. 3 shows the arrangement of the resistances for testing both 1000-ampere and 2000-ampere meters, Fig. 4 the connections for testing 1000-ampere meters and Fig. 5 the connections for 2000-ampere meters. Fig. 6 is a reproduction of a

[INGALLS AND COWLES]

FIG. 3

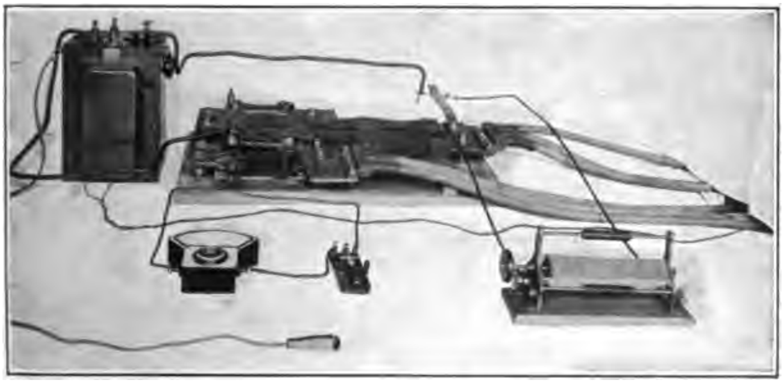


FIG. 6 [INGALLS AND COWLES]

photograph of the entire equipment, except the chest used for transporting the resistances and cables. This chest is approximately 32 by 19 by 14 inches (81 by 48 by 35 cm.).

In using the direct-current rotating standard care should be exercised to guard against the influence of external fields, and since this apparatus is designed for use in places where large currents are involved, precaution should be taken either to take two series of readings, one series to be with both the current and potential leads of the rotating standard reversed, or to change bodily the position of the standard 180 deg. and take a series of readings in both azimuths. In either case the average of the two series should be used.

Following are the results of tests on various 550-volt meters supplying street railways. In some instances the current varied from zero to the full capacity of the service meter during the test.

TEST NO. 1—2000-AMPERE, 550-VOLT TWO-WIRE METER

Position of standard		Revs. of standard	Average	Correct revolutions	Per cent of accuracy of service meter
A	0 deg.	23.42			
		23.52			
		23.29			
		23.46	23.42	24.18	103.2
B	90 deg.	23.41			
		23.37			
		23.51			
		23.52	23.45	24.18	103.1
C	180 deg.	24.20			
		24.11			
		23.96			
		24.02	24.07	24.18	99.5
D	270 deg.	24.17			
		24.39			
		24.17			
		24.13	24.22	24.18	99.8

Average A and C	101.35
Average B and D	101.45
Average A, B, C and D	101.4

TEST NO. 2—600-AMPERE, 550-VOLT TWO-WIRE METER

VERY FLUCTUATING LOAD ON THIS METER.

Position of standard		Revs. of standard	Average	Correct revolutions	Per cent of accuracy of service meter
A	0 deg.	10.81			
		10.92			
		10.96			
		10.79	10.87	11.48	105.6
B	90 deg.	11.45			
		11.39			
		11.47			
		11.39	11.42	11.48	100.6
C	180 deg.	11.79			
		11.69			
		11.84			
		11.76	11.77	11.48	97.6
D	270 deg.	11.31			
		11.23			
		11.20			
		11.29	11.26	11.48	102.0

Average of A and C.................................... 101.60
" " B and D.................................... 101.30
" " A, B, C and D................................ 101.45

TEST NO. 3—2000-AMPERE, 550-VOLT TWO-WIRE METER

Position of standard		Revs. of standard	Average	Correct revolutions	Per cent of accuracy of service meter
A	0 deg.	19.52			
		19.25			
		19.29			
		19.59	19.41	19.36	99.8
B	90 deg.	19.46			
		19.52			
		19.64			
		19.75	19.59	19.36	98.8
C	180 deg.	20.13			
		19.94			
		19.76			
		20.04	19.97	19.36	97.0
D	270 deg.	19.71			
		19.44			
		19.62			
		19.50	19.57	19.36	99.0

Average of A and C.................................... 98.4
" " B and D.................................... 98.9
" " A, B, C, and D................................ 98.65

TEST NO. 4—1200-AMPERE, 550-VOLT TWO-WIRE METER

Position of standard		Revs. of standard	Average	Correct revolutions	Per cent of accuracy of service meter
A	0 deg.	14.71			
		14.60			
		14.74			
		14.62	14.67	14.50	99.0
B	90 deg.	14.51			
		14.63			
		14.62			
		14.65	14.61	14.50	99.2
C	180 deg.	13.88			
		13.74			
		13.74			
		13.73	13.77	14.50	105.2
D	270 deg.	13.82			
		13.94			
		13.80			
		13.85	13.85	14.50	104.6

Average of A and C	102.1
" " B and D	101.9
" " A, B, C, and D	102.0

DISCUSSION ON "ELECTRICAL TRANSMISSION OF ELECTRICAL MEASUREMENTS" (BLISS), "METERING LARGE DIRECT-CURRENT INSTALLATIONS" (MAGALHAES), "MEASUREMENT OF ENERGY WITH INSTRUMENT TRANSFORMERS" (MAXWELL), "WHEATSTONE BRIDGE—ROTATING STANDARD METHOD OF TESTING LARGE CAPACITY WATT-HOUR METERS" (INGALLS AND COWLES), BOSTON, MASS., JUNE 28, 1912.

William J. Mowbray: It is somewhat presumptuous for me to congratulate Mr. Ingalls on this paper, but I will presume to do so, because I think that I can claim being the originator in the United States of the rotative watt-hour test meter. Seven years ago, in 1905, the chairman of this meeting, Mr. Robinson, presented a paper entitled *The Oscillograph and Its Use* at a meeting of the Institute held in New York City, and at that same meeting I had the honor of presenting a paper which disclosed for the first time the method of testing watt-hour meters with a rotative watt-hour test meter having several current and potential windings. The paper was entitled *Maintenance of Meters*, and brought in the rotative test meter. At that time this method of testing service meters was not generally used at all, having just been started in Brooklyn and New York. Boston was then using a standard resistance, a voltmeter and a stop watch. But I see that Boston has now fallen into line, and is not only using the rotative watt-hour test meter, but has added to the method of using it a degree of refinement that is characteristic of Boston. I congratulate Mr. Ingalls on this method, which is very clever and just the thing for testing large meters on fluctuating loads.

F. P. Cox: I have been familiar for some little time with the work that Mr. Ingalls has been doing with this method of testing. I do not feel I could pass the paper without saying it is a good and useful method.

Referring to Mr. Magalhaes's paper, and method 3, it seems to me the object of meters is to get a record of the energy used, and if this is the most accurate, as it certainly is, it is worth the money the extra meters cost.

As to getting a totalizing dial, this is quite a problem. I have done a little work on it in the past, by magnetic contact from different meters, to record the sum of the impulses, but the trouble in that case is that sometimes many impulses come in at once from the different meters and they must all be recorded. To do that, you find it necessary to record on the totaling dial one impulse, and then the others will have to wait and stand there until they get a turn to record; it can be done and has been done, but the device is rather expensive and rather complicated, and if you should add this to the already large expense of the separate meters, I am afraid the man who is paying the bills would object. But the separate meters and adapting the meter to the circuit, is the right way to do it, and if the job is worth doing at all, it is worth doing right.

In regard to the shunt meter, that has possibilities; it also has its troubles. I do not know how Mr. Magalhaes proposes to connect these things so as to do away with the troubles of the division, because if you are using the shunt meter as the total carrying meter, you still have the problem of one large meter against several small meters, and you have additional things to look after in regard to contacts. When you are shunting five or ten amperes, you have the larger losses in the higher capacity meters, because you would have the drop which would come from the low capacity. If these temperature effects and loads come in, while you would get a system which would be more flexible, I doubt very much if it would add to the accuracy of the meter. It has not been overlooked or forgotten, but it has troubles. We cannot say they never will be worked out, but I have not yet seen anything that is entirely satisfactory.

J. R. Craighead: First, with reference to *Electrical Transmission of Electrical Measurements.* There has been a constantly increasing call for various kinds of measurements which are to be recorded at a considerable distance from the place where the actual measurement is made, and it seems to me this paper shows a method of doing this in a very satisfactory way with a certain class of instruments. However, there is an alternative way of doing the same thing, namely, getting the measurement at the point where you want to have it, which consists in designing a special type of current transformer, in which the secondary current shall be reduced, for instance, to 0.5 ampere, instead of 5 amperes. It is perfectly practicable to make a current transformer with 0.5-ampere secondary of practically the same qualities as the 5-ampere secondary.

It is also perfectly practicable to make an instrument employing most of the standard types, of 0.5-ampere capacity, instead of 5 amperes capacity. The load of this instrument on the current transformer is about the same fraction of the capacity of the transformer in one case as in the other. This leaves the same difference, which may be used up in the line drop. If we take an ordinary current transformer, of 5 amperes capacity, we are limited by considerations of load to a small line drop, so that the practicable distance with the usual size of wire is only a few hundred feet if satisfactory accuracy is to be secured. By cutting the secondary down to 0.5 ampere, we multiply the length of the line using the same wire, and consequently the distance to which we can transmit over that wire, by 100, in some cases running to 10, 15, 20, or even 40 miles, the size of wire necessarily increasing with the length of the transmission.

There is one difficulty in connection with this method of building current transformers which ought to be considered, and that is, that the secondary has naturally a very much larger number of turns than the standard current transformers, and in consequence, if the secondary is accidentally open-circuited, the voltage on the secondary will be ten times larger than on the corresponding 5-ampere secondary. This implies rather special care in insulating the secondary to avoid damage.

As far as the potential transformers are concerned, for ordinary purposes, the line drop may be considered as part of the resistance of the instrument, and the ordinary potential transformer will therefore answer in many cases. For extreme cases, a higher voltage secondary may be used.

In regard to the paper on *Measurement of Energy with Instrument Transformers*, I want to say one or two things. One thing, particularly, is in regard to the use of the light-load adjustment for compensation. That has been argued a number of times, and I do not think we can say very much that is new. If we are going to cut down the safety against creeping by calibrating the meter to run fast on low load, we are going to increase the percentage of meters which actually do creep. It does not mean that the meter will necessarily creep because that is done to it, but simply means that out of a large number that are so calibrated, the number of meters that would creep is increased, and the result is that this method should not be used where a large number of meters are to be without examination for long periods. If the meter can be inspected frequently, as is usually the case where high accuracy is desirable, then this method of correction may sometimes be used with good results.

F. V. Magalhaes: I wish to emphasize the value of the apparatus Mr. Ingalls has developed. It is a combination of instruments and apparatus which are commonly used and owned by most of the large operating companies. He obtains an instrument which will properly check the watt-hour meters on fluctuating service loads. Stating the point in another way, he has produced an instrument by using apparatus which is at present developed and in use, and does not involve the design or development of new instruments. It is merely a combination of existing apparatus.

In connection with Mr. Maxwell's paper, the errors in performance of meters used with well-designed current transformers are small. It must be borne in mind also in analyzing these errors with a view to reducing them that with the present knowledge of current transformer design and performance any appreciable reduction in these errors is obtained only at a practically prohibitive increase in the physical dimensions of the transformers.

W. H. Pratt: Mr. Magalhaes's paper brings out a point which I wish to emphasize, and that is, in using current transformers for meters, the best current transformers should be selected. Meters ordinarily are expected to work over a very long range, in fact, I think that the meter has to take care of a longer range of observation, you might say, than almost any other piece of apparatus which is used in ordinary work. There is a vast difference between the good qualities of the current transformers that are available on the market, and by selecting those that have the best characteristics you have almost no trouble. Slight errors in ratio can be taken care of in the calibration of the meter, and likewise the phase angle can be taken care of by an adjustment of the lag angle of the meter, if limiting accuracy is required.

In Mr. Craighead's discussion, I think he undoubtedly has in mind current transformers which have also come under my own observation, which depart so far from ideal accuracy that correction would be unsafe.

L. T. Robinson: I may interpolate a comment here that will perhaps straighten out things. The papers of Mr. Maxwell and Mr. Magalhaes and the comments of Mr. Craighead and Mr. Pratt, are largely considerations of special cases that have come up. You must not read into the papers that all these things apply to all the work which we have to do ordinarily. If you give close attention to what the author says all the way through, it has been plainly brought out that for ordinary service and in general the present conditions are fairly satisfactory.

T. W. Varley: Mr. Ingalls pointed out in the sketch the bridge method of keeping track of the variation of temperature in the meter tested. He says that the drop in each zone is practically 400 millivolts. I would like him to explain how he adjusts these loads.

C. H. Ingalls: The resistances may be measured by a bridge, and from the ratio of the two resistances, the ratio of the current with a balance on the voltmeter, can be readily determined. It is preferable, however, to use two ammeters and then, by adjusting the resistances, get the galvanometer to read zero, and then take the ratio of these currents. Repeated tests have shown that the ratio remains very constant. There is another method. If the two shunts are not electrically connected in a very permanent manner, of course the instrument will get out of calibration. In order to get around that difficulty, if you want to use two ordinary shunts, that are not specially made for the purpose, by using a differential millivoltmeter you can obtain the zero reading.

T. W. Varley: Would it not be better to use a double bridge?

C. H. Ingalls: A differential voltmeter that is suitable for that purpose is on the market, I believe.

T. W. Varley: Would it not be better to use a Thomson double bridge? That is an easy way of using it.

C. H. Ingalls: Yes, but this method was also devised by Prof. Laws in his laboratory, but never used outside commercially.

Albert Ganz: If you have the two ammeters, why do you need to know the resistances of the shunt?

C. H. Ingalls: You do not, in that case. Three ammeters may be used for measuring resistances, or you can use two ammeters.

Alexander Maxwell: I think that reference to my paper will take care of most of the comments made upon it. It is there stated that for all ordinary cases, commercial transformers are quite satisfactory. Further than this, almost all other cases can be solved by lightly loading the transformers. The difficulties referred to generally occur where extra load is imposed upon the transformers, such as additional indicating meters, or relay coils. The manipulation of the meter light-load adjustment is altogether a last resort, which, I suppose, would only be employed very rarely. For all ordinary cases of reasonable loading commercial·transformers are quite satisfactory.

Paul MacGahan: I agree with Mr. Maxwell as to the desirability of using separate transformers for relays and for watt-hour meters. There is a strong tendency on the part of some switchboard builders to connect too many devices to the series transformers so as to economize in cost or space. This practise has been very hard to discourage, as the evil effects were not thoroughly understood by operating companies. It has been the invariable practise of one large company building switchboards to insist on separate series transformers for relays and for wattmeters, and nothing else in series with watt-hour meters when intended to be used for accounting purposes.

An ammeter of low internal drop, and possibly a power factor meter, may be also connected in if the watt-hour meter is merely used for operating purposes, and may also be used in connection with an indicating watt-meter, as the latter does not require the light-load accuracy of the watt-hour meter.

Although large enough series transformers might be built to take care satisfactorily of a watt-hour meter and several other instruments, this would be inadvisable, as two separate smaller transformers would be cheaper. Series transformers with two separate secondary coils on separate cores have been used, one secondary operating the relays and the other the watt-hour meters.

A convenient grouping of instruments on two sets of transformers would be as follows:

One set operating relays, ammeters and power factor meters.
One set operating wattmeters.

Elmer L. Kyle: Independent of the fact that shunted type watt-hour meters may be used in future installations of large capacity meters, there are a comparatively large number of the series type still being built and many are in use at the present time. The testing of the present type is rather awkward and in many cases inaccurate, especially in testing those of extremely large capacity. In the latter case it is practically impossible to test them except by the use of switchboard instruments.

The method devised by the authors of the paper is fundamentally simple in principle, easily manipulated, and the device is conveniently transported, making it possible more readily and more frequently to test and maintain the accuracy of the large capacity meters.

The importance of this class of testing may not be fully appreciated but the increasing demand for large loads makes it quite a matter of importance to electric lighting and power companies.

I might also add that although certain types of shunted meters possess the redeeming feature of testing in service with a comparatively low current, the method outlined by Mr. Ingalls and Mr. Cowles is much more desirable since it possesses many of the ideal features in meter testing.

John Gilmartin: It frequently happens that the diversity factor of the natural component parts of an installation is large enough to permit of a much smaller kilowatt capacity of meters to be installed if the total load is metered at one point than if method No. 3, as described by Mr. Magalhaes, were followed.

The light and full load accuracy of registration will be higher on the main meter or meters than on the sum of the individual meters.

For example, in an installation large enough to come under the heading of this paper, it is unlikely that janitor work, etc., would be performed only on one floor or in one building at the same time.

The usual result would be that instead of the individual meters working at favorable loads, they would each operate at a comparatively small load, and it is probable that if main meters had been selected with proper consideration of the diversity factor they would operate at a more favorable point on the accuracy curve than the individual meters.

The same reasoning holds for large installations having a number of motors, the diversity factor of which is frequently large.

Method No. 3, as pointed out in the paper, is very well adapted to metering separate converters or, as was shown in a recent case that the writer investigated, to the metering of separate generators in a power station.

It is the usual practise to operate generating units up to at least half-load rating, thus giving a very favorable condition for high meter accuracy, while on the other hand, if meters are installed in the station bus they will operate at small loads a considerable part of each twenty-four hours, because the load curve of the meters will follow the station load curve.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

INDUCTION TYPE INDICATING INSTRUMENTS

BY PAUL MAC GAHAN

The modern switchboard, controlling as it does large amounts of power, and often situated where space is at a premium, demands a different type of switchboard instrument from that to be found on older switchboards. Moreover, modern generating equipments, generally turbine-driven, have resulted in a readjustment of the comparative importance of the different kinds of electrical errors to which indicating meters are subject. For example, the frequency of a modern system does not usually vary more than one or two cycles from the normal speed, and therefore frequency characteristics are less important, whereas formerly this was one of the great sources of error. Again, due to operation with larger currents or higher potentials, the external magnetic or electrostatic field effects are greatly increased.

The tendency of the designer should now be toward principles of operation or construction that are not greatly influenced by external fields instead of those free from frequency errors. In addition to this, the questions of compactness, readability, aperiodicity, ruggedness, and simplicity are equal in importance to accuracy. Ordinarily the operator does not hesitate to repair or readjust a piece of electrical machinery, but due to the fact that early meters comprised " feather-weight " movements, delicate wires, pointers, and connections, the operators have developed a superstitious dread of breaking " seals " and making readjustments. The modern meters should be sufficiently rugged and simple to be readily handled by an operating company's " meter man."

VARIOUS PRINCIPLES OF OPERATION

For alternating currents the three principles of operation found in the best instruments today are as follows:

Moving Iron Electromagnetic Type. Good initial accuracy of calibration. Approximate freedom from frequency and temperature errors. Ratio of torque to weight—low. Some makes too delicate. Easy to repair. Subject to both alternating-current and direct-current external fields unless heavily shielded. Short scale length.

Moving Coil Electrodynamometer Type. Highest in initial accuracy of calibration and freedom from errors due to frequency and temperature. Ratio of torque to weight—low. Delicate. Difficult to repair. Subject to external fields of same frequency unless heavily shielded by internal laminated iron shields. Short scale length.

Induction Type. Good initial and continued accuracy. Ratio of torque to weight—very high. Rugged and simple movements. Easy to repair. Extremely long scales and high readability. Frequency errors greater than in moving coil or moving iron types. External field errors due only to fields of same frequency, in certain directions, and are slight.

Other principles have been from time to time employed, but the race has now narrowed down to the above three types.

The fundamental or distinctive advantage of induction instruments for switchboard use is their unequalled scale length. It should be borne in mind that the moving coil or moving iron meters, as now manufactured, evidently represent very nearly the highest state of development to which these principles can be brought, whereas in the case of the newer induction principle, much can be expected in the future in the way of greater refinements. It is the writer's opinion that the induction principle will eventually supersede the other types for switchboard work, for the same reasons that this principle has superseded all others in the case of a-c. watt-hour meters.

ACCURACY

Induction type instruments are especially free from external field influences. Nor are they as deficient in frequency error characteristics as is often assumed. Induction type ammeters and voltmeters having an error of less than 1/20 per cent per cycle are now obtainable, so the error due to this cause in a modern plant would not be noticeable.

Moving iron and moving coil instruments, although practically free from frequency and temperature errors when properly designed, are extremely subject to external field effects, and the best practise is to insert heavy shields of iron within the thin iron cases to overcome this. Without such shields the thin iron cases quickly get saturated by an external field, after which the further shielding effect ceases. Their light torque also causes them to be very susceptible to external electrostatic effects which cause the pointer to be attracted to the glass or case, introducing troublesome errors. It should be noted that moving coil meters have an advantage over moving iron types in being influenced only by external magnetic fields of the same frequency; whereas moving iron meters are affected by both alternating and direct stray fields.

Temperature errors in instruments are important, as variations in the temperature of switchboards may be considerable. Alternating-current instruments of either induction, moving coil, or moving iron construction are readily obtainable whose temperature errors are within satisfactory limits. Self-heating errors due to heat liberated in the meters themselves should be carefully avoided, and are not found in properly designed meters.

The mechanical sources of error are probably of greater importance than purely electrical ones in switchboard instruments, as the causes which produce them also reduce the life of the device and greatly increase the errors with usage and time. Instruments having the highest ratio of torque to weight of movement will have the greatest accuracy and longest life if equivalent in other respects, and if the movement is not sufficiently heavy to damage the jewels. Experience and tests have shown that 15 grams maximum is a safe limit for horizontal shafts in " V " sapphire jewels, and that a ratio of torque to weight of 0.15 is a satisfactory minimum, when torque is expressed in centimeter-grams, and weight in grams, in the case of switchboard meters. The disadvantages of very light movements, even if the torque ratio be high, is that the slightest mechanical strain due to overload, or even precipitation of moisture on the pointer, will throw the movement out of balance; thus such meters must necessarily be provided with external means for zero adjustment. The exceedingly delicate threaded rods, screws, and other parts visible only under a glass, render such meters difficult to repair outside the factory.

COMPACTNESS

A form of construction considered desirable for these induction meters consists of a round pattern 7-in. diameter case with a glass front. The scale length is 14½ in., subtending an arc of 300 deg. This gives the maximum possible compactness and readability. A compact arrangement of large switchboard equipment is considered important on account of the cost of space (particularly in large cities), reduced attendance, location in operating galleries, reduced cost of marble or busbars, and visibility of all instruments from point of operation. These features are of such importance that it is not unusual to find that the meters have been made to suffer in consequence by a reduction in scale length, as in previous types of 7-in. meters, or by the use of rectangular cases with curved glass, as in vertical or horizontal edgewise meters.

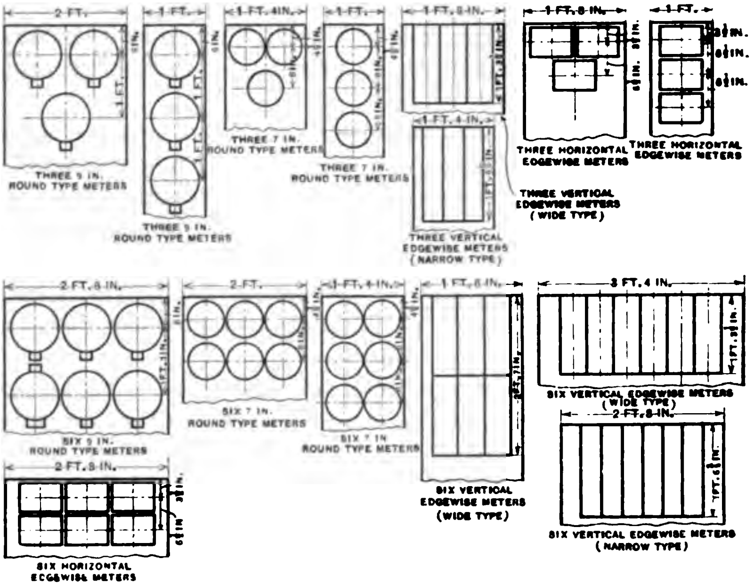


FIG. 1—DIAGRAM SHOWING COMPARATIVE AREAS REQUIRED BY VARIOUS TYPES OF METERS ON SWITCHBOARD PANELS.

The principal types of switchboard indicating meters are given in Table I, the area occupied on the marble by the circumscribing rectangle being tabulated compared to the scale length. To facilitate comparisons a schematic layout of various panels is shown in Fig. 1, using 7-in. and 9-in. round pattern, and edgewise meters. The limitations of round type 7 in. meters have heretofore been short scale length, and the fact that complete lines including wattmeters, frequency, power factor meters, and synchroscopes, as well as d-c. and a-c. ammeters and voltmeters, have not been available. The induction principle applied to the 7-in. ammeter, voltmeter and wattmeter has apparently placed this 7-in. construction on an entirely new basis, the scale length being equal or greater than in any previously designed 9-in. meter.

TABLE I

COMPARISON OF SCALE LENGTHS AND SURFACE COVERED

Type of meter	Area marble	Scale length
Round pattern 7½ in. diameter	58 sq. in.	5 to 14½ in. according to make
" " 9½ in. " "*	110 " "	6½ to 14½ in. " " "
Horizontal edgewise 6 x 8½ in.	51 " "	6 in.
Vertical " 4 x 18 in.	54 " "	12 in.
" " 4 x 18 in.	72 " "	12 in.
" " 5½ x 15½ in.	82 " "	12 in.

*Front connected, space including that taken by terminals.

TABLE II

COMPARISON OF AREA ON PANEL REQUIRED PER INCH OF SCALE

Type of meter •	Square inch area of panel required per inch length of scale
7½ in. round pattern (average)	11
7½ " " " (induction type)	3.9
9½ " " " " "	7.5
9½ " " " (average)	15
6 x 8½ in. horizontal edgewise	8.8
4 x 18 in. vertical "	6
5½ x 15½ in. vertical "	6.8
Illuminated dial (average)	16

READABILITY

Under this heading we may consider scale length and distribution, form of scale, reflections from glass and illumination. In a true comparison it should be noted that if the long scale takes a larger case the distance from the operator is increased by a less compact arrangement of panels. A basis for comparison is the ratio of area of circumscribing rectangle to the scale length in inches. Table II shows such a comparison.

In voltmeters, readability at the normal point should be high; in ammeters, readability should be a maximum at the high points of the scale, as overloads should be indicated with the greatest accuracy. Table III gives a comparison of the inches per volt, on the scale, at the 115-volt point, in various types of 150-volt scale voltmeters.

A consideration of importance as affecting readability is that of the proper scale and pointer illumination. The tendency is now to limit the so-called " illuminated dial " meters to switchboards of a highly decorative character, and to heavy capacity d-c. panels whose size is determined by the other apparatus mounted on them. Moreover, rear illumination is not of much value in an operating room in which the general illumination has been worked out upon proper lines. Full glass front plates instead of metal covers with curved slots in them for showing the scales, greatly improve the readability by thoroughly illuminating the dial and by allowing the whole length of the pointer to be seen instead of showing only an " index " through a slot. By proper arrangement of the illumination, troublesome reflections from flat glass fronts can be entirely eliminated and readings can be taken accurately from any angle, a matter of much greater difficulty in the case of the curved glass used in edgewise meters.

TABLE III

COMPARISON OF VOLTMETER POINTER DEFLECTIONS

Full scale capacity	Size	Type	Point	Inches per volt
150-volt	7½ in.	Round pattern (induction type) a-c.	115-volt	0.16
" "	7½ in.	" " (average) a-c.	" "	0.035
" "	9½ in.	" " (induction type) a-c.	" "	0.16
" "	9½ in.	" " (average) a-c.	" "	0.05
" "	9½ in.	" " (D'Arsonval type) d-c.	" "	0.052
" "	6 x 8½ in.	Horizontal edgewise a-c.	" "	0.023
" "	4 x 18 in.	Vertical edgewise a-c.	" "	0.13

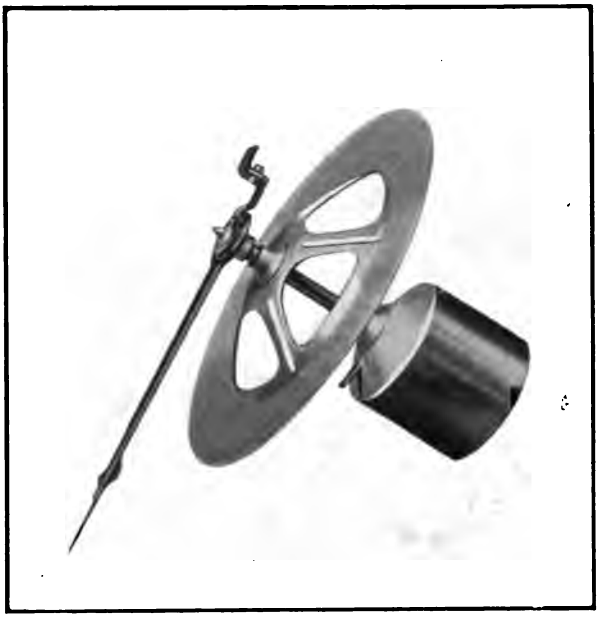
Fig. 2 shows a novel arrangement of a black dial with white figures and pointer which in certain instances will be found advantageous. A white mark on a black ground is much easier to see than a black mark on white. A white object causes a certain amount of " halation " in the eye or through a photographic lens, causing the mark to look larger. This halation thus tends to blur black lines on white dials. The eye automatically tends to adjust itself to this, causing a certain amount of strain.

[MAC GAHAN]

FIG. 2—BLACK DIAL METER.

[MAC GAHAN]

FIG. 3—BLACK AND WHITE DIALS COMPARED.



[MAC GAHAN]

FIG. 4—MOVEMENT OF INDUCTION TYPE AMMETER.

MAC GAHAN

FIG 5—ELECTROMAGNET ASSEMBLED ON BASE.

As a lens cannot adjust itself to such varying conditions, a photograph of a white dial alongside of a black dial meter under identical conditions of illumination will show the real difference in readability. The photograph reproduced in Fig. 3 was taken with every possible precaution to insure an exact comparison, and the result is in favor of the black meter. Meters thus arranged with black dials have been used very successfully on electric locomotives operating often at night or in tunnels, where the glare from a white dial would seriously interfere with the driver's view of the track ahead or the signals.

THEORY AND PERFORMANCE OF INDUCTION INSTRUMENTS

The ammeters, voltmeters and wattmeters with which the writer is most familiar consist of a movement comprising an aluminum drum rotating in the air gap of an electromagnet, through the coils of which pass the currents to be measured, in the manner generally known as the "induction type" construction. Such instruments may be said to differ from the moving coil electromagnetic instruments in that the currents in the movable element which react upon the field of the stationary element, thus producing torque, are induced in the moving element by the transformer action of the primary coil and core, instead of being conducted into it by means of flexible spring-conductors.

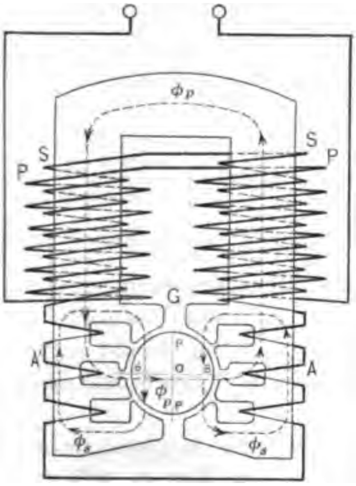


FIG. 6—DIAGRAM OF AMMETER ELECTROMAGNET.

In analyzing the action of this instrument it is clearer to consider it in the light of an ordinary moving coil electromagnetic instrument than as an induction motor, although it is in reality a special form of induction motor.

Thus in Fig. 6 the laminated iron circuit of an ammeter is shown, with its annular air gap in which the aluminum drum is free to rotate. *P* represents a primary winding through which passes the current to be measured. $S - S$ is a secondary winding short-circuited on itself. The dotted lines marked ϕ represent the various magnetic fluxes produced by currents in the coils.

The windings P and S are the same in relation to each other as the primary and secondary windings of a current transformer, and their currents are similarly related. Thus the functioning of this type of induction ammeter can be said to be due to a combination of the actions in a current transformer and an induction motor. In this respect it differs from all previous types of induction meters, the result being an exceptional freedom from frequency and temperature errors, as explained further.

Fig. 4 shows the movement of such a meter, and Fig. 5 shows the electromagnet assembled on the base.

Considering the induction type ammeter from the moving coil meter standpoint, we have,

$$\text{Torque} = \phi\, I \cos \gamma\, k \qquad (1)$$

in which

ϕ = flux produced by stationary coil, passing through the moving coil.

I = current, moving coil

γ = angle of lag.

k = constant.

In the induction meter, I in drum I_D is equal to $\frac{\text{voltage in drum}}{\text{impedance of drum}}$ or proportional to $\frac{\phi N}{Z_D}$; (N = frequency. Z_D = impedance of drum.) If ϕ were oscillatory, such as due to single-phase currents in primary coil P only, the secondary currents induced in the drum would be in the plane $O\,P$ only, and thus would not be in a position to cause rotary torque in connection with the primary flux ϕ_p.

If, however, an additional flux, differing in phase, is introduced by means of additional coils S, this flux ϕ_s will in the instrument as constructed be in a direction at right angles to ϕ_p, and will thus cause torque by reacting upon the secondary currents in the drum which flow in the direction $O\,P$. At the same time the flux ϕ_s will cause secondary currents in the drum in the direction $O\,S$, which are in a position to react upon ϕ_p to produce torque. Any secondary currents induced in the drum in intermediate directions may be resolved into components in directions $O\,P$ or $O\,S$ and thus are represented by currents in these directions only. It is understood that the fluxes ϕ_p and ϕ_s do not actually exist separately, but act in combination to produce a resultant flux ϕ_r which rotates with a frequency equal to that of the circuit. They may be treated separately for purposes of analysis, however. Thus the law of torque of such an instrument can be written:

$$\begin{aligned} \text{Torque} &= \phi_p\, I_s \cos\alpha + \phi_s I_p \cos\beta \qquad (2)\\ \alpha &= \text{angle between } \phi_p \text{ and } I_s\\ \beta &= \text{`` \quad ``} \quad \phi_s \text{ and } I_p \end{aligned}$$

It is assumed throughout this discussion that the values I_p, I_s, I', I'', etc., for currents are stated in terms of equal turns, or as "ampere-turns."

In order to produce currents in the coils S, differing in phase from those in the primary coils P, and thus produce the fluxes ϕ_s and ϕ_p, the "transformer" arrangement of coils is used in the ammeter. The coils P are wound directly over secondary coils, which are in turn short-circuited through the distributed pole-piece coils S. The relations between the currents and fluxes are the same as those in current transformers, shown graphically in Fig. 7, where I' = current in primary, I'' = secondary current, and I_m = magnetizing current.

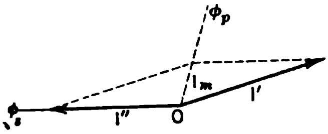


FIG. 7—DIAGRAM OF TRANSFORMER RELATIONS.

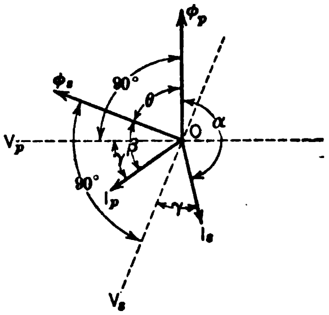


FIG. 8—VECTOR DIAGRAM OF METER RELATIONS.

The flux due to the magnetizing component of the primary coil is in the direction $O\ \phi_p$. The flux produced by the current in the secondary coils is in the direction $O\ \phi_s$, in phase with the current I'' in the secondary and pole-piece windings. It is seen that the phase angle between the fluxes ϕ_s and ϕ_p is, roughly speaking, 90 deg., thus producing a rotation of the moving element as previously explained.

The ϕ_p, as in a current transformer, is inversely proportional to the frequency, but ϕ_s is independent of the frequency, being only proportional to I''.

In the vector diagram Fig. 8, let $O\phi_p$ = the primary and $O\phi_s$ the secondary flux. At right angles to each are the voltages $O\ V_p$ and $O\ V_s$ induced by these fluxes in the moving drum. Lagging behind these voltages are components of the current in the drum, $O I_p$, due to ϕ_p, and $O I_s$ due to ϕ_s. (See equation 2).

Let θ = angle between ϕ_p and ϕ_s.

γ = lag of currents in drum behind V_p and V_s.

Then we have $\alpha = \gamma + \theta + 90$ deg.

$\beta = \gamma - \theta + 90$ deg.

Whence, $\cos \alpha = \sin(\gamma + \theta)$ and $\cos \beta = \sin(\gamma - \theta)$

Substituting in (2),

Torque $= \phi_p I_s \sin(\gamma + \theta) + \phi_s I_p \sin(\gamma - \theta)$ (3)

The currents in the drum being proportional to the voltage induced in it divided by the impedance of the drum circuit, we have

$$I_s = \frac{N \phi_s K'}{Z_D K''} \qquad (4)$$

$$I_p = \frac{N \phi_p K'''}{Z_D K''} \qquad (5)$$

in which K', K'', K''', are constants which will hereafter be omitted for clearness.

As $\phi_p = \frac{I'}{N}$ and $\phi_s = I'$, I' being the current in the primary coil, we obtain by substitution

$$I_s = \frac{N I'}{Z_D} \qquad (6)$$

$$I_p = \frac{I'}{Z_D} \qquad (7)$$

Substituting in (3)

$$\text{Torque} = \frac{(I')^2}{Z_D} [\sin(\gamma + \theta) + \sin(\gamma - \theta)]; \text{ whence,}$$

$$\text{Torque} = \frac{(I')^2}{Z_D} (\cos \gamma \sin \theta) \qquad (8)$$

It is evident that Z_D, γ and θ are functions varying with the frequency and therefore in order to make the meter independent of frequency we must make $\cos \gamma \sin \theta = Z_D$; that is, the function $\cos \gamma \sin \theta$ must vary as the impedance of the drum.

This condition for independence from frequency variations can in reality be only approximated. The actual design is necessarily the result of extended experimentation and laboratory work, combined with calculation, so as to secure the greatest possible range over which the meter will be independent of frequency. The performance curves on the ammeters in question show a maximum difference in readings for any two frequencies between 25 and 60 cycles of ½ per cent. (See Fig. 9).

In the case of the voltmeter, the primary coil is wound with fine instead of coarse wire, and an external series non-inductive resistor is used, wound with wire having a zero temperature coefficient.

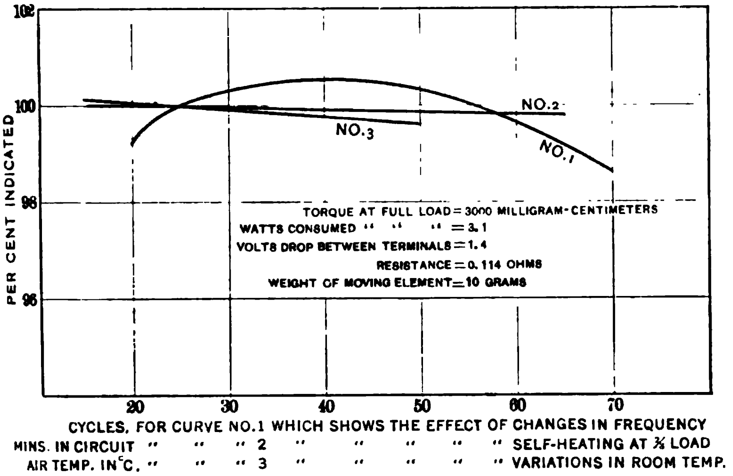


FIG. 9—PERFORMANCE CURVES, AMMETER.

The proportion of series ohmic resistance to the total impedance is made very high and the current in the primary coils of the voltmeter is almost independent of the frequency, thus approximating the results found in the ammeter. (See Fig. 10.)

In the above discussion, only the effect of the variation of frequency upon the torque was covered. In addition an error may be introduced by the varying temperature, changing the resistance of the drum and thus the currents I_p and I_s induced in the drum (see equation 3). In order to correct for this variation, the secondary coil circuit is arranged to have a temperature coefficient of resistance such as exactly to cancel the effect of increased resistance of the drum. To do this advantage is again taken of the effects taking place in current transformers.

If in a current transformer the primary current be kept constant, the secondary current will remain approximately constant for a considerable variation in secondary resistance. Thus any increase in secondary resistance causes a proportional increase of the flux in the core.

In the particular induction ammeter construction described, the secondary circuit is wound partly with copper and partly with wire of low temperature coefficient, the resulting temperature coefficient of the circuit being such as to increase the fluxes in the iron when the temperature of the aluminum drum rises.

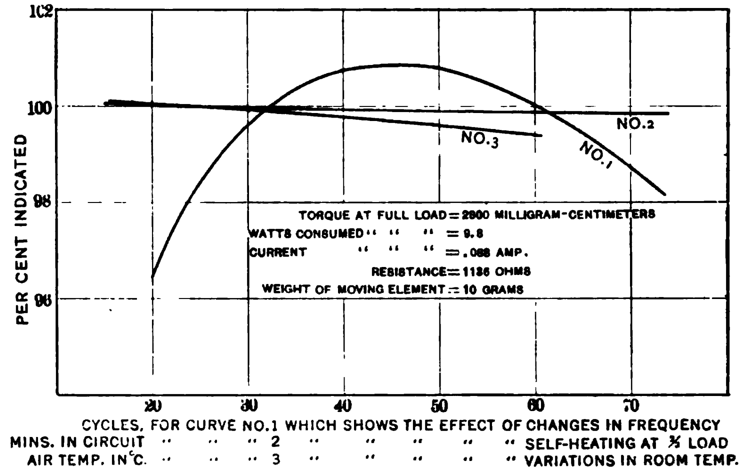


FIG. 10—PERFORMANCE CURVES, VOLTMETER.

By a proper proportioning of temperature coefficient of the secondary winding the temperature compensation is effected with great exactness.

The equations (4) and (5) show the effect of a variation of temperature, and consequently Z_D, upon the induced currents in the drum.

From equation (3) by substituting (4) and (5) and omitting constants we have

$$\text{Torque} = \frac{\phi_p N \phi_s}{Z_D} \sin(\gamma + \theta) + \frac{\phi_s N \phi_p}{Z_D} \sin(\gamma - \theta)$$

$$= \frac{N \phi_p \phi_s}{Z_D} (\cos\gamma \sin\theta)$$

From this we see that the condition for zero temperature error of meter is that

$$\phi_p \, \phi_s = Z_D \text{ (considering the frequency as constant).}$$

As ϕ_s is virtually independent of the resistance and thus of temperature, we may for simplicity write this condition,

$$\phi_p = Z_D$$

At a fixed current, ϕ_p is a function only of the impedance of the secondary coil circuit. From this it is evident that the temperature coefficient of the secondary winding must be the same as that of the drum, in order to make the temperature error of the meter zero.

In actual practise, there are a number of factors tending to complicate the above relations, such as the temperature variations of the iron and of the control spring, etc., so that the proper proportions of copper wire to resistance wire in the secondary circuit can best be determined experimentally. The actual temperature errors are shown in Figs. 9 and 10.

It will be noted that the results as to temperature coefficient and as to frequency errors compare very favorably with those in meters operating on the moving iron or moving coil principles.

A similar arrangement for temperature and frequency compensation has been worked out in the wattmeter.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

COMPENSATING WATTMETERS

BY A. L. ELLIS

In these days of large units and stupendous engineering undertakings one is apt to overlook the problems involved in assigning to little things an accurate valuation.

The output of a very large generator can be determined within one per cent by means of instruments easily obtainable, if not already at hand; yet assigning a value to the energy delivered to a small metal filament lamp or the potential circuit of an induction meter presents some difficulties not readily overcome. This is chiefly due to the low watt consumption which gives a very small deflection on the scale of wattmeters designed for other than laboratory use.

There are a number of cases where a suitable indicating wattmeter is greatly needed, as for instance, in measuring the core loss of small transformers, bell-ringing transformers, compensators for metal filament lamps, small fan motors, small three-phase motors running light, shunt losses in induction meters, etc. It is generally desirable to make such measurements when a given e.m.f. is applied to the terminals of the devices. As low-capacity wattmeters are produced by increased turns in the coil in series with the load it is also desirable to connect the voltmeter and the " potential terminals " of the wattmeter across the load itself, in order to avoid the phase displacement and $I R$ drop which occurs in the wattmeter current coils.

This arrangement has the disadvantage that the potential circuit losses of both the voltmeter and wattmeter are then included in the watts indicated by the latter instrument, thus making it necessary to apply corrections to the readings. It frequently happens that the instrument losses are many times greater than the loss to be determined, hence the result obtained is the difference between two nearly equal quantities. This together with small scale deflection makes accurate determinations practically impossible.

An instrument for this work should possess the following characteristics distinguishing it from the ordinary low reading wattmeter.

1. It should be so designed that its errors can be readily computed for all conditions of load, power factor of load, scale position, etc., and readings corrected for these errors.
2. Its indications should be compensated for its own losses.
3. Its indication should be compensated for loss in the voltmeter or other instruments which may be connected across the terminals of the device being measured.
4. It should have a large current capacity in terms of its full scale watt value, as a great many of the small energy consumers operate at low power factors.
5. It should possess high torque in order that its life of unimpaired accuracy may not be shortened.
6. Its moving system should be damped.
7. It should be shielded to protect it from stray magnetic and electrostatic fields.

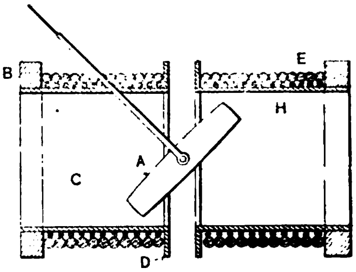


FIG. 1

Fig. 1 shows diagrammatically the compensated wattmeter as commonly constructed.

The moving coil A is pivoted between two similar spools upon which are wound the series or current coil E and the compensating coil H.

The spool comprises the brass supporting casting B, into which is soldered a brass tubing C, having a flange D to form a channel for winding. The spool is split radially by one saw-cut to reduce error due to eddy currents.

The turns of the series coil E should be concentrated about the moving coil in the most effective position, the available space should be filled with copper, and as little insulation used as will insure freedom from short circuits. Some of the available space must be given up to the compensating coil; hence it is usually composed of fine wire, 0.005 to 0.010 in. (0.125 to 0.254 mm.).

In Fig. 1 the compensating coil *H* has approximately the same number of turns as series coil *E* and is wound beneath because, being fine wire, it is best supported when wound directly upon the metal spool.

Sometimes the compensating coil is wound upon the series coil either directly or on a separate support. In either case, the adjustment of the compensating coil is obtained by adding or subtracting turns, until no deflection is obtained when the current for the moving coil is taken through the series and compensating coils connected in series and opposing.

Since the coils *E* and *H* have not the same radius they will not affect the moving coil equally for all scale positions; consequently the compensation can be made exact for one scale position only. This is also true for more than one layer and the error becomes more pronounced as the layers increase, or if the compensating circuit is wound outside of the series coil, either directly or as a separate coil.

When constructed as in Fig. 1, an average in equality of 4.5 per cent and a maximum of 6 per cent has been observed for the different scale positions.

True compensation for all scale positions can only be obtained by using a concentric cable when winding the series coil, the wire of the compensating coil forming the core upon which the strands of the series coil cable are laid up. Such an instrument possessing a 150-watt scale has been made.

There are, however, structural difficulties which preclude the general use of this method, namely: (1) the problem of bringing out the compensating core and securing same so that it will not break off at the point where it enters the finished coil; (2) the difficulty of securing sufficiently high insulation between core and cable to permit the use of the instrument upon 150-volt circuits; (3) the fact that, because where small conductors are concerned cable construction greatly reduces the amount of copper that can be wound in a given space because this is still further reduced by the compensating core, the current is so limited that the instrument is suitable for measurements around 100 per cent power factor only.

Very good results have been obtained by winding the series coil in several layers and at the same time winding one or more fine compensating wires so distributed that their respective magnetic effects in relation to the moving coil are substantially equal.

Fig. 2 gives the departure from the compensation for various scale positions. The curves are plotted from observations, using a wattmeter like that in Fig. 1, and one having specially wound coils.

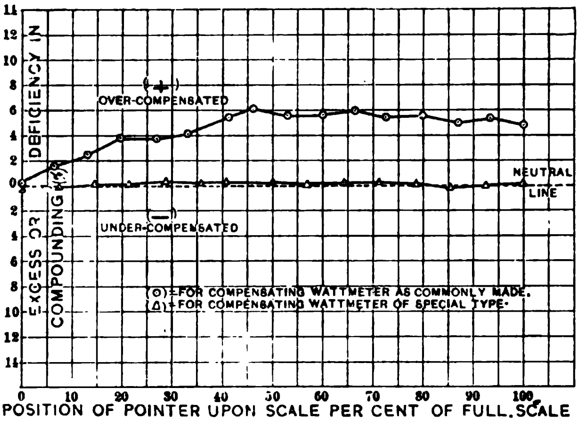


FIG. 2—CURVES SHOWING COMPOUNDING BETWEEN CURRENT AND COMPENSATING WINDINGS

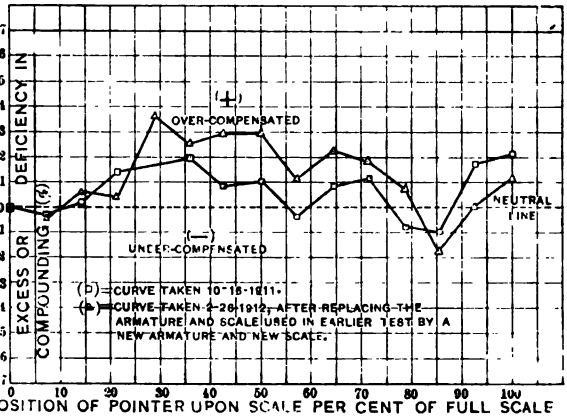


FIG. 3—COMPOUNDING BETWEEN CURRENT COILS AND COMPENSATING WINDING IN WATTMETER OF SPECIAL TYPE.

Curves drawn to twenty times the scale of those in Fig. 2.

Fig. 3 is interesting, as it shows the accuracy to which the actual compensation was observed. The curves are for the specially wound wattmeter of Fig. 2 and are plotted to a scale twenty times larger. The second set of observations was taken four months later than the first, during which time the moving coil had been replaced by a new one and a new scale marked for it. The greatest difference between observed points on the two curves does not exceed 0.2 per cent of the compensation, showing that between 0 and 25 per cent of full scale the compensation is correct within 0.2 per cent and, excepting one observed point, within 0.3 per cent for the remainder of the scale.

Equally good results can be obtained with a second fine wire wound in the series coil, which may be used to feed a voltmeter or other device and automatically subtract from the wattmeter indication the energy so delivered. The connections in this case are shown in Fig. 4, which is self-explanatory.

Table I gives the percentage difference in the watts observed when measuring a given load first " direct " and then compensating; the number of watts obtained when used direct is taken as standard. This shows much better compensation in the case of the special type, under all conditions.

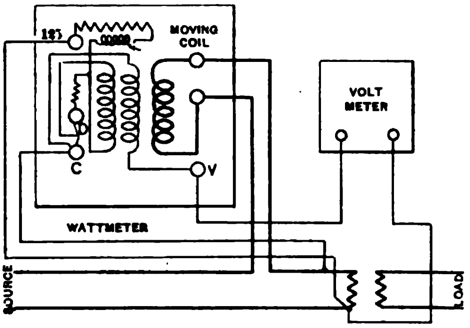


FIG. 4

The " computed variation " at the bottom of the table is the difference in per cent one would expect to observe, based upon the potential circuit losses and the departure from exact compensation, neglecting the effect of mutual induction.

While the wattmeter can be closely compensated for the voltmeter losses, the voltmeter indications must be corrected for the added ohmic resistance and the disturbance due to mutual inductance between series and compensating coils; the resultant self-inductance of these coils is equal to zero.

Fig. 5 gives the e.m.f. due to mutual induction at 60 cycles for two capacities of wattmeters, showing how this e.m.f. varies with the current taken by the load.

Fig. 6 gives the error in the indication of the voltmeter in volts at 60 cycles for all load power factors, when the particular wattmeter considered is loaded with its maximum rated current (2.25 amperes), and operated upon circuits of 100 volts or over with either lagging or leading current. It is to be noted that the error is roughly constant for all low power factors up to 50 per cent power factor, the total variation amounting to 0.2 volt. Beyond 80 per cent power factor the error falls rapidly to zero. If the ratio $\frac{\text{mutual e.m.f.}}{\text{line e.m.f.}}$ is less than 2 per cent, the indication expressed in volts is approximately equal to the mutual e.m.f. × sin θ, where θ is the phase angle of the load. The effect

TABLE I.—TEST OF COMPENSATING WATTMETERS

THE OBSERVED VARIATION IN CALIBRATION WHEN SHIFTING FROM DIRECT TO COMPENSATING

(Variation given in terms of the " direct " calibration taken as standard.)

Watts read on test instrument	On unity power factor			On power factor = 0.1		
	Wattmeter No. 1 common type (Per cent)	Wattmeter No. 2 (Special type)		Wattmeter No. 1 common type (Per cent)	Wattmeter No. 2 (Special type)	
		Alone (Per cent)	With voltmeter (Per cent)		Alone (Per cent)	With voltmeter (Per cent)
60 Cycles per Second; Current Lagging						
25.0	—1.25	—0.16	—0.27	—0.88	+0.15	+0.02
20.0	—0.71	—0.07	—0.17	—0.87	+0.11	—0.11
15.0	—1.12	—0.09	—0.30	—0.95	+0.05	+0.01
10.0	—0.90	—0.25	—0.26	—0.75	+0.16	+0.18
125 Cycles per Second; Current Lagging						
25.0	—1.03	—0.07	+0.07	—0.30	—0.07	—0.19
20.0	—0.73	+0.03	—0.05	—0.39	+0.09	+0.15
15.0	—1.01	—0.19	—0.34	—0.70	+0.49	+0.28
10.0	—0.50	—0.06	—0.06	—1.18	+0.41	+0.26
125 Cycles per Second; Current Leading						
25.0	—0.66	—0.14	—0.22	—0.56	+0.29	+0.33
20.0	—0.64	—0.08	—0.31	—0.48	—0.20	—0.17
15.0	—1.31	—0.46	—0.41	—1.05	—0.10	—0.21
10.0	—1.13	—0.12	—0.12	—0.89	—0.11	—0.16
Computed Variation or Error (Based upon potential losses and per cents on Fig. 2.)						
25.0	—0.59	—0.07				
20.0	—0.70	—0.10				
15.0	—0.68	—0.02				
10.0	—0.83	—0.03				

Note: The theoretically perfect wattmeter should show no variation, neglecting mutual induction.

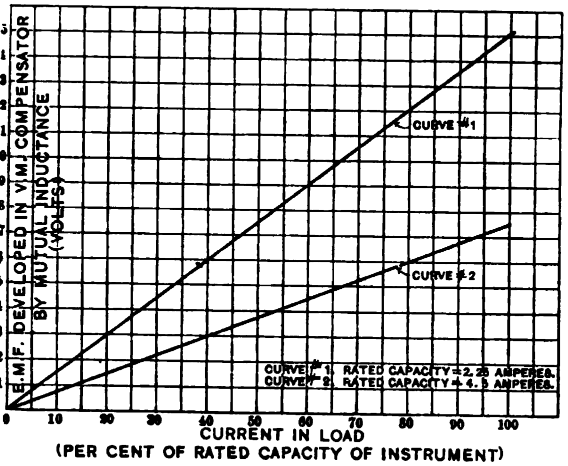


FIG. 5—CURVES GIVING THE E. M. F. INDUCED IN VOLTMETER COMPENSATOR BY MUTUAL INDUCTANCE.

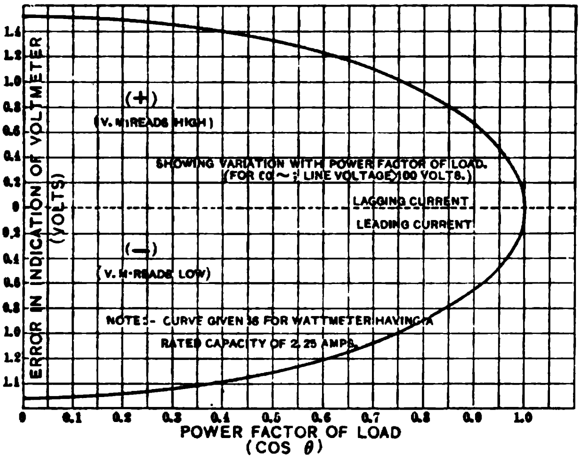


FIG. 6—CALCULATED CURVE, GIVING THE ERROR IN VOLTAGE INDICATED BY VOLTMETER WHEN USED WITH VOLTMETER COMPENSATOR.

With full load current upon the wattmeter.

of added resistance on the voltmeter indication is easily computed to any accuracy required.

The mutual inductance due to the compensating coil causes no appreciable error in the wattmeter at any load or any power factor. The reason may perhaps be better understood by referring to the vector diagram shown in Fig. 7, which, while not completely representing all that takes place in the operation of the wattmeter, shows the principal reason why the indication is not affected. In this diagram

I_T = phase of true load current.

E_m = phase of the e.m.f. induced by mutual inductance which leads I_T by 90 deg. in time phase (considering that compensating winding is reversed).

E_T = phase of true load potential.

θ = true angle between phases of I_T and E_T.

E_i = the total effective volts impressed upon the potential circuit = resultant of E_T and E_m.

Read E' for lagging and E'' for leading current.

It will be seen at a glance that, since a line can be drawn perpendicular to I_T and common to the vectors of the true load and the resultant instrument potentials, and since the distance of this line from the origin along I_T represents that component of the potentials in phase with I_T, or in other words determines the watts, whatever the value assigned E_m, the wattmeter indication will not be affected for any given relation between E_T, I_T and θ.

This is not strictly true when all factors are considered. The diagram considers only the e.m.fs. due to mutual induction, and neglects the effect of the moving coil, as also the current flow into the load and into the source, due to E_m. These disturbances are very slight; their combined effects do not produce an observed error. This is fortunate, as it would be difficult to correct for the current flow into the load and source, because, while the constants of the load can be measured, the constants for the source would be difficult to determine and are ever changing.

The common type of wattmeter designed for use on voltages around 110 has a maximum capacity of 150 watts; the ampere capacity is limited to 1.5, in some cases as high as 2 amperes. An instrument of this type, upon low power factors, does not produce a deflection such that the distance of the pointer from zero can be determined very accurately. The capacity of 150 volts is of little value, since the devices to be measured have been designed to operate upon commercial circuits; hence the voltage most frequently used is 110, with probable maximum of 120 volts. On this basis the full scale deflection would be obtained at 62 per cent power factor.

The sensibility of the instrument and its field of usefulness can be enhanced by so proportioning the potential circuit that it will be limited to potentials of 125 volts or less. The series or current coil should be rated as high as possible and the activity of the moving coil increased by increasing the ratio of the inductance to the resistance.

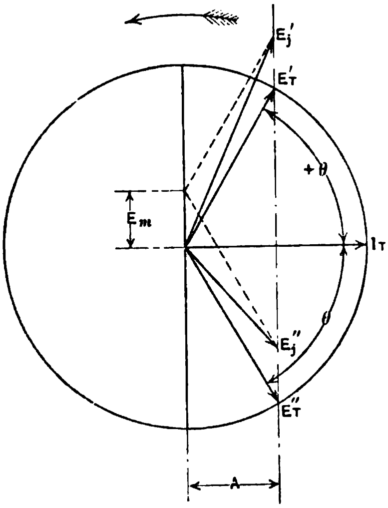


FIG. 7

The special wattmeter previously and subsequently referred to has an ampere capacity of 2.25 amperes, a potential limit of 125 volts and a full scale of 70 watts. On the basis of 120 volts the full scale deflection would be obtained at 26 per cent power factor as compared with 62 per cent power factor for the common type. Deflections around ⅓ scale can be obtained at power factors below 10 per cent within the rated capacity. If left continuously in circuit at rated load a small correction will be necessary, due to the heating effect, but no noticeable disturbance is produced if left in circuit for five minutes at a time with short intervals of rest.

In the design of an instrument, metal affords the most certain readily obtainable and eminently satisfactory mechanical means of definitely locating the various vital parts with respect to one another; yet, when utilized as found in the common type of wattmeter (illustrated in Fig. 1), it becomes a serious source of error due to eddy currents.

The error is greatest at low power factor, because the eddy currents are then nearly in phase with the current through the moving coil, the deflection of the instrument is small and the current producing eddy currents is large.

The magnitude of the error varies with the frequency, power factor, amperes of load, voltage across instrument terminals, and position of pointer on scale, making it practically impossible to correct readings for errors of this nature. The effect of this error is to cause the indications of the instrument to be too small or too large when the load current lags behind or leads the impressed e.m.f.

A comparatively large amount of metal can be used to secure mechanical stability and be so placed with respect to the stationary and moving coils that practically no error results due to eddy currents, even when the sensibility is greatly increased as in the case of the " special " wattmeter.

The " special " wattmeter, besides having robust metal supporting frames, was equipped with magnetically damped moving system and massive iron magnetic shields. Table II gives a comparison between the calculated errors and the observed total accumulation errors at 10 per cent power factor, for 60-cycle lagging current and 125-cycle lagging and leading current, for both the common and special type wattmeter, when used direct (as an ordinary wattmeter) and when used compensating. The calculated errors as given take nothing into account except the phase displacement caused by the self-inductance of the potential circuit—the theoretical effects which mutual inductance might produce being completely disregarded.

Referring to the errors observed in the common type of wattmeter, the effects of eddy currents are plainly in evidence. Where it would be expected that the instrument should read high due to the phase displacement of the moving coil circuit, the instrument actually reads low due to eddy currents. This is true whether used compensating or direct; the lack of correct compensation amplifies the error on lagging current and reduces the error on leading current. The magnitude of the error varies with the scale position, being more pronounced when the compensating coil is used, except on leading current, where the variations in the errors due to the different positions tend to neutralize one another. A useful correction factor cannot be supplied with wattmeters of the common type, because where we would expect it to read 0.53 per cent high it actually reads anywhere between 0.77 per cent and 2.15 per cent low.

TABLE II. TEST OF COMPENSATING WATTMETERS
THE TOTAL ACCUMULATIVE ERRORS OBSERVED ON POWER FACTOR LOADS

(Figures in table are corrected for scale errors.)

Watts read on test instrument	Power factor of load = 0.1				
	Used direct		Used compensating		
	Wattmeter No. 1 Common type (Per cent)	Wattmeter No. 2 Special type (Per cent)	Wattmeter No. 1 Common type (Per cent)	Wattmeter No. 2 Special type	
				Alone (Per cent)	With voltmeter (Per cent)
	60 Cycles per Second; Current Lagging				
25.0	—0.92	+1.54	—1.85	+1.68	+1.62
20.0	—0.77	+1.55	—1.82	+1.41	+1.30
15.0	—1.10	+1.48	—2.15	+1.54	+1.60
10.0	—1.15	+1.67	—1.51	+1.56	+1.58
*Calculated errors	+0.53	+1.69	+0.53	+1.69	+1.69
	125 Cycles per Second; Current Lagging				
25.0	—1.18	+4.70	—1.21	+4.63	+4.55
20.0	—1.02	+4.32	—1.29	+4.33	+4.47
15.0	—2.05	+3.47	—2.42	+4.09	+3.88
10.0	—2.00	+3.91	—3.14	+4.33	+4.18
*Calculated errors	+1.12	+3.63	+1.12	+3.63	+3.63
	125 Cycles per Second; Current Leading				
25.0	+1.63	—2.94	+1.01	—2.62	—2.58
20.0	+1.58	—2.95	+1.09	—3.16	—3.34
15.0	+1.42				
10.0	+1.68	—2.67	+1.02	—2.78	—2.83
*Calculated errors	—1.12	—3.63	—1.12	—3.63	—3.63

*The calculated errors take nothing into account except the self-inductance of potential circuit.

The wattmeter having special coils shows no observable error due to eddy currents, the calculated error and observed error have substantially the same magnitude and sign, while the error for the various scale positions is practically the same. The excellence of the compensation is to be noted in the good agreement between the errors when used direct and compensating, and even when compensating for a voltmeter in addition. A correction factor can be applied with advantage to the readings of this instrument, namely the phase angle of the potential circuit.

The correction factor is large, compared with that calculated for the common type, because in providing the large volt-ampere capacity the torque was kept up at the expense of the small time constant of the potential circuit rather than increase the impedance of the series coil, as doing the latter would be likely to disturb the condition of the circuit upon the introduction of the wattmeter. This would be undesirable, for it is a prime requisite, as pointed out in the beginning, that the design be such that its errors can be readily computed for all conditions of load, etc., to be useful as a wattmeter on low power factors.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

HOT WIRE INSTRUMENTS

BY A. W. PIERCE AND M. E. TRESSLER

In this paper we shall point out the special field for use of hot wire instruments, and support our statements by facts and figures drawn from long association with this particular type of instrument.

There is a large gap between pivoted instruments of the dynamometer or moving iron type, and the sensitive reflecting dynamometer, voltmeter or ammeter. This gap can be reduced by the use of hot wire instruments.

The lowest range pivoted voltmeter of the dynamometer type for use on alternating currents, with which we are familiar, requires 7.5 volts for full scale deflection, and has an appreciable frequency error even at 60 cycles per second, in addition to a temperature coefficient which must be taken into account in accurate measurements.

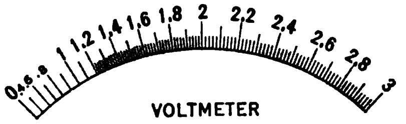


FIG. 1

The voltmeter scale shown in Fig. 1 was traced from one of several three-volt hot wire instruments which have been in use in a large testing department for several years. These instruments have no temperature coefficient, and when made with a properly aged hot wire have a very small zero error due to changes in temperature of the instrument as a whole or in part. The inductance of the hot wire is practically zero, and the instruments give equally accurate indications on direct and alternating voltages at all frequencies lower than 500 cycles per second. These voltmeters can be relied upon within one-half scale division as low as 1.2 volts, as shown by the following check made on direct current against a carefully calibrated laboratory standard voltmeter:

TABLE I

Standard reads..	3	2.8	2.6	2.4	2.2	2	1.8	1.6	1.4	1.2
Instrument reads........	3.00	2.795	2.60	2.395	2.195	2.00	1.795	1.60	1.40	1.195

These voltmeters can be used with suitable series resistance to measure higher voltages than three volts and require about 0.2 ampere for full scale deflection.

Hot wire ammeters can be made for a full scale range of 0.25 ampere, which will indicate 0.1 ampere with an accuracy closer than 1 per cent.

Fig. 2 shows a scale traced from one of these instruments in actual use.

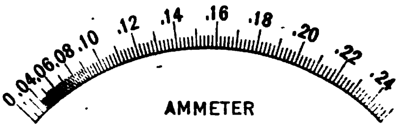


FIG. 2

0.25, 0.5, 0.75, 1, 1.5, 3, 5 and 6-ampere instruments can be made which will take all of the current measured through the hot wire and are not affected by wave form, frequency below 500 cycles per second, or stray fields. The *IR* drop and I^2R losses of these instruments will compare favorably with those of moving iron ammeters of corresponding ranges, as shown in Table II.

TABLE II

Capacity in amperes	*IR* volts	I^2R watts
	Iron vane ammeters	
5	0.63	3.15
2	1.52	3.04
7	9.34	6.54
	Hot wire ammeters	
6	0.25	1.5
5	0.3	1.5
1.5	1	1.5
1	0.75	0.75
0.75	1	0.75
0.5	1.5	0.75
0.25	3	0.75

Table III, which was copied from the calibration record of a hot wire ammeter adjusted for a series range of 0.25 ampere with shunts for 0.5, 1, 2 and 4 amperes, gives a fair idea of what can reasonably be expected from such an instrument when carefully used. These checks were taken on the one-ampere scale against a potentiometer and standard resistance.

TABLE III

The first line gives the settings of the standard; the dates and corresponding instrument readings follows.

Date	1.000	0.900	0.800	0.700	0.600	0.500	0.400	0.300	0.200
2-25-11	0.999	0.900	0.800	0.700	0.601	0.501	0.400	0.300	0.201
3-18-11	0.998	0.899	0.800	0.699	0.600	0.500	0.400	0.298	0.200
4-7-11	0.999	0.899	0.800	0.699	0.600	0.500	0.399	0.298	0.199
5-5-11	0.997	0.898	0.798	0.699	0.599	0.500	0.399	0.298	0.200
6-3-11	0.999	0.900	0.800	0.699	0.600	0.500	0.399	0.299	0.200
7-13-11	1.000	0.900	0.800	0.699	0.599	0.499	0.398	0.298	0.199
8-4-11	1.000	0.900	0.800	0.700	0.600	0.500	0.399	0.298	0.199
9-6-11	1.000	0.901	0.801	0.700	0.600	0.500	0.400	0.298	0.199
9-29-11	1.000	0.902	0.802	0.701	0.601	0.501	0.400	0.299	0.200
10-25-11	0.999	0.900	0.801	0.699	0.600	0.500	0.399	0.298	
11-25-11	1.000	0.900	0.800	0.700	0.600	0.500	0.399	0.298	
12-29-11	0.999	0.900	0.800	0.700	0.600	0.500	0.400	0.298	
2-1-12	0.999	0.900	0.800	0.700	0.600	0.500	0.399	0.298	
2-21-12	1.000	0.901	0.801	0.700	0.600	0.500	0.400	0.299	

For ranges higher than six amperes shunts can be used with the instruments, and currents as high as 2000 amperes have been measured in this way. A high range hot wire ammeter has an energy consumption greater than that of a good moving iron ammeter and current transformer. But it has the advantage over such a combination that it can be checked on direct current and used on alternating current of commercial frequencies without any appreciable error. It costs less, is easier to read and manipulate than a Kelvin balance or Siemens dynamometer. It is therefore well suited for use as a working standard for the calibration of moving iron instruments and current transformers.

Because of their very small inductance and capacity, hot wire instruments are better suited for measuring high frequency currents than any coil instrument, particularly for currents which come within the six-ampere range of the self-contained instruments. Even where shunts have to be used, the errors caused by unequal distribution of current between the instrument and shunt on direct current and at high frequencies will be less than those caused by the self-inductance of series transformer and coil instruments.

Conclusion. Hot wire instruments can be used to good advantage (1) in measuring small alternating currents and voltages; (2) as general utility instruments for indiscriminate use on alternating and direct current and for checking iron vane ammeters; (3) for measuring high-frequency currents where coil instruments would be useless.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

RESONANT CIRCUIT FREQUENCY INDICATOR

BY W. H. PRATT AND D. R. PRICE

The object of this device is to supply a method for accurately measuring the frequency of a circuit, to give a large scale deflection on the instrument for a small percentage change in frequency and to obtain readings which are accurate under all ordinary conditions of wave form, voltage variation and temperature.

The electric circuit whose impedance is the most sensitive to a change in frequency is that circuit which contains inductance and capacity connected either in series or parallel; the degree of sensitiveness of such a circuit can be changed and varied through a wide range at the convenience of the designer. These two characteristics admirably adapt this circuit to the construction of a frequency indicator and indirectly to the construction of a speed indicator, provided that it can be applied in a practical form.

Being extremely sensitive to a change of frequency it follows that it is also sensitive to a change in the constants of its own constituent parts (although in this case to a less degree, as will be shown) and the application of this circuit in a practical form for this reason presented some difficulties at first.

The theory of resonance is of course well understood, but in practise certain limitations are presented which in some cases make it very difficult to approach theoretical values of current in a tuned or partially tuned circuit. Theory presupposes a perfect inductance, a perfect condenser, and a perfect resistance, when as a matter of fact a perfect inductance and a perfect condenser are never realized. By a perfect inductance is meant a circuit having inductance alone with no losses—the same applies to a perfect condenser.

In order that the circuit be resonant or tuned, or partially tuned, the inductance and condenser must be of such a nature that the excess lines of force must be free to collapse as soon as the current flowing in them begins to diminish. On this characteristic the degree of success in tuning and the approach to theoretical values of current depend entirely. Numerous mechanical analogies of elastic and inelastic bodies will suggest themselves.

It is possible to reach almost theoretical conditions and to obtain almost theoretical frequency impedance curves by using an air core inductance and an air dielectric condenser. Space limitations, however, place them entirely out of the question for use on instrument work.

Owing to this limitation of space it is necessary to adopt an iron core inductance and a compact condenser with a solid dielectric of a specific inductive capacity somewhat greater than that of air. These two substances, iron and a solid dielectric, introduce losses and variations and other difficulties. An iron core inductance has the following faults: hysteresis loss, eddy current loss, magnetization curve not a straight line, and the variation in form due to temperature and mechanical trouble.

Of these the all-important one is hysteresis loss. Not only does this loss appear as an added resistance to the circuit, but it absolutely destroys all resonance if present beyond a certain degree; for if the lines of force which are once established in a circuit do not collapse when the source of current is withdrawn there can be no resonance whatever. This also will suggest mechanical analogies. It is then very important to keep down the hysteresis in the inductance element. On account of hysteresis it was found impossible to tune a closed magnetic circuit inductance.

The eddy current loss tends to lower the inductance of the circuit and acts as an added resistance. The amount of lowering of the inductance will have a temperature coefficient and for this reason the eddy currents should be kept as low as practicable. However, the eddy currents do not affect the tuning, like hysteresis, and this loss can be calibrated with the other parts of the circuit. The other variations due to the use of iron can be reduced to a low value by proper designs.

All the other troubles inherent to condensers can be overcome by proper design, so as not to affect this work, and all the other troubles met with in high-frequency tuning are not apparent in frequencies such as 60 cycles.

The constituent parts of the circuit were, therefore, designed as follows:

The inductance was wound on a laminated iron core which had an air gap in its circuit, and the flux was kept low so as to be well below the saturation point.

The condenser was made by the vacuum process, which insures a permanent high insulation, and low internal heating. It was designed to operate at a voltage well below the safe working voltage. The resistances were all zero temperature coefficient metal.

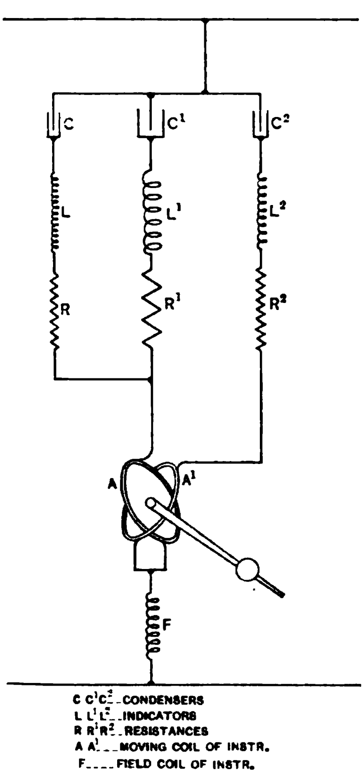


FIG. 1

A standard instrument was used with the capacities, inductances and resistances in a separate box. This standard instrument was essentially a field and two armatures set at an angle with each other and having a common diameter through which the shaft passed.

The external box contained three separate circuits, each having an inductance, a capacity and a resistance in series. Two of these circuits were identical and the third was designed for a much smaller current carrying capacity, for a reason to be explained.

One of the main circuits was adjusted so as to be in resonance at about 70 cycles; the other main circuit was adjusted so as to be in resonance at about 58 cycles. The third circuit was adjusted so as to be in resonance at about 36 cycles. This last circuit was connected in parallel with the circuit adjusted to be in resonance at 58 cycles. The circuit adjusted at 70 cycles was connected to that armature coil on the instrument which tended to move the needle up. The other two circuits were connected to the armature which tended to make the needle move down. The armatures were in series with the field coil.

The center of the scale was marked for 60 cycles, the left-hand end being 55 and the right-hand end 65. It was possible to get a 6-inch (15-cm.) movement for a change in frequency from 55 to 65 very easily, and it was also possible to get a 6-inch movement for a change in frequency from 60 to 61, on the same instrument. There appears to be almost no limit to the sensibility of this arrangement. The actual working of the apparatus is self-evident and needs no explanation.

When the frequency drops very low, for instance, 30 or so, the small auxiliary circuit supplies torque to prevent the needle from again going on the scale, due to the absence of torque from the main circuits, since both are far away from their resonant frequency.

When made up in a practical form, this instrument exhibits only a trace of variation, due to wave form, voltage or temperature.

The connections of the instrument are shown in Fig. 1.

DISCUSSION ON "INDUCTION TYPE INDICATING INSTRUMENTS" (MACGAHAN), "COMPENSATING WATTMETERS" (ELLIS), "HOT WIRE INSTRUMENTS" (PIERCE AND TRESSLER), AND "RESONANT CIRCUIT FREQUENCY INDICATOR" (PRATT AND PRICE), BOSTON, MASS., JUNE 28, 1912.

F. P. Cox: Taking up the paper on hot-wire instruments first, it seems to me that there are limits to the use of this instrument, and yet there are occasions and circumstances where this particular type of instrument is better suited than any other type. For the measurement of low voltages, and particularly for the measurement of circuits of high frequency, I think we must all agree that it has no peer. But beyond those particular fields, it seems to me that its usefulness is rather limited, and limited, indeed, by the very reason that Mr. Pierce mentions, its high energy loss, which, for the 2000-ampere meter mentioned, for the voltage given would come to 600 watts, which would be quite out of all reason. I would also mention, not from my personal experience, but a statement that I have very direct from some wireless people, that when you use it on the very high frequencies, it is desirable to use an air transformer rather than a shunt. I cannot give you any figures at all on that, but Mr. Price, who was with Fessenden, at Brant Rock, had very considerable experience with it, and strongly recommended the use of air transformers, in place of shunts, for high frequency.

So far as maintaining accuracy is concerned, the table that is given in the paper leaves little to be desired in this or even in any other type of instrument. It is well within the limits you would normally expect to find in the calibration of an instrument over a period of years, but I do not feel that this instrument will ever have a field except for service under the conditions for which it is particularly suited. I do not think it can "come back." That is almost too much to expect.

In regard to the induction type of instrument, I feel that here, too, we have an instrument of exceedingly valuable characteristics for certain fields, but of decided limitations for other fields, which will prevent it from "coming back." The long scale, which is inherent in the type, is a desirable feature, but we must not neglect to take into account that what we want to know is the current in the circuit, that if you can read an instrument beyond its limits of accuracy, or if you have an instrument which has an error greater than its reading capacity, you equally get into trouble. What you want is an instrument which will give you, so far as you can read it, the combination of being readable and possessing an accuracy which will give the closest approximation to the actual condition of the circuit. The longer scale is characteristic, and in itself, if obtained without any sacrifice, is good.

In regard to the question of the light moving element, I do not feel at all that a light moving element necessarily means a weak element. The small threads referred to are definite threads —it is all in proportion to the part you are using, and light weight does not mean that you necessarily have a weak part, or a part which is liable to be injured in operation and in service. It does mean that the average meterman cannot handle it. The delicate, light moving parts must be handled by human hands with great care and skill, and with much experience, but so far as their operation in the instrument is concerned, I do not feel that there is anything to be worried about in that respect; because the mass you are handling, the forces you are dealing with, are, after all, comparable with the lightness of weight which you have, and are not necessarily likely to give trouble. I fully agree that shielding is essential, that strong shielding, double shielding, is essential, where you can have it, and that the magnetic disturbances which you find in your circuit are the most important things to look out for.

As to the black and white scale, I believe that is properly a question of illumination. For tunnel work, there can be no shadow of a doubt that the black scale with a white figure is superior. For other conditions of illumination that may not be true, and for certain conditions of illumination it certainly is not true, but after all you must adapt your scale to the conditions of illumination, and should not expect that the illustrations given in the paper will be a true representation of average conditions. There will be conditions of illumination where you will get that, and as Mr. MacGahan says, the camera may be more accurate than the eye, but you are putting up your instrument to be used in connection with the eye, and not to be used in connection with the camera. Therefore, it seems to me that we cannot say definitely that the white letter is better, or the black letter is better, but there will be conditions of service where one will be superior and different conditions where the other will be definitely superior.

W. H. Pratt: I will speak on the paper by Mr. MacGahan. This paper is entitled *Induction Type Indicating Instruments*, but for the most part it deals with the ammeter. The switchboard instruments of particular importance are the ammeter, voltmeter and wattmeter, and their importance, I should say, is in the order of the voltmeter, the ammeter and the wattmeter, that is, it is absolutely certain that the voltmeter should be accurate, it is essential that the ammeter be accurate, so that you are sure you do not overload the machines and lines, and the wattmeter is of little use unless it is accurate. As I understand these various induction type instruments, the ammeter is the most easily susceptible of giving accuracy, the voltmeter comes second to the ammeter, and it is with difficulty that the wattmeter is made to perform its work. The performance of the indicating wattmeters, of course, must not be confused with that of the rotating watt-hour meter, in which there are automatic compensations coming in, which would make a remark of this character entirely inapplicable. I am sure that a light-weight moving element is to be trusted rather than a heavy-weight moving element, where it is properly designed, because a greater amount of structural strength can be given to a light-weight than a heavy-weight element in proportion to the strains to which it will be subjected.

Albert F. Ganz: I should like to confirm the statement made by the previous speaker to the effect that it is highly desirable to have the moving system in an electrical measuring instrument as light as possible, because this means a small moment of inertia requiring only a light damper, and also correspondingly small wear on the jeweled bearings. It is, of course, true, as already stated, that a light movement is much more difficult to repair by the ordinary meterman, but on the other hand an instrument with a very light movable system is much less likely to get out of order. In regard to the hot-wire instrument, I ask whether the instrument has a zero temperature coefficient, so that a series multiplier can be used with it having a constant multiplying factor.

A. W. Pierce: It has. The hot wire used in the voltmeter has a zero temperature coefficient.

F. V. Magalhaes: I ask Mr. Pratt to mention the temperature coefficient of the instrument, and it would be interesting to know if he has the figures, what the temperature coefficient is, and whether any attempt is made to compensate for temperature error.

William J. Mowbray: Concerning the induction type of ammeter and the black scale, I would like to say that the black scale was tried by me in the original experiment on the rotating watt-hour meter. This was used in cellars where the light is usually very poor, and we found it to be a fact that with very low illumination the black scale and white division showed up better, so that I believe for very low illumination the black scale is the better.

I would ask Mr. MacGahan to tell us just how he gets rid of the temperature coefficient in his induction ammeter. We know that the aluminum moving element will change some 4 per cent in temperature for every 10 deg. cent. change in temperature, and still the curve shows very little error due to temperature, and I have no doubt Mr. MacGahan can explain to us simply just how he does it.

A. L. Ellis: There are two or three points in the paper by Mr. MacGahan that have not been touched on by the speakers. One is in reference to the electrostatic disturbance. There is no occasion for electrostatic disturbance, because the moving system can be put at the same potential as the surrounding apparatus, and the only source of trouble would be static charges on the glass caused by rubbing the glass, and that certainly is not the thing to do, as it will affect the instrument.

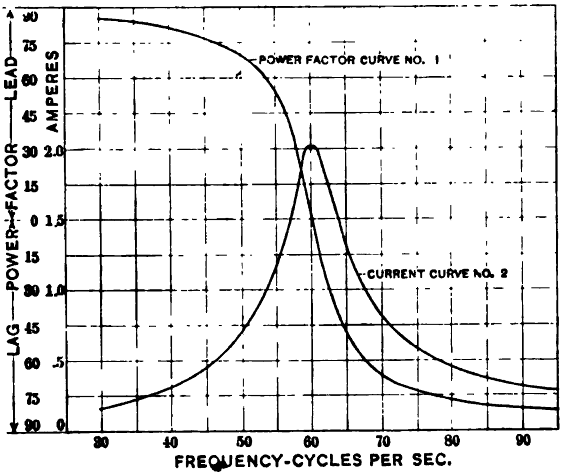
A little further on in the paper the statement is made: "Experience and tests have shown that 15 grams maximum is a safe limit for horizontal shafts in V sapphire jewels, and that a ratio of torque to weight of 0.15 is a satisfactory minimum, when torque is expressed in centimeter-grams, and weight in grams, in the case of switchboard meters." I would like to ask Mr. MacGahan what line of reasoning led to that conclusion? It would seem to me, from what experience I have had with jewels and pivots, that it is vital that the moving system be made just as light as possible.

It is impossible to make a V pivot and bring it down to a theoretical point, so if we take a cross-section at the point of contact between the pivot and the jewel, the point of contact will not coincide with the axis of the pivot, but will bear at a considerable radius from this axis, therefore, the pivot will roll in the jewel when the pointer is deflected up scale, the pivot rolling up hill. The action of gravity tending to roll the pivot down hill is in opposition to the torque of the instrument and in the same direction as the torque of the control spring, tending to make the instrument read too low. If the instrument has been operating with considerable deflection and the current is reduced, the pointer tends to read too high for the same cause, as in this case the action of gravity acts in opposition to the torque of the control spring. This is a source of error difficult to reduce below an observable amount or even an objectionable amount, unless a very large ratio of torque to weight can be obtained. I think the error will be very pronounced even with the ratio mentioned of 1.5 (in gram-millimeters).

The moving system should be as light as possible, for, although you can make the pivot out of hard steel, glass-hard in fact, and can use a sapphire as a jewel, which is very hard, yet a moving system of but very few grams weight is sufficient to deform the pivot and sapphire jewel. The pivot may be so hard and tough that it can be driven into a piece of brass or a spring tempered steel scale, without distorting the regularity of its surface, but if this pivot formed the support for a moving system, as for instance the D'Arsonval type weighing only 1.5 grams, simply dropping it a few inches, will be sufficient to crush the steel pivot or to force the point to mushroom. The changed form of the pivot is substantially that of the jewel and, therefore, friction is increased to a noticeable amount, because a larger area is exposed to the jewel.

Paul M. Lincoln: I am particularly interested in the paper on the resonant circuit frequency indicator, because some ten or twelve years ago I had an idea very similar to the one described. After I got the scheme pretty well worked out, a modification of the idea occurred to me depending on the same phenomenon, which seemed to me to be considerably better. That particular scheme was described in a paper which I prepared for the Institute and presented about eleven years ago at the Buffalo convention. I want to say a word or two to show the principle upon which it rests. As we increase the frequency on a circuit containing inductance and capacity in series, we come to a certain frequency that will give a marked peak in the current flow. This is the frequency of resonance, and a curve showing the variation of current with frequency is shown in No. 2 of the accompanying figure. The fact that there is a marked peak of current at resonance is utilized to actuate the instrument described.

There is another phenomenon, which occurs at the same point, and it was on this other phenomenon that I based the instrument I speak of. At the same time that the current changes its value, the power factor of that current also changes its values very rapidly. This current leads when below resonant frequency and lags when above, while close to resonant frequency the power factor changes very rapidly. This is shown in curve No. 1 of the accompanying figure. Hence, a standard power factor meter in a circuit that is adjusted for resonance at normal frequency makes an ideal frequency indicator. The sensitiveness of such an instrument may be varied as desired simply by varying the amount of resistance in the resonant circuit. All these points are brought out in my paper published in the 1901 TRANSACTIONS of the Institute.



F. H. Bowman: The hot wire instrument achieved a large measure of popularity some years ago, due, I think, to two causes. The instrument originally was imported from Germany, and on its way to America it did not lose its fine finish, which is characteristic of all fine instruments. Its fine finish was not lost when the instrument came to this country, and I ascribe the major portion of its popularity to the fact of this fine finish and its very splendid appearance. The other cause to which I ascribe its popularity is the fact that it is interchangeable, as between alternating current and direct current. That last feature has lost much of its importance in the last few years, due to the increased knowledge of the art of measuring alternating current. The fact that it is interchangeable between alternating current and direct current is not so important as it was some years ago, and on that account the hot-wire instrument had a certain lapse in favor which is now about at an end, and I believe there is a new lease of life, we might say, for the hot-wire instrument on account of the wireless telegraph which, of course, is growing very largely.

In reading Mr. Pierce's paper the thing that appeals to me is the marvellous accuracy which is obtained in the use of the hot wire instruments in Mr. Pierce's hands, and I think I can state here, without danger of being accused of fulsomeness, that Mr. Pierce is a very skilful man in handling hot-wire instruments. People who read this paper will assume, naturally, that by the use of hot-wire instruments they will secure the same degree of accuracy which Mr. Pierce reports, or if they fail to do so, they will condemn the instrument. Hence the conclusions I draw are these: Where the hot wire instruments are used skilfully, by a skilful man, who is aware of the tricks of the hot-wire instruments, such a man will procure excellent results from them, whereas another man who is less skilful in their use will get into more or less difficulty with them, and will be disappointed in the results obtained.

The question was brought up about the effect of the temperature coefficient in hot-wire instruments. We will take a voltmeter 0.03 in. in diameter, that is the smallest we can use. That wire is made with practically zero temperature coefficient, so the first thing is—the hot-wire instrument has a zero temperature coefficient. But this point I will make, and it may be new—the hot-wire instrument, although it has no general temperature coefficient, has an apparent temperature coefficient that is of considerable magnitude, and can easily be determined; that is to say, although the wire in itself has no temperature error, when you put a load on it, and heat the hot wire up to a point where it expands, it increases in resistance, and although the specific resistance of it is still the same, the apparent resistance changes, due, I believe, to a decrease in the cross-section of the hot wire, on account of the heating. For high voltages, 150 volts, I call that high for hot wire, that is negligible on account of the considerable resistance in series with the hot wire, but as you drop down, and the series resistance becomes low in the hot-wire instrument, the errors increase in importance, and when you have a low-voltage instrument, five volts or three volts, the apparent temperature coefficient is something you have to take into account.

F. P. Cox: There is a point which has a bearing, not only on the types of instrument under discussion, but also on the general instrument problem, and that is where Mr. MacGahan mentions the desirability of opening the scale at the top. I do not agree with him, not only as that point is applicable to induction types of instruments, but to any instrument. You have control of the scale of distribution. An ammeter put upon the circuit of a generator must take care of overloads, and that is rated at 100 per cent in excess of the capacity of the generator, and normally is working much below one-half of that. Therefore, within a certain limit as we have the scale at our disposal, it seems to me, we should not spend too much of our scale length in getting wide open divisions at that portion of the load which the instrument rarely meets and only for very short periods. Therefore, it seems to me that the equi-crescent scale is more suited to this purpose, or a scale which closes slightly in the upper portions, and remains open in those portions where the instrument is used nine hundred and ninety-nine times out of a thousand.

N. Monroe Hopkins: Are there any data on the weight in grams of the rotating member of the induction type meter as used?

Paul MacGahan: Referring to Mr. Mowbray's question: The method of compensating the ammeter for temperature changes is very simple. The windings consist, in fact, of a series transformer, wherein the secondary coil is wound on an electromagnet, the primary coil wound right over same, and the polepiece coils short-circuited across the secondary. As the temperature of the aluminum drum increases its resistance increases, tending to reduce the torque in the ratio of the temperature coefficient of the aluminum. At the same time, however, the resistance of the secondary winding, which is partially or mostly copper, increases which is equivalent to introducing resistance in the secondary circuit of a series transformer, which of course increases the magnetic flux. The increased magnetic flux gives greater driving power, and exactly compensates for the increased resistance of the drum. This is explained, somewhat theoretically, in the paper itself.

As regards the relative accuracy of the voltmeter and the ammeter, it is true that the ammeter has a greater accuracy than is possible with the voltmeter. This is at the same time true with all other principles of operation, so that it cannot be said to be exclusively a feature of the induction meter.

With regard to the errors of the wattmeters, the wattmeters as developed have temperature and frequency errors closely approximating those of the voltmeter and the ammeter. As stated by Mr. Pratt, accuracy of slightly lower order than of the ammeters or voltmeters is permissible in a switchboard wattmeter.

Messrs. Pratt, Ellis and Cox express themselves very much in favor of a very light weight moving element for indicating meters. In this I concur, only provided the lightness is not obtained at a sacrifice of torque ratio and staunchness. As a comparison it may be pointed out that in a-c. watt-hour meter practise certain manufacturers have greatly favored a movement of 30 grams weight rather than one of 15 grams and have argued that the increased torque obtained thereby is an advantage. If a weight of 30 grams upon one jewel is considered satisfactory by them, for watt-hour meters, should not they consider a weight of 10 grams distributed between two jewels satisfactory in every respect for an indicating instrument? The average of three makes of moving iron instruments made in this country and abroad, shows a weight of two grams for the movement, with a torque of $^1/_{10}$ centimeter-gram; the induction type movement described by me weighs 10 grams, with a torque 28 times as great, which shows quite a predominance in favor of the induction type, with regard to ratio of torque to weight.

It has been pointed out on one or two occasions, that the weight, acting upon the theoretical point of contact on the jewel, results in a pressure of several hundred thousand pounds per square inch. This is surely an academic point, otherwise the jewel would give way on the slightest impact. As a matter of fact the bearings operate very satisfactorily.

As regards scale length in switchboard indicating instruments, the readability of the scale should be of a higher order of accuracy than that of the meter element itself. This is on account of the fact that readings are often required to be taken hurriedly from a distance, and thus the condition is different from that obtaining in portable instruments, where a close observation may be made and thus a scale no more accurate than the inherent accuracy of the mechanism, is permissible.

W. H. Pratt: There was a question asked as to temperature errors in the frequency indicator which I described, and I may say that there are three elements in this device whose temperature coefficients must be considered. There are the condensers, the reactances and the resistances, besides the mechanical parts. It is easily possible to make the mechanical structure so that there are no temperature errors introduced thereby. The errors due to change in resistance can be reduced to negligible quantities, because the resistance does not come in as a large factor, and what there is of it can be made to have a low temperature coefficient. The reactance can also be made to have an entirely negligible temperature coefficient, and by properly designing the condensers these also can be made to have zero temperature coefficient so that the instrument, as stated, has a temperature coefficient that is almost exactly zero. It is extremely small.

A. W. Pierce: The question has been asked whether the voltmeter has a zero temperature coefficient. The voltmeter has a small temperature coefficient, but any slight alteration in resistance that may arise, or any other change of drop in the wire, is taken care of in the method of calibration, and automatically corrects itself when the instrument is calibrated.

It has also been stated that the results shown in the paper are those where extreme care was used. Personally, I had nothing to do with the checking of these instruments. This is the routine calibration of our standard as it was taken by men in the laboratory, most of whom have been there only a short time, and some of them less than two months, though they have been instructed in the care of hot-wire instruments and have been told something of their limitations.

John Gilmartin: (communicated after adjournment): It is very interesting to note how the many obstacles to an accurate induction type instrument have been met and skilfully overcome, as is so ably shown in the paper on induction type meters. One characteristic of the induction type instrument not mentioned by Mr. MacGahan is that the torque developed on severe overloads is excessive and may shift or break the pointer.

A certain central station switchboard has the feeder panels equipped with induction type instruments and it has been found that circuit disturbances occur quite frequently that are severe enough to cause the pointers of the instruments to bend and in some cases break off when the pointer hits the stop and in others to slip on the armature shaft and thus shift zero. Attempts to overcome these effects by improving the spring stop have been only partly successful.

A brief discussion of the characteristic action of the other types of instruments on overload is of value in bringing out the comparative effects.

The magnet vane and dynamometer type instruments have a limited scale movement, that is, the vanes or moving coils usually, as the load increases, move from a position across the field of the fixed coils to a position parallel to it, after which there is no further torque no matter how excessive the overload. Such instruments, as is well known, usually have scales whose divisions become very small at both ends, that is, the torque per scale unit decreases rapidly as the pointer approaches the maximum scale point.

Induction type meters, on the contrary, by reason of the rotating field principle, have a constantly increasing torque with load, and the divisions and torque per scale unit become larger at the maximum point of the scale. The pointer is not naturally limited in its length of throw as are the other types referred to; that is, if the stops were removed the moving part would rotate at a definite speed as an induction motor.

In a test made on a modern switchboard type induction ammeter it was found that if 300 per cent of full load current was thrown on the meter the pointer was thrown so hard against the stop as to cause it to shift its zero position. On the other hand 500 per cent of load thrown repeatedly on a magnetic vane instrument caused no zero shift. Both types of instruments had magnetic damping. The inferior results given by the induction meter on this test were not considered due in any sense to poor design or workmanship, as both were excellent, but rather to the relatively tremendous overload torque inherent in the rotating field principle.

Paul McGahan (by letter): Referring to Mr. John Gilmartin's communication after adjournment, the effect of overload upon the pointers of induction meters is more severe than in other types, due to the increase in torque, but the movements can be made strong enough to withstand it.

Although trouble as stated appeared in certain cases, this can be said to be part of the development of the type, for the matter has been satisfactorily corrected. The ammeters described will withstand fifteen times full load current thrown on repeatedly without damage—in fact, the coils will burn out on overload before the pointer or other parts of the movement become damaged. This compares very favorably with the overload capacity of moving iron or moving coil meters. Although it is true that in moving iron vane instruments, the iron moves to a position parallel to the lines of force through the coil, this takes place only after an appreciable length of time, as the meters have inertia and damping. The overload effect takes place instantly while the iron is still in its position of maximum torque and thus the result is that an enormous torque is developed, the same as in induction instruments.

A. W. Pierce (by letter): The statement that hot wire voltmeters have no temperature coefficient was made on the strength of tests made some years ago, records of which have not been preserved. Since presenting the paper we have made a careful test on a hot wire voltmeter, with the following results:

Amperes through instrument	Volts at terminals	Ohms resistance
0.0009202	0.01403	15.25
0.01536	0.2343	15.25
0.01539	0.2348	15.26
0.04527	0.6904	15.25
0.1044	1.5937	15.26
0.1515	2.303	15.20
0.1774	2.7292	15.38
0.1861	2.8430	15.28
0.1970	3.0093	15.27

Current measurements were made with standard resistances and potentiometer.

Volts at terminals of the instrument were measured by the same potentiometer used for the current.

The two readings showing the greatest variation from the mean value of the resistance may be in error due to the difficulty of keeping the current constant while reading current and voltage on the same instrument.

The lowest current given was not large enough to cause any detectable deflection of the voltmeter needle and the highest current was slightly more than that required to produce full scale deflection.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

PERMEABILITY MEASUREMENTS WITH ALTERNATING CURRENT

BY L. T. ROBINSON AND J. D. BALL

In testing samples of sheet iron to determine whether or not the material is suitable for the specific purpose for which it is intended, it is desirable to know the core loss in a unit volume of the material. The total core loss obtained may be separated by well-known means into hysteresis and eddy losses or the total core loss without separation may be used as a measure of the quality of the material.

In designing apparatus it is also necessary to know with some degree of accuracy the permeability of the material.

Accurate measurements of permeability may be obtained by various methods, and approximate methods of practical value have been employed in which the ballistic galvanometer is not used, but for the most part these methods require that the sample under test be put through the permeability tests on direct current.

It is desirable to find means to measure permeability with accuracy and speed comparable with core loss measurements, and as core loss measurements are made on alternating current, a method using the same current supply as that used in making this test is sought.

The present paper deals with the general relations between maximum flux density, maximum exciting current and magnetizing current.(1)* The method has not been completely developed to deal with samples in the form of bundles of strips. The preliminary work referred to was confined to ring samples, but the general principles involved may be used later in dealing with samples of standard form.(2)*

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*See references (1) and (2) at end of paper.

In a sample of iron magnetized by an alternating current the maximum magnetizing current occurs quite obviously at the point of maximum flux, which is the point of zero induced voltage. The total primary current, however, contains eddy components which may include currents for supplying instruments, *e.g.*, a voltmeter for measuring the magnetic density, connected to a secondary winding, as well as eddy currents in the iron.

We will write I_m for the maximum magnetizing current.
I_e for the maximum exciting or total current.
I_w for the maximum eddy current, including any currents in the secondary.
i_m, i_e and i_w will be used to represent the instantaneous values of the above quantities.

For the present only samples will be considered in which the laminations are thin enough so that appreciable "screening" does not occur. The eddy current i_w may be considered to be exactly in phase with the induced voltage and therefore to pass through zero when the magnetizing current is at a maximum.

Therefore the instantaneous value of the primary current i_e which occurs at the instant that the induced e.m.f. passes through zero represents I_m, the magnetizing current to be used in plotting the *B-H* curve. *B* may be directly determined by voltmeter if sine wave of e.m.f. is employed and wave distortion does not occur in the apparatus. The distortion of secondary e.m.f. wave has been carefully considered in connection with the commercial apparatus already referred to and need not be discussed here.

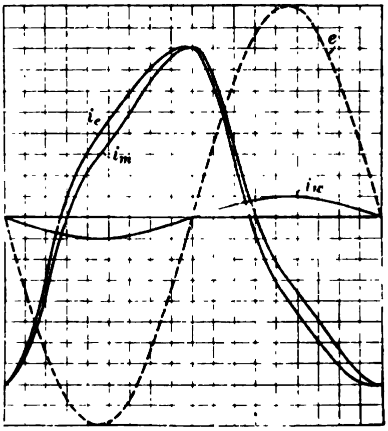

FIG. 1

Under some conditions the maximum magnetizing current very closely coincides with the maximum total primary current. The condition of coincidence will occur when the sinusoidal eddy and secondary component of the total primary distorted wave does not at any point exceed the difference between the magnetizing current at that point and the maximum magnetizing current.

While this relation is somewhat difficult to express concisely with words or symbols it is very quickly shown by reference to the figures and oscillograms which follow.

Fig. 1 shows an induced e.m.f. wave, a magnetizing current wave i_m derived from a hysteresis loop and an assumed energy wave i_w in phase with the induced e.m.f. A wave of total current i_e derived from the magnetizing and eddy waves is also shown. It will be seen from this figure that I_e is identical with I_m because the eddy current is at no point greater than the difference between i_m and I_m.

Fig. 2 is the same as Fig. 1, except that the eddy current has been assumed to be larger and in consequence the exciting current is larger. In this assumed case it is seen that I_e is greater than I_m and the assumption that they are alike would lead to an error of about 12 per cent.

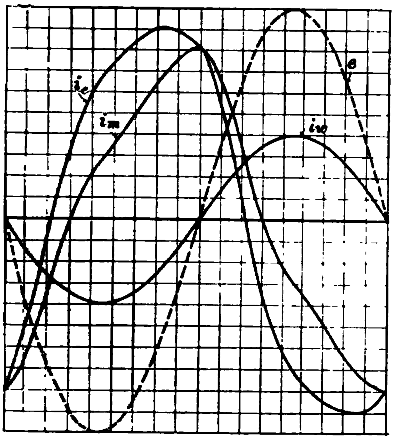

FIG. 2

Figs. 3 to 7 inclusive are records of current and induced e.m.f. at various inductions. The sample, of high-resistance iron 0.014-in. (0.035 cm.) thick, weighing about 22 lb. (10 kg.), was selected because several careful ballistic determinations for permeability and hysteresis had been made on the sample in connection with some earlier work.

Perpendiculars have been drawn from the point of zero voltage intercepting the exciting current curve at the point of maximum magnetizing current. From these and similar records the assumption for this sample that $I_e = I_m$ is in error by the following percentages:

B	60~ per cent error	25~ per cent error
14,150	0	0
12,140	0	0
10,075	2.5	0
8,315	2.52	0.81
5,000	1.8	0.64
2,861	1.77	0.53
2,020	1.41	1.41
999	0.78	0

In order to show the relationship more fully, the current and voltage of Fig. 4, $B = 10{,}075$, 60~, are plotted together with the magnetizing current wave derived from its hysteresis loop, Fig. 8. Subtracting the values of i_m from i_e and plotting the differences gives, as expected, a wave in phase with the induced e.m.f. and of form approximately sinusoidal.

Taking the effective value of this wave and of the voltage wave we obtain a value for the watts loss, which was found to agree closely with the watts consumed in the voltmeter plus the eddy current loss as determined by separation tests. The loss on the oscillograph circuit was included with the voltmeter loss. In order to reduce this loss as much as possible the oscillograph vibrator used for taking the voltage wave was connected to a separate winding having two to four turns and a very small resistance was included in the vibrator circuit.

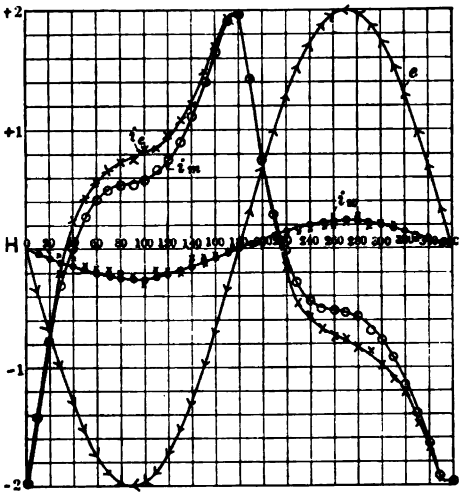

FIG. 8—SAME SAMPLE AS FIG. 3.

CURVES FOR e AND i_e TAKEN FROM FIG. 4. CURVE FOR i_m DERIVED FROM HYSTERESIS LOOP (BALLISTIC).

Points marked X on i_w curve are derived from i_m and i_e. Points marked 0 are for sine wave.

Oscillograms for all densities given in the preceding table were taken both at 60 ~ and 25 ~ but only representative ones are shown.

The accuracy of these results was tested by determining *B-H* curves in the usual manner with ballistic galvanometer and the general agreement between the results is shown in Fig. 9. The agreement is not what could be considered entirely satisfactory,

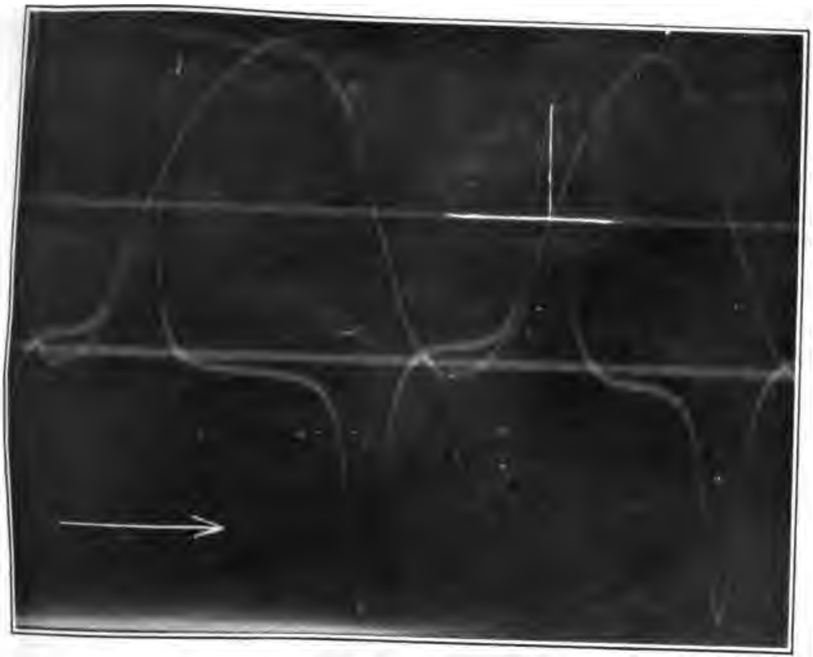

FIG. 3 [ROBINSON AND BALL]

Primary current wave (lower curve) and secondary induced e.m.f. (upper curve) on 22-lb. ring of 0.014-in. iron at 60 cycles per sec. Voltmeter resistance 1800 ohms—Induced voltage 116.5—B maximum 14.150, I_m 5.27, I_e 5.27, H = 14.63.

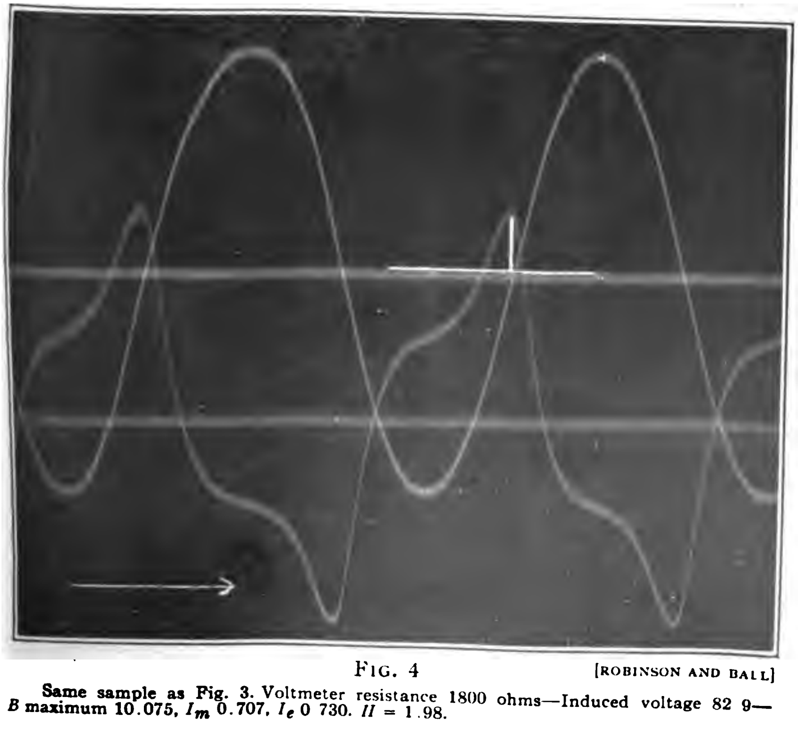

FIG. 4 [ROBINSON AND BALL]

Same sample as Fig. 3. Voltmeter resistance 1800 ohms—Induced voltage 82 9—B maximum 10.075, I_m 0.707, I_e 0 730. H = 1.98.

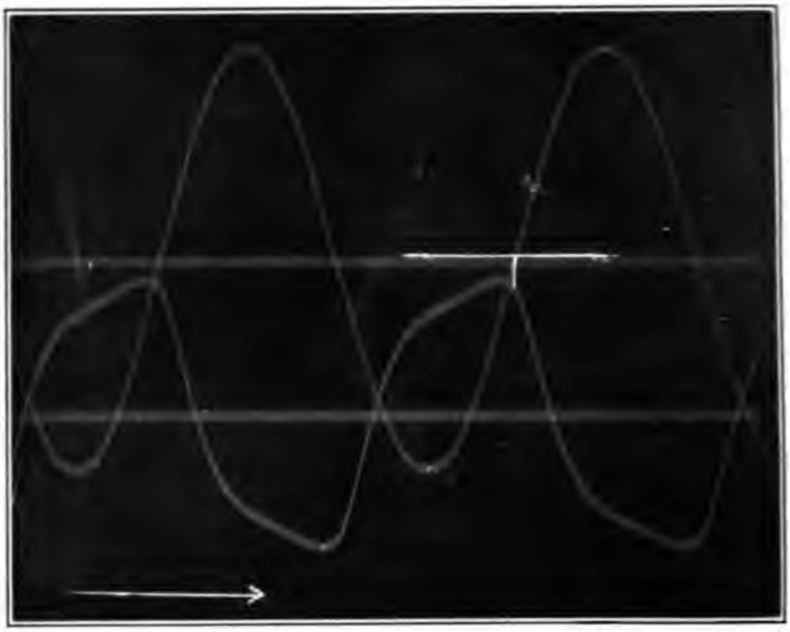

FIG. 5 [ROBINSON AND BALL]

Same sample as Fig. 3. Voltmeter resistance 1800 ohms—Induced voltage 41.2—B maximum 5000, I_m 0.260, I_e 0.264, H = 0.722.

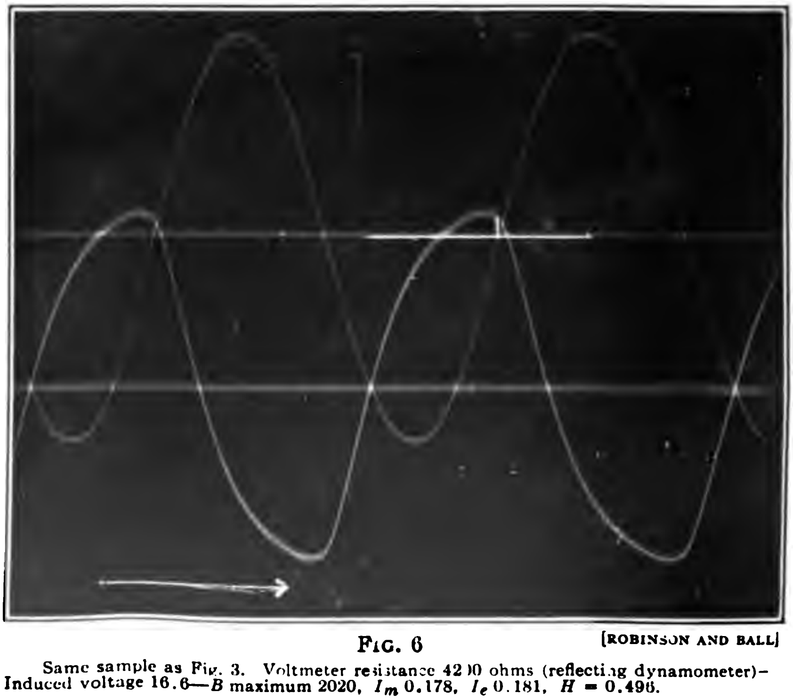

FIG. 6 [ROBINSON AND BALL]

Same sample as Fig. 3. Voltmeter resistance 4200 ohms (reflecting dynamometer)—Induced voltage 16.6—B maximum 2020, I_m 0.178, I_e 0.181, H = 0.496.

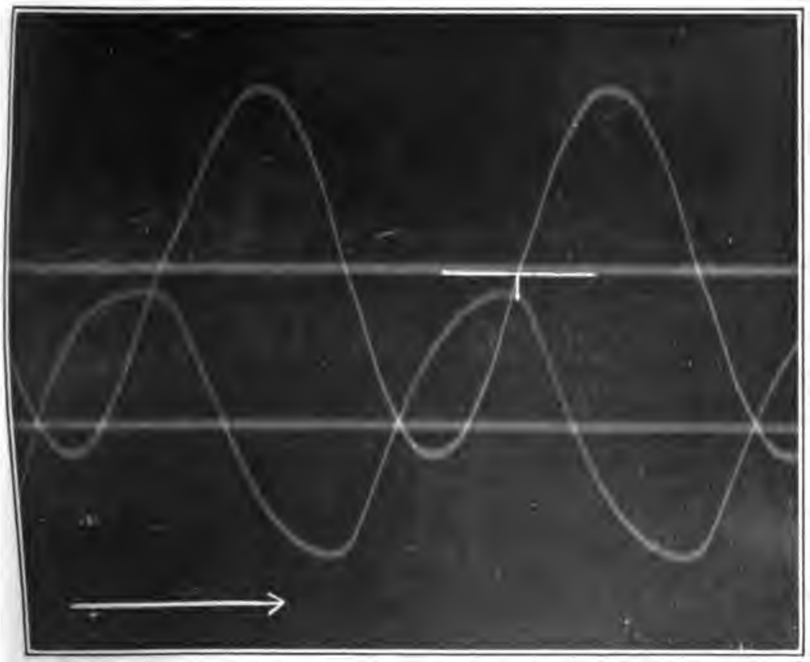

FIG. 7 [ROBINSON AND BALL]

Same sample as Fig. 3. Voltmeter resistance 2000 ohms—Induced voltage 8.16—B maximum 993, I_m 0.137, I_e 0.138, H = 0.381

as final values, but is sufficient to establish the fact that the preceding general conclusions are substantially true.

There remains to be determined by convenient means the value of I_e. The taking of an oscillogram for each induction is prohibitive in practical work, therefore tests were made with the oscillograph by observing for each induction the width of the band of light coming from the vibrator which was connected into the current circuit. The width of this beam corrected for the width of the spot as observed in the zero position is a measure of twice the maximum exciting current, which is evaluated by means of a d-c. calibration of the vibrator. Additional tests, similar to Fig. 9, were made on similar material, observing the width of the beam, and better results were obtained (see Fig. 10) than those found on the sample of Fig. 9, which was shown because waves and ballistic loops were available on this sample. A sample of low-resistance unalloyed iron was tested, showing a-c. and d-c. results not in good agreement between $B = 4000$ and $B = 10{,}000$. This would be expected in a sample having high permeability accompanied by relatively large eddy loss.

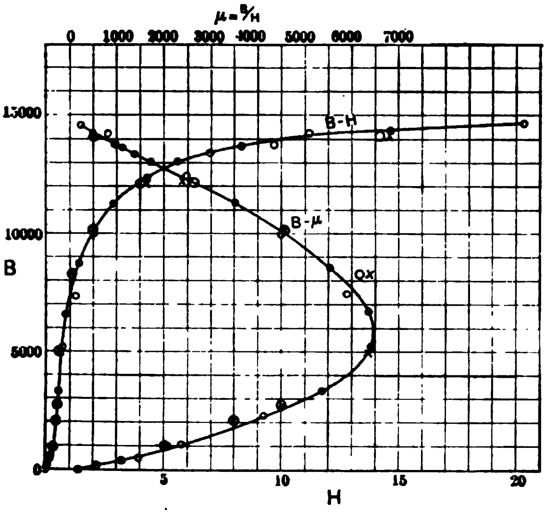

FIG. 9—SHOWING B–H AND PERMEABILITY CURVES. SAME SAMPLE AS FIG. 3.

X = 60 cycles per sec.; O = 25 cycles per sec.; o = direct current.

CONCLUSIONS

The measurement of maximum current (I_e) by elementary oscillograph, observing the width of the beam, is satisfactory and furnishes a convenient and fairly accurate means for determining the values in any work where the maximum rather than the average or effective value of a current or voltage is required.

The assumption that I_e represents I_m, in all cases, is not warranted, due to the causes explained, and further investigation is required before the limits of thickness of lamination, permeability, relative eddy loss, shape of hysteresis loop, etc., which can be successfully handled, are definitel ydetermined. The samples experimented on, particularly Fig. 10, were, by reason of relatively high hysteresis loss, low eddy current and medium permeability, well suited to obtaining good results by the method used, although the oscillograms show that the total primary current tends to reach a maximum in excess of the maximum magnetizing current.

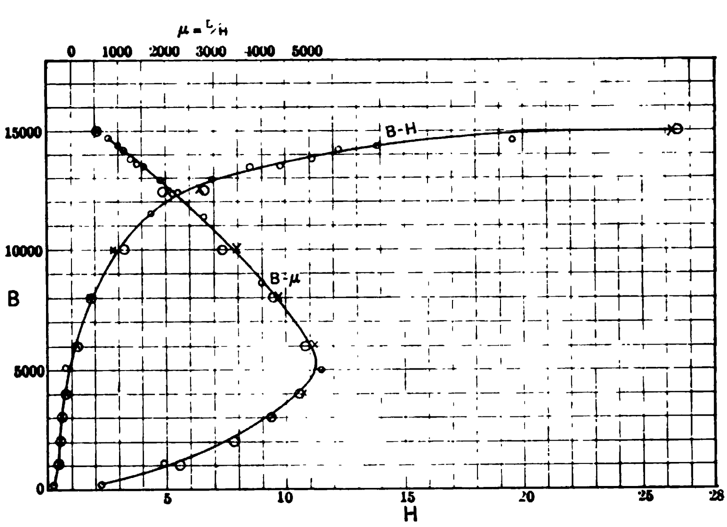

FIG. 10—SHOWING *B–H* AND PERMEABILITY CURVES, SAME DATA AS FIG. 9, ON A DIFFERENT SAMPLE.

The investigations will be continued in the hope of finding that the limits of practical application are not too narrow to be of value.

REFERENCES

1. During the progress of this work some results of a similar investigation were published under the title "A Method of

Measuring Permeability by Means of Alternating Currents" by R. Beattie, D. Sc., and H. Gerrard, M. Sc., *Electrician* (London), Vol. LXVIII, No. 11, pp. 436–438, Dec. 22, 1911.

A very interesting method is there presented for determining the maximum primary current by measuring the watt loss in a small iron core which has been calibrated previously and whose primary winding is included in series with the exciting winding of the sample to be tested.

The fact that the maximum primary current may not always represent the maximum magnetizing current is not referred to in the article, and the authors of the present paper believe that the determination of maximum current by observing the width of band on the elementary oscillograph is more convenient than the method proposed by Messrs. Beattie and Gerrard. The fact referred to in a footnote by Beattie and Gerrard that *B-H* curves on alternating current lie below those of direct current may be accounted for in part by the fact that secondary and eddy current may raise the maximum of the exciting current and consequently cause too large *H* values to be plotted on alternating current.

2. The standard sample according to the specifications of the American Society for Testing Materials is the same as that used in the Epstein apparatus, viz. 50 by 3 cm. (19 11/16 by 1 3/16 in.) weighing 10 kg. (22 lb.) and divided into four equal bundles.

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 28, 1912.

MEASUREMENTS OF MAXIMUM VALUES IN HIGH-VOLTAGE TESTING

BY C. H. SHARP AND F. M. FARMER

The breakdown strength of insulating materials is measured by the maximum voltage which they will withstand under given conditions. Tests are ordinarily made on alternating voltages, and the measurement of the maximum voltage is effected by indirect rather than direct means; that is, by measuring the virtual value of the voltage on either the primary or the secondary of the transformer and arriving at the maximum value by using a measured or assumed value of the peak-factor* of the wave. It is unfortunately true that this peak-factor is more often assumed than measured, and no doubt many tests of dielectric strength are inaccurate because of unsuspected changes in the wave-form produced by conditions of the test. Only in the spark-gap has an apparatus been available whereby a measure of the actual maximum value of the high voltage could be obtained. The spark-gap is however, a most uncertain piece of apparatus, the vagaries in the behavior of which have by no means been accounted for. Installed according to the Standardization Rules of the Institute, a spark-gap for measuring 250,000 volts requires a space such that no "extraneous" body comes nearer than 4 ft. 3 in. (129.4 cm.); that is, a clear space or room 8½ by 8½ by 8½ feet (259 cm.) is required. In view of this requirement, the spark-gap is a very large and cumbersome, as well as uncertain and unsatisfactory apparatus.

The arrangement here described is designed to give readings on a voltmeter of the maximum value of a high-voltage, wave.

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* The term "peak-factor" is used for the ratio of the maximum voltage of the wave to the virtual voltage.

The scheme is shown in Fig. 1. A series of condensers *C*, serving as a voltage divider, is connected across the high-voltage line or from one side of the high-voltage line to ground, if the transformer secondary is grounded. In parallel to the condenser C_1, which is grounded, is connected a rectifier or commutator *R* driven by a synchronous motor, the rectifier being connected in turn to an electrostatic voltmeter *V*. The commutator is adjusted to make instantaneous contact between the condenser and the voltmeter at the peaks of the waves. The voltmeter thus becomes charged to a potential corresponding to the maximum of the voltage waves and indicates this value. Inasmuch as the voltmeter is always charged in the same direction, it reaches its maximum charge after a few contacts of the brushes and after that draws no charging current from the condenser with which it is in parallel, except such as is necessary to supply leakage loss and to change the potential of the ungrounded side of the voltmeter with respect to the earth. Both of these charges should be relatively small. Hence the capacity of the electrostatic voltmeter does not change the multiplying ratio of the train of condensers, which is equal to the ratio of the capacity of the end condenser to that of the entire train, and the absolute value of the capacity of these condensers, be it large or small, has no influence. Of course for practical reasons the absolute capacity should not be too small.

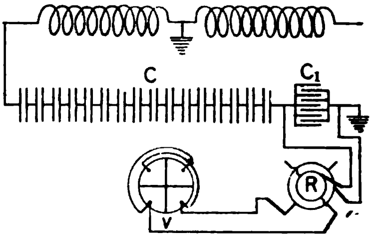

FIG. 1

The calibration of the arrangement may be carried out in two different ways, both of which assume that the virtual value of the high voltage can be measured.

Method 1. The synchronous motor is stopped in such a position that the brushes are making contact. Then the electrostatic voltmeter indicates a value proportional to the virtual value. By comparing this value with the known high-tension voltage a calibration of the arrangement in volts, high tension, is obtained. The calibration is not, however, exactly the same for volts maximum unless the capacity of the voltmeter is negligible in comparison with that of the condenser with which it is in parallel. Otherwise, when connected permanently in parallel with the end condenser, it alters the multiplying ratio of the train, which, as explained above, is not the case in measuring maximum volts. By properly proportioning the condensers, the capacity of the condenser may be many times that of the voltmeter, and this method may be used, or in any case where the capacity of the voltmeter is known, a correction corresponding thereto may be applied.

Method 2. The position of the contact brushes may be shifted and their positions read on a graduated disk. By shifting these brushes to different positions and taking corresponding readings of the voltmeter, data may be obtained for plotting a wave-form curve. By finding the r.m.s. ordinate of the curve and comparing it with the value in volts of the virtual voltage applied to the series of condensers, the multiplying power of the condensers is determined. This method of calibrating makes no assumptions as to the capacities and other properties of the condensers.

When once the calibration has been carried out, the electrostatic voltmeter may be graduated to read directly values of high-tension volts; with the brushes set to the right position, the apparatus reads the maximum voltage used in a breakdown test.

The actual apparatus constructed and used in applying the above method is as follows:

The condenser train (Fig. 2) consists of 21 glass plates 9 by 9 in. (23 cm.) coated on each side with tin-foil 5 by 5 in. (13 cm.) and having a capacity of about 0.0006 microfarad each. These are supported on a rack of dried hardwood impregnated with oil and are immersed in a metal tank filled with transformer oil. The tank is grounded and serves to prevent variations in the capacity of the condensers due to changes in outside conditions. The oil is required to prevent corona discharge at high tension and leakage due to dirt, moisture, etc., on the plates, either of which would cause a change in the impedance and introduce an error.

Since the electrostatic voltmeter has a comparatively short useful working range, the train needs to have a variety of multiplying ratios. For this reason a subdivided mica condenser is used as the grounded condenser, the one to which the voltmeter is connected. This condenser can be adjusted to give any required multiplying ratio. It need not be placed in the oil tank.

The commutator (Fig. 3) consists of a disk of hard rubber into which thin brass contactors are set in such a way that they strike the brushes. The brushes must not touch the rubber surface, for if they do they are liable to get a difference of potential through difference in friction, and to affect the voltmeter reading. The brush-holder is adjustable and its position can be read on a divided circle. A slow-motion tangent screw is provided for adjusting the position of the brushes accurately to the peak of the wave. The commutator is driven through an insulating coupling by a small synchronous motor. A Kelvin multicellular electrostatic voltmeter is used, fitted with a mirror and scale for exact reading. This is surrounded by a grounded electrostatic shield. The capacity of this voltmeter is very low, being approximately 0.00007 microfarad.

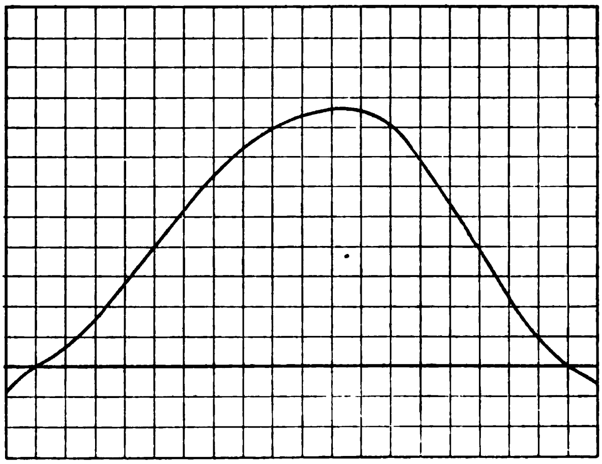

FIG. 4

This apparatus has been tested on a transformer rated at 50 kv-a., 250,000 volts, having the middle point of the secondary grounded. The condenser train was connected from one leg of the transformer to earth and thus was affected by one-half the total voltage. Calibrations were made by both methods given and the results were concordant with each other on a smooth wave form, nearly sinusoidal, and on a badly distorted wave; also on frequencies of 25 and 60 cycles per second. During the tests, which are not as yet completed, voltages as high as 140,000 volts, peak value, have been impressed on the apparatus.

The wave-forms and peak-factors as found with this apparatus were checked by tracing the wave-form by the standard instantaneous contact method and also by the oscillograph.

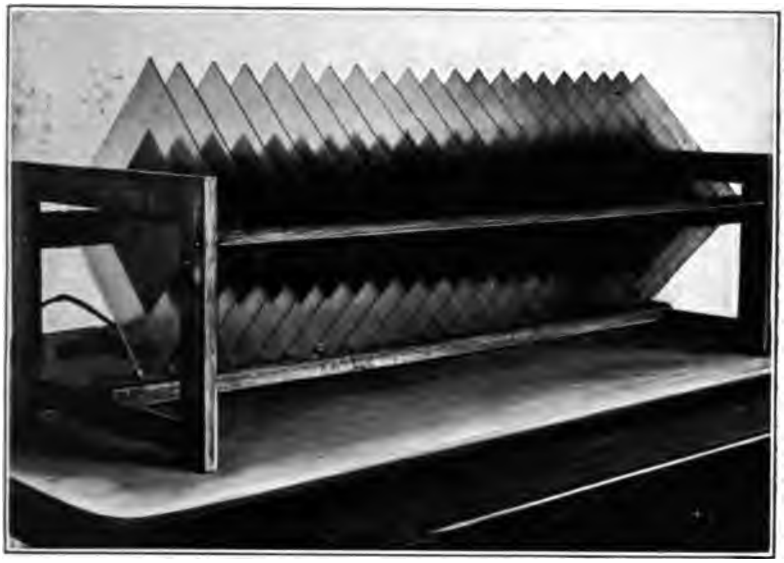

FIG. 2 [SHARP AND FARMER]

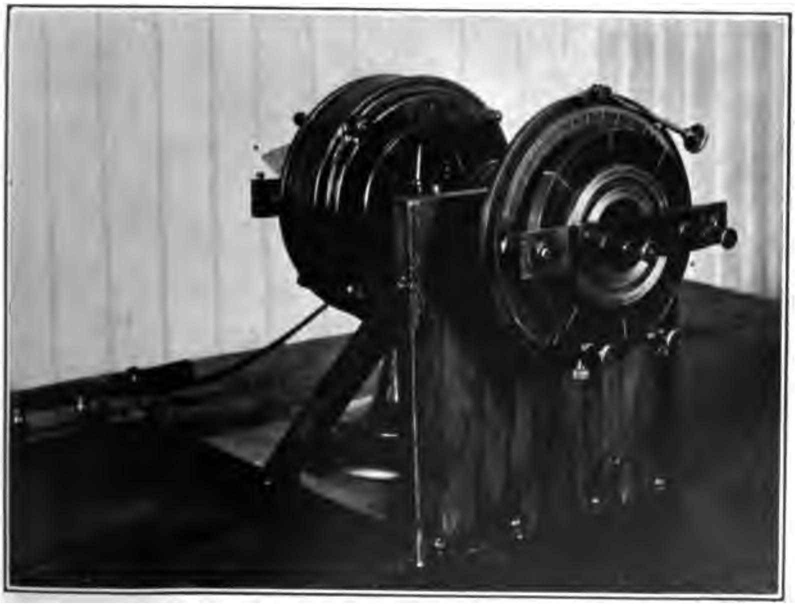

FIG. 3 [SHARP AND FARMER]

With the smooth wave (Fig. 4) of the 25-cycle current, the peak-factor as found by the standard method was 1.50; as found from the wave-form traced with this apparatus it was 1.51; as found from maximum and virtual voltage readings of the electrostatic voltmeter it was 1.52.

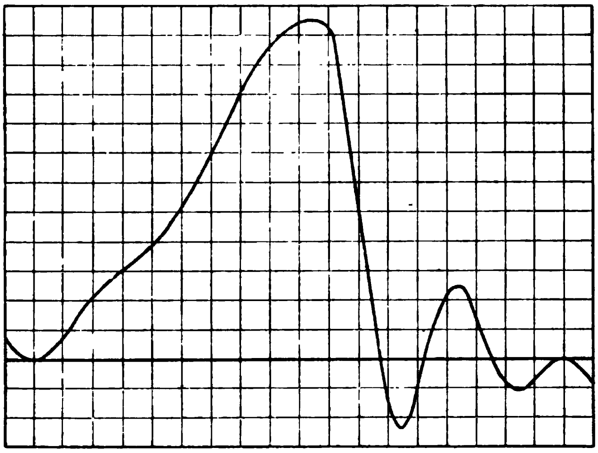

Fig 5

With the distorted wave (Fig. 5) difficulty was encountered in tracing the form by the electrostatic voltmeter. This arose from the fact that the readings of the voltmeter, being proportional to the square of the voltage, become very small at low voltages,

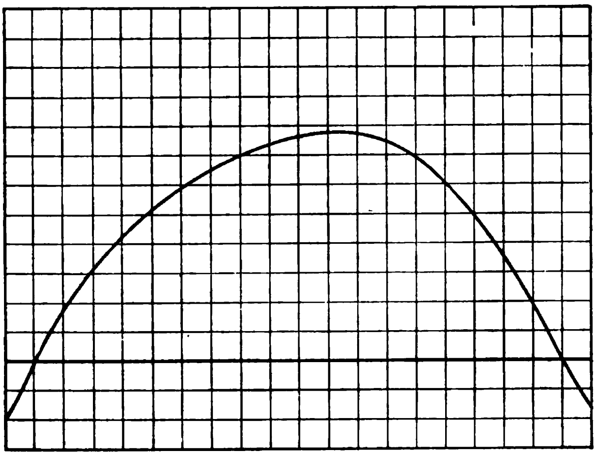

Fig. 6

and from the further fact that the instrument gives no indication of a change of polarity. Hence it was practically impossible to say, from readings of the voltmeter, on which side of the zero line the additional loops of this wave lay. To apply this method, therefore, to a wave which is badly distorted near the zero value would require more delicate means for measuring voltages.

The peak-factor of this wave as determined by the standard methods was 2.00; as determined from maximum and virtual voltage readings on the electrostatic voltmeter it was 2.00; so that this simple method of calibrating held even in this extreme case.

With the 60-cycle smooth wave (Fig. 6) the wave-form by the standard method gave a peak factor of 1.35_4; the voltmeter wave-form gave 1.36 and the maximum and virtual voltage readings gave 1.36_8.

The agreement of the results of the different method is sufficiently close for work of this character. There seems therefore to be no difficulty in calibrating the apparatus to give either maximum or virtual volts of the high-voltage line. The use of this apparatus should relieve high-voltage tests of the uncertainty as to the actual maximum voltage which is being applied. The elimination of guess-work as to this fundamental quantity cannot fail to give more satisfactory results in this important class of testing.

It may be noted that if the testing transformer has low-voltage measuring taps from the high-voltage winding, the commutator and voltmeter may be used directly without the condenser train. The change in range of the voltmeter cannot then be effected so easily, but considerable complication is avoided.

The above work has been performed at the Electrical Testing Laboratories with a view to realizing improvements in the accuracy of testing. The writers desire to express their high appreciation of the very efficient and enthusiastic assistance of Mr. E. D. Doyle in carrying out the experimental work.

Discussion on "Permeability Measurements with Alternating Current" (Robinson and Ball), and "Measurements of Maximum Values in High-Voltage Testing" (Sharp and Farmer), Boston, Mass., June 28, 1912.

E. D. Doyle: As has been suggested in the paper by Messrs. Sharp and Farmer, the electrostatic voltmeter should have small leakage losses. If the voltmeter has low insulation resistance, it will not hold its charge but will discharge according to the exponential law

$$e = e_0 \, \epsilon^{-t/rc}$$

where e_0 is initial voltage,
e is the voltage at time t,
c the capacity of the voltmeter
and r the resistance of the leakage path.

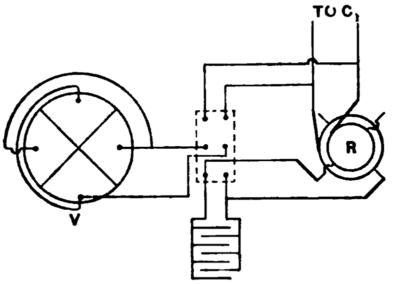

Fig. 1a

Hence the voltmeter will not indicate the maximum voltage, but one depending on the root-mean-square charge on the voltmeter between times of contact.

The effect of leakage can be largely eliminated by connecting a large condenser in shunt across the voltmeter terminals. The condenser acts as a storage reservoir and takes a large enough charge during the instant of contact to supply the leakage losses during the remainder of the cycle without an appreciable fall in potential.

A double-pole, double-throw switch connected as shown in Fig. 1a allows the condenser in shunt to be used for maximum indications and to be cut out for virtual indications. This arrangement has the further advantage of enabling all readings to be taken without stopping the synchronous motor.

In order to show the effect of the condenser in shunt, tests were made on a given voltage wave with various artificial leakage paths between the voltmeter terminals. The results were as follows:

Leakage path—megohms	Shunting condenser microfarads	Peak factor
16,000	none	0.87
1,000,000	"	1.35
50	0.1	1.35
1,000,000	0.1	1.35

From the above it can be seen that with a 0.1-microfarad condenser in shunt the resistance of the leakage path may be as low as 50 megohms without causing trouble, whereas operation is impossible without the shunting condenser if it is 16,000 megohms. The insulation resistance of the voltmeter was originally 8,000,000 megohms but has fallen to approximately 1,000,000 megohms. However, with the capacity in shunt, little trouble is anticipated from surface leakage.

The operation of the apparatus is now very satisfactory. The voltmeter is nearly dead beat and readings can be taken rapidly. Unless the voltage wave is very peaked, brushes do not need to be shifted until the voltage has passed through a wide range. The apparatus should be very useful in high-voltage tests.

M. G. Lloyd: A method for determining permeability by alternating current seems very important. I am glad to see a method proposed for doing that. Of course, methods have already been proposed along that line, but cannot be regarded as entirely satisfactory. In many cases, no doubt, the designer would prefer to have the value of the exciting current rather than the permeability curve, to use in designing; in other cases it is valuable to know the actual permeability at each value of flux density. This paper by Messrs. Robinson and Ball seems to indicate a way in which they may eventually be combined, at least in certain cases.

I think it is necessary, however, to bear the limitations very strongly in mind. It is shown, in the first place, that the maximum exciting current does not correspond to the magnetizing current which gives the maximum flux. This is brought out in the curves of the paper, and can be illustrated very well, if the hysteresis curve, or perhaps more properly, an energy-loss curve, is plotted in cases where there are eddy currents or energy supplied to secondary circuits. In some curves that I determined some time ago under such conditions* the difference from the static hysteresis curve was brought out in a very pronounced way. When the static curve is determined for hysteresis, it is found to go up to a sharp point at the corner of the loop. On the other hand, if the curve is determined with alternating current, and with the existence of eddy currents, that corner becomes rounded off, showing in a very marked way that the maximum exciting

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***Bulletin* of Bureau of Standards, V, page 402; 1908.

current does not correspond with the maximum flux-density. The oscillographic curves in this paper bring out the same thing. Some of the limitations have been expressed by the authors. One of them which is emphasized, is that the specimen must be thin enough to avoid magnetic screening. Another one, which is perhaps not emphasized enough, although it is definitely stated, is that the assumption is made that the eddy currents are in phase with the e.m.f. which produces them. Now, as a matter of fact, that is not generally true, and, of course, the more prominent the eddy currents become, the greater the effect which would be occasioned by the fact that the assumption is not entirely warranted. So that this method, while it may prove to be practicable in certain cases, is likely to be very limited in its application.

We have been in the habit of thinking of the oscillograph as an instrument for simply drawing curves of wave form. In one of the papers presented at the Boston convention, by Professor Harding, we saw how it could be used in making measurements of other quantities than wave form, and here we have an instance of its use in measuring the maximum value of a quantity, and in a case like this the maximum value can be determined without actually drawing the curve, merely observing the deflection on the oscillograph scale. It occurs to me that in the case of maximum voltage, as in the paper presented by Dr. Sharp and Mr. Farmer, it might prove a very convenient means of getting the maximum value. I do not think it would have the accuracy of the method presented by them, but in cases where the highest accuracy is not needed, and the oscillograph is sufficiently accurate, my experience with rotating commutators would indicate that it might be a much more satisfactory method for doing rapid work.

Clayton H. Sharp: I wish to point out the difference that the method I have referred to is one which requires no current. I do not know how you can use the oscillograph without consuming current. The electrostatic voltmeter, once charged, stays charged. There is the difference between it and the oscillograph, and it is a fundamental difference.

As to the rotating commutator not being satisfactory, the same statement applies—the poorest kind of contact is sufficient, because it is only a question of charging the condenser. Not only that, but the use of an actual voltmeter rather than an oscillograph is obviously a desirable thing.

T. W. Varley: What percentage of your contact is the width of the contact relative to the width of the sign? How much of the contact do you lose?

Clayton Sharp: Probably not over one per cent. It is very narrow.

L. T. Robinson: I was much interested in the term used in Dr. Sharp's paper, " peak-factor." It seems to me to be a very good one, but I think it is new. We have used the term " amplitude-factor " that was coined some years ago by Dr. Fleming, which, if I understand correctly, is the reciprocal of this term, and previous to the use of the term " peak-factor," we have had employed in some English publications the term " crest-factor." I like " peak-factor " better because it is quite commonly stated when things happen to the wave that the wave becomes peaked, and the fact of its becoming peaked could be, I think, properly expressed as " peak-factor."

It was intended to point out in Mr. Ball's paper, with which I had some slight connection, that this method never can be exactly right, but we were dealing with practical matters entirely, that is, there was no intention to enter into it from the standpoint of exact theory.

With reference to the eddy currents being out of phase, the best we could figure out along that line was that if there were appreciable screening the eddy current would be out of phase. If there were not, it would be in phase. If there is appreciable screening the method gives incorrect values, because the magnetic density determined by the voltage on the secondary winding would indicate the average value over the sheet. The average value, so determined, would not be the uniformly distributed induction through the sheet, which must of necessity be known in order to plot correctly the B values against the maximum magnetizing current.

The intention of the paper was not to speak of the advantages and wide scope of the method, but to call attention to the fact that even in the cases shown, which seem to be the most favorable kind of samples, that is, samples of iron with low eddy loss, very low indeed, and thin sheets, etc., there is found a tendency of the maximum primary current to exceed the magnetizing current which should be plotted in connection with the B-H curve. At least, the total current had a definite tendency to be so large at maximum as to exceed the magnetizing current, but at the same time the difference was not so large but that it still looked a little hopeful to us.

Elihu Thomson: I would like to say a word about the term " peak-factor." I think it is a good suggestion, but I would like to see " wave-peak-factor " the term, which would define the peak-factor intended. We use the word " peak " in so many significations, peak of the load, etc., that I think the term should be qualified. Of course, if the context of the paper shows what it means it is all right, but as Dr. Sharp has coined the term, it seems to me as a measure of prevention of confusion it might be well to put the word " wave " before it.

Clayton H. Sharp: Regarding that term " peak factor," I did not mean to coin anything. It seemed to be a rather obvious term to use, and I simply used it, without considering whether it was new or old. I doubt if it is a new term, although it may be. I agree with Professor Thomson in his suggestion that the term might be more specific, and it might be made " wave peak-factor."

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

POTENTIAL TRANSFORMER TESTING

NOTE ON THE EFFECT OF THE RESISTANCE OF THE DETECTOR CIRCUIT, IN DETERMINING THE RATIO OF TWO ALTERNATING VOLTAGES, AND THE PHASE ANGLE BETWEEN THEM, BY THE BALANCE METHOD

BY J. R. CRAIGHEAD

In the use of the balance method of determining the ratio of the primary and secondary voltages of potential transformers, certain variations in the result were noted which appeared to be dependent on the relation of the resistance of the detector (R_D in Fig. 1) to the balance resistance R_1 and R_2. A short theoretical investigation and a few tests were made to determine the cause and the order of magnitude of the errors involved, and to ascertain safe limits of operation. As the measurement of the detector voltage has frequently been suggested as a means of determining phase angle between voltages, the relation of the detector resistance to this measurement was also considered.

The cause of error is the current drawn in the detector circuit. If the two voltages to be compared are in phase and of the same wave form, no current flows in the detector circuit when a balance is obtained, and no error can result from this cause. In the usual condition, however, as in determining the voltage ratio and phase angle of a potential transformer, the voltages are slightly out of phase and may even differ slightly in wave form. Then the balance is obtained when the detector indicates minimum or zero, but a current flows in the detector circuit proportional to the voltage across the detector (practically in quadrature with the voltages compared) and inversely proportional to the resistance of the detector circuit. This current evidently passes through one section of the bridging resistance placed across the greater voltage, but not through the other. Since the balance will be obtained when the voltages across the two resistances reach a certain relation, and since the currents in these resistances are unlike, the ratio of resistances is in general not an exact representation of the ratio of the voltages compared; and since the detector current, taken in quadrature from the current in one of the bridging resistances, causes it to differ in phase from the current in the other bridging resistance, the minimum reading of the detector will be representative of an angle (α in Fig. 2) which is not identical with γ, the phase angle between the voltages compared.

The nature of the detector employed has an influence on the result. This may be (*a*) a simple voltmeter (see Figs. 1 and 2)

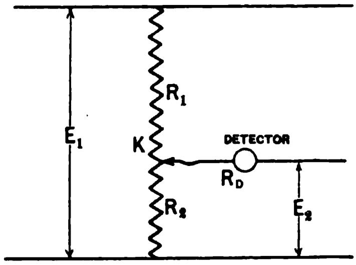

FIG. 1

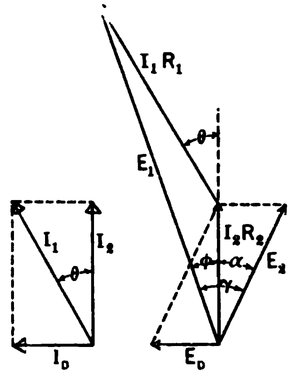

FIG. 2

or (*b*) a dynamometer separately excited. The excitation may be in phase with E_2, E_1, I_2 or I_1. The error with excitation in phase with I_2 is the same as under (*a*). If the excitation is supplied in phase with E_1, E_2 or I_1, the balance is obtained under slightly different phase relations, and the errors enter into the results in slightly different ways.

To obtain an idea of the order of magnitude of the errors involved, it will be sufficient to analyze case (*a*) where the detector is a simple voltmeter, reading a minimum at balance, and where the phase angle may be obtained from this minimum reading.

Referring to Figs. 1 and 2, assume E_1 and E_2 to be two sine wave voltages differing in phase by the angle γ, balanced for comparison as indicated in the sketch. The voltage E_D across the detector is in quadrature with the voltage $I_2 R_2$ across R_2, since the contact point K which marks the division of the total bridging resistance into R_1 and R_2 has been shifted until the reading of the detector is a minimum. If I_1, I_2, and I_D are the currents flowing in the resistances R_1, R_2 and R_D respectively,

$$I_2 R_2 = \sqrt{E_2^2 - E_D^2}$$

whence

$$I_2 = \sqrt{\frac{E_2^2 - E_D^2}{R_2^2}}$$

$$I_D = \frac{E_D}{R_D}$$

$$I_1 = \sqrt{I_2^2 + I_D^2} = \sqrt{\frac{E_2^2 - E_D^2}{R_2^2} + \frac{E_D^2}{R_D^2}}$$

The angle between I_1 and I_2, or between $I_1 R_1$ and $I_2 R_2$, is

$$\theta = \cos^{-1}\left(\frac{I_2}{I_1}\right)$$

Now

$$E_1 = \sqrt{I_1^2 R_1^2 + I_2^2 R_2^2 + 2 I_1 R_1 I_2 R_2 \cos\theta}$$

and for true ratio of voltages

$$\frac{E_1}{E_2} = \frac{\sqrt{I_1^2 R_1^2 + I_2^2 R_2^2 + 2 I_1 R_1 I_2 R_2 \cos\theta}}{E_2}$$

Substituting and simplifying,

$$\frac{E_1}{E_2} = \sqrt{\frac{E_2^2 - E_D^2}{E_2^2} \times \left(\frac{R_1 + R_2}{R_2}\right)^2 + \left(\frac{E_D R_1}{E_2 R_D}\right)^2} \qquad (1)$$

Equating to $\frac{R_1 + R_2}{R_2}$ and solving for R_D,

$$R_D = \frac{R_1 R_2}{R_1 + R_2} \qquad (2)$$

That is, if the resistance of the detector is adjusted to the value obtained from equation (2), the reading obtained from

R_1 and R_2 will accurately represent the ratio of voltages without correction for phase angle, the errors in ratio due directly to phase angle and those due to the detector current offsetting one another. When R_1 is large compared with R_2, this formula becomes approximately

$$R_D = R_2$$

For instance, in testing a transformer rated 2200 : 110 volts, the values of resistance used were R_1 = 19,000 ohms and R_2 = 1000 ohms.

$$R_D = \frac{R_1\,R_2}{R_1 + R_2} = 950 \text{ ohms.}$$

If R_D is kept at 1000 ohms, the error in ratio determination is negligible, amounting to 0.0006 per cent for γ = 1 deg., 0.0016 per cent for γ = 2 deg., and 0.006 per cent for γ = 4 deg.

The maximum limits to which the error may reach are shown as follows: If α is the angle between E_2 and $I_2\,R_2$, equation (**1**) may be rewritten

$$\frac{E_1}{E_2} = \sqrt{\left(\frac{R_1 + R_2}{R_2}\right)^2 \cos^2\alpha + \left(\frac{R_1}{R_D}\right)^2 \sin^2\alpha}$$

$$= \frac{R_1 + R_2}{R_2}\cos\alpha\sqrt{1 + \left(\frac{R_2}{R_D}\right)^2\left(\frac{R_1}{R_1 + R_2}\right)^2 \tan^2\alpha}$$

If ϕ is the angle between E_1 and $I_2\,R_2$, equalling $\gamma - \alpha$,

$$\cos\phi = \frac{I_2\,R_2 + I_1\,R_1\cos\theta}{E_1}$$

$$\text{Since } \cos\theta = \frac{I_2}{I_1} \text{ and } I_2\,R_2 = E_2\cos\alpha,$$

$$\cos\phi = \frac{E_2\cos\alpha + E_2\cos\alpha\,\dfrac{R_1}{R_2}}{\dfrac{R_1 + R_2}{R_2}\,E_2\cos\alpha\sqrt{1 + \left(\dfrac{R_2}{R_D}\right)^2\left(\dfrac{R_1}{R_1 + R_2}\right)^2\tan^2\alpha}}$$

$$\cos\phi = \frac{1}{\sqrt{1 + \left(\dfrac{R_2}{R_D}\right)^2\left(\dfrac{R_1}{R_1 + R_2}\right)^2\tan^2\alpha}} \qquad (8)$$

whence

$$\frac{E_1}{E_2} = \frac{R_1 + R_2}{R_2} \times \frac{\cos \alpha}{\cos \phi} \tag{4}$$

Now since $\gamma = \alpha + \phi$,

$\cos \alpha$ varies from 1 to $\cos \gamma$, while
$\cos \phi$ varies from $\cos \gamma$ to 1;

at the same time R_2/R_D varies from 0 to infinity.
Hence the correction factor to be applied to the ratio of resistances varies with changes of R_D from $\cos \gamma$ as one limit through unity to $1/\cos \gamma$ as the other. It will evidently be equal to unity (no correction necessary) when $\alpha = \phi = \gamma/2$. In this case, from equation (3)

$$\cos \alpha = \cos \phi = \frac{1}{\sqrt{1 + \left(\frac{R_2}{R_D}\right)^2 \left(\frac{R_1}{R_1 + R_2}\right)^2 \tan^2 \alpha}}$$

which, solved for R_D, gives

$$R_D = \frac{R_1 R_2}{R_1 + R_2}$$

which is equation (2) again. That is, the same value of R_D which gives a correct ratio reading, gives also a phase angle obtainable from the minimum reading of the detector by the formula

$$\alpha = \sin^{-1}\left(\frac{E_D}{E_2}\right)$$

which is one-half of the actual phase angle γ.

This method of obtaining phase angle, however, falls into serious error if the resistance R_D varies more than a few per cent from the theoretical value, and correction is too complicated for practical use. Other methods which do not involve these errors (as, for instance, the use of two dynamometers whose fields have a common excitation adjustable in phase) are much to be preferred. If the excitation of the dynamometer is in phase with E_1 or with I_1, the equations are more complicated, but the general order of the errors is similar to the above. If the excitation is in phase with E_2, the equation for ratio takes the form

$$\frac{E_1}{E_2} = \frac{R_1 + R_2}{R_2} \times \frac{1}{\cos\alpha \cos\phi}$$

$$\times \left[1 + \left(\frac{R_1}{R_1 + R_2}\right) \times \left(\frac{R_2}{R_D}\right) \times \sin^2\alpha\right] \quad \mathbf{(5)}$$

As the two factors indicating the error both have an effect in the same direction, there is no single value of R_D at which the ratio error is totally eliminated.

If $R_D = \dfrac{R_1 R_2}{R_1 + R_2}$, equation (**5**) becomes

$$\frac{E_1}{E_2} = \frac{R_1 + R_2}{R_2} \times \frac{1 + \sin^2\alpha}{\cos\alpha \cos\phi}$$

If $\alpha = \phi$, which would be very nearly true with this value of R_D,

$$\frac{E_1}{E_2} = \frac{R_1 + R_2}{R_2} \times \frac{1 + \sin^2\alpha}{1 - \sin^2\alpha}$$

This equation gives the following values:

γ	α	Correction factor	Per cent error
1 deg.	30 min.	1.00008	0.008
2 deg.	1 deg.	1.00061	0.061
3 deg.	1 deg. 30 min.	1.00137	0.137

It is evident that a satisfactory accuracy can be attained with about 2 deg. phase angle. These results change but slightly for moderate changes of R_D.

SUMMARY

Ratio of voltages may be taken by the balance method with entire accuracy, if the detector is either self-excited or excited in phase with I_2, by keeping

$$R_D = \frac{R_1 R_2}{R_1 + R_2} \cdot$$

If this value is even approximately maintained, errors are negligible.

With excitation in phase with E_1 or I_1, the errors are of a similar order of magnitude, but the equations involved are much more complicated, and the exact errors are much more difficult to determine.

With excitation in phase with E_2, the errors are never reduced to zero; but where the phase angle γ is 2 deg. or less, the error in ratio is only about 0.06 per cent if R_D is kept equal to or greater than the value in the above formula. This amount is negligible for ordinary purposes.

For phase angle, with any of the above connections, a result may be obtained by keeping R_D equal to the value given above, and doubling the angle obtained by direct calculation. It is, however, subject to considerable error if R_D varies, and correction is impracticable; therefore it is better to use some method which does not involve these errors, as for instance, the two-dynamometer method.

It should be noted that the above results are calculated for sine wave voltage. With a distorted voltage wave, or with slightly differing waves, harmonic currents flow in the detector which greatly complicate the theory. The actual additional errors caused by this are in general negligible for practical work. Where inductive devices are used to balance the voltage in the detector circuit, they do not, on account of wave form, wholly prevent the flow of current, and consequently only diminish, without entirely avoiding, the errors described above. The further discussion of these methods is not properly a part of this paper.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

THE TESTING OF INSTRUMENT TRANSFORMERS

BY P. G. AGNEW AND F. B. SILSBEE

The determination of the ratio and phase angle of instrument transformers has now become a very important part of the work of electrical testing laboratories. The method now almost universally used in accurate work depends upon the potentiometer principle. Various modifications of this method have been suggested and used*. A modification of the method has recently been developed at the Bureau of Standards which, while involving no entirely new principles, possesses some distinct advantages over any of these.

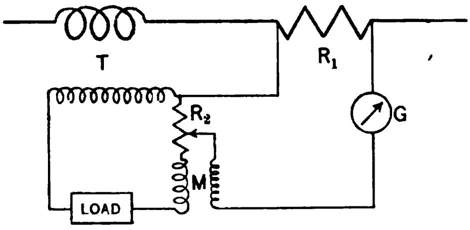

FIG. 1

The connections for the current transformer are shown in Fig. 1. Current from the source flows in series through the primary winding T of the transformer under test and through a standard non-inductive low-resistance shunt R_1. The secondary current flows through the normal load of instruments, through the primary winding of a variable mutual inductance M and through a non-inductive resistance R_2, a variable part of which

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* For a resumé of these methods and a bibliography, see *Bulletin*, Bureau of Standards, Vol. VII, p. 423, 1911, reprint No. 164.

may be included in the galvanometer circuit. The resistances R_1 and R_2 have values inversely proportional to the currents flowing in them so that the $I R$ drop is the same in both. The potential terminals are connected so that these equal voltages are in opposition and if there were no phase difference between them no current would flow through the vibration galvanometer G. On account of the phase-displacement in the transformer, however, it is necessary to introduce an e.m.f. in quadrature with $I_2 R_2$. This is done by the mutual inductance M. The procedure is therefore to adjust successively R_2 and M until the galvanometer shows no current. It can then be easily shown that the ratio of the currents is

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} \frac{1}{\cos\theta}$$

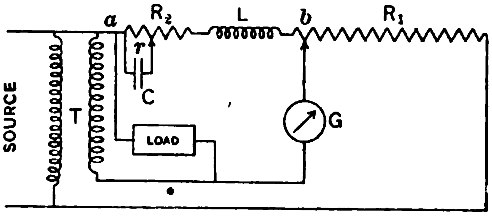


FIG. 2

and the phase angle is

$$\theta = \tan\theta = \frac{P\,M}{R_2} \text{ radians} = 3438\,\frac{P\,M}{R_2} \text{ min.}$$

In most transformers the factor $\frac{1}{\cos\theta}$ differs from unity by less than one part in 2000, and hence for most engineering work it may be omitted. It may be necessary, however, to correct the phase angle for the inductance of the shunts.

The connections for the potential transformer are somewhat analogous and are shown in Fig. 2. A high resistance R_1 is connected in series with a smaller resistance R_2 and a self-inductance L across the high-voltage side of the transformer. The low-tension winding is connected in a reversed sense to the points a and b of this resistance, the galvanometer G being in series with the low-voltage winding. The procedure is to adjust R_2 (or better

R_1) and L until a balance is obtained. It can then be shown that the ratio of transformation is

$$\frac{E_1}{E_2} = \frac{R_1 + R_2}{R_2} \cos \theta,$$

neglecting terms of higher order; and, assuming R_1 and R_2 to be non-inductive,

$$\theta = \tan \theta = P\,L \left(\frac{1}{R_2} - \frac{1}{R_1 + R_2}\right) \text{ radians } =$$

$$3438\ P\,L \left(\frac{1}{R_2} - \frac{1}{R_1 + R_2}\right) \text{ min.}$$

The adjustment for the phase angle may be made by a variable self-inductance in R_1 or R_2, or by a mutual inductance, or by shunting a variable amount of R_1 or R_2 by a condenser. This latter combination is sensibly equivalent to a negative self-inductance of magnitude $C\,r^2$. In practise it has been found best to use a self-inductance in series with R_2, together with a condenser shunting a variable portion of R_2.

With this arrangement the effective inductance of the circuit is

$$L - \frac{C\,r^2}{1 + p^2 C^2 r^2}$$

and the resistance is

$$\frac{R_2}{1 + p^2 C^2 r^2}$$

The term $p_2\,C_2\,r_2$ is practically always negligible, compared with unity, so that $L' = L - C\,r^2$, and R_2 is unaffected by the condenser. The advantage of this arrangement is that it is possible without changing the set-up to test a transformer in which the phase angle changes from leading to lagging.

Considerable difficulty was encountered in obtaining a sufficiently sensitive self-contained detector in the case of the current transformer. At first sight this seems surprising, since one naturally associates instrument transformers with heavy currents and high voltages. The trouble arises from the fact that the entire performance of the apparatus depends on the magnetic properties of its iron core, and consequently it must be tested under exactly the conditions of use, and sensitivity cannot be gained by forcing an abnormal amount of power into the circuit for a short time, as is possible with condensers, etc.

For the current transformer, in order to obtain a sensitivity of 1 in 10,000 at one-tenth load, it is necessary to use a detector capable of responding to about 2 microvolts a-c. We obtain this sensitivity by using a vibration galvanometer of the Campbell type, the moving system of which was reconstructed largely in accordance with suggestions of Dr. Wenner. The moving coil consists of but 4 turns of No. 28 wire. The total resistance is 0.66 ohm. The sensitivity is such that at 25 cycles one microvolt gives a deflection of 0.5 mm. at a scale distance of one meter. A range of frequency between 40 and 80 may be obtained by varying the length and tension of the suspensions. For lower frequencies between 40 and 20 cycles the moment of inertia is increased by the addition of a brass washer which may be dropped on a tiny cone at the top of the coil, thus automatically centering itself.

The advantages of the method are that only a single instrument is needed for all ranges of transformers, but one observer is required, and neither a polyphase source of voltage, a phase-shifting device, nor a rotating commutator is required.

DISCUSSION on "POTENTIAL TRANSFORMER TESTING" (CRAIGHEAD), AND "THE TESTING OF INSTRUMENT TRANSFORMERS" (AGNEW AND SILSBEE), BOSTON, MASS., JUNE 28, 1912.

Clayton H. Sharp: Regarding the last statement of Dr. Wenner, in his abstract of the paper by Messrs. Agnew and Silsbee, I find it rather surprising, inasmuch as the identical method for testing current transformers, with the exception of the vibration galvanometer detector, has been in use in our laboratory for two or three years, and a description of it was presented to the convention of the Institute three years ago, I think, at Frontenac. The method is absolutely identical with the one described in the TRANSACTIONS of the Institute, to which I refer, and we included a satisfactory detector, so that I do not see how in presenting a description of this method the statement could be made that no satisfactory detector was at hand. It was indicated at that time.

James R. Craighead: This paper on the testing of instrument transformers by Messrs. Agnew and Silsbee has brought forward the vibration galvanometer as a new device for use as a detector of small voltages on alternating-current circuits. A few points of comparison with the separately excited dynamometer may be worth consideration. First, in regard to the matter of sensitivity, we find that Mr. Agnew's galvanometer at 25 cycles gives a deflection of 0.5 mm. at a scale distance of one meter for one microvolt, or about 1.5 microamperes. The dynamometer which we are using for similar work requires about 4 microvolts or 0.1 microampere for the same deflection. This sensitivity can be considerably increased by simple changes, but has been found sufficient for the purpose.

Convenience. The vibration galvanometer must be adjusted by a change of the length and tension of the suspension or by adding weights for each frequency. This would involve much handling of delicate parts and consequent trouble if applied to commercial testing where change of frequency is made at short intervals. Also, reading to a zero with return in the same direction, presents a little more practical difficulty than reading a zero when the indicator passes through instead of to the point.

On the other hand, the separately excited dynamometer requires a phase-shifting transformer and a polyphase supply. A shift of phase without the polyphase supply is not difficult to arrange, but is much less convenient and in general less accurate than the polyphase method. The same adjustment of the dynamometer is correct for all frequencies. The reading is through a zero so that there is never a doubt in which direction to change the adjustment in finding a balance.

The use of condensers and reactance in connection with the resistances of a potential transformer outfit involves difficulties of commercial handling. Ordinary condensers are unsatisfactory apparatus where permanent accuracy is required. Wherever a considerable amount of testing is to be done, this consideration alone may offset the advantage of using only one observer in phase-angle tests on potential transformers; especially as the time required for adjustment of resistance, reactance and condensers would undoubtedly diminish the actual gain. The condenser-reactance combination, which does not make a satisfactory phase-shifting arrangement even for exciting a dynamometer, is here made a part of the measurement circuit.

In general, the gain in using the vibration galvanometer appears to be the elimination of the polyphase circuit and phase-shifting transformer, and, in comparison with some other methods, of one observer. The loss is in the added complication of the instrument, the probable increase of time spent in repairs and adjustment, and the difficulties involved in shifting the phase of the measured voltage by capacity and reactance.

Edward B. Rosa: This discussion brings out pretty clearly that one cannot generalize and say that a given method is better than some other method, for a series of reasons, without going further and specifying the circumstances under which they are to be used. It may appear very difficult for one man, with certain routine surroundings, to use, for example, mutual inductances and condensers, whereas another man, having them at hand, may find them much more convenient than a polyphase source of power and phase-shifting devices or something else. The truth in this case is, that in one laboratory one method has been found to be much more convenient, and in another laboratory the other method is much more convenient. The writer of this paper, from his standpoint and training, thinks this is a very distinct improvement over previous practise, for the reasons he specifies; nevertheless another method may be much preferred in other surroundings by other experimenters.

L. T. Robinson: I would like to endorse that view fully. The advantage of such papers and such discussions as this is to bring out these facts, and there is everything to be gained by the one man knowing the point of view of the other man. I feel very sure that all of us who have been working along the line referred to, appreciate the fact that perhaps unconsciously, but nevertheless quite truly, we have adopted a great many of the methods of other laboratories until there is more similarity than there was, at least in the test methods that are used. I know at the Frontenac meeting, three years ago, I had some very definite ideas myself on the subject, but they have become somewhat modified, although we hold to substantially the same practise as was described then.

Clayton H. Sharp: I want to say a word or two about the advantages and convenience of a synchronous reversing key or rectifier in measurements, not only of current and voltage transformers, but in some other alternating-current measurements as well. With the synchronous reversing key you can use the direct-current galvanometer, you can use as sensitive a galvanometer as you want, although beyond a certain point other troubles come in which will prevent the use of the highest sensitivity.

This detector in transformer testing has the additional advantage that it is selective of the resistance and the reactive components in the e.m.f. In testing a transformer two operations are gone through with: First, the key is set so that it reverses in phase with the resistance drop from one shunt to the other. The deflection is then brought to zero. The brush holder is then shifted through 90 deg., becoming in phase with the reactive drop, and the mutual inductance is then shifted until the deflection comes to zero. These two adjustments are made separately and not simultaneously, and they do not get in each other's way. The whole operation is performed in a moment with a high degree of certainty, whereas in the vibration galvanometer you have an instrument which does not differentiate and a double adjustment is necessary. With practise, however, it may become easy, but there is still an advantage in the use of the other system. The synchronous reversing key can be readily used in measurements of inductance or capacity by the ordinary bridge methods, and it has the same advantages, that you can separate the resistance drop from the reactive drop. It has worked out as a very convenient and very sensitive and good instrument in alternating-current laboratory work.

L. T. Robinson: I think Dr. Sharp's remarks bring out Dr. Rosa's point to the fullest value. I started first with the reversing commutator and direct-current galvanometer, and it did not suit me very well. We then took up the separately excited dynamometer. On the contrary, Dr. Sharp got a reversing commutator that went a little better than ours went, and it has remained his method. The Bureau of Standards has found the vibration galvanometer useful. I have never tried one. We bought some, and put them up in the cases, and they are there yet, but we never have had time to test them out and see what they would do. Therefore, it is only fair to say that ideas along these lines should be tempered with the influence of surrounding circumstances properly considered.

Frederick Bedell: A word on the question of the synchronous commutator and the non-synchronous commutator—as Dr. Sharp has pointed out, with the synchronous commutator various adjustments are made which have certain points of advantage in manipulation and which make it possible to determine the phase angle as well as the amplitude of the quantity measured. If the commutator is driven by a motor that is just off from synchronism, none of these adjustments are necessary, and one's attention is free from other things in connection with the test. The galvanometer will then have beats and the deflection will rise to a maximum and fall; the deflection may be reduced to a minimum or to zero, thus giving a very sensitive zero instrument.

Edward B. Rosa: I would like to say something in defense of, or rather in justification of the vibration galvanometer. We have used the synchronous commutator with a direct-current galvanometer at the Bureau of Standards. Years ago we undertook to make refined measurements of certain kinds with that combination, but while the sensitivity is high the sources of error, we found, were serious, the commutator being a serious disturbance. We have had most satisfactory results with the vibration galvanometers, and it is for that reason that we are using them in several of our laboratories. The fact that the vibration galvanometer, attuned to the frequency of the current, practically ignores the harmonics, is a very great advantage in much of the testing. The sensitivity is so small for harmonics, as compared with that of the fundamental, that it has a very great advantage over the other style of instrument; and as to being obliged to make two adjustments at once, or not knowing, from the fact that the deflection is both sides of zero, which kind of adjustment to make, I can assure you a little experience makes that difficulty seem very much smaller than it appears at first sight.

We have used the vibration galvanometer, now, for ten years, and have a good many of them of different types in service, using them for very many purposes; we have also used the other styles of indicating instruments, so that we can speak from experience with both instruments.

W. W. Crawford: In regard to Mr. Agnew's paper on the testing of instrument transformers, I noted that Mr. Agnew states that he considers the method of connection which he has used, that is, introducing a resistance in the secondary circuit of the current transformer, with a mutual inductance for balancing phase displacement, is the best method that can be used. I believe I can verify that statement from practical sources, because we used the method some time back and we found it very satisfactory. We did not use the vibration galvanometers in connection with it, but we used, as I presume Dr. Sharp has already pointed out, a synchronous rectifier, which did not consist of a commutator with sliding contacts, which always give trouble. We used a rectifier consisting of a vibrating tongue, driven by a synchronous motor and a cam. The vibrating tongue carried platinum contacts which reversed the connections. The contact resistances were negligible so we were able to obtain the full sensitiveness of the direct-current galvanometer for alternating-current measurements. We were able to get the limits of sensitiveness which Mr. Agnew mentions with a synchronous motor of the type developed by Mr. Robinson, which could be carried in one coat pocket, and a portable galvanometer of the type made by R. W. Paul, of London, which could be carried in the other pocket. We could get a sensitiveness of one microampere per division, or 50 microvolts per division, the apparatus being entirely portable and independent of telescopes, reflecting scales, etc.

Frank Wenner: In regard to Mr. Craighead's statement concerning the sensitivity of the separately excited dynamometer, I need only say that the sensitivity of the galvanometer used is sufficient for all purposes. If a higher sensitivity were needed, I do not think there would be any difficulty in getting ten times the sensitivity indicated. Dr. Agnew simply stated he would rather have a galvanometer of this sensitivity than one of higher sensitivity.

In regard to the method Mr. Craighead described as compared with the method that Dr. Agnew is using, as I understand the situation, Dr. Agnew has used, for a period of four years, the identical method which Mr. Craighead has described, and I believe he considers the method he is now using as a decided improvement upon the former method.

In regard to Dr. Sharp's reference to the synchronous rectifier, Dr. Rosa has already pointed out some of the difficulties in regard to that. At the present time we have in the Bureau a synchronous rectifier, and have for sometime been trying to make it operate satisfactorily. Dr. Burrows, who is working on that subject, has had difficulties, so has called upon the rest of us for suggestions. The various suggestions have been tried out, and at one time he made a visit to Dr. Sharp's laboratory to see if he could not get some more valuable suggestions there, but still the synchronous rectifier does not work satisfactorily.

P. G. Agnew and **F. B. Silsbee:** The discussion seems to have centered about the use of the vibration galvanometer as a detector and the question of what constitutes the most satisfactory detector. As has been very clearly stated by Dr. Rosa and Mr. Robinson, the answer to this question depends both upon the equipment and traditions of the laboratory and upon the training and experience of the observers. Certainly, Dr. Wenner did not intend to imply that the arrangement used by Dr. Sharp and Mr. Crawford of a mutual inductance with a rotating commutator and d-c. galvanometer as detector was an unsatisfactory one. Probably no one would claim that any of the detecting devices which have been used in the work is ideal, whether he is using a rotating commutator, a dynamometer, a vibration galvanometer, or, as has been used at the Physikalisch-Technische Reichsanstalt, an electrostatic instrument. Most of the instrument transformer testing at the Bureau of Standards during the last four years has been done by a dynamometer method very similar to that used by Mr. Craighead. However, it was always felt that a self-contained detector would be decidedly preferable. Both ratio and phase angle are determined by a single balance, and the accuracy does not depend upon any subsidiary or external adjustment, and no quadrature current is drawn from the network. This surely minimizes the chances of error. The condensers or inductances are used to shift the phase only by the small angle of the transformer, and the accuracy and permanency of such devices is far greater than that required by the precision which is desirable in phase angle measurements.

A point which has been entirely overlooked in the discussion is that the volt sensitivity is the essential consideration in current transformer work, while the current sensitivity is practically immaterial. In the case of potential transformers the reverse is true, but there is no difficulty in obtaining the requisite current sensitivity. Practically any commercial vibration galvanometer is sufficiently sensitive. In fact too sensitive a detector is undesirable, as it is likely to allow errors to enter from extraneous sources. The galvanometer described was designed to give a high volt-sensitivity and a low current-sensitivity.

It should be noted in this connection that a vibration galvanometer is analogous to a motor and the volt sensitivity cannot be obtained directly by multiplying the current sensitivity by the resistance, but account must be taken of the back e.m.f., as is pointed out by Dr. Wenner in a paper presented at this convention. He cites a case in which the back e.m.f. was approximately 40 times the $I R$ drop. Our galvanometer was designed to give a back e.m.f. approximately equal to the $I R$ drop, or a current sensitivity twice the value computed by Mr. Craighead.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

OPERATING CHARACTERISTICS OF LARGE TURBO-GENERATORS

BY A. B. FIELD

The requirements of the station engineer, with regard to the operating characteristics of large alternators, have materially changed during the last few years, concurrently with the rapid increase of size, measured in kw., of the individual power houses and of the individual generating units. Some characteristics which ten years ago were striven for, are now avoided and considered actually detrimental.

It is proposed here to consider briefly the trend of modern practise in respect of some of these requirements.

The condition referred to is not merely the result of increasing size of units, and of groups of units, but has been effected, for instance, by the radical change in speed for a given output, by changed methods of operation, etc. It was not many years ago that the largest rating of turbo-generators offered for a speed of 3600 rev. per min., was 500 kw., and even that was apt to be a troublesome machine on account of a design ill adapted to the speed.

At the present time there are thoroughly satisfactory generators in operation in this country having a continuous rating of 5000 kv-a. at 3600 rev. per min., and in Europe 4000 kv-a. at 3000 rev. per min. Eight years ago 750 rev. per min. was a high speed for 7500-kw., four-pole generators. At the present date six-pole turbo-alternators of over 20,000 kw. at 1000 rev. per min. in a single unit, have been constructed in Europe; and in this country two-pole generators for the same output at 50 per cent higher speed are under construction, and four-pole machines for 19,000 kv-a. output at 87 per cent higher speed, or 1875 rev. per min. From an electrical point of view, these high speeds are not economically desirable for these ratings, but the advantages to be gained when considering the set as a whole—turbine and generator—warrant their adoption, particularly as they entail no smaller factors of safety than have been tolerated in the smaller machines in the past. The size of the unit has been continually pushed further, and if there should be a sufficient call from the steam turbine builder and the operator, for a speed of 1500 rev. per min. for still larger sets there is little doubt but that 30,000- or 35,000-kv-a. units for high power factor operation may later be built of the two-pole type, though possibly we may then no longer depend for cooling upon the methods at present in use.

In a recent paper before this Institute, Mr. Samuel Insull advocated the concentration of power generation for public services in each district, and pointed out that in Greater New York there was already a total developed load of 600,000 to 700,000 kw. Without discussing Mr. Insull's arguments, we may note that the company of which he is the president committed itself more than a year ago to a 240,000-kw. station in Chicago, in addition to its two large stations at Fisk and Quarry Streets. Again, should the near future see any developments in Europe along the directions hinted at recently by Sir William Ramsay, with regard to the production of power from coal at the pit mouth, and turbine units be used, the size of these units would necessarily be much larger than any hitherto constructed. In fact, we must recognize that we have not yet reached the era of the " large " generator, though we cannot say, with quite the same assurance, that the high speed, relatively to output, at present in evidence, is to be similarly progressive.

In the early days of alternating-current station practice, alternators were sometimes specified " to be capable of running five minutes on a dead short circuit with normal excitation without injury," and when close regulation was not also called for, this clause was generally agreed to by the manufacturers. Comparatively little attention was paid to the way in which the short circuit was introduced, and such a requirement would have been considered to be met by short-circuiting the generator and then bringing up the excitation to normal value; in fact in the case of the type of generator involved, viz., slow speed, small rating, with many poles, the instantaneous current on short-circuiting would not be many times the sustained short-circuit current.

Conditions are very different, however, with the machines built now, and operating engineers are frequently wisely specifying that the machines they buy are to be capable of being short-circuited suddenly, when running at full speed fully excited, without any mechanical or electrical injury resulting. They are aware that under such conditions the current flowing through the stator winding may be very many times the final steady value obtaining a minute or two after short-circuiting. This requirement is by no means an easy one to meet sometimes, and necessitates details of construction which are somewhat costly and have some other disadvantages as well. However, it is recognized by some of the manufacturing companies that the operator has a good case, and that even if, in an up-to-date station, the arrangements should be such that an involuntary test of this nature is rare, yet the ability of the generator to stand such a test is a good guarantee that the machine will meet a number of other conditions occurring in practise which cannot be covered in detail in a purchasing specification.

The amount of instantaneous short-circuit current is of interest to the operating engineer from two points of view; viz., the effect upon his generator and that upon his circuit-opening devices. Both aspects have been simultaneously studied carefully by the manufacturers, so that now, while the current to be dealt with has been kept within moderate limits, and generator constructions have been developed which are amply able to stand the strains, at the same time switch gear is available which will meet the needs at present in sight.

It is of interest to consider the features which influence the amount of the instantaneous short-circuit current, the way in which this depends upon size, speed, frequency and regulation, and to do so we must picture in a general way the process by which it is produced. These have been well recognized for some years, but to facilitate the argument they are briefly described below.

Consider a generator running on no-load at normal voltage, on which a short circuit is developed between two terminals *B C* at the instant when the voltage *B C* is zero. At this moment, the windings of the short-circuited phase are inclosing their maximum rotor flux. If this flux were to be abstracted by the motion of the rotor and no self-inductive or other flux substituted, the current would mount up to a value of say 300 times that corresponding to the rated current (assuming a full-load I^2R

loss of 0.3 per cent). Actually, the current will rise at a rate to produce by self-inductive flux a voltage nearly corresponding to the phase voltage, and this self-inductive flux must to a large extent find a path clear of the rotor, as the rotor winding and solid metal form closed circuits hindering any rapid changes of enclosed flux. This stray flux, and the current producing it, will increase steadily in value until the rotor pole has abstracted its flux, and as the next pole comes forward with its flux, which similarly cannot be instantly quenched and must, therefore be largely deflected, the short-circuit current will still further increase to produce a stator leakage flux nearly counteracting, as far as the stator winding is concerned, the addition of this reversed rotor flux. This case—short-circuiting at the zero point of the voltage wave—gives the worst condition as regards magnitude of the stator current, and gives a current wave which for the first few cycles is practically all on one side of the zero line.

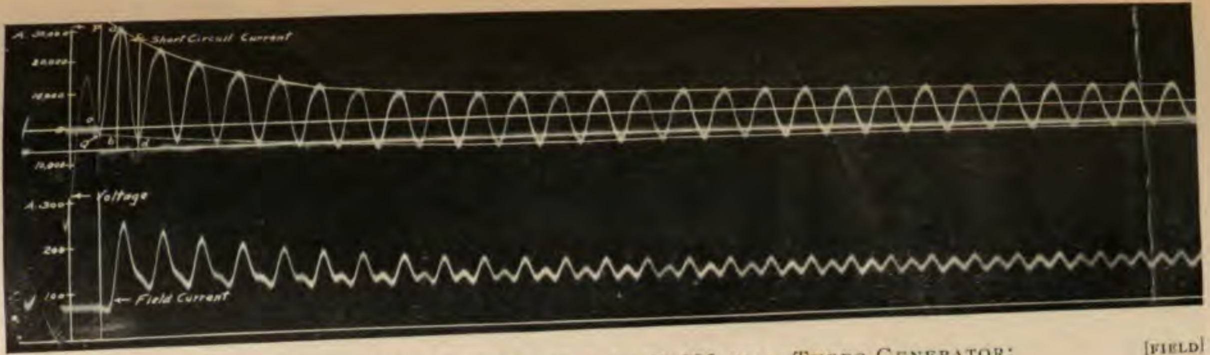
Considering the matter in this general way and leaving out refinements, it is clear that the maximum change of current in a half cycle, that is, the amount measured from the top of the positive peak to the bottom of the negative peak, will be that current which can produce a leakage flux nearly equal to twice the pole flux, and that this maximum change of current will be nearly independent of the point on the voltage wave at which the short circuit takes place. But the relative proportions of the current wave that lie above and below the zero line depend upon this feature. To be explicit, refer to a typical single-phase short-circuit oscillogram as given in Fig. 1. On this we have drawn a curve through the crests of the positive waves and similarly one through the crests of the negative waves and have extended these back to the axis drawn for the instant of short circuit. The two curves intercept on this axis a length $P\,Q$ corresponding to 37,000 amperes in this particular case, and our statement is, that for a given machine, short-circuited under given conditions, this intercept depends chiefly upon the rotor flux and but little upon the particular point on the voltage wave at which the short circuit takes place; while, on the other hand, the proportions of this intercept above and below the zero line, viz. $O\,P$, $O\,Q$, depend considerably upon the instant of short circuit. Hence, the approximate maximum of the short-circuit peak that could occur, were the machine to be short-circuited at the least favorable point of the voltage wave (namely, voltage zero) can be ascertained approximately from an oscillogram taken at random, short-circuiting the generator at any point on the voltage wave. This would be represented by the value PQ multiplied by the decrement factor for a one-half period, viz., by the ratio cd/ab.

It must be understood that this is true only in a general way, the whole phenomenon being affected by varying magnetic saturation of different parts and by actual I^2R loss in the paths of the short-circuit current and eddy currents produced.

This brings forward a question upon which we are in need of some conventional agreement; this Institute might with advantage formulate one. The " momentary short-circuit current" of a generator is nowadays frequently referred to, and discussed, without a proper recognition of the fact that this is not a definite quantity, even for definite values of the load and excitation at the instant of short circuit. In the first place, it will be convenient always to consider this quantity (as finally defined) in terms of the rated current of the machine, and for the sake of uniformity the " rated current " should be the maximum r.m.s. current which the generator is rated to carry continuously. In the next place, the *peak* momentary current should not be compared with the r.m.s. rated current, but rather the initial peak value divided by 1.414 should be thus compared. This is consistent with corresponding practise in other lines, as for instance, when an induction motor is specified to take from the line at starting a momentary current not exceeding, say, three times normal current. Finally, what is of real interest is the *most probable* ratio of initial short circuit to rated current, when the machine is short-circuited at random as regards the position on the voltage wave. If we wish, we can, in addition, very readily have a standard percentage to add to this, which will tell us approximately the highest possible momentary short-circuit current ratio under specified conditions. This would correspond to a current which would be approached, within a small percentage, perhaps once in a hundred short circuits.

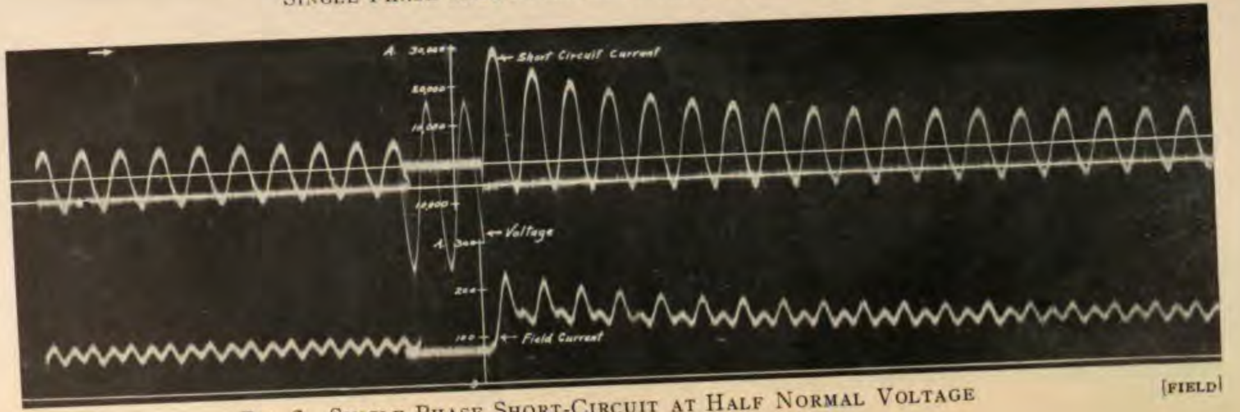
The most probable momentary short-circuit current can be approximately determined from the value of PQ referred to above. Having adopted a definition for the momentary short-circuit current, it will be convenient to define the " momentary short-circuit current ratio " as the ratio between this current and the normal current of the machine for maximum continuous rating.

From the oscillograms given in Figs. 1 to 4, we should say that



[FIELD]

FIG. 1—STATOR AND ROTOR CURRENT OF 10,000-KV-A. TURBO-GENERATOR; SINGLE-PHASE SHORT-CIRCUIT AT HALF NORMAL VOLTAGE



[FIELD]

FIG. 2—SINGLE-PHASE SHORT-CIRCUIT AT HALF NORMAL VOLTAGE

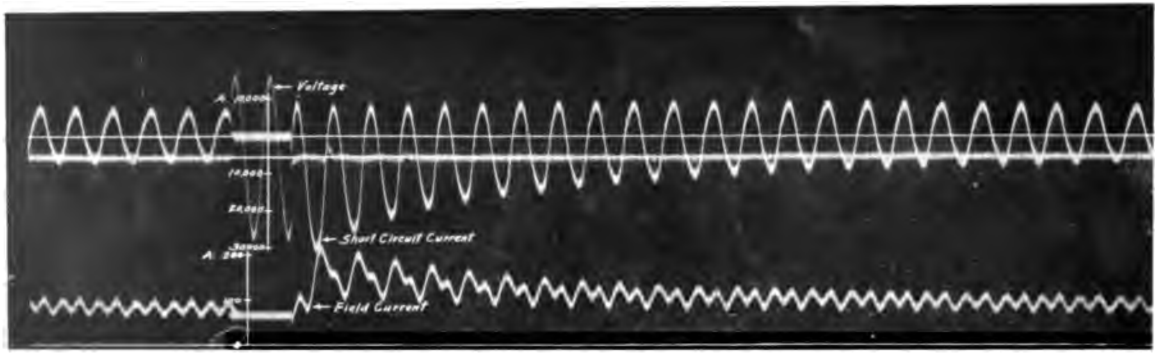


FIG 3—SINGLE-PHASE SHORT-CIRCUIT AT HALF NORMAL VOLTAGE [FIELD]

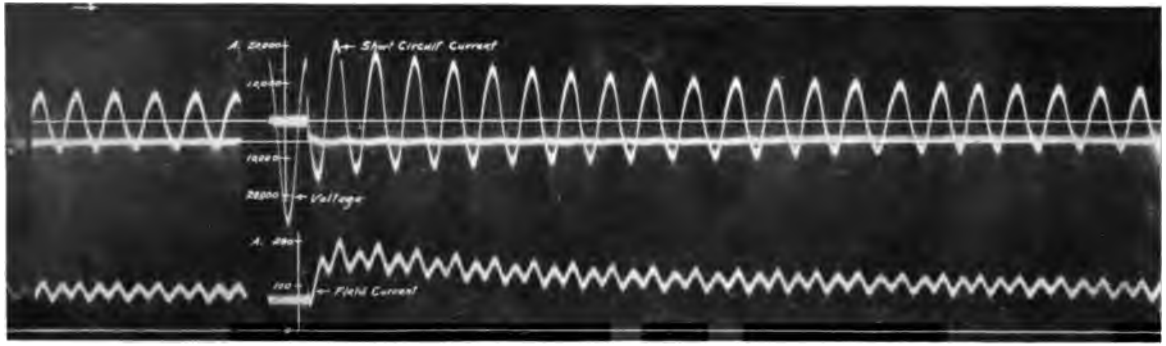


FIG. 4—SINGLE-PHASE SHORT-CIRCUIT AT HALF NORMAL VOLTAGE [FIELD]

with the rotor at rest, applying an external source of current. Such experiments, compared with similar ones taken with the rotor removed, show clearly the magnetic obstruction caused by the presence of the iron.

For instance, we may refer to tests on the machine which furnished the short-circuit curves already given, a 10,000-kv-a. 2400-volt, three-phase, 60-cycle, four-pole generator having a solid steel rotor of cruciform section, an air gap of ⅞ in. (22.2 mm.) each side, and stator slots 0.86 in. wide (see Fig. 6 for the type of stator). With the rotor removed, and an external source of 60-cycle current applied to the stator terminals, the impedance was found to be such as to give approximately 8.4 times normal current with full three-phase voltage applied, and 7.3 times normal current when rated voltage was applied across two only of the three terminals, that is, single-phase. Similar tests made on this machine with the rotor in place indicated an impedance which was not strictly independent of the magnitude of the current but which apparently would give about 12 times normal current with three-phase full voltage applied to the stator and about 10½ times normal current single-phase.

Comparing these tests, it will be noted that when the stator core was apparently magnetically short-circuited by the rotor with only a ⅞-in. (22.2 mm.) air gap, the impedance of the stator, instead of being increased, was only 70 per cent of that when the iron was removed and the stator flux found its path through the air. The power absorbed in this impedance test amounted to 340 kw. for rated current with the rotor in place, and less than one-sixth of this when the rotor was removed, again showing the effect of the heavy choking currents in the surface of the stationary rotor body.

We see, therefore, that on the occasion of the sudden short circuit of such a turbo-generator a large air gap separating the rotor from the stator will be apt to aid the restriction of the stator current by increasing the available space for the stator and rotor leakage flux, and thus, contrary to the generally accepted idea, changes of proportions which improve the regulation of the generator do not of necessity in every case cause an increase in the momentary short-circuit current. However, as pointed out later, it is in general necessary to adopt poor regulation in order to restrict to a reasonable degree the momentary short-circuit current, and to obtain other advantages.

From such general considerations as the above, the truth of the following statements will be apparent.

1. The momentary short-circuit current ratio is not directly affected by the frequency to any very large extent, if we consider for instance a 60-cycle turbo-generator operating at different frequencies, except by reason of the smaller penetration of the stator leakage flux into the rotor body at higher frequencies. However, comparing a 25-cycle design with a 60-cycle one, the changed proportions of design, such as the greater pole pitch, etc., involve a greater momentary short-circuit current ratio with the 25-cycle design.

2. For the same general features of design, a two-pole generator has a larger momentary short-circuit current ratio than a corresponding four-pole machine. However, the difference in this respect between the two- and four-pole machines is not greater than can occur between, say, two four-pole machines of considerably different design.

3. Using a given frame for a definite rating, the momentary short-circuit current ratio is nearly proportional to the square of the flux per pole, *i.e.*, if the number of stator conductors be increased 10 per cent for a given terminal voltage, the momentary short-circuit current ratio is reduced 20 per cent; at the same time the figure representing the full-load regulation at unity power factor is increased by an amount depending upon conditions, which may be as much as 50 per cent.

4. The manner in which the momentary short-circuit current ratio increases with the rating can not be stated definitely; it is complicated by a number of features which influence the magnetic proportions of the design.

It has been pointed out that by increasing the number of stator conductors for a given rating, the instantaneous short-circuit current is reduced; it might at first be supposed that on account of the increased number of conductors in a group, the mechanical forces on the end connections would nevertheless be increased. However, a little consideration will show that this is not so, and that the forces are decreased by nearly twice the percentage that the number of conductors is increased.

The method of supporting the end connections which is seen in Fig. 6 allows of effective clamping and incidentally provides a large space for leakage flux, while the field around the individual conductors is not excessive; thus the mechanical forces are minimized. The stator shown in this figure was re-

FIG. 6

[FIELD]

peatedly short-circuited at full voltage, both on one phase and across all terminals, without any signs of distortion of the winding.

A characteristic upon which great stress used to be laid, is close inherent regulation of the generator. It is not hard to see the reasons for abandoning this quality in the present-day purchasing specifications for large turbo-generators. In the first place, the price to be paid for it in efficiency, in heavy short-circuit currents, in inferior mechanical proportions, and in actual dollars of cost price, was altogether disproportionate to the supposed advantages. In the second place the advantages—for large units at any rate—are found to be of a more theoretical than practical nature. With regard to the cost: In a turbo-generator of say 10,000-kv-a. rating (max.) the friction and windage plus core loss amount to several times the I^2R loss plus excitation, the ratio depending upon speed and design, but varying from perhaps 3 to 7. Hence the point of maximum efficiency is always much outside the rating range, and any increase in variable losses with a reduction of fixed losses causes an increase in efficiency at the operating point. The place where limitations are most severely felt in a large turbo-generator is the rotor, and therefore, to obtain close regulation in such a machine, the flux is of necessity run up higher than it would be without this requirement, hence an impaired efficiency. The increased flux involves a momentary short-circuit current ratio, and mechanical forces on end connections augmented by twice the percentage by which it is itself increased. The rotor limitations preclude the possibility of obtaining the close regulation with the low flux, by means of simply an increased air gap. In several existing installations the consideration of short-circuit current alone has necessitated deliberately spoiling the regulation of the generators by inserting external reactance, a procedure which not only does not take advantage of the improvement of efficiency possible with a reduced flux but introduces some, even if small, extraneous losses.

In the case of large units the difference between close regulation and poor, will frequently represent the practicability or otherwise of a two-pole as compared with a four-pole design, or four-pole versus six-pole. This incidentally represents an even greater effect on steam consumption due directly to the speed of the turbine. Again, the increased flux required for close regulation represents increased rotor weight and changed proportions, which at certain stages will necessitate operation above the critical speed where before a stiff rotor was possible. As regards cost price, the closely regulating machine will be heavier, and while the cost per pound will be slightly less than that of the low flux machine, the total cost will always be somewhat more, except where other sacrifices have been made. We have been assuming that the close regulation is to be obtained by ordinary methods of proportioning. The clever compounding device introduced by Miles Walker, and used to some extent in England for fairly high power factor work, is said to provide the close regulation without any consequent very heavy momentary short-circuit current ratio.

With reference to the advantage obtained by close regulation, the following points must be borne in mind. Where close voltage regulation is required, an automatic regulator will be used whatever the regulation of the generator. Even with close regulation at unity power factor, that at lower power factors is poor. The size of the stations, and of the units, here discussed is much greater than a few years ago when close regulation was being insisted upon, and while it may be said that fluctuations of load on a section of the busbars will be correspondingly increased, this fluctuation is not generally so large a percentage of the total rating of the machines on the busbars. Further, in a large station, if the rapid changes of load are heavy enough to represent a considerable proportion of the connected generator rating, the problem of taking care of the sudden changes of demand for steam will be the principal one, rather than voltage adjustment. As regards parallel operation between machines of different regulations, there is, of course, some hand rheostat adjustment required, if all machines are to share equally the wattless load at varying busbar loads. But even if the regulation of the parallel units is the same, such hand adjustment will still be necessary, unless the shapes of the saturation curves are also similar. Frequently it is desirable anyway to adjust by hand the division of current load between generators old and new.

The greater rotative speed at which a given output can be handled now, as compared with earlier practise, is largely due to changes of design which increase the available output from a structure of given dimensions rather than to changes which allow of very much larger structures being run at the old speeds. The use of mica and asbestos for rotor insulation allows of operation at temperatures which were near the limit with the older inflammable materials. Modifying our ideas on regulation requirements enables the limitations of stator and rotor more nearly to approach one another, and so on.

As an illustration may be taken some 12,500-kv-a. 750-rev. per min. 25-cycle generators that have for several years done good service on one of our large traction systems. In these machines the stator is 127 in. (3.2 m.) in diameter, 81 in. (2.05 m.) long, and 85.3 in. (2.16 m.) bore, and the flux per pole is about 128 mega-lines. With these stator dimensions the flux would nowadays probably be run up some 30 per cent, or so, but the stator ampere conductors would also be increased to give a maximum rating in the neighborhood of 25,000 kv-a. The full load efficiency would be brought up from 96.4 per cent to 97.8 per cent, each case referring to unity power factor and with friction and windage included among the losses. The regulation at unity power factor, for say 75 per cent of maximum rated load, would be increased from 10 per cent to about 15 per cent. The momentary short-circuit current ratio would not be appreciably increased in spite of the fact that we are dealing with a machine of much larger kilowatt capacity; all the details of design would, of course, be modified to suit, and the machine would be considerably more costly to build.

With the increased ratings prevailing at speeds of 1500 and 1800 rev. per min., it becomes increasingly difficult to provide satisfactory and efficient blowers mounted directly on the rotor. There is the further consideration that the axial length taken by the blowers, and end bell partitioned spaces, increases the span between journals and lowers the critical speed. Some far-sighted buyers of large units are now adopting a separately driven external fan, allowing of a very stiff rotor construction. It then frequently remains possible to keep the critical speed above the running speed for large machines too; and the smoothness of operation obtained, even if we magnetically unbalance the rotor by temporarily short-circuiting one coil, is a great asset in a large machine. The external blower has several advantages which will be readily seen and which will be accentuated when it becomes standard practise in this country, as in Europe, to install air filters. The writer believes that our central station engineers will follow this practise a few years hence, as it is rational to arrest the dirt on accessible surfaces, whence it can be removed at a cost which is a very small fraction of the expense involved when the dirt is allowed to collect in the generators. One possible alternative to the separate blower handling all the air, is a small external direct-connected higher pressure blower producing the necessary low-pressure ventilation by an inducing jet in a properly shaped main duct, on the principle of the jet pump. The " high-pressure " blowers for these need not necessarily be direct-connected, but one could be installed to feed into all the ducts of the station.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

THE TRANSIENT REACTIONS OF ALTERNATORS

BY WILLIAM A. DURGIN AND R. H. WHITEHEAD

This paper is confined to demonstrating the existence of a characteristic of alternators provisionally named the *transient impedance* and to investigating the influence of this characteristic on

a. The maximum and minimum currents flowing through a 12,000-kw. turbo-alternator with and without external reactance coils, under various short-circuit conditions.

b. The maximum and minimum currents into different classes of faults from a system operating several such units in parallel.

c. The maximum cross currents obtainable when paralleling a unit to the system considered in (b), and

d. The torque developed by the maximum currents of (a) and (b).

SUMMARY

From these investigations we conclude that the short-circuit currents of alternators are limited by reactances much more complex and much higher than the self-inductive reactances of the armatures, but which are constant for similar units and can be obtained for any size and type of generator by simple low-voltage short-circuit tests. By means of this test value the maximum short-circuit current of a single unit may be readily computed from

$$I_m{}^0 = \frac{E_m{}^0}{z}\left(1+\epsilon^{-\frac{r}{x}\pi}\right)$$

and the maximum torque from

$$W_m{}^0 = \frac{3}{2}\,\frac{(E_m{}^0)^2}{z^2}\,r\left(1+\epsilon^{-\frac{r}{x}\pi}\right)^2$$

equations which show, when developed, that the current per unit in any given short circuit is less as the number of units in parallel increases; that the maximum current always results when the short circuit occurs at the zero point of the corresponding pressure wave, independent of the particular short-circuit conditions; that the maximum instantaneous torque merely varies inversely as the reactance in circuit and hence that instability of the system and generator stresses (except those in end turns) at times of short circuit, are only lessened by reactance coils in proportion to the resulting increase in total reactance; that the torque stress per unit with a given number of units in parallel may be greater or less than that with a smaller number of units, depending on the resistance of the short circuit; and that the maximum torque is entirely independent of the points of the pressure waves at which a three-phase short circuit occurs. Finally we find that the total reactance of an alternator should be at least 15 per cent per phase, divided about equally between the unit and external reactance coils, in order to secure protection of the unit from the system in cases of internal short circuit, and that even this reactance will not give complete protection from torque strains in the armature and field due to poor synchronizing and short circuits or from excessive power dissipation at faults or in oil switches in cases of breakdown.

TRANSIENT IMPEDANCE

The generally accepted theory of the short-circuit current of alternators is stated as follows by Dr. Steinmetz in "Transient Electric Phenomena and Oscillations," page 200, paragraph 113.

"When suddenly short-circuiting an alternator from open circuit, in the moment before the short circuit, the field flux is that corresponding to the impressed m.m.f. of the field excitation, and the voltage in the armature is the nominal generated e.m.f., e_0 (corrected for magnetic saturation). At the moment of short circuit, a counter m.m.f., that of the armature reaction of the short-circuit current, is opposed to the impressed m.m.f. of the field excitation, and the magnetic flux, therefore, begins to decrease at such a rate that the e.m.f. generated in the field coils by the decrease of field flux increases the field current and therewith the m.m.f. so that when combined with the armature reaction it gives a resultant m.m.f. producing the instantaneous value of field flux.

Immediately after short circuit, while the field flux still has full value, that is, before it has appreciably decreased, the field m.m.f. thus must have increased by a value equal to the counter m.m.f. of armature reaction. As the field is still practically unchanged the generated e.m.f. is the nominal generated voltage, and the short-circuit current is

$$i_0' = \frac{e_0}{x_1} \qquad (1)$$

Reactance is used in place of impedance in this equation as in comparison the resistance of the armature is negligible. It is to be remembered that x_1 is the self-inductive reactance of the armature due to flux linked only with the armature conductors and hence, as this can be calculated or at least approximated from the design of the machine, an estimate of the short-circuit current corresponding to the theory can be made. The equation gives this current as an a-c. phenomenon, that is, with equal positive and negative half-waves, but since it is really a transient phenomenon and may, therefore, have the initial waves displaced entirely above or below the zero value, the true maximum possible value is twice that shown by the equation, or

$$I_m^0 = \frac{2\,E_m^0}{x_1} \qquad (2)$$

The short-circuit tests made during the early part of 1911 on a 12,000-kw., 9000-volt, 25-cycle turbo-alternator at the Fisk Street Station of the Commonwealth Edison Company, as described in Messrs. Schuchardt's and Schweitzer's paper on *The Use of Power-Limiting Reactances with Large Turbo-Alternators*, and Mr. E. B. Merriam's paper on *Some Recent Tests of Oil Circuit Breakers*, both* in Volume XXX of the TRANSACTIONS of this Institute, gave an unusual opportunity for checking this theory, and the great discrepancy between the estimated values of short-circuit currents and those actually found led to the results now presented.

In these tests 167 short circuits, through circuits with 0 per cent, 3.9 per cent, or 6.3 per cent external reactance, were thrown on the alternator at open-circuit voltages from 1000 to 9000 volts. The peak value of the initial cycle of current in the three phases for each delta short circuit, as obtained from the oscillograms then taken, is plotted in Fig. 1 for 6.3 per cent external

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*Vol. XXX, (1911), Part II, page 1143; page 1195.

reactance, in Fig. 2 for 3.9 per cent external reactance and in Fig. 3 for 0 per cent external reactance. In Fig. 4 similar values are plotted for all single-phase and three-phase four-wire short circuits. The upper solid lines drawn in these plots thus represent the maximum currents from test, and making the single assumption that current continues proportional to voltage beyond the limits of the plot, the figures of column 5, Table I, give the test results for the maximum peak values of short-circuit currents corresponding to the various values of external reactance.

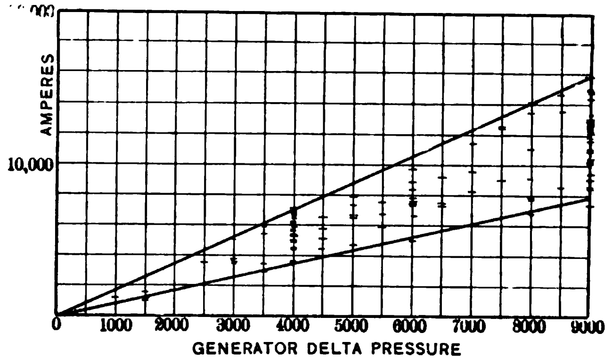

FIG. 1—INITIAL PEAK VALUES OF CURRENTS IN THREE-PHASE DELTA SHORT-CIRCUIT TESTS.
Through 6.3 per cent external reactance.

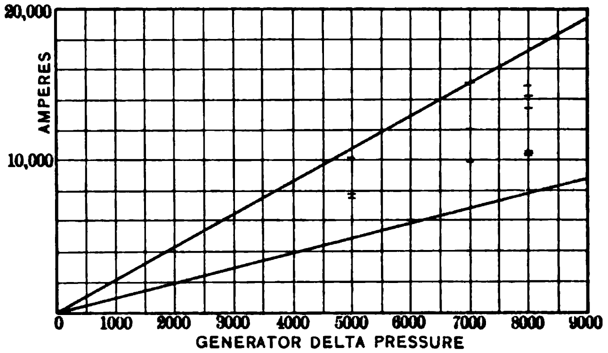

FIG. 2—INITIAL PEAK VALUES OF CURRENTS IN THREE-PHASE DELTA SHORT-CIRCUIT TESTS.
Through 3.9 per cent external reactance.

With external reactance in series with the armature the fundamental equation becomes

$$I_m^0 = \frac{2\,E_m^0}{x_l + x_{ext}} \qquad (3)$$

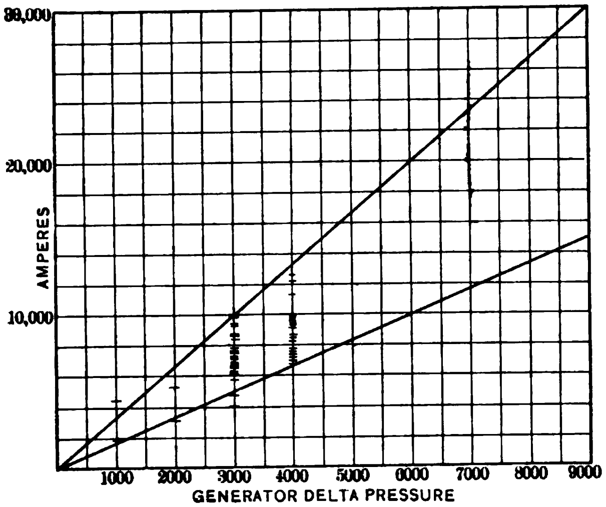

FIG. 3—INITIAL PEAK VALUES OF CURRENTS IN THREE-PHASE DELTA SHORT-CIRCUIT TESTS THROUGH ZERO EXTERNAL REACTANCE.

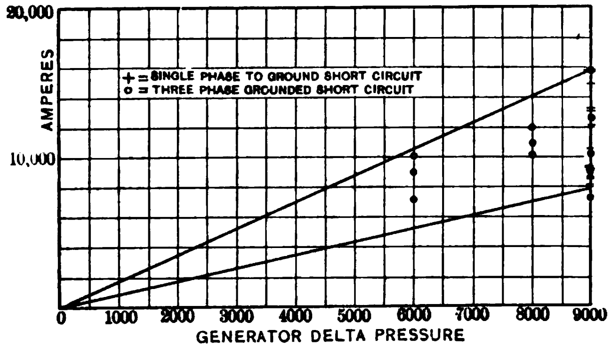

FIG. 4—INITIAL PEAK VALUES OF CURRENTS IN BOTH SINGLE-PHASE TO GROUND AND THREE-PHASE GROUNDED SHORT-CIRCUIT TESTS.
Through 6.3 per cent external reactance.

For the particular generator tested, x_l was estimated by various engineers as about 2 per cent or 0.135 ohms, and using this figure in equation (3) the values of column 4, Table I, were computed. The actual current without external reactance is seen to be only 28 per cent of this computed value, and making all due allowance for inaccuracies in estimating x_1, it seems evident that the current is limited by some reactance beside those contemplated in the original theory. Substituting the test values of I_m^0 and E_m^0 in equation (3) and solving for the denominator of the second member, we obtain the values given in column 6, Table I, and subtracting x_{ext} from these, the figures shown in column 7 result for the value of the total effective internal reactance. The agreement of these last figures obtained from three series of tests made under different conditions of external circuit is striking. Indeed, the variation from a mean of 0.5 ohm is well within the experimental error of oscillograph work, and although *the transient reactance*, as the writers have called this quantity, probably varies somewhat with conditions of field circuit and armature current even during the middle third of the first cycle of short circuit, these variations are comparatively small and for the purposes of the paper the transient reactance is taken as constant during this period under all conditions of short-circuit. Considered over the total period of the transient short-circuit phenomenon, it is, of course, a variable increasing from a lower limit x_1 to an upper limit x_0, where x_0 is the synchronous reactance developed when the machine is brought up to speed from standstill under short-circuit and normal excitation.

TABLE I

External reactance		Star Maximum Peak Values				
		Computed *		Observed current	Total reactance from test	Transient reactance
Per cent	ohms	Voltage	Current			
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0.00	0.000	7350	109,000	30,000	0.490	0.490
3.93	0.266	7350	36,700	19,400	0.758	0.492
6.26	0.424	7350	26,300	15,800	0.931	0.507

*Throughout this paper the following values are used for the rated voltage and current per phase:

$E = 5200 \quad E_m = 7350$

$I = 770 \quad I_m = 1090$

The existence of such a transient reactance, or rather the existence of complex reactions which are conveniently grouped and replaced by a single fictitious quantity called the transient reactance, is shown conclusively by the test results and has, indeed, been more or less clearly appreciated for some time. Miles Walker, in his paper on " Short-Circuiting of Large Electric Generators," *Proceedings*, Institution of Electrical Engineers, Volume XLV, page 295, states that in one case which he investigated the circuits of the eddy currents in the field poles had an equivalent inductance reduced to the armature, 2.4 times as great as x_1 and engineers in general have accepted the statement that the actual short-circuit currents obtained will be less than those indicated by theory on account of eddy current reactions. But the full significance of the large current induced in the field circuit does not appear to have been clearly formulated.

Dr. Steinmetz's statement of the original theory assumes a current induced in the field of such strength as to maintain the resultant flux constant against the effects of armature reaction. The induction of this current in the field, however, is so closely analogous to simple transformer action that the effects of its flow through the highly self-inductive secondary or field circuit may be considered equivalent to adding the field inductance multiplied by the square of the ratio of transformation to the primary or armature circuit, or, if

x_F = reactance of field circuit, reduced to armature,
x_E = reactance of eddy current paths in contiguous metal masses, reduced to armature,
x_2 = reactance representing decrease of total resultant flux due to energy dissipation, and
x_T = transient reactance,

then

$$x_T = x_1 + x_2 + x_E + x_F \qquad (4)$$

As x_E and x_F are only effective during the transient phenomenon or while alternating current is induced in the field, this equation for the permanent three-phase condition reduces to

$$x_T = x_1 + x_2' = x_0 \qquad (5)$$

In the above discussion reactance only has been considered. It is, of course, evident that the field circuit and especially the eddy-current circuits possess considerable resistance and that, as more definite data are obtained, investigations must be based on the *transient impedance*. But at present, unfortunately, no figures are available for the transient resistance, and the writers have been obliged to assume that as the known armature resistance of 0.03 ohms is negligible, the values of column 7, Table I, represent true transient reactance, and in the cases discussed below, to treat the total transient resistance as negligible or as replacing an unknown part of the external resistance.

(a) *The Maximum and Minimum Currents Flowing Through a 12,000-kw. Turbo-Alternator With and Without External Reactance Coils, Under Various Short-Circuit Conditions.*

One of the principal advantages of considering all the armature reactions as a single transient reactance, practically constant during the middle third of the first cycle after short circuit, lies in the fact that the short-circuited armature then becomes strictly analogous for this period to a circuit possessing the same resistance and reactance upon which is impressed a constant e.m.f. equal to the nominal generated voltage e_0 (corrected for magnetic saturation). The current in such a circuit is given by

$$i = \frac{E_m}{z}\left[\cos(\theta-\theta_0-\theta_1) - \epsilon^{-\frac{r}{x}\theta}\cos(\theta_0+\theta_1)\right] \tag{6}$$

in which equation, as applied to the short-circuited armature,

E_m = maximum nominal generated e.m.f. (corrected for saturation).

$z = \sqrt{r^2 + x^2}$

r = transient resistance + resistance of external circuit.

$x = x_T + x_{ext}$

θ = time from instant of short circuit.

θ_0 = phase of pressure at instant circuit is closed, in terms of θ from equation $e = E_m \cos(\theta - \theta_0)$ or the time angle to the nearest positive E_m

$\theta_1 = \tan^{-1}\frac{x}{r}$

Considering first the case where r is negligible with respect to x, equation (6) reduces to

$$i = \frac{E_m^0}{x}\left[\cos\left(\theta-\theta_0-\frac{\pi}{2}\right) - \cos\left(\theta_0+\frac{\pi}{2}\right)\right] \tag{7}$$

and gives maximum values for i when $\theta_0 = \pm\frac{\pi}{2}$ or when the short circuit occurs at the zero point of the e.m.f. wave, for under these conditions,

$$i = \pm \frac{E_m^0}{x}\left(\cos\theta - 1\right) \tag{8}$$

and

$$I_m^0 = \pm \frac{2\,E_m^0}{x}$$

this being the same value as obtained from the original theory with the initial wave completely above or below the time axis (equation 2.) If the short circuit occurs at $\theta_0 = 0$ or $\theta_0 = \pi$, on the other hand, equation (6) becomes

$$i = \frac{E_m^0}{x}\cos\left(\theta - \frac{\pi}{2}\right)$$

or

$$= \frac{E_m^0}{x}\cos\left(\theta - \frac{3\pi}{2}\right)$$

giving

$$I_m^{0\prime} = \pm \frac{E_m^0}{x}. \tag{9}$$

that is, the minimum initial peak of the minimum phase when the short circuit takes place at the peak of the impressed e.m.f. wave for this phase.* Under these conditions the current wave is symmetrical about the time axis and the maximum is one-half that obtained when the wave is completely displaced.

The test results are in satisfactory agreement with this last relation, the lower solid line of Figs. 1, 2, 3 and 4 being plotted for values one-half those of the upper line. The fact that a few points fall below the limit indicated by the theory is probably to be explained, aside from the unavoidable inaccuracies of oscillograph measurements, by variation in the resistance of the external circuit. The importance of maintaining this resistance constant did not appear until the tests were completed, and in consequence, as the contacts of the oil circuit breaker used to open the short circuit became pitted, a resistance was introduced

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*Initial peak is used throughout this paper as meaning the highest peak occurring in the first cycle.

in each phase varying from several hundredths to perhaps a few tenths of an ohm as indicated by oscillograms of the pressure drop across the several contacts. The higher figure is by no means negligible in comparison with the reactance of the circuit and, together with the unknown transient resistance, introduced considerable variations from the purely reactive impedance assumed.

Fig. 5 shows the effect of various external reactances up to 20 per cent in reducing the current of one of the 12,000-kw. generators under short circuits of negligible resistance as computed from equation (2), the actual test values being plotted as circles. It is interesting to note that whereas an increase of external reactance from zero to 6 per cent results in a decrease in current of about 45 per cent, an increase from 6 per cent to 10 per cent external reactance gives only about 12 per cent further decrease of current.

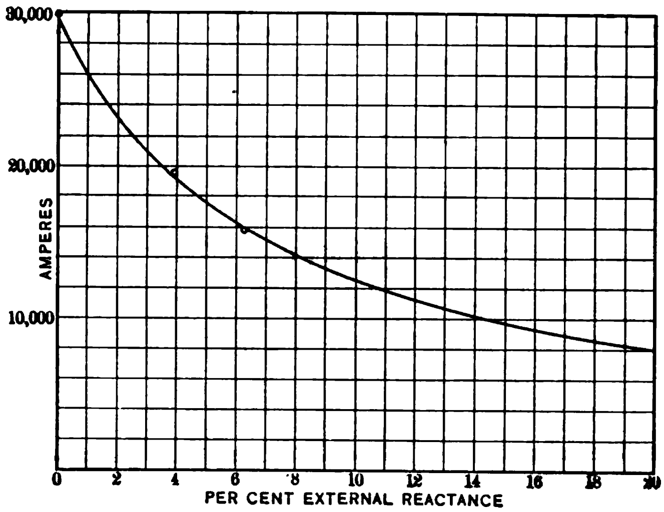

Fig. 5—Maximum Initial Peak Values of Current through 12,000-kw. Alternator at 9000 Volts on External Three-Phase Short Circuits of Zero Resistance and Various Reactances.

If the resistance is not negligible, the analytical solution of equation (6) for maximum i becomes difficult and the investigation is carried out most readily by plotting various families of curves. For this purpose the variables of equation (6) may be grouped:

$$Y = \cos\left[\theta - (\theta_0 + \theta_1)\right] - \epsilon^{-\frac{r}{x}\theta}\cos(\theta_0 + \theta_1) \qquad (10)$$

and θ, $\frac{r}{x}$ and $\theta_0 + \theta_1$ considered the new variables.

Taking $\theta_0 + \theta_1 = \pi$, the family of curves given in Fig. 6 is obtained, showing the values of (10) for representative values of $\frac{r}{x}$ and all values of θ from 0 deg. to 180 deg. Similar families have been plotted for other values of $\theta_0 + \theta_1$ and the maxima of

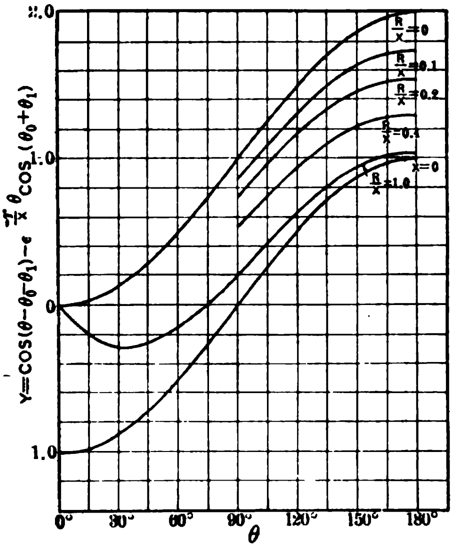

FIG. 6—VALUES OF Y, EQUATION (10), FOR REPRESENTATIVE VALUES OF $\frac{r}{x}$ AND ALL VALUES OF θ FROM 0 TO π WHEN $\theta_0 + \theta_1 = \pi$.

each of the several series made up of those curves having the same value of $\frac{r}{x}$ but different values of $\theta_0 + \theta_1$ are combined in Fig. 7 to form one of a new family of curves in which, therefore, for each value of $\theta_0 + \theta_1$ and $\frac{r}{x}$, θ has the value shown by Fig. 6 and the similar families to be necessary to make (10) a maximum.

The dotted line drawn through the peak of these last curves is found to pass through the points corresponding to $\theta_0 = \frac{\pi}{2}$

and it is apparent, therefore, that under all circuit conditions the maximum current is obtained when the short circuit occurs at the zero value of the corresponding e.m.f. wave.* From Fig. 7 too, it is seen that the maximum value of (10) for any value of $\theta_0 + \theta_1$, is in no case more than 2.5 per cent greater than that obtained for $\theta_0 + \theta_1 = \pi$, and as, when $\theta_0 + \theta_1$ is made equal to π, the maximum value shown by Fig. 6 for any value of θ is not more than 0.5 per cent greater than the corresponding value

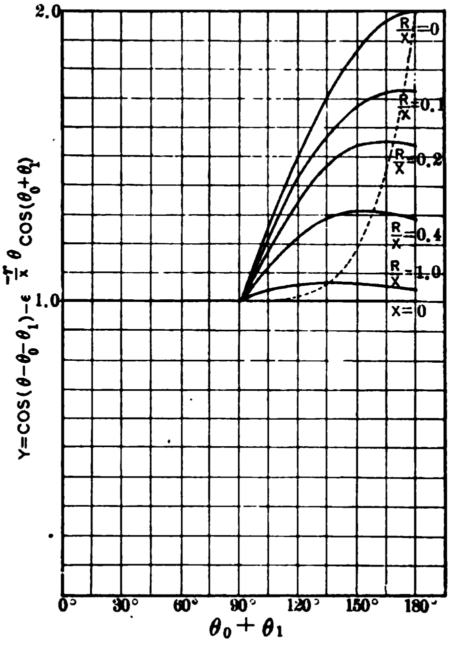

FIG. 7—VALUES OF Y, EQUATION (10), FOR ALL VALUES OF $\theta_0 + \theta_1$ FROM $\frac{\pi}{2}$ TO π, AND REPRESENTATIVE VALUES OF $\frac{r}{x}$ WHEN θ HAS SUCH A VALUE AS TO MAKE Y A MAXIMUM.

when $\theta = \pi$, by taking both $\theta_0 + \theta_1$ and θ equal to π we may obtain a simplification of equation (6) which will result in values of I_m^0 within 2 per cent or 3 per cent of the absolute maximum. So simplified,

$$I_m^0 = \frac{E_m^0}{z} \left(1 + \epsilon^{-\frac{r}{x}\pi} \right) \tag{11}$$

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*An analytical demonstration of this fact is given in Appendix A.

gives the approximate maximum of the maximum phase, the minimum initial peak of the minimum phase being given by

$$I_m^{0\prime} = \frac{E_m^0}{z} \tag{12}$$

Applying (**11**) and (**12**) to the 12,000-kw. generator with no external reactance, the upper double branched curve of Fig. 8 results, the two branches showing the decrease in the range of possible values for the initial peaks of the three phases as the resistance of the short circuit is increased.

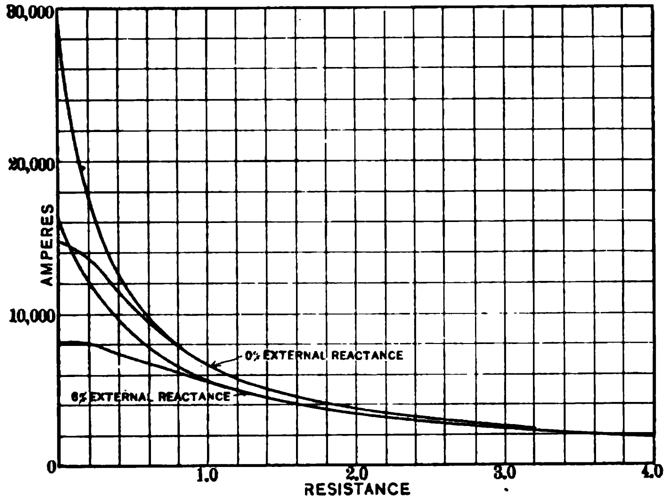

FIG. 8—LIMITS OF CURRENT THROUGH SHORT CIRCUITS OF VARIOUS RESISTANCES, SUPPLIED BY A 12,000-KW. ALTERNATOR.

Both when the unit is protected by 6 per cent reactance coils and when it is connected directly.

It is noteworthy that a resistance of one ohm per phase eliminates the transient term entirely, both for this curve and the lower double branched curve showing similar values when 6 per cent external reactance coils are included in the circuit. That is, for resistance greater than 0.8 or 1.0 ohm all three phases have equal initial peaks, or we have a simple a-c. phenomenon. As the unit is earthed through a 2.5-ohm neutral rheostat, cable breakdowns or faults from phase to sheath are thus purely a-c. phenomena, and from the closeness of the upper and lower curves of Fig. 8 at the 2.5-ohm point, are unaffected by any practicable amount of external reactance.

(*b*) *The Maximum and Minimum Currents into Various Classes of Faults from a System Operating Several* 12,000-*kw. Units in Parallel.*

With n units in parallel, feeding a short circuit beyond the station busbars, equations (**11**) and (**12**) take the forms

$$I_m^0 = \frac{E_m^0}{\sqrt{\left(r_{ext} + \frac{r_T}{n}\right)^2 + \left(\frac{x}{n}\right)^2}} \left[1 + \epsilon^{-\left(\frac{n\, r_{ext} + r_T}{x}\right)\pi}\right] \qquad (13)$$

and

$$I_m^{0\prime} = \frac{E_m^0}{\sqrt{\left(r_{ext} + \frac{r_T}{n}\right)^2 + \left(\frac{x}{n}\right)^2}} \qquad (14)$$

The assumption that the transient resistance term is negligible as compared with the external resistance, however, becomes more nearly true as n increases, so that for several units these equations may be simplified as

$$I_m^0 = \frac{E_m^0}{\sqrt{r_{ext}^2 + \left(\frac{x}{n}\right)^2}} \left[1 + \epsilon^{-\frac{n\, r_{ext}}{x}\pi}\right] \qquad (15)$$

and

$$I_m^{0\prime} = \frac{E_m^0}{\sqrt{r_{ext}^2 + \left(\frac{x}{n}\right)^2}} \qquad (16)$$

From these latter equations the curves of Fig. 9 for five 12,000-kw. units in parallel are plotted similarly to those given in Fig. 8 for a single unit. With a three-phase short circuit on a standard 250,000-cir. mil cable fed from a five-unit system, if the breakdown is a mile or more from the station, the decrease in current due to 6 per cent external reactance coils is negligible and no transient term occurs, this critical distance being one-fifth that which obtains for a single unit. But for an appreciable resistance the three-phase short-circuit current of five units is considerably less than five times that of a single unit, so that although up to about two ohms per phase resistance those effects of a breakdown which depend only on the amount of current, increase in severity at the fault and in the feeder switch with the number of units in service, the effect on the individual units decreases as more units are operated in parallel. The application of these statements to a breakdown from phase to ground depends on the scheme followed in operation. If, as is usual, a single unit is earthed, that unit takes the entire short-circuit current and this is practically independent of the number of units on the bus. If, however, all units are connected to a neutral bus which is earthed through a neutral rheostat the total short-circuit current will be independent of the number of units and the strain per unit inversely as this number.

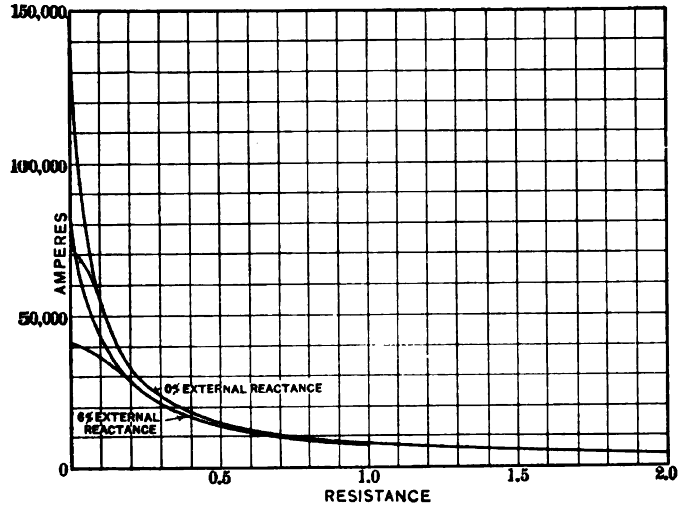

FIG. 9—LIMITS OF TOTAL CURRENT THROUGH SHORT CIRCUITS OF VARIOUS RESISTANCES SUPPLIED BY FIVE 12,000-KW. ALTERNATORS IN PARALLEL.

With and without the protection of 6 per cent external reactance coils on each unit.

(c) *The Maximum Cross Currents Obtainable when Paralleling a 12,000-kw. Generator to a System Operating several such Units in Parallel.*

As a special case of the the parallel operation of units, we may consider the cross currents flowing when an additional unit is connected to a bus supplied by n similar units. Here r_{ext} is zero, r_T is negligible and the e.m.f., assuming the pressure of the incoming unit to be equal to that of the bus, is twice the bus pressure, multiplied by the sine of one-half the phase angle between bus and the incoming unit. Taking the worst case, when the unit is thrown in 180 deg. out of phase and the switch closed at the zero value of the pressure waves,

$$I_m^0 = \frac{2\,(2\,E_m^0)}{x + \frac{x}{n}} \tag{17}$$

and the numerical values applying to the system under discussion for external reactances from 0 to 10 per cent and *n* from 1 to ∞ are shown in Fig. 10.

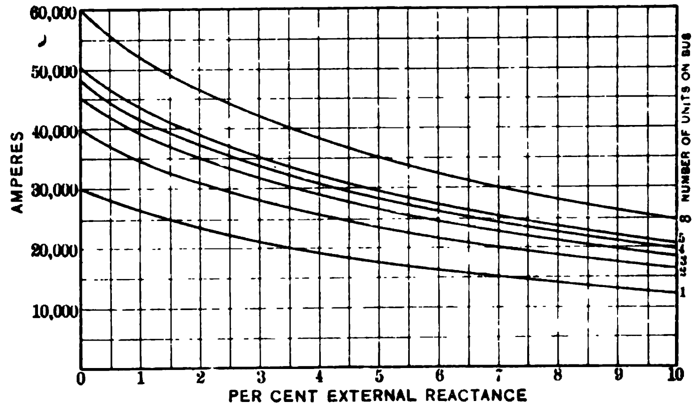

FIG. 10—MAXIMUM INITIAL PEAK VALUES OF CURRENT WHEN A SINGLE 12,000-kw. UNIT IS CONNECTED 180 DEG. OUT OF PHASE TO A BUS SUPPLIED BY ANY NUMBER OF SIMILAR UNITS.

Each unit equipped with external coils having from 0 per cent to 10 per cent reactance.

At the Fisk Street station with four units previously operating, the 6.3 per cent reactances installed would only limit current to 26,000 amperes in the worst case of synchronizing. This, while little more than half that obtained with no external reactances, is still probably quite sufficient to wreck the incoming unit. Although, therefore, reactance offers considerable protection against poor synchronizing, no amount considered in any of the installations yet made will give complete security.

(*d*) *The Instantaneous Torque Developed by the Maximum Short-Circuit Currents of* (*a*) *and* (*b*).

Applying the conception of transient impedance to the investigation of the maximum instantaneous torque which tends to twist or spring the shaft or to strain the entire armature of a short-circuited alternator, we obtain the very simple formula

$$W_m{}^0 = \frac{3}{2}\,\frac{(E_m{}^0)^2}{z^2}\,r\left(1 + \epsilon^{-\frac{r}{x}\pi}\right)^2 \qquad (18)$$

For when $r = r_T + r_{ext}$ the torque is evidently the sum of the i^2r losses for the three phases, and in a three-phase short circuit through any reasonable amount of external resistance r_T may be taken as equal in each phase, making,

$$\begin{aligned} w^0 = \frac{(E_m{}^0)^2}{z^2}\,r \Bigg\{ &\left[\cos(\theta-\theta_0-\theta_1) - \epsilon^{-\frac{r}{x}\theta}\cos(\theta_0+\theta_1)\right]^2 \\ &+\left[\cos\left(\theta-\theta_0-\theta_1-\frac{2\pi}{3}\right) - \epsilon^{-\frac{r}{x}\theta}\cos\left(\theta_0+\theta_1+\frac{2\pi}{3}\right)\right]^2 \\ &+\left[\cos\left(\theta-\theta_0-\theta_1-\frac{4\pi}{3}\right) - \epsilon^{-\frac{r}{x}\theta}\cos\left(\theta_0+\theta_1+\frac{4\pi}{3}\right)\right]^2\Bigg\} \end{aligned} \qquad (19)$$

Expanding these expressions and reducing by the formulas given by Dr. Steinmetz in "Engineering Mathematics", page 105,

$$w^0 = \frac{3}{2}\,\frac{(E_m{}^0)^2}{z^2}\,r\left[\left(\cos\theta - \epsilon^{-\frac{r}{x}\theta}\right)^2 + \sin^2\theta\right] \qquad (20)$$

This expression does not contain θ_0, or, in other words, the torque is entirely independent of the point of the pressure wave at which the short circuit occurs. Furthermore, the transient term becomes practically negligible for $\frac{r}{x}$ = or > 4 and (20) then reduces to

$$w^0 = \frac{3}{2}\,\frac{(E_m{}^0)^2}{z^2}\,r = 3\,E\,I\cos\theta_1,$$

the fundamental power equation of the three-phase circuit. To obtain $W_m{}^0$, the latter part of (20),

$$\left(\cos\theta - \epsilon^{-\frac{r}{x}\theta}\right)^2 + \sin^2\theta,$$

may be investigated graphically as is done in Fig. 11, where the solid lines represent the values of the expression for various values of $\frac{r}{x}$ from 0 to ∞, the dotted lines showing the component terms for $\frac{r}{x} = 0.2$. Here again, as in the case of the current curves of Figs. 6 and 7, the peaks are so flat that the absolute maximumt orque is never more than 4.5 per cent greater than the torque for $\theta = \pi$ and hence, for all practical purposes, (**20**) may be written as in (**18**). It is interesting to observe that this equation can be derived from the three-phase power equation written in the form $W = \frac{3}{2} I_m^2 r$ by substituting the approximate value of I_m^{0} given in (**11**). That is, the maximum transient

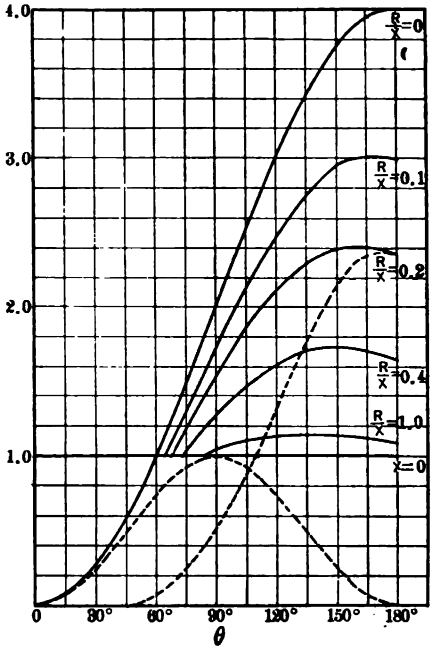

FIG. 11—VALUES OF $\left(\cos\theta - \epsilon^{\frac{-r}{x}\theta}\right)^2 + \sin^2\theta$, EQUATION (**20**), FOR REPRESENTATIVE VALUES OF $\frac{r}{x}$ AND ALL VALUES OF θ FROM 0 TO π.

torque is the same as the constant torque of a three-phase circuit in which the I_m of the sine current equals the maximum possible peak of the maximum phase under short circuit.

Using in equation (**18**) the values of x for the 12,000-kw. alternator, the curves of Fig. 12 are obtained, showing the decrease of torque with increase of resistance. For any given resistance, the decrease due to the addition of 6 per cent external reactance is equal to the difference in ordinates of the upper and lower curves and is directly proportional to the decrease in the square of the current. The end turn stresses in the armature winding are also proportional to the square of the current, so that in any specific short circuit all stresses on the alternator are reduced in the same ratio by additional reactances. But the maximum possible end turn and torque stresses do not occur simultaneously, for the maximum current flows with minimum transient impedance, or in a zero resistance bus short circuit, while the maximum torque results when some considerable resistance—the exact value depending on the simultaneous value of the reactance—is in circuit. In the case considered in Fig. 12 the possible maximum torque is thus reduced only 45 per cent by 6 per cent reactances or directly as the maximum current. This variation of the maximum possible torque in direct proportion to the short-circuit current at zero resistance, as suggested by the last statement, or in other words, a variation of the maximum torque inversely as the total reactance x

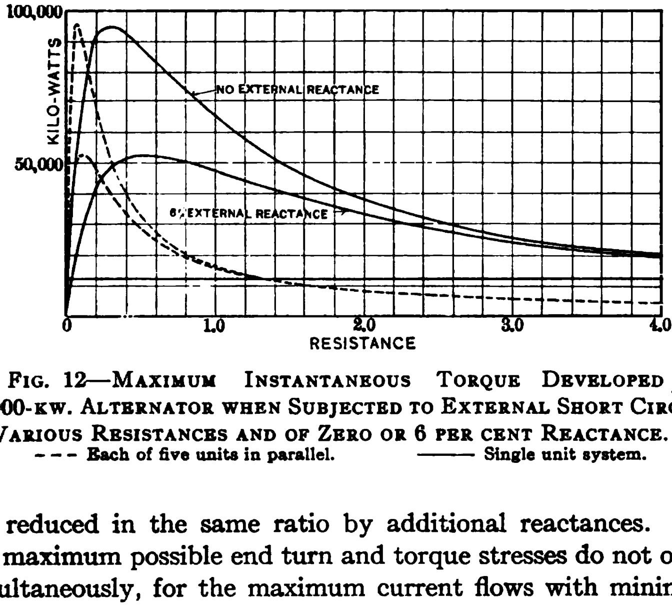

FIG. 12—MAXIMUM INSTANTANEOUS TORQUE DEVELOPED IN A 12,000-KW. ALTERNATOR WHEN SUBJECTED TO EXTERNAL SHORT CIRCUITS OF VARIOUS RESISTANCES AND OF ZERO OR 6 PER CENT REACTANCE.

– – – Each of five units in parallel. ——— Single unit system.

so that maximum $W_m^0 = \frac{K}{x}$, is found empirically to be a true property of equation (**18**) by plotting curves as in Fig. 12 for other values of x. The current curves of Fig. 5 may thus be redrawn to show the percentage decrease in possible maximum torque, as well as in short-circuit current, secured by the use of various external reactances, as is done in the upper curve of Fig. 13. The lower curve of this figure showing the corresponding decrease in end-turn stresses is plotted to the same scale, but the great difference in the actual magnitudes of the end-turn and torque stresses must be kept in mind. Thus, with no external reactance the torque is 7.9 times, the short-circuit current 27 times, and the end-turn stresses 729 times, the magnitudes existing at full load. Hence, although the end-turn stresses are reduced 69 per cent by 6 per cent reactance coils, and the torque but 45 per cent, the torque is 4.3 times full load, while the end-turn stresses are still 226 times normal. Indeed, even 20 per cent reactance coils leave the end-turn stresses 58 times normal.

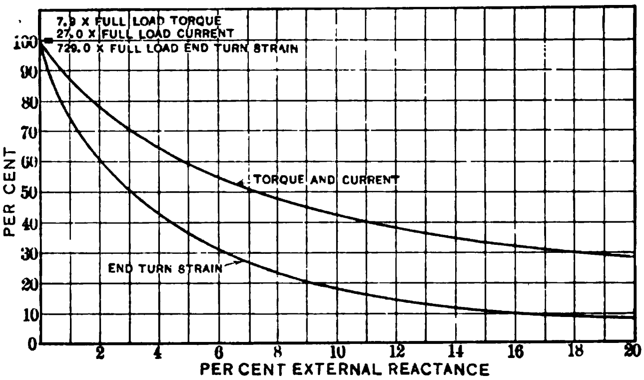

FIG. 13—MAXIMUM SHORT-CIRCUIT CURRENT, MAXIMUM TORQUE AND MAXIMUM END-TURN STRESSES IN A 12,000-KW. ALTERNATOR, UNDER SHORT CIRCUITS OF VARIOUS EXTERNAL REACTANCES.

Plotted in percentage of values without external reactance.

As, however, external reactances have a large percentage effect in reducing end-turn stresses, the introduction of reactance coils evidently gives great protection to end turns even though still leaving these stresses large, but in lessening mechanical shock and retardation of the generator the percentage effect is considerably smaller and thus the protection much less than has been claimed.

With n units in parallel supplying a short circuit of fixed resistance the torque on each unit is equal to that produced in a single unit short-circuited through n times the given resistance. The lower dotted curve of Fig. 12 thus shows the torque on each of five machines protected by individual 6 per cent reactance coils and short-circuited through various external resistances (the upper dotted curve showing similar relations for five units without reactance coils). Comparing the corresponding curves for one and five units it is seen that the answer to the question as to whether a unit will receive a more severe shock on a short circuit when it is operating alone or in parallel with other units depends entirely on the particular short-circuit conditions. For station short circuits, including cable breakdowns within a short distance of the station, the blow per machine will be much more severe with five units than with one, while the total power to be interrupted with five units—given by five times the ordinates of the dotted curves—may reach 265 megawatts with 6 per cent reactance coils as against the 53 megawatts which can be supplied by one unit. For short circuits of more than 0.25 ohms resistance the blow per machine with five units in parallel rapidly becomes less than that with a single unit, reaching full load torque for a short circuit of 1.4 ohms, at which point a single protected unit would experience a torque 3.5 times full load. With resistances of three or four ohms per phase, magnitudes, that is, corresponding to substation short circuits, the total power to be interrupted, which has now decreased to about 20 megawatts, is practically the same with five units as with one, and the blow per machine with three or more units in parallel is hardly more than may be met in normal operation.

In review it will be noted that all the conclusions of this paper are based on two assumptions; first, that the transient reactance is constant at and near the middle of the first cycle; and second, that when this reactance is introduced in equation (6), true current values are obtained at and near $\theta = \pi$. The first of these assumptions is discussed under the heading Transient Impedance. The second remains to be validated. The dotted curves of Fig. 14 represent the simultaneous three-phase current waves taken from oscillograms No. 317 and No. 318 made in test No. 190—a three-phase short circuit at 9000 volts Δ with 6.3 per cent external reactance coils. Considerable discrepancies, due to the oscillograph, to current transformer distortion, or to other errors in measurement, exist in one or all of these wave forms, as is shown by the dashed curve which represents the sum of the dotted curves for *A* and *B* phases and should, therefore, coincide with the dotted or oscillograph curve for *C* phase, and these discrepancies must be remembered in judging the agreement between the oscillograms and the theory. From the oscillogram of the generator pressure (a curve not shown in the figure) θ_0 for *A* phase is found by actual measurement to be -72 deg., and substituting this figure and appropriate figures for *B* and *C* phases in equation (7), r being assumed negligible and $x = 0.924$ ohms, the full-line curves of Fig. 14 are

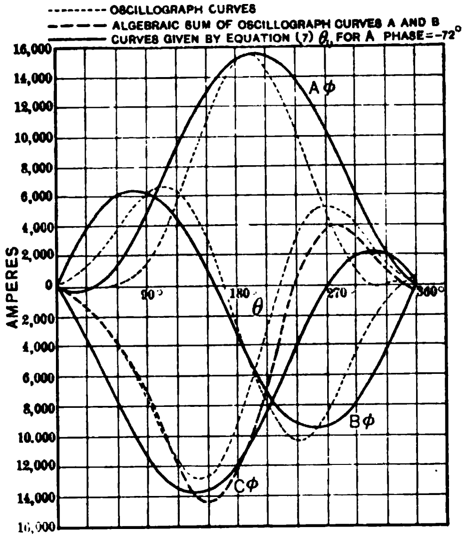

FIG. 14—AGREEMENT OF EQUATION (7) WITH OSCILLOGRAMS.

obtained. A considerably better agreement may be secured by trial, using various values of r, but at the 180-deg. point the coincidence shown in the figure appears quite sufficient for all practical applications of the work.

These curves are fairly typical of all those investigated, and although the variations of the oscillograms from the mathematical curves show that the reactions are much too complex to be perfectly represented by a simple law of variation for the transient reactance, it is believed that the two main assumptions of this paper give a practical means of closely predicting from a single low-voltage short-circuit test the transient reactions of an alternator.

APPENDIX A

To demonstrate that the equation

$$i = \frac{E_m^0}{z} \left\{ \cos(\theta - \theta_0 - \theta_1) - \epsilon^{-\frac{r}{x}\theta} \cos(\theta_0 + \theta_1) \right\}$$

gives the maximum value of i when $\theta_0 = \frac{\pi}{2}$ or when the circuit is closed on the zero point of the e.m.f. wave for all values of r and x. Let $\frac{r}{x} = \cot\theta_1 = K$ a constant in any specific case.

As θ and θ_0 are independent variables the expression is a maximum when $\frac{d\,i}{d\,\theta}$ and $\frac{d\,i}{d\,\theta_0}$ are both equal to zero, but

$$\frac{d\,i}{d\,\theta_0} = \cos\theta_0 \sin\theta_1 \left\{ \tan\theta_0 \left[K\,\epsilon^{-K\theta} - K\cos\theta - \sin\theta \right] + \left[\epsilon^{-K\theta} - \cos\theta + K\sin\theta \right] \right\}$$

and ∴ when

$$\frac{d\,i}{d\,\theta_0} = 0,\ \tan\theta_0 = \frac{-\epsilon^{-K\theta} + \cos\theta - K\sin\theta}{K\,\epsilon^{-K\theta} - K\cos\theta - \sin\theta}$$

also

$$\frac{d\,i}{d\,\theta} = \left[\frac{-\cos(\theta_0 + \theta_1)}{K - \tan\theta_0} \right] \left\{ \tan\theta_0 \left[K\,\epsilon^{-K\theta} - K\cos\theta - \sin\theta \right] - \left[-K^2\,\epsilon^{-K\theta} - \cos\theta + K\sin\theta \right] \right\}$$

and ∴ when

$$\frac{d\,i}{d\,\theta} = 0,\ \tan\theta_0 = \frac{K^2\,\epsilon^{-K\theta} + \cos\theta - K\sin\theta}{K\,\epsilon^{-K\theta} - K\cos\theta - \sin\theta}$$

Hence for the maximum value of i

$$\tan \theta_0 = \frac{-\epsilon^{-K\theta} + \cos\theta - K\sin\theta}{K\,\epsilon^{-K\theta} - K\cos\theta - \sin\theta} = \frac{K^2\epsilon^{-K\theta} + \cos\theta - K\sin\theta}{K\,\epsilon^{-K\theta} - K\cos\theta - \sin\theta}$$

This is only possible for real finite values of K and θ when

$$K\,\epsilon^{-K\theta} - K\cos\theta - \sin\theta = 0$$

or when

$$\tan\theta_0 = \infty$$

and

$$\theta_0 = \frac{\pi}{2}$$

DISCUSSION ON "OPERATING CHARACTERISTICS OF LARGE TURBO-GENERATORS" (FIELD), AND "THE TRANSIENT REACTIONS OF ALTERNATORS" (DURGIN AND WHITEHEAD), BOSTON, MASS., JUNE 28, 1912.

H. M. Hobart: I consider Mr. Field's paper to be an excellent statement of the situation in regard to turbo-generators. Developments of the last few years have made it quite necessary to introduce considerable deviation from what was formerly considered the best design. This has come about largely from the necessity for better construction because of the stresses due to the large short-circuit currents, and for other reasons.

My attention was attracted by the last paragraph of the paper, in which Mr. Field recommends the avoidance of handicapping the design of the alternator to any extent as the result of incorporating the ventilating fans in the design. I am strongly inclined to believe that he is quite right. It always seems to me that a characteristic feature of almost all engineering methods is that the engineer's work will be more in accord with the strict commercial line of progress when he is free to let each element in the engineering work be adapted to its own particular purpose. In large work at any rate, this policy is generally in the interest of true commercial economy, and I believe with Mr. Field that it will often be preferable, where the generators are of very large capacity, to provide completely independent ventilating apparatus. This plan has various advantages. If we try to incorporate the fans, we handicap the design of the alternator. The design of the alternator cannot be quite as good as if that requirement was not in the designer's mind. Moreover, if the ventilating apparatus is distinct from the generator, that apparatus also can be made more efficient and appropriate.

Occasions will often arise where a centralized ventilating plant can be successfully employed. One reason for that, as Mr. Field suggests, is that the air can be treated before it is sent on its way to the machine. Great developments are in store in this direction. It is a very important matter indeed that the air should be thoroughly cleaned. That can be best done as a separate department of the business. The humidity of the air may also with advantage be controlled prior to sending it on to the machinery through which it is to be circulated. Moreover, there are many otherwise fine stations which could be distinctly improved were the air taken from outside, as of course is done in many other stations, circulated through the machine, and sent—not into the engine room—but again outside, at any rate in many seasons of the year. In those seasons of the year where it would be useful to have it sent inside, it could be readily arranged. So that from every standpoint—from the standpoint of getting the very best generator for the money spent on it, the very best fans for the money spent on them, from the standpoint of having the air clean and in the most appropriate condition before entering the machine, and from the standpoint of having the most appropriate condition in the engine room, Mr. Field's suggestions are excellent.

B. G. Lamme: I wish to make a few general remarks on the paper of Messrs. Durgin and Whitehead. It is now, I believe, pretty generally accepted that all large alternators should have considerable reactance. You should put all you can inside, and if that is not enough, then put some outside. In some types of machines it is difficult to get enough internal reactance. There are some advantages in both arrangements. For instance, if a short circuit occurs in one machine, an outside reactance between the machine and other machines will protect the other machines. On the other hand, if a short circuit occurs at the winding of one machine, you may save that machine by having a high internal reactance, regardless of the other machines. A good proportion of the short circuits that occur in turbo-alternators are in the end windings and, in many cases, in the terminals. In those cases, if a ground occurs on the machine, the internal reactance may still save the winding and it may damage the machine only slightly. If a machine has very little internal reactance, then in the case of an internal short circuit or ground, the whole machine may be ruined; so there are some advantages in having considerable internal reactance, and also some in having additional reactance for protection against other machines. I am a great believer in having high reactance in the machine, and also, wherever necessary, in putting some outside.

In connection with the effect of armature short circuits on the field winding, in the New Haven Railroad power house, when we first installed the generators, we had many short circuits on the trolley system, and we had more trouble at first in the generator field windings than in the armatures. Some of these troubles consisted of short circuits or grounds which we could not explain for awhile, but later we discovered that they were due to the high voltage generated in the field windings at the time of the short circuits on the line. We then put a low-resistance shunt across the exciter circuit. That helped matters. Somewhat later we equipped the rotors of these machines with very heavy copper dampers, of the cage type; after that all trouble with field windings disappeared. That was four years ago. The dampers on the machines have suppressed the voltage rises, as was expected, and the field trouble has entirely disappeared, thus showing the effect of the cage damper in protecting the field winding.

P. M. Lincoln: I note that Messrs. Durgin and Whitehead in their paper have developed a formula by which they may obtain the maximum current in a short circuit and also the torque that is developed by the short circuit. I am not prepared to discuss the accuracy of this formula because I have not had a chance to study it sufficiently, but I would like to ask whether or not any of the members have really come across any difficulties due to the torque which has been developed on any generators due to short circuits. Generator shafts are usually so constructed that the amount of torque which can be transmitted is very much in excess of normal full load torque, and there is so much excess that, so far as my experience goes, there is sufficient so that, whatever abnormal torque is developed by short circuit or any other condition, there is no difficulty. This formula, I believe, gives a comparatively small excess above full load torque as the maximum that can be obtained, amounting to perhaps two or three times the normal full load torque. This seems to bear out the experience stated above, viz.: that no difficulty may be expected from the torques due to short circuits.

Henry G. Reist: Some years ago, when we did not fully appreciate the stress of the high current that we get in generators, we had an experience with a generator which did shear coupling bolts, and I think there must have been nine or ten times the normal torque in the machine in order to have done this. Of course later machines are designed very much more cautiously and do not cause any harm. But there is no doubt in my mind that the torque in the older machines in the case of short circuits went up as high as ten or twelve or perhaps fourteen times the normal torque.

B. G. Lamme: In regard to the point Mr. Lincoln has raised regarding the torque, it may be said that the torque is developed in the alternator itself, but the transmission of this torque to other parts is a question of how much of it will be absorbed in the alternator rotor itself and how much in the other parts. In large high-speed turbo-alternators the rotor will absorb considerable of it. I know of one case of a turbo-alternator that had a special coupling on it, that was figured out to stand a maximum of three times the rated load. That machine was subjected to severe short circuits frequently, which in several cases affected the armature winding, yet the coupling was never injured.

Henry G. Reist: I think that might be true on some machines, but on a steam turbine generator the effect is large in comparison with the revolving part of the generator, so that a short circuit on the generator would transmit a great deal of stress to the coupling.

B. G. Lamme: The case I refer to was an engine-driven generator.

Henry G. Reist: On engine-driven generators I might state that I have not found much sign of excess.

In regard to Mr. Field's paper, I heartily agree with the author and I would like to add that the engineers of this country should, I think, as rapidly as possible, filter the air for turbine alternators. It is done, if at all in this country, practically on a very small scale, but it is a matter of very great importance, a method of great merit, and this country is far behind what is being done in Europe. It is the almost universal practise, abroad, to have the air for cooling turbine alternators filtered through cotton cloth filters. I think it is open to question whether the form of filter that they use in Europe is the best or whether some other form may not be better, but it seems to me it is a problem that American engineers should work out and then adopt the method which seems to be best adapted for the purpose.

Comfort A. Adams: There is one point that I wish to consider briefly; it relates to the internal and transient reactances. The difficulty in dealing with the internal or leakage reactance of an alternator armature is twofold. Not only is this term very loosely defined and loosely used, but the quantity, when once defined as accurately as possible, is still practically impossible of even reasonably accurate measurement, unless defined in terms of the results of some specific tests, in which case the result is pretty sure to involve different phenomena in different types of alternators. It is even more difficult to compute than to measure, and there is no accurate method of checking the computations. For example, I seriously question the estimate of two per cent as the reactance of the machine in question. Ordinary short-cut methods of computing the leakage reactance are likely to give very erroneous results when applied to an extreme type of alternator such as that referred to in the paper. A method which serves very well for one type of machine may be useless for another, unless it is completely rational. For example, any method which groups the coil-end reactance with the slot reactance on the assumption that the former is relatively small or that it bears a fixed relation to the latter, will yield much too small results for this type of machine, since the slot reactance is inversely proportional to the peripheral velocity, other things being equal, while the coil-end reactance is roughly proportional to the ratio of pole pitch to gross core length, and otherwise independent of the frequency and peripheral velocity. There would thus be a comparatively small change in the coil-end reactance in passing from an engine-driven alternato with a peripheral velocity of 100 ft. per second, to a turbo-alternator at 400 ft. per second, while the slot reactance would be reduced to about one-fourth. This large change in ratio is only slightly neutralized by the considerable reduction of coil pitch common to bipolar machines, since this change affects both elements in the same direction, but the coil-end reactance in the greater degree. The belt leakage also becomes quite appreciable at high peripheral velocities, although it varies tremendously with the coil pitch, being a maximum at full and two-thirds pitch, and a minimum (practically negligible), at $\frac{5}{6}$ and $\frac{1}{3}$ pitch, for a three-phase machine.

It should also be observed that the definition for x_r given in the middle of page 1663 is merely descriptive or qualitative rather than workably quantitative, owing to the serious difficulty in defining and computing the field reactance, or what might for the present purpose be more appropriately designated the *equivalent* field reactance.

A question has been asked in this discussion as to the cooling effect of moisture in the air supplied to a piece of working apparatus. I have had recent opportunity to observe a case where the temperature rise of a machine under test was reduced eight deg. cent. or 25 per cent by the presence of considerable quantities of condensed steam in the air supply. After the air had passed through the machine there were no visible signs of the moisture, which had obviously evaporated.

A. B. Field: It is very satisfactory to find engineers of the experience of Messrs. Hobart and Reist standing out for air filtration in turbo installations. There seems little doubt that, if our manufacturing companies will strongly advocate the adoption of such processes, the operating engineers will be only too ready to see the advantages and install suitable apparatus.

Professor Adams has referred to the reactance introduced by the end connections of the stator winding. A considerable proportion of the reactance which is effective on a sudden short circuit is due to the part of the winding external to the core. However, in large two-pole machines, it is generally not feasible to adopt a coil pitch which is equal to the pole pitch, or even nearly so. The length of coil external to the core is already much greater than that of the buried portion, even when the coil is chorded considerably; the difficulties of satisfactorily clamping the ends increase with too great a coil throw; the rotor span, between journal centers, becomes lengthened, and further, in those cases in which complete coils are used instead of half coils, it is necessary to proportion the coil so that it can be passed through the bore of the stator for assembly purposes.

Sanford A. Moss (communicated after adjournment): Exception must be taken to Mr. Field's statement that it is difficult to provide for efficient and satisfactory blowers mounted directly on the rotor. Considerable experience with direct-mounted blowers of the type shown* in Fig. 20 of the paper by Messrs. Hobart and Knowlton, *The Squirrel-Cage Induction Generator*, shows that they can be made very satisfactory.

Blowers of this type, if properly designed, and if made with proper diameters, blade angles, etc., can be made fully as efficient as any separately connected blower, and often more efficient. The peripheral speeds are, of course, very high, but with proper design of blades this does not serve in any way to decrease the efficiency. One fact which makes a properly designed direct-mounted blower more efficient than a separate blower is that there are no separate rotation losses. The blower, being mounted directly on the rotor, has no disk losses of its own. Actual tests of machines with carefully designed blowers of the type above referred to, first with blower vanes removed and then with vanes in place, show that the increased power required for driving bears a very favorable relation to the theoretical power required

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*See this volume of the TRANSACTIONS, page 1743.

for compression of the actually measured volume of air to the actually measured pressure.

The room taken by the blower itself is negligible and does not increase the length of shaft in the designs referred to. There must always be a certain space left for proper passages for carrying the air to the various parts to be cooled. These air passages must exist whether the blower is directly mounted or separately mounted. They, of course, take up some room, which is inevitable and due to the necessity of ventilation, not to the direct mounting of the blower on the rotor. The use of air filters with the direct-mounted blower is as convenient as, if not more convenient than with separate blowers. In all cases air should be taken from some outside source by a conduit leading to the blower inlet. It is very bad practise to take air directly from the engine-room even with a direct-mounted blower. The air filter can, therefore, be placed at the beginning of the conduit leading the air to the blower.

The method of ventilation by use of a high-pressure jet which Mr. Field mentions would be very inefficient. Most schemes of moving air by injector action entail large losses.

H. R. Woodrow (communicated after adjournment): I would like to ask the question why the reactance of the field circuit and the reactance of eddy-current paths on contiguous metal masses reduced to armature are to be added, since they are in parallel? And also, is the reactance in the exponential function the value called " transient impedance"?

The maximum instantaneous torque is not the sum of the I^2R losses of the armature, but many times that value, since there is considerable energy required to build up the field of the armature reactance. Also the field current rises to enormous values, requiring energy from the generator.

Assuming that equation (6), in the paper by Messrs. Durgin and Whitehead, is correct for the armature current, although it cannot hold true for any appreciable length of time (1 to 2 cycles), that is,

$$i_1 = \frac{E}{z}\left[\cos(\theta-\theta_0-\theta_1) - \epsilon^{-\frac{r}{x}\theta}\cos(\theta_0+\theta_1)\right],$$

where the voltage is

$$e_1 = E\cos(\theta-\theta_0),$$

the instantaneous power is equal to

$$p_1 = e_1 i_1 = \frac{E^2}{z}\cos(\theta-\theta_0)\left[\cos(\theta-\theta_0-\theta_1) - \epsilon^{-\frac{r}{x}\theta}\cos(\theta_0+\theta_1)\right]$$

or, for any phase a in an n-phase machine,

$$p_a = e_a i_a = \frac{E^2}{z}\cos\left(\theta-\theta_0+\frac{2\pi a}{n}\right)$$

$$\left[\cos\left(\theta-\theta_0-\theta_1+\frac{2\pi a}{n}\right) - \epsilon^{-\frac{r}{x}\theta}\cos\left(\theta_0+\theta_1+\frac{2\pi a}{n}\right)\right]$$

The total instantaneous power on the shaft is the sum of that on the individual phases:

$$p = \sum_{a=0}^{a=(n-1)} e_a \, i_a$$

which reduces to

$$p = \frac{3}{2} \frac{E^2}{z} \left[\cos(\theta_1) - \theta^{-\frac{r}{x}\theta} \cos(\theta + \theta_1) \right]$$

If z is represented in per cent, and on non-inductive full load $z = 1$, $\cos\theta_1 = 1$ and $\epsilon^{-\frac{r}{x}\theta} = 0$, and the full-load power P is

$$P = \frac{3}{2} K E^2 \text{ or } K = \frac{2}{3} \frac{P}{E^2}$$

Hence the instantaneous value of power in terms of full-load power is

$$p = \frac{P}{z} \left[\cos\theta_1 - \epsilon^{-\frac{r}{x}\theta} \cos(\theta + \theta_1) \right]$$

and

$$\cos\theta_1 = \frac{r}{z}$$

Then

$$p = \frac{P}{z} \left[\frac{r}{z} - \epsilon^{-\frac{r}{x}\theta} \cos(\theta + \theta_1) \right]$$

and the instantaneous power is independent of the point of the voltage wave at which the circuit is closed, but is pulsating in magnitude so long as the transient expression of current exists.

Assuming the expression for current to hold true for the first cycle, and a condition where

$$x = 10\,r,\quad z = 7 \text{ per cent},\quad \theta_1 = \tan^{-1}\frac{X}{r} = 84 \text{ deg. } 18 \text{ min.}$$

and

$$p = \frac{P}{0.07}\left[0.1 - \epsilon^{-0.1\,\theta} \cos(\theta + 84 \text{ deg. } 18 \text{ min.})\right]$$

the instantaneous values of power or torque will be as shown in Curve 2, on the following page.

To determine the maximum point of the torque, differentiate the above expression with respect to time θ and equate to zero.

$$\frac{\delta p}{\delta \theta} = \frac{P}{z} \left\{ \frac{r}{x} \epsilon^{-\frac{r}{x}\theta} \cos(\theta + \theta_1) + \epsilon^{-\frac{r}{x}\theta} \sin(\theta + \theta_1) \right\} = 0$$

and

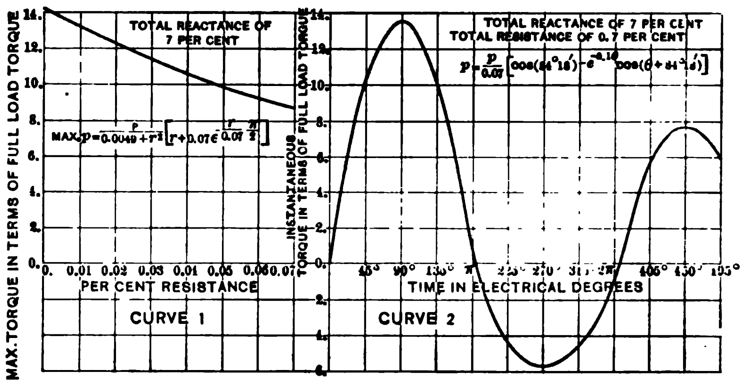
$$\frac{\cos(\theta + \theta_1)}{\sin(\theta + \theta_1)} = -\frac{r}{x}$$

hence

$$\theta = \frac{\pi}{2}$$

Therefore

$$\max p = \frac{P}{z^2} \left\{ r + x \epsilon^{-\frac{r}{x}\frac{\pi}{2}} \right\}$$



Max. p with respect to the armature resistance is plotted in Curve 1, which shows that the maximum instantaneous power occurs with zero armature resistance in a circuit of constant reactance.

With n generators operating on a bus when a short circuit of resistance r is made on the bus, the effect on the individual generator is the same as if $n \times r$ resistance were in each individual generator, hence the maximum instantaneous torque on the individual generators occurs with but one machine operating on the bus.

W. L. Waters (communicated after adjournment): The history of the turbo-generator has been one of continually increasing speed to meet the requirement of efficiency in the steam turbine, and it is only during the past few years that it has become possible to operate the generator at any speed found advisable for the turbine.

An idea of the progress made can be obtained from the fact that 5000-kv-a., 3600-rev. per min. maximum rated units have been built in the United States, and 6000-kv-a., 3000-rev. per min. units with 25 per cent overload capacity have been built in Europe; while I understand that Mr. Field has designed and is prepared to build 30,000-kv-a., maximum rated, 25-cycle generators to operate at 1500 rev. per min. The question of high speed vs. low speed for turbine sets is similar to the question of high-speed vs. low-speed steam engines. It is to be decided by the relative cost, floor space, maintenance, and efficiency of the sets. One handicap of the high-speed steam engine is that when it gets out of adjustment, trouble develops very much more rapidly than with the corresponding low speed; but the same criticism hardly applies to steam turbine sets, as there is practically no difference in this respect between an 1800-rev. per min. and a 3600-rev. per min. unit.

The phenomenon which takes place at the instant of short-circuiting an alternator was investigated by the writer a number of years ago, when it was found that on account of the eddy currents there was a time lag in the effect of the armature reaction in reducing the flux. So that—as I think was first stated in the paper on *Non-Synchronous Generators*, which I presented before the Institute in February, 1908—the instantaneous rush of current at the moment of short circuit is equal to

$$\frac{\text{e. m. f.}}{\text{total impedance in circuit}}$$

About the time this was published, it was found from the oscillographic records that the value of the first few waves of current is dependent upon the phase of the voltage at the moment of short circuit, and that—as stated by Mr. Field—the first current wave can have a value approximately double that given by the above equation if the short circuit occurs at the instant when the e.m.f. is zero. It is not clear to me what Mr. Field means by "most probable" value of the initial short-circuit current, as it is the maximum possible value that we most protect against. For this reason, a short-circuit test on an a-c. generator is often of no value, as it may happen that the circuit is closed when the e.m.f. is a maximum, which would give the lowest value of the initial current rush. In practical operation, the generator might be thrown on the busbars with a bank of similar machines, 180 deg. out of phase, and at a time when the e.m.f. is zero. In such a case, the first rush of current would be four times as great, and the stresses on the end connections of the armature coils sixteen times as great, as those in the short-circuit test. As to the question of the capability of enduring the short circuit likely to be met with in practical operation, the purchaser is to a great extent dependent upon the manufacturer. Adequate tests are almost impossible to make, and in addition, are somewhat dangerous, especially in large vertical units, on account of the mechanical shock to the machine and the violent flashing and consequent burning of the rotor, due to heavy induced currents.

As Mr. Field points out, the modern tendency is to design large a-c. generators with high internal self-induction, and consequent poor regulation, in order to reduce the stresses on the generator and system generally caused by short circuits. A voltage regulator seems to have become a necessary adjunct of a modern power station, and since Mr. Stott has successfully overcome the difficulty of applying such regulators to a large system like the Interborough in New York, the day of closely regulated a-c. generators for power station work can now be considered as past.

The practise of using separate blowers and filtering the air through screens offers a number of advantages, but requires careful planning.. The over-all efficiency, including friction, windage, and blower losses, may be very materially reduced with an external blower, unless the station is very carefully laid out; and unless the filter screens are cleaned frequently, they merely obstruct the air supply, or allow all the dirt to pass through. If the air supply to the screens and generator is at all dusty, it is practically impossible to avoid frequent cleaning of the air ducts in the machine.

I think that Mr. Field's valuable paper would be more complete if he emphasized that fact that the operating engineer and purchaser must depend to a great extent upon the ability and integrity of the manufacturer for the most suitable design for large high-speed units, as it is almost impossible to make specific tests which are of any practical value.

When the Cos Cob power station of the New York, New Haven and Hartford Railroad was first operated, five years ago, numerous short circuits on the 11,000-volt single-phase system were experienced; and this was probably the first occasion on which phenomena of high-power short circuits were urgently brought to the attention of engineers. A large number of experiments were carried out by Mr. Lamme and the writer, which covered, to a great extent, the subject of the present paper by Messrs. Durgin and Whitehead. After Mr. Lamme had decided to install external reactance coils in the circuit of each generator (at that time quite an original idea), but before it was actually carried out, the operating engineers tried the effect of inserting a resistance in series with the generator—this being accomplished by connecting a feeder two miles (3.2 km.) long permanently in the circuit between the overhead line and the power house. The comparatively small resistance inserted had an extraordinarily good effect in reducing the shock of short circuits on the power house—so much so that it was even suggested that this resistance be left in circuit and the reactance coils not installed. These results started us investigating the relative value of resistance and reactance in limiting short circuits. Oscillographic records of the current obtained under different conditions were found to check with those determined theoretically from the following well-known equation covering sudden changes in the impedance of a power circuit:

$$I = \frac{E}{\sqrt{R^2 + p^2 L^2}} \sin \overline{p\,t - \omega}$$

$$+ E\left(\frac{\sin \overline{\theta - \alpha}}{\sqrt{\overline{R_0 + R}^2 + p^2\,\overline{L_0 + L}^2}} - \frac{\sin \overline{\theta - \omega}}{\sqrt{R^2 + p^2 L^2}}\right) \epsilon^{\frac{R}{p\,L}(\theta - p\,t)}$$

Where

R_0 and L_0 are resistance and self-induction of circuit beyond the short circuit,

R and L are resistance and self-induction of generator and circuit inside of the short circuit,

$\omega = \tan^{-1} \frac{pL}{R}$ $\alpha = \tan^{-1} \frac{P\,(L + L_0)}{R + R_0}$

I = current E = e.m.f.

θ = value of $p\,t$ at instant of short circuit

$p = 2\pi \times$ frequency ϵ = exponential

t = time measured from arbitrary zero.

Curves similar to those shown in Figs. 8, 10 and 12 in Messrs. Durgin and Whitehead's paper, showing the beneficial results of the presence of resistance in circuit, were soon obtained—both theoretically and experimentally. The final decision to adopt choke coils, rather than resistance, to limit the short-circuit shock on any station, was decided by the disadvantage caused by the waste of energy in the resistance. This is of interest historically as showing the steps that led up to the installation of choke coils at Cos Cob, which set a precedent for what has now become standard practise in almost all new large power stations.

This paper is an extremely useful and complete explanation of the general phenomena of the a-c. generator short circuits and is especially valuable as being based upon a complete series of tests under practical operating conditions. The author's remarks in reference to " transient reactance " in an a-c. generator bring to mind the discussions that have taken place during the past twenty years involving the question of the self-induction of an alternator. Those who have followed these discussions know what was, I think, first pointed out fifteen years ago by M. Blondel, that the term " self-induction of an alternator " is a meaningless expression until a definition is given of exactly what is meant. The e.m.f. of self-induction in any electrical circuit is the e.m.f. caused by the time rate of change of the lines of force linking with the circuit, and due to the current in that circuit.

In any alternator, this is an extremely complicated phenomenon. The self-induction varies with the reluctance of the magnetic circuit, which again varies with the relative position of the iron and electric circuits of the field magnets and armature; and also depends on the permeability of each part of the iron circuit, which again varies with the value of the current. The fact that the " transient reactance," as found by experiments, appeared to be only 28 per cent of that calculated by the authors, is not surprising, and only emphasizes the necessity of depending upon experiments and actual tests, rather than upon calculations based necessarily upon assumptions.

William A. Durgin (by letter): Some confusion seems to prevail as to the purpose of this paper. It does not at all claim to give a method of computing the transient reactance from design data, nor to substantiate the existence of any actual ***simple inductive*** characteristic, but it is intended to show the value of the conception "transient reactance" in certain useful computations, based on low-voltage short-circuit tests that can be readily made on any alternator without the slightest hazard to the unit.

We fully appreciate the fictitious nature of the conception, and in such equations as (4) we have tried to show merely a descriptive relation, being under no delusion as to the possibility of actually computing the components. Transient reactance is no more real than the self-inductive reactance of the armature, the synchronous reactance of the machine or any of the many other terms which are commonly accepted as convenient names for covering complex relations which enter our work as a single quantity.

The paper shows that the maximum initial peaks of short-circuit currents obtained on a large number of tests are limited by reactions having a reasonably constant combined effect, and results of practical value are obtained by considering the effect as due to a single reactance of transient character.

The discussion of torque in the paper is in error in that it refers to the torque developed by conversion of energy into heat as the total torque on the unit. Under the conditions assumed, this torque is in reality only that portion of the total which is transmitted to the external circuit. Consequently, the torque curves shown in Figs. 12 and 13 indicate the magnitude of energy to be ruptured by main oil switches, to be transmitted through station buses and to be consumed in cables or at faults, rather than the total torque developed within the alternator. The true total torque contains, in addition to the I^2R torque considered, a term representing the storage of energy in the field, which can be shown to equal

$$w'_\phi = \frac{3}{2}\frac{(E_m{}^0)^2}{Z^2}\, x\, \epsilon^{-\frac{r}{x}\theta}\left[\sin\theta + \frac{r}{x}\left(\cos\theta - \epsilon^{-\frac{r}{x}\theta}\right)\right]$$

The combination of this latter equation with equation (**20**) of the paper gives for the total torque developed:

$$w_T = \frac{3}{2}\frac{(E_m{}^0)^2}{Z^2}\, x \left[\frac{r}{x} + \epsilon^{-\frac{r}{x}\theta}\left(\sin\theta + \frac{r}{x}\cos\theta\right)\right]$$

This is easily shown to be a maximum when $\theta = \frac{\pi}{2}$, and in consequence, the maximum torque for any given value of $\frac{r}{x}$ is ·

$$W_m{}^0 = \frac{3}{2}\frac{E^2}{Z^2}\left(r + x\,\epsilon^{-\frac{\pi}{2}\frac{r}{x}}\right)$$

a result which agrees with that derived by Mr. Woodrow, from a somewhat different line of reasoning.

It is to be noted, however, that these latter results are in reality based on the assumption that the transient reactance is a true inductive effect from which the equivalent inductance can be computed and that, therefore, although the results may be taken as indicating maximum limits which the actual torque will never exceed, they are open to more serious question than those deduced for the values of current and I^2R torque.

The importance of short-circuit torque in practical operation, as has been indicated elsewhere in the discussion, is less with units of more recent design, but a few years ago a generator armature sometimes sheared its frame bolts and turned perhaps 90 deg. about its axis when subjected to heavy short circuit.

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 28, 1912.

DETERMINATION OF POWER EFFICIENCY OF ROTATING ELECTRIC MACHINES

SUMMATION OF LOSSES VERSUS INPUT-OUTPUT TESTS

BY E. M. OLIN

Recently there has been a considerable movement on the part of several large buyers of electrical apparatus to the end that efficiency tests of rotating apparatus be made by input-output measurement rather than by the summation of separate losses.

The National Electric Light Association has also lent its approval to this movement.

Paragraph 92 of the Standardization Rules of this Institute, headed " Comparison of Methods " (for the determination of efficiency), states " The output and input method is preferable with small machines. When, however, as in the case of large machines, it is impracticable to measure the output and input, or when the percentage of power loss is small and the efficiency is nearly unity, the method of determining efficiency by measuring the losses should be followed."

The terms " small machines " and " large machines " in this paragraph are indefinite and unsatisfactory. The purpose of this paper is to discuss both methods and from a consideration of certain data to show that efficiencies can be satisfactorily computed from no-load losses in all cases, provided empirical correcting factors are used therewith to compensate for load losses, and that efficiencies so calculated will in general be much nearer the true values than those made by the average input-output test.

It is well known that certain of the losses occurring in electrical machines can be accurately determined from no-load measurements. Some of the losses, however, cannot be so determined, as, owing to conditions which develop, as load is applied a gradual increase in these losses takes place.

The difference between the total losses under load and the sum of the separate losses as determined from no-load measurements is commonly known as " load loss."

It is proposed by the writer to indicate a method which will establish the ratio of this load loss to the losses indicated by the no-load measurements. This ratio will vary for different types of apparatus.

Briefly stated, the method proposed is as follows:

From a series of reliable input-output tests derive the actual losses of a large number of machines of varying types and sizes.

Determine the losses of these same machines by the summation of loss method without increasing the separate losses to allow for field distortion or other load factors.

The difference in the losses as found by the two methods will be the so-called *load loss.*

Having determined the magnitude of this load loss for different types and sizes of apparatus, derive multiplying constants which can be applied to the separate loss values to obtain their true values under load.

It is highly desirable to use the separate loss measurements for computing efficiency for the following reasons:

The necessary tests are simple and require but few observers. For that reason they can be easily and accurately taken.

On the other hand the input-output test is complicated, and if the desired accuracy is to be obtained it must be carried on with all the safeguards and refinements employed in the most delicate laboratory work. For that reason only the most expert operators can be used. A large number of simultaneous readings are required and the errors of observation are likely to be additive. Experience has shown that repeated tests must be made before consistent results are obtained.

According to the Standardization Rules of this Institute (paragraphs 7 to 21) the term " Rotating Machines " includes:

a. Direct-current generators
b. Alternators
c. Double-current generators
d. Induction generators
e. Boosters

f. Direct-current motors
g. Alternating-current motors
h. Synchronous condensers
i. Motor-generators
j. Dynamotors
k. Converters
    Direct-current converters
    Synchronous converters (rotaries)
    Motor converters
    Frequency changers
    Rotary phase converters

(a) (b) (c) (d) and (e) may be driven by prime movers or by motors. When motor-driven they are included under class (i).

The most ardent advocate of the input-output test would hardly recommend this method for generators driven by prime movers, involving as it would the determination of mechanical power delivered at the shaft of the generator, so we can at once dismiss the first five items from our consideration.

The power efficiency of the synchronous condenser running idle is nil and when running under load this type falls under (g), so that we need not consider it in a special class.

There remain then for our attention the following:

1. Motors.
2. Motor-generators.
3. Dynamotors.
4. Converters.

1. *Motors.* The efficiency of motors may be determined by measuring the losses and subtracting them from the input to derive the output or by measuring the input and output directly. In the latter case the mechanical output is measured by some form of brake or other dynamometer.

2. *Motor-Generators;* 3. *Dynamotors;* 4. *Converters.* The efficiency of a motor-generator, dynamotor or converter may be determined by measuring the losses and adding them to the output to derive the input, or by measuring the input and output directly. In the latter case simultaneous readings of the electrical input and output are taken with suitable measuring instruments.

The losses which take place in rotating electrical apparatus are well known. Briefly stated they are:

Frictional losses
    of shafts with bearings
    of brushes with commutators
    of brushes with collector rings
    of rotating element with air (windage)

I^2r losses

- a. Due to the resistance of windings, brushes and sliding contacts to useful current flowing in the apparatus.
- b. Due to the resistance of any part of the apparatus to non-useful current. These losses include the following:
  - Losses due to eddy currents in the copper conductors, laminations, pole faces, damper windings and other metallic parts.
  - Losses in armature coils and commutator leads which are short-circuited by the brushes.
  - I^2r losses in multiple-circuit windings.

Hysteresis or molecular magnetic friction.

To derive efficiency by the separate loss method it is necessary:

1. To determine the resistance of windings, brushes and sliding contacts at a known temperature.

2. To determine the regulation with reference to speed, voltage, and current flowing in the various windings.

3. To determine the frictional losses over the range of speed indicated by the regulation.

4. To determine the "rotation loss" (commonly known as the "core loss.") This loss includes hysteresis, the eddy current losses in iron, copper and other metallic parts, I^2r losses in cross connections and I^2r losses in armature coils and armature leads which are short-circuited by the brushes, so far as these losses are due to rotation.

5. To determine the eddy current losses in the iron and especially in the copper conductors, so far as these losses are due to stray fields set up by useful currents flowing in the windings.

6. To determine the alternating or transformer loss. This loss occurs only in machines whose field windings are excited with alternating current, as in the case of a-c. commutator motors. It includes hysteresis and eddy current losses due to the alternation of the magnetic field, I^2r losses in cross-connections of armatures and I^2r losses in armature coils and commutator leads which are short-circuited by the brushes, so far as these losses are due to the alternation of the magnetic field.

1. *Resistances.* The resistances of windings can be measured with the greatest accuracy by several well known methods, which need not be discussed here.

The resistance of brushes and sliding contacts can also be determined with precision. The method is as follows: Current of normal characteristics from an external source is sent through the brushes and sliding contacts while operating at normal speed, the fall of potential indicating the resistance. A commutator or set of collector rings, for example, is assembled for rotation with its brush holder and brushes, but without connections to the armature windings. In the case of the commutator the bars are short-circuited by band wires at the ends. The apparatus is then driven at normal speed and the brush holders placed in series with current of normal characteristics from an external source. The fall of potential across the brush holders indicates the resistance of brushes and sliding contacts. Such tests have been made repeatedly by various engineers, and the values for different grades of carbon or copper brushes with varying speed and brush densities have been accurately determined. So that in computing the loss due to the resistance of brushes and sliding contacts it is usual to refer to data already compiled rather than actually to measure the resistance in each particular case.

2. *Regulation.* What constitutes regulation is defined in paragraphs 187-203 of the Standardization Rules and the *conditions for and tests of regulation* are covered by paragraphs 204-209.

It is necessary to determine over the entire range of load, (A) speed, (B) voltage, (C) current flowing in the windings.

The apparatus should be operated under normal conditions if possible, but when, as in the case of large machines, it is impracticable to make actual load tests the regulation can be approximately determined from data taken at no-load. Such regulations are sufficiently accurate for efficiency determination by the summation of loss method.

3. *Frictional Losses.* Losses due to mechanical friction, including windage, are independent of the load. The most satisfactory method for measuring these losses is by separate drive from an independent motor, preferably of the direct-current, commutating pole type. The apparatus is driven at normal speed on open circuit without current in any winding. When so operating, the input to the driving motor is greater than its own no-load losses by an amount equal to the frictional losses of the driven apparatus plus a small increase due to load loss in the driving motor itself. This load loss is composed as follows:

a. The increased I^2r loss in the armature circuit.

b. The increased rotation loss due to field distortion.

c. Eddy current losses caused by the stray fields of useful currents in the armature circuit.

(a) can be computed by a simple calculation involving the known current flowing and the resistance of the armature circuit (copper conductors, brushes and sliding contacts).

(b) cannot be satisfactorily determined by the separate loss method, as will be pointed out under " Rotation Loss." It is usually disregarded in figuring the increased power input to the driving motor.

(c) is usually so small in motors of this type that it can be ignored. In fact it is customary to ignore (a) (b) and (c) in measuring frictional and rotation losses. It is to be noted, however, that the error introduced by so doing lowers the calculated efficiency, since the loss is incorrectly charged to the driven machine instead of to the driving motor.

To determine the frictional loss at a given speed it follows that two power input readings to the driving motor are necessary, one when driving the machine under test and the other when running free at the same armature voltage and speed.

4. *Rotation Loss.* In determining the rotation loss of induction motors the apparatus is operated at no-load and normal voltage, the power input under these conditions being the sum of the frictional losses, the rotation loss, and a small copper loss due to the no-load current in the windings. The rotation loss can then be segregated by subtracting from this result the frictional loss as determined above, and the copper loss as computed from the current flowing and the resistance.

In all other rotating apparatus the rotation loss is best measured on open circuit by the separate drive method in a manner similar to that described under " Frictional Losses."

The power input to the driving motor is noted with the fields of the driven apparatus charged, and with the fields uncharged, the difference in the input, when corrected for the driving motor loss, being the " rotation loss."

This loss is composed of two parts:

m. Hysteresis and eddy current losses caused by rotation through the magnetic field.

n. I^2r losses in cross-connections of armature.

I^2r losses in armature coils and armature leads which are short-circuited by the brushes.

I^2r losses which may exist in multiple-circuit windings.

That part of the " rotation loss " due to hysteresis and eddy currents will increase somewhat under actual load conditions over its value at no-load as measured above. This increase is due to field distortion and may be a considerable percentage of the value measured at no-load.

There is no satisfactory method of computing from no-load readings the increased rotation loss due to field distortion under load.

The I^2r losses in cross-connections of armatures and the I^2r losses in armature coils and armature leads which are short-circuited by the brushes depend upon the voltage and are independent of the load. That part of the "rotation loss" due to these factors may be assumed to be correct for all loads as measured by the separate drive method at no-load.

5. The losses in the iron, and especially in the copper conductors, due to eddy currents from stray fields set up by useful currents flowing in the windings, are often a considerable item, particularly in machines having deep slots with conductors of large cross-sections.

These losses may be approximately determined in certain types of machines by operating them on short circuit at several different speeds and currents.

Paragraph 167 of the Standardization Rules described this method as applied to induction motors. Some modifications must be made, however, in order to obtain accurate results. This paragraph states "These losses (load losses) may for practical purposes be determined by measuring the total power, with the rotor short-circuited at standstill and a current in the primary circuit equal to the primary energy current at full load. The loss in the motor under these conditions may be assumed to be equal to the load losses plus I^2r losses in both primary and secondary coils."

It is to be noted that with the rotor at standstill, and current of normal characteristics flowing in the primary, the frequency of the secondary current is the same as that of the primary. In practise, however, the frequency of the secondary (which is proportional to the slip) is very low. Therefore the losses due to eddies in the secondary conductors will be greatly magnified during the above test because of the high frequency.

To approximate these losses more nearly, a series of readings should be taken with currents of varying frequency in the primary windings. This varying frequency should be brought down to as low a value as practicable. A comparison of the values thus obtained will indicate the losses under normal conditions.

The power input during these tests will of course include the ordinary I^2r losses of primary and secondary windings. These must be subtracted from the total input readings to arrive at the loss due to eddies.

There is no satisfactory no-load method of measuring this eddy current loss in the case of direct-current motors and generators and in alternating-current machines of the synchronous type. When operating such machines on short circuit so many other losses occur that it is practically impossible to segregate the eddy current loss due to the stray fields set up by currents flowing in the windings.

6. The alternating or transformer loss is measured simultaneously with the " rotation loss " by noting the power consumed by a wattmeter connected across the field circuit. A wattmeter so connected will measure

a. The I^2r loss of the field windings.

b. The I^2r loss of armature coils and commutator leads which are short-circuited by the brushes, so far as these losses are due to the alternation of the magnetic field.

c. Hysteresis and eddy current losses due to the alternation of the magnetic field.

> (a) can be computed from the measured resistance and known current flowing.
>
> (b) can be separated from the other losses by running the machine with and without brushes on the commutator.
>
> (c) is the difference between the total watts and the sum of (a) and (b).

The alternating or transformer loss is equal to the sum of (b) and (c).*

This loss is a function of the alternating current in the field windings, and for any given current will be the same whether the motor is doing work or is running free, driven from a separate motor.

The general expressions for calculating efficiency by the *Summation of Loss Method* are as follows:

---

*An exception is to be noted in alternating-current commutating motors where commutating compensation is obtained by the use of a cross field. Under this condition a portion of the loss ordinarily supplied by the alternating-current exciting current will be furnished by the driving motor.

For Motors $$\text{Efficiency} = \frac{\text{Input} - \text{Losses}}{\text{Input}}$$

For $$\left\{\begin{array}{l}\text{Motor-Generators}\\ \text{Dynamotors}\\ \text{Converters}\end{array}\right. \quad \text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

$$\text{Losses} = W_{I^2R} + W_F + W_R + W_E + W_T$$

Where W_{I^2R} = Watts lost due to the resistance of windings, brushes and sliding contacts to useful current flowing.

W_F = Watts lost in friction.

W_R = Rotation loss.

W_E = Watts lost due to eddy currents in iron and especially in copper conductors caused by the stray field of useful currents flowing in the windings.

W_T = Transformer or alternating loss.

Before proceeding further we will examine some data relating to the separate losses of rotating apparatus as compared with the rated output. The no-load values of W_R are given in these data. No values of W_E are shown, as this loss was not investigated in the case of machines given in these lists.

Apparatus	Description	Rating		Per cent of rated output				
		Output h.p.	Frequency cycles	W_{I^2R}	W_F	W_R	W_T	Total losses
Direct-current motors	Commutating pole	25		8.90	1.77	1.65		12.32
		35		6.25	1.95	2.74		10.94
		40		5.50	2.48	2.40		10.38
		50		4.65	1.87	2.08		8.60
		60		5.24	1.80	1.70		8.74
		75		6.10	1.64	1.64		9.38
		75		4.10	1.60	1.78		7.48
		75		6.00	1.02	1.81		8.83
		100		7.15	1.04	1.15		9.34
		250		6.95	0.61	0.96		8.52
		270		7.55	0.69	0.72		8.96
		300		3.92	0.89	2.41		7.22

Apparatus	Description	Rating		Per cent of rated output				
		Output h.p.	Frequency cycles	W_{I^2R}	W_F	W_R	W_T	Total losses
Direct-current motors	Non-commutating pole	6		13.20	2.07	3.46		18.70
		90		11.30	2.38	0.95		14.68
		400		4.60	0.93	3.74		9.27
Synchronous motors		290	60	1.47	1.94	2.43		5.84
		720	25	1.89	1.73	3.79		7.41
		1080	25	1.29	1.25	1.99		4.53
		2860	50	1.65	1.28	1.90		4.83
		3000	60	0.70	0.73	2.73		4.16
Alternating-commutator motor	Series type	150		7.60	3.18	2.39	3.16	16.33
		315		5.30	2.77	2.20	3.42	13.69
Induction motors	Wound secondary	7½	60	10.00	4.28	4.00		14.28
		50	60	3.60	3.22	3.63		10.45
		75	60	5.95	2.14	2.02		10.11
		150	60	2.19	1.87	2.38		6.44
		200	60	6.34	1.68	2.69		10.71
		350	60	5.40	1.46	2.30		9.16
		500	60	3.77	1.66	2.06		7.49
		1200	60	1.42	1.79	1.67		4.88
		3000	25	5.20	0.90	1.52		7.62
		11	60	10.30	1.71	6.23		18.24
		18	60	9.26	1.87	6.13		17.26
		25	60	4.55	1.88	5.42		11.85
		35		5.15	1.53	9.25		15.93
		75	60	3.85	1.34	5.80		10.99
		100	25	9.00	2.28	6.30		17.58
		125	60	10.50	1.29	5.15		16.94
		225	60	6.85	0.65	3.10		10.60
Induction motors	Cage secondary	5	60	10.82	2.28	4.50		17.60
		20	50	4.07	2.35	4.56		10.98
		20	60	11.35	2.15	3.39		16.90
		40	50	4.82	1.68	6.22		12.72
		20	60	3.46	1.47	3.55		8.48
		50	60	3.73	0.59	1.96		6.28
		50	25	3.35	0.86	2.76		6.97
		75	25	3.74	0.82	1.50		6.06
		150	60	1.90	2.32	3.22		7.44
		2	60	8.58	4.02	4.50		17.10
		5	60	4.22	6.30	2.98		13.50
		20	60	5.30	1.61	3.17		10.08
		30	60	2.37	5.35	1.45		9.17
		40	25	6.10	2.68	2.01		10.79
		100	60	2.07	1.72	1.96		5.75
		125	60	1.92	2.57	2.25		6.74
		200	25	4.71	0.87	2.69		7.50
		300	60	5.06	1.70	1.90		8.66
		450	60	4.08	1.67	2.91		8.66
		750	25	4.90	0.72	3.03		8.65

Apparatus	Description	Rating		Per cent of rated output			
		Output kw.	Frequency cycles	W_{I^2R}	W_F	W_R	Total losses
Direct-current generators	Commutating pole	20		5.15	6.03	3.60	14.78
		75		6.29	1.53	2.40	10.22
		100		4.86	1.49	2.15	8.50
		150		3.72	3.24	2.13	9.09
		150		3.75	3.04	3.00	9.79
		150		4.85	2.90	1.80	9.55
		175		5.51	1.28	4.45	11.24
		200		3.99	2.25	2.14	8.38
		200		4.03	2.25	1.61	7.89
		200		5.10	1.95	2.62	9.67
		200		4.24	1.92	2.80	8.96
		200		3.37	2.37	1.62	7.36
		250		4.85	4.00	1.45	10.30
		250		4.17	1.70	1.82	7.69
		300		3.49	2.89	2.43	8.81
		300		3.58	2.27	1.32	7.17
		300		3.29	1.28	1.90	6.47
		400		2.85	2.11	1.00	5.96
		400		3.84	2.80	1.65	8.29
		500		2.57	1.73	2.08	6.38
		500		3.50	1.65	1.88	7.03
		600		2.88	1.97	1.50	6.35
		750		3.21	1.20	2.33	6.74
		750		3.71	2.07	2.54	8.32
		1000		2.75	1.00	2.70	6.45
		1000		2.90	2.15	1.75	6.80
		1000		2.46	1.55	2.42	6.43
		1500		3.35	1.76	1.93	7.04
Direct-current generators	Non-commutating pole	12 5		8.20	2.64	2.84	13.68
		40		6.75	1.77	1.16	9.68
		100		6.78	0.52	1.52	8.82
		300		3.79	1.44	2.07	7.30
Alternating-current generators		100	60	2.78	1.08	3.50	7.36
		100	60	6.14	0.82	3.30	10.26
		125	60	3.19	3.70	2.97	9.86
		200	60	2.58	1.72	2.45	6.75
		300	25	1.77	0.71	3.33	5.81
		300	60	1.89	1.90	2.40	6.19
		333	60	0.83	1.47	2.94	5.24
		400	60	2.64	0.61	3.00	6.25
		500	25	2.25	0.50	1.42	4.17
		500	60	0.65	3.66	4.16	8.47
		600	60	0.83	1.79	2 27	4.89
		700	60	1.65	0.94	1.86	4.45
		725	60	1.52	0.70	1.27	3.49
		1000	60	1.67	1.52	1.83	5.02
		1000	60	0.74	4.10	1.66	6.50
		1250	60	1.25	0.83	2.65	4.73
		1250	60	1.04	0.83	2.59	4.46

Apparatus	Description	Rating		Per cent of rated output			
		Output kw.	Frequency cycles	W_{I^2R}	W_F	W_R	Total losses
Alternating-current generators		1500	60	0.66	3.16	3.16	6.98
		2000	60	1.03	0.92	2.10	4.05
		2000	60	1.20	1.19	1.83	4.22
		2500	60	0.56	2.00	2.40	4.96
		3000	60	0.95	2.01	2.46	5.42
		3000	60	0.76	1.47	2.57	4.80
		3000	25	0.51	3.73	2.00	6.24
		3000	60	1.18	1.62	1.70	4.50
		3750	60	1.47	0.49	1.46	3.42
		4000	60	0.47	4.13	2.53	7.13
		5000	60	0.91	0.89	1.98	3.78
		6666	60	0.41	2.17	2.55	5.13
		8000	60	0.32	2.77	2.23	5.32
		10000	60	0.40	2.40	1.85	4.65
Dynamotors		10		4.18	2.33	5.42	11.93
		9		4.01	2.23	4.84	11.08
Synchronous converters		100		2.9	2.64	3.10	8.64
		200		1.91	2.69	4.73	9.33
		300		1.93	2.05	2.27	6.25
		300		2.61	1.33	0.99	4.93
		400		2.16	0.72	2.08	4.96
		500		1.67	2.07	1.48	5.22
		500		1.59	2.23	1.50	5.32
		800		1.51	3.46	1.14	6.11
		1000		1.16	3.49	1.45	6.10
		1000		2.55	1.30	0.82	4.67
		1500		1.66	1.18	0.82	3.66
		2000		1.69	1.08	0.77	3.54
		2000		2.19	0.93	0.56	3.68
		3000		1.81	0.99	0.79	3.59
Motor-generators	*A	200		4.97	5.30	4.97	15.24
		500		5.82	4.71	5.74	16.27
		1000		4.98	4.07	3.94	12.99
		2000		4.47	2.98	3.92	11.37
Motor-generators	*B	100		11.8	3.93	5.64	21.37
		150		9.45	7.05	5.10	21.6
		300		9.06	3.59	5.40	18.00
		500		4.88	2.74	6.26	13.88
Motor-generators	*C	160		8.82	3.73	3.19	15.74
		300		5.57	3.58	5.28	14.43
Motor-generators	*D	94		5.95	2.68	5.83	14.46
		750		4.32	1.36	3.67	9.35
		1500		2.69	1.55	3.96	8.20

*A—Synchronous motor and direct-current generator.
*B—Induction motor and direct-current generator.
*C—Direct-current motor and direct-current generator.
*D—Frequency changer.

From these figures it will be seen that in the case of single units, the total losses, as computed from separate loss measurements, vary from 3½ to 20 per cent of the rated output, while the sum of the frictional and rotation losses ranges from 1.4 to 10 per cent. Now the measured values of the frictional and rotation losses are likely to be slightly inaccurate due to observation errors, as will be pointed out later. Since these losses are very small as compared with the total output, a considerable error in the no-load readings will affect the calculated efficiency but slightly.

In the preceding paragraphs the following points have been brought out:

(1) At any given load, W_{I^2R}, W_F and W_T can be accurately determined from readings taken at no-load.

(2) W_R is composed of two parts, one of which (n) is constant at fixed voltage under all conditions, while the other, namely, the hysteresis and eddy current loss, increases somewhat with load.

(3) The increase in the rotation loss due to the application of load cannot be satisfactorily determined from readings taken at no-load.

(4) It is difficult, and in the majority of cases impossible, to approximate from no-load measurements the eddy current loss due to the stray field of useful currents.

Owing to the difficulty of arriving at the true value of the rotation loss under load, it is the practise of most manufacturers to specify efficiencies on the basis of the no-load values of this loss. The eddy current losses due to the stray fields of useful currents flowing have also been generally disregarded in specifying and demonstrating efficiency, owing to the difficulty of obtaining accurate values.

Efficiencies as usually calculated by the summation of loss method are therefore slightly higher than the true values. This fact is now generally understood by those who use electrical machinery, and for the reason that more exact information as to the actual power efficiency is desired by the users, the present agitation for input-output tests began.

To the uninitiated the input-output test appears to be a perfectly simple and the only rational method of measuring efficiency, particularly when both input and output are electrical, as in the case of motor-generators and converters.

From a purely academic standpoint nothing seems easier than to derive efficiency by comparing simultaneous readings of measuring instruments connected in the incoming and outgoing circuits of electrical apparatus.

Those of us, however, who have conducted some of these tests on circuits other than those of college laboratories can tell a different story. Many factors contribute to invalidate the accuracy of the results obtained. Chief of these is the tendency of ordinary power circuits to fluctuate slightly. Because of this tendency it is extremely difficult to get accurate results when measuring the input to motors. This is especially true in the case of machines having heavy revolving elements rotating at high speeds.

When operating from ordinary power circuits the indicating pointers of ammeters and wattmeters connected in the feeders of such apparatus will often oscillate 25 per cent each way from the mean of a large number of readings.

This tendency of the current to fluctuate has a bearing on the accuracy of all input readings taken while the apparatus is revolving, either with power applied to its own terminals, or when driven by a separate motor.

Referring to the separate loss measurements and to the expression for the losses,

$$\text{Losses} = W_{I^2R} + W_F + W_R + W_B + W_T$$

it is to be noted that W_F and W_R are measured while the apparatus is revolving and that their measured values, as determined by power input readings, may be in error due to incorrect readings caused by fluctuations of the supply circuit.

From the data given in the foregoing tables we find that the sum of these two losses ranges from 1.4 to 10 per cent of the rated output. Assuming an error of 5 per cent in the driving motor input due to incorrect readings of swinging meter pointers when measuring the no-load losses, the calculated efficiency at rated output will be in error by not to exceed 7/100 of 1 per cent in the one case and ½ of 1 per cent in the other.

Referring now to input-output measurements, it is evident that an error of 5 per cent in the input reading will affect the calculated efficiency by approximately the same amount, that is to say the result will be in error by approximately 5 per cent.

The complicated nature of the input-output test, the large number of observers required, and the discrepancies that appear in the results in spite of the exercise of the greatest care, are shown in the following data of an actual test made under the most favorable conditions by a corps of experts.

TABLE A

MOTOR-GENERATOR SET—1200 REV. PER MIN. GENERATOR—150-KW., 250-VOLT, DIRECT-CURRENT, COMPOUND-WOUND COMMUTATING POLE. SYNCHRONOUS MOTOR—235-H.P., 4000-VOLT, THREE-PHASE, 60 CYCLES. NATURE OF LOAD—GRID RESISTANCE. CONNECTIONS AS PER DIAGRAM ON FOLLOWING PAGE.

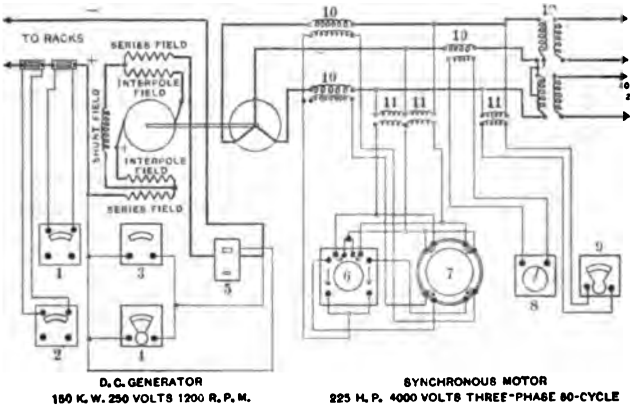
Kw. output			Kw. input		Efficiency by input-output						*Efficiency by separate losses
					Using readings of meters corresponding to numbers given						
Precision wattmeter No. 5	Ammeter No. 1 Voltmeter No. 3	Ammeter No. 2 Voltmeter No. 4	Indicating wattmeter No. 6	Integrating wattmeter No. 7	1, 3 and 6	1, 3 and 7	2, 4 and 6	2, 4 and 7	5 and 6	5 and 7	
	37.83	37.79	54.90	55.48	68.90	68.20	68.80	68.10			
37.5	37.48	37.42	54.27	54.98	69.10	68.15	68.95	68	69.10	68.20	70.40
	75	74.93	94.17	95.45	79.65	78.55	79.55	78.50			
75	75.10	75	93.99	95.15	79.90	78.93	79.80	78.85	79.80	78.85	79.50
	112	111.60	134.32	135.63	83.85	82.55	83.12	82.28			
112.5	112.60	112.20	134.92	135.73	83.48	82.95	83.17	82.68	83.35	82.82	84 50
	149	149	176.59	176.59	84.40	84.40	84.40	84.40			
150	150	149.90	178.49	179.69	84.04	83.47	84	83.42	84.04	83.47	86
	149.80	149.80	177.25	177.99	84.52	84.20	84.52	84.20			
	187.10	187	220.67	224.16	84.80	83.48	84.73	83.45			
	186.80	186.10	221.33	223.02	84.40	83.76	84.07	83.45			86.50
	187.80	186.70	223.27	222.57	84.10	84.40	83.60	84.09			
	226.30	225.30	266.82	271.85	84.80	83.20	84.40	82.85			
	224.30	223.90	265.69	269.90	84.41	83.10	84.25	82.95			87
	225	224.50	268.80	268.64	83.70	83.78	83.52	83.58			

* No allowance made for " load losses."

For location of meters see corresponding numbers on diagram of connections.

No. 1—Direct-current millivolt-meter with 1000-ampere manganin shunt.
No. 2—Direct-current millivolt-meter with 1000-ampere manganin shunt.
No. 3—Direct-current voltmeter Range 375–750.
No. 4—Direct-current voltmeter. Range 375–750.
No. 5—500-ampere precision wattmeter.
No. 6—60-cycle polyphase indicating wattmeter.
No. 7—60-cycle polyphase integrating watthour meter.
No. 8—Portable alternating-current ammeter.
No. 9—Alternating-current voltmeter.
No. 10—30 to 5 series transformer.
40 to 5 series transformer.
No. 11—4000 to 100 voltage transformer.
No. 12—400 to 4000-volt, 250-kilowatt power transformers arranged for Scott two-phase three-phase connection.

An observer was stationed at each of the instruments shown in the diagram. In addition several assistants were necessary in order to control properly the supply circuit and to maintain constant load.



INPUT-OUTPUT TESTS, MOTOR-GENERATOR SET
DIAGRAM OF CONNECTIONS

The test was conducted as follows:

Having adjusted the voltage and current of the generator, and the power factor, voltage and frequency of the motor supply circuit, at each load a series of simultaneous readings was taken at definite time intervals. The signal to read was given by blowing a whistle. Ten readings, five seconds apart, were taken at each load and the average of these ten readings was considered the true value.

Notwithstanding the precautions taken to insure accuracy, an examination of the tabulated results shows that the efficiencies indicated by the readings of different instruments differ by as much as 2 per cent.

It is to be noted that the use of current and potential transformers or other multipliers necessary in tests of this kind increases the liability of error.

In addition to the fluctuations of the supply circuit, another contributing factor tending to inaccuracy is the variation in the generator load due to changes in the resistance of that circuit. If grid resistance or water rheostats are employed for loading, fluctuations will occur due to slight changes in the temperature of the water or metal used. These fluctuations will affect all of the measuring instruments. If the current is " pumped back " into a power circuit the tendency of such circuits to oscillate will be magnified, causing greater swinging of the meter pointers.

The use of integrating instruments has been proposed as a solution of the difficult problem of accurately measuring the fluctuating currents during these tests. It is argued that if such instruments were used and comparative readings taken in both incoming and outgoing circuits over a long period of time, the true value of efficiency would be indicated.

Tests which have been conducted according to this plan have not been satisfactory. In fact the results have been uniformly more unreliable than with indicating instruments. This is due to the inherent inaccuracy of the heavy capacity direct-current watt-hour meter. No heavy capacity instrument of this type with which the writer is acquainted can be relied on to give correct values within 2 per cent.

In discussing the derivation of efficiency by the summation of loss method it has been pointed out that at any given load the only losses which cannot be accurately determined from no-load measurements are the rotation loss and the loss due to eddy currents caused by the stray fields of useful currents.

Therefore the empirical correcting factors which it is proposed to use in connection with the no-load values of the separate losses would be applied to these losses only, and not to the sum of all the losses.

The data given in Tables B and C, at the end of this paper, show the use of these constants in working up some actual tests. A comparison is made between the efficiencies obtained from input-output tests and those computed by the separate loss method using correcting factors as outlined above.

The data cover tests of direct-current motors, induction motors, motor-generators and synchronous converters. The tests of motors are all average tests, that is, they have been taken at random from a large number of tests made by average men, who did not have in mind the determination of load-loss constants when making the tests.

The constants used are the averages of those indicated by a number of very careful input-output tests of motor-generators. Two of these were made for the particular purpose of determining these constants. The same constants are used in all cases for the same types of machines, and it is worthy of note that the results throughout are fairly uniform. In some cases the values run higher by separate losses, and in some cases lower, than by input-output.

Two different constants have been used, constant K, a multiplying factor applied to the I^2r loss values to compensate for eddy current losses under load, and constant K', applied to the rotation loss values to compensate for increased losses due to field distortion.

The values of K and K' will vary over a considerable range depending upon the characteristics of the apparatus.

In the case of both alternating- and direct-current machines of low frequency, K is in most cases but slightly greater than unity, but for the higher frequencies this constant is considerably greater, especially with machines having deep slots and conductors of large cross-section.

The value of K' for compensated machines, such as induction motors and synchronous converters, is but little, if any, greater than unity, whereas in non-compensated generators and motors with large field distortion, K' may be as high as two at rated load.

Attention is called `to the data in Table D relating to input-output tests of 15 induction motors made under average conditions. In working up the efficiencies from the separate losses no multiplying factors were used, as load losses were considered negligible. When compared with the efficiencies obtained by prony brake, in nine cases the efficiency is lower by the separate losses than by input-output, showing not only the unreliability of the prony brake, but also that the load losses, if any, are so small that they can be ignored.

In Table E, data are given relating to some careful input-output tests of a 50-kw. motor-generator and of a 1000-kw. synchronous converter.

Considering first the motor-generator data, Table E, tests No. 1, 2, 3 and 4 refer to separate and distinct tests made on different days, by the same observers with the same instruments. Although the conditions were as nearly ideal as possible and extreme care was taken, the results, which should have been identical, showed a maximum variation of 2.3 per cent.

In the case of the synchronous converter, four tests were made with different sets of instruments, each of which had been adjusted and carefully calibrated immediately before the tests were made. As much care was exercised as in the case of the motor-generator, but the results show discrepancies of as much as 2.4 per cent in efficiency.

In these synchronous converter tests, as in several others made under the writer's supervision, the efficiencies by input-output very frequently show higher than by the separate losses, indicating that load losses in machines of this type are a negligible quantity.

It is not contended that the constants used in working up these tests are the values that will finally be indicated after a large amount of data has been collected. The data submitted herein are given to demonstrate the method and not to indicate the values of the constants. It is conceded that an insufficient number of accurate test records are available at present to establish the values of these constants. It is doubtful if such records are in existence, as the writer's investigations lead him to believe that surprisingly few accurate input-output tests have been made. This belief is based not only on his own experience but also on conversations and correspondence with engineers in different localities.

It is urged that those who have data bearing on this subject will bring them forward and that hereafter the determination of these constants will be kept in mind when efficiency tests are being made.

The fact that these figures are not available does not indicate that few input-output tests have been conducted. On the contrary they have been made repeatedly. Few engineers, however, have had the time, the money, or the patience necessary to obtain accurate results. The average input-output test of motor-generators and converters is perhaps accurate within 1½ to 2 per cent. Motor efficiency by prony brake probably averages between 1 and 1½ per cent of the true value.

In conclusion it may be stated that efficiency guarantees based upon the summation of the separate losses without change to allow for increases due to load, are entirely satisfactory as a basis for comparing one manufacturer's machines with those of any other maker. It is true that the actual efficiencies in either case will in some types of machines be slightly lower than those indicated by the separate losses. But, for the same separate no-load losses, the load losses will be practically identical, provided the temperatures, the regulation and the commutation correspond.

It is of course desirable that the actual efficiencies be known, and it is the writer's opinion that the simplest and most accurate method for determining the true values is by the summation of losses with some correcting factors as described in this paper. Ultimately he believes that this general method should be adopted as the Institute standard.

TABLE D

INDUCTION MOTORS

Kw. Input	Kw. output		Efficiencies		Discrepancy
	Input minus losses	Input-output test	*By separate losses	†By input-output test	
40.3	36.7	37.3	91.1	92.5	+1.4
42.2	38.0	37.3	90.0	88.5	-1.5
41.3	37.0	37.3	89.5	90.3	+0.8
40.9	36.9	37.3	90.2	91.2	+1.0
50	44.4	44.76	88.8	89.6	+0.8
62.2	57.2	56.0	92.0	90.0	-2.0
60.1	55.3	56.0	91.9	93.2	+1.3
62.5	56.5	56.0	90.3	89.6	-0.7
61.4	56.1	56.0	91.3	88.0	-3.3
4.4	3.8	3.73	86.3	85.0	-1.3
6.63	5.53	5.6	83.4	84.5	+1.5
12.45	11.13	11.2	89.3	90.0	+0.7
16.34	14.78	14.92	90.2	91.1	+0.9
119.5	119.5	111.9	93.5	93.5	0.0
29.4	25.55	26.1	86.8	88.8	+2.0

*No allowance made for "load losses."

†Mechanical output by prony brake.

TABLE B
MOTOR-GENERATORS

		Synchronous motor			Direct-current generator					Total Input			Efficiencies			
	Frac. load	W_{I^2R} (stator)	K	$K\ W_{I^2R}$	W_R	K'	$K'\ W_R$	Total load losses	Total output in kw.	Output plus losses	Input-output test	By use of constants	*1 By separate losses	2 By input-output test	3 By use of constants	Difference between 2 & 3
1000-kw, 250-volt 514 rev. per min. comm. pole generator 1440-h.p. 13,200-volt synchronous motor	1/2	2.54	1	2.54	16.5	1.4	23.1	6.6	502.4	606.5	607.2	613.1	82.8	82.75	81.9	-0.85
	3/4	5.72	1.05	6.	16.8	1.7	28.6	12.08	751.8	867.5	873.5	879.6	86.7	86.08	85.5	-0.58
	4/4	10.14	1.1	11.15	17.1	2	34.2	18.11	989.9	1117	1135	1135	88.5	87.23	87.23	0
	1¼	15.9	1.2	19.1	17.4	2.4	41.7	27.5	1254	1403	1435	1433	89.5	87.43	87.4	-0.03
150-kw. 250-volt 1200 rev. per min. comm. pole generator 225-h.p. 4000-volt synchronous motor	1/2	0.63	1	0.63	1.95	1.4	2.73	0.78	75	94.9	95.2	95.2	79.5	78.8	78.8	0
	3/4	1.42	1.05	1.49	2.1	1.7	3.57	1.74	112.5	133.3	134.9	135.04	84.5	83.5	83.1	-0.4
	4/4	2.52	1.1	2.77	2.3	2	4.6	2.55	150	174.4	178.5	176.95	86	84	84.7	+0.7
	1¼	3.94	1.2	4.73	2.5	2.4	6	4.29	186.9	216	221.8	220.3	86.5	84.3	84.7	+0.4
	1½	5.68	1.5	8.5	2.7	2.8	7.55	7.67	224.9	258.7	267.1	266.4	87	84.2	84.4	+0.2

*No allowance made for " load losses."

TABLE C
DIRECT-CURRENT MOTORS

Machine	Fractional loads	Assumed constant K'	W_R at no-load	W_R under load	Kw. input	Kw. output			Efficiencies			Difference between 2 and 3
						No. 1 Input minus losses	†No. 2 Output test	No. 3 By use of K'	*No. 1 By separate losses	†No. 2 By input-output	No. 3 By use of K'	
20-h.p., 230-volt 650 rev. per min. d-c. commutating pole motor	2/4	1.4	0.244	0.341	8.76	7.61	7.46	7.51	86.9	85.2	85.8	+0.6
	3/4	1.7	0.240	0.408	12.77	11.32	11.19	11.17	88.7	87.6	87.5	—0.1
	4/4	2.0	0.230	0.460	17.00	15.15	14.92	14.97	89.2	87.9	88.1	+0.2
	5/4	2.4	0.218	0.523	21.50	19.05	18.65	18.75	88.7	86.9	87.3	+0.4
	6/4	2.8	0.208	0.583	26.63	23.35	22.38	22.85	87.6	84.3	85.7	+1.4
20-h.p., 115-volt 650 rev. per min. d-c. commutating pole motor	2/4	1.4	0.270	0.378	8.87	7.52	7.46	7.43	84.7	84.1	83.7	—0.4
	3/4	1.7	0.263	0.447	13.04	11.40	11.19	11.24	87.3	85.8	86.1	+0.3
	4/4	2.0	0.248	0.496	17.30	15.18	14.92	14.99	87.7	86.3	86.6	+0.3
	5/4	2.4	0.230	0.553	21.73	18.90	18.65	18.63	87.0	85.9	85.7	—0.15
	6/4	2.8	0.215	0.581	26.38	22.70	22.38	22.25	86.0	84.9	84.4	—0.5
25-h.p., 115-volt 825 rev. per min. d-c. commutating pole motor	2/4	1.4	0.450	0.630	11.23	9.58	9.32	9.42	85.3	83.0	83.8	+0.8
	3/4	1.7	0.440	0.748	16.38	14.38	13.98	14.11	87.8	85.4	86.2	+0.8
	4/4	2.0	0.420	0.840	21.75	19.20	18.65	18.84	88.4	85.7	86.7	+1.0
	5/4	2.4	0.400	0.960	27.36	24.13	23.30	23.72	88.3	85.1	86.7	+1.6
	6/4	2.8	0.385	1.178	33.30	29.10	27.95	28.41	87.5	84.0	85.5	+1.5
30-h.p., 230-volt 975 rev. per min. d-c. commutating pole motor	2/4	1.4	0.433	0.607	12.97	11.33	11.20	11.19	87.4	86.3	86.2	—0.05
	3/4	1.7	0.428	0.728	19.06	17.11	16.80	16.88	89.8	88.2	88.5	+0.3
	4/4	2.0	0.418	0.836	25.08	22.77	22.38	22.38	90.7	89.2	89.2	0
	5/4	2.4	0.405	0.973	31.12	28.30	27.95	27.80	90.9	89.9	89.2	—0.7
	6/4	2.8	0.393	1.100	37.28	33.81	33.55	33.20	90.7	90.0	89.0	—0.1
35-h.p., 230-volt 1150 rev. per min. d-c. commutating pole motor	2/4	1.4	0.783	1.100	15.60	13.58	13.06	13.30	87.0	83.7	85.2	+1.5
	3/4	1.7	0.770	1.310	22.70	20.30	19.58	19.80	89.4	86.3	87.2	+0.9
	4/4	2.0	0.755	1.510	29.70	26.93	26.10	26.20	90.6	87.9	88.3	+0.4
	5/4	2.4	0.740	1.770	36.80	33.45	32.65	32.55	91.0	88.8	88.5	—0.3

*No allowance made for "load losses."

†Mechanical output by prony brake.

TABLE C—DIRECT- CURRENT MOTORS (*Continued*)

Machine	Fractional loads	Assumed constant K'	W_R at no-load	W_R under load	Kw. input	Kw. output			Efficiencies			Difference between 2 and 3
						No. 1 Input minus losses	†No. 2 Output test	No. 3 By use of K'	*No. 1 By separate losses	†No. 2 By input-output	No. 3 By use of K'	
40-h.p., 230-volt	2/4	1.4	1.300	1.820	18.56	15.38	14.92	14.93	82.8	80.4	80.5	—0.1
1100 rev. per min.	3/4	1.7	1.280	2.175	26.50	23	22.38	22.25	86.7	84.3	83.8	—0.5
direct-current	4/4	2.0	1.260	2.520	34.50	33.50	29.84	29.60	89.0	86.5	85.7	—0.75
motor	5/4	2.4	1.240	2.980	42.50	38.30	37.30	36.83	90.1	87.8	86.7	—1.1
	6/4	2.8	1.210	3.390	50.50	45.85	44.76	43.85	90.9	88.6	86.8	—1.8
40 hp., 230 volt	2/4	1.4	0.750	1.050	17.98	15.10	14.92	14.90	84.0	83.0	82.8	—0.2
850 rev. per min.	3/4	1.7	0.740	1.257	26.05	22.88	22.38	22.40	87.8	86.0	86.1	+0.1
direct-current	4/4	2.0	0.730	1.460	34.40	30.73	29.84	30.15	89.3	86.9	87.6	+0.7
motor	5/4	2.4	0.720	1.725	42.70	38.48	37.30	37.60	90.1	87.4	88.0	+0.6
	6/4	2.8	0.710	1.990	51.20	46.40	44.76	45.15	90.7	87.5	88.2	+0.7
50-h.p., 230-volt	2/4	1.4	1.060	1.485	22.12	19.10	18.65	18.73	86.4	84.2	84.7	+0.55
750 rev. per min.	3/4	1.7	1.040	1.770	31.80	28.65	28	27.93	90.0	88.1	87.8	—0.3
direct-current	4/4	2.0	1.020	2.040	41.50	37.95	37.30	37	91.4	89.9	89.2	—0.1
motor	5/4	2.4	1.000	2.400	51.45	47.25	46.70	45.90	91.9	90.9	89.3	—1.6
	6/4	2.8	0.985	2.760	62.00	57.30	56	55.80	92.5	90.3	90.0	—0.3
60-h.p., 230-volt	2/4	1.4	1.500	2.100	25.96	22.39	22.38	21.85	86.4	86.3	84.4	—1.9
650 rev. per min.	3/4	1.7	1.480	2.520	28.10	34.20	33.60	33.25	89.8	88.2	87.3	—0.9
direct-current	4/4	2.0	1.460	2.920	50.20	45.88	44.76	44.60	91.4	89.2	88.8	—0.4
motor	5/4	2.4	1.440	3.460	62.00	57.25	56	55.40	92.3	90.2	89.4	—0.8
	6/4	2.8	1.415	3.970	73.90	68.50	67.10	66.15	92.7	90.8	89.5	—1.3

*No allowance made for " load losses."

† Mechanical output by prony brake.

TABLE E

MOTOR-GENERATOR INPUT-OUTPUT TEST

75-H.P., THREE-PHASE, 60~, 2300-VOLT INDUCTION MOTOR; 50-KW., 95-VOLT, COMPOUND-WOUND, DIRECT-CURRENT GENERATOR

Test No. 1		Test No. 2		Test No. 3		Test No. 4		Efficiencies*				
Input	Output	Input	Output	Input	Output	Input	Output	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Losses
33.5	25.64	33.04	25.1	32.66	24.9	34.07	26.45	76.67	76	76.2	77.8	77.9
32.8	24.88	32.2	24.6	32.6	24.9	33.05	25.5	75.97	76.45	76.3	77	
47.6	37.39	48.13	38.35	48.43	38	48.7	38.2	78.5	79.7	78.4	78.5	80.2
47.9	37.54	48.32	38.01	48.7	38.2	48.3	38.4	78.3	78.6	78.3	79.5	
63.2	50	63.1	50.5	64.8	51	61.9	50	79.1	80	78.75	80.8	81
63.9	50.48	63.1	51	64.53	50.6	62.7	50.7	79.03	80.7	78.4	80.6	

SYNCHRONOUS-CONVERTER INPUT-OUTPUT TEST

1000-KW.,—615 VOLTS, DIRECT CURRENT—SIX-PHASE—25~, EIGHT-POLE

Test No. 1		Test No. 2		Test No. 3		Test No. 4		Efficiencies*				
Input	Output	Input	Output	Input	Output	Input	Output	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Losses
525	507.5	528.7	494.8	529	507.5	524.6	494.8	96.73	93.6	95.98	94.3	95
757.7	740.4	755	736.6	762.5	740.4	755	736.6	97.83	97.54	97.25	97.53	96.3
1038	1008	1053	993.8	1053	1003	1032	993.8	96.53	94.2	95.28	96.23	96.9

*No allowance made for "load losses."

DISCUSSION ON "DETERMINATION OF POWER EFFICIENCY OF ROTATING ELECTRIC MACHINES" (OLIN), BOSTON, MASS., JUNE 28, 1912.

C. M. Green: I have had quite a little experience and difficulty in making efficiency tests on old arc machines—particularly the Brush arc generator. The input and output method, to the best of my knowledge, is the only method by which the efficiency of these machines can be determined, due to the fact of the large influence which the current in the armature has, at ordinary loads, on the eddy currents in the pole shoes and core loss. Furthermore, the field excitation on the Brush, etc., machines with no current in the armature, and rated volts, runs about 25 per cent of that with normal current and rated volts in the armature, so you may see that the effect of the armature current upon the field windings is very abnormal. There is absolutely no question about the difficulty of making input and output efficiency tests. It is extremely difficult to get results which will check day in and day out. There is a continual variation of at least 2 or 3 per cent in the efficiency.

B. G. Lamme: I have gone over this paper of Mr. Olin's and discussed the matter with him personally to some extent, and I gather that the object of his paper was not so much to bring out a definite method of determining efficiency, as to show that there is a possibility of getting better results by the summation of separate losses than by the input and output method, unless the latter is carried out under laboratory methods. He has made a pretty good case of it. I have gone into this matter pretty thoroughly myself, and have calculated the load losses of various machines, and it is a very complicated problem to calculate these losses with any great accuracy; too complicated to be practicable as a basis for an acceptance test. But such calculations indicate that there are certain relations of load losses in most machines to the other losses, so that by some form of correcting factor, which we will doubtless determine some day, we can add a correction to the known measurable losses and obtain a result which is more reliable than can be obtained with the input-output tests. I have seen some very accurate input-output tests made, and even in the case of the most accurate ones, I had no confidence in the first one made; I had to see a second test to verify the first, or possibly sometimes a third one to verify the other two. If they all agreed, then I considered either that they were all accurate, or that there were equal errors in each. If I knew, beforehand, what the true losses were, then I might accept the first test; otherwise I would not. I believe that, in practise, any method is an approximation; but what we want is an approximation in which the principal items can be computed directly from simple and reliable measurements. I believe, as sufficient data are gathered a satisfactory method will be obtained for introducing a correcting factor for load losses, which factor may be varied for different types of machines.

E. M. Olin: In regard to the difficulty of testing the machine of which Mr. Green has spoken, by the input-output method, my recollection is that it does not have any efficiency anyway, and any method will do as well as another. The point I make in this paper is that the input-output method is a laboratory method and as such is not adapted to an ordinary shop test.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

SINGLE-PHASE INDUCTION MOTORS

BY W. J. BRANSON

The purpose of this paper is to develop a complete vector analysis of single-phase induction motor performance as the basis for an accurate circle diagram applicable to motors of even the smallest commercial sizes. To accomplish this, it will be necessary to derive mathematically correct formulas or graphical construction for several quantities and relations which have been treated very loosely heretofore. Of these the most important are

1. The value of the secondary no-load current, as reflected in the primary.
2. The construction of the current circle.
3. The revolutions per minute.

The analysis by which the required formulas and graphical processes are to be derived will be based on the transformer theory of the induction motor as distinguished from the rotating field theory. At the outset, therefore, it is necessary to consider some of the general problems involved in the phenomena of primary-secondary transformation as affected by magnetic leakage.

I. PRIMARY-SECONDARY TRANSFORMATION

Fig. 1 represents a transformer having magnetizing and leakage characteristics similar to those of an induction motor. For the purpose of simplification, it will be assumed for the present that the primary and secondary windings have 1 to 1 ratio and that the resistances of both primary and secondary, as well as the iron loss, are negligible.

Let

$K_p = \dfrac{\text{permeance of mutual path}}{\text{permeance of mutual and primary leakage paths in parallel}}$

$K_s = \dfrac{\text{permeance of mutual path}}{\text{permeance of mutual and secondary leakage paths in parallel}}$

L_1 = coefficient of self-induction of primary.

L_2 = coefficient of self-induction of secondary.

M = coefficient of mutual induction.

P = 2π frequency.

i_m = the primary magnetizing current, *i.e.*, the current which flows in the primary with the secondary open.

From the physical meaning of K_p and K_s as given above,

$$K_p L_1 = M$$

$$K_s L_2 = M$$

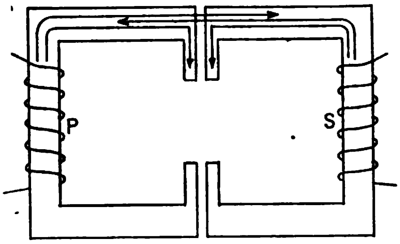


FIG. 1

Since, by definition, the reactance of a simple inductive circuit is equal to $P L$, it is evident that the reactance of the primary winding when the secondary circuit is open,

$$X_0 = P L_1$$

Therefore, the magnetizing current

$$i_m = \frac{E}{P L_1}$$

and the e.m.f. induced in the primary winding is represented by the expression

$$P L_1 i_m$$

At the same time an e.m.f. is induced in the secondary equal to

$$P L_1 i_m K_p$$

or

$$P M i_m$$

In other words, the current i_m produces a flux which induces in the primary winding an e.m.f. equal to $P\,L_1\,i_m$ and the portion of this flux which enters the secondary core induces in the secondary winding an e.m.f. equal to $P\,M\,i_m$. When the secondary circuit is open, these are the actual e.m.fs. in the primary and secondary windings. When the secondary circuit is closed, however, the m.m.f. of the secondary current opposes and partially neutralizes the m.m.f. of the primary current.

Under load conditions, therefore, the expressions given above do not represent actually existing e.m.fs. The actual e.m.f. values are obtained by taking the vector sum of the e.m.f. which the flux due to the primary current would induce if the secondary current did not exist, and the e.m.f. which the flux due to the secondary current would induce if the primary current did not exist.

The mathematical relation between the current values of these hypothetical e.m.f. values, which become actual values only when there is no reaction between the primary and secondary, are expressed by the equations which follow:

If i represents the primary current and e_1 the primary e.m.f. due to the flux produced by i,

$$e_1 = i\,\frac{P\,M}{K_p} \tag{1}$$

and

$$i = e_1\,\frac{K_p}{P\,M} \tag{2}$$

If e_2 represents the e.m.f. induced in the secondary by the flux produced by i,

$$e_2 = i\,P\,M \tag{3}$$

and

$$i = \frac{e_2}{P\,M} \tag{4}$$

If i_2 represents the secondary current and e_2 the secondary e.m.f. due to the flux produced by i_2,

$$e_2 = i_2\,\frac{P\,M}{K_s} \tag{5}$$

and

$$i_2 = e_2\,\frac{K_s}{P\,M} \tag{6}$$

If e_1 represents the e.m.f. induced in the primary by the flux produced by i_2,

$$e_1 = i_2 P M \tag{7}$$

and

$$i_2 = \frac{e_1}{P M} \tag{8}$$

In applying this method of analysis to the problems which immediately follow, and which lead to the derivation of an expression for reactance, the resistance of both windings and the iron loss will be treated as negligible.* The hypothetical e.m.fs. will therefore be either in phase or directly opposed and may be added or subtracted directly.

1. *Relative value of primary and secondary currents when the secondary is short-circuited.*

Let i_k = primary current.

i_{2k} = secondary current.

Secondary e.m.f. due to $i_k = P M i_k$ (equation 3)

Secondary e.m.f. due to $i_{2k} = \dfrac{P M i_{2k}}{K_s}$ (equation 5)

There is no resistance drop and there can be no induced e.m.fs. other than those represented by the above expressions, since all fluxes have been taken account of. Therefore the e.m.fs. corresponding to the primary and secondary currents respectively are equal and directly opposed.

$$P M i_k = \frac{P M i_{2k}}{K_s}$$

$$i_{2k} = i_k K_s$$

This shows that, when the resistances and iron loss are negligible, the secondary short-circuit current is equal to the current existing at the same time in the primary, multiplied by K_s.

2. *Demagnetizing effect of secondary current.*

Primary e.m.f. due to $i_{2k} = P M i_{2k}$ (equation 7)

The above e.m.f. opposes and neutralizes an equal component of the e.m.f. due to the primary current which balances the

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*Primary resistance will be neglected in all discussions preceding Section VII, and iron loss will be neglected in all discussions preceding Section VIII. Both quantities will be correctly treated in the working diagram.

impressed e.m.f. This leaves a portion of the impressed e.m.f. unbalanced and, as a consequence, a larger primary current flows. The primary current must increase until the balance is restored between impressed and induced e.m.fs., that is, until the e.m.f. due to the added primary current equals and neutralizes the e.m.f. due to i_{2k}.

The additional primary current required will be

$$P\,M\,i_{2k} \times \frac{K_p}{P\,M} \qquad \text{(equation 2)}$$

or

$$i_{2k}\,K_p$$

This shows that the increase in the value of the primary current due to the demagnetizing effect of the secondary current equals

secondary current × K_p

3. *Relative value of the primary current with the secondary open and the primary current with secondary short-circuited.*

From (1) above, $i_{2k} = i_k\,K_s$

From (2), the increase of primary current due to the demagnetizing effect of i_{2k} equals

$$i_{2k}\,K_p$$

or, substituting from (1),

$$i_k\,K_p\,K_s$$

This is the additional primary current due to short-circuiting the secondary.

Therefore, the total primary current

$$i_k = i_m + i_k\,K_p\,K_s$$

$$i_m = i_k - i_k\,K_p\,K_s$$

$$= i_k\,(1 - K_p\,K_s)$$

$$i_k = \frac{i_m}{1 - K_p\,K_s}$$

4. *Equivalent reactances.* Let X_1 = equivalent reactance (total) reduced to primary, such that, neglecting the effect of resistance and iron loss, if E be impressed on the primary with secondary short-circuited, the current equals E/X_1.

Let X_2 = equivalent reactance (total) reduced to secondary, such that if E be impressed on the secondary with primary short-circuited, the current equals E/X_2.

By definition,

$$\frac{E}{X_1} = i_h$$

$$= \frac{i_m}{1 - K_p K_s}$$

$$X_1 = \frac{(1 - K_p K_s)\, E^*}{i_m}$$

$$= \frac{(1 - K_p K_s)\, P L_1 i_m}{i_m}$$

$$= \frac{(1 - K_p K_s)\, P M}{K_p}$$

By similar reasoning it may be shown that

$$X_2 = \frac{(1 - K_p K_s)\, P M}{K_s}$$

II. TRANSFORMER CURRENT LOCUS

Neglecting the effect of primary resistance, the current locus of a transformer is represented by a semicircle drawn on $M H$ (Fig. 2) as a diameter. The correctness of this construction is demonstrated as follows:

Draw the base line $O H$ equal to E/X_1 and locate M by making $O M$ equal to i_m. Also draw the lines $O L$ and $M L$ to represent the primary and secondary currents.† At right angles to $O L$ draw the line $O W$ to represent a primary e.m.f. equal to $P L_1 i$ and the line $O Y$ to represent a secondary e.m.f. equal to $PM\, i$. Also, lay off at right angles to $M L$ the line $E W$ equal to $P M i_2$ and the line $D Y$ equal to $P L_2 i_2$.

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*The product of $K_p K_s$ which is represented by the symbol (K_r) may be derived from i_m and X_1 as follows:

$$X_1 = \frac{(1 - K_p K_s)\, E}{i_m}$$

$$\frac{i_m X_1}{E} = 1 - K_p K_s$$

$$1 - \frac{i_m X_1}{E} = K_p K_s$$

$$= K_r$$

†It should be noted that $M L$ represents, directly, the current which flows in the primary as a result of the demagnetizing effect of the secondary current. This equals secondary current multiplied by K_p. Therefore in terms of the primary current scale $M L = i_2 K_p$.

The vector sum $D\,O$ of the two secondary e.m.fs. $P\,M\,i$ and $P\,L_2\,i_2$ is the resultant e.m.f. in the secondary and is, consequently, equal to the secondary resistance drop.

Centering attention now on the triangle $O\,W\,E$, it will be noted that

$$\begin{aligned} E\,W &= P\,M i_2 \\ &= P\,L_1\,i_2\,K_p \\ &\propto P\,L_1 \times M\,L \end{aligned}$$

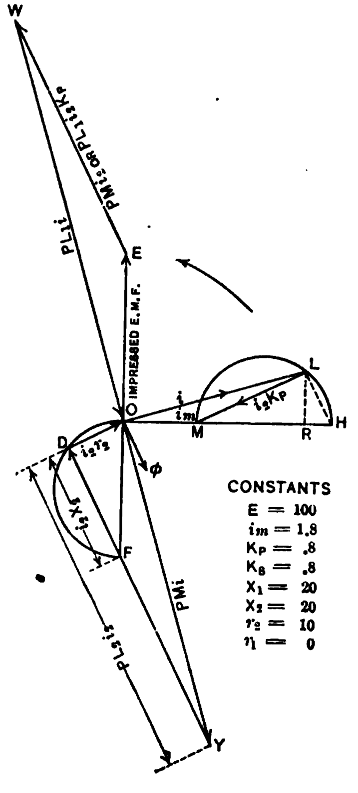

FIG. 2

and since

$$\begin{aligned} O\,W &= P\,L_1\,i \\ &\propto P\,L_1 \times O\,L \end{aligned}$$

it is evident that $E\,W$ is to $M\,L$ as $O\;W$ is to $O\;L$, and since the angles at W and L are equal, it follows that the triangle $O\,W\,E$ is similar to the triangle $O\,L\,M$ and therefore $O\,E$ is at right angles to $O\,M$.

By definition,

$$\frac{E}{X_1} = i_k$$

$$= \frac{i_m}{1 - K_p K_s}$$

$$X_1 = \frac{(1 - K_p K_s)\, E^{*}}{i_m}$$

$$= \frac{(1 - K_p K_s)\, P L_1 i_m}{i_m}$$

$$= \frac{(1 - K_p K_s)\, P M}{K_p}$$

By similar reasoning it may be shown that

$$X_2 = \frac{(1 - K_p K_s)\, P M}{K_s}$$

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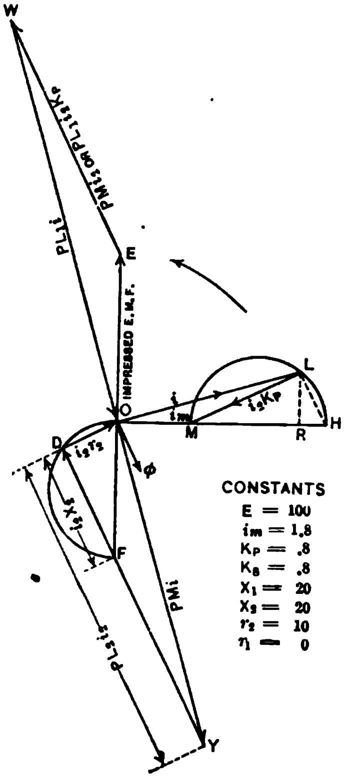

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and since

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it is evident that $E\,W$ is to $M\,L$ as $O\,W$ is to $O\,L$, and since the angles at W and L are equal, it follows that the triangle $O\,W\,E$ is similar to the triangle $O\,L\,M$ and therefore $O\,E$ is at right angles to $O\,M$.

Continue the line $E\,O$ to intersect $D\,Y$ at F. Since $O\,F$ has been constructed at right angles to $O\,M$, $O\,Y$ at right angles to $O\,L$ and $F\,Y$ at right angles to $M\,L$, it is evident that the triangle $O\,Y\,F$ is also similar to $O\,L\,M$ and therefore similar to $O\,W\,E$, and since the side $E\,O$ of the triangle $O\,W\,E$ is of constant length, being proportional to the impressed voltage, the corresponding side $O\,F$ of the triangle $O\,Y\,F$ is also of constant length.

From the similarity of the triangles, it is evident that

$$F\,Y = O\,Y \frac{E\,W}{O\,W}$$

and the voltage represented by

$$F\,Y = P\,Mi \frac{P\,Mi_2}{P\,L_1 i}$$

$$= P\,Mi \frac{P\,Mi_2}{P\,Mi/K_p}$$

$$= P\,Mi_2\,K_p$$

It will be noted by reference to the figure that

$$F\,D = D\,Y - F\,Y$$

therefore the voltage represented by

$$F\,D = \frac{P\,Mi_2}{K_s} - P\,Mi_2\,K_p$$

$$= i_2 \frac{(1 - K_p K_s)\,P\,M}{K_s}$$

$$= i_2\,X_2$$

$= i_2$ times equivalent reactance reduced to the secondary.

That is, the voltage represented by line $F\,D$ equals i_2 multiplied by X_2, the latter being a constant. Therefore $F\,D$ is proportional to i_2 and may represent it in value though not in phase.

As regards phase, $F\,D$ is, by construction, at right angles to i_2, and $D\,O$, which represents the secondary resistance drop, is in phase with i_2. Therefore $F\,D\,O$ is a right angle.

It has now been shown that the line $O F$ is of constant length and that the angle at D is a right angle. Therefore, the locus of the line $F D$, which is proportional to the secondary current, is a semicircle. It follows that the locus of the secondary current vector is also a semicircle. In other words, if the secondary resistance be varied from zero to infinity, the point L will move from H to M along the semicircle $M L H$.

Inasmuch as the triangles $F D O$ and $M L H$ are similar, it is evident that in value, though not in phase, the line $M L$ may represent $i_2 X_2$, and the line $L H$ may represent $i_2 r_2$. It is necessary, in connection with formulas to be developed later, to note the scale to which the reactance and resistance drops are represented by these lines.

Let S_e = volts per inch.

S_1 = primary amperes per inch.

$S_2 = S_1/K_p$ = secondary amperes per inch.

Since $i_2 X_2$, the reactance drop, is represented by the same line (ML) as the secondary current (i_2), it follows that

$$\frac{i_2}{S_2} = \frac{i_2 X_2}{S_e}$$

$$S_e = S_2 X_2$$

$$= \frac{S_1 X_2}{K_p}.$$

This shows that the e.m.f. scale equals the secondary current scale multiplied by X_2. In other words,

reactance drop $= M L \times S_2 X_2$ volts

and

resistance drop $= L H \times S_2 X_2$ volts.

It should also be noted that the secondary resistance drop is equal to the secondary current vector multiplied by

$$\frac{r_2}{X_2} S_e$$

This may be demonstrated as follows:

$$i_2 r_2 = L H \times S_e$$

$$= M L \frac{L H}{M L} S_e$$

$$= M L \frac{i_2 r_2}{i_2 X_2} S_e$$

$$= M L \frac{r_2}{X_2} S_e$$

Another relation which is important in practical work may be derived from the above. Since

$$L H \times S_e = M L \frac{r_2}{X_2} S_e$$

it follows that

$$\frac{L H}{M L} = \frac{r_2}{X_2}$$

In determining the starting torque of a single-phase induction motor, it is convenient to make use of the fact that the resultant flux in the secondary is proportional to

$$L H S_2 \sqrt{X_2}$$

It was shown above that the secondary resistance drop, which is equal to the e.m.f. induced in the secondary, is represented by the expression

$$L H S_2 X_2$$

For a given flux the e.m.f. induced in the secondary varies as the turns, or as the square root of the reactance.

$$L H S_2 X_2 \propto \phi \sqrt{X_2}$$

$$\phi \propto \frac{L H S_2 X_2}{\sqrt{X_2}}$$

$$\propto L H S_2 \sqrt{X_2}$$

as stated above.

III. EFFECTS OF ROTATION IN THE TWO-PHASE MOTOR

Inasmuch as an induction motor, under locked conditions, is simply a transformer with a short-circuited secondary, the foregoing may be considered to be an analysis of the flux e.m.f. and current relations which exist when the rotor is at rest in either a single-phase induction motor or in one phase of a polyphase induction motor. The next step is to include in this analysis the effects of rotation.

The flux, e.m.f. and current relations in the rotor of a single-phase induction motor are very complicated and difficult to analyze directly. The most satisfactory method of procedure is to take the simpler relations of the two-phase motor as a basis or point of departure and consider the changes which must take place in the rotor when one primary phase is disconnected from the line. In order to make use of this method, we must make a preliminary analysis of the effects of rotation in the two-phase induction motor.

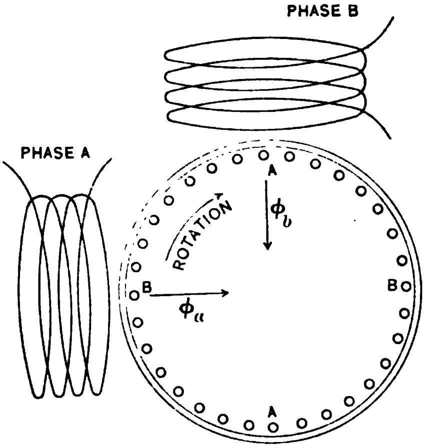

FIG. 3

Fig. 3 represents the electric and magnetic circuits of a two-phase induction motor, equipped with a squirrel cage rotor. If an alternating e.m.f. be impressed on phase *B*, a flux ϕ_b will appear in the rotor core and the e.m.fs. induced in the rotor conductors will cause a current to circulate in the plane *B B*. Similarly, if an e.m.f. be impressed on phase *A*, the flux ϕ_a will appear and a current will circulate in the plane *AA*. If the rotor be allowed to rotate, these currents will continue to circulate in the same planes, passing through whatever conductors and whatever parts of the end rings happen at the instant to be in the right position. In other words, the two secondary circuits remain fixed in the planes *A A* and *B B* whether the rotor is in motion or at rest. These two secondary circuits will be designated circuit *A* and circuit *B* respectively. It will be noted that circuit *A* is in inductive relation with phase *A*, while circuit *B* is in inductive relation with phase *B*.

It will be evident from Fig. 3 that when the rotor is in motion the conductors constituting circuit *A* will cut the flux ϕ_b and also that the conductors of circuit *B* will cut the flux ϕ_a. An e.m.f. due to rotation will therefore be generated in each circuit.

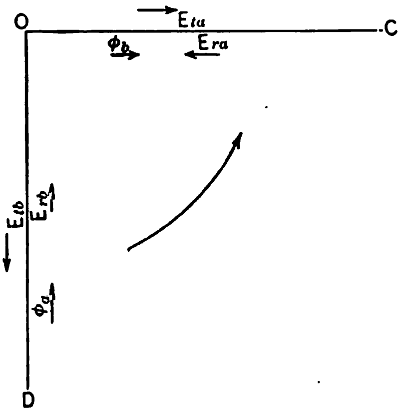

Fig. 4—Represents Conditions at the Instant when Impressed e.m.f. is at the Positive Maximum, for Phase *B*.

It may easily be demonstrated that in each circuit the rotational e.m.f. is directly opposed in phase to the transformer e.m.f. which caused the rotor current referred to above, and also that at synchronous speed, the transformer and rotational e.m.fs. will be not only opposed in phase, but exactly equal, so that no currents will flow in the rotor.

Throughout the following pages these rotor e.m.fs. will be designated by the letter E with the subscript *t* or *r* indicating transformer or rotational and *a* or *b* indicating the circuit.

E_{tb} = transformer e.m.f. in circuit *B*
E_{rb} = rotational e.m.f. in circuit *B*.
E_{ra} = rotational e.m.f. in circuit *A*.
E_{ta} = transformer e.m.f. in circuit *A*.

Fig. 4 shows the phase relations of the fluxes and secondary e.m.fs. of a two-phase motor running at synchronous speed, *i.e.*, mechanically driven at synchronous speed by external power.

The flux e.m.f. and current relations in one phase of a two-phase induction motor, when the rotor is at rest, are represented in the transformer diagram, Fig. 2. Assuming the resistance of both primary and secondary as well as the iron loss to equal zero, the primary current

$$i_k = \frac{E}{X_1}$$

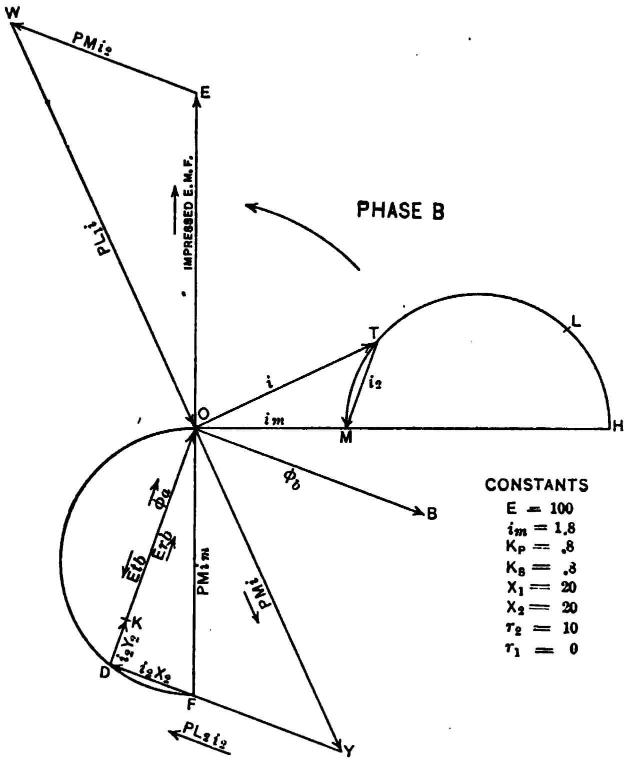

Fig. 5

and is represented by OH. In case, however, of an actual motor, having a *secondary* resistance greater than zero, the end of the locked current vector will be at some point on the semicircle, as at L. When the motor is running at synchronous speed, and no current flows in the rotor, the primary current will have the same value $i_m = E/X_0$ that would exist if the rotor were open-circuited.

From the last statement, it is evident that rotation at synchronous speed has the same effect on the primary current as a rotor resistance of infinite value. Similarly, as will now be shown, rotation at any speed below synchronism has the same effect on the current values as the introduction of a resistance of some finite value into the rotor circuit.

Referring to Fig. 5, which represents the flux e.m.f. and current values of phase B under operating conditions, it will be noted that the resultant rotor flux ϕ_b is at right angles to the secondary current. The resultant flux of phase A will therefore be in phase with the secondary current of phase B. Consequently the e.m.f. (E_{rb}) generated in circuit B by rotation through the flux of phase A will add directly to the resistance drop, and the effect of rotation on the current values is the same that would result from increasing the secondary resistance to such an extent as to make the resistance drop equal to

$$i_2 \, r_2 + E_{rb}$$

Since any rotational e.m.f. equals a transformer e.m.f. due to the same flux multiplied by

$$\frac{\text{rev. per min.}^*}{\text{synchronous speed}}$$

it follows that

$$\frac{\text{rev. per min.}}{\text{syn.}} = \frac{E_{rb}}{E_{ta}}$$

and since in a two-phase motor E_{ta} is equal to E_{tb}, the fluxes being equal,

$$\begin{aligned} \frac{\text{rev. per min.}}{\text{syn.}} &= \frac{E_{rb}}{E_{tb}} \\ &= \frac{O\,K}{O\,D} \\ &= \frac{O\,D - D\,K}{O\,D} \\ &= \frac{T\,H - M\,T\frac{r_2}{X}^{\dagger}}{T\,H} \end{aligned}$$

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*For sinusoidal space distribution of flux.

†As will be shown later, $O\,D = T\,H \times \frac{S_1\,X_2}{S_e\,K_p}$. Also, as shown below, $D\,K\,S_e = i_2 r_2 = M\,T\,\frac{S_1}{K_p}\,r_2$ and $D\,K = M\,T\,\frac{S_1\,r_2}{S_e\,K_p}$.

This expression equals secondary efficiency, as will be evident from the following:

Secondary input $= E_{tb} \times i_2$

Secondary copper loss $= (E_{tb} - E_{rb})\, i_2$

$$\text{Secondary efficiency} = \frac{E_{tb} \times i_2 - (E_{tb} - E_{rb})\, i_2}{E_{tb} \times i_2}$$

$$= \frac{E_{rb}}{E_{tb}}$$

IV. SINGLE-PHASE PERFORMANCE—NO-LOAD ROTOR CURRENTS

Suppose, now, that with the motor running at synchronous speed, phase *A* (Fig. 3) be disconnected from the line. The flux ϕ_a and the two e.m.fs. due to it (E_{rb} and E_{ta}) will disappear. The two remaining e.m.fs., E_{tb} in circuit *B* and E_{ra} in circuit *A*, will then be left unopposed, so that currents will begin to flow in both circuits. It is especially important at this point to note the actions which take place in circuit *A*. Circuit *A* surrounds the magnetic path from which, at the instant we are considering, the flux of phase *A* has disappeared. Until the actions about to be described have been completed, no flux traverses this path.

The e.m.f. E_{ra} will act, therefore, just as an original impressed voltage. A current will flow; a flux, usually called the "cross flux," will appear, and an e.m.f. will be induced. The phase relation of this induced e.m.f. (E_{ta}) will be approximate but not exact opposition to the impressed e.m.f. (E_{ra}), as shown in Fig. 6, which is the ordinary vector diagram of flux e.m.f. and current relations in a simple inductive circuit.

The cross flux occupies the magnetic circuit of phase *A* and it is therefore cut by the rotation of the *B* conductors. Consequently, with the appearance of the cross flux, a rotational e.m.f. appears again in circuit *B*, and the phase relation of this rotational e.m.f. (E_{rb}) to the opposing transformer e.m.f. (E_{tb}) is such as to leave an effective or unopposed e.m.f. in the circuit so that a current will flow.

It will now be shown that at synchronous speed the value and phase relation of the effective e.m.f. in circuit *B* is such as to make the current exactly equal and at right angles to the magnetizing current in circuit A. At synchronous speed, transformer and rotational e.m.fs. due to the same flux must be equal and in phase quadrature. The main flux induces in circuit B the transformer e.m.f. E_{tb}, represented by the line $O\ D$ (Fig. 7), and generates in circuit A the rotational e.m.f. E_{ra} represented by the line $O\ C$. Therefore, $O\ D$ must equal $O\ C$ and $C\ O\ D$ must be a right angle. For similar reasons the lines $O\ K$ and $O\ G$, representing e.m.fs. due to the cross flux, must also be equal and at right angles. Therefore, the angle $D\ O\ K$ equals the angle $C\ O\ G$ and consequently the triangles $D\ O\ K$ and $C\ O\ G$ are equal.

From the above it is evident that $D\ K$, which represents the resistance drop in circuit B, is equal and at right angles to $G\ C$, which represents the resistance drop in circuit A. Therefore the currents also must be equal and at right angles. These no-load rotor currents will be designated i_a and i_b respectively.

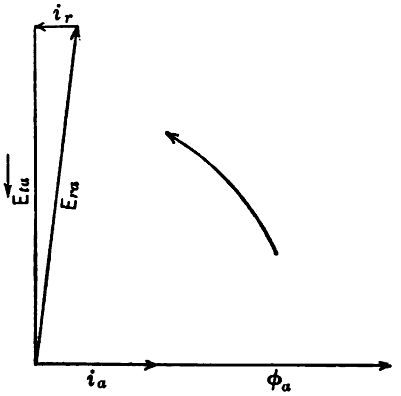

FIG. 6—REPRESENTS CONDITIONS AT THE INSTANT WHEN E_{ra} IS AT THE POSITIVE MAXIMUM.

All other figures represent conditions, ¼ cycle later, when the impressed e.m.f. in phase B is at the positive maximum.

The cross-field magnetizing current i_a cannot react directly on the primary, since circuit A in which it flows is not in inductive relation with the active primary winding. The current i_b, however, which flows in circuit B—the working circuit of the rotor—reacts on the primary in the same manner as the working current, and as a result of its demagnetizing action, an additional no-load current i_{ms}—represented by the line $M\ S$, Fig. 8—flows in the primary winding. At a speed slightly above synchronism, as will be shown below, the current i_{ms} becomes wattless and is represented by the line *M V*. The length of the line *M V*, which we shall now proceed to determine, is the first of the three problems enumerated in the opening paragraph.

The lines *O S* and *M S*, Fig. 8, represent the primary and secondary currents when the motor is running at synchronous speed. The lines *O W*, *E W*, *O Y* and *D Y* represent, as heretofore, the hypothetical e.m.fs. corresponding to the primary and secondary currents. As in Fig. 7, which, it will be noted, is reproduced as a part of Fig. 8, *D O* represents E_{tb}, the resultant or effective transformer e.m.f. in circuit *B*; *O C* at right angles to *D O* represents the resultant main flux and also the rotational e.m.f. in circuit *A*; *C G* represents the resistance drop in circuit *A* due to the current i_a; *O G* represents the transformer e.m.f. in circuit *A*; *O K*, at right angles to *O G*, represents the cross flux and the rotational e.m.f. in circuit *B*; while *D K*, the vector sum of E_{tb} and E_{rb}, represents the unopposed e.m.f. which produces the current i_b.

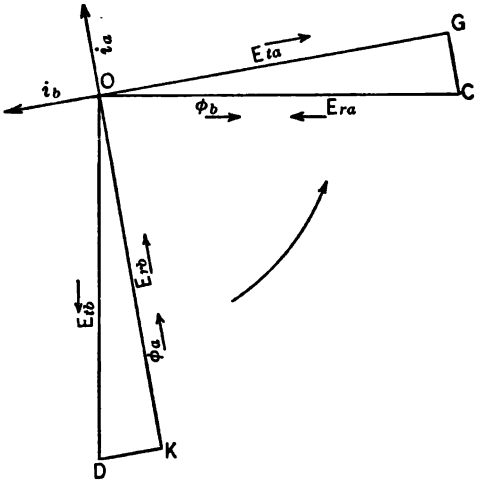

FIG. 7—REPRESENTS CONDITIONS AT THE INSTANT WHEN THE IMPRESSED E.M.F. IS AT THE POSITIVE MAXIMUM.

Since the rotational e.m.fs. vary with the speed, it is evident that at slightly above synchronism the value of E_{rb} will be increased to such an extent as to bring *D K* into exact phase with *O M*. At this speed, as was stated above, i_m, will be represented by *M V*. The primary current will then be wattless and the rotor copper loss will be supplied mechanically.

This condition is represented by Fig. 9. At the speed at which the current i_{ms} becomes wattless, that is, when the angle $O\,D\,K$ is a right angle, the cross flux is equal to the main flux, as will now be demonstrated.

Inasmuch as $K\,O\,G$ and $D\,O\,C$ are right angles, it is evident that the angles $D\,O\,K$ and $G\,O\,C$ must be equal, and since $O\,D\,K$ and $O\,G\,C$* are right angles by construction,

$$\cos\theta = \frac{O\,D}{O\,K} = \frac{O\,G}{O\,C}$$

Therefore

$$\frac{O\,D}{O\,G} = \frac{O\,K}{O\,C} \text{ or } \frac{E_{tb}}{E_{ta}} = \frac{E_{rb}}{E_{ra}}$$

and since

$$\frac{\text{rev. per min.}}{\text{syn.}} = \frac{E_{ra}}{E_{tb}} = \frac{E_{rb}}{E_{ta}}$$

it follows that

$$E_{ra} = \frac{E_{tb} \times E_{rb}}{E_{ta}} = \frac{(E_{rb})^2}{E_{ra}}$$

and

$$(E_{ra})^2 = (E_{rb})^2$$

$$E_{ra} = E_{rb}.$$

Therefore

$$\phi_b = \phi_a$$

Further, since the triangles $O\,G\,C$ and $O\,D\,K$ have been shown to have a side and two angles equal and are therefore equal in all parts, it follows that the side $G\,C$, which represents the drop in circuit A, is equal to $D\,K$, which represents the drop in circuit B, and consequently the currents i_a and i_b which cause the drops are equal.

It has now been shown that at the speed at which the current i_{ms} coincides with $M\,V$, the cross flux equals the main flux and

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*The assumption that $O\,G\,C$ is a right angle neglects the effect of the cross-field iron loss, which reacts on circuit A just as the main field iron loss reacts on the primary. Actually the angle $O\,G\,C$ is slightly larger than a right angle. This fact does not, however, detract from the practical accuracy of the conclusions reached in regard to the value of the current i_{ms}.

the current in circuit B equals the current in circuit A. For this speed the physical conditions which determine the value of i_m, may be stated as follows:

The current i_m, *is the increase of primary current due to the demagnetizing action of* i_b; i_b *equals* i_a; *the value of* i_a *is fixed by the fact that it is the magnetizing current which produces the cross flux; the cross flux equals the resultant rotor main flux.* Briefly, we have to determine the demagnetizing effect on the primary of a rotor current of such a value as to produce in the rotor core a flux equal to the resultant main flux in the rotor.

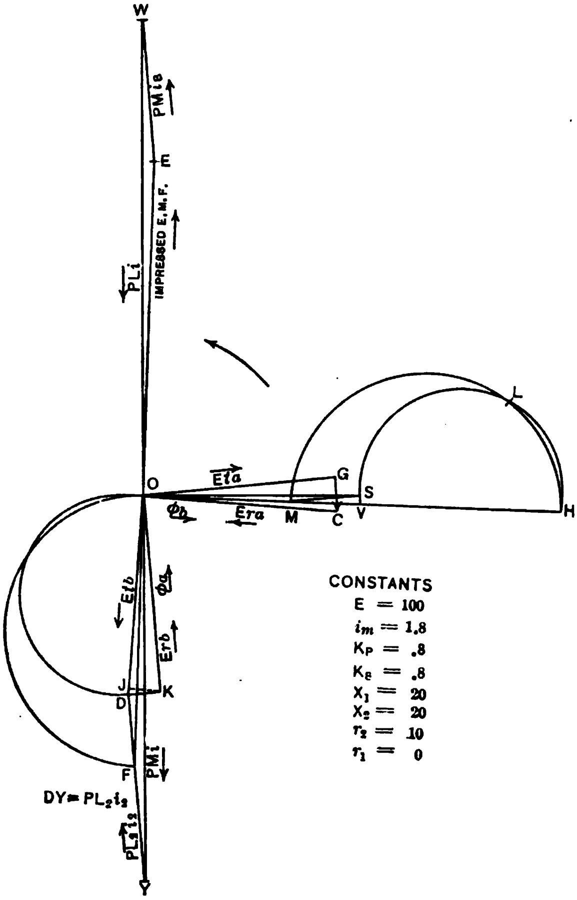

FIG. 8—SYNCHRONOUS SPEED.

From the hypothetical e.m.f. vectors, Fig. 9, corresponding to the currents i and i_b, we find that the effective e.m.f. in the rotor

$$E_{ib} = P\,Mi - \frac{P\,Mi_b}{K_s}$$

The rotor magnetizing current required to produce the flux by which the above e.m.f. is induced,

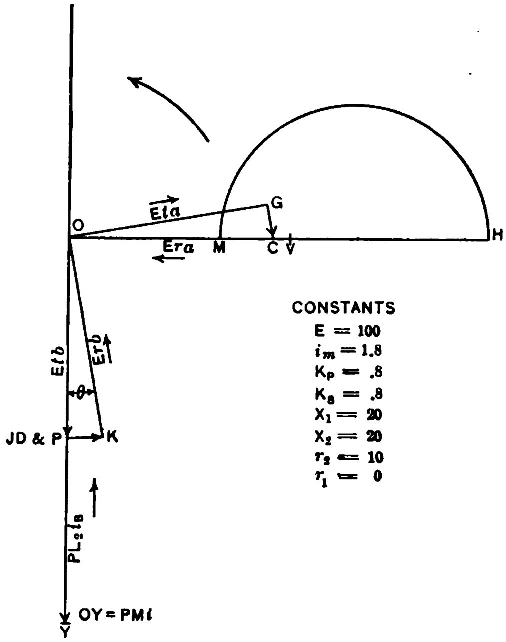

FIG. 9—THIS FIGURE SHOWS CONDITIONS AT THE SPEED, ABOVE SYNCHRONISM, AT WHICH THE PRIMARY CURRENT IS WATTLESS

$$i_a = \left(P\,Mi - \frac{P\,Mi_b}{K_s}\right) \times \frac{K_s}{P\,M} \quad \text{(equation 6)}$$

$$= K_s i - i_b$$

and since i_a and i_b are equal,

$$i_b = K_s i - i_b$$

$$= \frac{K_s}{2}\, i$$

It has been shown above that the increase of current in the primary due to the demagnetizing effect of a secondary current, equals the secondary current multiplied by K_p.

Therefore,

$$i_{ms} = \frac{K_p K_s}{2} i$$

$$= \frac{K_p K_s}{2} (i_m + i_{ms})$$

$$i_{ms} \left(1 - \frac{K_p K_s}{2}\right) = \frac{K_p K_s}{2} \times i_m$$

$$i_{ms} = i_m \left(\frac{K_p K_s}{2} \times \frac{2}{2 - K_p K_s}\right)$$

$$= i_m \times \frac{K_p K_s}{2 - K_p K_s}$$

$$M V = O M \frac{K_p K_s}{2 - K_p K_s}$$

$$= O M \times \frac{1 - \frac{i_m X_1}{E}{}^{*}}{1 + \frac{i_m X_1}{E}}$$

It is interesting to note that the value of MV is independent of the secondary resistance.

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* When this equation is used in practical work, it is necessary to take account of the fact that i_{ms} is affected less by saturation than i_m, owing to the low density of the cross flux in the primary core.

$$\text{If } S F M = \frac{\text{total ampere turns}}{\text{ampere turns for air gap}} \text{ for main field,}$$

$$\text{and } S F C = \frac{\text{total ampere turns}}{\text{ampere turns for air gap}} \text{ for cross field,}$$

the complete working formula for $M V$ becomes

$$M V = O M \times \frac{1 - \frac{i_m X}{E}}{1 + \frac{i_m X}{E}} \times \frac{S F C}{S F M}$$

V. SINGLE-PHASE CURRENT LOCUS

Neglecting the effect of primary resistance, the current locus of a single-phase induction motor is represented by a circle passing through V, L and H, Fig. 10. That the current locus passes through V and L is obvious, but that it is a true circle and also passes through H, requires demonstration.

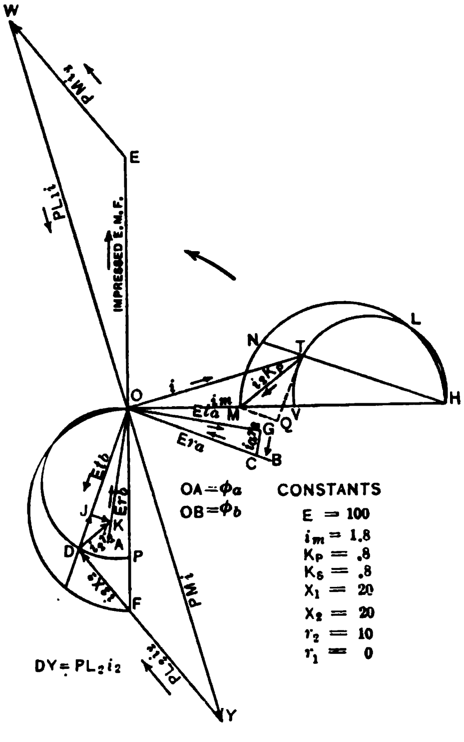

FIG. 10

In constructing Fig. 10, $O\,M$ and $O\,H$ are made equal, as in the previous figure, to i_m and E/X_1 respectively, and

$$M\,V = O\,M \times \frac{K_p K_s}{2 - K_p K_s}$$

From any point T on a circle passing through V and L, draw $O\,T$ and $M\,T$ to represent the primary and secondary currents, and lay off, as in preceding figures, the lines to represent the corresponding hypothetical e.m.fs.

At the outset it should be noted that the triangles $F\,D\,O$ and $M\,T\,H$ are similar, each line of $F\,D\,O$ being equal to the corresponding line of $M\,T\,H$ multiplied by the expression

$$\frac{S_1\,X_2}{S_e\,K_p}$$

in which

$$\frac{S_1}{K_p} = \text{secondary amperes per inch, and}$$

$$S_e = \text{volts per inch.}$$

Considering first the lines $F\,D$ and $M\,T$,

$$F\,D\,S_e = i_2\,X_2 \text{ and}$$

$$M\,T\,S_1 = i_2\,K_p$$

$$M\,T\,S_1 \times \frac{X_2}{K_p} = i_2\,K_p\,\frac{X_2}{K_p}$$

$$= i_2\,X_2$$

Therefore,

$$F\,D\,S_e = M\ T\ S_1\,\frac{X_2}{K_p}$$

and

$$F\,D = M\,T\,\frac{S_1}{S_e}\,\frac{X_2}{K_p}, \text{ as stated above.}$$

Taking next the lines $F\,O$ and $M\,H$,

$$F\,O\,S_e = P\,M\,i_m{}^*, \text{ and}$$

$$M\,H\,S_1 = (O\,H - O\,M)\,S_1 = \frac{E}{X_1} - i_m$$

$$M\,H\,S_1\,\frac{X_2}{K_p} = \left(\frac{E}{X_1} = i_m\right)\frac{X_2}{K_p}$$

---

*From the similarity of the triangles $O\,W\,E$, $O\,Y\,F$ and $O\,T\,M$ $F\,O$ represents $P\,Mi \times \frac{O\,M}{O\,T}$, which equals $P\,M\,i_m$.

Substituting for X_1 and X_2 the expressions

$$\frac{(1 - K_p\,K_s)\,P\,M}{K_p} \text{ and } \frac{(1 - K_p\,K_s)\,P\,M}{K_s} \text{ respectively,}$$

we obtain

$$M\,H\,S_1\,\frac{X_2}{K_p} = \frac{E}{K_s} - \frac{P\,M\,i_m - K_p\,K_s\,P\,M\,i_m}{K_p\,K_s}$$

Substituting

$$\frac{P\,M\,i_m}{K_p} \text{ for } E,$$

$$M\,H\,S_1\,\frac{X_2}{K_p} = \frac{P\,M\,i_m - P\,M\,i_m + K_p\,K_s\,P\,M\,i_m}{K_p\,K_s}$$

$$= P\,M\,i_m$$

Therefore,

$$F\,O\,S_s = M\,H\,S_1\,\frac{X_2}{K_p}$$

and

$$F\,O = M\,H\,\frac{S_1}{S_s}\,\frac{X_2}{K_p} \text{ as stated.}$$

The above results show that, in length, $F\,D$ is to $M\,T$ as $F\,O$ is to $M\,H$, and since $F\,D$ is at right angles to $M\,T$, and $F\,O$ is at right angles to $M\,H$, the triangles $M\,T\,H$ and $F\,D\,O$ are similar.

Therefore, the line $D\,O$ is at right angles to $T\,H$ and equals

$$T\,H\,\frac{S_1}{S_s}\,\frac{X_2}{K_p}$$

In a similar manner it may be shown that $O\,P$ is proportional to $V\,H$ and equals

$$V\,H\,\frac{S_1}{S_s}\,\frac{X_2}{K_p}$$

Directing attention now to the e.m.f. and flux vectors, $D\,O$ represents, as in preceding figures, the resultant induced e.m.f. in the rotor; $O\,B$, at right angles to $D\,O$, represents the resultant main rotor flux ϕ_b; $O\,C$, a section of $O\,B$, represents the rotational e.m.f. in circuit A, while $C\,G$ and $O\,G$ represent respectively the resistance drop and the induced e.m.f. in circuit A. $O\,A$, at right angles to $O\,G$, represents the cross flux, while E_{rb}, the rotational e.m.f. in circuit B, is represented by $O\,K$, a section of $O\,A$.

It will be noted that E_{rb} and the resistance drop $D\,K$ are not in phase as they were in Fig. 5. This is one of the main distinctive features of the single-phase induction motor. It is due to the fact that the secondary current $M\,T$ has a component $M\,Q$ which is 90 deg. out of phase with E_{tb}, or, in other words, parallel to $T\,H$. The existence of this wattless component in the secondary current is the cause of the difference between the two-phase and the single-phase current locus.

At a speed slightly above synchronism, as was shown on a preceding page, the secondary current in circuit B is wattless and $M\,T$ coincides with $M\,V$. At lower speeds the wattless component of the secondary current is represented by $M\,Q$.

The copper drops, due to the two components of the secondary current, are

$$D\,J\,S_e = T\,Q\,\frac{S_1}{K_p}\,r_2$$

$$= N\,M\,\frac{S_1}{K_p}\,r_2$$

and

$$J\,K\,S_e = M\,Q\,\frac{S_1}{K_p}\,r_2$$

$$= N\,T\,\frac{S_1}{K_p}\,r_2$$

in which S_1/K_p = secondary amperes per inch.

The angle $D\,O\,A$ equals the angle $G\,O\,B$, which is constant, and since $O\,J\,K$ is a right angle by construction,

$$J\,K \propto O\,J$$

At the speed at which $M\,T$ and $N\,T$ coincide with $M\,V$, the line $O\,J$ coincides with $O\,P$. See Fig. 9.* Consequently,

---

*In Fig. 9, J coincides with D because $O\,D\,K$ is a right angle. D coincides with P because $F\,D$, which represents the secondary reactance drop, being proportional and at right angles to $M\,T$, must coincide with $F\,P$ when $M\,T$ coincides with $M\,V$. Therefore $O\,J$ coincides with $O\,P$.

$$N\,T \frac{S_1}{K_p} r_2 = M\,V \frac{S_1}{K_p} r_2 \times \frac{O\,J}{O\,P}$$

$$N\,T = M\,V \frac{O\,J}{O\,P}$$

$$= M\,V \frac{O\,D - D\,J}{O\,P}$$

Since

$$O\,D = T\,H \frac{S_1\,X_2}{S_e\,K_p},\ O\,P = V\,H \frac{S_1\,X_2}{S_e\,K_p},\ \text{and}\ D\,J = N\,M \frac{S_1\,r_2}{S_e\,K_p},$$

we obtain by substitution,

$$N\,T = M\,V \frac{T\,H \dfrac{S_1 X_2}{S_e K_p} - N\,M \dfrac{S_1 r_2}{S_e K_p}}{V\,H \dfrac{S_1 X_2}{S_e\,K_p}}$$

$$= M\,V \frac{T\,H - N\,M \dfrac{r_2}{X_2}}{V\,H}$$

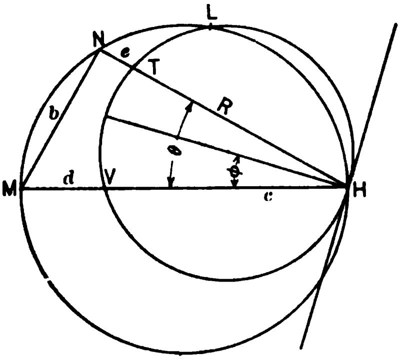

Fig. 11

To simplify the analytical equations which follow, let $e = N\,T$, $d = M\,V$, $R = T\,H$, $b = N\,M$, $c = VH$, $D = M\,H$ and $K = r_2/X_2$

$$e = d\,\frac{R - Kb}{c}\ ^*$$

$$R = e\,\frac{c}{d} + Kb \quad (9) \qquad \frac{R + e}{D} = \cos\theta \text{ (Fig. 11)} \quad (10)$$

$\dfrac{b}{D} = \sin\theta$, and $b = D\sin\theta$, also $e = D\cos\theta - R$.

---

*The analytical demonstration which follows is due to Mr. Harold W. Brown.

Substituting in equation (9) we obtain

$$R = (D \cos \theta - R) \frac{c}{d} + K\, D \sin \theta$$

$$R + R \frac{c}{d} = D \cos \theta \frac{c}{d} + K\, D \sin \theta$$

$$R\left(1 + \frac{D}{d} - 1\right) = c \frac{D}{d} \cos \theta + K\, D \sin \theta$$

$$R \frac{D}{d} = c \frac{D}{d} \cos \theta + K\, D \sin \theta$$

$$R = c \cos \theta + Kd \sin \theta \qquad \textbf{(11)}$$

Let ϕ be an angle whose tangent $= Kd/c$, and M the denominator of a fraction such that $\sin \phi = Kd/M$.

Then

$$\cos \phi = \frac{\sin \phi}{\tan \phi} = \frac{\frac{Kd}{M}}{\frac{Kd}{c}} = \frac{c}{M}$$

Dividing equation (11) by M we obtain

$$\begin{aligned} \frac{R}{M} &= \frac{c}{M} \cos \theta + \frac{Kd}{M} \sin \theta \\ &= \cos \phi \cos \theta + \sin \phi \sin \theta \\ &= \cos (\theta - \phi) \\ R &= M \cos (\theta - \phi) \qquad \textbf{(12)} \end{aligned}$$

Since R is proportional to the cosine of a variable angle, the curve on which the point T (Fig. 10) lies must be a circle passing through the origin H. (See Cor. 2, Prop. 39, Nichols, "Analytic Geom"., ed. 1893.)*

---

*Inasmuch as the circle passes through three known points, V, L and H, an expression for the elevation of the center above the base line is not essential. It is easily shown, however, that the elevation of the center above the line $O\,H$ is equal to

$$0.5\, M\, V \frac{r_2}{X_2}$$

From an inspection of Fig. 11, it is evident that the center is above $O\,H$ a distance equal to the diameter × 0.5 sin ϕ, and also that when R coincides with the diameter, θ is equal to ϕ. Equation (12) above shows that when θ equals ϕ, M is equal to R, and therefore to the diameter. It follows that:

$$\begin{aligned} \text{Diameter} \times 0.5 \sin \phi &= M\, 0.5 \sin \phi \\ &= 0.5\, Kd \\ &= 0.5\, M\, V \frac{r_2}{X_2} \end{aligned}$$

VI. Revolutions per Minute

Attention has already been called to the fact that at synchronous speed, the rotational and transformer e.m.fs. due to the same flux are equal. That is,

$$E_{ra} = E_{tb}$$

and

$$E_{rb} = E_{ta}$$

(See Fig. 8).

At any speed below synchronous,

$$\frac{\text{rotational e.m.f.}}{\text{transformer e.m.f.}} = \frac{\text{rev. per min.}}{\text{synchronous speed}}$$

Therefore,

$$\frac{E_{ra}}{E_{tb}} = \frac{\text{rev. per min.}}{\text{syn.}}$$

and

$$\frac{E_{rb}}{E_{ta}} = \frac{\text{rev. per min.}}{\text{syn.}}$$

Substituting for the e.m.f. symbols, the e.m.f. vectors of Fig. 10, we have

$$\frac{O\,C}{O\,D} = \frac{\text{rev. per min.}}{\text{syn.}}$$

and

$$\frac{O\,K}{O\,G} = \frac{\text{rev. per min.}}{\text{syn.}}$$

from which we obtain

$$\frac{\text{rev. per min.}}{\text{syn.}} = \sqrt{\frac{O\,C}{O\,D} \times \frac{O\,K}{O\,G}}$$

$$= \sqrt{\frac{O\,K}{O\,D} \times \frac{O\,C}{O\,G}}$$

Since

$$O\,K = \sqrt{(O\,D - D\,J)^2 + (J\,K)^2}$$

we obtain

$$\frac{\text{rev. per min.}}{\text{syn.}} = \sqrt{\frac{\sqrt{(O\,D - D\,J)^2 + (J\,K)^2}}{O\,D} \times \frac{O\,C}{O\,G}}$$

Since

$$\frac{O\,C}{O\,G} = \frac{O\,K}{O\,J}^{*}$$

$$= \frac{\sqrt{(O\,D - D\,J)^2 + (J\,K)^2}}{O\,D - D\,J}$$

we obtain

$$\frac{\text{rev. per min.}}{\text{syn.}} = \sqrt{\frac{\sqrt{(O\,D - D\,J)^2 + (J\,K)^2}}{O\,D} \times \frac{\sqrt{(O\,D - D\,J)^2 + (J\,K)^2}}{O\,D - D\,J}}$$

$$= \sqrt{\frac{(O\,D - D\,J)^2 + J\,K^2}{O\,D\,(O\,D - D\,J)}}$$

It was shown above that

$$O\,D = T\,H \frac{S_1\,X_2}{S_e K_p}$$

$$D\,J = N\,M \frac{S_1\,r_2}{S_e K_p}$$

and

$$J\,K = N\,T \frac{S_1\,r_2}{S_e K_p}$$

Substituting, we obtain

$$\frac{\text{rev. per min.}}{\text{syn.}} = \sqrt{\frac{\left(T\,H - N\,M \frac{r_2}{X_2}\right)^2 + \left(N\,T \frac{r_2}{X_2}\right)^2}{T\,H \left(T\,H - N\,M \frac{r_2}{X_2}\right)}}$$

If $N\,T \times r_2/X_2$, which represents the resistance drop due to the wattless component of the secondary current, be treated as negligible, this expression reduces to

$$\frac{\text{rev. per min.}}{\text{syn.}} = \sqrt{\frac{T\,H - M\,N \frac{r_2}{X}}{T\,H}}$$

which usually gives the speed with sufficient accuracy for practical purposes.

---

[*] It is assumed here that $O\,G\,C$ is a right angle. As was shown above, the effect of cross-field iron loss makes the angle $O\,G\,C$ slightly larger than a right angle. The effect on the speed is too small, however, for practical consideration.

VII. EFFECT OF PRIMARY RESISTANCE

In developing the formulas and graphical processes, used in the construction of Fig. 10, the effect of primary resistance has in all cases been neglected. In other words, the induced e.m.f., $O\,E$, has been assumed to be equal to the impressed e.m.f. and constant. The advantage gained by constructing the diagram on this basis is that it gives the diameters of the semicircles, $F\,O$ and $M\,H$, as well as the lines $O\,M$, $M\,V$ and $F\,P$, a constant length. The fact that these lines are of constant length, so that the points M, H, etc. are fixed, renders possible the use of a number of processes, among them the rev. per min. formulas, developed above, which would otherwise be incorrect.

No error or inconvenience results from this method of construction, since the effect of primary resistance can be taken account of, with all necessary precision, in a very simple manner, as has been shown by De Latour and other writers.

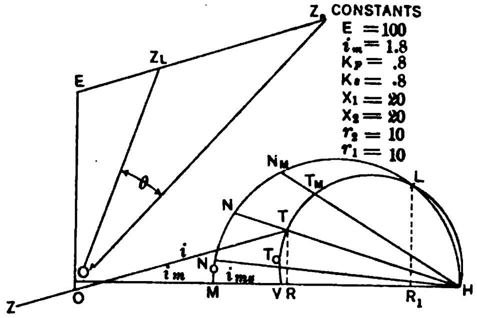

FIG. 12—WORKING DIAGRAM.

We extend the primary current vector $O\,T$, Fig. 12, to Z, making $O\,Z$ of such a length as to represent the resistance drop due to the current represented by $O\,T$. The vector sum $Z\,E$ represents the impressed e.m.f. which would be required in order to make the induced e.m.f. equal to $O\,E$, and therefore

$$\frac{O\,E}{Z\,E} = \frac{\text{induced e.m.f.}}{\text{impressed e.m.f.}}$$

Correct current values are obtained from the diagram by multiplying each current vector by the corresponding value of $O\,E/Z\,E$

$$\text{primary current} = O\,T\,S_1 \times \frac{O\,E}{Z\,E}$$

and

$$\text{secondary current} = M\,T\,S_2 \times \frac{O\,E}{Z\,E}$$

Also, in determining the secondary input, the fact should be borne in mind that the e.m.f. impressed on the secondary is equal to the e.m.f. induced in the primary, multiplied by K_p, that is,

$$E \times \frac{O\,E}{Z\,E} \times K_p$$

and therefore

$$\text{secondary input} = T\,R\,\frac{S_1}{K_p} \times \frac{O\,E}{Z\,E} \times E \times \frac{O\,E}{Z\,E} \times K_p$$

$$= T\,R\,S_1 \times E \times \left(\frac{O\,E}{Z\,E}\right)^2$$

The value of $O\,E/Z\,E$ must, of course, be separately determined for each value of the current vector $O\,T$.

VIII. Working Diagram

Fig. 12 shows a practical working diagram, based on the analysis of flux, e.m.f. and current relations represented in Fig. 10. If the greatest possible degree of accuracy be desired, the following data, in addition to the line voltage E, are required for its construction.

1. Main field magnetizing current................ i_m
2. Primary leakage coefficient.................... K_p
3. Secondary leakage coefficient.................. K_s
4. Reactance (total reduced to primary)........... X_1
5. Reactance (total reduced to secondary)......... X_2
6. Primary resistance.......................... r_1
7. Secondary resistance (reduced to primary)...... r_2
8. Iron loss due to main field.................... P_{im}
9. Iron loss due to cross field.................... P_{ic}
10. Friction and windage loss.................... P_f

In practical work, however, it is not necessary to distinguish between the values of K_p and K_s. The product

$$K_p\,K_s = 1 - \frac{i_m\,X_1}{E}$$

and sufficient accuracy will be obtained by assuming that either K_p or K_s is equal to

$$\sqrt{1 - \frac{i_m X_1}{E}}$$

If K_p and K_s are equal, it follows from the formulas previously developed that X_1 is equal to X_2. Only one calculation, therefore, is required for reactance. Also, it is not usually necessary to calculate separately the iron loss due to the main and cross fields. It will be sufficiently accurate to make the calculation of the total iron loss just as in the case of the two-phase motor and assign one-half to the main field and the same, or a slightly smaller value, to the cross field.

The quantities, therefore, which it is necessary to determine by previous calculation are

1.	Main field magnetizing current	i_m
2.	Reactance (total)	X
3.	Primary resistance	r_1
4.	Secondary resistance	r_2
5.	Iron loss (total)	P_i
6.	Friction and windage loss	P_f

Let

S_1 = primary amperes per inch

$S_2 = \frac{S_1}{K_p}$ = secondary amperes per inch

S_e = volts per inch, for the impressed e.m.f. ($O\,E$), and resistance drop ($O\,Z$).

In reconstructing the diagram,

$$O\,H = \frac{E}{X \times S_1}$$

$$O\,M = \frac{i_m}{S_1}$$

$$M\,V = \frac{i_{ms}}{S_1}$$

$$O\,O' = \frac{0.5\,P_i}{E \times S_1}$$

$$O\,E = \frac{E}{S_e}$$

After the above lines have been drawn the larger semicircle should be constructed on $M H$ as a diameter. The locked point L may then be located by making

$$L H = M H \frac{L H}{M H}$$

the factor $L H/M H$ being obtained from the curve Fig. 13. When the location of L has been determined, the smaller circle may be drawn through V, L and H.

The next step is to select a point T for calculation and draw the line $O Z$ of a length equal to

$$\frac{O T S_1 r_1}{S_e}$$

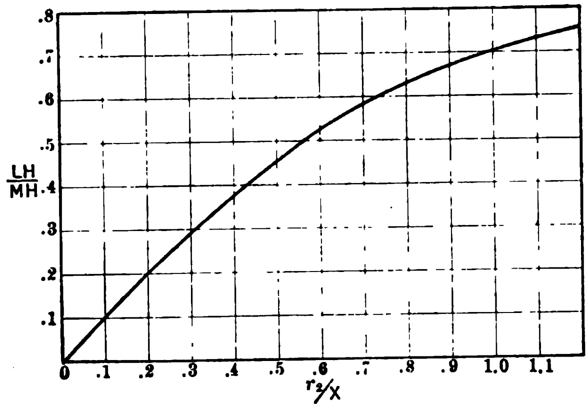

FIG. 13—CURVE FOR LOCATING LOCKED POINT (L)

$L H/M H$ is the sine of the angle of which r_2/X is the tangent.

In calculating the performance for various values of the primary current, it will be convenient to use a data sheet similar to the one shown herewith. The measurements taken from the diagram are the lengths of the lines $O T$, $M T$, $N M$, $N T$, $T H$, and $T R$, which constitute the first six items on the data sheet, and the length $Z E$ from which ($O E$ being previously known) the ratio of primary induced e.m.f. to impressed e.m.f. may be obtained. This constitutes item No. 7 of the data sheet. When these values for a selected load point have been recorded, the calculation may be completed without further reference to the diagram. The various formulas required are given on the data sheet.

The motor input is equal to the sum of the primary copper loss, the main field iron loss and the secondary input.

The losses fall into two classes:

1. Losses supplied directly by the primary.
2. Losses supplied from the secondary input.

The losses supplied directly by the primary are

1. Primary copper loss.
2. Main field iron loss.

____H.P._______V.______~_______R.P.M.

$r_1 =$ $r_2 =$ $\frac{i_{ms}}{K_p} =$ $\frac{r_2}{X} =$ $s_1 =$ $s_2 =$ $s_c =$

1	O.T	FROM DIAG.					
2	M T	" "					
3	M N	" "					
4	N T	" "					
5	T H	" "					
6	T R	" "					
7	OE/ZE	" "					
8	MN r_2/X	③ x r_2/X					
9	NT r_2/X	④ x r_2/X					
10	TH − MN r_2/X	⑤ − ⑧					
11	R.P.M.	$\sqrt{\frac{⑩^2+⑨^2}{⑤ \times ⑩}}$ or $\sqrt{\frac{⑩}{⑤}}$					
12	PRIM. AMPS.	① x ⑦ x s_1					
13	SEC. AMPS.	② x ⑦ x s_2					
14	SEC. C-LOSS A	$\left(\frac{i_{ms}}{K_p}\right)^2 \times r_2 \times \left(\frac{\text{R.P.M.}}{\text{SYN.}} 7\right)^2$					
15	SEC. C-LOSS B	⑱^2 x r_2					
16	FE.-LOSS CROSS	PREVIOUSLY FOUND					
17	F. & W. LOSS	" "					
18	FE.- LOSS MAIN	" "					
19	PRIM. CU-LOSS	⑫^2 x r_1					
20	SEC. INPUT	⑦^2 x s_1 x E x ⑥					
21	INPUT	⑱ + ⑲ + ⑳					
22	TOTAL LOSSES	⑭+⑮+⑯+⑰+⑱+⑲					
23	OUTPUT	㉑ − ㉒					
24	TORQUE (OZ-FT.)	㉓ x 112.7÷R.P.M.					
25	EFFICIENCY	㉓ ÷ ㉑					
26	APP. INPUT	⑫ x E					
27	POWER FACTOR	㉑ ÷ ㉖					

DATA SHEET

The losses supplied from the secondary input are

1. Secondary copper loss in circuit *A*.
2. Secondary copper loss in circuit *B*.
3. Iron loss due to the cross field.
4. Friction and windage loss.

At synchronous speed the secondary copper loss in circuit A is equal to

$$(M\ V \times S_2)^2\ r_2 \left(\frac{O\ E}{Z\ E}\right)^2$$

At lower speeds the value becomes

$$(M\ V \times S_2)^2\ r_2 \left(\frac{O\ E}{Z\ E} \times \frac{\text{rev. per min.}}{\text{syn.}}\right)^2$$

The derivation of the other formulas on the data sheet will be evident.

The maximum torque is obtained when the end of the current vector is slightly beyond the center of the arc $V\ L$. The *effective* maximum torque, as determined by a brake test, is usually about 92 per cent of the calculated value.

IX. STARTING TORQUE—SINGLE-PHASE INDUCTION MOTOR WITH AUXILIARY STARTING WINDING

Neglecting the effect of friction, the starting torque of a two-phase induction motor in ounces at one-foot radius is equal to

$$\frac{225.4 \times P_b}{\text{syn.}}$$

in which P_b is the secondary input from one phase.

The starting conditions of a single-phase induction motor equipped with an auxiliary starting winding differ from those of a two-phase induction motor in two respects.

1. The secondary flux ϕ_s due to the starting winding is not necessarily equal to the secondary flux ϕ_b due to the main winding. Other conditions remaining the same, the starting torque will vary with ϕ_s/ϕ_b.

2. The phase angle θ between ϕ_s and ϕ_b is less than 90 deg. Other conditions remaining the same, the starting torque will vary as the sine of θ.

Therefore the expression for starting torque of a single-phase induction motor is

$$\frac{225.4 \times P_m \times \phi_s \times \sin\theta}{\text{syn.} \times \phi_b}$$

Fig. 14 represents the secondary flux and the currents and induced and impressed e.m.fs. of the main winding, and, to a different scale, the same quantities of the starting winding.

If S_1 = amperes per inch for main winding,
then $S_1 \times X_m/X_s$ = amperes per inch for the starting winding, since the same line $O\,H$ represents E/X_m and E/X_s.

The two secondary fluxes ϕ_s and ϕ_b are represented by the same line $O\,B$, while the e.m.f. impressed on the main winding is represented by $O\,Z_L$, and the e.m.f. impressed on the starting winding by $O\,Z_s$. Actually, of course, the impressed e.m.f. is identical in the two cases, both in amount and in phase, and there is a phase displacement equal to θ between ϕ_s and ϕ_b.

When the working diagram, Fig. 12, has been constructed for the determination of running performance, it is only necessary to add the lines $O\,Z_L$ and $O\,Z_s$* to obtain the values which enter into the starting torque formula.

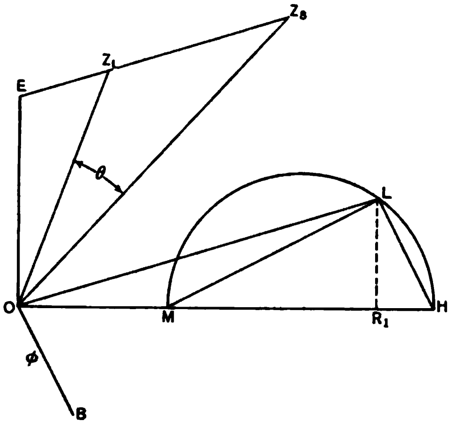

Fig. 14

As was shown previously,

$$\phi_b \propto L\,H\,S_2\,\sqrt{X_m} \times \left(\frac{O\,E}{O\,Z_L}\right)$$

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*$E\,Z_s$ is parallel to $O\,L$ and equal to

$$\frac{O\,L \times S_1 \times r_{1s} \times X_m}{S_s \times X_s}$$

$$E\,Z_L = \frac{O\,L \times S_1 \times r_1}{S_s}$$

Therefore

$$\phi_s \propto L\,H\,S_2\,\frac{X_m}{X_s}\,\sqrt{X_s} \times \left(\frac{O\,E}{O\,Z_s}\right)$$

Also,

$$\theta = \text{the angle } Z_L\,O\,Z_s$$

and

$$P_m = L\,R_1 \times S_1 \times \left(\frac{O\,E}{O\,Z}\right)^2 E$$

Substituting these expressions in the starting torque formula given above, we obtain

$$\text{starting torque} = 225.4 \times \frac{L\,R_1 \times S_1 \times E}{\text{syn.}}$$

$$\times \frac{\overline{O\,E}^2}{O\,Z_L \times O\,Z_s} \times \sqrt{\frac{X_m}{X_s}} \times \sin\theta\,\dagger$$

The effective starting torque is usually about 92 per cent of the calculated value.

X. COMPARISON OF CALCULATED AND TEST RESULTS

The results tabulated below were obtained in the course of regular commercial work on motors built to meet special requirements. The reactances and magnetizing currents were calculated by C. A. Adams's formulas and the secondary resistances by DeLatour's formula.

	H.p.	Efficiency		Power factor		Max. torque*		Starting torque*	
		Test	Calc.	Test	Calc.	Test	Calc.	Test	Calc.
1	1	73.5	73.3	71	68.8	144	141	not av	ailable
2	1/2	66.2	66.5	67.1	66.8	70	70	21	21.3
3	1/2	70.4	71	72.6	71.5	49.5	51	not av	ailable
4	1/3	59.5	60.2	66.7	67.5	44.5	44.5	"	"
5	1/12	51	48.6	62.6	64.2	8.1	7.9	"	"
6	1/4	61.6	59.6	64.5	65.6	35	34	23	23.2
7	1/6	56.5	57.7	72.5	75.5	17.25	17.2	16.25	16.6
8	1/6	52	51.8	66.3	65.7	22.4	22.7	14	16.3
9	1/10		63.5		65.6	16.6	16.4	12.25	12.5
10	1/3	64.9	65.8	68.3	67	36.5	35.3	22.2	22.5
11	1/4	61.5	61.7	69	67.2	26	25.4	19	18.3
12	1/12	49	46.8	58.2	62	13.25	11.6	9	9.5

*Calculated values of maximum and starting torques, as given in the table, are the values obtained by the formulas multiplied by 0.92.

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† In ounces at one-foot radius.

The larger discrepancies between test and calculated values are due to errors in the calculation of the constants rather than to the diagram. As an illustration of this fact, the running performance of the 1/12-h.p. motor, which appears as the last item in the above list, was re-figured from test constants, with the results which follow:

Horse power	Efficiency		Power factor		Max. torque	
	Test	Calc.	Test	Calc.	Test	Calc.
1/12	49	48.7	58.2	59.5	13.25	13.3

APPENDIX I—NOTATION

E = impressed voltage.

E_{ta} = transformer e.m.f. in circuit A.

E_{ra} = rotational e.m.f. in circuit A.

E_{tb} = transformer e.m.f. in circuit B

E_{rb} = rotational e.m.f. in circuit B.

i = primary current.

i_m = magnetizing current for main field.

i_{ms} = secondary no-load current as reflected in primary.

i_k = primary current with rotor at rest, assuming r_1 and $r_2 = 0$.

i_2 = secondary current.

i_{2k} = secondary current with rotor at rest, assuming r_1 and $r_2 = 0$.

i_a = cross-field magnetizing current in circuit A.

i_b = secondary no-load current in circuit B.

P_b = secondary input from phase B.

P_m = secondary input from main winding.

r_1 = primary resistance (main winding).

r_{1s} = primary resistance (starting winding).

r_2 = secondary resistance reduced to primary.

X_1 = reactance (total reduced to primary).

X_2 = reactance (total reduced to secondary, but assuming a 1 to 1 ratio).

X = reactance (total, either X_1 or X_2, assuming $X_1 = X_2$).

X_0 = reactance with secondary open-circuited.

X_m = reactance of the main winding (total reduced to primary).

X_s = reactance of the starting winding (total reduced to primary).

ϕ_a = flux of phase A, or the cross flux of a single-phase motor (effective or resultant value in the rotor).

ϕ_b = flux of phase B, or the main flux of a single-phase motor (effective or resultant value in the rotor).

ϕ_s = flux of starting winding (effective or resultant value in the rotor).

$K_p = \dfrac{\text{permeance of the mutual path.}}{\text{permeance of mutual and primary leakage paths in parallel.}}$

$K_s = \dfrac{\text{permeance of the mutual path.}}{\text{permeance of mutual and secondary leakage paths in parallel.}}$

$K_r = K_p\, K_s$.

M = coefficient of mutual induction.

L_1 = coefficient of self induction of the primary.

L_2 = coefficient of self induction of the secondary.

$P = 2\pi \times$ frequency.

S_1 = primary current scale (amperes per inch).

S_2 = secondary current scale (amperes per inch).

S_e = e.m.f. scale (volts per inch).

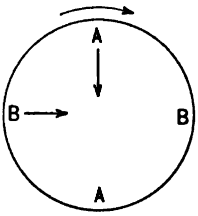
APPENDIX II—PLUS AND MINUS SIGNS

All diagrams in this paper are constructed in accordance with the following conventions:

A flux entering the rotor from the top or left is assumed to be positive.

A current which tends to produce a positive flux is assumed to be positive.

A voltage which tends to produce a positive current is assumed to be positive.



From these conventions it follows that:

1. Ohmic drops are of opposite sign to the currents producing them.

2. All voltage triangles of which two sides are opposing induced e.m.fs. and the third side a resistance drop or an impressed voltage, must close without two arrows pointing toward any one angle.

3. When ϕ_a is positive, E_{rb} is positive, but when ϕ_b is positive, E_{ra} is negative, for rotation as per sketch.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

MOTOR STARTING CURRENTS AS AFFECTING LARGE TRANSMISSION SYSTEMS

BY P. M. LINCOLN

From time to time those responsible for the operation of electrical systems have displayed a disposition to place a definite limit upon the size of motors which they will allow upon their circuits. This tendency seems to be more pronounced in alternating-current than in direct-current systems, but is observable in both. Moreover, in alternating-current systems the tendency is not confined to central stations for city supply, but is spreading to the larger transmission systems that deal in wholesale power.

So far as the writer has been able to analyze, the reasoning that has led to these restrictions is about as follows:

1. A desire to avoid tying up too much load to a single piece of apparatus, thereby endangering a comparatively large income by the loss of a single motor.

2. A fear that the starting currents and the fluctuations in the operating currents of relatively large motors will cause fluctuations in voltage.

3. A fear, more or less undefined, that the cumulative effect of starting many large motors at nearly the same hour will cause so large a draft of current as to be beyond the ability of the generating plant to take care of it.

It may be of interest to analyze further these reasons and see just how much bearing they may have upon a typical large transmission system which presumably deals in wholesale power only.

The writer recognizes the first of the above reasons as an entirely legitimate one. It is, no doubt, desirable to keep the power supply as much subdivided as possible, thereby avoiding the danger of a relatively large loss of revenue by crippling of a single motor. Its application, however, is wholly commercial in its nature. There are many cases where these same commercial considerations may make it desirable to advocate rather than deprecate the use of large motors, since on no other basis can some kinds of business be secured. Take for example an existing cotton mill or other industry that is already equipped with an engine connected to its load by shafting and belts. The most natural way of applying electric drive to such a case is simply to substitute one large motor in place of the engine. Commercial considerations will often demand that a given load be taken in this manner or not at all. This case is cited merely to indicate that commercial considerations are not, and of necessity cannot be, controlling in fixing the size of motors or in any ruling which looks toward the limitation of the size of motors which might be permitted on a given system. The size of the motor is simply a matter of expediency. If the advantages of subdivision can be obtained along with electric drive well and good, but if circumstances forbid these advantages, also well and good. The decision as dictated by commercial considerations will be to take the business however it can be obtained, entirely independent of the size of the motor that may thereby be placed on the system.

The second reason mentioned above, namely, the desire of avoiding voltage fluctuations, is also one that must be recognized as having a logical basis. However, this reason is one which appeals with much more force to the typical city supply system, whose main function is the supply of lighting, than to the large transmission system for the supply of wholesale power. In any event the logic of any ruling having this object in view demands not simply a limitation in the size of the motor but a consideration as well of other conditions that surround the installation of this motor. The point involved is simply the question of the voltage fluctuation which will be caused when a given motor is started or stopped or when its load fluctuates. The voltage fluctuation depends not only upon the size of the motor, but also, among other things, upon the size and regulation of the transformers supplying the motor and upon the size, voltage and length of the transmission line connecting it with the source of power. A logical restriction which has for its object the elimination of voltage fluctuation, should depend even more upon these other features than upon the size of the motor. A five-h.p. motor, for instance, supplied along with some lighting customers, by a three-kw. transformer at the end of a comparatively long and low-voltage transmission might be more of a menace to lighting in its neighborhood than a 100-h.p. motor close to the power station and supplied by large-capacity, high-voltage transmission lines and good regulating transformers.

Any restriction which has as its basis the elimination of voltage fluctuation is, as indicated above, much more applicable to a central city supply station than to a large transmission system dealing in wholesale power. It is highly important for the city supply station to maintain voltage as steady as possible, since a large part of its revenue is derived from the supply of lights. With the transmission system supplying wholesale power, however, the conditions are far different, the revenue from lighting being a very small proportion of its total revenue. The responsibility for voltage fluctuations at customer's premises is, therefore, by no means as heavy as it is with the city supply system.

In general there are two effects that must be borne in mind when considering the question of voltage fluctuations that may be caused by the presence of motors, and these two considerations hold whether the primary object of the circuit in question is the supply of lighting or the supply of wholesale power. These two effects are: first, the transient fluctuation of voltage due to starting current or to a change in running current, and second, the permanent voltage which is due to the permanent assumption or rejection of load by these motors. In dealing with the wholesale supply lines much of the first-mentioned variety of voltage fluctuation may be forgiven, since it is confined to a few relatively short and predetermined periods of the day, namely, the regular morning, noon and evening starting and quitting hours of the mills and factories that are supplied with power. This is particularly true since the customers who make use of wholesale power supplies directly for lighting, invariably recognize that they are applying it to a use not primarily intended and are willing to make allowances therefore. It is sometimes necessary to take some special means to care for the permanent voltage change where the power circuits are used directly for lighting, since the difference in voltage between loaded and unloaded line may reach such a value as to be destructive to the lamps. However, where the typical individual mill draws a starting current from the line that is less than the running current (as will be shown later in this discussion), it is evident that the question of motor starting current and transient voltage fluctuation caused thereby is of secondary importance.

The third cause for contemplating the limitation of the size of motors mentioned in the opening paragraph, namely, the fear that the draft of starting current of many motors starting about the same time may be beyond the capacity of the power plant, is the question whose investigation has led to the preparation of this paper. The conditions which led up to this investigation are, briefly, as follows:

A certain large transmission system operating in the south at one time in the course of its growth experienced considerable difficulty in picking up its load at the time of the usual morning start of the mills. In this case, as is usual with southern transmission systems, most of the load consisted of cotton mills, which started up nearly the same hour of the morning all over the system. From certain effects noted it seemed that the starting currents taken by the motors at these periods were the cause of the failure to pick up the load and it was largely this consideration that led this particular system to consider a restriction in the size of the motors which might be allowed upon its circuits. This attitude led in turn to taking up for systematic investigation the general question of starting conditions which might actually be found in the mills that were taking power from this company's lines. An investigation of this character was, therefore, undertaken.

The method of making this investigation was extremely simple. Graphic recording meters were placed in the supply circuits of the mill under test. Meters showing the draft of both current and kilowatts were used in each case, so that both the kilovolt-amperes and the kilowatts of the mill could be secured. The effect during starting periods of the mill could thereby be readily observed and record thereof made. Nine typical mills were selected and tests of this character made upon each of them. A number of starts, both morning and noon, were made, in order to avoid the possibility of observing some condition which was not entirely typical.

A summary of the results which were obtained upon these nine mills by these tests is contained in the following table.

In addition to this summary, some of the more representative records made by the graphic meters are reproduced herewith.

Mill No.	Number of motors	Total capacity of motors in h.p.	Type of motors	Capacity of largest motor in h.p.	Percentage of total capacity in largest motors	Excess of demand in starting period over running period	
						In kv-a.	In kw.
1	37	981	Wound secondary	100	10.2	None	None
2	257	2440	Wound secondary	125	5.0	None	None
3	31	1284	Squirrel cage	150	11.7	None	None
4	37	3055	Squirrel cage	150	4.9	None	None
5	24	457	Squirrel cage	35	7.7	None	None
6	24	2626	Wound secondary	175	6.7	None	None
7	2	150	Squirrel cage	75	50.0	25%	25%
8	12	1125	Wound secondary	175	15.5	None	None
9	3	300	Squirrel cage	200	66.7	50%	None

It was recognized that in obtaining records of the starting conditions there was a possibility of error owing to the time lag of the graphic meters behind the actual current and kilowatt conditions which produced the meter indications. This matter was given careful attention in the taking of these particular records. The speed of the pen was adjustable in the graphic meters used, and this speed was so fixed that on the one hand the pen did not move so fast as to overshoot the amperes per kilowatt it was endeavoring to follow and on the other hand it had sufficient speed so as not to have too great a discrepancy between actual amperes or kilowatts and the position of the pen at the same time. The range of adjustment was such as to allow a speed of pen which would travel over the entire range in less than five seconds. Since the process of starting a large motor is one which always requires a period several times as long as this, and further since the travel of the pen is never but a fraction of the entire scales we may rest assured that the graphic meter indications which are shown here give a reasonably accurate indication of the starting conditions which we are observing.

Figs. 1 A and 1 B show, for instance, the starting conditions in a cotton mill, equipped with total of 1284 h.p. in motors. This is the mill given as No. 3 in the foregoing summary. In this mill there are two motors of 150 h.p. each and three of 100 h.p. each. All motors in this particular mill are of the squirrel cage type. An inspection of the records reproduced in Figs. 1 A and 1 B shows at once that the maximum demand during the starting period as compared to the demand during the running period is less than 70 per cent in kilovolt-amperes and about 50 per cent in kilowatts.

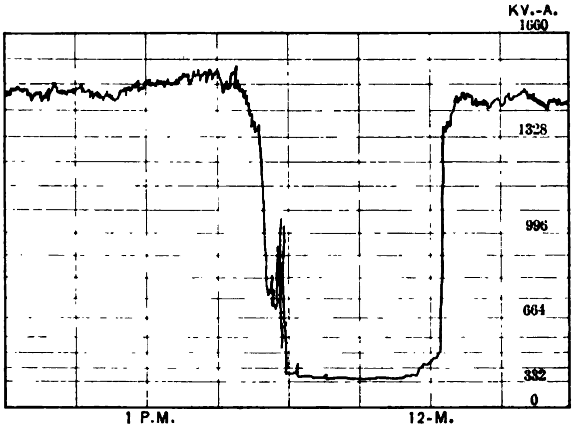


FIG. 1A

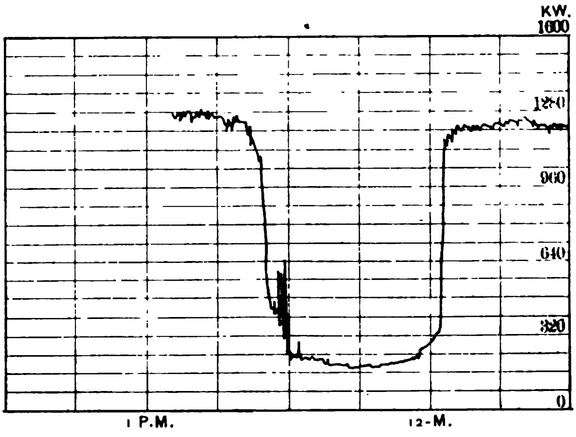


FIG. 1B

Figs. 2 A and 2 B show the conditions in another mill, No. 8 in the summary. Here the maximum demand during starting period is about 70 per cent of the running kilovolt-amperes and about 62 per cent of the running kilowatts. The motors in this case are of the wound-rotor type instead of squirrel cage as in the preceding case. The result of this difference in type of motor is shown in the fact that the kilovolt-amperes and kilowatts during the starting period come nearer together than is the case with the squirrel-cage motor. On the other hand a comparison of the charts indicates that the kilowatts of the wound-rotor motor taken during the starting period are higher than for the squirrel-cage type. It is, of course, possible to obtain much more rapid acceleration with the wound-rotor type than with the squirrel-cage type, and this power placed in the hands of a mill operator who is in a hurry to get started in the morning may lead to drafts of current during the starting period that are considerably greater with the wound-rotor type than with the squirrel-cage type. This is a fact which does not seem to have been properly appreciated by those who are using motors for mill purposes.

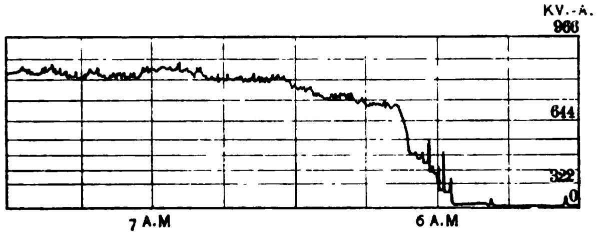


FIG. 2A

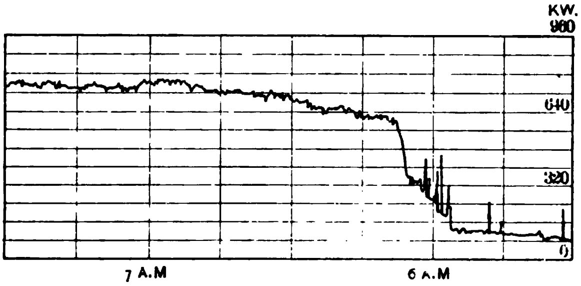


FIG. 2B

Figs. 3 A and 3 B illustrate mill No. 6 in the foregoing summary. The capacity of the largest motor in this mill is the same as in No. 8 just described, but the total capacity of all motors is more than double that in mill No. 8. Although the actual kilovolt-amperes and kilowatts taken for starting a single motor are about the same they become a smaller proportion of the running conditions.

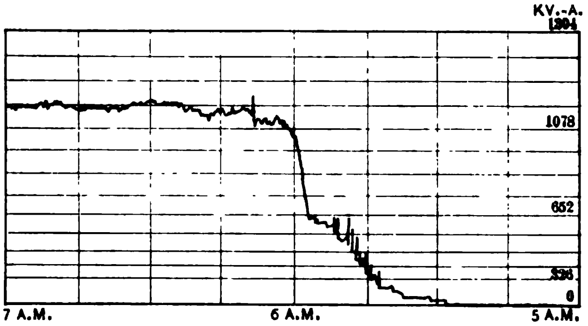


FIG. 3A

Figs. 4 A and 4 B show by far the most severe condition of any that was found in these tests. This mill is No. 9 in the summary, and is provided with only two motors, one a 200-h.p. and the other 100-h.p., both of the squirrel-cage type. In this case, therefore, the largest motor amounts to two-thirds the

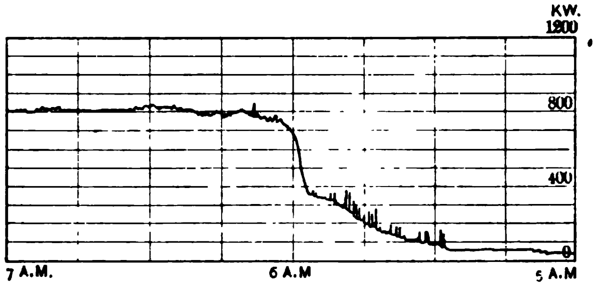


FIG. 3B

total motor capacity. However, even in this most severe case the kilovolt-amperes during the starting period exceed the running kilovolt-amperes by only 50 per cent and the kilowatts during the starting period does not exceed the running kilowatts at all. If this mill had had a total of 500 h.p. instead of only 300 h.p., the starting kilovolt-amperes would not have exceeded the running kilovolt-amperes. We might note that if this mill had been increased to a total of 500 h.p., its total capacity would have been only about 20 per cent of mill No. 4 and only about 25 per cent of mills No. 2 and No. 6. The foregoing records are typical of those for all of the other mills taken. On account of this similarity no further records are here reproduced. There are some conclusions which may readily be drawn from an inspection of these records and the foregoing summary of the nine mills that were observed.

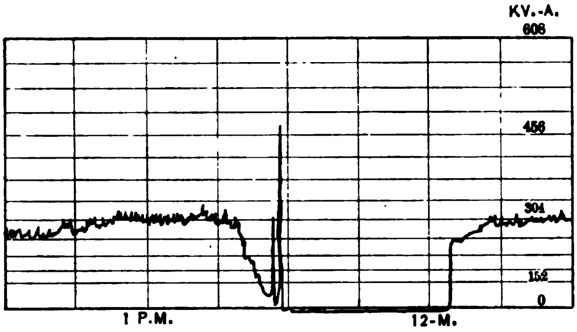


FIG. 4A

In the first place it is evident that so long as the largest motor in a mill is less than a certain percentage of the total capacity in motors, the power demanded for starting purposes will always be less than for running purposes and this will be true no matter whether the demand be measured in kilovolt-amperes or in kilowatts. The evidence of the foregoing records indicates that the largest motor may be at least 25 per cent of the total capacity

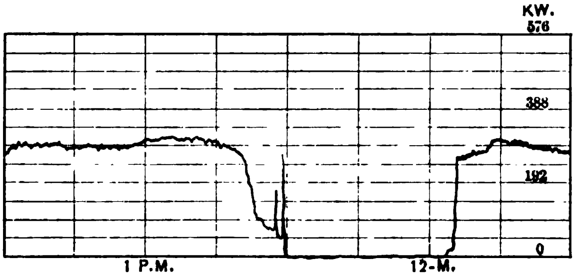


FIG. 4B

in a given mill and still this relation will hold. Possibly the largest motor may be even higher than this percentage of the total, but 25 per cent is certainly a safe figure, judging by the actual records taken.

It is further evident that so long as the current during the starting period is less than during the running period the draft of starting current cannot be a menace so far as ability to pick up load is concerned. A power plant that can pick up and carry the running current can also pick up and carry the starting current, provided this starting current is less than the running current. What is true of one mill is, of course, still more true when many of these mills are carried upon a given transmission system. The foregoing summary shows three mills that have total capacity of more than 2000 h.p., one of them exceeding 3000 h.p. Twenty-five per cent of the total capacity of any one of these mills will mean a single motor having a capacity of 500 to 750 h.p. Therefore, in any one of these mills a motor of 500 h.p. could have been started and still the draft of current during running conditions would have been more than that during starting conditions. If the starting of a 500-h.p. motor can be accomplished in one mill without exceeding a safe limit, there is no reason why the same thing cannot be done in another independent of the total capacity. In other words, so far as picking up the load is concerned, this particular system can certainly take care of single motors as large at least as 500 h.p.

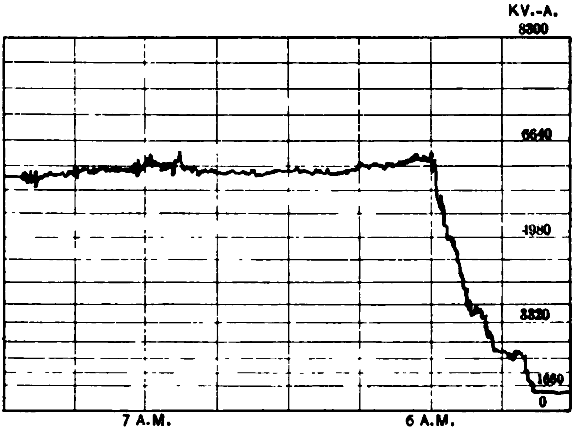


FIG. 5

The writer does not mean to say that he advocates motors of so large a size as this, since he believes that they are objectionable for other reasons, but so far as the ability to pick up the load is concerned there seems to be no doubt that motors of this size are entirely feasible. In fact, if necessary, the writer sees no reason why from this standpoint the size of the maximum motor cannot be increased considerably if such a step were ever found necessary.

While the foregoing records were being taken on individual mills there were also similar instruments recording the output of one of the high-tension lines feeding this system. Fig. 5 is a typical record of one of these transmission lines at the power plant. This record was taken during a typical morning start. The shape and character of this record does not indicate any possibility of distress on account of current draft during starting period.

A further consideration of these graphic records indicates almost to a certainty that it was not the motor starting currents that caused the failure to pick up load, but the high rate at which increments of real kilowatt-load are assumed by the power during the starting period. The source of power in this case was water power, and it is well known that waterpower plants are by nature much more sluggish in their ability to assume increments of real load than are steam plants. It seems very probable, therefore, that the cause of the inability to pick up load was due to the high rate of real kilowatt assumption, coupled, probably, with an unusually sluggish adjustment of governors.

This probability seems all the more certain when we consider the method of starting up cotton mills. The method used in such mills is first to start all motors some five or 10 minutes before the blowing of the morning or noon whistle. However, the starting of the motors does not put into operation the looms and other mill machinery that these motors drive. Each motor drives a more or less extensive system of countershafting to which the individual looms and other machinery are connected by tight and loose pulleys. Therefore, until the starting whistle blows, each motor operates only a relatively short section of countershafting. As soon as the starting whistle blows, each operator starts his own group of machines as rapidly as possible and it is during this period that the real kilowatt load rises so rapidly. An inspection of the accompanying graphic records clearly indicates the period at which the real load is thrown on.

From the data that have been given herein, the writer believes that the following conclusion is entirely logical—

That the only logical restriction in size of motor is one that will prevent it becoming more than 25 per cent of the capacity of the largest mill on the system. Such a restriction as this usually leads to so large a motor that no restriction whatever is necessary.

Discussion on "The Squirrel-Cage Induction Generator" (Hobart and Knowlton), "Single-Phase Induction Motors" (Branson) and "Motor Starting Currents as Affecting Large Transmission Systems" (Lincoln). Boston, Mass., June 28, 1912.

Lee Hagood: My remarks will be confined to the question of exciting current in connection with Mr. Hobart's and Mr. Knowlton's paper. As you will see from reading their paper, the matter of exciting currents bears very much on the question of air gaps. To some extent, the amount of exciting current required may appear to be a very great objection to these machines. I wish to make the point that neither the design of the machine nor its application should be very much restricted on account of exciting current.

On most commercial systems, the exciting current is already large, due to the transformers and induction motors. The former require from 4 per cent to 8 per cent of the actual current, and the latter from 40 per cent to 80 per cent. Exciting current is wattless and 90 deg. out of phase with the energy current. Its magnitude depends upon matters of design. It may be supplied to a system by either synchronous motors or synchronous generators, and the amount supplied by any given machine to a system depends upon the direct current applied to the field of the unit in question. In the circuits involved in its transmission, it produces two important effects, one being a voltage difference, and the other energy losses. The losses are mostly copper losses.

The effect of exciting current on I^2R losses can be seen from the following equation:

$$\text{per cent losses} = \frac{\text{per cent losses at unity power factor}}{(\text{power factor})^2}$$

For example, if the losses in a transmission line were 8 per cent at unity power factor, they would be 16 per cent at 0.7 power factor.

The following equation represents approximately the voltage drop in a transmission, or feeder line:

$$V = I_e R + I_w X \text{ when } I_w = I'_w - I_c/2$$

V is the voltage difference between a generating and receiving station: if the difference is a voltage drop, V must be taken as positive and if the difference is a rise V must be taken as negative; X and R represent the three-phase resistance and reactance between the points under consideration; I_e is the energy component of the current supplied the load; I'_w is the wattless component of the transmission line current at the receiving end; and I_c is the amount of wattless current required to charge the transmission line.

This formula is based on the assumption that the voltage drop, due to the charging current, is equal to $(I_c/2)\,X$, and that we can disregard a very small quantity which should appear in the equation, namely $E_G\ (1 - \cos\alpha)$, where E_G is the generating voltage and α is the phase relation between the generating and receiving voltage.

Fig. 1 represents a synchronous generator and an induction generator in the same station supplying, in parallel, a non-inductive load. The induction generator will require about 30 per cent exciting current, or 800 wattless kv-a. This is substantially independent of load, and must be supplied by a synchronous machine. In the case illustrated in Fig. 1, neither the losses nor the voltage are of consequence, due to the smallness of the exciting current and distance of its transmission.

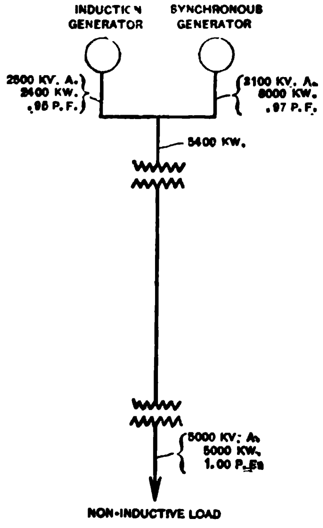


FIG. 1

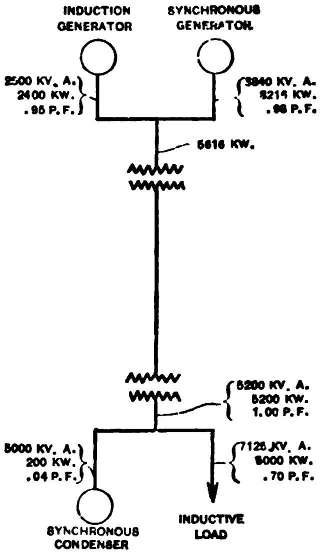


FIG. 2

Fig. 2 is similar to Fig. 1, except that the load is inductive and a synchronous condenser is applied, of sufficient capacity to carry the maximum wattless component of the load. The value of 70 per cent power factor used is one that often obtains in practise. The field of the synchronous condenser can be under automatic control by means of an automatic voltage regulator in such a manner that the power factor in the transmission line is corrected, and the voltage maintained constant across its bus-bars with a regulation of 2 per cent. Thus we can accomplish not only an excellent voltage regulation at a distribution center, but a saving in I^2R losses and the full use of the kilovolt-amperes of the apparatus involved. In the case given in Fig. 2, it is assumed that the transmission losses at unity power factor are

8 per cent. Without the synchronous condenser, the demand on the receiving and generating stations respectively would be 7125 and 7625 kv-a., whereas with the synchronous condenser the demand is only 5200 and 5600 kv-a. To maintain this condition, a 60-cycle, 5000-kv-a. synchronous condenser would be suitable and would cost, with its switchboard and accessories, about $20,000. This additional investment is quite small, when we appreciate that the total investment in an installation for delivery of power to any point over a transmission line is based principally on kilovolt-amperes, and is in the magnitude, in a great many cases, of $150 per kv-a. In the above, we have reduced the kilovolt-ampere demand by about 2000 kv-a.; the line losses have been reduced 8 per cent, and an excellent voltage regulation is accomplished. The losses in the synchronous condenser are about 4 per cent, but the better power factor in the generators has reduced their losses about 2.5 per cent: hence a net economy in losses of 6.5 per cent, or 375 kw., is obtained.

The smaller the constant voltage difference maintained between the generating and receiving station, the nearer constant will be the power factor. If we make this difference zero, the equivalent line power factor will be constant from no load to full load: for most transmission lines the equivalent power factor will be around unity, the exact value depending upon the relation $I_e/I_w = X/R$. The action of the synchronous condenser, controlled by its voltage regulator, is to hold constant voltage at the receiving station and in so doing it automatically carries all or part of the load's wattless kv-a., at all loads maintaining I'_w at such values as to meet the given voltage setting of the regulator.

I notice Mr. Lincoln referred to a system having a voltage regulation around 10 per cent. I have in mind two or three systems in which the regulation is 20 to 30 per cent. Induction regulators usually compensate for a voltage variation of about 20 per cent, and they cost, in general, for similar service, about half the price of a synchronous condenser for 60-cycle service; however, a synchronous condenser can not only take care of voltage regulation, but it corrects the power factor, as well, causing the consequent economies. Hence, there exists a wide application for its general use.

I believe that we will come to a very extensive application of synchronous condensers used for power factor correction and automatic voltage control. In view of this, I feel that but little restriction should be placed on exciting currents required by induction generators, induction motors and transformers. The designs of all these should lend themselves only to matters of cost, durability, etc.

Comfort A. Adams: In connection with the question of excitation in an alternating-current system, I wish to present the following point of view, which may be helpful to some. In any alternating-current system there are various magnetic fields for all of which excitation must be provided; whether it be the field of an alternator, synchronous motor, induction motor, or the magnetic field surrounding the line wires. In most systems the only* or at least the principal fundamental source of excitation is the direct current supplied to the fields of the synchronous machines of the system. Any other magnetic fields, such as in induction motors, transformers or around the line wires, must be excited through the medium of reactive lagging currents which act as conveyers of the excitation from the source in the synchronous machines to the place of consumption. The greater the excitation demanded by these various secondary magnetic fields, the greater must be the excitation supplied by the direct-current field currents of the synchronous machines, in order to maintain the desired voltage, and the greater must be the lagging reactive currents required for conveying the excitation. Thus one advantage of supplying the excitation at or near the point of consumption is the obvious saving in the cost of transmitting it. But there is another sometimes greater advantage, namely the improvement in regulation and the ability to control the voltage at the receiving point by the adjustment of the excitation at that point. This point of view leads naturally to the consideration of a system in which the voltage is maintained at the same value at all points by means of properly distributed excitation.

Referring now to the paper of Messrs. Hobart and Knowlton, consider the question of core losses. We are sometimes tempted to pride ourselves upon the accuracy and definiteness of electrical engineering calculations, but in ordinary computations of the core losses of induction motors and induction generators, we must multiply the rational part of the formula by from two to four in order to make the results check with observations; that is, we acknowledge that the part of the core loss which we do not take account of rationally in our formulas is in some cases two or three times as large as the part rationally accounted for. The inevitable result is a very large probable error in any machine differing appreciably in design or construction from those previously tested.

One of the sources of this large discrepancy is clearly demonstrated by the oscillograms, Figs. 17 and 18; namely the pulsations of flux in the teeth at what may be called tooth frequency, and due to local variations of equivalent air gap permeance, caused by the slots and slot openings combined with a short air gap. But this local variation of gap permeance may also cause considerable tooth-frequency pulsations in the core back of the teeth. For example consider a rotor and stator with 20 and 21 slots per pole respectively. Starting with a rotor tooth that is exactly opposite to a stator tooth at a particular instant,

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*Electrostatic capacity either artificially inserted or natural to the system, such as the capacity of a transmission line, obviously contributes more or less exciting current.

there will be in this vicinity at the same instant a group of seven or eight rotor teeth each of which is nearly opposite to a stator tooth, and ten slots from our starting point there will be a similar group of seven or eight rotor teeth each of which is nearly opposite to a stator slot. The first group mentioned constitutes a region of high gap permeance and the second group a region of low gap permeance. But as the variation of gap permeance from point to point is gradual from maximum to minimum and back again, we shall have at any instant a complete wave or cycle of gap permeance variation for each pole. Had the number of slots per pole on rotor and stator differed by two instead of one, there would have been two complete waves for each pole; and so on.

A little consideration will show that these waves of gap permeance variation move along the gap periphery with a velocity corresponding exactly to tooth frequency; that is, the wave of variation moves one complete wave length while the rotor is moving one tooth pitch, or since the wave of gap permeance variation means a wave of gap flux density variation, the pulsation of flux density in the teeth will be at tooth frequency. But in the first case cited each half-wave includes 10 teeth, and the resulting maximum of the flux wave must penetrate back into the core behind the teeth to a depth depending upon the length of the half-wave along the periphery, which is one-half of the pole pitch in the assumed case. The greater the difference between the number of rotor and of stator slots per pole the greater will be the number of gap permeance waves per pole and the less the depth to which the resulting flux pulsations penetrate back of the teeth.

It is obvious that in any case the resulting eddy currents will tend to damp out these pulsations, and to reduce the depths to which they penetrate, but that does not affect the validity of the above explanation.

It is also obvious that the more nearly the slots are closed and the longer is the air gap, the less will be the amplitude of the wave of reluctance variation.

There are thus in some cases tooth-frequency flux pulsations in a portion of the core back of the teeth as well as in the teeth themselves.

There is also the wave loss* due to the eddy currents induced in the tips of the stator teeth as the edges of the rotor teeth pass across them.

And finally there is the extra loss due to the breakdown of the insulation between the laminations. This last can be largely eliminated by more careful lamination, or by using less pressure when assembling the plates, or by both, although considerable pressure is desirable for mechanical reasons.

If these phenomena could be readily subjected to reasonably accurate analysis, there would be five separate core loss compu-

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*See *Pole Face Losses*, A. I. E. E. TRANS. 1909, XXVIII, Part II, p. 1133.

tations to make, excluding breakdown of insulation, in place of the one or two now employed. But unfortunately these phenomena are not as yet amenable to even roughly approximate quantitative analysis, as a little consideration will show. It is reasonable to expect, however, that some at least semi-rational method will be discovered for computing these losses separately. The speaker has been carrying on a series of experiments to this end and hopes later to present some useful results, although those thus far obtained are chiefly confirmatory of our previous conclusion, that the problem is a very difficult and complicated one.

Referring now to the question of neutralizing the pulsation of single-phase armature reaction by means of a squirrel-cage damper, it is stated on page 1745 that " if the aggregate cross-section provided by the face conductors of the squirrel cage equals the aggregate cross-section of the stator conductors, then the loss incurred in neutralizing the pulsations of the stator current is about equal to the stator I^2R loss."

This damper loss has also been estimated at one-half and one-quarter of the above, respectively, by well-known engineers.

All of these estimates are presumably based upon the assumption of perfect damping, that is that the leakage reactance between stator and damper windings is negligible, which is not the case.

The speaker has made careful computations of this loss, with the following results. The method of computation will be set forth at another time. Suffice it to say for the present that there are many factors entering into the computation, and that many approximations are necessary.

Assuming perfect damping as above and assuming the same current density in the damper as in the armature copper, the damper loss will about equal 70 per cent of the armature copper loss; with the same copper section in damper and armature, the damper loss will be somewhat less than 50 per cent of the stator copper loss. Practically the losses will be slightly less than indicated by these figures, owing chiefly to the leakage reactance between armature and damper conductors, as the resistance is relatively a small factor.

E. F. W. Alexanderson: In connection with the remarks of Professor Adams I should like to mention the results of an investigation which I made in order to determine a practical equation for finding the high-frequency tooth losses in induction motors. It is a well-known fact to designers that the additional core loss, due to magnetic disturbances, is higher in induction motors than in synchronous machines. A number of induction motors were examined, using data available for machines of greatly varying losses and speeds, in order to find a law for the variation of the losses due to high-frequency magnetic disturbance in the teeth. It was anticipated that a formula could be based on the frequency of the magnetic disturbance or on the width of the teeth. However, on going over the material available, it was found that in machines of the same peripheral speed the high-frequency loss was practically independent of the frequency, because a higher loss that might be expected from the higher frequencies is offset by the smaller penetration of the disturbance that necessarily accompanies a greater number of slots. As a result, it was concluded that the variations due to any other cause than the peripheral speed itself and the average flux density are smaller than the variation that occurs between machines of the same design, due to difference in the grade of iron or the mechanical treatment of the same. A formula was, therefore, evolved to determine the core loss due to high frequency in the teeth, which is based on peripheral speed and magnetic density of the gap only. The loss is proportional to the square of the speed, and the square of the density and the empirical constant is apparently the same from the largest and highest-speed machines to the small or low-speed machines.

For induction motors of ordinary design with open slots and standard iron, the empirical formula for core loss due to tooth frequency is

$$\text{loss in kw.} = 0.13\,\frac{\text{diameter}}{\text{length}}\left(\frac{\text{rev. per min.} \times \text{flux} \times \text{poles}}{10{,}000}\right)^2$$

The core loss in the original induction generator referred to in the Hobart paper may seem excessive, but it is in accord with the general law, as expressed by the above formula, and in order to reduce the tooth losses to such values as might be expected in synchronous machines, it was necessary to employ special measures. This condition will apply, in general, to induction generators, and is a circumstance that may make it difficult for such machines to compete with synchronous generators. However, this is a question that will answer itself, because the preference for one type of machine or the other can be expressed in dollars cost per kilowatt.

There is another consideration which I think is of importance, *i.e.*, the one referred to by Capt. Hagood, whether the power companies will favor a generator which needs lagging current for excitation. If it is agreed that the lagging component can be taken care of to advantage by synchronous condensers, a field is opened for other types of generators which have been practically forgotten, such as the Stanley double synchronous generator which makes it possible to operate a 25-cycle turbine set at 3000 rev. per min.

Lester McKenney (by letter): It seems to me that in making a rule as to the largest size motor to be allowed on a system, the rule should be based on the capacity of the system, or that part of the system supplying the section in which the motor is to be installed, rather than upon the capacity of the largest mill in that section, for the reason that a rule based on such a method would be more general in its application. As a result of the rule based upon the capacity of the largest mill, we see that if the load on the system were made up of a great number of small mills, the largest motor would be of comparatively small size, and all out of proportion to the capacity of the system and its ability to furnish motor starting currents.

The number of motors of the maximum size allowable also deserves special consideration. The idea here is not so much to protect the consumer having a motor of the maximum size against voltage disturbances, when his motors are started, as to protect the rest of the consumers against such starting.

It is to be regretted that no charts were taken showing the voltage disturbances at the mills and at the centers of distribution, during the investigation, as such records would have given much valuable information on one of the principal points mentioned in the paper.

It hardly seems possible that poor voltage regulation would be tolerated, even on a large transmission system dealing in wholesale power, if it were not for the large expenditure required for its elimination. A considerable part of the cost of our equipment is due to the demand for good voltage regulation. It therefore seems desirable that we take advantage of everything to secure this result, even to limiting the sizes of motors permitted on our transmission systems, providing the result is not obtained by too great a sacrifice of other things.

Referring to the charts Figs. 1 and 2, it will be noted that in plant No. 3 the motors are overloaded, while in plant No. 8 they are underloaded; and that the ratio of the starting current to the running current is based on the actual load which obtained at the time. On this basis, the ratio was nearly the same in both plants. The starting currents are independent of the load on the motors, and it seems desirable, for the purpose of future comparisons, that the ratio of the starting currents to the running currents, be based on the rated full-load current of the motors.

On this basis, the maximum starting current in plant No. 3, having squirrel-cage motors, would be 80 per cent of rated full-load running current; while in plant No. 8, having wound-rotor motors, the starting current is only 50 per cent of the rated full-load running current. This seems a most reasonable basis of comparison, as it shows the relation of the starting currents to the capacity of the motors.

It seems to me that the starting of squirrel-cage motors, with compensators, can be hurried to as great an extent as the starting of wound-rotor motors, and just as great drafts of current caused thereby.

There is one other point in this comparison, which the paper does not bring out, and that is, the higher power factor of the starting currents of wound-rotor motors, which, for equal values, cause less voltage disturbance than the starting currents of squirrel-cage motors. The wound-rotor motor is, therefore, most to be desired where close voltage regulation is an important feature.

H. M. Hobart: Capt. Hagood first spoke of the synchronous condenser, and it would seem that if it should become customary to use a synchronous condenser to control the power factor of distribution systems the field for the induction generator would at the same time be slightly widened. I do not feel that the field for the induction generator in any case is going to be very extensive, but it certainly has several very important characteristics to which Mr. Knowlton and I have called attention in our paper. We have endeavored also to call attention to its faults and limitations so that both sides of the question could be understood.

There are certainly many cases where it would be of commercial advantage to have a considerable proportion of the plant consist of induction generators. Consequently, from the standpoint of being in a position to realize these commercial advantages, it is to be hoped that Captain Hagood's views as to the rapid introduction of the synchronous condenser will be realized. It seems to me his argument is very sound, that they should be widely used. Professor Adams spoke of many interesting attributes of windings and the effect of employing either full pitch or fractional pitch. These were very interesting and it certainly is up to designers to keep this matter carefully in mind in such work. As to the loss in squirrel-cage windings it looks as if Professor Adams is correct, and that we have overestimated the I^2R loss needed in the squirrel-cage winding to effect a certain degree of compensation. On the other hand I believe we have underestimated the parasitic iron loss which will still remain on our hands due to incomplete compensation of the pulsations of magnetomotive force. I should personally be of the opinion that the net result would be substantially the same except that we ascribe it to I^2R loss where it is partly I^2R loss and partly hysteresis and eddy losses in the iron. Mr. Alexanderson spoke of the greater losses which he considered to be inherent in the induction type of machine. I personally feel that any excess losses are nearly if not entirely attributable to the American plan of employing form-wound coils, and the consequent necessity of wide-open slots. Of course it is a great commercial advantage to have form-wound coils, but if you were to test European motors with nearly closed slots on both stator and rotor, the losses would be found to be down to the values obtained on other types of electric machines. It is of more importance in induction machines to have closed slots because of the necessity of employing a very small air gap. It is also interesting to keep in mind the point that Mr. Alexanderson made that the recent revival of interest in induction generators carries our attention back to various less simple types of induction generators that have been brought out from time to time. And I am aware that Mr. Alexanderson has given a great deal of attention to some of these types and finds that they possess qualities which will probably be of commercial value in the future.

E. Knowlton (by letter): On page 1742 mention is made of the method of ventilation for a high-speed induction generator. The statement regarding the less amount of cooling surface required with axial ventilation should not be construed as meaning that this feature can be entirely neglected. The amount of surface can be considerably reduced because of the lower temperature drop through the iron when the heat is transmitted along the plane of the laminations instead of transversely thereto, but one should not lose sight of the fact that the temperature drop at the surface should be taken into account, as it is, even with axial ventilation, an appreciable part of the total drop. When the air passes through any machine in parallel paths the resistance of the paths should bear some relation to the heat to be absorbed by the air in the path. Because of other considerations it is usually difficult to predetermine the paths accurately, but a careful test of a machine will generally suggest means of improvement. With some designs the inherent characteristics are such that the greater amount of air will be supplied to the hotter parts where it is needed, but in others special construction must be used to accomplish this result.

W. L. Waters (by letter): The paper of Messrs. Hobart and Knowlton is a very useful presentation of the status of the induction generator to date. As has been frequently pointed out in the past, the main field for this type of generator at the present time is in large city power systems operating synchronous machinery or in water-power systems consisting of a number of comparatively small isolated stations.

The authors describe the first really important installation of the induction generator on a large scale, and the tests made are both interesting and instructive. The suggestion that this type of generator is suitable for single-phase work is, I think, a somewhat radical one. It is essentially a generator for high power factor or leading power factor loads, while a single-phase load is usually a railway one of low power factor. The low efficiency of the single-phase generator is due almost entirely to the low output for given dimensions and weight, compared to the three-phase rating. The total losses are approximately the same for both single- and three-phase, so that the slight reduction in the eddy current loss in the damping circuit of the rotor claimed for the induction generator would have little effect upon the efficiency.

I fully expect that the induction generator will have an important future in power station work as soon as operating engineers realize fully its advantages, and the demand increases so that manufacturers can standardize them like synchronous units. I think Messrs. Hobart and Knowlton's paper will help greatly in again bringing this type of generator before the public and in familiarizing it with its characteristics.

A paper presented at the 29th *Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June* 28, 1912.

DEVELOPMENT OF A SUCCESSFUL DIRECT-CURRENT 2000-KW. UNIPOLAR GENERATOR

BY B. G. LAMME

This paper is not intended to be a theoretical discussion of the principles of unipolar machines; neither is it a purely descriptive article. It is rather a record of engineering experiences obtained, and difficulties overcome, in the practical development of a large machine of the unipolar type. For those who are interested in the design and development of electrical machinery there may be many points of very considerable interest in this record. Some of the conditions of operation, with their attendant difficulties, proved to be so unusual that it is believed that a straightforward story of these troubles, and the methods for correcting them, will be of some value as a published record.

Two theoretical questions of unipolar design have come up frequently: (1) whether the magnetic flux rotates or travels with respect to the rotor or the stator; and (2) whether it is possible to generate e.m.fs. in two or more conductors in series in such a way that they can be combined in one direction, without the aid of a corresponding number of pairs of collector rings, to give higher e.m.fs. than a single conductor.

To the first question the answer may be made that in the machine in question, it makes no difference whether the flux rotates or is stationary; the result is the same on either assumption. To the second it may be said that when the theory of interlinkages of the electric and magnetic circuits is properly considered, it is obvious that the resultant e.m.f. is equivalent to that of one effective conductor, and therefore it is not practicable to obtain higher e.m.fs. than represented by one conductor, without the use of collector rings or some equivalent device. It has been proposed in the past, by means of certain arrangements of liquid conductors in insulating tubes, to add the e.m.fs. of several conductors in series, but such a scheme does not appear to be a practical device. Therefore, the theoretical considerations being largely eliminated, the author confines himself to the practical side only.

In 1896 the writer designed a small unipolar generator of approximately three volts and 6000 amperes capacity at a speed of 1500 rev. per min. This machine was built for meter testing and the occasion for its design lay in the continued trouble encountered with former machines of the commutator type designed for very heavy currents at low voltages.

The general construction of this early machine is shown in Fig. 1. The rotating part of this machine consisted of a brass casting of cylindrical shape, with a central web, very similar to a cast metal pulley. The two outer edges of this pulley or ring served as collector rings for collecting the current as indicated in the figure, while the body of the same ring served as the single conductor. The object of this construction of rotor was to obtain a form which could be very quickly renewed in case of rapid wear, as this arrangement would allow a small casting to be made and simply turned up to form a new rotor. However, this renewal feature has not been of very great importance, for the rotor of the first machine was replaced only after 12 years' service. This period of course did not represent continuous service, for this particular machine was used for meter testing purposes or where large currents were required only occasionally.

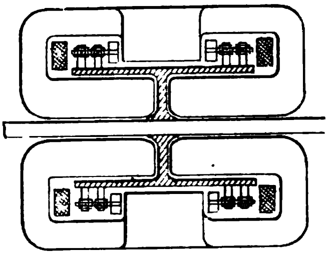

FIG. 1

A number of peculiar conditions were found in this machine. In the initial design the leads for carrying the current away from the brushes were purposely carried part way around the shaft in order to obtain the effect of a series winding by means of the leads themselves. In practice, they were found to act in this manner and, in fact, they over-compounded the machine possibly 30 to 40 per cent. In consequence, it was necessary to shunt them by means of copper shunts around the shaft in the opposite direction.

Shortly after this machine was put in operation there was considerable cutting of the brushes and rings, especially at very heavy currents. It was found that block graphite, used as a lubricant, gave satisfactory results. This machine was operated up to 10,000 to 12,000 amperes for short periods.

The description of the above machine has been gone into rather fully, as it was a forerunner of the 2000-kw. machine which will be described in the following pages. The general principle of construction and the general arrangement of the two parts, or paths, of the magnetic circuit are practically the same in the two machines, as will be shown.

In 1904, due to the rapidly increasing use of steam turbines, the question of building a turbo-generator of the unipolar type was brought up, and an investigation was made by the writer to determine the possibilities. This study indicated that a commercial machine for direct connection to a steam turbine could be constructed, provided a very high peripheral speed was allowable at the collector rings or current-collecting surfaces. It appeared that the velocity at such collector surfaces would have to be at least 200 to 250 feet per second, in order to keep the machine down to permissible proportions of the magnetic circuit, and to allow a reasonably high turbine speed. Contrary to the usual idea, the very high speeds obtainable with steam turbines are not advantageous for unipolar machines. For example, while maintaining a given peripheral speed at the current collecting surface, if the revolutions per minute of the rotor are doubled, then the diameter of the rotor collecting rings is halved, and the diameter of the magnetic core surrounded by the collector rings is more than halved, and the effective section of core is reduced to less than one-fourth. The e.m.f. generated per ring or conductor, therefore, on the basis of flux alone, would be reduced to less than one-fourth, but allowing for the doubled revolutions per minute, it becomes practically one-half.

On the other hand, if the revolutions are reduced, while the speed of the collector ring is kept constant, then the e.m.f. per ring can be increased, as the cross-section of the magnetic circuit increases rapidly with reduction in the number of revolutions. But at a materially reduced speed, the total material in the magnetic circuit becomes unduly heavy. In consequence, if the speed is reduced too much, then the machine becomes too large and expensive, while with too great an increase in speed, the e.m.f. per ring becomes low or the peripheral speed of the rings must be very high. It is desirable to keep the number of collector rings as small as possible, for each pair of rings handles the full current of the machine, and therefore any increase in the number of rings means that the full current must be collected a correspondingly large number of times. Therefore, it works out that the range of speeds, within which the unipolar machine becomes commercially practicable, is rather narrow.

In 1906, an order was taken for a 2000-kw., 1200-rev. per min., 260-volt, 7700-ampere unipolar generator to be installed in a portland cement works near Easton, Pa. The fact that it is a cement works should be emphasized, as having a considerable bearing on the history of the operation of this machine, as will be shown later.

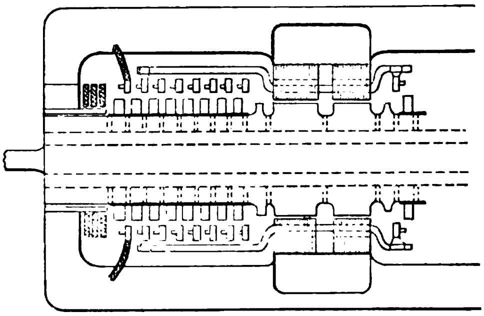

FIG. 2

This 2000-kw. machine does not represent any theoretically radical features, being similar in type to the smaller machine already described, but modified somewhat in arrangement to allow the use of a large number of current paths and collector rings. The general construction of this machine is indicated in Fig. 2.

The stator yoke and the rotor body are made of solid steel, the stator being cast, while the rotor is a forging. There are eight collector rings at each end of the rotor, the corresponding rings of the two ends being connected together by solid round conductors, there being six conductors per ring, or 48 conductors total. In each conductor is generated a normal e.m.f. of 32.5 volts, and with all the rings connected in series, the total voltage is 260.

The stator core, at what might be called the pole face, is built up of laminated iron, forming a ring around the rotor. This was laminated in order to furnish an easy method for obtaining the stator slots in which lie the conductors which connect together the brushes or brush holders for throwing the pairs of rings in series. The slots in the stator laminations were made open, as indicated in Fig. 3, in order readily to insert the stator conductors. There are 16 slots in this ring, and in each slot there is placed one large solid conductor.

As first assembled, non-metallic wedges were used to close these slots, but later these were changed to cast iron, for reasons which will be explained later.

The rotor core consists of one large forging, as indicated in Fig. 2. Lengthwise of this rotor are 12 holes for ventilating purposes, originally 2¾ in. in diameter. Each of these holes is connected to the external surface by means of nine 1⅜-in. radial holes at each end of the rotor, these holes corresponding to mid-positions between the collector rings. It was intended to take air in at each end of the rotor and feed it out between the collector rings for cooling. In addition, as originally constructed, there was a large enclosed fan at each end, as indicated in Fig. 4. These fans took air in along the shaft and directed it over the collector rings parallel to the shaft. The object of this was to furnish an extra amount of air for cooling the surfaces of the rings, and the brushes and brush holders, as it was estimated that the brushes and brush holders themselves could conduct away a considerable amount of heat from the rings by direct

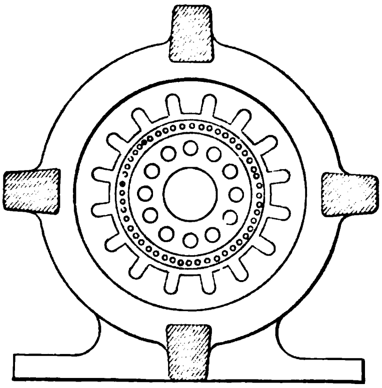

FIG. 3

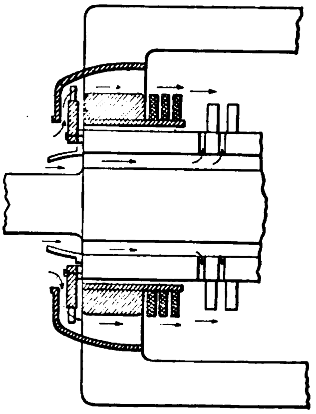

FIG. 4

contact, and that the cooling air from the fans, circulating among the brush holders, would carry away this heat. These fans were removed during the preliminary tests, for reasons which will be given later.

The rotor collector rings consisted of eight large rings at each end, insulated from the core by sheet mica, and from each other by air spaces between them. Each ring has 48 holes parallel to the shaft. These holes are of slightly larger diameter than the rotor conductors outside their insulation. Six holes in each ring were threaded to contain the ends of six of the conductors which were joined to each ring. The six conductors connected to each ring were spaced symmetrically around the core. Fig. 5 shows this construction.

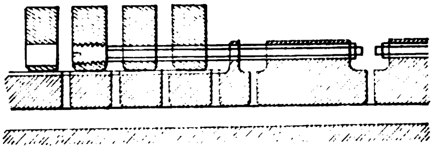

FIG. 5

The rotor conductors, 48 in number, consist of one-in. copper rods, outside of which is placed an insulating tube of hard material. Each conductor, in fact, consists of two lengths arranged for joining in the middle. The outer end of each conductor is upset to give a diameter larger than the insulating tubes, and a thread is cut on this expanded part. After the rings were installed on the core, the rods were inserted through the holes to the threaded part of a ring and were then screwed home.

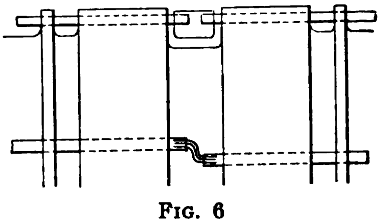

FIG. 6

At the middle part of the rotor core, a groove is cut as shown in Fig. 6. Into this groove the two halves of each conductor project. These two ends are then connected together by strap conductors in such a way as to give flexibility in case of expansion of the conductors lengthwise. This arrangement is also shown in Fig. 6.

With this arrangement there is no possibility whatever of the conductors turning after once being connected. There is a series of holes from the axial holes through the shaft to this central groove, for the purpose of allowing some ventilating air to flow over the central connections.

As originally constructed, the conductors passed through completely enclosed holes near the surface of the rotor core, as indicated in Fig. 7. This construction was afterwards modified to a certain extent. The face of the rotor at this point was also solid, as originally constructed. This was afterwards changed, as will be described later.

The collector rings, as originally constructed, consisted of a base ring with a wearing ring on the outside, as shown in Fig. 8. Both rings were made of a special bronze, with high elastic limit and ultimate strength. On the preliminary tests these rings showed certain difficulties and required very considerable modifications, and several different designs were developed during the preliminary operation.

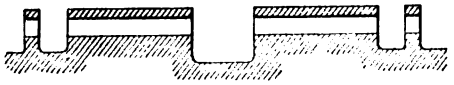

FIG. 7

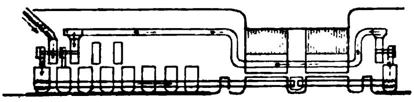

FIG. 9

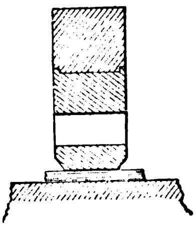

FIG. 8

The eight sets of brush holders at each end are carried by eight copper supporting rings. These supporting rings are insulated from the frame of the machine but are connected in series by means of the conductors through the stator slots. There are 16 brush holder studs per ring and two brush holders per stud, each capable of taking a copper leaf brush $\frac{3}{8}$ in. thick by $1\frac{3}{8}$ in. wide. These brush holders are spaced practically uniformly around the supporting rings. The supporting copper rings are continuous or complete circles, so that the currents collected from the brushes are carried in both directions around the ring. There are two conductors carried from each ring through the stator slots to a ring on the opposite side of the machine, in order to connect the various brush holders in series. The arrangement is illustrated in Fig. 9.

The above description represents the machine as originally constructed and put on shop test. From this point on, the real story begins. Various unexpected troubles developed, each of which required some minor modification in the construction of the machine, and moreover, these troubles occurred in series, that is, each trouble required a certain length of time to develop, and each one was serious enough to require an immediate modification in the machine. In consequence, the machine would be operated until a certain difficulty would develop; that is, that trouble would appear which took the least time to develop. After it was remedied, a continuation of the test would show a second trouble which required a remedy, and so on. Some of these troubles were of a more or less startling nature.

This machine, after being assembled according to its original design, was operated over a period of several weeks in the testing room of the manufacturing company. It was operated both at no-load and at full-load current, and a careful study was made of all the phenomena which were in evidence during these tests.

The machine was first run at no-load without field charge to note the ventilation, balance, and general running conditions of the machine. The ventilation seemed to be extremely good, especially that due to the fans on the ends of the shaft. The noise, however, was excessive—so much so that anyone working around the machine had to keep his ears padded. At first it was difficult to locate the exact source of this noise, but it was determined that the end fans were responsible for a considerable part of it.

On taking the saturation curve of the machine, it was found to be extremely sluggish in following any changes in the field current. The reason for this sluggishness is obvious from the construction of the machine, each magnetic circuit of the rotor core being surrounded by eight continuous collector rings of very heavy section, and also by eight brush-holder-supporting rings of copper of very low resistance. These rings, of course, formed heavy secondaries or dampers which opposed any change in the main flux. The total effective section of these rings was equivalent in resistance to a pure copper ring having a section of 49 sq. in. One can readily imagine that such a ring would be very effective in damping any sudden flux changes. This sluggishness of the machine to changes in flux, however, was not an entirely unexpected result.

The saturation curve showed that the machine could be carried considerably higher in voltage than originally contemplated, for apparently the magnetic properties of the heavy steel parts were very good, and it was possible to force the inductions in these parts to much higher density than was considered practicable in working out the design. This gave considerable leeway for changes which later were found to be necessary.

In taking the saturation curve, the power for driving the machine was measured and it was found that there were practically no iron losses in the machine; that is, at full voltage at no-load the total measured losses were practically the same as without field charge. This apparently eliminated one possible source of loss which was anticipated, namely, that due to the large open slots in the stator pole face, these slots being very wide compared with the clearance between the stator and rotor.

After completion of this test the machine was then run on short circuit. Apparently, as there was no iron loss shown in the no-load full voltage condition, the short-circuit test with full-load current should cover all the losses in the rotor which would be found with full-load current at full voltage. Experience afterward proved this assumption to be correct, for in its final form the machine would operate under practically the same condition as regards temperature, etc., at full voltage as it would show at short circuit, carrying the same current, the principal difference being the temperature of the field coil.

It was in this short-circuit temperature run that the real troubles with the machine began. The measured losses, when running on short circuit, were somewhat higher than indicated by the resistance between terminals times the square of the current. These extra losses were a function of the load and increased more rapidly with heavy currents. The measured power indicated that these excess losses were principally due to eddy currents. However, the total losses indicated in these preliminary tests, although somewhat higher than calculated, were still within allowable limits, as considerable margin had been allowed in the original proportions to take care of a certain amount of loss. It was therefore considered satisfactory to go ahead with the short-circuit tests, and in making these it was the intention to operate long enough to determine the necessary running conditions as regards lubrication, heating, etc.

As mentioned before, the original collector rings of the machine each consisted of a base ring upon which was mounted a secondary or wearing ring, it being the intention to have this latter ring replaceable after it was down to the lowest permissible thickness, as it would be rather expensive and difficult to replace the base ring which carried the rotor conductors. As the inner ring was shrunk on the core and the outer ring was shrunk on over the base ring, with a very small shrinkage allowance, it was considered that the outer ring was in no danger of loosening on the inner ring, especially as both rings, being of bronze, and in good contact, should heat each other at about the same rate. This assumption, however, was wrong. The machine was put on short-circuit load of about 8000 amperes early one evening and an experienced engineer was left in charge of it until about midnight. Up to that time the machine was working perfectly, with no undue heating in the rings and no brush trouble, although vaseline lubrication was used. About midnight the engineer left the machine in charge of a night operator, and at about three o'clock in the morning this operator saw the brushes beginning to spark and this very rapidly grew worse, so that in a very few minutes he found it necessary to shut the machine down. An examination then showed that several of the outer rings had shifted sideways on the base ring, as indicated in Fig. 10. One of these rings had even moved into contact with a neighboring ring so as to make a dead short circuit on the machine. It was also noted that all the rings which loosened were on one side of the machine, and that the surfaces of the rings exposed to the brushes were very badly blistered. The brushes also were in bad shape, indicating that there had been excessive burning for a short time. An investigation of the loose rings showed that they had loosened on their seats on the inner or base rings. Investigation then showed that a temperature rise of 70 to 80 deg. cent., combined with the high centrifugal stresses, would allow the rings to loosen very materially. It was then assumed that as the ring had heated up, bad contact had resulted between the inner and outer rings and this, in turn, had caused additional heating, so that the temperature rose rather suddenly after bad contact once formed. It developed later that this was probably not the true cause of the trouble, but at the time it was considered that the remedy for the trouble was in the use of rings which could be shrunk on with a greater tension.

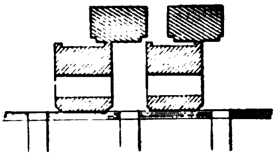

Fig. 10

It was then decided to try steel outer rings instead of bronze on the end where the bronze rings had loosened. However, upon loading the machine, after applying the steel rings, a new difficulty was encountered. It was found that the loss was very greatly increased over that with the bronze rings. This loss was so excessive as to be prohibitive, as far as efficiency was concerned, and also the tests showed excessive heating of the rings and of the machine as a whole. Also, there were continual small sparks from the tips of the brushes, these sparks being from the iron itself, as indicated by their color and appearance. However, during the time these rings were operated there did not seem to be any undue wear of either the brushes or the rings, but obviously there was continued burning, as indicated by the sparks. With these steel rings it was found to be impossible to operate continuously at a current of 8000 amperes, due to the heating of the steel rings in particular and everything in general. At a load of 6000 amperes the loss was materially reduced and it was possible to operate continuously, but with very high temperatures. The tests showed that with the steel rings, at full rated current, the loss was approximately 200 kw. greater than with the bronze rings, or about 10 per cent of the output. With both ends equipped with steel rings, this would have been practically doubled.

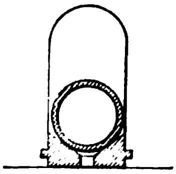

FIG. 11

While this was recognized as an entirely unsatisfactory operating condition, yet it allowed the machine to be run for a long enough period to determine a number of other defects which did not develop in the former test. One of these defects was an undue heating of the rotor pole face. This was obviously not due directly to bunching of the flux in the air gap on account of the open stator slots, for this heating did not appear when running with normal voltage without load. Further investigation showed that this was apparently due to some flux distorting effect of the stationary conductors in the stator slots, which carried about 4000 amperes each at rated load. On account of ample margin in the magnetizing coils the air gap was then materially increased, with some benefit. A further improvement resulted in the use of magnetic wedges, made of cast iron, in place of the non-magnetic wedges used before. These wedges are illustrated in Fig. 11. This produced a further beneficial effect, but there was still some extra heating in the pole face. Cylindrical grooves alternating $\frac{1}{2}$ in. and 1 in. deep and about ⅛ in. wide, with a ¼-in. web of steel between, were then turned in the pole face. The resultant pole face was therefore crudely laminated, as shown in Fig. 12. Also, on account of an apparent local heating of the metal bridge over the rotor slots, a narrow groove was cut in the closed bridge above each rotor slot, thus changing it to a partially open slot, as shown in the figure. This effectively eliminated the excess loss in the rotor pole face. This, however, led to another unexpected difficulty, which will be described later.

After this trouble was cured, the short-circuit test was continued with a current of about 6000 amperes. After a considerable period of operation, a very serious difficulty in the operation of the machine began to show up, namely, trouble with lubrication. At first the lubrication was vaseline fed on to the rings by lubricating pads. This was apparently very effective for awhile, but eventually it was noted that slight sparking began, which, in some cases, would increase very rapidly, and in a comparatively short time became so bad that the rings or brushes would become badly scored or blistered. Examination of the sparking brushes showed a coating of black "smudge" over the surface which seemed to have more or less insulating qualities. A series of tests then showed that whenever sparking began, the contact drop between a brush and the collector ring was fairly high and this drop increased as the sparking increased. For instance, it was found that on good, clean surfaces, the voltage drop between the brushes and the ring might be 0.3 to 0.5 volt. As each brush carried about 250 amperes at full load, this represented 75 to 125 watts per brush. When this contact resistance rose to about one volt, noticeable sparking would begin, the watts being, of course, proportionally higher, and when the contact drop became as high as two volts, representing about 500 watts per brush, very bad burning of the brushes and rings was liable to occur. A series of tests then showed that vaseline, or any other lubricating oil, would tend to form a coating over the brush contact and this coating would gradually burn, or be acted upon otherwise by the current, so that its resistance increased and the black smudge was formed which had more or less insulating qualities.

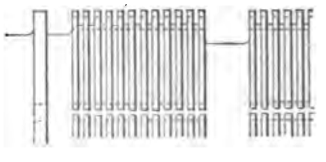

FIG. 12

A great number of tests was then carried out with various kinds of lubricants and it was found that anything of an oil or grease nature was troublesome sooner or later, as the smudge was formed on the brush contact. Then graphite, formed into cakes or brushes by means of high pressure, was tried on the rings and the results were very favorable compared with anything used before. In fact, the tests indicated that soft graphite blocks or brushes could furnish proper lubrication for the rings. The graphite is a conducting material, and a coating of it on the brush contact does not materially increase the resistance of the contact. This was supposed to have practically settled the question of lubrication and brush contact trouble, but experience later gave an entirely new turn to this matter.

While these tests were being carried on, a study of the ventilation of the machine was being made. The tests indicated that the end rings, that is, those next to the exciting coils, were considerably cooler than those near the center of the machine. However, as there were excessive losses and heating in the steel rings themselves, it was not possible to make any material improvement until the rings were changed.

The steel rings at one end of the rotor, and the bronze rings at the other end, were then removed and a second set of bronze rings was tried. These rings were specially treated in the manufacture so that the elastic limit was very high, and they were put on much tighter than in the former case. The load tests were then continued and the excess losses were again measured at various loads. It was found that the losses were very small compared with those of the steel rings, thus verifying the former results. The temperatures of the rings were much lower than with the steel, but it was found that the heating of the rings was unequal. It was finally determined that this unequal heating was due to the large external blowers which were driving the air over the rings in such a way as to heat those next to the center of the rotor to a much higher temperature than those at the outer ends. It was assumed at first that the air entering the axial holes through the core and blowing out between the rings as shown in Fig. 1, was more effective on the outer rings, and that this possibly caused the difference in temperatures. However, the radial holes at the outer ends were closed, and this made but little difference. The axial holes were then closed, and while the temperatures of the rings, as a whole, were increased, about the same difference as before was found between the end rings and the center ones.

It was then decided to remove the two large blowers to determine whether some other method of ventilation would be more effective. When this change was made, the windage of the machine was greatly reduced and there was greater uniformity in the temperatures, and the average temperature of the rings was only about 10 deg. higher than with the fans. Moreover, the windage loss was only about one-seventh as great as before, although the average temperature rise was not much higher, which indicated that the ventilation through the rotor holes was much more effective than that due to the blowers. In consequence, it was decided to increase the size of the axial holes through the rotor core from 2¾ in. to 3¾ in. diameter, and to " bell-mouth " them at their openings at the ends, in order to give a freer admission of air to the holes. When this was done it was found that the temperatures of the rings were lower than in any of the preceding tests, and moreover, they were fairly uniform. Also, after the removal of the blowers, the objectionable noise, already referred to, was largely eliminated, so that it was not disagreeable to work around the machine. The graphite lubrication was continued with the bronze rings, on this test, and no difficulty was encountered, although the machine was operated for very considerable periods at approximately 8000 amperes.

On the basis of these tests, the machine was shipped to its destination and put in service. Then the real difficulties began—difficulties which were not encountered in the shop tests, principally because the conditions under which the machine operated in service were radically different from those at the shop, and also, because the shop test had not been continued long enough. This machine was operated in service, although not regularly, for a period of about two months, being shut down at times due to difficulties outside of the generating unit itself. However, this period of operation of the generator was suddenly ended by the stretching of one of the outer collector rings, which loosened it to such an extent that it ceased to rotate with the inner ring. This required the return of the rotor to the manufacturer.

This two months' operation gave data of great practical value, and in consequence, a number of minor difficulties were eliminated in the repaired rotor.

Upon the return of the rotor to the shop, an examination of the collector rings showed that the separate shrunk-on type of ring was not practicable with any design of ring then at hand. Therefore, it was decided to make the collector rings in one solid piece with a very considerable wearing depth. This necessitated the removal of all the base rings and, in fact, it required a complete dismantling of the entire rotor winding. As the outer ring had loosened, there was a possibility of the base rings loosening in the same way, and therefore it was considered necessary to apply some scheme for preventing this loosening in case of sudden heating and expansion of any of the collector rings. It was then decided to apply some form of spring support underneath these rings, which could follow up any expansion in such a way as to keep the rings tight under any temperature conditions liable to be met with in practise. The spring support used consisted of a number of flat steel plates arranged around the rotor core, as indicated in Fig. 13. These plates were of such length and stiffness that a very high pressure was required to bend them down to conform with the rotor surface. These plates were arranged around the rotor core and drawn down with clamp rings until they fitted tightly against the mica. The collector ring was highly heated and slipped over the springs, the clamps being removed as the ring was slipped on. Tests were made to find at what temperature such a ring would loosen. While the best arrangement without springs would loosen at about 100 to 125 deg. cent., it was found that a ring supported in the above manner was still fairly tight at 180 deg. cent., which was far above any temperature which the machine would attain under any condition. It may be said here that, after several years' operation, this construction still appears to be first-class, and no loosening of any sort has occurred.

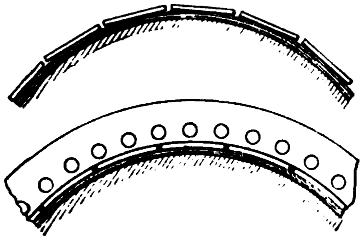

FIG. 13

In removing the winding from the rotor, it was discovered that the insulating tubes over the rotor conductors had traveled back and forth along the rods a certain amount. This travel, if continued for a long enough period, would apparently have injured the insulation, although no trouble had yet developed. Apparently, during heating and cooling, the expansion and contraction of the rods would carry the tubes with them lengthwise a very small amount. The tubes would then seat themselves in the supporting rings or core and would not return to their original positions. It was found that in the slotted pole face already described, the webs or laminations of metal overhanging the rotor slots would hold the tube when the rod was traveling in one direction, but would sometimes allow the tube to move slightly when the rod traveled in the other direction, so that there was a sort of extremely slow ratchet action taking place. It was evidently necessary to have the tubes fit rather tightly in the retaining or supporting holes in the rings and the core, and to have the rods fit rather loosely in the tubes. Also, it appeared that shellac or other " gummy " material on the inner surface of the insulating tubes was harmful, for wherever shellac was present the insulating tube always stuck to the rod and would tear at either side of such place. In consequence, the new set of tubes was made with a dry, hard finish on both the outside and the inside, and the inside surface was also paraffined. This, when carried out properly, served to remedy this trouble.

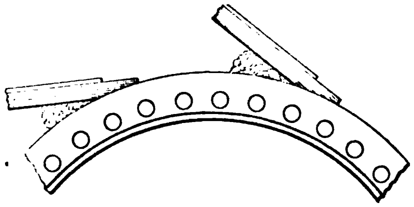

FIG. 14

The reconstructed rotor, with the solid collector rings, was shipped to the customer and the service was continued. After operation for a considerable time, certain extremely serious difficulties appeared. One of these was brush trouble, and another was undue wear of the rings.

The brush trouble was a most discouraging one. The machine was located in an engine room adjacent to a rock-crushing building. Fine dust was always floating around the machine and this dust, continuously passing through the machine, tended to form a deposit immediately behind the brushes, as shown in Fig. 14. This dust packed in rather solidly behind the brush, due to the high speed of the rings, and eventually it tended to lift the brushes away from the rings. It also showed a tendency to get under the brush contact, with consequent increased resistance of contact. Frequent removal and cleaning of the brushes was impracticable, as they were not sufficiently accessible to do this readily. This rock dust, packed behind the brushes, also had a scouring or grinding action on the rings themselves. Accompanying this was an undue rate of wear of the rings. This, however, was not entirely mechanical wear, as it appeared also to be dependent upon the current carried and was, to some extent, due to a burning action under the brush which tended to eat away the surface of the rings. However, while the undue wear was not altogether due to dust back of the brushes, this accumulation of dust appeared to have a very harmful action on the machine. Various methods were considered for overcoming this collection of dust, one of which consisted of enclosed air inlets to the machine, fitted with screens for sifting out the dust. This lessened the trouble to some extent, but it was evident that it would not cure it entirely, as the entire machine was so located that dust could come in around the brush holders without going through the ventilating channels.

The method finally adopted for overcoming the difficulty of accumulation of dirt was rather startling. It was casually suggested that the copper leaf brushes be turned around so that *the rings would run against the brushes*, so that the dirt or dust over the rings would be " skimmed off " by the forward edge of the brushes. This obviously would prevent the collection of dirt, but the question of running thin leaf copper brushes on a collector ring operated at a speed of about 220 feet per second (or 13,200 feet per minute) looked like an absurdity to any one with experience in electrical machinery, so that we all hesitated at first to consider the possibility of it. However, as something had to be done, the writer suggested to the engineer in charge that he change the brushes on one of the rings so that they would be inclined against the direction of rotation. This gave no trouble and the other brushes were then changed to the same direction and the operation ever since has been carried on with this arrangement. To the writer this has always seemed an almost unbelievable condition of operation, but as there has not been a single case of trouble from this arrangement during several years of operation, one is forced to believe that it is all right. This change entirely overcame the trouble from accumulation of dirt. However, it did not entirely cure the burning of the brushes and rings above described, but rendered the matter of lubrication somewhat easier than at first.

As to the other serious trouble, it was mentioned that there was a burning action under the brushes which tended to " eat " or " wear " away the surface of the rings. This also tended to burn away the brush surfaces, the amount of burning in either case depending, to a considerable extent, upon the direction of the current. At one side of the machine the brushes would wear more rapidly, while at the other side the rings would wear faster. The polarity of the current was influential in this action. Particles of the metal appeared to travel in the direction of the current; that is, where the current was from the ring to the brushes, the ring would wear more rapidly, and the brush would show but little wear, while at the other end of the machine, the opposite effect would be found. However, the particles of metal taken from the ring did not deposit, or " build up," on the brushes.

During all this operation, graphite had been used for lubrication. In the earlier stages, powdered graphite, compressed into blocks, had been used. Later it was found that very soft graphite brushes in insulated holders would give ample lubrication for the rings. However, even with this lubrication and the removal of the dirt trouble, there was still an appreciable burning of the brushes and rings as indicated by the more rapid wear of the rings at one end of the rotor, and of the brushes at the other end. Extended tests showed that this burning was a function of the contact drop between the brushes and the rings. Neither the rings nor the brushes would burn appreciably if the contact drop between the brushes and the ring could be kept very low. When this drop became relatively high (about one volt), the rings or brushes would show an undue rate of wear. It was found also that, after a considerable period of operation, it was very difficult to obtain a low brush contact drop, as the brush wearing surface became coated with a sort of " smudge," which seemed to have resisting qualities. An analysis of this coating showed a very considerable amount of zinc in it, and it was determined that the zinc in the collector rings was burning out and forming an insulating coating on the brush contacts. The remedy for this condition was the application of some cleaning agent which would chemically act on the smudge and dissolve it or destroy its insulating qualities. The right material for this purpose was found to be a weak solution of muriatic acid— about 4 per cent in water. When this was applied to the rings by means of a " wiper," at intervals, the brush contact drop could be reduced to a very low figure— frequently to 0.1 or 0.2 of a volt—

and the rings would take on a very bright polish. Also, while this low contact drop was maintained it was found that the rings showed an almost inappreciable rate of wear. However, one set of rings continued to wear somewhat faster than the other. This difficulty of unequal wear of the two sets of rings was overcome by arranging a switch so that the polarity of the two ends of the machine could be changed occasionally.

The temperature of the machine was reduced by the above treatment of the rings. Obviously, part of the heat was due to the loss at the brush contacts, which, of course, was reduced directly as the contact drop was reduced.

The machine was now running quite decently with comparatively heavy loads, from 7000 to 10,000 amperes, and the only trouble was in several minor difficulties which were then taken up, one at a time, in order to ascertain a suitable remedy. These difficulties, however, were not interfering with the regular operation of the machine.

One of the difficulties which finally developed was due to stray magnetic fluxes through the bearings. These fluxes, passing out through the shaft to the shell of the bearing, constituted, in themselves, the elements of a small unipolar machine, of which the bearing metal served as collecting brushes. The e.m.f. generated in the shaft was a maximum across the two ends of the bearing. Consequently the current collected from the shaft by the bearing metal should have been greatest near the ends of the bearing, and least at the center. This was the case as indicated by the appearance of the bearing itself, which showed evidence of pitting near the ends but none at the center.

To remedy this trouble, a small demagnetizing coil was placed outside the stator frame, at each end of the rotor, between the rotor core and the bearings. These coils were excited by direct current which was adjusted in value until practically zero e.m.f. was indicated on the shaft at the two ends of each bearing. This indicated that the unipolar action was practically eliminated. This arrangement has been in use ever since it was installed, and no more trouble of any sort has been encountered from local currents in the bearings or elsewhere.

Some of the brushes did not show as good wearing qualities as desired and various experiments were made with different combinations of materials and various thicknesses and arrangement of the brush laminæ. Brass leaf brushes were tried; also, mixtures of copper, brass, aluminum and various other leaf metals in combination. None of these gave any better results than the thin copper leaf brush. The tests finally showed that such a brush, very soft and flexible, with a suitable spring tension, would give very satisfactory results. Also, instead of two brushes side by side, a single brush, covering the full width of a ring, was found to be more satisfactory. Some tests were also made with carbon brushes, consisting of a combination of carbon or graphite combined with some metal, such as copper, in a finely divided state. These brushes were claimed to have a very high carrying capacity and also to have a certain amount of self-lubrication. A set of these brushes was tried on one of the rings, but lasted only for a very short time. The apparent wear was rapid, but it is not known whether this was due to the very high speed of the collector rings, or rapid burning away of the brush or the inability of this type of brush to follow quickly any inequalities of the collector rings. This test was abandoned in a comparatively short time.

After getting rid of the old troubles, a new and unexpected one had to appear. For some unknown reason, the insulating tubes on the rotor conductors began to break down; also grounds occurred between the collector rings and the core.

On account of the delay required in making any changes in the rings or rotor winding, the customer arranged with the manufacturer to have a new rotor built as a reserve, as it was obvious that sooner or later there would have to be considerable reconstruction of the insulation on the first rotor due to unexplained short circuits and grounds. A new rotor was at once constructed, embodying all the good features of the first rotor, with some supposedly minor improvements. The old rotor was then removed for investigation and repairs. The cause of the breakdowns of the insulation on the tubes was then discovered. The air entering through the axial rotor holes and passing out through the radial holes between the rings, carried fine particles of cement or crushed stone dust and this had "sand-blasted" the under side of the tubes. When the rotor had been operated during the preliminary two months' period, previously described, before the replacement of the rings, no evidence of this sand-blasting had been visible. Investigation showed that the insulating tubes in the former winding had been made with a fullerboard base, which is rather soft and fibrous in its construction. The tubes on the second winding had been made with "fish paper" instead of fullerboard, in order to give a hard finish on the inside and outside. It was due to this hard material that the troubles from sand blasting occurred. However, fish paper tubes were superior to the fullerboard in strength and other qualities, and as they were inferior only in this one characteristic, they were used again in rewinding the rotor, but whereever the tubes were exposed in passing from one ring to the next, they were taped over with several layers of soft tape which was also sewed. This gave a soft finish which would resist sandblasting, and no trouble from this source has occurred for several years.

From the breakdowns to ground, it was evident that an entire replacement of the rings was necessary in order to repair the mica bush or sleeve lying beneath the rings. This required the removal of the entire rotor winding and rings. It was found that cement dust coming up through the radial holes had sifted in through various crevices or openings around the holes and that, finally, conducting surfaces and paths were formed which allowed the current to leak to ground sufficient to burn the insulation eventually. Therefore, when replacing the mica sleeve over the rotor, extra care was taken to fit insulating bushings at the tops of the radial holes in such a way as to seal or close all joints, thus allowing no leakage paths between collector rings and the body of the core. This is shown in Fig. 15. No further trouble has occurred at this point.

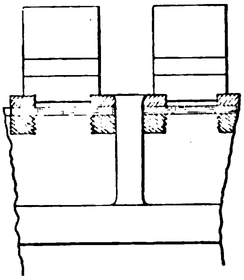

Fig. 15

In removing the collector rings for these repairs, it was found that the flat spring supports shown in Fig. 13 had been entirely effective and there was no evidence whatever of any disturbance of the rings on the core, and there was no injury to the mica, such as would be shown by any slight movement. The rings were also very tight so that it took a very considerable temperature to loosen them sufficiently for removal.

In view of the delay and expense of repairing one of these rotors when the collector rings had to be removed, with the possibility of damaging the insulating tubes over the conductors, and the insulating bush over the core, it was then decided that a movable wearing ring was practically necessary in order to make this machine a permanent success. Therefore, the problem of a separate outside wearing ring, as originally contemplated, was again taken up. The difficulty, already described, of the zinc burning from the rings and forming a coating on the brushes, indicated that some other material, without such a large percentage of zinc, should give better results. The difficulty was to obtain such a material, with suitable characteristics otherwise. All data at hand showed that rings with desirable characteristics electrically, did not have the proper elastic limits, or proper expansion properties when heated. In other words, when such rings were shrunk on the base or supporting ring they would stretch to such an extent, when cooled, that they would become loose again with very moderate increase in temperature. The solution of this problem of a separate ring construction was found in the use of some spring arrangement underneath the outer ring which would still keep it tight on the inner ring even when hot. The spring arrangement used under the inner rings, as shown in Fig. 13, was then applied with certain modifications. In order to get good contact between the inner and outer rings for carrying the current, each of these steel springs or plates was covered by a thin sheet of copper as shown in Fig. 16. While each copper sheet was of comparatively small section, the large number of springs used gave sufficient total copper to carry the current from the outer to the inner or base ring without any danger of current passing through the spring plates themselves. This arrangement was used in reconstructing this rotor and has proved entirely successful.

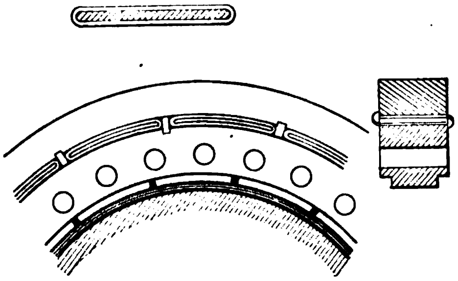

Fig. 16

In order to determine the effects of various materials without zinc, or with but a small quantity of it, several rings were fitted up on a test rig and were operated for long periods with currents up to 12,000 amperes in some cases. In these tests, four different kinds of material were used, all of them representing different mixtures of copper with a small percentage of other materials, but with little zinc in any of them. It was feared that copper brushes on the copper rings would not work satisfactorily, but while there was apparently some difference between the action of the different rings, it was found that copper brushes running on copper were, in general, satisfactory. The brushes were inclined against the rings, as in the actual machine, during this series of tests.

These tests were carried through with various numbers of brushes, etc. It was found that the number of brushes could be reduced to about one-third the full number, and still collect the total rated current, but that any great reduction from the full number of brushes made the operation of the rings and brushes more sensitive, and more attention was required to keep them in perfect condition. It was also found that any hardness or undue "springiness" in the brushes, or brush material, would tend to give increased wear. Brushes of very thin leaf copper eventually gave best results. It was also shown by these tests that if a very good polish could be maintained on the rings, the rate of wear from day to day was practically unmeasurable on account of its smallness.

As a result of these ring tests, the rotor undergoing repair was equipped with outside copper wearing rings, spring-supported. The material in the rings was about 92 per cent pure copper, 2 per cent zinc and 6 per cent tin.

The rotor was then installed in service and has been operating steadily for several years, with entire success. The other rotor, which had been operating while this rotor was being repaired, was then thoroughly examined after removal, to determine any possible defects. It was noted that the insulating tubes over the rotor conductors were badly cracked or buckled in a number of places. Upon removal of the rods or conductors it was found that the insulating tubes were stuck so tightly to the copper rods that they would be torn in pieces in trying to remove them. As it had been intended that these tubes should move freely on the rods or conductors, as previously described, it was evident that there was something radically wrong. The true cause of the trouble was then discovered. In first fitting this set of tubes over the rods, they had been too tight, and, in order to make them fit easily, the men who assembled the machine had reamed them on the inside to enlarge them, and, in doing so, had cut away the inner hard sheet of fish paper which had formed the lining, thus exposing a shellaced surface. As soon as heated, this shellac stuck the tube to the rod so that there could be no possible movement between the two. In consequence, when the rods expanded or contracted, the tubes moved backward and forward in the supporting holes, and wherever they stuck fast in the outer holes, something had to give, so that eventually the tubes buckled or cracked or pulled open. This was readily remedied by putting on new tubes properly constructed. As the rings on this rotor were in very good condition with but little worn away, the removable type of ring was not added, as this would require turning off a large amount of effective material on the existing rings and replacing it with new outer rings. It was decided that as there was several years' wear in the old rings, it would be of no material advantage to throw this away when it could be worn away in service, just as well as it could be turned off in a lathe. After the rings in this machine are worn down the permissible depth, they will be refilled by the addition of the removable type.

This unipolar generator has now been in service for quite a long period, with no difficulty whatever, and with an average ring wear of less than 0.001 in. per day, or less than ⅜ in. per year. This may seem like an undue rate of wear; but in reality it is an extremely low rate, if the high peripheral speed, and the number of brushes, are considered. This machine operates day and night, seven days in the week, and practically continuously during the entire year. Taking the peripheral speed into account, the above rate of wear represents a total travel of each ring of about 3.6 million miles for each inch depth of wear, or about 150 times around the earth along a great circle. Considering that there are brushes bearing on each ring at intervals of about eight in., a wear of one in., for every 3.6 million miles traveled, does not seem unduly large. If, at the same time, it is considered that the brushes are collecting from 7500 to 10,000 amperes from each ring on a total ring surface of about 3½ in. wide by 42 in. diameter, it is not surprising that there should be more or less " wear " due to the collection of this current. In fact, the current collected averages from 16 to 20 amperes per square inch of the total ring wearing surface. This may be compared with standard practice with large d-c. commutators, in which 1½ to 2 amperes per square inch of commutator face is usual and 3 amperes is extreme.

On account of the final success of this machine, the story of its development is a more pleasant one to tell than is the case in some instances where entirely new types of apparatus are undertaken. It might be said, after reviewing the foregoing description, that many of the troubles encountered with this machine could have been foreseen; but such a statement would be open to question, for the engineers of the manufacturing company were in frequent session on all the various phases and difficulties which developed. The writer knows that in many cases, after any individual trouble was known, suggestions for remedies were not readily forthcoming. The writer does not know of any individual machine where more engineering and manufacturing skill was expended in endeavoring to bring about success, than was the case with this machine. As an example of engineering pertinacity, this machine is possibly without a rival. A mere telling of the story cannot give more than a slight idea of the actual fight to overcome the various difficulties encountered in the development of this machine.

The results obtained were valuable in many ways. Many data were obtained which have since been of great use, both from a theoretical as well as a practical standpoint, in other classes of apparatus. Certain fundamental conditions encountered in this machine have led to the study of other allied principles which point toward possibilities in other lines of endeavor. Therefore this machine, which was very costly in its development, may eventually pay for itself through improvements and developments in other lines of design.

The writer wishes to say a good word for the purchaser of this new apparatus. He was long-suffering, and was undoubtedly put to more or less trouble and inconvenience, but nevertheless he gave opportunity to correct difficulties. He recognized that the engineers were confronted with a new problem in this machine and he gave them an opportunity to carry it through to success. Apparatus of this type could only be developed to full success in commerical operation, as all the difficulties encountered would never have been found on shop test. Therefore, the attitude of the customer was of prime importance in the development of such a machine.

DISCUSSION ON "DEVELOPMENT OF A SUCCESSFUL DIRECT-CURRENT 2000-KW. UNIPOLAR GENERATOR" (LAMME), BOSTON, MASS., JUNE 28, 1912.

J. E. Noeggerath: It is a great pleasure indeed to congratulate Mr. Lamme upon his frank and exceedingly important paper on acyclic machines, and to comment on it, as, naturally, having been in a position to overcome similar difficulties in the development of the unipolar machines I am connected with, I appreciate the extraordinary problems that have to be met.

A few of the troubles mentioned by the author did not materialize, as those connected with the slots for the conductors, since the machines were built differently from the start; also the rings never came loose, but, as fair exchange, experiences were bought dearly in other ways. Of the problems in common some were solved in the same manner, some entirely differently, by which statement I do not lay claim to a better solution.

Mr. Lamme's design of the collector rings is ingenious. He states that one of the reasons for building them up out of two concentric rings was to facilitate their exchange. A different way of solving this difficulty is not to mount the collector rings on the armature directly, but rather *on a separate shell* which, magnetically, forms part of the armature. (Fig. 1.) This eliminates the necessity of handling the heavy bulk of the armature, reducing the weights that have to be taken care of in shipping and dismounting, to considerably less than 10 per cent.

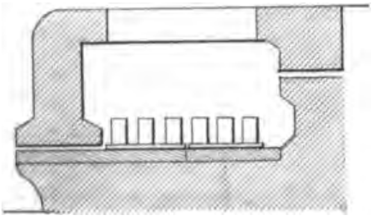

FIG. 1

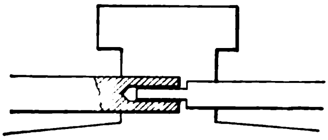

FIG. 2

The collectors are so designed that one-half of the rings can be taken off from one end and the other half from the other end. In case of a large number of rings two or more collector shells are used for each set.

Due to the length of the conductors, it is necessary to provide in some way against the stresses produced by heat expansion. For the purpose of eliminating them, Mr. Lamme inserted a *flexible* element.

The corresponding solution which avoids the necessity of taking away space from the magnetic section, consists in *dividing the conductor lengthwise*, the end of one-half protruding into the end of the other half (Fig. 2), or in providing a sliding connection, the conductor fitting loosely into a hole in the ring. Since the peripheral speeds are very high, this connection forms a perfect contact which has proved successful in years of operation.

Bearing troubles were solved in identically the same way by Mr. Lamme and myself, both of us using coils in the bearings to counteract the stray fields.

Part of the collector ring troubles, too, was taken care of in the same way, as in both cases soft insulated graphite brushes of a specific kind are used; if I am not mistaken, even the same make is used.

Mr. Lamme's investigation relating to the other brush troubles and supplementing my investigations of the theory of the electric contact are ingenious and I gladly acknowledge that where I have taken the first step, Mr. Lamme at the present stage has obtained superior results as to the voltage drop in the contacts. He succeeds in permanently keeping it down to an average of 0.4 volt; he even mentions 0.1 volt; these are excellent results.

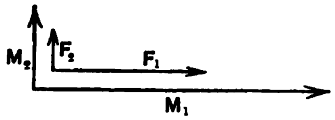

Fig. 3.

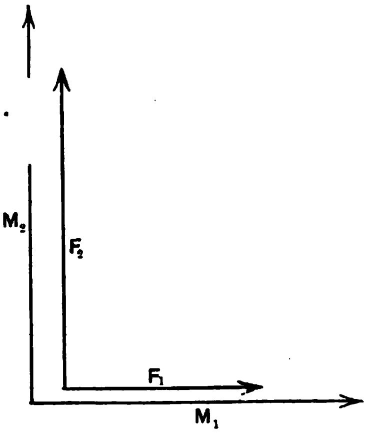

Fig. 4.

I am glad to have Mr. Lamme a commiserator as to the mileage that has to be traveled over by the brushes. If such requirements had been fulfilled by single-phase commutator motors, the maintenance expense would have become reasonable long ago.

As to running the generator, *i.e.*, the rings against the brushes, it has been my experience for a long time that this is feasible; an additional advantage not mentioned but probably known to Mr. Lamme, is that in running against the brushes, a compounding action takes place.

If any criticism can be made outside of those mentioned by the author of the paper himself, it would refer to the great bulk of the machine; this can probably be explained to a considerable extent by the comparatively low speeds employed.

As Mr. Lamme has brought up again the question of the magnetic fields of unipolar machines, I put now before the Institute the results of an investigation which originally I intended to elaborate into a paper.

I have found that, in contradistinction to the accepted ideas—this ought to be of fundamental importance with regard to the theory of the magnetic field—***magnetic fields set at right angles to each other do not affect each other in the least*** (Fig. 3 and 4).

In other words, if a field is set up in a magnetic material which is permeated by a second field at right angles to it, the relation of the first field to its electromagnetic force is not in the slightest degree affected by the second field, although the second field may be so strong as to have completely saturated the iron at right angles to the first field.

If for instance in Fig. 3, *M*-1 and *F*-1 represent respectively a strong magnetomotive force and a strong magnetic field, it is natural that it will be little or not at all affected by a small second magnetomotive force and magnetic field, etc., *M*-2 and *F*-2, set at right angles to 1.

However, it should be expected, according to the usual conception, that if *F*-2 and *M*-2 reach saturation (Fig. 4), then with the same *M*-1, *F*-1 should be considerably reduced, because one should assume that if the iron is saturated in one direction of the field *F*-2 there will be no possibility for any magnetic flux to pass through it, even though directed at right angles.

However, *F*-1 is not at all affected by *F*-2. This is not in contradiction to the phenomena observed with fields which are said to be and are in some respects at right angles to each other in alternating-current machinery, in commutating direct-current machinery and even in many types of unipolar machines. (However, unipolar machines can be so designed that the fields are in such relation to each other so as to be actually at right angles. This is of course not usually the case when conductors are placed in slots or holes as in Mr. Lamme's machine). This is, as I stated, not a contradiction, as a close scrutiny will show that the fluxes in the cases usually considered are affected in their mutual relationship not because they are at right angles but for any of a number of other reasons.

These conditions seem to find a parallel in the modern theory of light.

In concluding, I take pleasure in stating that I have observed the successful operation of Mr. Lamme's 2000-kw. machine. It ran very well indeed; there was no sparking; it ran cool, noiselessly and without vibration.

It is almost needless to say that I hope the paper will give a new impetus to this development, which though apparently stagnant in the United States, I had the pleasure of reviving in Europe.

Elihu Thomson: I listened to Mr. Lamme's account of his experiences with the unipolar machine with much interest. It is an example of how bold an engineer must be at times even to undertake the problems of which so little is known. He enters the field and tries to do the work and then finds so many difficulties that it is a wonder he ever gets through or does not lose his enthusiasm before he has gone as far as Mr. Lamme has gone. I congratulate him on the final result in having a machine that will do the work. Now, in regard to unipolar construction, it will be recalled that in 1884 in the old electrical exhibition in Philadelphia George Forbes showed two or three examples of unipolar dynamos. They had great blocks of carbon for brushes, but it is about the worst material to be used in the case of a unipolar machine where the contact resistance is high. The loss involved would be very great. About 1885 or '86 we were studying the problem of the possibility of large power stations for continuous work, from the point of unipolar design, thinking possibly we might construct a number of machines in series for a very large output such as 25,000, or 30,000 kilowatts, large in those days. I was led to look into the unipolar design. I built two machines of moderate size to test out the conditions; the armature conductor was single without series connection. This single conductor was used much as in Fig. 2 of Mr. Lamme's paper, only the compounding which I obtained in that machine was by making the current-collecting ring connect with the inner conductor by a spiral band going around two or three times, as if a huge ribbon had been wound around, which carried the current to the outside ring. That is simply doing the same thing as carrying the leads from the brushes around in order to get compounding. The machine, however, developed difficulties and it was evident that we did not have enough knowledge in those days for proper construction. The iron losses were evidently, however, quite low. I would say that the rotor itself was composed of a plain cylindrical bar which was evenly plated with copper on the outside so as to confine the conduction to the outside, and in the air gap. I was led to suspect in those days that possibly there was a lessened loss to be expected in iron, where we did not have a reversal of flux, and in building some inductor dynamos later we found the iron losses so low that they were hardly measurable because the flux merely changed direction from one point to another, so that the amount of iron subject to magnetic changes was very small. That, I think, would apply in the case of unipolar machines and account for the low iron losses.

I was interested to note the remarks that Mr. Lamme makes as to the brushes. This problem in a way reminds me very strongly of the early days of railway motors. We had a hard fight to get railway motors to work in the street, where they were exposed to the dust and dirt of the street, and the commutators likewise. We attempted to run them open, without any boxes or casing, and encountered many difficulties. I was on the point of telling our company to hold up on railway motor business because the commutator repair bills would swamp them. We then introduced the carbon brush. The box type of motor kept the dust off, and our hard work was over. For a time it was a very serious outlook. I recall that in 1889 Mr. C. E. L. Brown, known to us all as one of the most competent engineers, whose work has stood as the very highest, was engaged at that time in unipolar design, and the Oerlikon works had a contract to build a machine for 10 volts for electrolytic work. It was of large output, something like 12,000 or 15,000 amperes. I saw the parts of the machine in the shop. The rotor was a large copper pulley with rims turned up at each side for the traverse of the brushes. I said to Mr. Brown, " That is all right; but how about collection of current from that ring? The wear will be terrific on those surfaces and your ring will soon have the flanges worn off." He said " Do you really think so?" I said " I know so. I don't believe it is possible for you to run at those high speeds without wearing them off." In about a year's time a letter came from Mr. Brown saying he had found exactly what I told him about the brush wear was true, and he said " Now I am going to try carbon." I wrote back that I thought he would be in worse trouble with carbon than with leaf brushes, because the leaf brush will accommodate itself to the surface, while the block of carbon will dance and jump, and cannot possibly follow the vibration of the machine unless the pressure be so high as to cause a mechanical friction that will be absolutely prohibitive. Later on I heard from Brown that these things were true. I have been interested very much to see the chemical methods of keeping contacts clean as applied in the way that Mr. Lamme says has been done. When I was analytical chemist, to keep our metal surfaces clean we washed them with a little hydrochloric acid. If applied to cases of the kind in such a way that the acid would not do any damage around, it would often solve difficulties.

W. L. Waters (by letter): Mr. Lamme, at the end of his paper, states—" As an example of engineering pertinacity, this machine is possibly without a rival." I would change the word " possibly " to " probably." The writer had the pleasure of assisting Mr. Lamme in some of the work described, and I think that engineers that have been through similar difficulties will realize that his bare narrative covers a long period of strenuous work—work that would never have been brought to a successful conclusion, but for the extraordinary resourcefulness and perseverance of the man who was directing it. As stated in the paper—" It might be said......................that many of the troubles encountered with this machine could have been foreseen," but when it is considered that this is merely one of a thousand machines that were being handled in the routine work by the engineers responsible for this unipolar machine, it is easily seen that the only way to decide the numerous points which arose was by the direct experiments described in the paper.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

EXCITATION OF ALTERNATING-CURRENT GENERATORS

BY D. B. RUSHMORE

The Problem of Excitation

In order to induce an electromotive force in electrical machinery some sort of excitation must always be provided. In direct-current machines an e.m.f. is induced in the armature conductors by their motion across a stationary magnetic field. This is sometimes also the case with alternators, although it is more usual that the field is revolving, so that the magnetic flux travels past the armature conductors, which are stationary.

In the inductor alternator both the field and armature windings are stationary and only the pole pieces revolve. Due to the varying reluctance of the magnetic circuit, caused by the revolving poles, the flux linked with the armature coils will vary periodically, and induce an alternating e.m.f. in the armature winding. In the polyphase induction motor the stator and rotor currents produce a resultant magnetomotive force resulting in a rotating field which induces e.m.fs. in both the primary and secondary windings. In a transformer, the applied primary current magnetizes the core and produces an alternating magnetic flux which links with both the primary and secondary windings, causing e.m.fs. to be induced therein.

The above cases can in general be divided in two groups: first, those of the transformer action, where the field and the windings, in which the e.m.f. is to be induced, are both stationary relative to one another and where the voltage is induced by the alternating magnetic flux; second, those of the generator action, where the field and the windings, in which the e.m.f. is to be induced, move relatively to one another, so that the armature conductors cut the lines of force of the magnetic field.

In this paper it is only the intent to cover that part of the second group which refers to the excitation of alternating-current synchronous generators.

ALTERNATING-CURRENT GENERATORS

Induced E. M. F. An alternating-current synchronous generator is absolutely dependent on a direct-current excitation for its operation, the e.m.f. induced in the armature circuit being determined by the formula

$$E = 4.44\, k_s\, k_w\, f\, n\, \phi\, 10^{-8}$$

in which

k_s = slot factor.

k_w = winding pitch factor.

f = frequency in cycles per second.

n = armature turns in series per phase.

ϕ = magnetic lines of force.

VALUES OF SLOT FACTOR k_s

Slots per pole per phase	Single-* phase	Two-phase	Three-phase
1	1.000	1.000	1.000
2	0.707	0.924	0.966
3	0.667	0.911	0.960
4	0.653	0.907	0.958
5	0.647	0.904	0.957
6	0.643	0.903	0.956

The values of the winding pitch factor, k_w, are given in Fig. 1.

Characteristics. The field ampere-turns required to produce the magnetic flux which is necessary in order to induce a desired e.m.f. depends on the character of the magnetic circuit, *i.e.*, on its dimensions and on the material of which it is made up. The values are readily obtained by referring to standard saturation curves, similar to the ones shown in Fig. 2, these curves, of course, depending upon the qualities of the iron or steel which is used. The curves are plotted as ampere-turns per inch against kilo-lines per sq. inch, although occasionally ampere-turns per centimeter are plotted against kilo-lines per square centimeter. The total magnetomotive force per magnetic circuit is equal to the sum of the m.m.fs. necessary for establishing the required

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*If part of the slots are left open, the breadth of the winding is reduced and the value of k_s is increased to approximately that given for a two-phase winding.

flux in the separate parts of the circuit which are in series, viz., the pole pieces, the field spider, the air gaps, the teeth and the armature core.

The relation of the e.m.f. produced by an alternator at no-load, *i.e.*, at open circuit, to the field current when the alternator is driven at constant speed is represented by the no-load saturation curve. Such a characteristic curve is shown in curve A, Fig. 3, and it is seen that this curve is almost a straight line for small exciting currents. At low excitation, the reluctance of the air gap is very high and that of the iron very low, and therefore the former may be considered as constituting the entire reluctance of the magnetic circuit. Since the reluctance of air is constant,

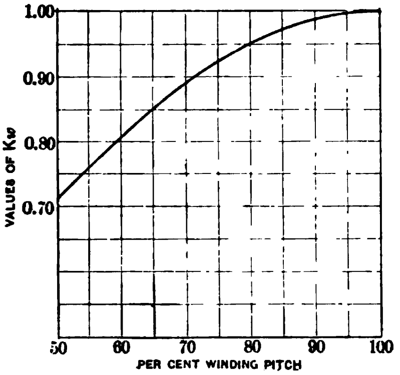


FIG. 1—VALUES OF WINDING-PITCH FACTOR, k_s.

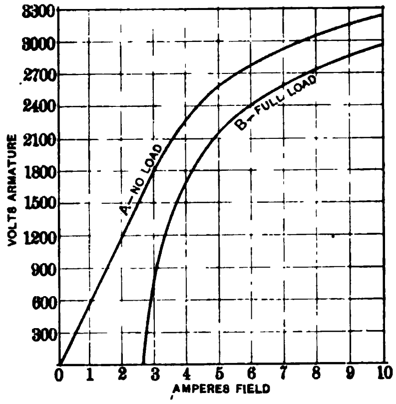


FIG. 3—ALTERNATOR CHARACTERISTICS.

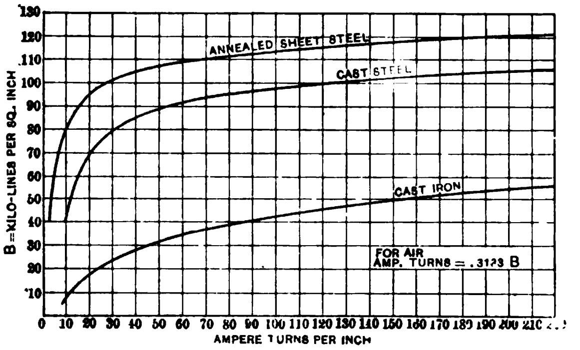


FIG. 2—SATURATION CURVES.

regardless of the flux density, at small excitations the flux will be proportional to the magnetomotive force, and therefore the open-circuit voltage is proportional to the field current, hence the curve is straight. As the field becomes stronger, however, the proportion of the air-gap reluctance to the entire reluctance decreases because the permeability of iron decreases with increased flux density, and therefore the e.m.f. increases less rapidly with increased excitation.

When a current is flowing in the armature circuit, *i. e.*, under load, the field ampere-turns required to maintain normal terminal voltage exceed the no-load ampere-turns required for normal voltage. This is due to the following:

1. The resistance drop in voltage caused by the armature current.
2. The demagnetizing effect of the armature current.
3. The increased leakage flux caused by a greater full-load field excitation.

A number of methods have been proposed for calculating the above components, and thus determining the total field excitation. A detailed explanation of these methods is, however, beyond the scope of this paper. Knowing the resistance and the leakage reactance of the armature, the voltage drop in the armature is added geometrically to the terminal voltage, and this gives the induced voltage in the machine. Knowing from the no-load saturation curve the required net excitation at this voltage, and correcting it for the effect of the armature reaction, the necessary field ampere-turns are obtained. The result of such calculations for different values of the armature current and for various power factors are represented by the load-characteristic curves. The full-load saturation curve of an alternator is shown by curve B in Fig. 3.

Effect of Power Factor. When the armature current leads the induced e.m.f. in the armature conductors, the armature m.m.f. assists the field m.m.f. and so strengthens the field. When the armature current lags behind the induced e.m.f., the armature m.m.f. opposes the field m.m.f. and so weakens the field.

When the current and the induced e.m.f. are in phase, the two m.m.fs. neither assist or oppose each other, and the influence of the armature reaction is only to distort the main field without changing its value. The current in the armature, however, always lags behind the induced e.m.f. by reason of the inductance, and even with unity power factor in the external circuit the armature reaction is demagnetizing to a certain extent.

The induced armature e.m.f. is proportional to the flux per pole, and thus, with leading current in the armature the induced e.m.f. is greater than the open-circuit voltage, and with lagging current less than the open-circuit voltage. In the latter case, when load is put on the machine the field excitation must, therefore, be increased in order to overcome the armature reaction by an amount sufficient to neutralize the armature-demagnetizing magnetomotive force.

Range of Excitation. In order to get the best combination for automatic voltage regulation an alternator should preferably have a range in excitation from no-load to maximum load, with approximately 80 per cent power factor, of the ratio of not more than one to two. With 125 volts excitation, the voltage should therefore not be allowed to exceed 125 volts at maximum load, 80 per cent power factor, and the corresponding no-load excitation should be about 70 volts. Should the excitation voltage be 250, the same ratio should hold true.

Excitation required varies considerably for different machines, depending upon the size, the number of poles, the speed and the regulation. For alternators of different capacities, but otherwise similar, the relative excitation naturally decreases as the size of the alternator increases. High-speed machines generally require a less excitation than low-speed, due to the less number of poles. With a large number of poles, however, the air gap is usually smaller, and this will somewhat offset the higher excitation for low-speed machines.

In general, it may be said that small machines of many poles require a large excitation, and large machines with few poles a comparatively small excitation. The percentage of the excitation of alternators as compared to their output may approximately be taken as from 2 per cent or more for the former class to 0.5 per cent for the latter. In Fig. 4 are given some curves showing approximately the average values of excitation required for different types of alternators.

EXCITERS

Exciter Characteristics. When exciters are to be operated in connection with automatic regulators it is most important that they be designed with this point in view. The densities, especially in the fields, should be fairly low, as with a high density the time element required to vary the voltage from one point to another would be so long as materially to affect the regulation.

The exciter should preferably have a time element so that it will be responsive to changes in the field excitation to the extent that, by inserting an external resistance equal to about three times the resistance of the field, the voltage will fall from 125 to 25 volts in from four to six seconds. An ideal exciter designed along these lines should also give at full field 165 volts, and the increase in the field current from 125 volts to 150 volts should not be over 50 per cent.

For alternators operating at maximum inductive overload, 125 volts is generally required for the excitation, and in order to get satisfactory regulation when a T A regulator is used, the exciter must be designed so as to be able to give 165 volts momentarily. It is also necessary that the increase in the exciter field current should be small, so that the exciter will respond quickly to the short-circuiting of the rheostat, and thus insure the desired alternator excitation. Should the excitation voltage be any other value than 125, *e.g.*, 250 volts, the above values would be proportionally changed.

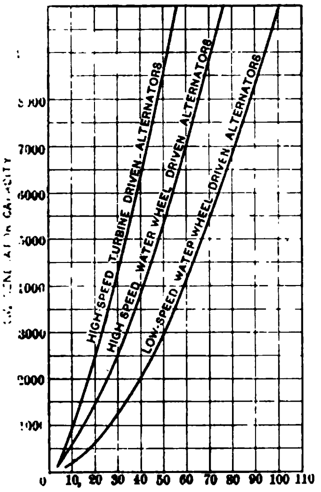


FIG. 4—APPROXIMATE AVERAGE EXCITATION OF ALTERNATORS.

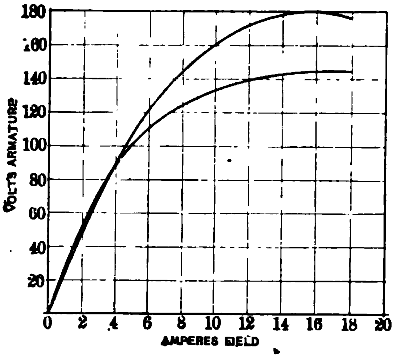


FIG. 5—SATURATION CURVES OF DIRECT-CURRENT EXCITERS.

The curves in Fig. 5 show the saturation curves of two exciters, one representing the characteristics of a machine with a low density, as required, and the other representing the characteristics of a machine with high density and consequently requiring a large increase in the field current. It can readily be seen that the latter exciter is not as desirable for good voltage regulation as the former exciter when an automatic regulator is used.

The series field excitation should not exceed 30 per cent of the total excitation so that a good regulation may be obtained by control of the shunt-field rheostat. In order to obtain the desired variation in the voltage it becomes necessary to provide a rheostat of sufficient size, its resistance being about three times that of the resistance of the exciter shunt field when hot.

Shunt vs. Compound-Wound Exciters. While an exciter can be either of the shunt or compound-wound type, the latter is preferable. The main reason for this is that a better parallel operation is obtained with compound windings, this being especially true where two or more machines of different size are to be operated in parallel. It makes no difference whether an automatic regulator is used or not, although the series winding loses its value in connection with automatic regulators if the exciters are not operated in parallel.

When operating without automatic regulators, compound-wound exciters have the advantage that they will give the same excitation from no load to full load, or they can be slightly over-compounded to take care of the increased load, and will thereby compensate in a measure for the drop or rise in the voltage as the load varies.

Exciters with Commutating Poles. In operating exciters with commutating poles in parallel, there is sometimes a tendency for the incoming machine to take all the load. The reason for this is generally due to the fact that a commutating-pole machine, when flat-compounded at 125 volts, has a rising characteristic when operated at voltages less than normal, as shown in Fig. 6. To overcome this it is therefore desirable to flat-compound all exciters with commutating poles at 80 volts, so as to give a drooping characteristic at higher voltages, as shown in Fig. 7.

Rating. It is the general practise so to determine the capacity of the exciters that their combined normal rating will correspond to the maximum excitation required for the total generating equipment when operating at the specified power factor.

An overload capacity of 25 per cent is therefore generally considered ample to take care of possible excessive load variations and for furnishing current to auxiliary station apparatus and lighting.

The temperature rise at normal load should not exceed 45 deg.

DIFFERENT METHODS OF EXCITATION

The excitation of alternators can in general be classified under the following three divisions: *self-excited*, *compositely excited* and *separately excited*. Of these, however, the last named is almost entirely used.

Self-Exciting Alternators. The simplest form of self-excited alternator is the one where the field current is supplied through a rectifying commutator from the armature under consideration.

Self-excited alternators may be divided into series-wound and shunt-wound, depending upon whether the whole current is rectified and led through a comparatively small number of turns around the field magnets, or whether only a portion of the current is rectified and led through a shunt circuit several times around the field poles. Of these, the shunt-wound type has been mostly used, and either the full pressure of the armature, or that of one or more coils, may be impressed directly upon the rectifying commutator, by means of a transformer attached to the armature.

The Alexanderson self-excited alternator is possibly best known in this country. A novel feature of this machine is the automatic voltage regulation accomplished by a special application of the field rheostat. While in ordinary generators the field current is controlled by hand regulation, this machine employs a three-phase field rheostat in which the voltage drop is automatically cut down to the desired extent by a three-phase current forced through the rheostat in opposite directions to the field currents. The current used for reducing the drop in the rheostat is taken from a transformer connected in series with the armature circuit. In this way the field current is regulated with respect to the power factor as well as to the amount of current taken from the generator.

A diagram showing the general connections of this machine is given in Fig.8. The stationary part is provided with two windings, the main winding, A, and the auxiliary winding, B, which is placed in the same slots as the main winding and consists of a few turns of small wire.

The exciting current is generated in the auxiliary three-phase winding, its terminals being connected to three sets of brushes bearing on a special rectifying commutator. R represents three non-inductive resistances connecting the windings to the neutral point. Three series transformers are connected in the main lines of the alternator, the secondaries of which are connected to the resistance in the *Y*-connection of the auxiliary winding. *F* is the field winding of the alternator, which can be of the ordinary construction. The commutator has one active segment per pole, each alternate segment being connected to one side of the field winding and the remaining segments to the other. By this arrangement it is possible to make the commutation independent of the reactance which is inherent in the ordinary type of field winding, and the whole process of commutation is carried out in the stationary circuits before the current enters the field.

The operation of the machine is as follows: full-load inductive excitation of the machine is obtained from the voltage generated

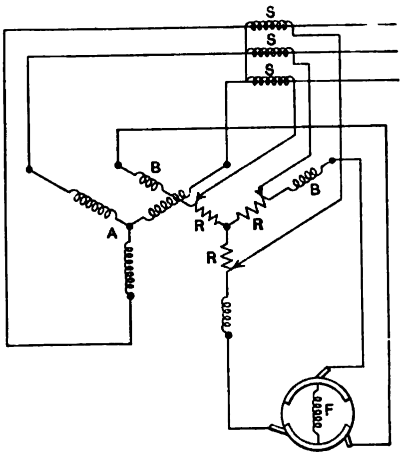


FIG. 8—DIAGRAM OF ALEXANDERSON SELF-EXCITED ALTERNATOR.

in the auxiliary winding, and the resistance in series with the winding is so adjusted that the current from the winding to the brushes is right at no load. With full-load wattless current of the alternator, the current in the secondary of the series transformer and its potential is such that the drop in the resistance which occurs at no load is completely compensated for, so that there is no potential difference although the resistance is in series with the commutator. With full non-inductive load, since the arrangement of the circuits is such that the opposing e.m.f. by the series transformer is displaced 90 deg. from that generated in the auxiliary winding, the resultant drop in the resistance is of some magnitude and therefore the exciter voltage is less than at full-load wattless current, but more than at no load. The true relation between excitation at no load, full non-inductive load and full inductive load is illustrated in Fig. 9, in which *A B* is the excitation at full non-inductive load, *A C* the excitation at full inductive load, and *A O*, equal to $A\,C - O\,C$, is the no-load excitation. The circle is the locus for the field excitation for different power factors. It is evident that the voltage so obtained at the rectifying commutator is correct for proper compounding, since the relation between the no-load ampere-turns and the full non-inductive load ampere-turns is quite closely found by combining the no-load ampere-turns and synchronous impedance ampere-turns at right angles. This full inductive excitation is very closely obtained, if the no-load ampere-turns and the synchronous impedance ampere-turns are directly added. This corresponds in the diagram to the conditions when *A O* is added to *O C*.

Composite-Wound Alternators. In order to obtain the result for which compound windings are used with direct-current generators, compensating windings are used with alternators. The field is excited for its normal open-circuit voltage by an exciter either direct-connected or geared to the generator, while the voltage drop caused by the load current is compensated for by series ampere-turns from self-excitation.

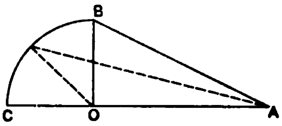
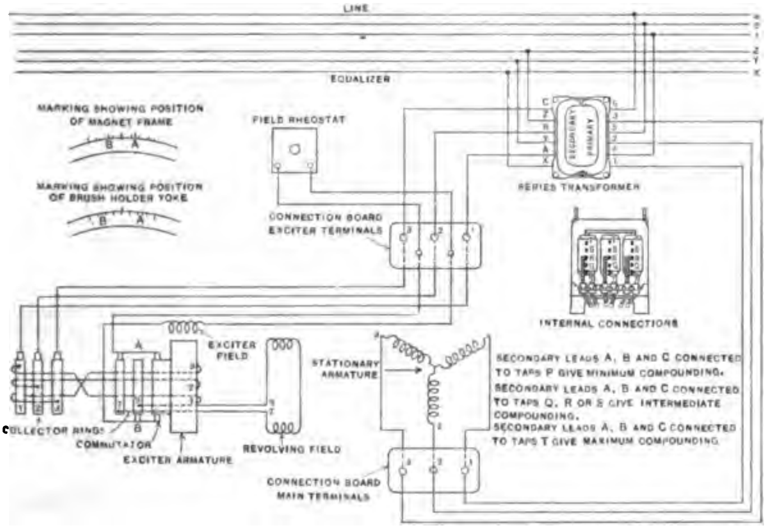


FIG. 9—EXCITATION DIAGRAM—SELF-EXCITED ALTERNATOR.

The compensating winding can be connected in many different ways; for example, the armature current may all be rectified for use in excitation, or it may pass through a special transformer attached to the armature, and the secondary of this transformer may supply the current for rectification and self-excitation. Again, the rectified current may be passed through a few turns of wire on each pole, or all the necessary series turns may be placed on one or two poles.

The connections of one type of compensated generator are shown in Fig. 10. There are two collector rings for supplying current to the revolving field, and three collector rings for supplying alternating current from a series transformer to the armature of the compensating exciter. This set of three rings is mounted outside of the bearing in the case of the smaller belt-driven generators, and inside the bearing, just outside the field collector rings, on the larger belt-driven machines. On the engine-driven generators these rings are mounted on the exciter-shaft.

The compounding of these machines is accomplished by passing three-phase current into the exciter armature in such a way that it reacts magnetically on the exciter field in proportion to the strength and phase relation of the alternating current. Consequently, the magnetic field and hence the voltage of the exciter are due to the combined effects of the shunt field current and the magnetic reaction of the alternating current. The alternating current passes through the exciter armature in such a manner as to give the necessary rise of exciter voltage as the non-inductive load increases, and without other adjustment, to give greater rise of exciter voltage with additions of inductive load.



SECONDARY LEADS A, B AND C CONNECTED TO TAPS P GIVE MINIMUM COMPOUNDING.
SECONDARY LEADS A, B AND C CONNECTED TO TAPS Q, R OR S GIVE INTERMEDIATE COMPOUNDING.
SECONDARY LEADS A, B AND C CONNECTED TO TAPS T GIVE MAXIMUM COMPOUNDING.

FIG. 10—CONNECTIONS OF THREE-PHASE COMPENSATED GENERATORS.

An illustration of a compensating generator of the above type is shown in Fig. 11.

Separate Excitation. A separately excited generator has no inherent tendency toward regulation, this being effected either by a rheostat in the field circuit or by means of different systems of automatic regulator operation, as treated more fully in another part of this paper.

With separate excitation the direct current is obtained by means of exciters, or from some other existing source of direct-current supply or from a storage battery. The first method, however, is the most advantageous and is the one almost invariably used.

DIFFERENT METHODS OF VOLTAGE REGULATION

Hand Regulation. The simplest system of operation is by means of hand-operated rheostats connected in the field circuits of each generator. The pressure of the exciter bus is then generally kept constant at the rated exciter voltage and all the regulation is done by manipulating the generator rheostats. In order to regulate the exciter voltage it is, of course, also necessary to provide rheostats in the exciter fields.

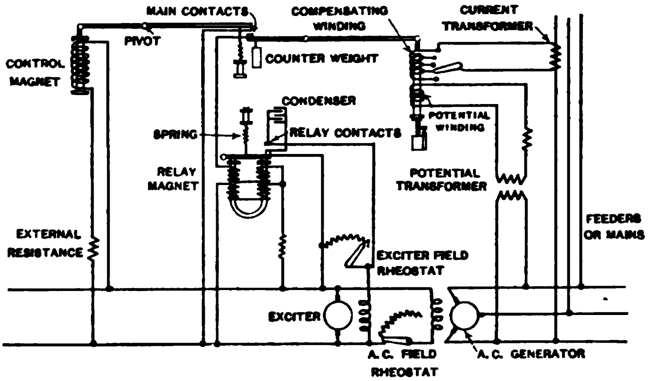


FIG. 12—ELEMENTARY DIAGRAM OF TYPE T A FORM A REGULATOR

T A Regulators. Of the various schemes proposed for automatic voltage regulation, the T A regulator is now most widely used. With this system the desired voltage is maintained by rapidly opening and closing a shunt circuit across the exciter field rheostat. The rheostat is first turned in until the exciter voltage is greatly reduced and the regulator circuit is then closed. This short-circuits the rheostat through contacts in the regulator and the voltage of the exciter and generator immediately rise. At a predetermined point the regulator contacts are automatically opened and the field current of the exciter

FIG 11—THREE-PHASE COMPENSATED GENERATOR.

FIG. 20—VOLTAGE REGULATOR.

must again pass through the rheostat. The resulting reduction in voltage is arrested at once by the closing of the regulator contacts, which continue to vibrate in this manner and keep the generator voltage within the desired limits.

Method of Operation. An elementary diagram of the type T A, form A regulator's connections with an alternating-current generator and exciter is shown in Fig. 12. The regulator has a direct-current control magnet, an alternating-current control magnet, and a relay. The direct-current control magnet is connected to the exciter busbars. This magnet has a fixed stop-core in the bottom and a movable core in the top which is attached to a pivoted lever having at the opposite end a flexible contact pulled downward by four spiral springs. For clearness, however, only one spring is shown in the diagram. Opposite the direct-current control magnet is the alternating-current control magnet, which has a potential winding connected by means of a potential transformer to the alternating-current generator or busbars. There is an adjustable compensating winding on the alternating-current magnet connected through a current transformer to the principal lighting feeder. The object of this winding is to raise the voltage of the alternating-current busbars as the load increases. The alternating-current control magnet has a movable core and a lever and contacts similar to those of the direct-current control magnet, and the two combined produce what is known as the " floating main contacts."

The relay consists of a U-shaped magnet core having a differential winding and a pivoted armature controlling the contacts which open and close the shunt circuit across the exciter field rheostat. One of the differential windings of the relay is permanently connected across the exciter busbars and tends to keep the contacts open; the other winding is connected to the exciter busbars through the floating main contacts and when the latter are closed neutralizes the effect of the first winding and allows the relay contacts to short-circuit the exciter field rheostat. Condensers are connected across the relay contacts to prevent severe arcing and possible injury.

Cycle of Operation. The circuit shunting the exciter field rheostat through the relay contacts is opened by means of a single-pole switch at the bottom of the regulator panel and the rheostat turned in until the alternating-current voltage is reduced 65 per cent below normal. This weakens both of the control magnets and the floating main contacts are closed. This closes the relay circuit and demagnetizes the relay magnet, releasing the relay armature, and the spring closes the relay contacts. The single-pole switch is then closed and as the exciter field rheostat is short-circuited the exciter voltage will at once rise and bring up the voltage of the alternator. This will strengthen the alternating-current and direct-current control magnets and at the voltage for which the counterweight has been previously adjusted the main contacts will open. The relay magnet will then attract its armature and by opening the shunt circuit at the relay contacts will throw the full resistance into the exciter field circuit, tending to lower the exciter and alternator voltage. The main contacts will then be again closed, the exciter field rheostat short-circuited through the relay contacts and the cycle repeated. This operation is continued at a high rate of vibration, due to the sensitiveness of the control magnets, and maintains not a constant, but a steady exciter voltage.

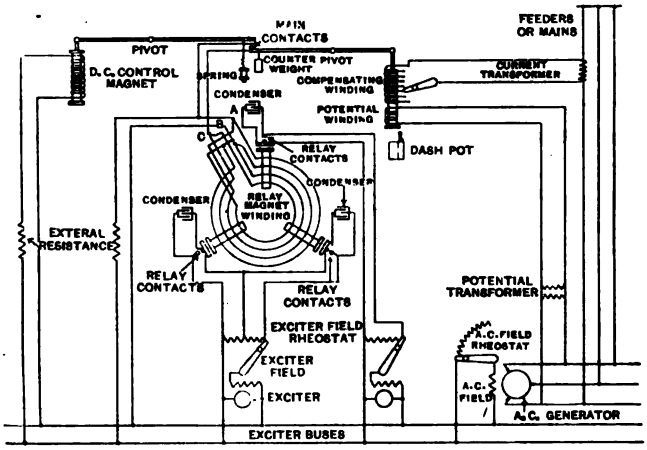


FIG. 13—ELEMENTARY DIAGRAM OF TYPE T A FORM F REGULATOR CONNECTIONS.

For larger installations the type T A, form F regulator is generally used, an elementary connection diagram of this type being shown in Fig. 13. This regulator has several relays, varying from two to twelve in number according to the size, capacity and character of the exciters used. While the fundamental principle of operation of these regulators is the same as for the form A, as described above, certain modifications are necessary in controlling two or more generators. As will be seen by reference to the elementary diagram of the form F regulator, relay No. 1 is connected across the field rheostat of one exciter, while relays No. 2 and No. 3 are placed across sections of the field rheostat of the second exciter. This is necessitated because the second exciter is of larger capacity than the first. Similar modifications are necessary in special cases, but the method of control by the rapidly moving main floating magnets and sensitive control magnets remains identical and maintains the same steady rise and fall in voltage required by the alternating-currrent system.

Compensation for Line Drop. Compensation for line drop may also be obtained with these regulators. For ordinary installations the compensating winding on the alternating-current control magnet is connected to a current transformer in the main feeder. A dial switch is provided by which the strength of the alternating-current control magnet may be varied and the regulator made to compensate for any desired line drop up to 15 per cent, according to the line requirements.

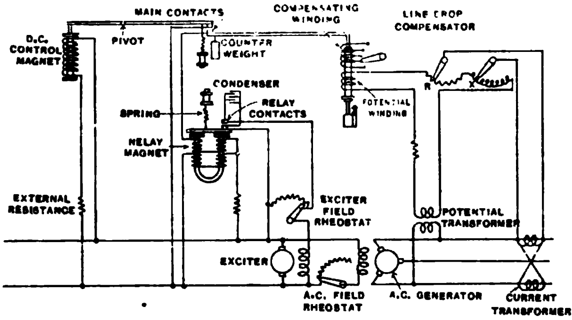


FIG. 14—CONNECTIONS OF AUTOMATIC REGULATOR FOR ALTERNATING-CURRENT GENERATOR, USING LINE-DROP COMPENSATOR.

This arrangement is very satisfactory for general use, but where the power-factor of the load has a wide range of variation, as in long-distance transmission lines, better results can be obtained with a special line-drop compensator adapted to the regulator. This compensator, see diagram Fig. 14, has two dial switches with many taps to the resistance and the reactance in the box so that it can be adjusted to compensate accurately for line losses with loads of varying power factor.

Systems. In larger stations with a number of alternators, the general practise has been to provide two or more exciters operating in parallel and controlled by one common voltage regulator by a suitable arrangement of equalizing rheostats. The connections of such a system are shown in Fig. 15.

A system using T A regulators for preventing cross-currents between generators operating in parallel is shown in the diagram, Fig. 16. This particular arrangement covers two generators operating on separate buses provided with a tie-line. With the tie-switch closed, however, the condition will be the same as if both generators operated in parallel on one bus. One exciter

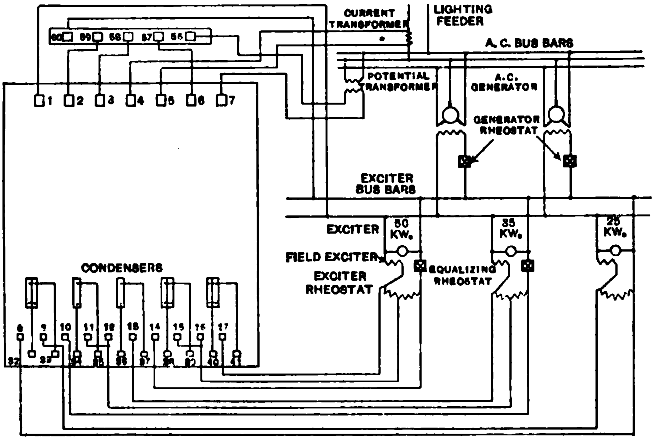


Fig. 15—One Arrangement of External Connections of Type T A Form F Regulator.

with its own regulator is provided for each generator, and the current and potential transformers are connected 90 deg. out of phase with each other, so that if cross-currents tend to flow between the generators, the regulator will reduce these cross-currents by strengthening or weakening the field of the generator to which the regulator is connected.

Cut-out Relay. This relay has been devised to be used in connection with T A regulators for guarding against short-circuits and voltage rises in transmission systems. If a voltage regulator is used and a short-circuit should occur somewhere on the system, for example in the transmission lines, the action of the regulator would naturally be to deliver the maximum excitation to the fields of the exciters and generators, so as to keep up the voltage of the system. This in turn necessitates that the governors of the prime movers be wide open, and if the short-circuit should be suddenly relieved, the voltage often rises to very high values, owing to the time element involved in closing the governors and in demagnetizing the fields. The connections for a high-voltage, high-current relay operating in connection with one exciter and one T A regulator are shown in Fig. 17. The relay is provided with a current coil and a potential coil,

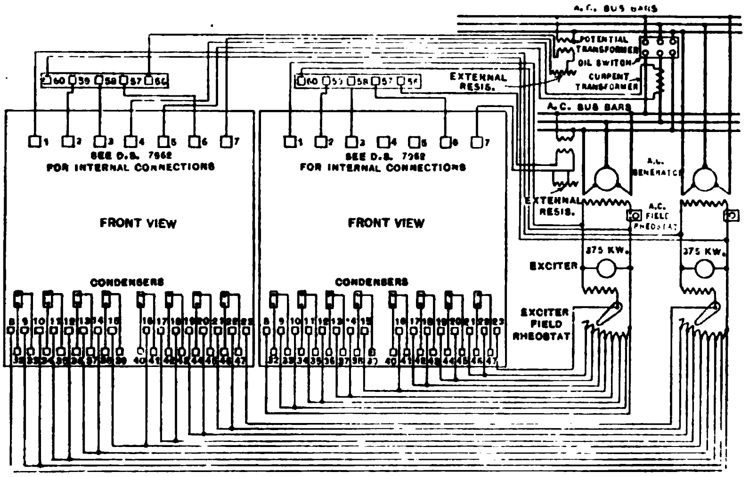


Fig. 16—Connections of Two Voltage Regulators Operating in Parallel with One Arrangement of Two Exciters not in Parallel

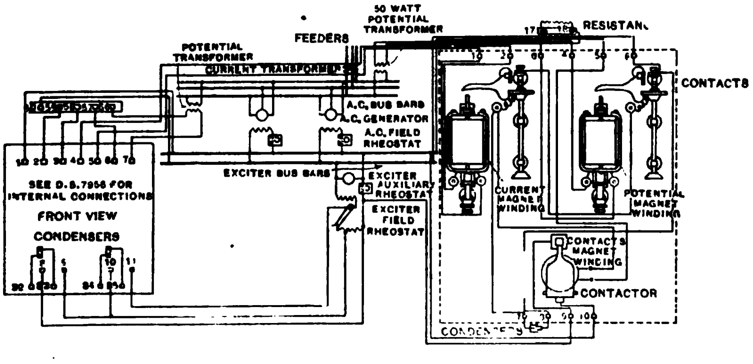


Fig. 17—Connections of High-Voltage High-Current Cut-out Relay with Voltage Regulator and One Exciter.

and will automatically reduce the excitation on the exciters in case of excessive loads, high voltages, or any other cause tending to increase the voltage.

Operating Results. The result of installing T A regulators is shown in the attached charts, Figs. 18 and 19, taken before and after the installation of the regulator. With much greater load fluctuations, it is seen that the variations in the voltage are practically eliminated by the introduction of the regulator. A type T A , form F regulator is shown in Fig. 20, Plate XCIII.

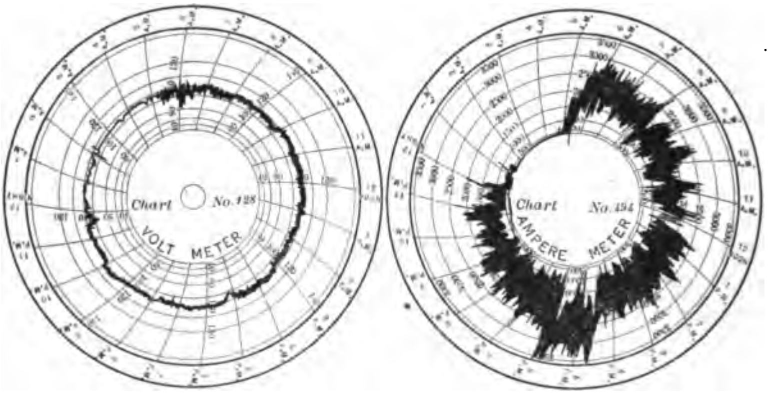


FIG. 18—CHART SHOWING VOLTAGE REGULATION AND LOAD BEFORE REGULATOR WAS INSTALLED.

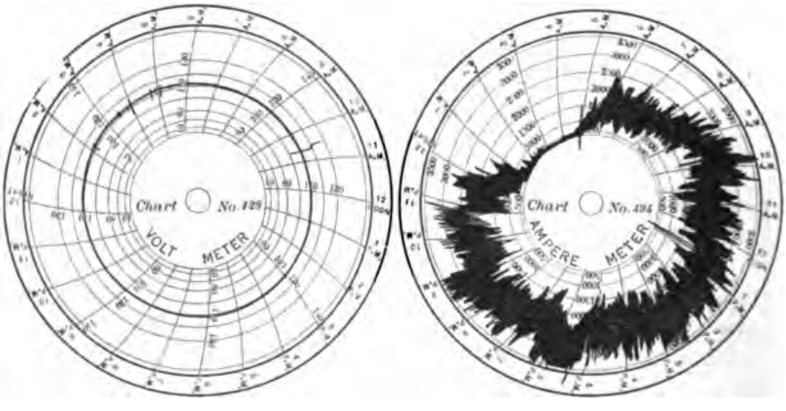


FIG. 19—CHART SHOWING VOLTAGE REGULATION AND LOAD AFTER REGULATOR WAS INSTALLED.

The K. R. System of Regulation. This system of regulation is for use where the excitation for the generators varies considerably, and where at the same time it is desirable to maintain a constant pressure on the exciter busbars, so that current can be taken therefrom for lighting, operation of relays, oil-switch mechanisms, etc.

An elementary diagram of this system is given in Fig. 21. By referring to the diagram it is seen that three buses are provided, the upper, which can be called the field bus, while the others may be called the exciter buses. A motor-driven booster is connected across the two upper buses as shown, its object being to boost or buck the exciter voltage and thus vary the voltage applied across the generator fields in proportion to the required excitation, without, however, varying the exciter busbar pressure.

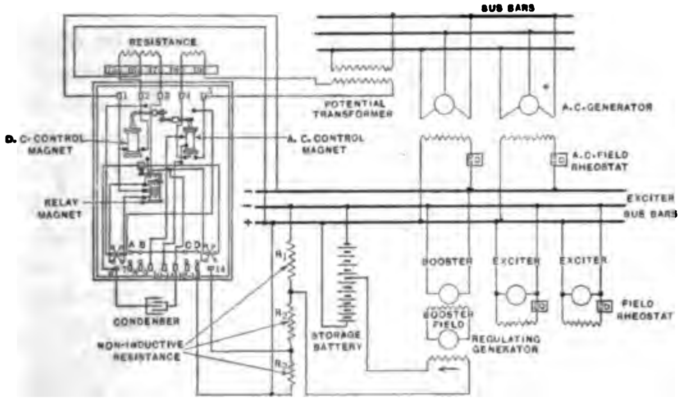


FIG. 21—CONNECTIONS OF VOLTAGE REGULATOR WITH ONE ARRANGEMENT OF TWO EXCITERS IN PARALLEL IN CONJUNCTION WITH STORAGE BATTERY AND BOOSTER.

The boosting or bucking action of the booster is effected by merely reversing its field, this in turn being accomplished by reversing the field of a small regulating generator or exciter which is direct-connected to the booster. One terminal of the field of the regulating generator is connected to the middle point of a storage battery which is connected across the exciter busbars, while the other terminal of the field is connected to a series of resistances as shown in the diagram, this series of resistances also being connected across the exciter busbars. The connection is made between R_1 and R_2 and a T A regulator is connected across the terminals of resistance R_3. The object of the storage battery is simply to provide for a neutral point, and a resistance could equally well be provided, although it would not be so efficient. The values of the resistance units are such that $R_1 > R_2$ and $R_2 + R_3 > R_1$.

The operation is as follows: In case the alternating-current busbar voltage tends to drop, the main contact circuit of the regulator will close, this in turn closing the relay contacts and short-circuiting resistance R_3. As resistance R_1 is greater than R_2, the excitation current for the regulating generator field will flow from the lower bus, through resistance R_2, then through the field and hence through the upper half of the storage battery to the middle bus. This will cause the booster to raise the voltage of excitation, thus increasing the pressure of the alternating bus, until it reaches the value for which the regulator is adjusted. At this instant the regulator main contact circuit opens, thereby opening the relay contacts, thus releasing the short circuit across the resistance R_3. The resistances $R_3 + R_2$, being greater than R_1, will cause the field current of the regulating generator to flow from the lower bus through the lower half of the battery, then through the field and hence through resistance R_1 to the middle bus, thus in opposite direction to which it was flowing before. This will also reverse the booster field, causing it to lower the voltage applied to the generator fields and the alternating-current busbar voltage will drop.

This action of opening and closing the regulator main contact circuit takes place at the rate of from 300 to 600 times per minute, thereby insuring a perfectly constant voltage across the alternating-current busbars. If line compensation is desired, it can also be arranged for in the same manner as previously mentioned under T A regulators.

Thury Regulators. The Thury regulator which is generally used in Europe is primarily intended to keep the generator voltage constant by regulating the field resistance. In order to combine rapidity and reliability of action with sensitiveness, the field rheostat is not actuated directly by the fluctuations in voltage, but is operated by a small electric motor of about 1/20 h.p., the regulating mechanism being merely brought into play or stopped by the fluctuations of voltage. Fig. 22 is a diagrammatic sketch of the voltage regulator for alternating-current systems, being practically identical with that used in continuous-current installations. *H* is a toothed wheel keyed to the shaft

L which carries the switch arm of the rheostat. *D* is a casting which is rocked to and fro about the shaft *L* by the miniature motor referred to. The pawls *I* and *I′* are attached to *D* in the manner shown, but are held off the toothed wheel by the spring-actuated levers *K* and *K′*. Each of these two levers carries a projection at its upper end; the projection on *K* passes normally above the blade *C*, while that on *K′* rocks to and fro underneath this blade. Consequently, when the blade *C* is lowered or raised in the manner presently to be described, it will strike against *K′* or *K* respectively, thus permitting pawl *I′* or *I* to drop into the teeth of the wheel *H*. The latter is now rotated in the one or the other direction—thus cutting in or cutting out field resistance—until the blade *C* regains its horizontal position, when it no longer strikes against *K* or *K′*. Pawls *I* and *I′* are then drawn by spring-action out of contact with the teeth of the wheel *H*.

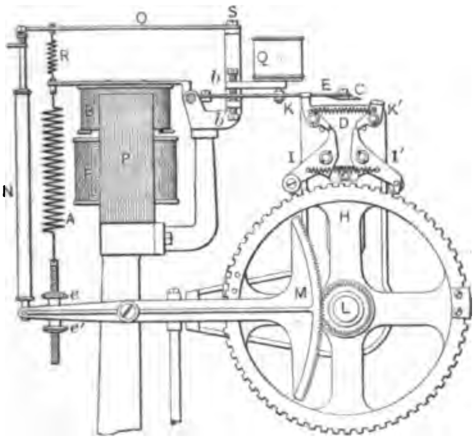


FIG. 22—DIAGRAMMATIC SKETCH OF THURY REGULATOR.

The electromagnetic mechanism for controlling the position of the blade *C* is as follows: *P* is one of the limbs of the laminations which constitute part of the magnetic circuit through which a flux is maintained by the coil *F*. A very light coil *B*, connected across the busbars whose voltage is to be controlled, is free to move up or down above *F*, the movement being limited by adjustable stops *b* and *b′*. When the voltage of the supply is normal, the current through *B* is such that the lever *E* carrying the blade *C* is in a horizontal position, and nothing happens.

But when the supply voltage is higher or lower than the normal, then a correspondingly larger or smaller current flows through the shunt coil *B*, which rises or falls in consequence and causes the blade *C* to move into the way of the oscillating levers *K* and *K′*, thus actuating the rheostat as previously explained.

The coil *B* moves against the tension and compression of the two springs *A* and *R*, the latter being, in its turn, attached to the free end of a flat spring, *O*, fixed at *S*. The free end of *O* is also in connection, through the intervention of a dash-pot *N*, with the pivoted lever *M*, which takes up a position in accordance with the position of the switch arm by means of the gearing shown. This arrangement tends to steady the removal of coil *B* and to bring it back speedily to its horizontal position after having been deflected. In order to prevent vibrations of the blade *C* in regulators for alternating-current or where the regulation is required to be unusually sensitive, a dash-pot, *Q*, is also provided.

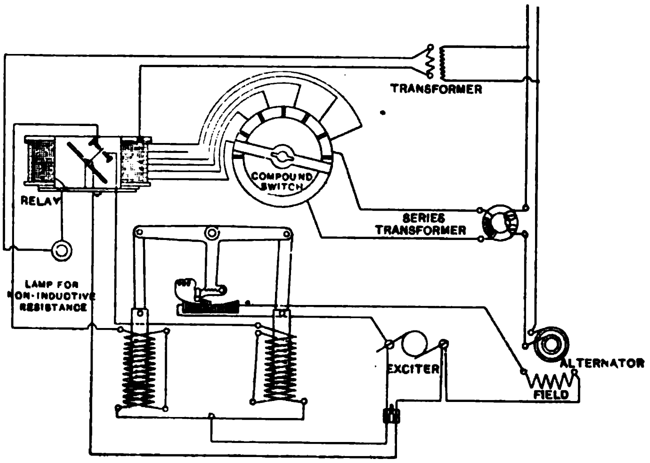


FIG. 23—DIAGRAM OF CONNECTIONS OF CHAPMAN REGULATOR.

Chapman Regulator. This regulator, a connection diagram of which is shown in Fig. 23, is composed of three distinct parts, viz., a voltmeter, or relay, for detecting small changes of voltage; a rheostat to connect into the field magnet circuit of the generator to be regulated; and a pair of working solenoids to operate the rheostat.

The voltmeter, or relay, consists of a coil of wire wound on a brass spool. Inside of the coil is a thin iron disk pivoted at opposite ends of its diameter. The tendency of the coil is to move this disk to an angle of 90 deg. with itself, and this force is opposed by a spring, the tension of which is adjustable by a thumbscrew below the coil. The turning of this thumbscrew thus enables one to adjust the voltage of regulation. The disk of the relay has a platinum-tipped spring attached to it which is arranged to make contact with one or another of two platinum-tipped screws and these admit current to one or another of two working solenoids. The platinum points are protected from dust by a metal case with glass top fitting on the top of the brass spool. A resistance lamp is placed in circuit with the relay coil, the resistance of the lamp being many times that of the coil.

The rheostat part of the regulator consists of a set of resistance units in the smaller sizes of regulator and of cast-iron grids in the larger sizes. The resistance units are connected to a set of contact segments arranged in the arc of a circle on the face of the regulator, and a lever arm carrying the contact shoes moves as a radius to the circle. The contact shoes are pivoted to the lever arm and held in contact with the segments by coil springs.

The lever arm carrying the contact shoes is part of a beam lever that has the cores of the working solenoids pivotally connected to its two ends. These working solenoids are consuming no current except when the regulator is called upon to act, and they are, therefore, in circuit only a small portion of the time. These solenoids have two windings, a primary and a secondary, both wound in the same direction. The primary winding alone is fed with live current, while the secondary has a current induced in it just at the instant of rupture of the contact points, and the induced current, being in the same direction as the live current, prevents the formation of an induction spark at the points of contact, and these points, being sparkless, will last indefinitely.

An adjustable dash-pot is attached to one side of the apparatus at the bottom. This adjusts the quickness of movement of the regulator to correspond with the characteristics of the generator to be regulated. This dash-pot consists of a brass tube having a spline extending its whole length on the inside. A groove in the piston fits this spline, and whenever the tube is turned it turns the piston also, and opens or closes ports in the piston, which allow a more or less free passage for oil from one side to the other of the piston. All that is necessary in order to adjust the dash-pot is to turn the containing tube by hand.

The relay of this regulator can be compound-wound and may thus be made to compensate for line loss. There is also another way of compensating for line loss which in some instances is more feasible than compounding the regulator, and that is to connect the relay of the regulator directly to a pair of potential wires coming back from the center of distribution.

Booster System. A system used in Europe is shown in Fig. 24. The main feature of this arrangement is a constant exciter busbar pressure, while the voltage for the generator field excitation can be varied by means of varying the excitation of a booster connected in series with the generator field circuit.

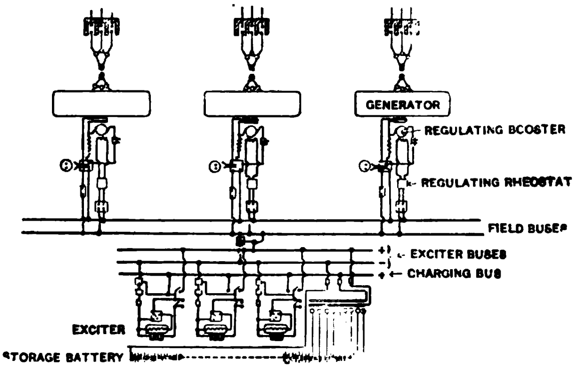


FIG. 24—REGULATING BOOSTER CONTROL.

The system consists of two or more exciters driven by separate prime movers and adjusted to keep a constant exciter busbar pressure. Their design, however, is such that by manipulating their rheostats a considerably higher voltage than normal can be obtained. This is in order to permit of charging a storage battery, which is done from one of the exciters, this being connected to a charging bus so as not to interfere with the busbar pressure.

In order to vary the voltage across the generator fields one booster regulating generator is provided for and direct-connected to each main generator. It is connected in series with the generator field, and the booster field is also excited from the exciter busbars as shown in the illustration. By reversing and varying the booster field, which is generally done by a manually operated controller, it is possible to vary the field excitation considerably—in one particular instance from 0 to 440 volts, while the exciter busbar voltage is kept constant at 220 volts.

DIFFERENT EXCITER ARRANGEMENTS

Number of Units. The standard practise for larger stations has in the past been to provide two or more exciters operating in parallel, and of sufficient capacity to excite all the generators in the station. In many installations one or more spare units have also generally been provided as reserve, the number depending on the capacity of the generating equipment.

In some of the recent developments, however, individual exciters are provided for each main generator, each exciter having a capacity sufficient for exciting its own generator only. The exciters are not arranged for parallel operation, but the main generators are generally operating in parallel, being arranged for connection to a common bus, which, however, can be sectionalized if desired.

Method of Drive. Exciters driven by independent prime movers, either waterwheels or steam engines, are generally found in almost all large installations. While in some modern developments they are used entirely for furnishing the excitation, in others they are generally kept as reserve, and the excitation is normally obtained from motor-driven units. It is obvious that a material saving can be accomplished by reducing the number of exciters driven by separate prime movers to a minimum. This is especially true in hydroelectric developments where the cost of the hydraulic part of such an equipment is very high. Separate pipe lines are preferable for the exciter turbines as the tapping of the penstocks for the main units may seriously interfere with the constant speed of the exciters, due to the fluctuating water supply for the main units, as the load varies.

A view of a station containing two 400-kw. 250-volt vertical waterwheel-driven exciters for exciting a number of large generators is shown in Fig. 25.

Another method of drive is to have the exciters either direct-connected or belted to the main generators. One of the objections to this method is the speed variation of the main units, which naturally also affects the exciters. Another objection is that a trouble in the exciter unit involves the shutting down of the large generating unit. Couplings, etc., can, however, be provided, for readily disconnecting the exciter from the main units, and the generator can be excited from the other exciter units, which can be provided with some reserve capacity over what would be required for normal operation. A generator of the horizontal design with a direct-connected exciter is shown in Fig. 26, and one of the vertical design in Fig. 27.

The system which seems to be most generally used is the one where the exciters are driven both by prime movers and motors. While both drives are occasionally used at the same time by coupling the turbine or engine to one end of the exciter and a motor to the other, separate drives are, however, mostly used. In case of the combination method either the prime mover or the motor will have to run idle, unless methods are provided for mechanically disconnecting them from the exciter.

With separate drives, enough motor-driven exciters are generally provided for exciting the total generating capacity and the exciters driven by prime movers are used as reserve and in starting up the system. This arrangement will therefore give two independent sources of excitation, and in larger stations it might even be advisable to provide two or more exciters driven by prime movers.

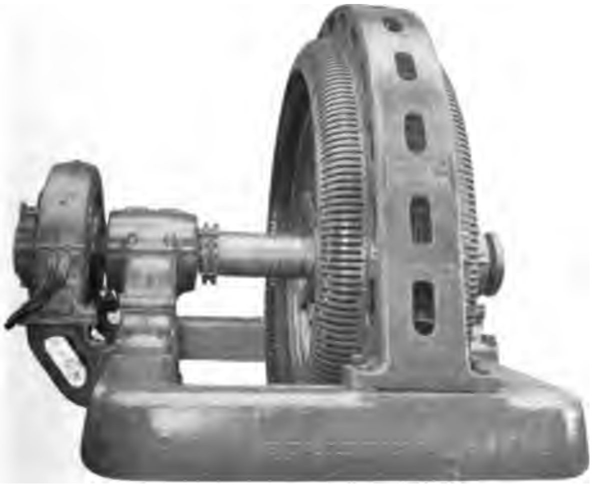
In certain of the recent installations one small induction-motor-driven exciter is provided for each generator, the current for the motors being supplied by separate alternating-current low-voltage generators, driven by independent prime movers so as to insure a perfect operation free from fluctuations in speed. Sometimes provision is also made, whereby these auxiliary generators can be driven by motors connected to the main buses, or also whereby the motors of the exciters can be connected through transformers and also fed from the main busbars. A small induction-motor-driven exciter set is shown in Fig. 28.

Different Systems of Connection. The system of connections for an exciter equipment varies widely in different installations depending upon the layout of the station, the number of units, the method of drive and other special requirements which must be provided for, such as lighting, storage battery charging, etc. It is therefore difficult to give specific rules for any particular system to be selected, but in the following will be given a description of a number of systems which are in general use.

The diagram shown in Fig. 29 represents a system where three prime-mover-driven exciters, operating in parallel, are feeding into one common exciter bus extending along all the alternating-current generators. Each generator field is then

[RUSHMORE]

FIG. 25—POWER STATION CONTAINING TWO 400-KW., 250-VOLT WATERWHEEL-DRIVEN VERTICAL EXCITERS FOR EXCITATION OF SEVERAL LARGE ALTERNATING-CURRENT GENERATORS.



[RUSHMORE]

FIG. 26—HORIZONTAL GENERATOR WITH DIRECT-CONNECTED EXCITER

FIG. 27—VERTICAL GENERATOR WITH DIRECT-CONNECTED EXCITER.

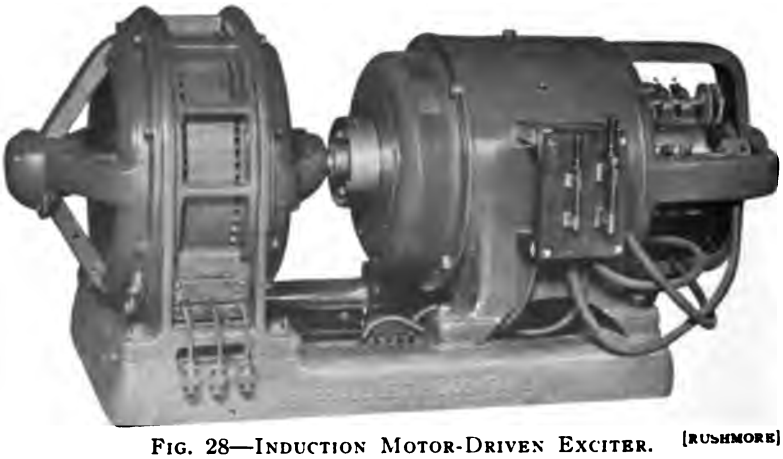


FIG. 28—INDUCTION MOTOR-DRIVEN EXCITER. [RUSHMORE]

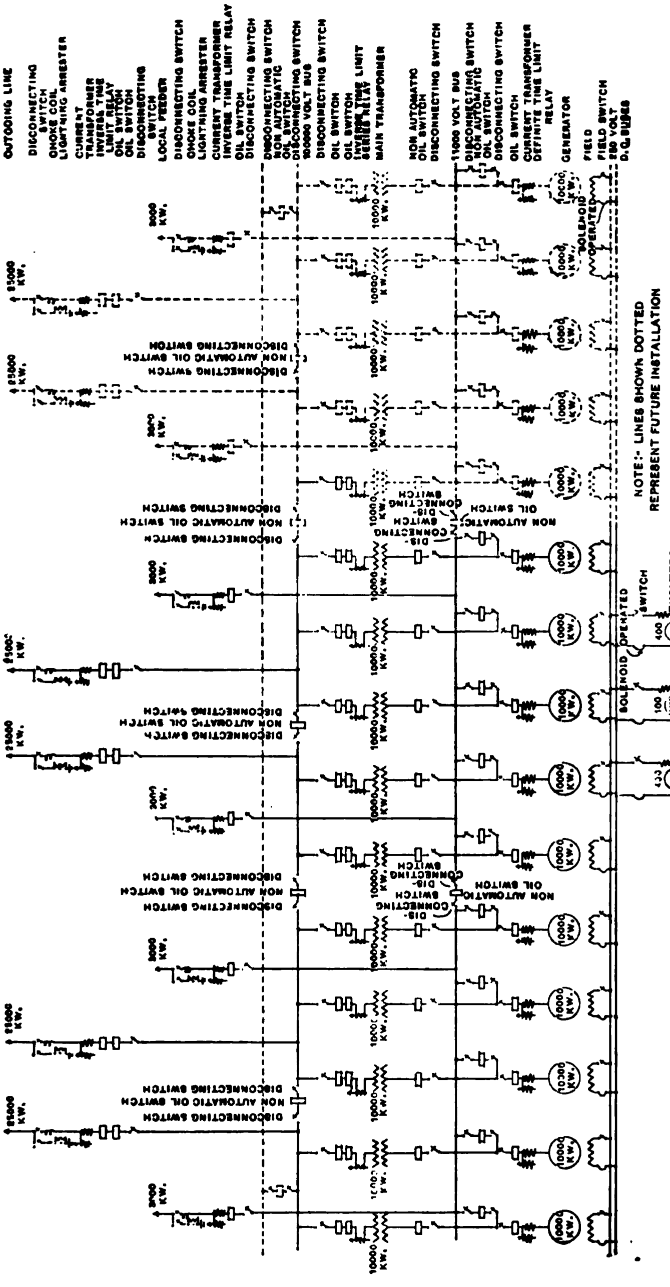


FIG. 20—SYSTEM OF CONNECTIONS

connected directly to this bus, the pressure of which is generally regulated by means of automatic regulators, although it can also be done by manual manipulation of the exciter rheostats. In each generator field circuit is also provided a rheostat so that a

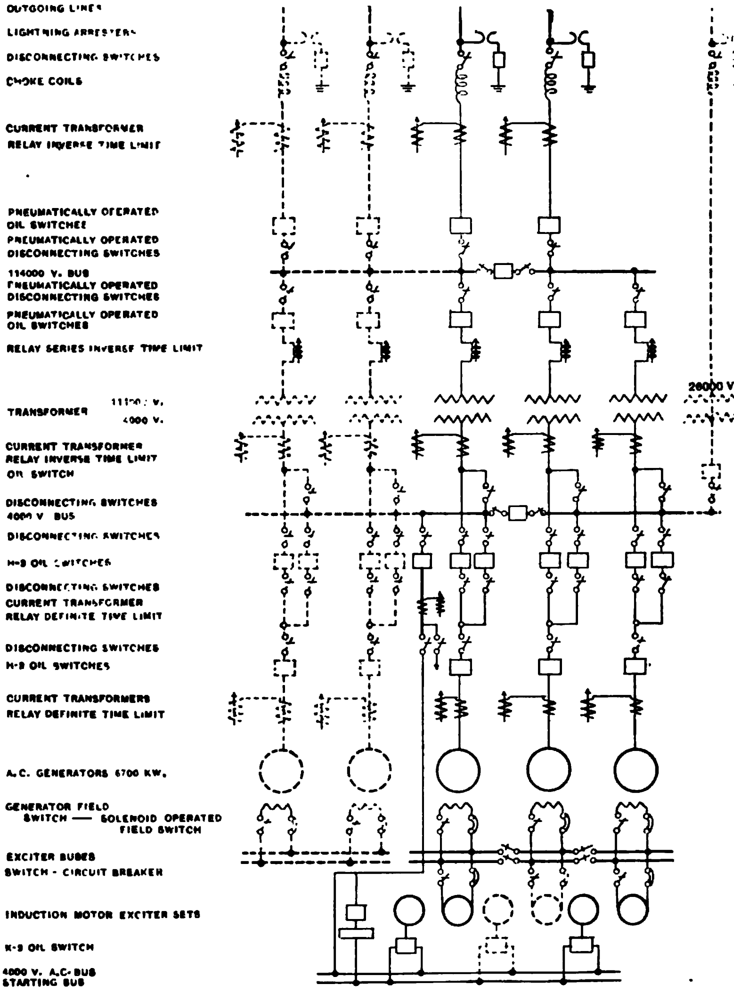


FIG. 30—SYSTEM OF CONNECTIONS.

separate adjustment of the field excitation for the different generators can be accomplished.

In Fig. 30 are shown the connections of another system in which the exciters are also operating in parallel on a common excitation, but where they are driven by induction motors fed from the low-tension main bus. Two buses are shown for the motors, one being the running bus and the other the starting bus, the reduced voltage of which is obtained from taps of an auto-transformer. In a system of this kind some means must be provided for obtaining direct current when starting up the system. For this reason a small exciter s usually installed, being sometimes driven by a gasolene engine or also belted to one of the main units. A storage battery would of course also serve this purpose well.

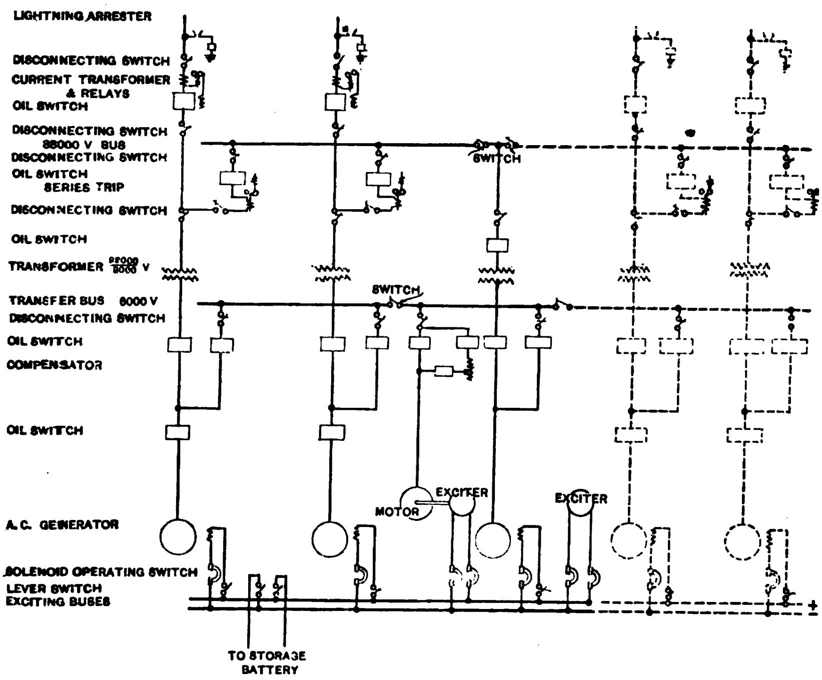


FIG. 31—SYSTEM OF CONNECTIONS.

A system using both a separate waterwheel-driven and a motor-driven exciter is shown in Fig. 31. The waterwheel-driven exciter is then generally used when starting up and for reserve, while the motor-driven unit is used for normal operation. Both units can, of course, be operated in parallel if desired.

A system of more flexibility is shown in Fig. 32. Two positive and one negative exciter buses are provided and by means of double-throw switches it is possible to connect the exciters to either bus and also to excite the generator fields from either bus. If it is desired, two different exciter voltages can be maintained by operating one exciter on either bus. One exciter can also furnish the current for the excitation and the other the current

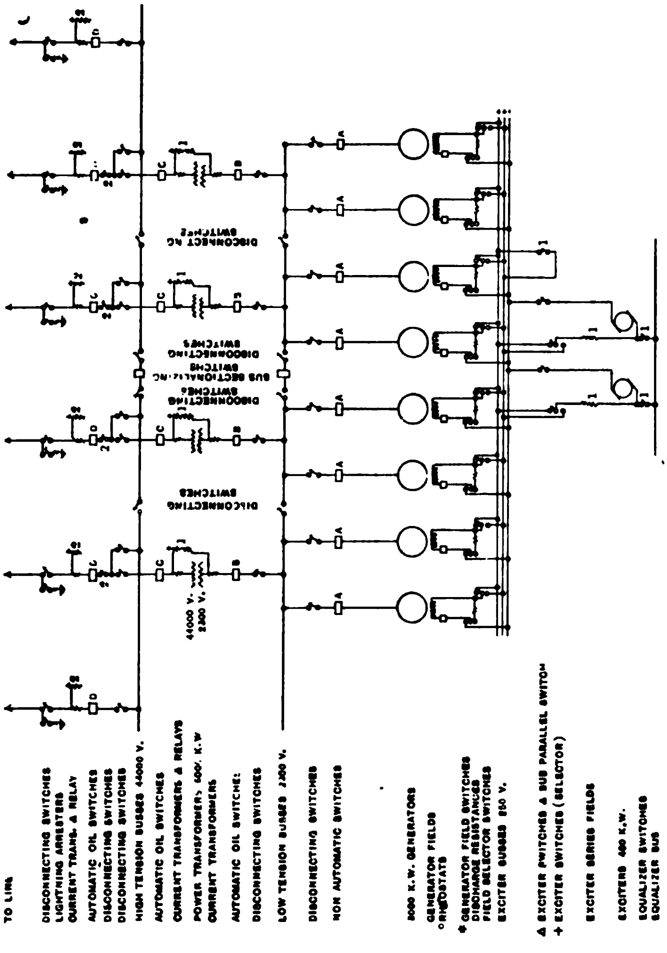


FIG. 32—SYSTEM OF CONNECTIONS.

for lighting, etc. The fluctuation in the exciter voltage caused by an automatic regulator connected to the first-named machine would therefore not be felt on the auxiliary or lighting bus, the pressure of which could be kept constant. A similar arrangement is shown in Fig. 33, with the exception that both sets of buses are double-pole.

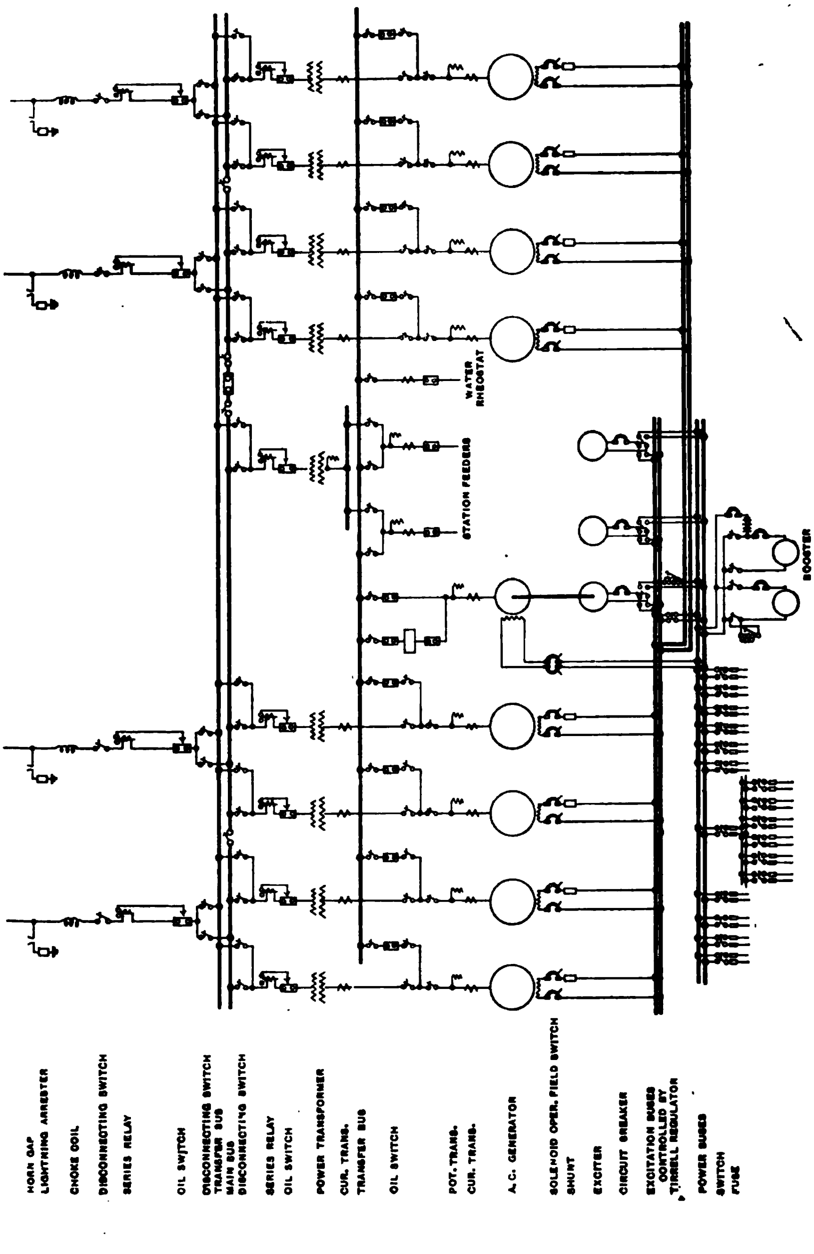


FIG. 33—SYSTEM OF CONNECTIONS.

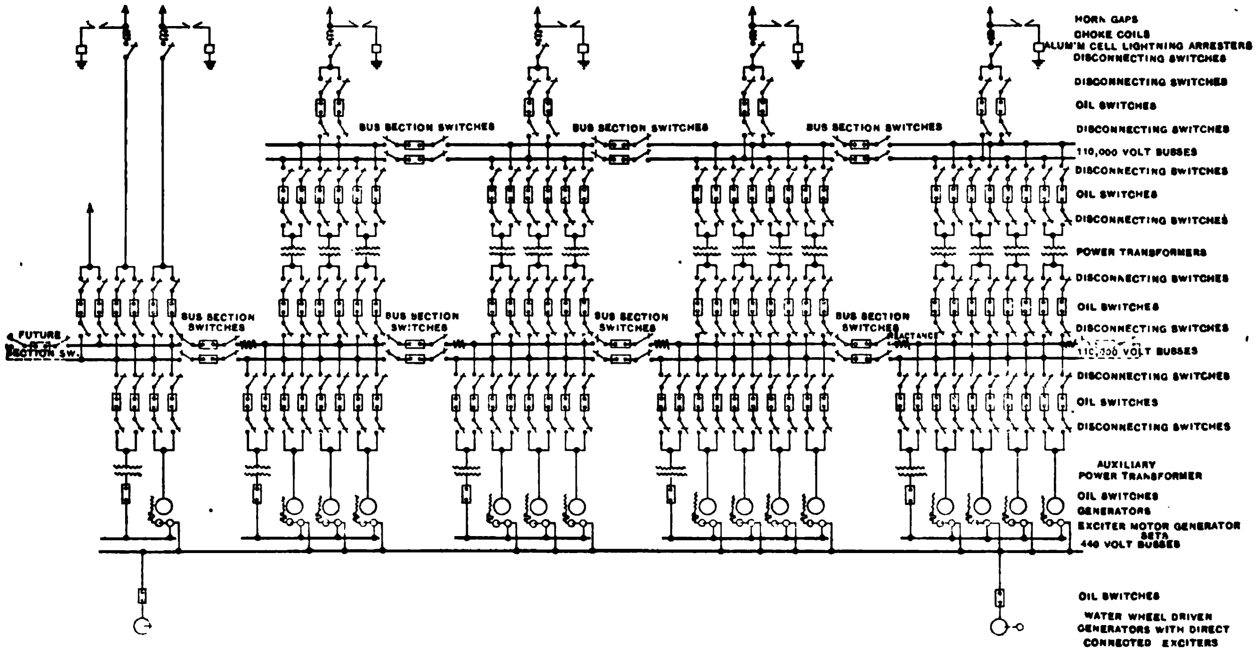


FIG. 34—SYSTEM OF CONNECTIONS.

In the arrangement shown in Fig. 34 one motor-driven exciter is provided for each generator. The exciters are not intended to operate in parallel and one automatic regulator is provided for each exciter. In general, the reason for operating a number of units with the exciters not in parallel is on account of the possibility of an accident. In systems where one or more large exciter units are provided, the operation of a large part of the system may be materially affected if one exciter unit is shut down, while, in the event one of the smaller units becomes disabled, the operation of the system will not be affected to such a great extent.

The possibility of compensating for cross-currents between the machines, as previously explained, is also one of the reasons for selecting this system.

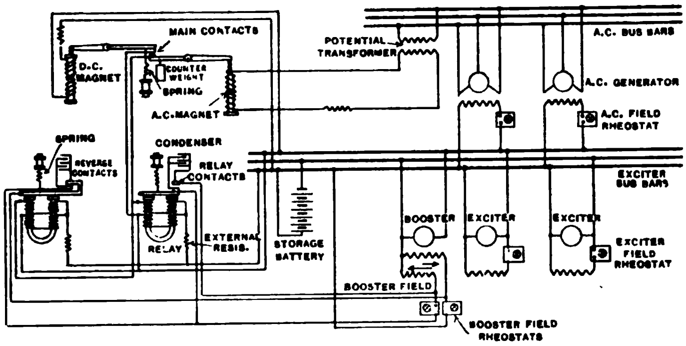


Fig. 35

The motors driving the exciters are fed either from the main bus or from the two auxiliary waterwheel-driven generators, thus giving two independent systems. In another installation, the auxiliary generators are provided with combination drive, *i.e.*, they can be driven either by waterwheels or by induction motors fed from the main buses. In this particular case, however, the individual exciter sets are not intended for being driven directly from the main buses as in the systems shown in Fig. 34.

Storage Batteries. The use of storage batteries in connection with exciters has of late been increasing considerably. The advantages of such a combination are obvious, as, with the failure of the exciters for some reason or other, the storage battery would automatically keep up the excitation. The storage battery is generally floating on the exciter buses, the pressure of which is kept constant. A separate exciting bus is provided and between this bus and one of the exciter busbars a booster is installed which can be operated to either raise or lower the voltage, its field being controlled by an automatic voltage regulator. The voltage fluctuation is therefore entirely on the exciting buses, being caused by varying the booster voltage by means of the regulator, while the voltage of the exciter busbars is kept constant.

In case of failure of the exciters the excitation would be furnished by the storage battery, and the booster in connection with the regulator would take care of the voltage regulation. Should the booster be disabled, provisions are made whereby it can be short-circuited and the system operated without the regulator.

In the diagram, Fig. 35, are shown the connections of such a system.

The author desires to acknowledge the assistance of Mr. E. A. Lof in the preparation of this paper.

DISCUSSION ON "EXCITATION OF ALTERNATING-CURRENT GENERATORS" (RUSHMORE), BOSTON, MASS., JUNE 28, 1912.

B. G. Lamme: I have only a few points to bring up in connection with this paper. On page 1842 is a table which I did not understand. For example, the constants given for single-phase and three-phase windings do not agree, and yet very frequently three-phase windings are used to give single-phase. However, I may not understand how these constants are used. In the method of calculation which I have been using, I do not have any fixed constants. I first work out the magnetic field distribution. From this I then derive the constants for each individual case. The use of a constant is all right in the hands of a skilful designer, if he knows how it is derived, but in special designs it is likely to be misleading. The table given probably refers to a standard type of machine in which the constant has been determined, and has been proved to be *constant* in all cases.

A second point is the value of K_w, the winding-pitch factor, that is shown on page 1843. The curve shown is part of what is practically a sine curve. It is so close to a sine that it is almost impossible to find the difference.

On page 1845 the "Range of Excitation" is referred to, where it is stated that "with 125 volts excitation, the voltage should therefore not be allowed to exceed 125 volts at maximum load, 80 per cent power factor, and the corresponding no-load excitation should be about 70 volts." That statement can apply only to fairly well regulating machines; but for high-speed machines such as turbo-alternators where the regulation is made purposely rather bad, the ratio of 70 to 125 is much too small, and we find in practise that 50 volts at no-load is about right, with 110 at full load, which leaves a little margin for rheostat.

On page 1847, "Exciters with Commutating Poles," it is stated, "The reason for this is generally due to the fact that a commutating-pole machine, when flat-compounded at 125 volts, has a rising characteristic when operated at voltages less than normal." I think that, while that is frequently true in practise, it is not necessarily true; because it is due partly to the fact that a machine at 125 volts is usually worked farther over the bend of the saturation curve than at lower voltages. Part of the over-compounding may be due to the presence or absence of local currents in the coils short-circuited by the brushes. When a machine with commutating poles is operated as a motor, and the commutating poles are over-excited, the main field of the machine is weakened as the load goes on, due to the local currents under the brushes. If it is operated as a generator, the local currents will tend to strengthen the field and compound it. At 80 volts, for instance, the magnetic circuit is less saturated than at 125 volts. If part of the saturation lies in the yoke of the machine, which is usually the case, then this saturation will affect the magnetic circuit of the commutating pole, and more commutating pole ampere-turns are required at 125 volts than at 80 volts. Therefore the commutating pole will be over-excited at the lower saturations, and the local currents will tend to compound the machine. But I have seen many machines in which there was no evidence of this compounding action.

On page 1867 reference is made to the use of one exciter for each generator. That has been the practise in many large European stations, but judging from my experience, it is not an advisable arrangement in general. I think a better scheme is to put in one or two large independent exciters, to excite all the machines. However, if individual exciters are used, they can be adjusted to operate without rheostats in the main fields. With turbo-alternators, however, the total loss in the exciting circuit is generally so low that the rheostatic loss does not make much difference. There is some demand for large turbo-alternators with an exciter with each machine, but it is a practise that I do not think is right, and I have objected to it, so far as I could.

H. M. Hobart: This morning there seemed to be a pretty general agreement that it was better to have the ventilating apparatus distinct from the generator; that the generator could then be designed so as to be better for its purpose, and the ventilating apparatus for *its* purpose. I think the same argument applies in the case of the exciter. The plan of employing direct-connected exciters is very disadvantageous, from various standpoints. It is hard to conceive of a worse practise, for obvious reasons which I will not take time to review. It is desirable to ascertain whether there is any clearly defined common agreement among engineers who have studied the subject thoroughly, as to having independent exciters. Mr. Lamme has voiced his opinion that that is the only reasonable thing to do, and if others would give their support to this plan I think it would help to discourage men from concluding that their individual requirements would justify them in using direct-connected exciters.

J. Lester Woodbridge: On page 1847 the statement is made that compound exciters are preferable, the main reason for this being that better parallel operation is obtained with compound windings, this being especially true where two or more machines of different size are to be operated in parallel. I suppose that refers to the question of stability, or the equal division of load between two machines, but I do not see how compound winding, that is, the series windings, can improve the stability over what would be obtained with shunt-wound machines, connected in parallel. The cause of instability in compound-wound machines operating without equalizing connections is the fact that if any disturbance occurs in one machine, such as a change in speed, which causes local currents to circulate between the machines, the result is aggravated by the series windings. By using the equalizing connection, the same stability results as is obtained with two shunt-wound machines without the series winding, provided the equalizing connection has practically zero resistance. Any departure from this last assumption introduces some instability, due to the fact that some of the local current will flow through the series windings. Therefore I do not see how any better stability can be obtained with the compound winding than is inherent in two shunt-wound machines operated in parallel.

E. A. Lof: With regard to Mr. Lamme's remarks as to the advisability of using a few large units rather than a number of small ones, there may also be objections to such an arrangement. In one large central station the exciter equipment consists of both waterwheel-driven and motor-driven exciters, the latter being intended for the normal operation. Considerable trouble has been experienced from the motor-driven unit falling out of step, thus shutting down the whole system. This, however, might not have been the case if the exciter unit had been driven by an induction motor instead of a synchronous motor. With a number of small motor-driven exciter units, preferably operated from a separate alternating-current source, such a complete shut-down would, of course, be very remote, and this is evidently the reason why such a system of excitation has been provided in a number of recent installations of the largest capacity. In one particular plant which contained two or three large exciters the original equipment has been discarded and one small motor-driven unit has been installed for each main generator.

With reference to the single-phase slot factors, these values are under the assumption that the winding is distributed over the whole armature. If part of the slots are not occupied, the breadth of the winding is reduced and the values should be increased to approximately those given for a two-phase winding.

B. G. Lamme: In my remarks I did not refer to a number of small exciters as compared with a large one, but to two large exciters direct-connected with the generators.

Lester McKenney: I wish to emphasize the necessity, where automatic voltage regulators are to be installed, of using exciters designed especially for the purpose. It is of the greatest importance that the exciters have a voltage range considerably in excess of the maximum excitation requirements, that the range of excitation required by the alternator be narrow and that the time element of the alternator and exciter combined be as short as possible; as upon these things, largely, depends the success of automatic voltage regulation.

A considerable margin of exciter voltage is desirable, as when the maximum voltage of the exciter is called for, the relay contacts remain closed and voltage regulation is no longer obtained. When operating near the maximum voltage the density in the fields becomes high and large variations in field current are required for small variations in voltage, the time element is increased, and the operation becomes in general unsatisfactory.

A time element of less than from four to six seconds is desirable, providing it is not obtained by the use of excessive resistance in the exciter field rheostat, which greatly increases the duty of the relay contacts and impairs the operation of the regulator. The series field excitation should be limited to about 30 per cent of the total, as with higher percentages shunt field rheostats of excessive resistance are required for reducing the exciter voltage to the required minimum in a reasonable length of time.

In a great many cases, where automatic voltage regulators have been installed, the results have been disappointing, due to the lack of a proper appreciation of the instantaneous effect of the armature resistance and reactance upon the alternator voltage and of the effect of the time element introduced by the inductance of the alternator and exciter field windings. When these points are given consideration it will be evident that momentary fluctuations of voltage are to be expected during unusual disturbances.

It would seem, other things being the same, that compound-wound exciters would be somewhat more sluggish in their action than shunt-wound exciters, due to the damping effect of the local circuit formed by the series field winding and the external shunt. This, of course, applies only in automatic voltage regulation where the exciter field strength is varied as rapidly as possible from one value to another.

It is advisable, where belted exciters are used in connection with automatic regulators, to make the pulleys of more liberal proportions than are usual in ordinary applications, as the exciters are subject to higher excitation and greater overloads in time of trouble.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

LOCALIZERS, SUPPRESSORS, AND EXPERIMENTS

APPLICATION OF LOCALIZERS OF FAULTY FEEDERS AND AN ARCING GROUND SUPPRESSOR TO THE SYSTEM OF THE PUBLIC SERVICE ELECTRIC CO., AND DESCRIPTIONS OF SEVERAL EXPERIMENTAL STUDIES

BY E. E. F. CREIGHTON AND J. T. WHITTLESEY

The object of this paper is expressed briefly in the title. The localizer is a special type of relay which is connected to the current transformers of each feeder. When an accidental contact or arc occurs between one phase and ground on any feeder, the localizer of that feeder lights a signal lamp and sounds an alarm in the switchboard room.

The localizer is part of the general scheme of protection of cable systems. It is used especially in connection with the arcing ground suppressor.* The arcing ground suppressor extinguishes an accidental arc from one phase to ground in a small fraction of a second after it forms. The localizer indicates the feeder that is faulty. The switchboard attendant may leisurely substitute a spare feeder for the faulty one and clear the circuit of the fault without an interruption of service.

The Public Service Company of New Jersey covers the entire state. There are three systems, namely, the northern, middle and southern. The tests were made on the northern system. On this system are both overhead and underground transmissions. There are 47 miles of cable operating at 60 cycles, as much more at 25 cycles, and 32 miles of spare cable. There are 72 miles of open wiring on poles used exclusively on the 60-cycle system. The generated potential is 13,200 volts and the generators are directly connected to the lines. There are several

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*See TRANSACTIONS, A. I. E. E., 1911, Vol. XXX, I, page 257.

power plants and two systems at different frequencies which are operated together at times through a frequency changer. All the tests herein described, however, were made at the Marion Station, using only one generator of 9000 kw. capacity.

Some idea of the extent of the 60-cycle system may be gleaned from the value of the electrostatic grounding current. When a contact is made between one phase and ground the unbalanced condenser current rises to 60 amperes (measured). The momentary rush of current to ground is, naturally, many times greater.

The Remarkable Changes in Potentials by Grounding. When there is no ground on the system the potential from each phase to ground is the *Y* potential (7600 volts). This is shown in Fig. 1 by the lines *O*1, *O*2 and *O*3. When phase 2 is brought in direct contact with the ground its potential to ground is zero and the potentials of phase 1 and phase 3 to the ground is tne delta potential, 13,200 volts. Without special consideration one is inclined to assume that when there is a medium value of resistance interposed between phase 2 and ground, the potentials to ground will be represented by some such intermediate values as phase 1, phase 2 and phase 3, Fig. 1. This, however, is far from true. This was first noticed from the behavior of the selective relay of the arcing ground suppressor. When one phase of a circuit was grounded through a relatively high resistance there was no movement of the corresponding arm of the selective relay, but the arm corresponding to one of the other phases moved toward its contact. Much to our dismay we found that this effect promised to put a limit on the maximum sensibility at which the selective relay could be set to operate.

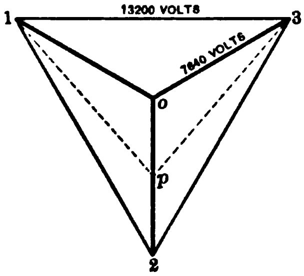


FIG. 1

The actual potentials from each phase to ground are shown in Fig. 2 for all values of grounding current. These measurements were obtained by varying the resistance from phase 2 to ground by means of a water rheostat. A remarkable condition is shown. When the resistance is gradually decreased from an infinite value the potential of the grounded phase shows scarcely any change. But the potential of phase 3, which is not being grounded, shows a gradually diminishing value until the current reaches

16 to 20 amperes, then it gradually increases. Over the total range of grounding current, the potential of phase 1 to ground very consistently increased, but not along a straight line. Before a dead ground is reached the potential of phase 1 rises to a value actually greater than the delta potential of the circuit. When the resistance to ground reaches zero, phases 1 and 3 both assume the delta potential. In considering the potential of phase 3, attention is directed to the impossibility of setting the selective relay for a drop in potential of less than 19 per cent, as such a setting would cause the relay to close the wrong switch of the arcing ground suppressor. This condition of the relay applied to cable systems has no significance, nor importance. Faults in a cable develop immediately into a condition of low resistance. This matter of resistance of accidental grounds will be treated in more detail farther on in the paper.

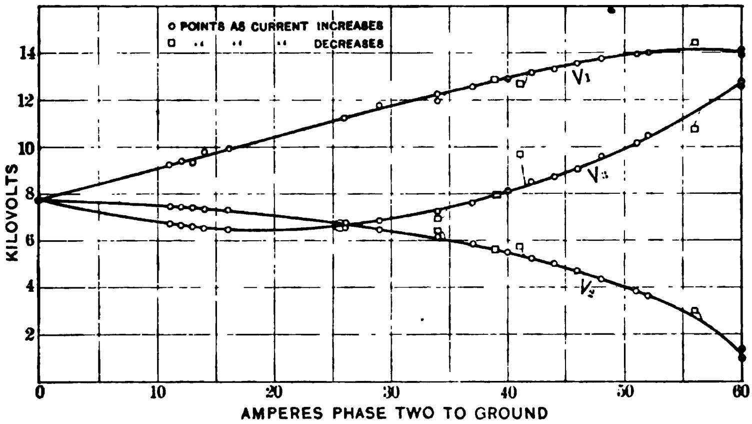


FIG. 2—VARIATION IN VOLTAGE OF EACH PHASE TO GROUND AS CURRENT, PHASE 2 TO GROUND, VARIES.

Curves from test data, readings 27 to 49, Aug. 22, 1911.

The volt-ampere relation of the different phases relative to earth are shrouded in a mist of mystery when plotted in rectangular coordinates. This mist is immediately dissipated if the plot of the data of potentials is made on a triangle of the three phases. As a basis to justify this method we know from measurements that the generator continues to generate the same potential between phases independent of the presence or absence of an accidental ground. Since we are not treating of transient effects at present, it must be understood that the foregoing statement is not intended to apply to the first instant that a ground appears. Under normal conditions of load, then, the delta potentials are not materially disturbed by a ground on one phase. This means that the points 1, 2 and 3 of the triangle in Fig. 3 are fixed and the potential of each phase to ground may be plotted from its corner. Since the earth potential itself is the same for all three phases, the length of the lines from the three corners must meet in a point. Plotting the simultaneous potentials of the three phases gives a semi-circle on the *Y* potential as a diameter. For a particular condition of resistance to ground the point *p* is given. The potential from phase 1 to ground is represented by the length of the line 1 *p*. The direction of this line indicates its phase relation. Likewise the potential from phase 3 to ground is represented by the line 3 *p*. In the potential from phase 2 to ground, represented by the line 2 *p*, it is known that the current is in phase with the electromotive force. This potential is in the drop across the resistance situated between phase 2 and ground. By actual measurement it was found that during these tests the generator continued to generate the normal value of *Y* potential which is represented by the line *O*2. From fundamental considerations it is known that the *Y* potential *O*2 must be the vector sum of the resistance drop *p* 2 and the reactance drop *O p*.

Since there is no inductance in this circuit the angular displacement of the current, which is in phase with the line *P* 2, must be due to capacity in the circuit.

The question arises, which electrostatic capacity comes into play to cause this angular advance of the current? The capacity in question is evidently not the capacity of phase 2 to ground. Conditions are represented in a simplified form in Fig. 4. In this figure the capacities between the three conductors are not shown because the charging currents between conductors, except for transitory effects, remain practically constant whether a phase is grounded or not, since the potentials between the phases remain constant. In other words, an artificial separation of the different capacities is made for the sake of convenience. Returning to the consideration of phase 2, the resistance between this phase and ground is in parallel with its capacity to ground. After the first moment, the current which flows in the resistance comes directly from the generator and not from the condenser 2. The current which flows through the resistance to the sheath returns to the generator through the condensers 1 and 3. The potential *O p* in the diagram Fig. 3 is the vector potential drop across the condensers in series with the resistance.

The current, then, that flows through the resistance from phase 2 to ground, returns not only by phases 1 and 3 of the grounded cable but also by the same phases of all the other cables through their electrostatic capacity to ground. In this way it is seen, from one viewpoint, that current goes out from the generator on the phase of the grounded cable, to a value in this case of 60 amperes, and returns in a subdivided form by being distributed among all the cables. From another viewpoint, a current flows out in one of the current transformers of the grounded cable which does not return through two adjacent transformers on the other phase of the same cable. This makes the sum of the currents in the three transformers not equal to zero. This unbalanced condition produces the current in the localizer relay which causes it to operate. It should be noted that the same condition holds only to a lesser extent in all the other cables which are not grounded.

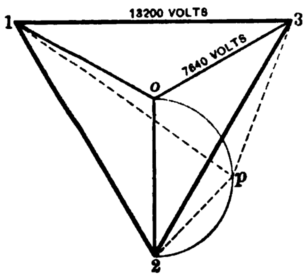


Fig. 3

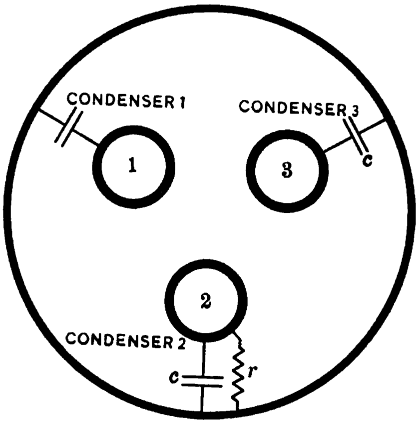


Fig. 4

The relations of the potentials to the current expressed in the rectangular coordinances of Fig. 2 are worked out mathematically from the diagram of Fig. 3 and are given in the summary of this paper. It may be evident to some engineers that this whole matter could have been worked out symbolically. The experimental method used with the interpretation of the data is much more trustworthy than the symbolical method, however, on account of the difficulties in obtaining by abstract analysis all the factors involved.

In Fig. 5 the conditions are shown for two values of resistance. When the resistance is very high then the potential from phase 2 to ground represented by $m\,2$ is nearly equal to the Y potential, and the current is nearly in phase with the Y potential. The potential $O\,m$ across the condenser at this time is very small.

If further proof were required that the condenser involved is not the capacity of phase 2 to ground, it is given by this diagram of Fig. 5 when the resistance to ground is high, as in the case assumed. Then the potential from phase 2 to ground, which is the potential on condenser 2, is practically the normal *Y* potential and not *O m*.

When the resistance to ground is low then the potential across the condenser is *O n* and the potential across the resistance is *n* 2. Since the condenser effect now predominates, the current to ground is practically 90 deg. in advance of the *Y* potential *O* 2. At this time the capacity current has reached practically its full value, as the resistance is too small to affect it sensibly.

Comments on the Tests

These tests were made to investigate the applicability of the arcing ground suppressor to cable systems. It is of interest to note here that although the system was grounded more than 100 times by the arcing ground suppressor, no high potentials were caused. The condition of full ground was approached very gradually. During this time needle gaps were placed between phases and from each phase to ground. Note was taken also of discharges on the lightning arresters. On one day at a particular time the lightning arresters in two stations discharged during the grounded condition. Every effort was made to reproduce these effects, but without success. The tests show that a contact ground on one phase of this system produces no abnormal potentials. The two non-grounded phases simply rise to delta potential above ground. The factor of safety in the insulation of the cables makes the application of delta potential harmless. During the periods of grounding, which sometimes were purposely carried to several minutes' duration, there were no disturbances of the power on the system, although there were synchronous machines in operation. During part of the time a two-phase system was connected to this three-phase system. This we believed would increase the possibility of surges, but no surge was noted.

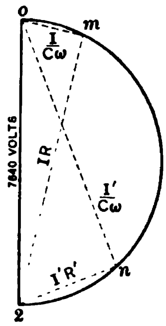


Fig. 5

In making and breaking the grounds on the circuit, it is well known from volumes of theory on the subject of transients, especially the classical work by Dr. Steinmetz, that oscillations will take place. If no resistance had been used one might look for high potentials from these oscillations. It is well to note that in every case the grounds were made initially with some resistance in series. In a former paper before the Institute, on the arcing ground suppressor, the construction of the grounding switch is shown with a resistance in the oil pot. As the contact blade descends it first picks up this series resistance, which is designed to damp out oscillations. An instant later after this ground takes place the resistance is cut out by a further movement of the blade which makes a direct contact between a phase and ground. In opening the switch the first movement of the blade throws the resistance in series again with the ground and when the contact to ground is finally broken it is done through the damping resistance in the oil pots. To this condition in the protective apparatus we can attribute the immunity from troubles such as occur from the usual accidental arcs to ground. The value of the use of the critical resistance in the oil pots was evident when the arcing ground suppressor switch was harmlessly made to pump open and shut rapidly for some time.

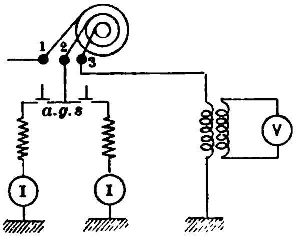


FIG. 7

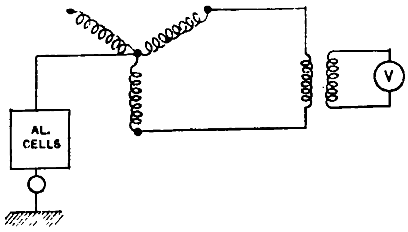


FIG. 9

OSCILLOGRAPHIC STUDIES OF CURRENTS AND POTENTIALS WHEN THE SYSTEM IS GROUNDED SUCCESSIVELY THROUGH A RESISTANCE TO GROUND AND THE SWITCH OF THE ARCING GROUND SUPPRESSOR

In making these oscillographic tests, two instruments were used simultaneously. One instrument had its vibrators numbered 1, 2 and 3; the other, 4 and 5.

For the first oscillogram, *P.S.* 7, Fig. 6, the connections of the circuit for the vibrators 1, 2 and 3 are shown in Fig. 7.

The object of this test was to show the operation of the arcing ground suppressor. For vibrators 4 and 5 the connections are shown in Fig. 9, and the oscillogram in Fig. 8. One vibrator measured delta potential and the other vibrator measured current to ground through an aluminum cell connected directly between the neutral of the generator and earth.

Fig. 6. *Oscillogram P.S.* 7, *Vibrators* 1, 2 *and* 3*a*. Phase 2 of generator No. 8 was grounded. Generator No. 8 was not connected to the power system when this test was made.

Upper Record:	Vibrator 1.—Voltage of non-grounded phase to ground.
Middle Record:	Vibrator 2.—Current to ground through a resistance of about 300 ohms. This current is the electrostatic capacity current of the generator.
Lower Record:	Vibrator 3.—A circuit parallel to the one of the middle record from phase 2 to ground. This circuit was a single pole switch of the arcing ground suppressor.

In this preliminary test a resistance of about 300 ohms was also placed in series with the switch of the arcing ground suppressor.

NOTES: The exposure on the film starts at a point at the right of the film marked zero time. At this instant both switches between phase 2 and ground are open, and therefore, the vibrators 2 and 3 show zero current and vibrator 1 on phase 3 shows normal *Y* voltage to ground (7740 volts effective.)

The small lumps in this generator wave represent the 17th harmonic. The 17th harmonic corresponds to 18 teeth per pair of poles. After about 2.75 cycles from the time marked zero time, the first grounding switch closes, connecting phase 2 to ground through about 300 ohms resistance. This is shown in the oscillogram by the disappearance of the zero line. Due to vibration of the contacts of the oil switch the record of vibrator 2 is initially so broken as not to be clear. It becomes clearer, however, in its continuation at the left end of the oscillogram.

When the first switch closes to ground the voltage of phase 3 as indicated on vibrator 1 immediately jumps to approximately delta potential. This takes place in spite of the 300 ohms in series to ground. The electrostatic capacity of the generator is so small that the resistance of 300 ohms has very little effect in limiting the grounding current from reaching its full value. Note has already been made of the high value of the 17th harmonic. This harmonic is greatly magnified by the capacity of the windings of the generator. In a later oscillogram it will be shown that when the generator is loaded by being connected to the system the effect of the teeth of the generator in producing the 17th harmonic disappears.

Coming now to a consideration of the arcing ground suppressor switch as shown in vibrator 3—sixteen cycles (about ¼ second) after the first ground is put on the generator, the switch of the suppressor closes. The two circuits parallel to ground then divide the current between them.

Fig. 8. *Oscillogram P.S.* 7, *Vibrators* 4 *and* 5. The general conditions of the circuit have already been described.

Upper Record: Vibrator 4.—Delta potential.
Lower Record: Vibrator 5 is the current from the neutral of the generator through aluminum cells to ground. There is no visible current to ground shown until the first switch closes. The higher current initially on this record is due mostly to the charging current of aluminum cells. In a later oscillogram surges at the neutral will be shown in this circuit.

Fig. 10. *Oscillogram P.S.* 10, *Vibrators* 1, 2 *and* 3. The electrostatic capacity current to ground with a strong 17th harmonic is shown more clearly by choosing only a small part of the oscillogram. This test is a repetition of the previous one described. The film velocity is somewhat greater in order to bring out the form of the harmonics.

Upper Record: Vibrator 1 is the potential of phase 3 to ground.
Middle Record: Vibrator 2 is the electrostatic capacity current of the generator from phase 2 to ground.
Lower Record: Vibrator 3.—Zero line only is shown.

Fig. 11. *Oscillogram P.S.* 11, *Vibrator* 4 *and* 5. Grounding of generator No. 8, not loaded.

Upper Record: Vibrator 4.—The delta potential of the generator.
Lower Record: Vibrator 5.—The current from the neutral of the generator through the aluminum cells to ground.

NOTE: This oscillogram is reproduced especially on account of the initial surge that took place at the neutral the instant the generator was grounded.

Fig. 12. *Oscillogram P.S.* 19, *Vibrators* 1, 2 *and* 3. This record shows the opening of the grounding switch when the generator is connected to the whole system. There were about 500 ohms in series in the grounding circuit.

Upper Record: Vibrator 1 is the voltage of phase 3 to ground.
Middle Record: Vibrator 2 is the current from phase 2 to ground.
Lower Record: Vibrator 3 shows only a zero line.

NOTES: Only the last half cycle of the current to ground is shown on this oscillogram, vibrator 2. When the current ceases in vibrator 2, vibrator 1 shows a distortion of its zero line which is probably due to a magnetic effect in the potential transformer. It should be noted in the small part of the current wave that is visible that since all the cables were connected to the generator and the normal load was being taken, the 17th harmonic disappears, leaving the current wave smooth.

Fig. 13. *Oscillogram P.S.* 20, *Vibrators* 4 *and* 5. This test illustrates conditions while phase 2 is being grounded, first, through 25 ohms resistance, then, 16 cycles later, through the arcing ground suppressor switch, which in its final closed condition had no series resistance.

Upper Record: Vibrator 4 was again the delta potential.
Lower Record: Vibrator 5.—The current from the neutral of the generator through aluminum cells to ground.

NOTES: The only subject worthy of note in the wave of delta potential is the absence of harmonics. In the current from the neutral to ground (the lower record), the initial current rush is shown of comparatively small magnitude. After about 16 cycles the switch of the arcing ground suppressor closes and cuts out all the resistance in phase 2 to ground. Under this condition there is an unusual and remarkable, although harmless, surge of potential at the neutral which makes itself evident by considerable current from the neutral to ground. This surge first increases, then decreases slightly, and then increases again, and decreases to zero. The cause of this surge was not found, and it could not be reproduced. Although many tests were made it appeared but one other time. It may have been due to an unbalanced condition which occurred only when the ground connection was made at a certain unknown point in the cycle of the generator wave.

Fig. 14. *Oscillogram P.S.* 34, *Vibrators* 1, 2 *and* 3. This record demonstrates the operation of the arcing ground suppressor under normal running conditions of the loaded system.

Upper Record: Vibrator 1 is the potential of phase 1 to ground.
Middle Record: Vibrator 2 is the current from phase 2 to ground, through a contact intentionally placed on the circuit to start the operation of the arcing ground suppressor.
Lower Record: Vibrator 3.—Current through the switch of the suppressor from phase 2 to ground.

NOTES: The potential of phase 1 to ground is shown initially at the middle of the film, where the record starts, at its normal value of 7600 volts. After about five cycles, the intentional ground was placed on the circuit. This shifts the neutral and causes the potential of vibrator 1 to rise somewhat (9150 volts). Sixteen cycles later the arcing ground suppressor switch closes on its first contact and raises the potential from 9150 volts to 11,750 volts. Four cycles later when the suppressor switch is entirely closed the potential of phase 1 rises to the delta value, namely, 13,150 volts effective.

Following through the conditions of vibrator 2, the intentional ground to start the operation of the suppressor occurred about five cycles after the shutter of the oscillograph opened. There was a small resistance in series in this circuit from phase 2 to ground, which limited the grounding current to 42.5 amperes. After a duration of about 16 cycles the arcing ground suppressor switch partially closes and reduces the grounding current in vibrator 2 to 20.4 amperes, and when the suppressor switch closes entirely, four cycles later, it shunts out the current from this intentional ground which takes the place of the accidental ground in the operation of the device.

Tracing now the zero recorded in vibrator 3, the suppressor switch contact touches the resistance one-fourth of a second after the first ground was put on the system—34.2 amperes flows through this resistance. The wave is perfectly smooth. The switch blade requires four cycles to pass through the resistance contact to its home contact. When this resistance is shunted out there is a slight momentary oscillation of grounding current of a frequency of about 480 cycles per second, which quickly dies out. During this test there was a discharge of the lightning arresters at Garfield substation and also at City Dock station. Note is made of this because of the impossibility of getting sufficient potential at any other time to cause a discharge of the lightning arresters.

STUDY OF PHASE RELATION OF THREE-PHASE POTENTIALS WHEN ONE PHASE IS GROUNDED THROUGH MORE OR LESS RESISTANCE

Fig. 15. *Oscillogram P.S.* 42, *Vibrators* 1, 2, 3,. 4 *and* 5. Oscillograms were taken with different values of resistance from phase 2 to ground. From these oscillograms are chosen the following:

Oscillogram	Resistance to ground	Current to ground
P.S. 42	Infinite	Zero
" " 50	835 ohms	9 amperes
" " 51	180 "	34 "
" " 46	21.6 "	60 "

The system was operating under normal conditions of day load.

Upper Record: Vibrator 1 is the potential of phase 3 to ground.
Middle Record: Vibrator 2 is the potential of phase 2 to ground.
Lower Record: Is the potential of phase 1 to ground.

NOTE: It just happened in this oscillogram that the separation of the zero lines from each other corresponded to the difference in calibration of the vibrators and this brought the tops of the peaks of the three phases about on a line. This is only incidental but it may cause some confusion in reading the oscillogram. This oscillogram shows the natural condition of the waves when there is no ground on the system.

Vibrator 4 shows the delta potential of 13,200 volts. Vibrator 5 shows the potential of the neutral to ground. This neutral potential shows the presence of a 3rd harmonic which has an effective value of 660 volts.

Fig. 16. *Oscillogram P.S.* 50. In this case the resistance from phase 2 to ground is 835 ohms, which limits the current to ground to 9 amperes. The voltage of phase 2 to ground is 7500 volts while the potential of phase 3 to ground is only 6730 volts. This illustrates the condition already described, of the reduction of the potential of phase 3 to ground when phase 2 is grounded through a comparatively high resistance. There is not yet sufficient shifting of the phase relation of the potentials of each phase to ground to be noted in this oscillogram.

Vibrator 5 shows an interesting development of the superposition of the third harmonic on the fundamental generator wave which appears as the neutral is displaced by the condition of ground.

Fig. 17. *Oscillogram P.S.* 51. The resistance to ground has now been reduced to 180 ohms and the current from phase 2 to ground has risen, correspondingly, to 34 amperes. It will be noted also in vibrators 1, 2 and 3 that the potential of phase 2 ground has decreased to 6120 volts, and the potential of phase 3 to ground has increased to 7220 volts, while the potential of phase 1 has already increased to the relatively high value of 12,200 volts.

Fig. 18. *Oscillogram P.S.* 46. Resistance to ground is 21.6 ohms. The current from phase 2 to ground has reached practically its full value of 60 amperes. The potential of phase 2 to ground has decreased to 1295 volts. The potential of phase 3 has increased to 12,600 volts, and the potential of phase 1 to ground has increased to 14,000 volts, which is greater than the delta value. The potential from neutral to ground shown on vibrator 5 has increased to 7630 volts and the effect of the third harmonic shows relatively little in this large wave.

Fig. 19. *Oscillogram P.S.* 60, *Vibrators* 4 *and* 5. The entire 60-cycle system through the suppressor switch on phase 2 is grounded.

Upper Record:	Current from the generator neutral to ground through aluminum cells and a small gap.
Lower Record:	Zero line only.

NOTES: On the upper record, the shutter of the oscillograph opens at the extreme left. There is a period of zero current until the suppressor switch strikes the resistance contact in the switch pot. At this instant the current from the neutral to ground through the aluminum arrester is so great that it carries the deflection off the width of the film. By continuing the traces of the oscillogram until the lines meet an approximate value of 20 amperes is given. After the fourth cycle the resistance to ground in the switch pot is cut out by a movement of the blade of the suppressor switch. The surge of current at the neutral again goes off the film. The maximum value of current gradually decreases as the electric system becomes adjusted to the new condition of ground. It may be noticed that all the way through this record there are three to five small current surges before the large one takes place in each half cycle. This surge is due to the small gap that was placed in series with the aluminum cells in this test. This gap was placed there simply to determine its effect on the current to ground. The large deflections, however, are not due to this small series gap. The subsequent oscillograms were taken under the same conditions, but this condition could not be reproduced. It may be noted that this surge is similar to the one previously noted in Fig. 13. It is included in this paper with the idea of showing everything unusual and abnormal.

Fig. 20. *Oscillogram P.S.* 62, *Vibrators* 1, 2 *and* 3.

Upper Record:	Vibrator 2 shows a zero line, as it was not used.
Middle Record:	Vibrator 1 is the voltage from phase 1 to ground.
Lower Record:	Vibrator 3 is the current in the lightning arrester.

NOTES: This oscillogram was taken especially to record a discharge of an aluminum lightning arrester in a station. Since there was insufficient potential from the surges to cause a discharge over the horn gaps at their minimum setting, the gaps were shortened sufficiently to spark at delta potential. The effective current in the arrester was 3.3 amperes by ammeter measurement. The peak of the instantaneous value given by the oscillograph showed about 5 amperes maximum.

Fig. 21. *Oscillogram P.S.* 65, *Vibrators* 4 *and* 5. During this exposure of the film, phase 2 of the entire system was grounded through the suppressor switch. During this time the lightning arrester had its gap so that it discharged but this discharge has no effect on either of the records of the vibrators shown.

Upper Record:	Vibrator 4 is the current from the generator neutral through aluminum cells to ground. The cells were directly connected without the intervention of a gap, such as existed in the previous figure.
Lower Record:	Vibrator 5 is the voltage from generator neutral to ground.

NOTES: At the left end of the record the third harmonic is prominent in both the current and potential wave, but naturally more prominent in the latter. When the suppressor switch closes, the third harmonic becomes of relatively little importance. While the resistance in the switch pot is in series to ground the voltage of the neutral rises only to 6200 volts, but after about four cycles this resistance is cut out and the voltage rises to 7630 volts. At the instant complete ground takes place the aluminum cells at the neutral show a surge current of 1.75 amperes maximum.

Fig. 22. *Oscillogram P.S.* 68, *Vibrators* 1, 2 *and* 3. This oscillogram gives a record of the main load currents in the three phases during the period of grounding.

NOTES: The ground takes place at about the tenth cycle of the generator after the opening of the shutter of the oscillograph. There is no visible disturbance of the load currents resulting from grounding. This result was checked in a subsequent test. The absence of disturbances is explained by the fact that the 60 amperes of grounding current is nearly at right angles to the greater value of power current. The power current at this time was about 310 amperes per phase, at 87 per cent power factor. The total load was 6200 kw.

Fig. 23. *Oscillogram P.S.* 70, *Vibrators* 1, 2 *and* 3. Charging current in the three phases of an unloaded cable which is not grounded. Energy was taken from generator No. 8 the same as in the previous test. The length of cable was 6.5 miles. The size of the copper conductor in the cable was No. 1 and the insulation was paper, 7/32 in. thick.

NOTES: It is interesting to compare the wave form in this oscillogram with that shown in several others. For example, if it is compared to the one shown in Fig. 10, it will be seen that a different harmonic is magnified. In the present figure the most prominent harmonic is the eleventh, whereas in Fig. 10, oscillogram 10, the most prominent harmonic is the seventeenth. In regard to the oscillogram 10, it is necessary to explain that a cable only 3.5 miles long was connected to the generator at that time, but it had the effect of magnifying the seventeenth harmonic. In this case, Fig. 23, an idle cable 6.5 miles long was connected. It is somewhat confusing to find the eleventh harmonic magnified. This is explained by the fact that when the seventeenth harmonic was prominent the generator was without load, whereas when the eleventh harmonic was magnified the generator was carrying the normal day load of the system. Other comparisons will be made in the notes of subsequent oscillograms.

Fig. 24. *Oscillogram P.S.* 71, *Vibrators* 1, 2 *and* 3. Charging current in three phases of an unloaded cable, the same as in the previous test except that phase 2 is grounded at the busbar. The generator is still carrying its normal load.

NOTES: The effect of grounding phase 2 is to steal away some of the capacity current in the wire and divert it to the cable sheath. Phases 1 and 3 show an increase in capacity current of perhaps 40 per cent. The capacity current in phase 2 drops off about half. Special attention is directed to these variations and capacity currents during ground. The variations indicate a change in capacity. In another paper on a localizer it is endeavored to prove that this capacity current in the grounded phase does not affect the localizers in the non-grounded cables.

Fig. 25. *P.S.* 73, *Vibrator* 1. Charging current to ground in the same unloaded cable, 6.5 miles long (cable *H*). The potential is taken, however, from generator No. 4, which is not carrying any power.

NOTES: In this record the thirteenth harmonic is more prominent even than the fundamental wave at 60 cycles. One might even consider the frequency from this generator in the cable as 780 cycles per second instead of 60. This record should be compared with previous records where the seventeenth and eleventh harmonics were prominent. Since there was no load in the generator the 12 teeth per pair of poles in the generator gave their distorting effect undiminished by any armature reaction from load current. The effective current to ground was 19.1 amperes. The thirteenth harmonic is free of any visible higher harmonics. In comparing this oscillogram with that of the generator No. 8 shown in Figs. 6 and 10, the difference in design of the generator armatures explains the difference in wave form. In the case where the eleventh harmonic was prominent the explanation is probably found in attributing the eleventh harmonic to a generator in the City Dock power station.

It is evident these harmonics exist in more or less magnified forms under different conditions of operation. The possibility of resonance with these harmonics is very remote. The possible chance of occurrence is about the same as that of winning a prize in a Chinese lottery. Still, the possibility must always be kept in mind, and whenever occasional troubles occur of unusually damaging effects, no doubt the magnification of the harmonics by resonance may at times come in for part of the blame. It has often been noticed, for example, on a system, that arcing grounds will take place many times without causing any trouble, but finally one single arcing ground will cause widespread damage. These oscillograms are reproduced especially to point out the *possible* source of high potentials from resonance.

Measure of Capacity Currents Made on Three-Phase Transmission Cables when One Phase is Grounded, and Generator Not Loaded. A number of tests were made of the distribution of capacity currents between the cables and sheath under conditions of construction. It was found that these currents deviated in value from the empirical laws that are given to cover such conditions. Not having time to look up the literature on this matter and fearing that the subject has been thoroughly covered, space is economized by not including them in this report. The fact that the currents do not check with the standard equations is easily explained by the changes in the harmonics that have been illustrated in the preceding oscillograms.

In introducing this subject the object is simply to call attention to the fact that the usual equations given for capacity between wires and sheath have little practical value in determining the charging current from any generator to a cable.

Data of a Grounding Test. Readings, Nos. 27 *to* 50. Returning to the subject of accidental grounds, the following table of a complete test is given for reference:

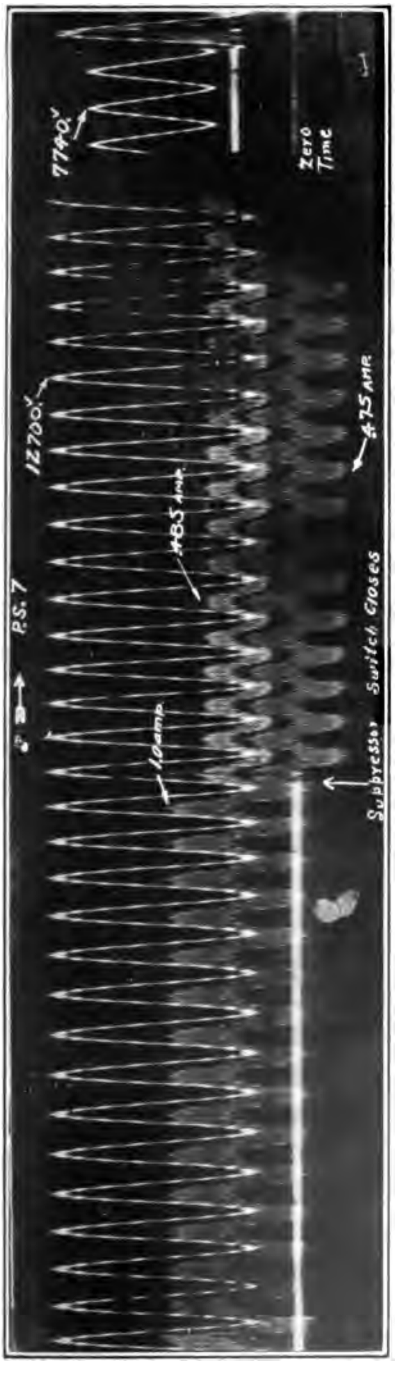


FIG. 6. [CREIGHTON AND WHITTLESEY]

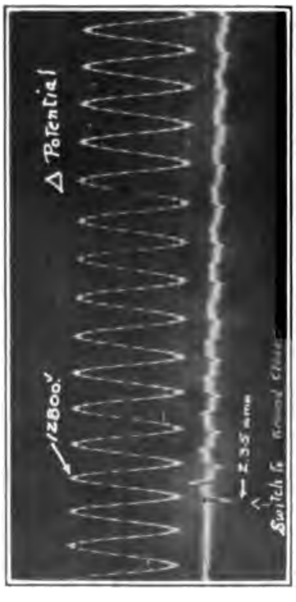
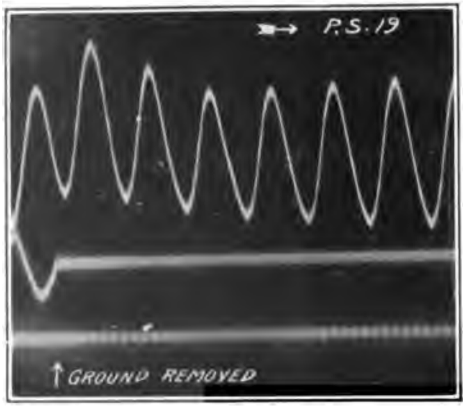


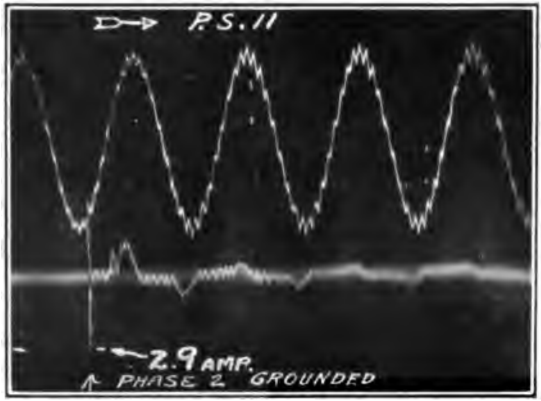
FIG. 8. [CREIGHTON AND WHITTLESEY]

FIG. 10. [CREIGHTON AND WHITTLESEY]



[CREIGHTON AND WHITTLESEY]

FIG. 12.



[CREIGHTON AND WHITTLESEY]

FIG. 11.

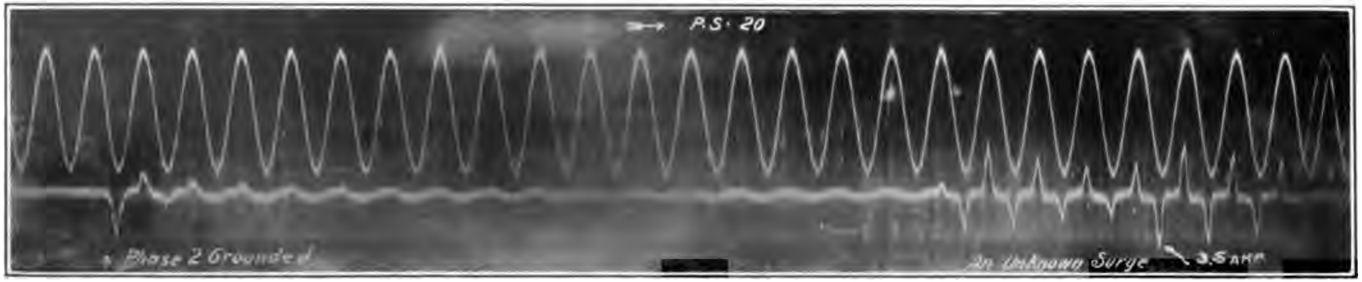


FIG. 13.

[CREIGHTON AND WHITTLESEY]

PLATE XCVIII
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VOL. XXXI, 1912

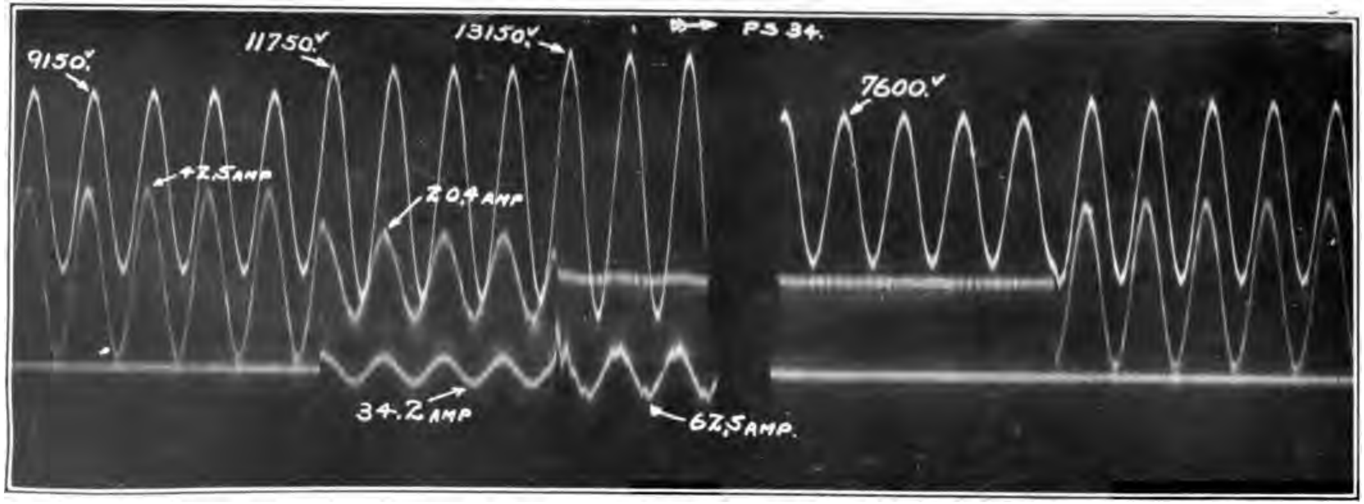

Fig. 14.

[CREIGHTON AND WHITTLESEY]

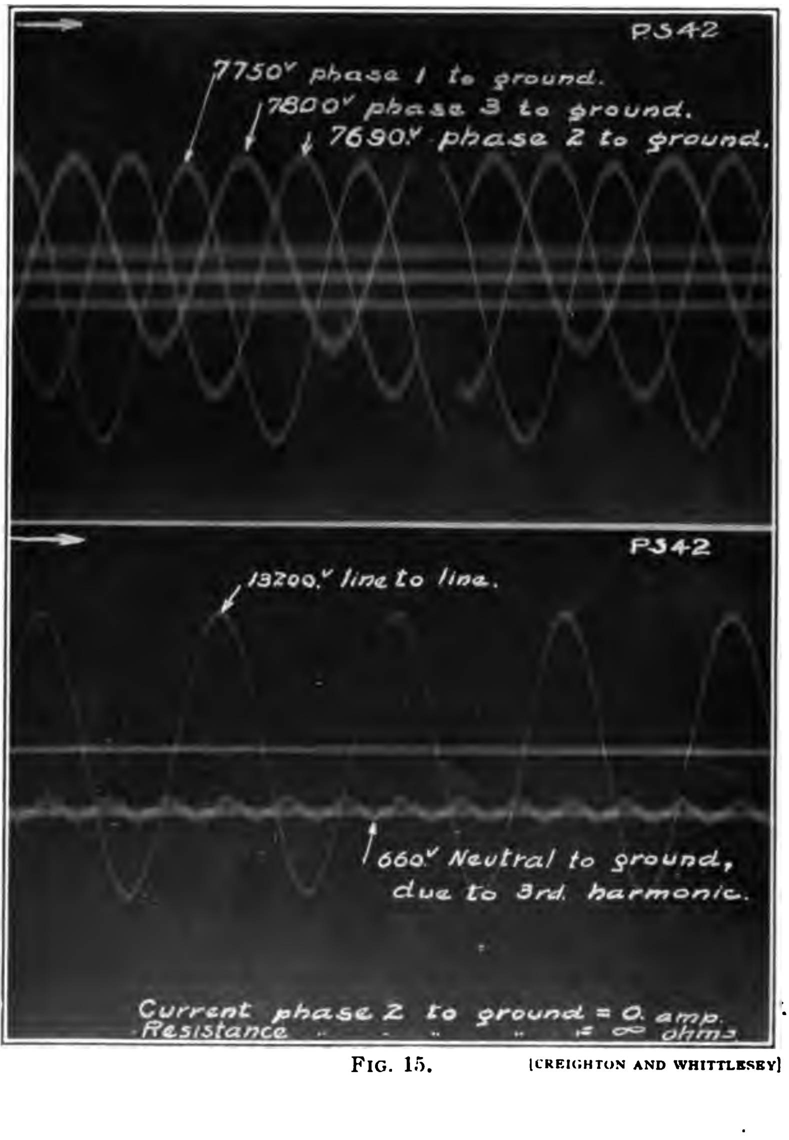

FIG. 15. [CREIGHTON AND WHITTLESEY]

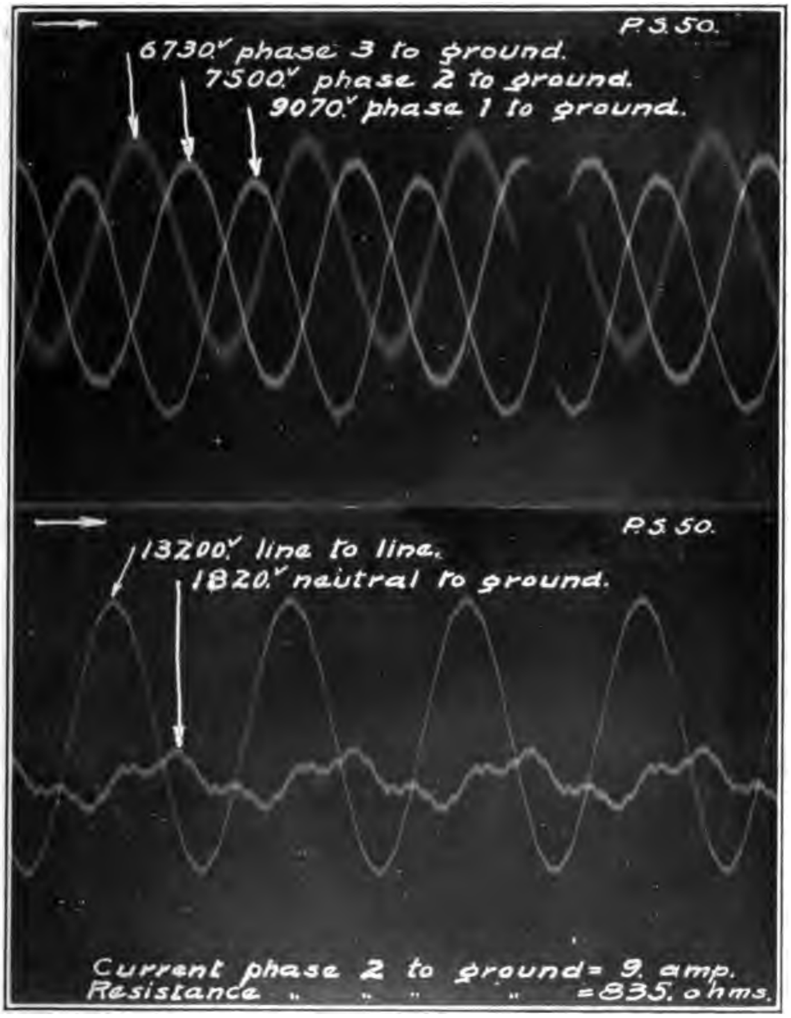

FIG. 16.

[CREIGHTON AND WHITTLESEY

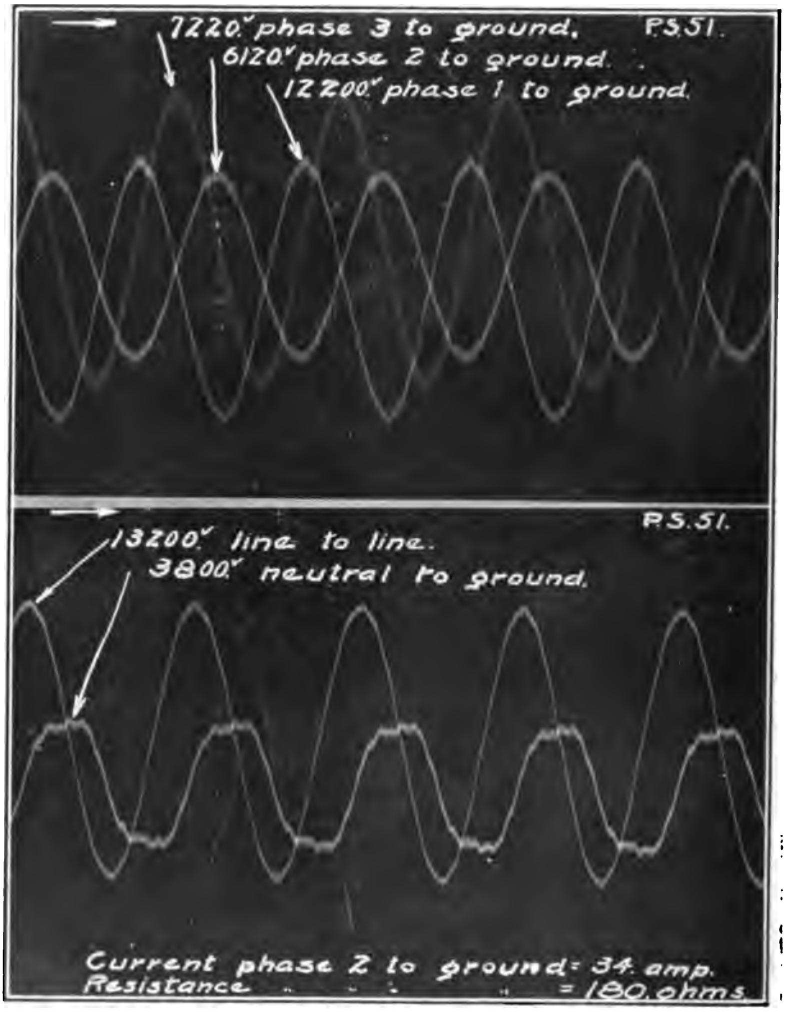

FIG. 17. [CREIGHTON AND WHITTLESEY]

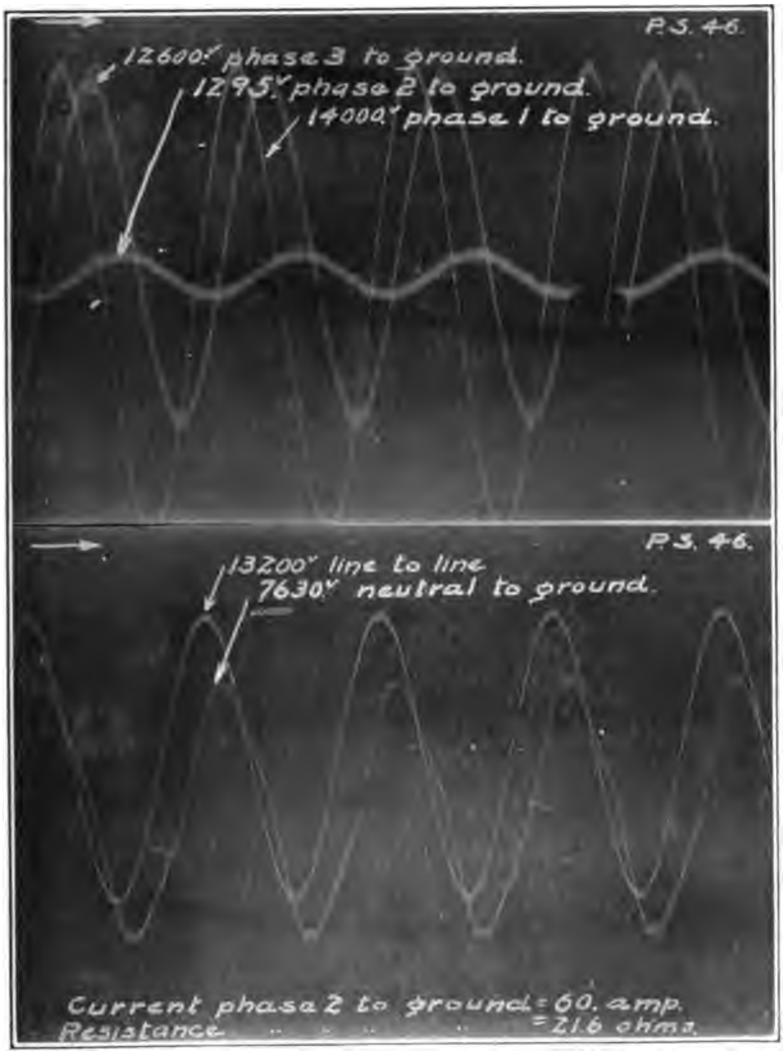

FIG. 18. CREIGHTON AND WHITTLESEY]

[CREIGHTON AND WHITTLESEY]

FIG. 19

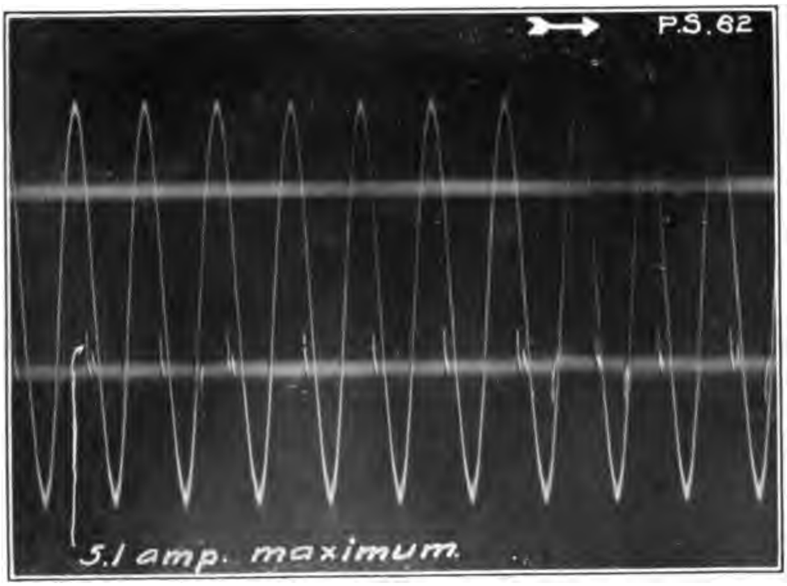

FIG. 20. [CREIGHTON AND WHITTLESEY]

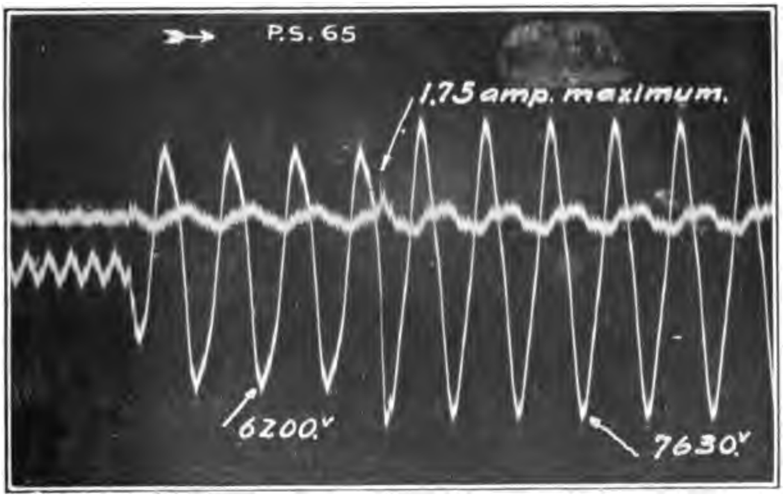

FIG. 21. [CREIGHTON AND WHITTLESEY]

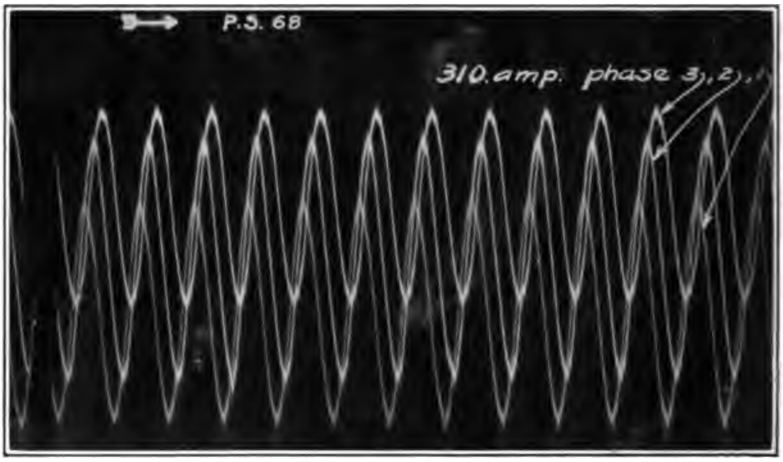

FIG. 22. [CREIGHTON AND WHITTLESEY]

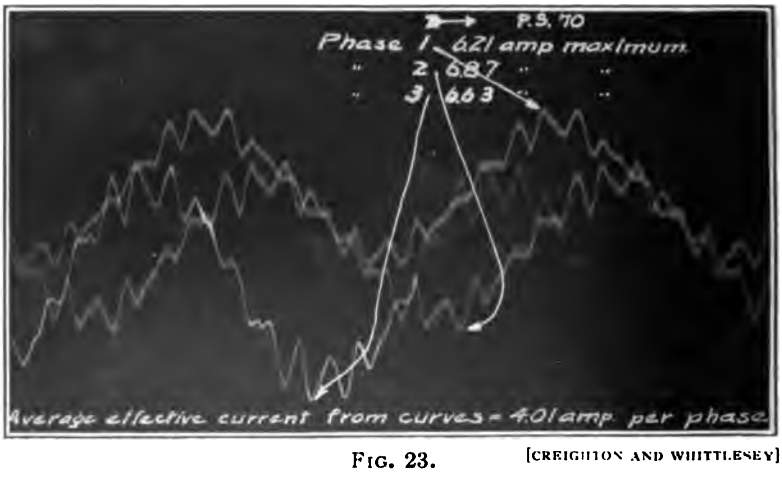

FIG. 23. [CREIGHTON AND WHITTLESEY]

FIG. 24. [CREIGHTON AND WHITTLESEY]

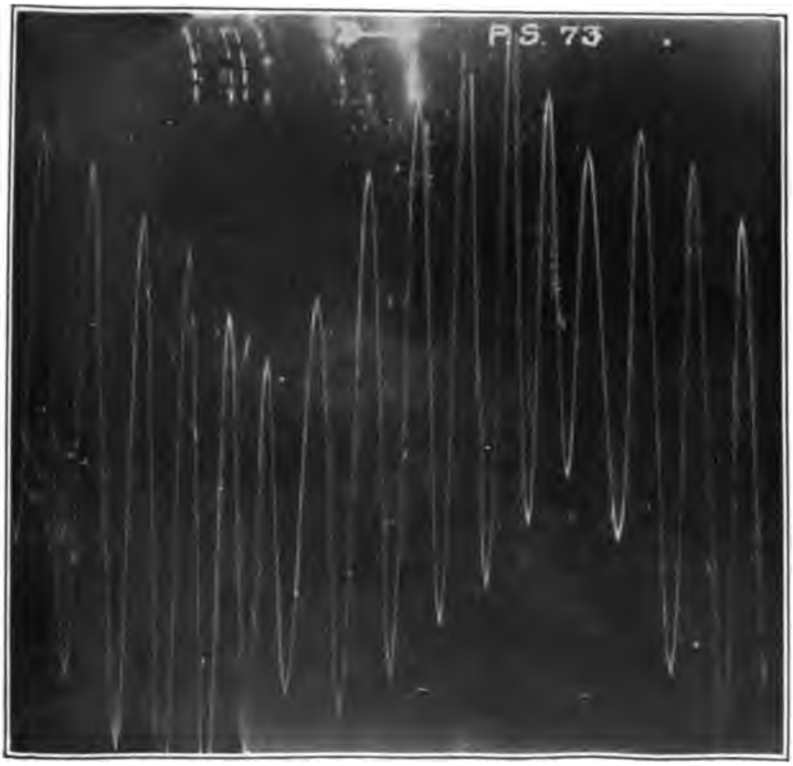

FIG. 25. [CREIGHTON AND WHITTLESEY]

Reading No.	Hour	Potential to ground			I_3 to ground	R to ground	I localizer	Oscillogram
		V_1	V_3	$V.$				
27	3:24	7,740	7,720	7,800	0	00	0	
28	3:25½	9,250	7,500	6,700	11	682	0.3 ?	47
29	3:26½	9,400	7,450	6,620	12	621	0.35?	
30	3:27	9,370	7,440	6,600	13	572	0.35?	
31		9,720	7,380	6,500	14	527	0.35	
32	3:27½	9,930	7,360	6,480	16	461	0.35	
33		11,250	6,780	6,600	26	261	0.48	
34		11,730	6,490	6,900	29	224	0.52	
35		12,250	6,180	7,260	34	182	0.60	
36	3:29	12,550	5,880	7,680	37	159	0.64	
37		12,930	5,520	8,050	40	138	0.70	
38		13,180	5,260	8,520	42	125	0.74	
39	3:30	13,310	5,040	8,760	44	114.5	0.76	48
40		13,530	4,780	9,180	46	104	0.80	
41	3:31	13,770	4,320	9,660	48	93.7	0.86	
42		13,910	3,900	10,150	51	76.5	0.88	
43		14,000	3,700	10,500	52	71.2	0.90	
44	3:33½	14,090	1,140	12,720	60	19	1.2	
45	3:34½	13,930	1,105	12,650	60	18.4	1.2	49
46		14,300	2,990	10,690	56	53.4	1	
47		12,600	5,760	7,680	41	140.5	0.70	
48		12,840	5,580	7,980	39	143	0.70	
49	3:36	11,950	6,360	6,960	34	187	0.56	

RELATION OF KILOVOLTS TO GROUNDING RESISTANCE IN A GROUNDED PHASE

In the previous illustration the relation between current and voltage for the three phases was given. In some cases it is valuable to know the relation between the voltages and resistance from a phase to ground. This is given in Fig. 26.

Relation of Power Lost in the Ground Circuit and the Current to Ground. For several reasons the energy lost in the grounded circuit is of value, also the conditions at which maximum energy loss occurs. It is evident that when the resistance is infinite there is no loss of energy, and again when the resistance is zero there is no loss of energy. The maximum loss occurs when the current is about ¾ its full value to ground. The relation at every instant is shown in Fig. 27.

Relation of the Power Lost in the Grounded Circuit, and the Difference of Potential between the Grounded Phase and Earth. This relation is shown in Fig. 28.

Rate of Development of an Accidental Ground. When this work was first begun it was hoped that some device might be constructed which would indicate the early stages of the development of an accidental ground so that the arcing-ground suppressor could be used to prevent an actual arc to ground by closing on the fault during this early stage. A brief consideration of the power curves already given will show the difficulties involved. For example, in Fig. 28 when the potential of the grounded phase is diminished by only 10 per cent the energy lost is 170 kw. From the standpoint of potential, it is not easy to make a device sensitive to a change of only 10 per cent and still maintain a high degree of reliability. From the standpoint of rapidity of development of the fault, it is quite evident that 170 kw. applied to a small hole in the insulation about one-half inch long will carry the resistance immediately down to a negligible value. Taking another example in which the drop in potential is less, the conditions still seem to be hopeless. When the drop of potential to ground is only 1 per cent there is a loss of 70 kw. at the fault. Seventy kilowatts concentrated in a small fault is sufficient to develop it with enormous rapidity. In order to get the loss at the fault down to a value that will develop at such a rate as to permit the operation of a safety device, let us assume that the energy loss in an incandescent lamp is the upper value that can be allowed in the fault. When one considers that an incandescent lamp has a filament longer than the fault in the insulation, and that that filament becomes incandescent with 50 watts in it, we have surely not chosen, as a basis, a value of energy loss that

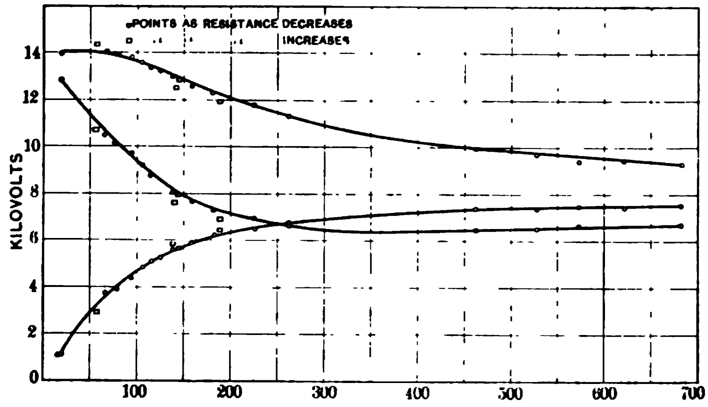

FIG. 26—VARIATION IN VOLTAGE OF EACH PHASE TO GROUND AS RESISTANCE, PHASE 2 TO GROUND, VARIES.
Curves from test data, readings Nos. 27 to 49, Aug. 22, 1911.

is too small. Still, when we consider this energy loss, the problem is far more difficult. A loss of 50 watts in the fault corresponds to a resistance of 1,000,000 ohms. When it comes to locating a fault of 1,000,000 ohms in a system where the insulation resistance runs from 2000 ohms up to 500 megohms, the difficulties seem insurmountable and unsolvable by any of the devices that have been described in scientific literature. From a standpoint of utilization of the current of the fault to ground, it is interesting to note that the value is only 77 milliamperes. When one considers that the load current on the system is several hundred amperes, and the electrostatic charging current five amperes or more per cable, the difficulties in this approach to the problem are obvious. It is evident that for large systems the solution in sight is either to allow the fault to develop when it will and take care of it with the arcing ground suppressor, or to utilize the following proposed method:

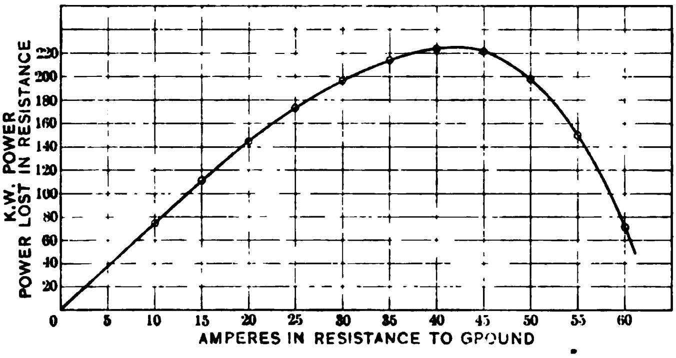

FIG. 27

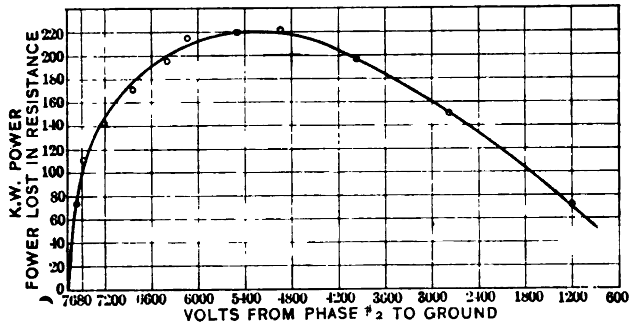

FIG. 28

Predetermining the Faults in Cable Systems. Experience shows that practically all the faults in a cable system develop initially between a single phase and ground. If the arc is not extinguished the arcing ground will very quickly burn the insulation between phases so badly as to cause a short circuit. In fact, this is what has always taken place when a fault has occurred on a cable system. There are certain weaknesses and accidents that cannot be foreseen, and the arcing ground suppressor with the localizer seems to be the only practicable solution in sight at present. There are, however, many faults which can be prematurely developed at a time most convenient to the operating engineer. Operators have often need to paraphrase an old saying in the form: "Grounds never come singly." One arcing ground will set up surges which will weaken other parts of the cable system, and these weakened points will subsequently develop into grounds. From experience in the laboratory, and from our knowledge of the phenomena, it is evident that most of these faults develop very gradually in the early stages. Laboratory experience shows very convincingly that insulation will stand a fairly definite limiting potential without any deterioration. Also, that slightly above this limit the deterioration is exceedingly slow, but becomes more and more rapid, along a descending logarithmic curve, as the potential across the insulation is increased more and more. If a test potential for a cable is chosen at a value that is less than the deteriorating value, then there can be no objection to applying it as frequently as desired. If, while this test potential is applied, there are inherent faults in the insulation which are still in their early stages of development, then the higher potential will hasten the development of these faults. Any inherent fault, then, may be developed at a time of the day and week when it is most convenient to make repairs, and when a spare cable may be substituted for the faulty one with the least inconvenience and disturbance in handling the load. To meet this situation, then, it is proposed to introduce at an artificial neutral, direct-current potential which will raise the total potential of the entire system by a specified amount above ground. Faults which stand this strain for several minutes are not likely to develop at normal potential within several days. The application of such a method would, we believe, tend greatly to keep the system free of incipient or embryonic faults. It is a refinement which, in the future, perhaps, may find considerable application. The assumption is made that some faults will always develop in cables due to inherent weaknesses and age, or due to troubles which may come from electrolysis of the sheath. It is, then, reasonable to develop these unavoidable faults at the most convenient time without switching or disturbance of the load. Plans are being made to apply this method.

INSULATION RESISTANCE OF THE SYSTEM OF THE PUBLIC SERVICE ELECTRIC COMPANY

This system consists of both overhead and underground construction. A statement has already been made that the insulation resistance under normally safe conditions of operation varies from 2000 ohms to 500,000,000 ohms. While Mr. A. H. Davis was making a study of the factors involved in the design of a localizer, he carried on, incidentally, continuous tests of the insulation of the system. The results show several features of interest.

The tests were made along the lines proposed above, that is, a direct current was applied at an artificial neutral formed by three potential transformers. In series with this direct-current generator was a recording ammeter. The current was kept within the range of the ammeter by different values of direct-current applied. Some typical results are shown in the following plotted curves of the *resistance of insulation* of the system as ordinate, and *time* as abscissa. Since the range of insulation resistance was so very large, a special method of plotting the curves was used. Three scales are used in the ordinates. These scales are placed one above the other, but there will be no difficulty in reading the resistance in the usual way by jumping from one scale to the next where the changes in resistance require it. The diurnal variations which actually took place are shown in these curves—also the variations in resistance from minute to minute when the insulation resistance was low. The needle of the recording ammeter under these conditions moved over a very wide range. Low resistance invariably came from the overhead lines and was due entirely to weather conditions. The resistance varied according to the variations in the precipitation. Resistance might be of a medium high value, and a fog, or slight precipitation, might cause changes from minute to minute over a small range. When there was a steady downpour of rain over all the insulators, then the resistance became very low and unsteady. This may have been largely due to spattering of water up under the petticoats of the insulators. The measurements brought out one interesting condition that has been noted elsewhere, but so far as the writer knows, never measured. Just before sunrise there is nearly always a sudden drop in the insulation resistance. A little later the insulation returns to a fairly high value. This is explained by the fact that when the sun rises, the temperature of the atmosphere around the insulator is above the temperature of the insulator. In other words, the insulator absorbs heat more slowly than the air does. This leaves a cold insulator in contact with a more or less moist atmosphere and the result is a precipitation of dew on the surface of the insulator. This dew lowers the insulation resistance. Later, the insulator takes the same temperature as the ambient atmosphere and again dries off, which restores the insulation to its previous value. The tendency of insulators to break down at sunrise was noted years ago on some Mexican lines. Typical curves of the insulator resistance of the system are given in Figs. 29 to 34.

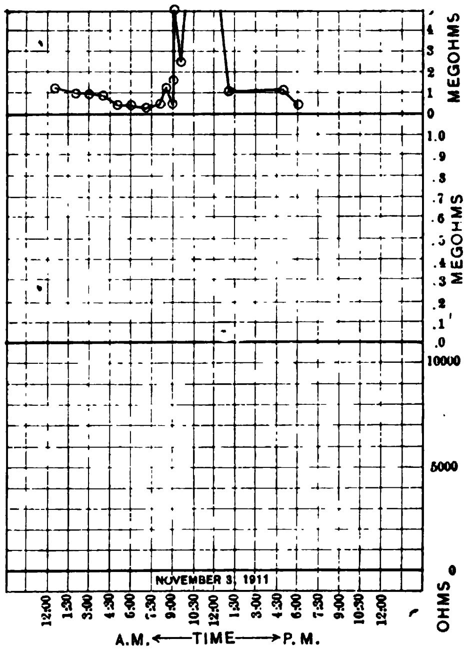

FIG. 29

The insulation resistance on one day (Fig. 29) ran above 100,000 ohms. Between the hours of 10:00 and 12:30 the insulation ran above five megohms. The day was clear and the atmosphere fairly dry.

The curve of insulation resistance two days later as shown in Fig. 30 has a medium value all day. In the early morning between 1:30 and 3:00 o'clock there was either a shower or heavy fog. This we have indicated on this curve by a zigzag line in imitation of the movement of the ammeter needle over the same period of time. The insulation varies from 300,000 ohms to 600,000 ohms during the day. As in the previous figure, the insulation increases during the middle of the day, although, due to the moisture in the atmosphere, the actual value of resistance is not nearly so high as shown in the previous figure. The day was cloudy.

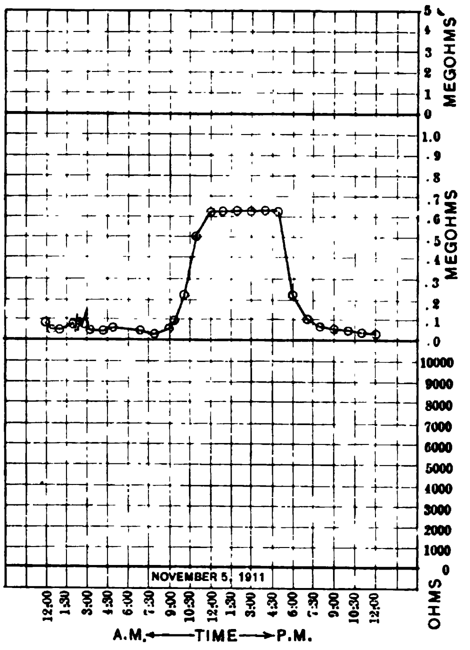

FIG. 30

The resistance during the next day (Fig. 31) is typical of bad weather. Along about 5:00 o'clock in the morning there was evidently a light shower. At 9:00 o'clock the resistance became so low that the deflection of the ammeter went off the scale.

This condition of the meter was not corrected by lowering the voltage until 1:30. During this time the resistance dropped from 100,000 ohms down to 7000 ohms. There was a shower about 2:00 o'clock, another one at 4:30, and another at 9:00 p.m. During this entire time the resistance was varying up and down over a wide range, as indicated in this figure by the zigzag lines. The lowest resistance of insulation recorded during the day was 3000 ohms.

The record in Fig. 32 was taken on the following day. It rained heavily in the early hours of the morning but cleared up in the afternoon and dried off sufficiently to carry the insulation resistance from 5000 ohms at 4:00 a.m. to 5,000,000 ohms at 5:00 p.m. Part of the record was lost during the middle of the day due to the lack of adjustment of the voltage on the recording ammeter. The variation of resistance was so great as to require a variation in the direct-current potential in order to keep the needle of the ammeter on the scale.

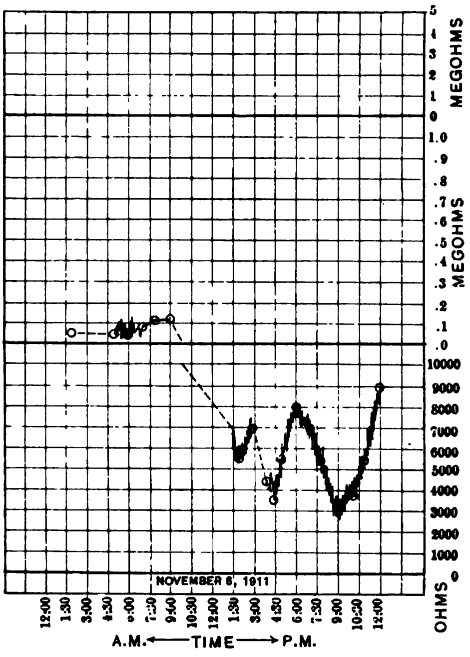

FIG. 31

The record in Fig. 33 was taken two days later. It is typical of the usual cloudy weather conditions and illustrates a condition of precipitation of dew already referred to. At 3:00 a.m. moisture in the atmosphere begins to make itself felt and the resistance drops from 650,000 ohms to 100,000 ohms at 7:00 o'clock. The dissipating effect of the sun's rays then begins to make itself felt and the resistance of the system rises rapidly and reaches a value of about one megohm at 9:00 a.m. While the sun is directly overhead the resistance remains high, but at 3:00 p.m. the insulation resistance again drops and reaches a value of 200,000 ohms at 6:00 p.m. Due probably to a favorable dry wind the insulation rises again until 9:00 p.m., but drops rapidly thereafter and reaches a value of less than 100,000 ohms by midnight.

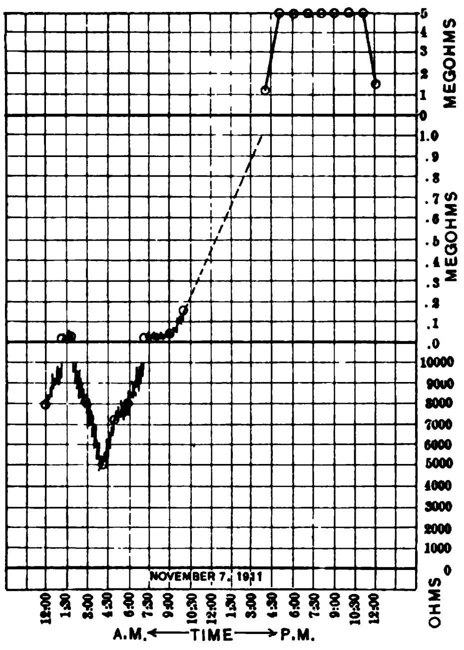

FIG. 32

The record of a later day (Fig. 34) illustrates a condition that is difficult to explain. During the early morning hour the resistance ran low but steady. At noon time it began to rain. At 5:00 o'clock the rain ceased and the resistance rose rapidly to over two megohms, but dropped in a few minutes back to its former value. This same condition was repeated five times up to midnight. There is a possibility that this variation might have been due to a fault in the measuring apparatus such as might result from some accidental condition of contact between the brushes of the direct-current generator and the commutator, Considerable variations have been noted, although not as great as shown here, due to the passing of a cloud and a burst of sunshine, but this could not be the explanation here. In this case such a variation might also be caused by the accidental contact of a live wire with the limb of a tree, which was removed during short intervals. In such case the limb would finally be burned away and leave the insulation high. One of the above conditions, we suppose, accounts for the form of these resistance curves.

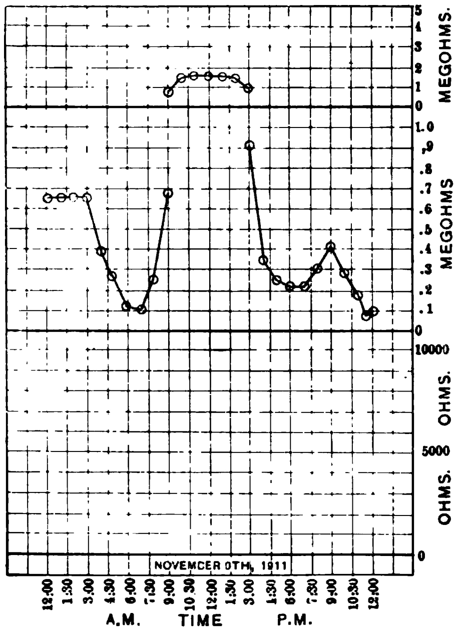

Fig. 33

Some Characteristics of the Arc in the Arcing Ground on a Cable

Those who have made observations on the length of time required for an arcing ground to develop into a short circuit, and also on the difference in the destructive effect of arcing grounds occurring at different times and different places, cannot help but be impressed by remarkable differences. If we compare the accidental arcs of one system with those on another, naturally we will expect to find different harmonics. Furthermore, due to differences in electrostatic capacity, different values of grounding current will also occur. These fundamental differences will naturally give different effects. The cause of the difference is not so evident, however, when we consider arcing grounds on the same system at different times, when, apparently, all the conditions of generation and capacity are identical.

In discussing this subject it might be well to bring up at this time the possibilities of variations coming from the reactions of the receiver apparatus on the circuit, such, for example, as synchronous motors, induction motors, etc. The presence of these machines has to do with the harmonics, but apparently has no effect on the duration of the accidental arcing ground before it burns into a short circuit. This latter seems to depend very greatly on the peripheral location of the accidental arc on the sheath of the cable. If, on the one hand, the arc should take place on the under side of a horizontally placed cable, the melted lead from the crater of the arc would drop down and there would be a tendency to melt the lead away from the fault, and thereby constantly increase the arc length. We know that a varying arc length will cause a magnification of different high frequencies. On the other hand, suppose the accidental arc takes place on the upper side of a horizontally placed cable, then the melted lead from the sheath will tend to run into the punctured hole in the insulation and make a direct contact from the faulty phase

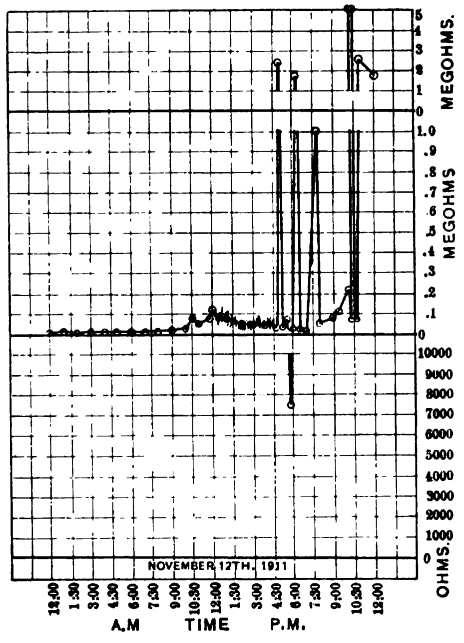

Fig. 34

to ground. If the charging current is not large, then the lead in a solidified form may have sufficient conductivity to radiate the I^2R given to it by the grounding current. The extinguishment of the arcing ground in this case will cut off the surges and a system would be able to run for hours without interference to the power service. If, however, the lead from the sheath which melts and runs into the hole is not quite sufficient to carry the grounding current, it will be continually breaking up, forming a short arc which melts more lead, which in turn again shortens the arc. In other words, there will be an intermittent arc to ground. The duration of the fault before it burns into a short circuit may still be many minutes.

By taking into account the possible variable locations of the three phases relative to a vertical line, and the variable peripheral location of the arc on the sheath, it seems possible to explain many of the different effects that have been obtained on the same system with different accidental arcs to ground.

Another factor is the peripheral location of the fault on the insulation of a single phase. If the fault should occur where the insulations of the two adjacent phases come in contact it will, naturally, burn into a short circuit much more rapidly than if the fault should occur at a point nearer the lead sheath.

Another condition that will cause differences in transient potentials has been mentioned in previous papers. This difference comes from the location of an accidental arcing ground relative to the length of the feeder. Like the light touch of a finger on a violin string which makes it vibrate on high notes by oscillations in sections, the same condition may occur electrically on a feeder. There are certain locations on a violin string where a light touch will simply dampen the vibrations. Apparently there exists the same condition in the electrical circuit. There are, however, many places on the violin string which give different clear high tones, and by analogy, there are the same conditions on the electrical circuit. If any one of these high frequencies happens to resonate with some localized inductance and capacity in the circuit, damage results. This is mere chance and is a condition which, happily, does not occur often during accidental grounds.

When a short circuit takes place which is not the result of the development of an arcing ground it usually occurs at a defective joint. In order to give the arcing ground suppressor a maximum efficiency in preventing interruptions of service, special care should be taken to prevent weakness in the joints.

A difference has been noted in the strength of joints on different sections of a system which results from a difference in the policies of the repair foremen. On one section the foreman makes a repair just as soon as it can be done at any time of day or night. On the other section the foreman waits for daylight and other favorable conditions of the atmosphere and weather. The foreman who waits for propitious conditions has fewer breakdowns in joints than the one who pays less attention to the conditions. If it is assumed that each is equally conscientious in his work, and that no other factors enter, the extra care seems very much worth while.

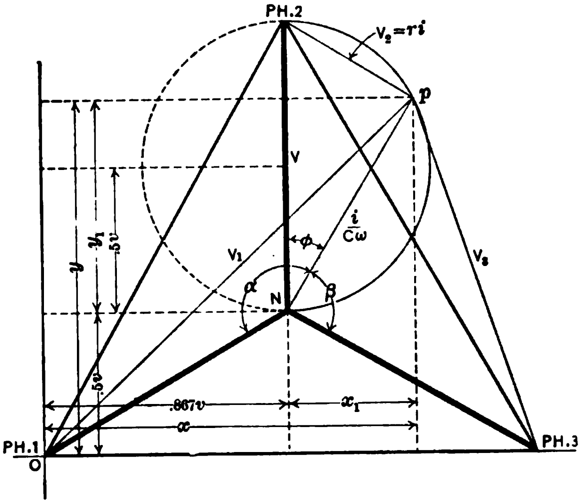

FIG. 35

From the relations shown in Fig. 35 the equation for the potential of one of the non-grounded phases (V_1) in terms of the delta potential (V) has been worked out:

$$V_1=\sqrt{V^2 \pm 1.734\,V\sqrt{K-\frac{K^2}{V^2}}+2\,K}$$

in which $K = \frac{i}{C^2\,\omega^2}$

Since the diagrammatic solution is so much simpler, this particular analytical form has little to recommend it. The expression in polar coördinates is simpler.

SUMMARY

Generators on a *loaded* three-phase system maintain practically constant delta potential between phases. The generators themselves generate nearly constant and stable *Y* potentials. Any shifting of the neutral of the generator on a loaded system is transitory. The values of potential of the three phases to ground are determined by lines drawn from the corners of the delta triangle to a point on a semicircle drawn on the *Y* potential as diameter. This semicircle is drawn on the side of the *Y* potential next to the succeeding phase (see Fig. 35). For example, if phase 2 is grounded the semicircle is on the side of phase 3.

In the oscillograms of the operation of the arcing ground suppressors, no dangerous potentials were observed. The suppressor operates in one-quarter of a second in accordance with the usual design of switch.

Different harmonics were found on the system, namely: 11, 13 and 17, which were magnified more or less according to the conditions of capacity. In themselves, these harmonics have no baneful significance.

The effects of an arcing ground on a cable are modified by movements of the melted metal of the lead sheath. On the under side the lead drops away and thus increases the arc length. On the upper side the molten metal runs down into the fault and shortens the arc.

For a certain value of resistance to ground, the value that drops the potential to ground by about one-third, the loss of energy in the fault is a maximum of 220 kw.

A method of predetermining faults in the insulation while the system is in normal operation, is proposed, in which high-potential direct current is applied at the neutral, protection being given by arresters, suppressors and localizers.

All the protective effects of a grounded neutral may be obtained by connecting aluminum cells between the generator neutral and ground and, at the same time, all the objectionable effects of short circuits and cross currents that attend a grounded neutral are avoided.

The insulation resistance of a mixed overhead and underground system is determined almost entirely by the relatively high leakage over the insulators. Weather conditions changed the insulation from 5000 ohms to over 500 megohms.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

RELAY PROTECTIVE SYSTEMS

BY L. L. ELDEN

Reviewing American practise in the use of relay protective devices for electrical generating, transmission and distributing systems, there appears to have been no material change in the construction or commercial application of this class of apparatus in a considerable period of years.

Such improvements as have been made relate principally to mechanical details for increasing the reliability of operation and maintenance of adjustment of relay apparatus. Recently, in response to demands for modifications of the electrical characteristics of time limit overload relays, certain changes have been made in existing types of relays, and in addition a new type of relay has been introduced. These developments have tended to increase greatly the facilities for obtaining selective action between different relays in stations where such operation of relays is desired.

Experience has shown that no single part of an electrical system is free from the possibility of injury, either accidental or unavoidable as may be the case, and that it is incumbent upon operating and designing engineers to protect their systems as far as possible from such occurrences, through the use of protective devices suitably designed to afford such protection.

We may summarize American practise in the application of relay protection to the various parts of alternating-current electrical supply systems of moderate and large capacities as follows:

Generators. In general, generators are not arranged for automatic disconnection from the system which they supply, upon the occasion of a fault developing within their windings or their connections to the main buses. Reverse current relays are used in many cases to operate signals to indicate reversal of current in generator circuits, but under all conditions the judgment and movements of the operator are usually depended upon for the proper operation of generator switches.

Transmission Lines. Relay protection for transmission lines varies with type and method of operating different systems, but in general either instantaneous, inverse time limit or definite time limit types of relays have been used, according to engineering judgment.

In systems operating radial feeders, with each feeder connecting to only one substation and not operated in parallel at substation ends, reasonably satisfactory service has been rendered by the types of relays referred to.

In systems operating ring systems of feeders, or radial feeders with several substations in tandem on a single feeder, where selective adjustments are required between different relays in order to prevent interruption of service from all stations between a fault and the source of power, satisfactory results have rarely been continuously attained with any of the types of relays mentioned. In attempting such operation recourse has been had to reverse current relays in combination with time limit overload relays, with equally unsatisfactory results.

In addition to these regular or standard methods of employing relays for line protection, many attempts have been made to devise arrangements for cutting a defective feeder out of service from among a group of feeders operating in parallel at both ends, without affecting the remaining feeders. Combinations of reverse current and time limit relays have been used for this purpose, arranged with interlocking attachments to prevent other than faulty feeders being affected.

It may fairly be said that indifferent success has uniformly been the result of the use of such arrangements, due in some part to the failure of the apparatus itself to operate consistently and continually as designed, and in other ways the apparatus has failed to meet the conditions developed by faults. There are of course some instances where radial systems of transmission lines have operated with reasonable satisfaction, using some form of standard relay for protection, still, it is well known that failures have been experienced through faults inherent in the relays themselves, thereby producing a feeling of uncertainty as to their operating condition at all times while in service.

Recourse has been had to frequent inspection and tests to prevent failure in service, all of which creates undesirable expenditure for maintenance without adequate return in security from failure.

Putting the situation plainly, the standard relay devices in use in our alternating-current systems are inadequate properly to protect the apparatus they are intended to protect, simply because they do not discriminate between faults and excess current conditions.

It is probable that very few engineers on this side of the water appreciate the great difference between American and European practise in the use of relay protective devices. Articles have appeared in the technical press from time to time in which brief comment has been made in reference to certain developments and applications of protective systems in England and on the Continent, without, however, attracting the attention they deserved.

A personal inspection of some of the larger European undertakings reveals substantial advances in the art of relay protection which, as applied to generators—sections of busbars—transmission lines and substation apparatus, have operated with marked success. Several systems have been developed which possess merit, but among them all the system invented by Messrs. Merz and Price of London, England, is apparently the most flexible and best adapted for application to any of the problems of such a character as are met with in the protection of the various apparatus and connecting links comprising electrical supply systems.

This form of protection has proved so reliable in practise that it has become not only safe, but possible, to operate high-tension interconnected transmission systems without risk of the failure of a single section interfering with the remainder of the system. Individual ring feeders may not only be cross-connected at will, but may with perfect safety be interconnected with other ring or radial feeders as desired, either for reasons of capacity or insurance of service to consumers. The economic advantages resulting from such use of investment, particularly in systems covering wide areas, are too obvious to require comment. The extent to which the interconnection of feeders and generating stations is carried out in regular service is indicated in some measure by reference to Fig. 1, in which is shown a typical arrangement of interconnected high-tension feeders.

This system of protection has the further advantage of being discriminative in action, operating only under fault conditions, and possessing the further valuable characteristics of cutting out defective apparatus instantly, or while troubles are in the incipient stage, thus preventing the destructive aftermath which sometimes follows minor troubles if allowed to develop to serious proportions. Its introduction and subsequent use has modified foreign practise to such an extent that there is a strong tendency to apply the system to generator protection in many new installations, while some important companies are adopting this system for the protection of existing generating and transforming apparatus.

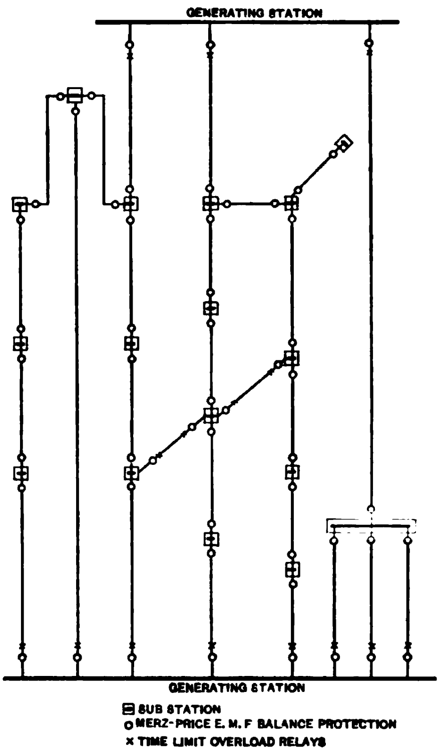

Fig. 1—Typical Arrangement of Relay Protection with Merz-Price System.

The Merz-Price system of relay protection is based on the principle that if a conductor in service is in a sound condition the current entering and leaving it must be of the same value, due allowance being made for losses. It will thus be apparent that such a system is capable of being arranged for the protection of any generator, section of busbar or transmission line, by introducing suitable relay equipment at the proper points.

The apparatus employed in this system consists of suitably designed series transformers and relays, and, in addition, pilot wires forming a connecting link between the relay apparatus located at the terminals of the protected section of line.

The limitations of the system lie mainly in the first cost and construction incident to the installation of the pilot wires, the remainder of the apparatus or its application being no more costly and at the same time far simpler than the devices which we regularly use for similar purposes. In the commercial use of this system two standard arrangements of the apparatus are generally employed, although many other combinations may be arranged for special purposes. These two standard arrangements are designated as " current balancing " and " potential or e.m.f. balancing." " Current balancing " is usually employed for the protection of generators, transformers, frequency changers, etc., while " e.m.f. balancing " is used in connection with feeder protection where the energy losses in the pilot wires make the current balancing scheme undesirable. In addition another development is called the " magnetic balance system ", which has its application in similar locations to those in which current balancing is used.

Fig. 2 illustrates the principles of these three arrangements of protective devices, in which

A represents the " current balance system " applied to the protection of a transformer,

B represents the " e.m.f. balance system " applied to feeder protection, and

C represents the " magnetic balance system " applied to transformer protection.

In *A* it will be noted that series transformers are installed on both primary and secondary sides of the main transformer. The series transformers are of such ratios that their secondary currents are equal at all loads on the main transformer, and are connected with their secondaries in series, with the current flowing in the same direction through the secondary circuit. Suitable pilot wires are employed to complete a relay tripping circuit, with the relays connected to the central points of the secondary circuit as shown. As the connection of the relay circuit to the secondary circuit is made at the point of zero potential, no current flows in the relay circuit so long as the current in the main conductors, and therefore in the secondaries of the series transformers, remains balanced or in the same ratio. Any variation in this current balance results in a flow of current through the relay circuit, thus causing the relays to operate to open the main switches on both sides of the main transformer, upon the unbalance reaching predetermined values for which the relays may be adjusted. Series transformers of any standard design are suitable for use with this scheme of protection, provided, however, they are of sufficient capacity to furnish the necessary current to overcome the resistance of the pilot wires and trip coils as well as their own impedance. What is more important, they must maintain their own ratio with great accuracy under extreme overloads, otherwise the relays may be operated at times unnecessarily, through the difference in secondary currents delivered by the protective transformers under the same load.

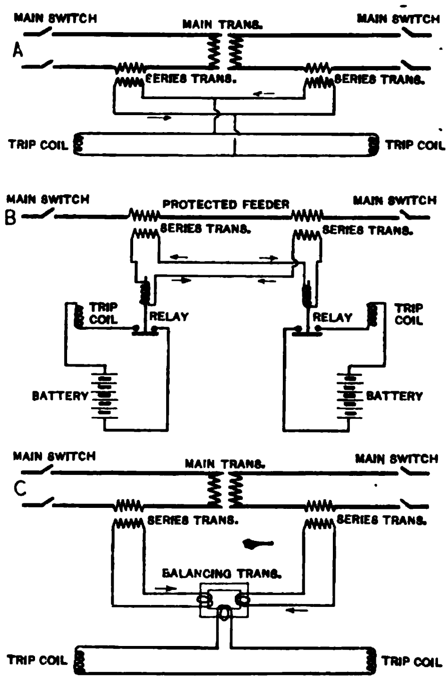

FIG. 2—TYPICAL ARRANGEMENTS OF MERZ-PRICE PROTECTIVE SYSTEM.

B illustrates the " e.m.f. balance system " as applied to a single feeder. Series transformers are used as in the preceding case except that in this system they are connected with their secondaries opposed or bucking, under which conditions no current flows in the secondary circuit as long as the current in the main conductor is normal throughout the protected section. Upon this balance becoming affected, the difference in potential thus created between the series transformers will force current through the secondary circuit and actuate the relays included in that circuit, to close the trip circuit and open the main switches. Series transformers for the " e.m.f. balance system " must usually be of special design, as most types of standard transformers cannot be operated on open circuit without burning out. These transformers must be designed to operate with a low temperature rise, and be of ample capacity to supply the energy necessary to overcome the resistance of the pilot wire and relay circuit. What is most important, they must be able to maintain exact ratios of transformation under all conditions of load, including extreme overloads. Substantial insulation must be provided between secondary turns in these transformers to withstand successfully the high potentials developed by heavy rushes of current in the main conductors when occasioned by faults elsewhere in the system, or by the heavy starting currents of motors of large capacity.

C illustrates the " magnetic balance system " as applied to the protection of a single transformer. The series transformers are arranged with their secondary circuits connected to a balancing transformer provided with a one to one winding. As the series transformers are designed for equal secondary currents with relation to the ratio of the main transformer, the resultant flux in the core of the balancing transformer is zero and no current will flow in the winding connected to the trip circuit, so long as the main transformer is in sound condition. Upon the occurrence of a fault within the main transformer, the currents in the secondary circuits of the series transformers will become unbalanced, resulting in an induced potential in the trip circuit windings, sufficient to operate the relays to open the main switches. Standard series transformers may be used with this system, providing they are of suitable capacity and of correct ratio. The addition of the balancing transformer may or may not offer advantages over the regular " current balance system " according to conditions, although it is to be noted that the latter system appears to be preferred in all recent installations.

Relays used with the Merz-Price system are of the simplest forms of the instantaneous type of circuit-closing relay, capable of adjustment for different currents and arranged with time limit attachments when used for the protection of certain classes of apparatus such as generators or transformers. These time limit attachments are provided to prevent the opening of main switches by heavy rushes of current which may be developed when synchronizing generators, or switching large transformers into service.

Experience indicates that for reliability it is best to use a battery for operating the trip coils on switches, in preference to using alternating-current trip coils directly in the secondary circuits of the system. The battery system requires series transformers of less capacity and makes certain that low voltage in the main system will not lower the secondary potentials to values insufficient to operate the trip coils.

Important as are the other features of this system, no less important is the part played by the main switches used in connection with these relay devices. A quick-acting switch is a necessity if the full benefit of the action of the relay on minor faults is to be obtained.

That such switches have been developed is shown by the absence of serious damage to cables or their surroundings upon the occasion of cable failures, there being every evidence that such faults are cut out very early in their development. It should also be noted in this connection that the duties imposed on oil switches when used on systems provided with balance protection, are not nearly as severe as in situations where ordinary overload protection is provided, due to the early disconnection of defective equipment under conditions which require the actual rupture of relatively small amounts of current.

The remaining link to be considered to complete the connections between the several parts of this system is the pilot cable. Where employed with either overhead or underground construction a No. 12 B. & S. gage 3-conductor, lead-covered, paper-insulated cable of low capacity is generally employed. although in some modifications of the standard methods of connection, only two pilot wires are used. In underground installations this cable is laid beside the main cable in the same trench in the solid system of construction, or is drawn into a separate duct where the drawing-in system of construction is used. Where used in connection with overhead lines, a catenary suspension is provided for the pilot cable which is ordinarily attached to the poles or carrying structures at a considerable distance below the main conductors. In certain undertakings open wires have been used for pilot wires on overhead lines, but not with as satisfactory results as cable installations have shown, owing to the induced currents developed in the pilot circuit, due to proximity to the high-tension wires. These currents have caused relays to trip upon the occasion of disturbances in the system, when there was no trouble with the main conductor being protected. As previously stated, the first cost, installation and maintenance of the pilot wires is the serious drawback to this system, amounting to approximately $1000 per mile as far as the cost of underground construction is concerned, although varying conditions may make it possible materially to reduce this cost, when a number of cables are to be protected. It is obvious that the maintenance of the pilot cable is of no less importance than that of the main cable, as a break in the pilot wires immediately causes the relays to operate the main switches exactly as though a fault had occurred in the main cable. Troubles of this character are more liable to occur with overhead construction, owing to the exposed positions in which they are placed with respect to opportunities for malicious damage, or that resulting from the action of the elements.

The really excellent feature of the Merz-Price system, aside from its extreme simplicity, is its ability to protect against faults in any part of a system, thereby permitting the operation of momentary and continuous overloads at the discretion of the operator, without fear of interruption from the operation of the relay devices.

This is a sharp contrast to American practise, where heavy momentary overloads are likely to cause interruptions of service unless special provisions have been made to the contrary, and in the case of continuous overloads special relay adjustments may be required.

The Merz-Price system may properly be termed a system of protection which makes possible for the first time the supply of continuous service in alternating-current systems, in that it makes possible the operation of ring systems of feeders, or systems of feeders operating in parallel at both ends, and at the same time insures the instantaneous disconnection of any faulty feeder or section of a ring feeder, without affecting the service of the rest of the system. In making this assertion it is assumed that in the design of ring systems of feeders, the conductors forming each ring are of suitable capacity to carry the entire load in either direction, or that interconnection with other feeders will afford the same capacity.

Consideration of the value of a protective system such as is here under consideration naturally involves discussion relative to the desirability of using any one of several arrangements of transmission lines, that is, whether ring systems or radial systems of duplicate independent feeders, or combinations of both, are most desirable. This is a question to be decided on its merits in each case, and has no particular bearing on the relay question as that is adapted to all, but it is fair to assume that in supplying service to any substation, more than one source of supply is desirable. In widely scattered districts it is apparent that a ring main will more economically serve such business, and at the same time afford full protection against failure of service. Conditions of supply in large cities usually require the delivery of large quantities of energy to individual substations, making it necessary to employ several feeders for each station, under which plan the radial system is adopted with each feeder carrying full load, with perhaps a duplicate feeder or equivalent capacity in reserve. In this case there can be no advantage in a ring system from any point of view. Certain companies employing duplicate radial feeders with a number of substations in tandem, would obviously greatly improve the capacity and reduce the losses in their systems, if such lines were operated with their ends in parallel at the most distant substation, or possibly at other substations as well.

The fact remains that this system provides opportunities for operating economies in substations which at first glance may not be appreciated. It is not unusual to find many English substations in service without attendance of any character, where the Merz-Price system of protection is employed for the protection of feeders and apparatus. This is possible in transformer substations located on consumer's property, where energy is sold in bulk to a consumer through step-down transformers, without regulation or further attention. Under such circumstances if the main switches on a ring main and the transformers supplying the service are protected by this system of relays, it is obvious that a certain number of such stations in a system require no operators, and no unfavorable conditions will result to the consumer from their absence, provided the transmission system is properly designed and the consumer's own equipment is protected by suitable overload devices.

It is evident that a switch failure or short circuit on the station busbars is a form of trouble to which the balance system of protection is applicable with satisfactory results. It is noted in actual practise, however, that owing to the success attending the operation of oil switches in the protection of feeders and station apparatus, the need for special protection for busbars is rarely recognized in commercial operations.

While mention has been made of the simplicity of the relays, it is not to be inferred that a certain amount of care and testing is not required for their maintenance. On the contrary, it is desirable to test the operation of the relays and continuity of the pilot circuit at regular intervals, by manually operating the relays to open the switches at the ends of a protected line. The amount of fault current upon which the relays are to operate having been previously determined and adjustments made for such values, no further tests are required except those to determine the mechanical condition of the relays and switches, and the continuity of the pilot wires.

To those who may contemplate the use of the balance system of relay protection, too much cannot be said in emphasizing the necessity of using series transformers of ample capacity and exactly similar ratios.

Determination of actual transformer ratios should be ascertained by actual tests on each group of transformers to be balanced against each other in service. By this method errors in ratio under abnormal overloads may be determined in advance and corrections made to insure the proper operation of the protective apparatus under all conditions.

In English practise a series transformer with a single primary turn and an open magnetic circuit has proved most satisfactory in all respects. Transformers of this design may be more conveniently tested and adjusted for balance than any other type, although series transformers of both open and closed magnetic circuit types are in general use, and after adjustment render equally efficient service.

Transformers used for feeder protection must be constructed with ample insulation between secondary turns, for when operated with secondaries open-circuited or bucking, potentials are created in the secondary circuits which are usually in excess of those for which standard series transformers ordinarily used in our practise are designed. These potentials often reach 600 to 700 volts in transformers used with the Merz-Price system for the protection of long high-tension feeders.

In order to illustrate the application of this system of protection to various situations, there follows a series of diagrams, Figs. 3 to 8, showing typical arrangements and connections of transformers, relays and pilot wires, as used in protecting certain apparatus.

Fig. 3 illustrates the application of " current balance protection " to generators—series transformers of proper capacity and ratio are inserted in the generator circuit with their secondaries connected through pilot wires to relays arranged to control the opening of the main generator switch.

Any failure within the generator windings or connections to the buses, which affects the balance of current in the main and secondary circuits, causes the relays to open the main switch and disconnect the generator from the system.

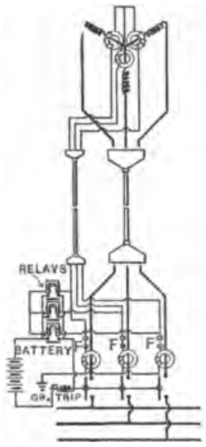

FIG. 3—GENERATOR PROTECTION —CURRENT BALANCE.

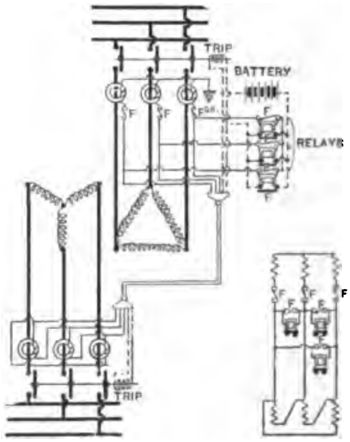

FIG. 4—TRANSFORMER PROTECTION —CURRENT BALANCE.

Fuses are inserted at *F* to shunt the relays when a time element feature is desired to prevent the main switch opening upon the development of heavy currents which sometimes occur during synchronizing.

In Fig. 4 is shown the arrangement of series transformers and relays for the protection of transformers. The small sketch shows the secondary circuits only. Fuses for the time limit protection, marked *F*, are included to provide for momentary rushes of magnetizing current, when the main transformer is connected to the system. It is customary to remove these fuses after the transformer is in service if no time limit protection is then desired.

Fig. 5 shows a method of protecting against faults in feeders by the " e.m.f. balance method." This has been found more desirable than current balancing, as the energy required to overcome the resistance of the pilot wires on long feeders would be prohibitive. The two small sketches show methods of connection employed with grounded and non-grounded neutral systems.

Fig. 6 illustrates the application of " e.m.f. balance protection " to main feeders with tee connection on systems with insulated neutral. Tee connection on such feeders should be avoided wherever possible.

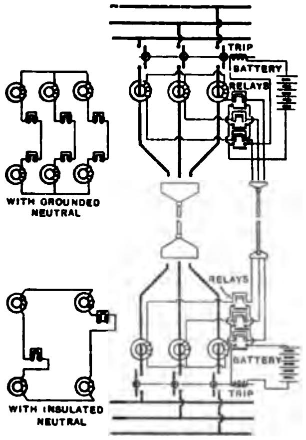

Fig. 5—Feeder Protection—
E. M. F. Balance.

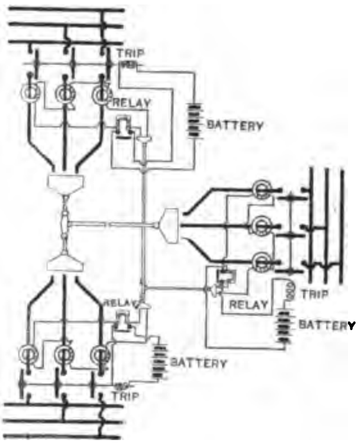

Fig. 6—Feeder Protection—
E. M. F. Balance.

Fig. 7 illustrates a method of protection occasionally used, styled " neutral wire balancing." The transformers are connected as for current balancing, with the neutral wire connecting between the two points of equal potential at the ends of the protected section. In this case no current passes through the pilot system in which the relays are connected, under normal conditions.

The method shown in Fig. 8 has its application to single radial feeders and depends for its operation upon the leakage of current to earth, from one of the conductors in a three-conductor feeder. Such unbalancing in the current in the three conductors of a feeder destroys the balance in the relay or trip circuit, and results in opening the main switch to disconnect the feeder.

As previously noted, the most reliable operation is secured where a storage battery is used to supply tripping current, although these batteries are not shown in some of the diagrams.

Referring for a moment to Fig. 1, there is shown the application of balanced protection to a high-tension feeder system in which both ring and radial systems are combined. Two generating stations are shown feeding into the same network, indicating the flexibility possible in the application of this form of protection to all situations. It will be noted that a combination of two methods is employed at the ends of the feeders at generating stations, and at points where cross-connections between feeders are made at substations.

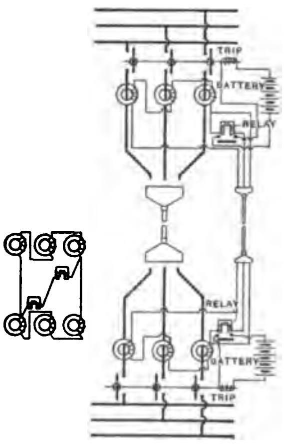

FIG. 7—FEEDER PROTECTION—E.M.F. BALANCE—NEUTRAL WIRE METHOD.

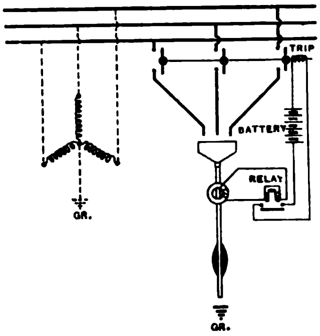

FIG. 8—MERZ - PRICE CORE BALANCE OR LEAKAGE PROTECTION METHOD.

As the Merz-Price protection is for faults and not for overloads, it is advisable to add a time limit relay for overload protection at certain points as indicated, to provide for possible contingencies such as a busbar fault or switch failure in a substation, which, being simply a short circuit between the conductors of a feeder, would still result in a uniform current throughout the length of the feeder, and therefore not affect the balanced protection. This possibility is actually very remote, as ordinarily such a fault would naturally develop short circuits to earth, producing conditions favorable for the operation of the balanced protective devices.

Time limit relays on cross-connections between feeders serve to separate the feeders into groups upon a short circuit occurring on any single feeder, thereby limiting the spread of trouble beyond the original feeder or group of feeders in which it occurred.

It is advisable to adjust time limit relays for practically instantaneous tripping when used on cross-connections between feeders, and when employed at generating station ends of such feeders in conjunction with balance protection, relatively long time limit settings should be employed.

After personally observing the results attained by users of the Merz-Price system in England in protecting station apparatus, such as transformers, the writer deemed it desirable to apply this form of protection to the transforming apparatus in the substations of the company with which he is connected.

Current balancing proved the most desirable system of protection to employ, affording as it did an opportunity to use existing series transformers for operating the relays. These transformers were tested carefully to determine their actual capacity and ratio under heavy overload conditions. The results show that certain types of standard transformers are entirely satisfactory for use with this system of balance protection. Experimental circuit-closing relays were constructed and substituted for the time limit overload relays formerly used in the protection of three 5000-kw., three-phase, 7000/14000-volt, 60-cycle transformers in the main generating station of the Boston Edison Company. Several months' use of the apparatus has given most satisfactory results in handling the heavy rushes of magnetizing current developed by switching operations when the transformers are cut into service, as well as those caused by faults in overhead and underground feeders. The relay which was finally adopted is of the simplest form, comprising suitable circuit-closing contacts and a single solenoid provided with two similar windings of the same number of ampere-turns. One relay was provided for each phase of the main transformer to be protected, with its two windings so connected to the secondaries of series transformers that they opposed each other when the current in the main transformer windings was normal.

The relays, Fig. 9, were adjusted to close with an unbalanced current equivalent to 150 per cent of the normal full load current of the transformer, this allowance covering the magnetizing currents developed when a transformer was switched into service, without making it necessary to resort to time limit attachments on the relay to meet these conditions.

Following this experimental installation, it is now proposed to equip similarly all transformer installations in substations throughout the system, using standard transformers now in service and substituting the special relay for the present equipment of inverse time limit relays.

The introduction of this system of protection will afford immunity from the interruptions of service sometimes caused by heavy short circuits on distributing circuits unnecessarily opening the main switches on substation transformers, through the action of instantaneous or time limit overload relays as now employed.

The use of this system of protection will be extended to all new transmission lines as installed, particularly those lines serving suburban districts. This course will finally introduce many protected sections of line into the system and materially aid in improving the present methods of relay protection. Where such protected lines are conveniently located the operation of closed ring systems will become feasible, for through the introduction of one or more such protected sections, improved selected action may be obtained from the relays now in use on existing lines which may go to make up a ring feeder.

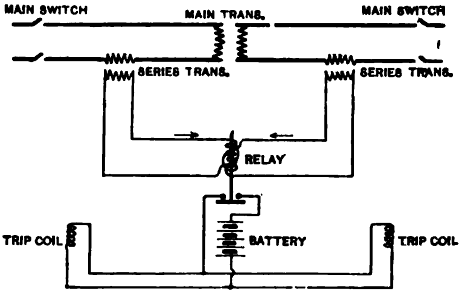

FIG. 9—TRANSFORMER PROTECTION—EXPERIMENTAL APPLICATION OF CURRENT BALANCE METHOD.

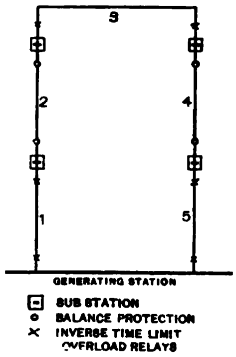

FIG. 10—RING SYSTEM OF FEEDERS.

Sections 1, 3, 5, protected by I. T. L. overload relays.

Sections 2, 4, protected by Merz-Price system.

The possibilities of improving conditions by applying the " balance system " of protection to a limited number of lines in an existing system, where the expense involved to equip all lines is prohibitive, is illustrated in Fig. 10, in which is shown a typical ring feeder supplying several substations.

Three sections of this feeder are equipped with standard inverse time limit overload relays and two sections with the "balance protection."

Assume that sections 2 to 4 are adjusted to trip on fault currents equivalent to 20 per cent of normal full line current. Adjust time limit overload relays on 1 to 5 for twice normal full line current in three seconds, and adjust similar relays on section 3 for half these values. It will then be possible for a fault to appear on 3, causing its relays to open, without interrupting the service on the other sections of the ring.

Similarly, either section 2 or 4 may prove defective and be cut out of service automatically by the "balance protection" without affecting the other sections, assuming in each case that the lines comprising the ring are of sufficient capacity to carry the whole load in either direction.

Should section 1 be damaged it is probable that the relays on section 1 to 3 would open on account of their relative adjustments, thus interrupting service from two substations for a time at least. The same conditions would apply to a fault on 5, and although somewhat unsatisfactory in the last two cases, the results are a great improvement over those obtained from the use of inverse time limit overload relays ordinarily used for such stations. Variations in the location of the section of lines equipped with balance protection will introduce new combinations of relay adjustments, but the conditions suggested in Fig. 10 will illustrate the possibilities and results obtainable by a partial application of the balance protection to an existing system of feeders.

Another arrangement of the Merz-Price system is shown in Fig. 11, representing the application of the "magnetic balance system" to the protection of certain important tie line feeders connecting two large generating stations of the Commonwealth Edison Company, of Chicago.

In this case the magnetic balance system was chosen, as it afforded an opportunity to employ existing series transformers, by simply adding relays and a special balancing transformer with windings arranged as shown in the illustration. The adaptation of this apparatus to an existing switchboard panel is shown in Fig. 12, where the change from inverse time limit overload protection was made with scarcely any disturbance to existing switchboard arrangements. Experience with this installation is somewhat limited, but in so far as operated the results are satisfactory, and the engineers of the company are studying the further application of the system of protection to other parts of the system.

Another system of relay protection has been devised by Mr. Höchstädter of Cologne, Germany, which, while somewhat different in principle, effects the same results in feeder protection as the Merz-Price system. In this system, when applied to a three-phase feeder, a copper ribbon is wound spirally around each main conductor of a three-conductor cable during the process of manufacture. These ribbons are insulated from the main conductors and sheath, and from each other, and in service are connected to an auxiliary storage battery and suitable relays, all arranged to operate the main feeder switches upon the occasion of a fault in the main cable.

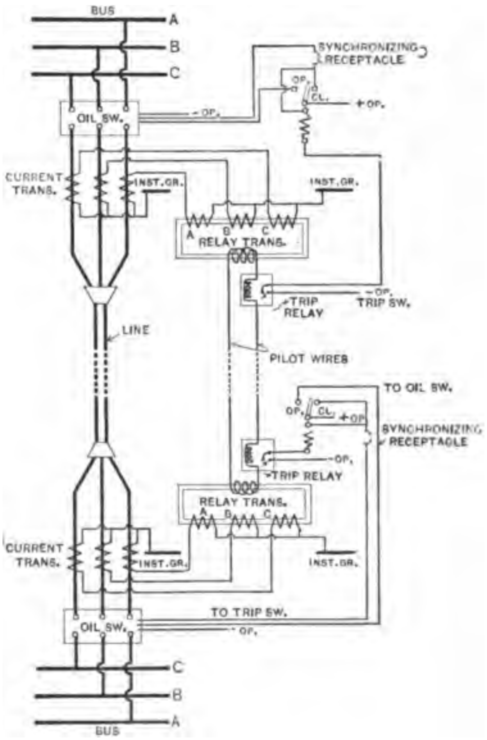

FIG. 11—SPECIAL PROTECTIVE RELAY SYSTEM USED BY COMMONWEALTH EDISON COMPANY.

Whenever the insulation breaks down at any point in the cable, a connection is established between the main conductor and its copper ribbon, or between conductor, copper ribbon and sheath, thereby allowing current to flow in the relay circuit to actuate the feeder switches at both ends of the defective feeder, as clearly shown in a typical diagram of this system reproduced in Fig. 13.

Choke coils are included in the relay circuit to limit the alternating current which would otherwise flow in the circuit formed by the copper ribbons around the conductors.

This system admittedly possesses some admirable features, particularly in the absence of a separate pilot wire cable, and while somewhat complicating the construction of the main feeder cable by the introduction of the copper ribbons, this detail appears to have been satisfactorily accomplished.

A number of installations using the Höchstädter system of protection have been made in Germany, notably in Cologne, where an extensive three-phase ring transmission system has been in operation at 25,000 volts for a considerable period with great success.

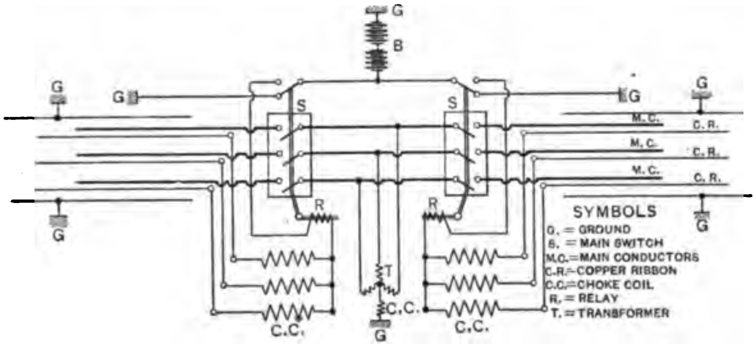

FIG. 13—DIAGRAM OF CONNECTIONS OF HOCHSTADTER SYSTEM OF PROTECTION APPLIED TO A THREE-PHASE FEEDER.

While other modifications of the Merz-Price system have been developed and applied to commercial practise, there is always evident a desire in the minds of all engineers interested in the subject to do away with the pilot wires and accomplish the same results in other ways.

Messrs. Faye-Hansen and Harlow, of England, have brought out a system of balanced protection, in which the balancing of secondary currents from series transformers is accomplished by the insertion of variable artificial resistances in the secondary circuits, in a manner said to be more convenient than in the Merz-Price method. However, as the system is based on the principle of balanced protection and still requires pilot wires, although in some cases less in number, there appears to be no decided advantage in using it in preference to the earlier method, unless it be that one prefers a scheme in which relays may be omitted and straight alternating-current trip coils employed to operate the main switches.

A method of protection for parallel feeders without pilot wires has been used by an English company, which consists of a combination of overload balanced relays at one end and simple trip coils at the other end of such feeders.

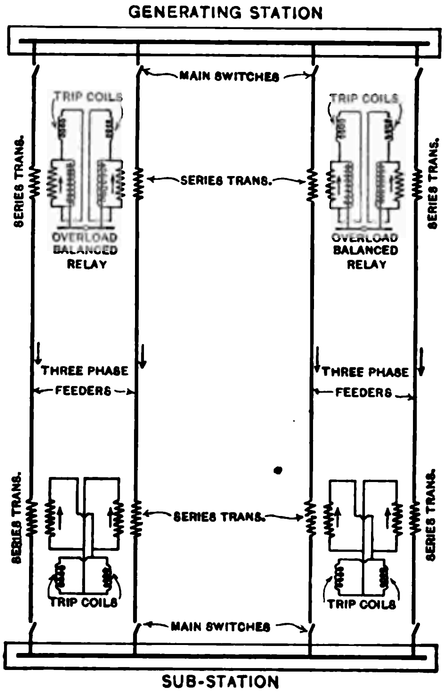

Fig. 14—Selective Relay System without Pilot Wires.

Fig. 14 illustrates the method of applying this protection, from which it will be noted that if used with a single pair of feeders, both will be cut out should either feeder prove defective.

If, however, two pairs of feeders are in service the protection may be made selective, in so far as trouble on one feeder in a pair will only cause that pair to be cut out of service, leaving the station running from the remaining feeders without interruption. While this method has been used to some extent with success, it

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APPLICATION OF ELECTRIC DRIVE TO PAPER CALENDERS

BY E. C. MORSE

Motors have been used in paper mills for the last twenty years and have been applied with success to every machine used in the process of making paper.

By means of motors it has been possible to study the power requirements of various machines and much useful information has been obtained for the manufacturer of the paper, of the machine, and of the motor.

As far as the writer knows, very little of this information has been published and it is the intention of this paper to set forth facts that have been observed and state the possible laws that may be deduced from these facts.

This paper is confined to the finishing department of the paper mill and more particularly to the motor drives for three types of paper calenders.

Paper as it leaves the machine does not, for many purposes, have a sufficiently high glaze and it is therefore necessary for it to undergo some further process known as calendering. This may be done in one of three ways: first, the whole roll may be calendered by passing the paper through a " super or web calender;" second, the paper may be cut in sheets and these sheets calendered in a " sheet calender;" third, the paper may be cut in sheets and calendered in a " plater." The method used depends on the kind of paper and the kind of finish desired. All " loft " or air-dried papers are finished either in a sheet calender or a plater, as the paper must be cut into sheets before drying. These papers are usually of the higher grades.

SUPER CALENDERS

A super calender (Fig. 1) consists of a stack of rolls carried in upright housings, each roll having its own bearings, which are so constructed that they are free to move vertically. Power is usually applied to the bottom roll (occasionally to the third) and the other rolls are driven by friction from this one. Oil for lubrication is supplied to the top journals and is carried down through the other bearings by gravity. The top and bottom roll and the small or intermediate rolls are nearly always steel; the other rolls may be either steel, chilled iron, paper or cotton, depending on the kind of paper and finish desired. A system of levers with weights is used to apply pressure to the top roll in order that there will be proper pressure on the paper. The number of rolls is nearly always odd and may be three, five, seven, or nine, usually seven or nine. The diameter of the bottom roll varies from 18 in. to 24 in., the intermediate from 10 in. to 16 in., the cotton or paper rolls from 14 in. to 20 in. Calenders are built varying in width from 36 in. to 125 in.

Requirements for Drive of a Super Calender. One end of the paper is taken over the top of the calender and then passed back and forth between the rolls, shown in Fig. 1, to the bottom of the stack and then to the winding roll. In order to pass this paper through between the rolls, which process is known as " threading in," it is necessary to operate the rolls at a slow speed and it is very important that this speed be constant. This speed varies in different mills from 20 ft. per minute to a maximum of 100 ft. per minute. As soon as the paper is " threaded in " and started on the winding roll, the calender must be speeded up and will then operate at a speed between 400 ft. to 800 ft. per minute, depending on the method of drive, the operator, and the kind of paper calendered. It is therefore necessary to provide at least two speeds on each stack, one a low speed and the other a high speed, regardless of the method of supplying power. It is very important that the acceleration be smooth from the low speed to the high speed in order not to break the paper and cause the consequent loss of production. It is also very advisable to have a method of slowing down, when a weak or torn place in the paper appears, and of smoothly accelerating to highest speed again. It is convenient to be able to stop the calender from other places than at the operator's usual stand, in case of emergency.

FIG. 1—WEB CALENDER. [MORSE]

a—top roll, steel.
i — bottom roll, steel.
b, *c*, *e*, *f*, *h*— fabric rolls
d, *g*—intermediate rolls, steel.

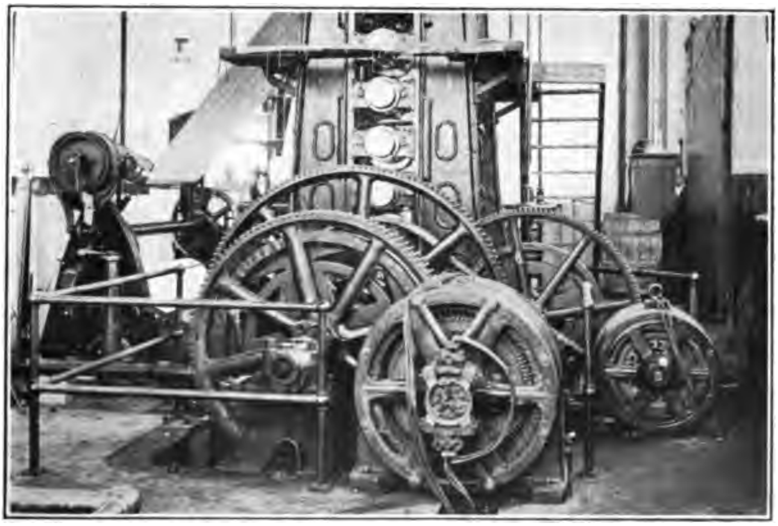

FIG. 3—WEB CALENDER—TWO-MOTOR DRIVE. [MORSE]

METHOD OF DRIVE

Group or Shaft Drive. Calenders were originally driven from a line shaft and still are in many mills. This shaft may or may not be driven by a motor. Fig. 2 shows the method of drive and how the " threading in " speed is obtained. The cycle of operation is as follows:

Throw in horn clutch *a* which starts rolls at their low speed. After paper is threaded in throw in friction clutch *b* which connects high-speed driving pulley and increases roll speed to maximum. As the speed increases clutch *a* is automatically thrown out. To stop the calender throw out friction clutch *b*. Both pulleys are running all the time. Clutch *a* is now nearly always made a friction clutch and a horn clutch put on pulley *c*, both being operated from the same lever. With this arrangement the horn clutch is thrown in first and then the friction clutch which is now at *a*. This reduces the shock and allows the calender to be stopped if need be while " threading in."

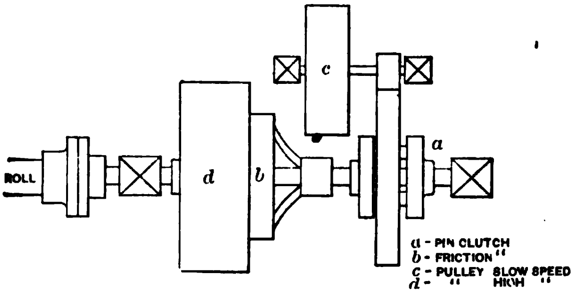

FIG. 2—WEB CALENDER—MECHANISM FOR GROUP OR BELT DRIVE.

The high speed must be a compromise between the maximum that any of the paper will stand, and a lower speed, which is best for the weakest paper.

Engine Drive. Abroad, and in one or two cases in this country, individual variable-speed engines are used to drive calenders. As no steam is required ordinarily around a calender this engine drive means long live and exhaust steam lines. This drive requires space in the basement and an engineer in attendance. A belt drive through floor is used, with the attendant grease and dirt which is always present around a reciprocating engine. A two-cylinder engine must be used and even then a uniform torque is not obtained. This type of drive does not meet with favor among American manufacturers.

Two-Motor Drive. The most natural step, when motors were applied to calenders, was to belt motors to the old mechanism which was used when the calender was belted to the line shaft. It was at once seen that a simpler, more compact arrangement could be made, as well as the belts eliminated, if the motors were mounted on same base with the clutches and gears, and geared to the driving mechanism. (See Fig. 3). This arrangement is shown diagrammatically in Fig. 4 and the cycle of operation is as follows:

Close the circuit breaker, then start small motor, now throw in horn clutch at *a*, which will start the calender at the low speed. After paper is threaded in, advance controller on large motor, which increases speed of calender and automatically throws out horn clutch at *a*. The small motor may be shut down or left running, as desired. To stop calender the power is thrown off.

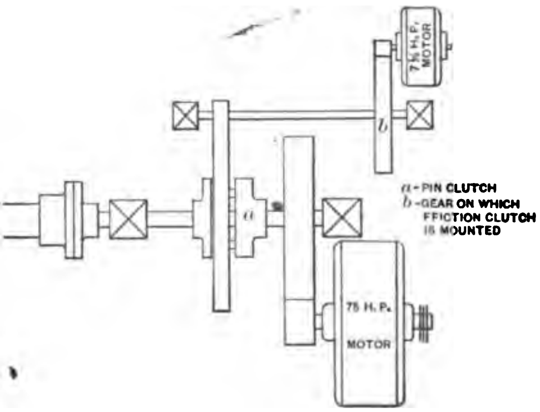

FIG. 4—WEB CALENDER—MECHANISM FOR TWO-MOTOR DRIVE

It is usual practise now to mount a friction clutch also at *b* which is controlled from same lever as *a* and operated as described under "Group Drive."

It is now a simple matter to make the large motor an adjustable speed motor and obtain smooth acceleration from low to high speed. This type of motor makes it possible to gear the calender so that the maximum speed will be the maximum at which it is possible to finish any of the paper and the calender can easily be slowed down to accommodate weaker paper or for a different finish.

Two Motors Replaced by One. It is possible to do away with the small motor used in a two-motor drive and by means of gearing and clutches to operate the calender at the " threading in " speed from the large motor. This is shown in Fig. 5. The cycle of operation is as follows:

Close the circuit breaker and start up motor. The large gear *d* and pinion *e* are mounted on a bushing loose on the shaft. In starting, horn clutch *a* is first thrown in, the friction clutch *c* being open. As gear *d* is loose on shaft the calender is driven at the low speed through back gears. After the paper is " threaded in " friction clutch *c* is thrown in, connecting gear *d* to shaft and calender speeds up to maximum, while horn clutch *a* is thrown out automatically.

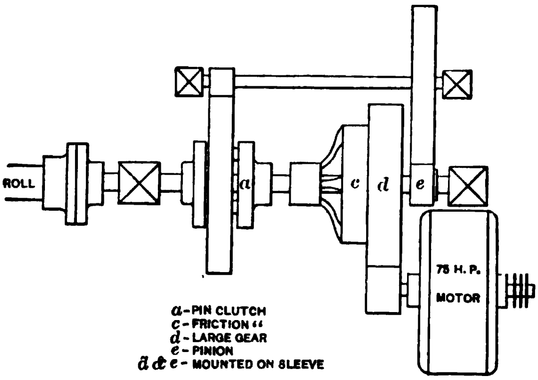

FIG. 5—WEB CALENDER—MECHANISM FOR ONE-MOTOR DRIVE.

From the operator's standpoint this drive is practically as good as the " Two-Motor Drive " previously described. The electrical features will be discussed later.

One Motor Direct-Geared. In this method of drive there is only one large motor direct-geared or belted to the driving roll as shown in the diagram, Fig. 6. It is therefore necessary to obtain the " threading in " speed or a speed ⅛ to 1/13 of the maximum by reducing the speed of the motor by inserting resistance. The cycle of operation is as follows:

Close the circuit breaker and adjust the controller until the motor operates at the desired speed. All speed changes are made by the movement of the controller handle.

This drive eliminates all clutches, nearly all the gears and makes mechanically a very compact and simple drive. The " threading in " speed, necessarily, is very unstable, as will be seen when the electrical features are taken up.

POWER REQUIREMENTS

General Characteristics. The power consumed by a calender is entirely used in overcoming friction, therefore a calender requires (within limits) a constant torque. It has further been found, from tests, that with most grades of paper, only 15 to 20 per cent of the power consumed is required by the paper itself, and 80 to 85 per cent of the power is consumed in overcoming the friction of the machine. Therefore, to drive a given calender at various speeds, a motor or engine is required that will give constant torque rather than constant horse power over the range of speed desired.

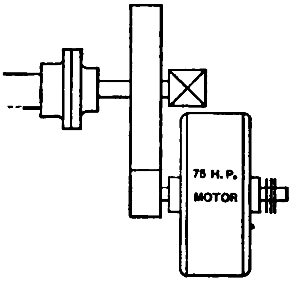

FIG. 6—WEB CALENDER—ONE-MOTOR DRIVE, DIRECT-GEARED.

Low-Speed Power Requirements. As previously stated, means must be provided to obtain a slow or " threading in " speed, approximately ⅛ to 1/13 the maximum speed of the calender, in order that the feeding in of the paper may be done as easily and quickly as possible. This speed should remain practically constant with the change in torque from the calender alone without weights, to the calender with paper completely "threaded in" with weights. This increase in torque varies from 10 to 75 per cent, depending on the kind of paper or cardboard being calendered. Many low-speed drives have been tested and the maximum power required by the motor at 50 to 60 ft. per min. on the paper has never exceeded five to six horse power, regardless of the size of the calender, kind of paper, and the type of drive. Fig. 7 shows the results of various tests on different paper calenders at " threading in " speeds. The points all fall close to a straight line, showing the condition of constant torque. These values represent the power consumed by calender and drive with paper completely " threaded in ". A motor smaller than 7½ h.p. is not to be recommended if a separate motor is used, and the gearing can be made easily to accommodate a motor speed of 850 revolutions.

High-Speed Power Requirements. When we come to determine the power required by a calender when calendering paper, there are many points to be considered. These are listed in order of their relative importance, and then each taken up in detail:

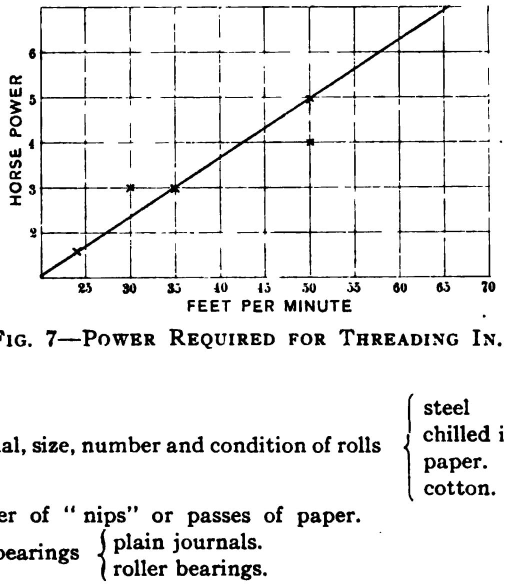

Fig. 7—Power Required for Threading In.

a. Material, size, number and condition of rolls { steel, chilled iron. paper. cotton.
b. Number of " nips" or passes of paper.
c. Type bearings { plain journals. roller bearings.
d. Kind of stock { paper. cardboard.
e. Pressure on rolls.
  (1) Power varies with kind of rolls.
f. Width of stack or rolls.
  (1) Active width is width of paper calendered.
g. Surface speed of rolls in feet per minute.
  (1) Difference in speed between rolls and paper.

a. The varying of the power with the kind of rolls is closely interlinked with the varying of power due to different pressures applied. This subject as far as the writer knows has never been investigated carefully. It is known that the power varies accord-

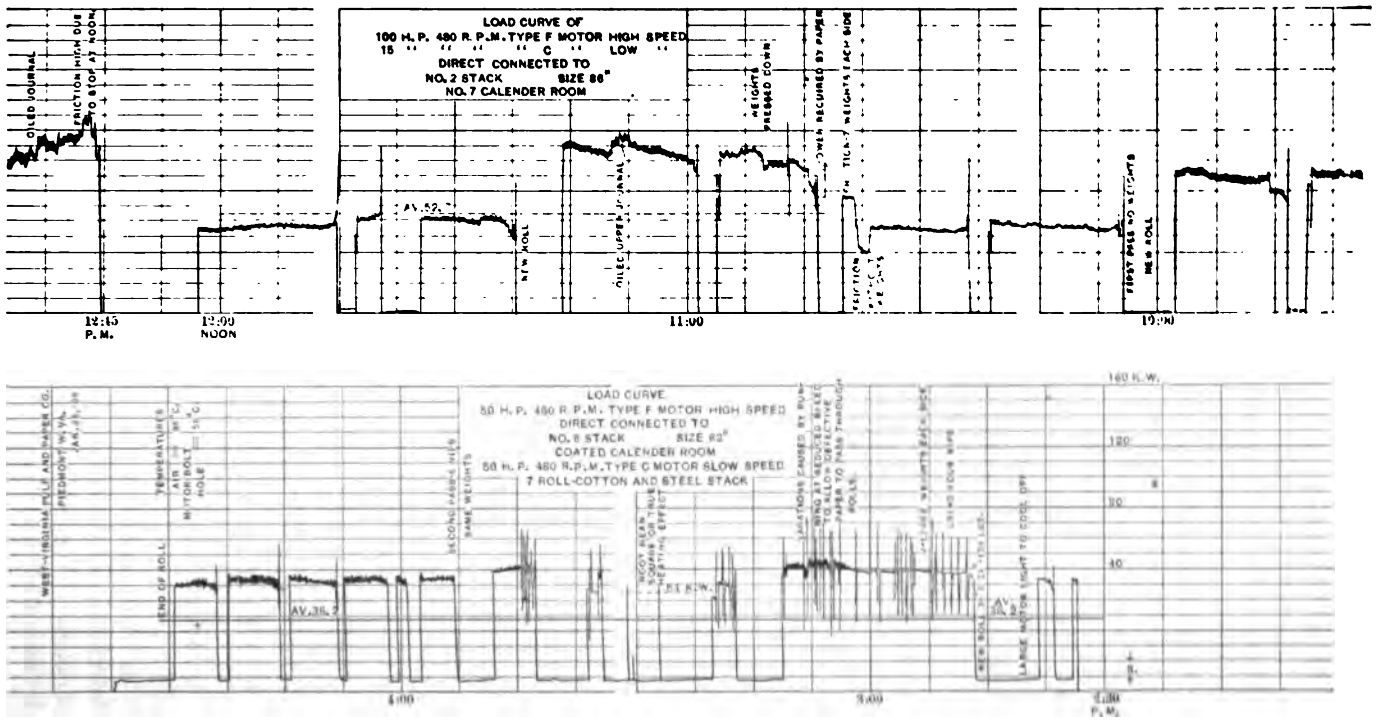
LOAD CURVE OF
100 H. P. 480 R. P. M. TYPE F MOTOR HIGH SPEED
15 " " " " C " LOW "
DIRECT CONNECTED TO
NO. 2 STACK SIZE 86"
NO. 7 CALENDER ROOM
OILED JOURNAL
FRICTION HIGH DUE TO STOP AT NOON
AV. 52.
NEW ROLL
OILED UPPER JOURNAL
WEIGHTS PRESSED DOWN
POWER REQUIRED BY PAPER
TIGHT WEIGHTS EACH SIDE
FRICTION
FIRST PASS NO WEIGHTS
NEW ROLL
12:45 P. M.
12:00 NOON
11:00
10:00
LOAD CURVE
50 H. P. 480 R. P. M. TYPE F MOTOR HIGH SPEED
DIRECT CONNECTED TO
NO. 8 STACK SIZE 82"
COATED CALENDER ROOM
50 H. P. 480 R. P. M. TYPE C MOTOR SLOW SPEED
7 ROLL-COTTON AND STEEL STACK
WEST-VIRGINIA PULP AND PAPER CO.
PIEDMONT W. VA.
END OF ROLL
TEMPERATURES
AIR
MOTOR BOLT HOLE
AV. 36.
SECOND PASS
SAME WEIGHTS
WOOD BEAN SQUARE OR TRUE HEATING EFFECT
51 K.W.
VIBRATIONS CAUSED BY RUN
RING AT REDUCED SPEED TO ALLOW DEFECTIVE PAPER TO PASS THROUGH ROLLS
WEIGHTS EACH SIDE
NEW ROLL
AV.
LARGE MOTOR LIGHT TO COOL OFF
160 K.W.
120
80
40
4:00
3:00
2:30 P. M.

FIG 8

ing to hardness of the roll, therefore steel or chilled iron requires the minimum power, then comes paper and then cotton. This variation is probably only a few per cent in most cases. A temporary increase of 20 to 25 per cent in the power may be required by a calender when starting up with rolls and bearings cold; this will not usually last more than 15 to 30 minutes and can be taken care of by overload capacity of the drive. It has also been found that a calender takes a little less power as the diameter of rolls is increased, due to the fact that the wedging effect is less.

b. Even though a seven or nine-roll stack is installed, it may be found possible to obtain the finish desired without passing the paper between each pair of rolls. Each pass is known to the paper maker as a "nip." The more "nips" taken, the larger the power, and this increase varies from nearly zero with hard paper to 10 per cent with heavy cardboard for each "nip."

c. Practically all calenders are equipped with plain bearings, although roller bearings have been used in a few cases. It is claimed that roller bearings reduce the bearing friction about 30 per cent, but the first cost and maintenance is probably higher than for plain bearings. It is also essential to keep the bearings well lubricated, for, referring to the top curve of Fig. 8, it is noticed that the power dropped 8 to 10 kw. or nearly 12 per cent when the upper journal was oiled.

d. The amount of power required by a calender will vary according to the thickness of the stock being calendered. This stock varies from the thin book paper to heavy cardboard. The power required for the heavier grades of board may be from 25 to 30 per cent more than for the ordinary weights of book paper. It is not customary to use as much pressure on the heavy cardboards as on the thinner papers. The power requirements for different grades of papers of approximately the same thickness do not vary to any extent. There is also very little difference in power consumed between plain and coated papers.

e. As the power consumed by the rolls alone of a calender is used in overcoming rolling friction, it is correct to assume that it will increase about in proportion to the pressure. The total load consists not only of the friction of the rolls but also of the roll bearings and driving mechanism; which friction will not increase directly with the pressure on the rolls. For all practical purposes, however, as regards the motor sizes, it is safe to assume that the torque will vary directly with the pressure applied to the rolls. Tests made in Germany show that increasing the pressure 3.43 times increases the power 2.74 to 2.78 times. Another variable that now enters is whether the rolls are steel, chilled iron, paper or cotton. The friction of the last mentioned increases somewhat faster than the others as pressure is applied.

f. Approximately 80 to 85 per cent of the power used in a calender is consumed in overcoming the roll and roll bearing friction, except in the case of cardboard. Of this, the amount consumed by the bearings is a very small percentage. The friction of the rolls varies directly as the length of contact, therefore with any given design of calender on the same grade and same speed of paper, the power required will vary almost directly with the width of stack, or the active length of roll face, when calendering.

The following table shows that the constant per inch active width remains fairly uniform, the speed being the same.

Active width roll Inches	Constant per inch width Minimum	Maximum
28	0.78	0.97
62	0.905	1.03
72	0.80	0.94
75	0.81	0.987
86	0.93	1.02
Average	0.85	0.93
Total average = 0.89		

The active width of roll is determined by width of paper and this not being known in some of the above cases, probably accounts for the lower values. A constant near the maximum should be used in determining maximum power required by a given calender.

g. The power required by any given stack with same width and grade of paper will vary directly with the speed at which the paper is calendered, assuming same pressure at all speeds. This must be true if a calender is considered as a friction or constant torque machine.

Two Germans found from tests which were recently published that the power required at full speed was 1.95 times power required at 50 per cent speed, while the amount of paper turned out was 1.75 times without weights and 1.81 times with weights. The increase of pressure reduces slippage between rolls and paper, as might be expected.

Summary of Power Requirements

In determining the amount of power required by a calender the maximum should be considered that would be required with paper of full width, making all the passes, running at maximum speed for which gearing is designed, and with all weights on pressure levers. Calenders are usually designed so that the maximum pressure per inch width is constant. If the above points are considered, then the overload capacity of the drive should be capable of handling any increase in load due to poor lubrication and different roll material. (This applies to paper only, as power required for cardboard is materially different). Tests have shown that the average load on a motor driving a calender is from 50 to 66 per cent of maximum while the true heating effect is from 20 to 30 per cent larger than the average, or from 60 to 80 per cent of maximum.

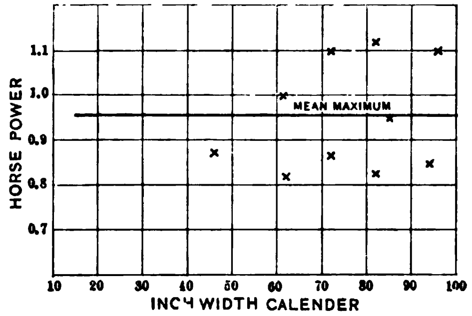

Fig. 9—Horse Power per Inch Width, Calender—500 Feet per Minute.

Fig. 9 shows the maximum horse power per inch width required on ten calenders varying from 36 to 86 inches, reduced to a 500-foot per minute basis. The low points recorded are probably due to narrow paper in the calender. Unfortunately, complete data as to what weights were used are not available on all the tests. This might also account for some of the low points. It is probable, however, that a value of 0.95 to one h.p. per inch width is the correct constant to use at 500 feet per minute calender speed, and if used, the drive will be of sufficient capacity to drive the ordinary calender finishing paper with practically all the weights on pressure levers. Fig. 10 is convenient for quickly ascertaining the size of motor for any width calender at any common speed and is based on numerous observations and tests.

The question will probably be asked, " Why not choose the capacity of the motor such that full load on the motor will be the same as the true heating effect of the load, that is, from 60 to 80 per cent of that shown in Fig. 9?" Maximum production is desired by the manufacturer and an alternating-current motor having 4 per cent slip at full load will have 6 to 7 per cent, at least, at 40 per cent overload, and this means a loss of 2 to 3 per cent production if the motor is operated at overload while calendering paper, as well as increased stresses in the motor.

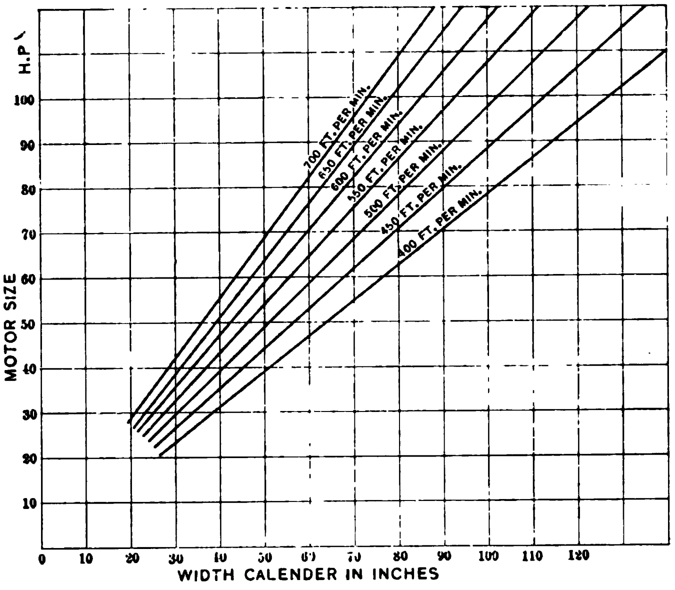

Fig. 10—Power Required by Web Calenders.

Power Required by Cardboard. The power used when cardboard is calendered depends largely on the personal element of the mill and on the condition of the stock as it comes to the calender. For a low speed of about 60 ft. per minute a 10-h.p. motor is required, while the power requirements for high speed should be studied for each particular situation, inasmuch as the power required may easily be 25 to 30 per cent more than for the same calender if calendering paper. In many cases, however, very light pressure is used on the rolls. The power required by the calender without the cardboard threaded in is therefore smaller (about 40 per cent of the total), while the power consumed by the cardboard is more (about 60 per cent of the total), and the total load on the motor may be about the same as if the calender was working on paper with heavy pressure on the rolls.

DISCUSSION OF MOTORS AND CONTROL FOR DRIVING CALENDERS

As we have previously stated, motor drive for calenders must, to be successful, meet certain conditions, as follows:

a. Give uniform " threading in " speed.

b. Give smooth acceleration to maximum speed.

c. Must be possible easily and quickly to slow down and again accelerate.

d. Must be able to operate at various speeds to accommodate various grades of paper.

e. Should be able to shut down motor from various points around calender.

f. Control should be simple and extremely substantial.

g. Should be capable of stopping calender quickly.

Two-Motor Equipment—Alternating Current. Fig. 4 shows in outline the mechanical drive using two motors. For the small motor a 7½-h.p. 850-rev. per min. squirrel-cage type of motor is used, which may be provided with an induction type starter, or preferably a small oil switch mounted close to the controller for large motor. For the large motor a wound-secondary type is nearly always used and a full load speed of 495 or 580 rev. per min. is required in order to keep the pitch line speed and size of the gears within reasonable limits. This motor is controlled from a drum controller, with external resistance, usually, of such a capacity that the motor may be operated continuously at any speed as low as 50 per cent of the maximum. Occasionally, the resistance is designed for only three- or five-minute service on the low speeds. In addition, an automatic oil circuit breaker should be installed to protect the large motor and also control circuit to small motor. This breaker should be equipped with an inverse time element relay so that the momentary peak demand for power on accelerating will not trip the breaker.

One of the most satisfactory controls which has yet been designed for a calender drive consists of a panel on which is mounted a set of solenoid-operated switches for main circuit, a circuit breaker with inverse time element relay and an ammeter for check on power consumed. With this panel is used a modified drum controller and the operation is as follows:

Close the circuit breaker, throw in the small oil switch starting small motor. When ready, move controller handle to first notch, which closes solenoid switches, and continue to advance handle until the large motor takes the load from the smaller motor. In series with the solenoid winding of switches and first notch of controller, may be inserted as many emergency stations as are desired. If one of these stations is opened the solenoid switches immediately drop out and shut down the large motor and the switches cannot again be closed until controller is returned to the first notch. The small motor remains running but disconnected from the driving mechanism by the pin clutch. It is always preferable to stop calender by one of these stations, which should be mounted at the controller. This control puts the work of making and breaking the current on the solenoid switches, which can be made very rugged and provided with arcing tips. In many mills the number of times the current is broken is 8 to 12 or even more times an hour, and if the calender runs 24 hours a day, six days a week, the switches are called on to break approximately full-load current 1100 to 1700 times a week.

The above equipment meets conditions (a) to (f), leaving now only the quick stop. From calculations based on a 65-in. seven-roll stack, operating at 600 feet per minute, it was found that the flywheel effect of the rolls and mechanism, exclusive of the motor and large gear driven by the motor, was 35 h.p-seconds, the motor 38 h.p-seconds, and the large gear 34 h.p-seconds. The flywheel effect of a motor-driven stack is therefore about three times that of a stack driven from line shaft and the time required to stop after disconnection from power is about three times as long. This is not so important on light-weight paper as on heavy weights. An electric brake may be attached to the large motor which will overcome its flywheel effect. It appears, however, more satisfactory, and introduces fewer complications to use a mechanical brake on the lower roll outside of the calender housing, this brake being applied by a foot lever extending close to the controller. This brake is usually made so that its operation is very effective and the calender can be stopped even quicker than in the group drive.

Direct Current. The motor end of a direct-current drive is the same as with alternating current, with the exception that in some cases part of the speed control is obtained by varying field strength of the motor. The control is worked out in the same manner as before; in some instances the drum controller is replaced by one of a face-plate type. Sometimes a master controller only is used, which controls magnetic switches for handling the current. One advantage with direct current is the fact that dynamic braking can be obtained automatically and the calender stopped very quickly.

One-Motor Drive (Small Motor Omitted). Fig. 5 shows that this drive resembles the two-motor drive, except that by means of gearing and a clutch the large motor is made to do the work previously done by the small motor. The same type of motor and control is used as before and the same facts regarding flywheel effect and braking are true. The calender is stopped by cutting the power off the motor. If the clutch is thrown out then there is only the flywheel of the calender alone, as in the belt drive. This type of drive so far as is known has never been used with direct current, but could be if desired.

One Motor Direct-Geared—Alternating Current. In this drive as shown in Fig. 6, the one large motor of the wound-rotor type is geared or belted direct to the driving roll. It is, therefore, necessary to decrease the speed of this motor, by inserting resistance in secondary, to ⅛ or 1/12 the maximum speed in order to obtain the proper " threading in " speed. It is impossible to obtain a stable " threading in " speed in this manner, owing to the well-known characteristics of an a-c. wound-rotor variable speed motor. If the calender is running without paper at the proper speed and paper is fed in, the friction increases and if this increase amounts to approximately 8⅓ per cent the motor will stop. With some cardboard this increase in friction has been found to be as high as 60 per cent. It is impossible, in nearly every case, to complete the " threading in " without changing the controller setting, which may mean a third man on the calender. After the paper is " threaded in " the motor operates like any other variable speed motor. The control which should be used with this drive is the one using solenoid switches described under " Two-Motor Drive." The controller must be supplied with a large amount of resistance in order to obtain the very slow speed. The flywheel effect and braking conditions are as in the two-motor drive.

One Motor Direct-Geared—Direct Current. If a d-c. motor is used direct-geared, the conditions are not quite so bad. A d-c. motor giving a 3:1 or a 4:1 reduction in speed from the maximum by field control should be used. The power input of this motor is proportional to the load within its speed range and is not constant as in the case of the a-c. motor. It is now necessary to reduce the speed from the full field speed, or ¼ the maximum to only ½ or ⅓ in order to obtain a " threading in " of ⅛ to 1/12 the maximum speed. Using a commutating-pole motor of good inherent regulating qualities, a fairly stable speed is obtained and it will take 33 per cent increase in friction to stop motor instead of 8⅓ per cent as in the a-c. motor. Therefore, with a 30 per cent increase in friction in " threading in " one would not expect to stop the motor. With paper this increase is much smaller and this speed change would not be troublesome. Another feature is that dynamic braking can be used and quick stopping assured. Fig. 11 shows a control panel for this drive.

MECHANICAL AND ELECTRICAL ADVANTAGES AND DISADVANTAGES OF EACH DRIVE

In the following comparisons it should be remembered that the paper maker is primarily interested in cost of production. He is, therefore, interested in mechanical and electrical simplicity, ease of control and operation, small maintenance, minimum labor, minimum power cost per unit output.

It has been found from many tests and observations that calenders are run on slow speed from 25 to 33 per cent of the time; 10 to 22 per cent of the time is consumed in " threading in," varying with weight of paper or length of roll.

The following comparisons are bare statements of facts and it is not the intention to recommend one drive over another. A large advantage for one drive, in some mills, may be insignificant in another.

GROUP DRIVE BY MOTOR—SAME FOR A-C. AND D-C.

Advantages. With this drive the manufacturer has a constant slow speed, only one motor and starter for entire group, minimum chance of trouble with electrical apparatus. Lower first cost, therefore lower fixed charge per calender.

A 70-in. calender arranged for drive from line shaft costs	**$4600**
Shaft per calender approx.	100
Share of capacity in large motor for 70-in. calender...	400
Total	**$5100**

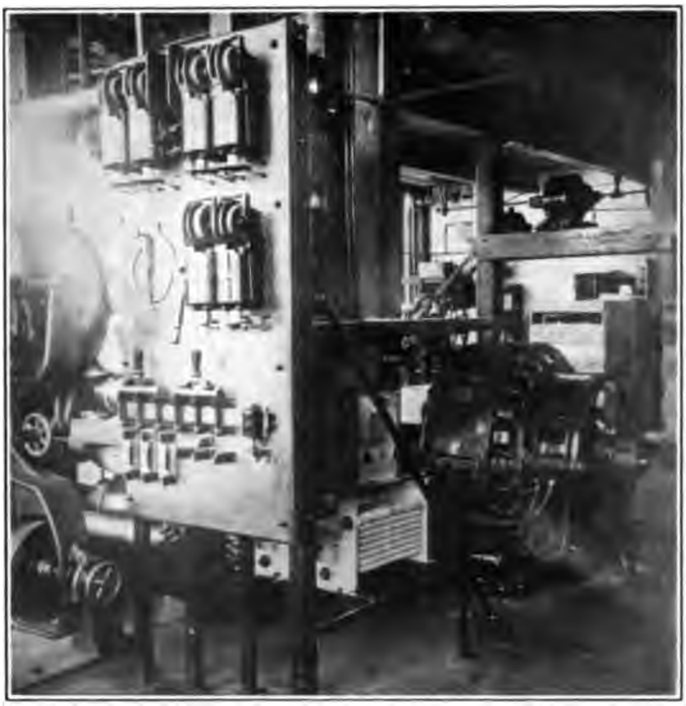

FIG. 11—DIRECT-CURRENT CONTROL PANEL. [MORSE]

FIG. 12—SHEET CALENDERS. MORSE]

Disadvantages. Belts to maintain, two clutches to keep in repair; main shaft takes space on floor below calenders; friction clutch to throw in high speed, and as usually operated there is a sudden strain on paper with consequent possibility of breaking and lost production. Only one high speed and no way to vary it. Large motor operating on a widely fluctuating load, from 15 per cent to 150 per cent load, which means poor efficiency, poor power factor, and a variation in the speed of shaft of 5 per cent or more. It has also been found that the shafting and belting loss alone, per calender, is approximately four kw. This means for a 24-hour day, 96 kw-hr. at $0.01 per kw-hr., $0.96 per day, $288 per year. This capitalized at 5 per cent means $5770.

TWO-MOTOR DRIVE. SAME FOR D-C. AND A-C.

Advantages. Constant "threading in" speed, smooth acceleration from low to high speed, reducing strains on paper and lost production. Ability to slow down to any desired point easily and quickly. Calender can be geared to run at maximum speed that any of paper will stand, as lower speeds are available for weaker paper. This speed can easily be 10 to 15 per cent higher than in the group drive. Only one clutch necessary and that a pin clutch. Sometimes a friction clutch is also used on large gear on low speed so the pin clutch may be thrown in without starting the rolls and the rolls started by friction clutch. Both these clutches are operated from one lever. Large motor operated at good efficiency and power factor. Losses minimum on low speed. The low-speed motor running light has an average input of 0.6 kw. This corresponds to the friction of the shafting in the group drive, as the large motor does not consume energy except when driving the calender at its operating speeds. Moreover, the efficiency of the motor in the group drive will be nearly the same as this large motor. It may be assumed that this 0.6 kw. is a 24-hour loss, as the small motor is usually left running continuously and is used for "threading in" only 10 to 15 per cent of the time. Thus 0.6 kw. for 24 hr. per day at $0.01 per kw-hr. = $0.144, or $43.20 per year of 300 days—a gain of $234.00 per stack over group drive. or 5 per cent on $4700.

Good power factor is maintained on the line since the idle current of the small motor is small.

Disadvantages. High first cost: A 70-in. calender,

For two-motor drive	$4750.00
For small motor	170.00
For large motor	900.00
For control	300.00
Total	$6120.00

Maximum chance of trouble exists with electrical equipment. Large floor space is required. It requires three times as long to stop after power is shut off as group-driven calender. Large motor requires the same kilowatt input regardless of speed, assuming constant torque. This disadvantage is more than overcome by increased production possible, due to variable speed feature.

TWO MOTORS REPLACED BY ONE. SAME FOR D-C. AND A-C.

Advantages. One less motor to care for than in two-motor drive. Less floor space required, constant "threading in" speed obtained, smooth acceleration from low to high speed, ability to slow down easily if desired. Calender can be run at maximum speed any paper will stand, as slower speeds are available for weaker papers. As motor and gear may be disconnected from stack on stopping, flywheel effect is the same as in group drive. If stack is stopped by cutting power off the motor the flywheel effect is the same as in two-motor drive.

Calender, 70-in., and mechanism	$4925.00
Large motor	900.00
Control	275.00
	$6100.00

Disadvantages. Two clutches, one being friction; large gear on quill which may wear and cause excessive gear wear. Requires same kilowatt input regardless of speed, assuming same torque. This is turned to an advantage by increased production possible. Light load losses larger. Based on a 70-in. stack, a three-phase 550-volt 75-h.p. motor running light will operate with a current approximately 25 amperes, power factor 15 to 20 per cent, kilowatt input 4.0 to 6.0. Assuming 5 kw. to be average and the motor running light 20 per cent of time or 4.8 hours per day, we have $5 \times 0.01 \times 4.8 =$ $0.24 per day or $72.00 per year, or $28.80 per year more than two-motor drive. This is 5 per cent on $575.00 and small motor costs $170.00. The worst effect is in the power factor of the system if many of these motors are installed. As far as power consumed goes, there is ordinarily not much choice.

SINGLE MOTOR, DIRECT-GEARED

Advantages—a-c. Only one motor is used, no clutches, minimum possible amount of gearing and smallest floor space of any drive. The calender can be geared for maximum speed that any of the paper will stand and can be easily retarded at will, and operated at lower speeds for weaker paper. Smooth acceleration from " threading in " to running speed is obtained. The first cost is lower:

Calender	$4185.00
Motor	900.00
Control	450.00
Total	$5535.00

Additional Advantages on d-c. Dynamic braking can be used to stop calender quickly. More stable " threading in " speed due to the fact that full field speed is about ⅓ maximum and the speed has to be further reduced by armature resistance to ⅓ or ¼ instead of ⅛ or 1/12 as with a-c. Losses are less on reduced speeds than with a-c.

Disadvantages. Very unstable " threading in " speed is obtained; controller setting usually has to be changed during " threading in." Extra large controller and resistance is required to obtain the low speed. The large flywheel effect causes the calender to run three times as long as if group-driven. It has been found on this type of drive that the " threading in " requires from 9 to 14 per cent of total time and on a 72-in. calender the power consumed varied from 16 to 29.8 kw. during this period, as against about 2.2 to 4 kw. with two-motor drive. As this time required to " thread in " is also somewhat longer' the cost of power used for the " threading in " process is from 6 to 10 times that of the other two types of drive. This motor is practically never running except when paper is in the calender, and therefore has no " running light " loss to correspond to the other drives. The power factor is low while motor is running light and during " threading in." The control for this drive is subjected to the hardest service of any, as 60 per cent to 100 per cent full load current is broken every time the current is shut off. Motor tests show that the current is broken 13 to 15 times per hour as an average. This means for a 24-hour day, six-day week, 1870 to 2160 breaks per week. The ordinary circuit breaker contact is said to be good for about 3000 breaks, so a very substantial switch must be used in order to get any reasonable length of service. This drive may require more labor, or in other words a third man may be needed at controller during "threading in." This same man, can, however, take care of several stacks.

WHY SHOULD MOTOR-DRIVEN SUPERCALENDERS BE USED?

From the preceding pages certain advantages of motor-driven supercalenders have been pointed out which tend to lower cost per unit product and to increase the production per machine. These may be summarized as follows:

a. Long mechanical transmissions eliminated with maintenance of their shafts, belts, hangers, etc.

b. Reduced chance of all calenders being shut down at once. With mechanical drive this often happens due to belt breaking or shaft trouble and the loss of production is large.

c. Smooth acceleration from low to high speed, reducing strains on paper, therefore reducing breakage and loss of production.

d. Ability to operate calender at maximum speed which the particular paper will stand. With group drive only one speed is available.

e. Ability to slow down easily for a weak place in paper saves much time and increases production. Referring to Fig. 8 (lower half) it will be seen at one point the paper ran 25 minutes without a break but the controller was used 26 times to reduce the speed, and it is further seen that it requires on the average three to five minutes to paste together the paper and feed it in again. If the paper had broken 13 times only it would mean

$$\frac{13 \times 4 \times 500}{3} = 8700 \text{ yards of production lost.}$$

f. The speed of calender is much more likely to be uniform, as in group drive the number of calenders operating varies the belt slip and speed of line shaft.

g. The kilowatt-hours per unit output required are less than in group drive.

h. The power factor of system is better than when a large motor drives group, if a two-motor drive is used.

i. That the above facts are true is proved by figures of one of the largest and best managed mills in the United States which give the average efficiency of all motor-driven calenders as 35 per cent better than group-driven and of two of the most recent drives, 50 per cent better.

SHEET CALENDERS

Use. A sheet supercalender is used to give "loft"-dried papers their final finish where that finish can be given by passing the paper between rolls, as contrasted with finish given by platers. It is also used in certain machine-dried papers to give the final finish after they have been cut into sheets.

Construction. Fig. 12 shows motor-driven sheet calenders, taken from the feeding-in side. The strips of webbing run vertically in front of the calender. These endless bands run around a system of rollers. There is a set of these bands on both the front and back of the calender and they serve to take the sheets from the operator feeding in, guide them through the rolls and deliver the paper after it has been calendered to the " catch box " and to the operator taking care of the finished paper.

The general mechanical construction of a sheet calender is similar to a web calender, except that it is lighter. The widths commonly used are from 26 to 48 in. and the stacks are from three to five rolls high, the five-roll stack being the most common. On these, as in web calenders, the top and bottom rolls are of steel and larger than the others. The intermediate rolls may be either steel, chilled iron or fabric.

Sheet calenders do not require a low speed for " threading in ", so they may be driven direct from the power supply to a pulley or gear mounted on the lower or driving roll.

The paper is finished under pressure, which is applied by screws at the top of the stack. This pressure is varied according to finish desired and kind of paper being calendered.

Power Required. The power required by a sheet calender varies according to the same laws as were discussed under web calenders. The power required by a five-roll, 36-in. calender will be discussed, as this is the most common size in use. This calender requires from 2½ to 3 h.p. to drive the rolls, without pressure on them or paper going through, at a surface speed of 400 feet per minute. By means of the pressure screws this power is increased to 9 or 12 h.p. for ordinary work and can be increased to as high as 18 or 20 h.p. The following table shows the power required by this size calender for various papers:

Paper	Friction h.p.		Paper h.p.	Total h.p.
	No pressure	Usual pressure		
20 lb. flats, 17 × 22 in.	—	5½	1	6½
32 lb. flats, 17 × 28 in.	—	6	3	9
No. 4 bond, 24 × 32 in.	3	10	4	14
Heavy envelope 24 × 38 in.	2½–3	9–10	2½–3	11½–13
170 lb. paper 30½ × 29½ in.	2½–3	10	7½–10	17½–20
300 lb. paper 31 × 26 in.	2½–3	10	10–14	20–24

Fig. 13 shows a typical power curve taken from a 42-in. five-roll calender with a speed of 400 feet per minute. Comparing this with the above table it will be noted that the same paper takes practically the same power whether the calender is 36-in. or 42-in. width. A sheet calender should be run at the highest speed at which the operator can feed in the paper and not have any space between the sheets. These spaces are shown in Fig. 13 where the power drops to the friction load. The size of sheets and the weight of paper determine the speed with which any given operator can work, but this speed is not necessarily the same with the various operators. It is obviously a waste of power to run the calender too fast for the operator and a waste of the operator's time and of production to run the calender too slow. This shows that the motors driving sheet calenders should be adjustable-speed and the range of speed is determined by the range of grades of paper to be finished. The maximum possible speed seems to be about 500 feet per minute and the minimum speed ever necessary is 200 to 250 feet per minute. Usually a range of about 30 per cent is sufficient. The following motor sizes appear to be about correct for five-roll calenders at 400 to 450 feet per minute maximum speed:

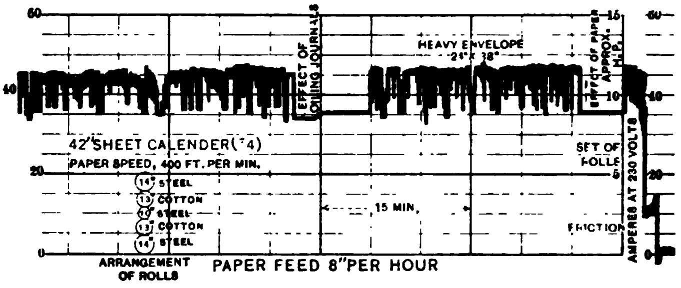

Fig. 13

28 in.	15 h.p.
36 in.	15 h.p.
42 in.	20 h.p.

Methods of Drive. With group drive it is not possible to vary the speed of the rolls to suit the operator or paper and the production per calender is less than it should be. Direct-current motors have been used in many mills very successfully. A commutating-pole motor of approximately 700 to 800 rev. per min. should be used, direct-geared to the bottom roll. This motor should have a speed reduction of at least 30 per cent by field control, keeping in mind that it is driving a constant torque load.

It was not thought feasible to use a-c. adjustable-speed motors until recently, when a test was run using a 15-h.p., 850-rev. per. min., wound-rotor type with a speed reduction of 50 per cent by insertion of resistance in secondary. This test proved that excellent results could be obtained using such a motor, and there is no reason for hesitating to install a-c. adjustable-speed motors on sheet calenders anywhere. The most satisfactory way to equip a group of sheet calenders with a-c. motors would be to drive part by constant-speed motors and part by adjustable-speed motors, as in every case the work could be so laid out that the constant-speed calenders could be working at their best efficiency and the special papers finished on the adjustable-speed calenders.

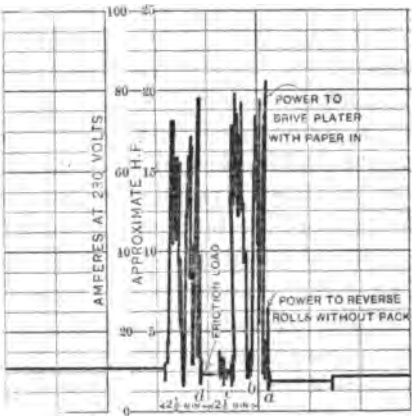

FIG. 14—POWER CURVE OF 36-IN. PLATER.

PLATERS

Use. In nearly every mill making a high-grade finished paper there will be found a machine known as a "plater." This machine is used to put certain kinds of finish on the paper after it has been cut into sheets. Probably the most common finish is the so-called "linen finish" which is found so often on writing papers. This is obtained by making a stack of paper with sheets of linen between the sheets of paper (at the top and bottom of this stack are pieces of zinc) and passing this paper through between the rolls, under pressure, several times. In the packs the linen may be replaced by sheets of any other material which will impart the desired finish to the paper. This may be either some kind of fabric or even metal sheets.

Construction. The general construction of the plater is as follows. The machine consists primarily of two steel rolls, operating under pressure, a table on which the pack is laid, and the driving mechanism. The driving pulley consists of two tight and one loose, as it is necessary to reverse the rolls with each pass of the paper. Originally, platers were constructed with a minimum space of one inch between the rolls and an adjustment of three-quarters of an inch. With the increased use a demand was made for a wider opening and more adjustment. By a careful design and arrangement of the gearing it is now possible to obtain an adjustment from zero to two inches, or, from any desired minimum opening, an adjustment of two inches.

The size of plater in common use has two rolls approximately 17 in. in diameter and a working length of 40 in. By means of weights and a system of levers, a pressure as high as 40 tons is applied to the rolls. Platers are built as narrow as 36 in. and up to a maximum width of about 48 in.

Power Requirements. Fig. 14 shows a typical power input curve for a 36-in. plater. This is an ordinary belted plater and the motor is belted to the countershaft. There is also a large pulley on this shaft which has considerable flywheel effect and helps out on the peaks a certain amount. This plater has a pressure of about 40 tons, and a surface speed on the rolls of about 61 feet per minute. It will be noted that about 10 amperes or approximately 2½ h.p. was required to drive this machine light, but that it jumped to 80 amperes or approximately 20 h.p. at (*a*) when the pack was inserted. It can be seen from the fluctuations about how many times the rolls were reversed. The pack is not allowed to pass entirely out from between the rolls before reversal. At (*b*) the pack is turned around to make sure that the finish will be the same on each edge. At (*c*) the pack is finished, removed, and a new one started at (*d*). It takes about two minutes to finish a pack and about as long to change packs. The average load while plating is about 15 h.p. but the load factor on the motor is very poor.

In a group drive having four or more platers it is safe to choose a motor allowing about 10 to 12 h.p. per machine. If the platers are to be driven by individual motors, from 15 to 20 h.p. should be used.

Method of Drive. Nearly all platers up to the present time have been driven by a belt from a line shaft. It is a simple matter to use a motor belted to this line shaft.

Many paper makers would like to obtain an individual drive on their platers. Considerable time has been spent in trying to obtain a motor and a reversing switch which would stand this service. This means about five reversals of the motor a minute and in order to obtain this number it would require a motor of small flywheel effect but large torque. In order to obtain quick reversal it would be necessary to " plug " the motor; that is, apply the power for reverse direction before the motor stopped. No one has as yet had the courage to attempt this on a standard 40-in. plater. There are three platers of a small size taking paper pack 9 by 14 by 1⅝ in. with rolls set at one-inch opening, driven by a d-c. 5-h.p. 400-rev. per min. commutating-pole motor, direct-geared and reversing with each reversal of the pack. These have been operating several years with the best of results. It is reasonable to suppose that the same thing could be done with larger motors. The big advantage to be obtained with individual drive on platers is doing away with shafting and belts with their attendant dirt and grease, and the maintenance and replacement of the plater belts, which wear out very rapidly. It would also give a greater flexibility in the finishing room. A group drive will give a much lower first cost, smaller motor, better load factor, better power factor if alternating current is used, and better efficiency of the motor.

CONCLUSION

From the preceding pages it is quite evident that increased quality and quantity of production is obtained by the use of electric drive in the finishing department. This is due to the fact that each machine is operated, and each kind of paper finished, at the correct speed.

A paper presented at the 29th Annual Convention of the American Institute of Electrical Engineers, Boston, Mass., June 28, 1912.

ELECTRICITY ON THE FARM

BY PUTNAM A. BATES

Never in the history of this country has there been such a great arousing of public opinion, such an arousing of interest of the people generally, in the agriculture of the country. We are commencing to appreciate that while in the early years of the past century two-thirds of our people were engaged in the producing business, producing food and clothing for the people, now but one-third are so engaged. And it also seems to be pretty clearly demonstrated that the average earning of the average farmer has netted too small a return for his labor. In many parts of the country, what he did earn was earned at too great a personal sacrifice—labor for long hours and no recreation. Plainly speaking, we have wakened up to the situation that though the yearly crop figures seem to indicate an abundance, we are actually approaching the condition where demand will soon exceed supply, and in most instances the farming business is badly out of gear and needs reorganizing. It has fallen to the lot of the electrical engineer to take a hand in many matters of reorganization, and I believe agriculture now requires his attention.

Betterment of the farmers' conditions and improved efficiency in all the operations involved in his work is the cry of the day. Bankers and business men's associations, federal departments, agricultural colleges and important engineering organizations are giving this feature of the country's welfare careful study, and yet there is perhaps no one improvement that may be counted upon to benefit the farmer so radically as the introduction of electricity on the farm.

The electric farm, however, is not a new idea, for several farms well worthy of this name have been in successful operation for some ten or twelve years, and perhaps longer than this. But there has been very little organized effort in disseminating existing knowledge of the practical use of electricity in agriculture, with the result that farms so equipped are generally regarded with suspicion and possibly in the light of a hobby.

I shall endeavor to show that such a point of view may at once be dismissed and we may look for a general use of electricity on the better class of farms in this country before many more years have elapsed. As a matter of fact, electricity is now being utilized for lighting and power purposes on a much larger number of American farms than perhaps many of us have heretofore realized.

Let us consider for a moment the farms of our great Southwest. In some sections of that wonderfully fertile country, well protected by the high mountain ranges, practically every farm is an electric farm. That is to say, the buildings are lighted by electricity and many of the laborious operations are accomplished by the use of electric power. These really were our first electric farms, the period of their establishment corresponding with the development of the water powers of the nearby mountains.

On the majority of these farms irrigation is practised and quite naturally electricity was first made use of for pumping purposes. Then under the influence of progressive local central station operators, it was almost universally adopted for light.

I can recall seeing electric lights and the electric flat iron in use in the farm homes on the Pacific coast, eleven years ago. The people were content to enjoy the advantages which these improvements made possible to them, but did not seem to regard their conditions as unusual. Their farms were in fact electric farms and their industries dependent upon the produce of the land were, as they are now, practically all operated by electricity. I refer to the canneries, fruit packing houses, etc.

The conditions surrounding the farming districts in Southern California, for example, at that time, were such that any other form of energy would have been unusual to adopt, a combination of circumstances being largely responsible for this happy situation. The high-tension transmission service systems were then new and the companies desired business; besides this, we did not have the gas engines we have today. The efficient and reliable gasolene and fuel oil motors were not developed until several years later. There was pumping to do, for irrigation was rapidly coming into favor, and, naturally, the electric companies secured this business.

It is hard to say whether the power plants, supplying service at rates within the reach of all, made the irrigated farms, or the electrical load, which these farms offered, insured the success of the power developments. Both interests seem to have worked together and in some instances practically the entire supply of the central station current was at once engaged for lighting, heating and power uses on the farms. This was the case ten years ago in the instances I speak of, and according to reports I have just received, the situation has not materially changed, except that both supply of and demand for the current have increased.

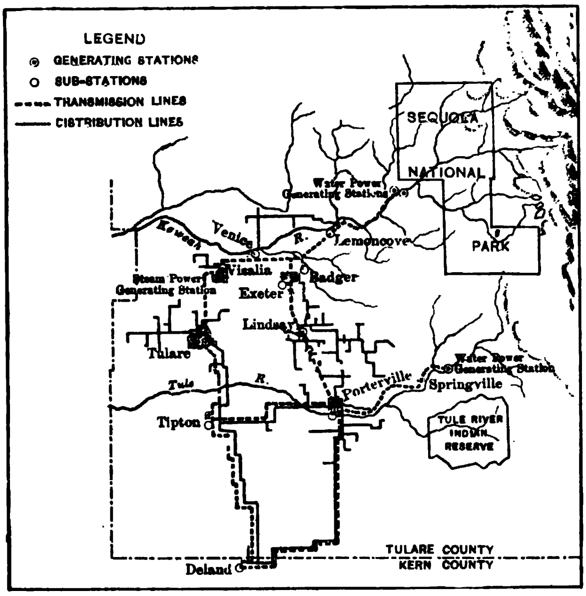

Fig. 1—Territory Covered by Mt. Whitney Power & Electric Co's Service, Visalia, Cal.—Typical of a Modern Intensive Farming District.

Such electric service plants may be regarded as "farmers'" central stations and I shall commence my illustrations with a description of the Mount Whitney Power and Electric Company's service in the vicinity of Visalia, Cal. This will serve as an illustration of a plant of this class.

Description of the power station itself or the transmission system is not necessary as the plant is well known, and possibly many readers are familiar with its equipment. Fig. 1 shows the territory covered by the service of this company and is typical of a modern intensive farming district where irrigation plays an important role.

Some of the farms in this district are large farms of several hundred acres, but the majority are small truck and fruit farms, ranging from 10 to 40 acres, an average of about 20 acres to each person, the total number of acres irrigated by electric power from the Mt. Whitney plant approximating 25,000, and representing about 6000 horse power in electric motors.

Fig. 2 shows a characteristic pumping installation employed on the irrigation farms in this district. It is interesting to note that on this 800-acre farm the electric service lines have been carried to several widely separated points, serving pumping motors in some cases of no greater capacity than five horse power. In fact, the loads these western central stations cater to, oftentimes, are of surprisingly small amount and quite distributed.

In the Exeter district, where this 800-acre farm is located, there are 32 plunger pumps aggregating 96 h.p., and 16 centrifugal pumps aggregating 125 ½ h.p. And in the Lindsay district, comprising about 25 square miles, there are in operation 217 pumping plants with a total connected horse power of 1794, of which 113 were plunger pumps (1100 h.p.) and 104 centrifugal pumps (694 h.p.) The total pumping load connected to the company's system is 374 plunger pumps (2385 h.p.), and 256 centrifugal pumps (2471 h.p.), or a total of 630 pumping plants with 4856 h.p., being on the average 7.7 h.p. for each pumping plant.

The irrigation pumping season in California is from five to six months at 24 hours per day. Contracts are on a basis of $50.00 per annum per horse power; the customer installing and maintaining at his own cost the motors, transformers, pumps, housings and all other appliances. He agrees to pay each year the sum of $50.00 for each horse power furnished him at time of his maximum consumption during the year. He further agrees that the amount of power to be paid for at that rate shall not be less than 75 per cent of the rated horse power of the motor. Motors of less than five h.p. are paid for at $50.00 per year for the rated horse power of the motor, instead of 75 per cent thereof.

In very few cases only, power is sold between the hours of sunrise and sunset at $30.00 per h.p. per annum, the company not having much power to sell at this rate as, during the irrigation season, the irrigators want to operate day and night. However, small power applications are taken care of in this way, consisting chiefly of cream separators, churns, grindstones, wood saws, heating flat irons, washing machines, fans and other domestic items.

There is also a partial meter rate contract which is used principally by growers of acidulous fruits and alfalfa, the essential points of which are as follows:

Current is furnished during the six months, February 1st to August 1st, at $25.00 for each horse power based on maximum demand, while for current furnished during the remaining months of the year, the rate is three cents per kilowatt-hour, it being agreed that the maximum amount of power to be used during the meter period will be equivalent to at least $6.00 per month horse power per of motor rating.

The straight motor rate is used for development work, grading from five cents for the first 26 kilowatt-hours per month (additions depending on size of the motor and the months), usually ranging around one and three-fourths cents to two cents per kilowatt-hour per month. Most of the irrigating power, however, is sold on the $50.00 flat rate.

The farms served by the Mt. Whitney system may be termed electrically irrigated farms, as in all cases the farmer operates his irrigation pumps by electricity. The details of this class of business, it will be seen, are well established. Electric companies in other sections have also built up businesses of this kind and in doing so have followed the same lines or a modification of them.

Another hydroelectric development and distribution system where irrigation pumping forms an important portion of the total load is that of the Pacific Power and Light Company.

The lines of this company traverse a fertile farming district lying in the southeastern corner of the State of Washington, just east of the Cascade Mountains. Several power developments are connected together making a complete distribution system, serving a total population of 101,900, including 39 towns, having an average population of 2500. In addition to the towns, the population of the rural communities is 5000.

There are 300 miles of primary lines at 66,000 volts, with 500 miles of 6600-volt secondary.

All of the plants making up this company's system are illustrations of a generating station designed to meet the lighting and power demands of a growing farming community. Fig. 3 shows the territory served.

It will be seen from this map that the power plant at Naches is close to the mountain range and Figs. 4 to 8 show the evolution from the snow-capped mountains to the power station where the energy of the falling waters is utilized first for generating electricity and then allowed to pass on, to be used again for irrigation.

These illustrations require very little description, for the development shown is complete. It is a beautiful illustration of the combination of the works of God and man. The magnificent orchards and gardens which have thus been made possible on the waste places of the earth are wonderful accomplishments of which we may well be proud. There can be no greater work for us all in this day of agricultural investigation, than to advance in all parts of our land the utilization of our resources as exemplified by these illustrations.

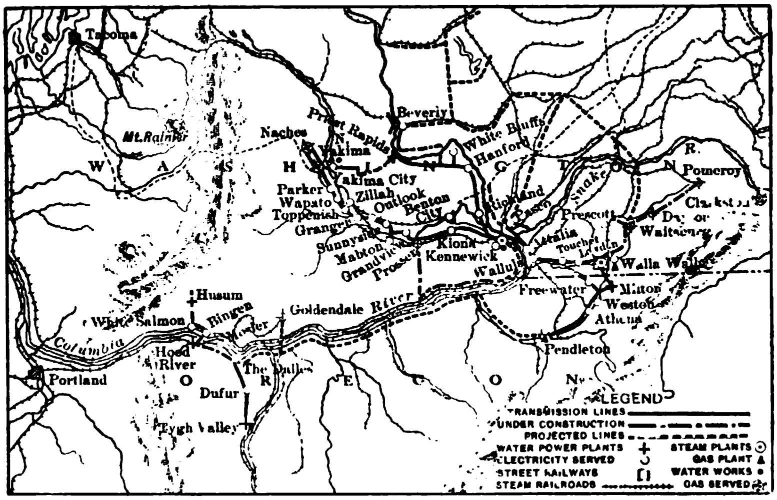

FIG. 3—TERRITORY SERVED BY SEVERAL POWER STATIONS OF THE PACIFIC POWER & LIGHT CO. IN AN IRRIGATED FARMING SECTION, WASH

Figs. 9 and 10 show further developments in electric power transmission, and Fig. 11 shows the acres of garden truck and the bountiful crops of hay or grain that result from the scientific application of water to the fertile soil.

During the early part of the history of American farming there was too much extensive husbandry and not enough intensive farming. Land was abundant and cheap, and much of it drained itself. The pioneer, believing the supply of land inexhaustible, selected a patch, killed off the trees, cultivated it until the fertility of the soil was exhausted, and then moved to another location. In this way, the increase in population being enormous, great and rapid inroads were made on the country's natural resources of soil. In time, all the naturally drained and naturally watered lands became absorbed, and a great deal of it exhausted, temporarily at least.

The reclamation of our western desert and prairie land along most approved scientific lines is an object lesson to us all. Those lands are now rapidly being taken up and have become very valuable, and fertile, low-cost farms by the tens of thousands are needed.

We have learned from these western developments that for proper crop culture all lands must be drained and all crops need water. And it is not sufficient to have a deluge of water from time to time, but water must be applied in such manner as to provide the food necessary to plant life, in order that development may be greatest at certain stages of its growth. This is especially interesting, in that it is a claim for the merits of irrigation, not only in the arid country, but also in sections where there may be an abundant rainfall.

Mr. C. J. Blanchard, statistician of the U. S. Reclamation Service, in a lecture on "Making the Wilderness Blossom,"* states that the desert of our old geographies has no place on the map. The magic of irrigation has transformed valleys long vacant into prosperous agricultural communities.

A brief summation of the work accomplished shows that construction is under way or has been completed on 29 projects involving an expenditure of $65,470,000. In the eight years of actual work there have been dug 7000 miles of canals and more than 19 miles of tunnels, mostly excavated through mountains. The total excavation of rock and earth amounts to 77,200,000 cubic yards. There have been built 570 miles of roads, 1700 miles of telephones, and there are now in operation 275 miles of transmission lines over which surplus power and light are furnished to several cities and towns. The small farms and villages grouped about these developments give the effect of suburban rather than rural conditions. The cheap power developed from the great dams or from numerous drops in the main canals

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is now utilized for the operation of trolley lines which reach out into the rural districts, bringing the farmer in close touch with the city. It runs numerous industrial plants, for storing, handling and manufacturing the raw products of the farm. The same power is used for lighting and heating in the towns and for cooking in the homes. On several of the projects the farmers are applying for electric power and in many farm houses electric power is utilized for many domestic duties.

More than a million dollars has been invested in the development of power on the Salt River project, of which the farmers have voluntarily raised $800,000. The sale of power up to the beginning of the present year amounted to $144,000 with the plant only partially constructed. This revenue will contribute materially towards lessening the cost of operating the irrigation system.

Thus it may be seen that scientific agriculture, irrigation and electricity have formed a powerful combination. The natural waters are played with at will, sometimes passing directly to the land, but more often the turbulent mountain streams are carried for miles in flumes or canals, only to give up energy at several points on the way, and ultimately to irrigate the land by gravity, or pumping, as the conditions may require.

Another method is to drain the marsh land and pump the water thus available on to the higher places adjoining. Suitable crops are then grown on land of any level with the result that the area for production is materially increased.

In many of our states, both East and West, there is a well established underflow of water which can be made available through pumping. In the sections where irrigation methods obtain, water ditches conveying this well water to various portions of the farmer's land are often carried to the next man's land, the compensation thus derived diminishing the pumping cost.

All through our Western and Southwestern country are to be found examples of well installations where electric power has replaced steam or gasolene engines, for it becomes economy to do this under the favorable rate charged by the electric generating stations there.

The San Joaquin Light and Power Corporation of Fresno, California, supplies electric service to seven counties in one of the most fertile farming sections of the country, the actual area being more than 200 miles long and 75 or 80 miles wide. This,

FIG. 2—800-ACRE FARM AT EXETER, CAL. [BATES]

Pump house containing 5-h.p. electric motor, belted to 5½-in. by 5-in. triple plunger pump with 3½-in. suction, using 5.56 h.p.

[BATES]

FIG. 4—MT. RAINIER, THE FOUNTAIN HEAD FROM WHICH DESCENDS A NEVER-FAILING SUPPLY OF WATER.

FIG. 5—NATCHES RIVER ABOVE INTAKE OF CANAL. [BATES]

FIG. 6—CAPTURED WATERS—FOREBAY OF NATCHES POWER CANAL. [BATES]

FIG. 7—PIPE LINES FROM CANAL TO NATCHES POWER HOUSE [BATES]

FIG. 8—NATCHES POWER HOUSE. [BATES]

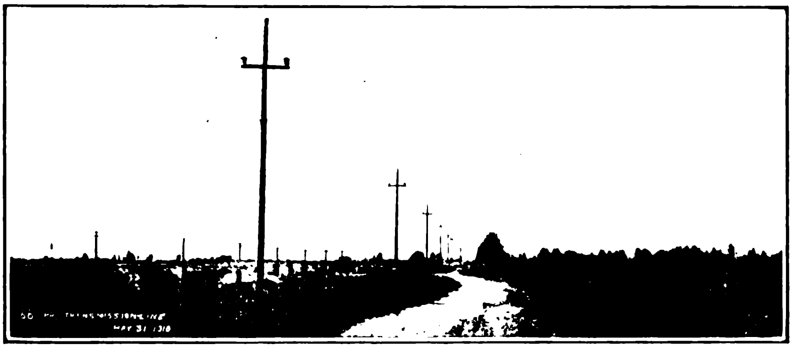


FIG. 9—POWER TRANSMISSION LINE. [BATES]

FIG. 10—AN IRRIGATION COMPANY'S PUMPING PLANT ON THE COLUMBIA RIVER. [BATES]

Two 50-h.p. motors driving centrifugal pumps supply gravity ditch furnishing water to many farms. These were recently supplemented with a 625-h.p. vertical type centrifugal pump to supply a new high-level canal.

[BATES]

FIG. 11—ACRES OF GARDEN TRUCK FORCED TO EARLY MATURITY BY IRRIGATION AND DRAINAGE.

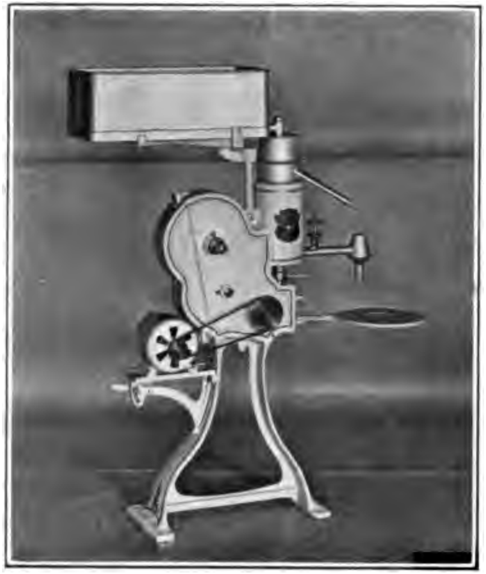
[BATES]

FIG. 13—IN A DAIRY OR CREAMERY PLANT ELECTRIC FIXTURES MUST BE WATERTIGHT.

In the bottling room the hose is used twice daily to " wash down " the entire interior, as in all the other buildings of this dairy farm at Morristown, New Jersey.

[BATES]

FIG. 14—MOTOR-DRIVEN CREAM SEPARATOR.



[BATES]

FIG. 15—CREAM SEPARATOR DRIVEN BY 1/5-H.P. MOTOR.

[BATES]

FIG. 16—BARREL CHURN WITH ELECTRIC MOTOR DIRECT-CONNECTED—¼ TO ⅓ H.P.

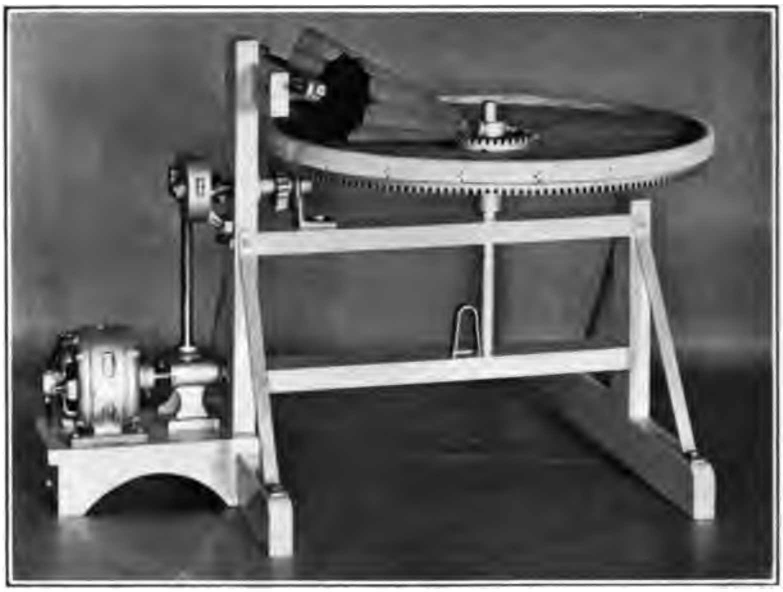


FIG. 17—DIRECT-CONNECTED MOTOR-DRIVEN BUTTER WORKER. [BATES

[BATES]

FIG. 18—MECHANICAL MILKING MACHINE, ELECTRIC MOTOR AND MILK RECEPTACLE FORMING A PART OF EACH INDIVIDUAL EQUIPMENT.

[BATES]

FIG. 19—2½-H.P. MOTOR BELTED TO AMMONIA COMPRESSOR USED FOR COOLING STORAGE REFRIGERATOR, MILK COOLER AND ICE-MAKING SET.
College Farm Dairy, New Brunswick, New Jersey.

[BATES]

FIG. 20—MILK COOLER AND AERATOR CONNECTED WITH INSULATED BRINE LINES RUNNING FROM BRINE TANK OF THE ELECTRICALLY-DRIVEN REFRIGERATING PLANT SHOWN IN FIG. 19.

[BATES]

Fig. 21—Harvesting Ice with Traveling Chain and Electric Power.

The "flights" are 33 ft. apart on the chain and there are ten of them, five on the "going side" covering a distance of 165 ft. The return trough for the chain is fastened up tight against the under side of the slide.

[BATES]

Fig. 22—A 2½-h.p. Motor, Connected by 200 ft. of Flexible Cable with the Electrical Supply of the Nearest Building, Drives this Ice Harvester.

FIG. 23—CATTLE AND HORSES MAY BE CLIPPED AND GROOMED BY ELECTRIC POWER. [BATES]

[BATES]

FIG. 24—SPINNING ON TINFOIL CAPS ON BOTTLES OF HIGH QUALITY MILK. THESE CAPS CANNOT BE REMOVED AND THEN REPLACED.

FIG. 25—CUTTING ENSILAGE AND DELIVERING IT INTO THE SILO BY ELECTRIC POWER. [BATES]

[BATES]

FIG. 26—WATERTIGHT TELEPHONE STATION SUITABLE FOR USE ON THE FARM.

[BATES]

FIG. 28—PORTABLE TELEPHONE STATION, INCLUDING TRANSMITTER, RECEIVER, MAGNETO AND CONNECTION TO LINE BY MEANS OF A "POLE JACK."

[BATES]

FIG. 27—ON THE RAMSDELL "ELECTRIC FARM" AT MINOT, MAINE, THE FARMER'S DAUGHTER ACTS AS TELEPHONE CENTRAL.

FIG. 29—THIS WINDMILL DRIVES A DYNAMO WHICH FURNISHES CURRENT FOR TWENTY-FOUR TUNGSTEN LAMPS. [BATES]

FIG. 30—THE DYNAMO HAS A CAPACITY OF 0.21 KW. [BATES]

It is set on the second floor of the mill, and is driven by a quarter-turned belt from a pulley on the vertical shaft of the windpower.

FIG. 31—STORAGE BATTERY IN ADJOINING BARN, ACCUMULATES ENERGY GIVEN BY DYNAMO WHEN RUNNING, AND STORES IT FOR USE WHEN LIGHTS ARE TURNED ON. [BATES]

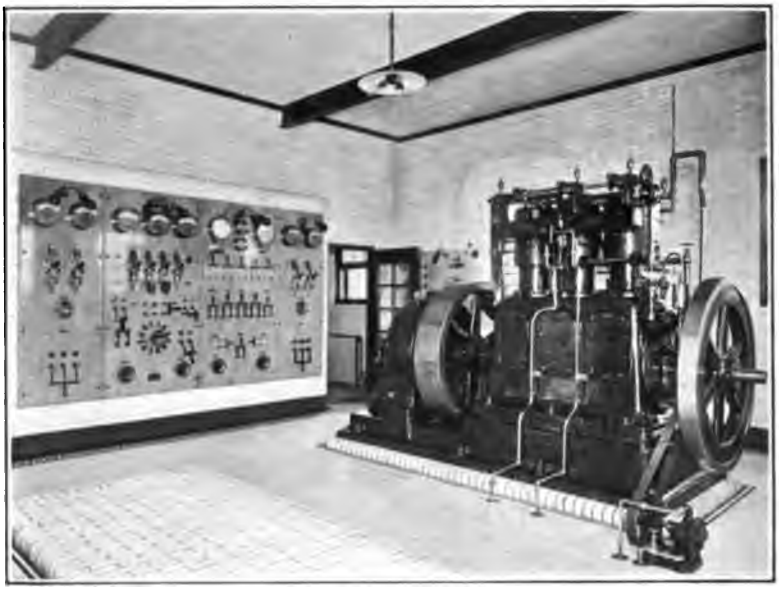


FIG. 32—A HIGH-POWERED EQUIPMENT FOR A LARGE FARM. [BATES]

FIG. 33—AN IDEAL PUMPING PLANT FOR FIRE PROTECTION. [BATES]

therefore, is a very important district, and information regarding its growth and present conditions cannot help but be of value.

Mr. A. G. Wishon, general manager of the company, reports as follows:

> We are now serving 140 pumping plants in our territory, which are used for the development of water for irrigation purposes. We wish to mention particularly a number of plants that we are operating for a water company located at Alpaugh, Tulare County, California. This proposition is somewhat unique. About twelve miles from a colony of 8000 acres, planted to alfalfa and various other farm products, are located seven artesian wells that are about 1000 ft. deep. These wells were flowing artesian wells, the capacity of which was about 60 in. per minute, per well. This water company made a contract with us to extend our transmission line to this nest of wells, which are located on a tract of about 10 or 15 acres, for the purpose of serving electricity to operate electric motors. There were seven 20-h.p. motors installed at seven different wells, belt-connected to 8-in. pumps. These pumps are located at the surface of the ground, with a 30-ft. suction pipe; each pumping plant is delivering about 1500 gallons of water per minute, with about 20 h.p.
>
> They are paying us $50 per h.p. per year for continuous service, the motors being operated almost continually throughout the entire year. The water discharged flows into a main canal which extends to the colony twelve (12) miles away, and at a point near the edge of the colony, this entire body of water is raised about 6 ft. with a 50-h.p. motor and distributed over a tract of 8000 acres. They are also paying us the same price per h.p. per year for the 50-h.p. motor. The cost, therefore, for irrigation is about $1.25 per acre, which is a very reasonable charge for water service throughout the entire year. These people are raising 10 or 12 tons of alfalfa per year, per acre, and in some instances the onion growers will clear $500 per acre.

Irrigation is the key which unlocks the fertility of the soil, and to comprehend its importance in agriculture, one must appreciate the fundamental principles governing plant growth and soil culture.

Rain may or may not come when it is needed most, and again, it may pour forth even in destructive quantities, but water under a well-managed irrigation system is turned on when and where required. This makes farming in so-called arid land a more definite and scientific proposition than it is in parts of the country apparently more favored by nature. When we have so arranged our soil conditions that water may be drained off the land as positively as it is applied, the application of irrigation methods is beneficial, no matter what may be the natural conditions of rainfall.

Pump irrigation results in intensive farming. And this is the direction in which our agriculture is moving. It may also be added that the power required for pumping has proved to be the opening wedge in introducing the use of electricity in the majority of those farming districts where dependence upon this form of energy has become established. The most scientific farming can be done only by pump irrigation where the work can be arranged and the farm run just as systematically as some of the big manufacturing and commercial undertakings.

Regarding irrigation in humid districts, Mr. Milo B. Williams,* Irrigation Engineer of the U. S. Department of Agriculture, states that it is the distribution of rainfall with respect to need of different crops which determines the necessity for irrigation in a locality. Drought records for several years past have led the National Department of Agriculture to encourage supplemental irrigation in the humid regions as a vital factor in crop insurance.

The most humid portion of the agricultural East is subject to the greatest irregularity of rainfall. This refers to the southern states bordering on the Gulf of Mexico and the Atlantic Ocean. Here the normal annual precipitation ranges from 45 to 55 inches and yet these states are subject to droughts lasting from 20 to 60 days or more during the growing season. Irrigation in various parts of Alabama, Georgia and Florida, has resulted in producing very profitable crops on land which has heretofore failed to yield sufficient returns to pay for cultivation. Irrigation will do for the South what it has done for the West. It will insure results to the small farmer. The coming of the small farmer to the South will cause the passing away of ruined plantations, as his going to the West has caused the passing away of great deserts and wasteful wheat ranches.

The South today represents one of the largest areas of dormant latent agricultural possibilities in this nation and when drainage of the low lands is coupled with the general practise of irrigation throughout our South and our East, much in the same way that water distribution has been conquered in our West, we will have added many millions of acres to the productive area of this great country.

These are great problems and promise an immense work for years to come, but the beneficial results will outweigh many times the cost and labor that will be necessary to bring them about. At present, an abnormal condition exists just as it did in the arid sections before irrigation was practised, and it is the writer's opinion that the reclamation of the worn-out farms and the barren

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lands of the Atlantic Slope presents agricultural opportunities unsurpassed at this time by any section.

In the drainage of water-soaked lands, as in irrigation, electric power may be used for short lift pumping. And as an indication of the magnitude of the work ahead of us in this field alone, it is sufficient to quote from the statistical records of the United States of 1910 issued by the Department of Commerce and Labor, which place the total swamp area and overflowed lands at a total of approximately 75,000,000 acres.

In their present condition, the swamps of the country are a source of weakness in our national economy. They are unproductive, but they can be made sources of great national wealth.

The policy of maintaining our agricultural lands in vast areas and thus, through what has been termed " extensive husbandry," failing to utilize to the utmost every acre of fertile soil, is rapidly falling into disfavor. And we are, on the other hand, moving toward an increased number of farm homes with more intensive methods of development. This change is going on all over our land. In the West, the old cattle ranges are passing away, merely to be replaced by irrigated farms, where diversified methods are practised.

The stock feeder of today makes his money on the weight o, the stock when purchased, the practise being to buy in the fallf feed through the winter and sell in the spring. Such increased weight as live stock make in that period, however, is not sufficient to pay for its portion of the feed given. Profit, therefore, comes through improved condition of the meat, and the difference between fall and spring values. The successful feeder aims for an increase of about 100 per cent.

To accomplish this, care must be exercised in feeding. The coarse and unbalanced rations which cattle had to depend upon on the ranges, proved anything but beneficial to them, particularly, out of the growing seasons. The method today is to use grains with the roughage, and to grind the grains and cut the roughage. For this the farmer must have power—in fact to meet competition the farmer must economize on his feeding, that is, he must work for the best results with the least expenditure for feed—power for cutting and grinding is now a necessity on every stock farm of any appreciable size, for with feed so prepared, there is better assimilation and less waste.

Of late years, an enormous impetus has been given to alfalfa grinding and corn cutting for ensilage. Feeders have found that by following this method the cost of the apparatus and the power for driving it is more than saved in a single season over the old method which involved waste through stock trampling their fodder under their feet. Further, by grinding and mixing the feed, any ration desired may be prepared.

One of our largest farming industries is that of stock " feeding," and in so far as the need for power is concerned, stock " raising " farms may be regarded as in the same class, balanced rations for young stock being perhaps even more important than for " feeders."

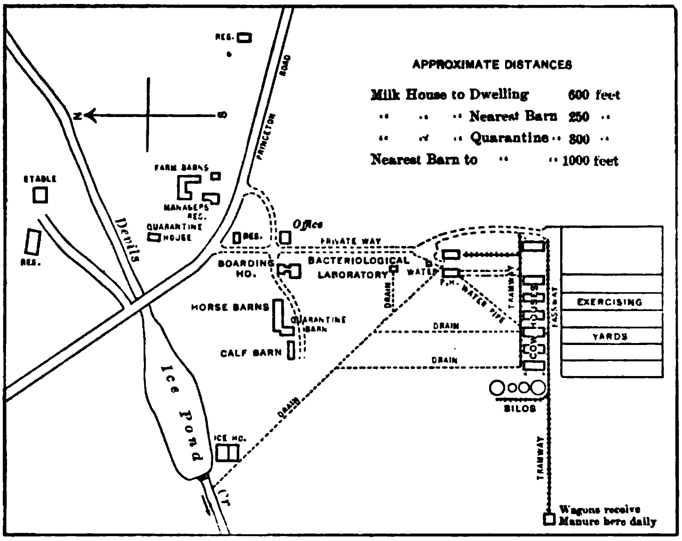

FIG. 12—DIMENSION PLAN SHOWING POWER HOUSE AND ARRANGEMENT OF BUILDINGS ON DAIRY FARM AT PLAINSBORO, N. J.

On all such farms there is considerable demand for power, ranging in most cases from 25 to 50 h.p. and sometimes considerably more. Besides the power necessary on the individual farms, there are in all farming districts industries that convert the farm produce into finished products.

Electricity is gaining a foothold for both lighting and power in our better class of dairy farms. Its great cleanliness and safety for lighting leave little room for argument when new dairy buildings are being planned. And on account of its convenience as a form of power, it is frequently used with cream separators, churns, refrigerating machines, milk testers, also in the barn or field work incidental to the preparation of feed and handling of crops.

Fig. 12 shows a large milk farm at Plainsboro, New Jersey, where electricity is used for lighting, clipping cows, operating a bottling machine, spinning on tinfoil caps or seals on bottles, cutting ensilage, running a saw mill, pumping water from a deep well, grinding feed and elevating it to storage bins.

The fact that this is a commercial plant turning out daily from 3500 to 4000 quarts of milk, where a high standard of quality is rigidly maintained, is evidence that there must be advantages in using electricity in such an installation.

The total acreage of the farm is nearly 1200, and at present about 70 per cent is under cultivation. Electricity is generated by steam power and distributed at 220 volts. The generating equipment, at present, consists of one 25-kw. direct-connected unit, steam boiler, etc.

This is not a large generating plant, to be sure, but it insures cleanliness of lighting equipment and safety from fire risk in the barns, bunk houses and outbuildings. It also makes possible a convenient source of power in any part of the farms or outbuildings, which, of necessity, are widely distributed, and cost of generating the current, including interest and depreciation charges, is probably not over 4 cents per kilowatt-hour.

Scientific milk production is more and more coming into prominence and the necessity for perfect cleanliness, immediate cooling and keeping the milk at a low temperature, compels such dairy farmers to adopt devices that will be most helpful in obtaining these results.

Fig. 13 shows the bottling room at a milk dairy in Morristown, New Jersey, where the walls, ceilings and floors of all rooms in which the milk is handled are washed down daily, both morning and evening—the electric lighting fixtures being entirely watertight.

" Dairying " and " stock raising " are usually followed where land needs upbuilding in fertility, and in either the silo is a necessity, cutting up succulent forage crops and storing them in the silo for later use being the accepted method of preparing the feed. To do this the farmer must have power, but a 10-h.p. electric motor with its capacity for momentary overload will do work that would stall a gasolene engine rated at 12 or 15 h.p. Hence, for silage cutting and elevating, a 10-h.p. electric motor is sufficient where a 20-h.p. gasolene engine would be recommended.

The farmer can easily recognize the advantage of the electric motor for this operation, and when once adopted, he soon wants to use the current for grinding feed, baling hay and other purposes.

On the dairy farm, however, electricity offers other opportunities, as it is the most convenient form of energy for operating an artificial refrigeration plant, the cream separator, churn and butter worker. The reason for this rests in the ease of control, making for economy. The current is used only while the apparatus driven is in operation and may be shut off when the work is done. No skill whatever is required to operate such equipments, it being necessary only to turn a switch.

Cream separators, while often turned by hand on small dairy farms, are more frequently driven mechanically where considerable cream is handled. Fig. 14 shows the use of the electric motor for separator driving where perfect cleanliness is a factor. Cream separators, except in the very large sizes, require not more than a 1/5-h.p. motor and they are in operation only for a comparatively short time. The operating cost, therefore, is practically negligible.

Figs. 15, 16 and 17 show a complete creamery outfit of excellent type, each piece of apparatus being driven by an individual motor. The power required for the various branches of creamery work is small, convenience and freedom from dust being the all-important factors.

In large dairies where hand milkers are difficult to obtain, the milking machine has a place and the records seem to show that these devices are favorably received in some of our western dairy sections, at least. Those that the writer is familiar with, which have been commercially used in this country, consist principally of a vacuum pump, milk chamber with specially constructed admission valves, rubber connecting tubes and special type of cups which fit directly on the cow's teats, a convenient method of driving the vacuum pump being by the electric motor. These equipments are often called "electric milkers."

The only "electric milker" really deserving the name that has come to the writer's attention is shown in Fig. 18.

This device is so designed that an electric motor of about 1/12-h.p. forms an integral part of the apparatus that does the milking, the whole machine being suspended under the belly of the cow. Through a worm and gear the motor moves an aluminum rod forward and backward, which carries the pressure plates, and the teats, being held in a fixed position by a corresponding set of stationary plates, are thus squeezed as in hand milking.

It is an ingenious device, free from springs, tubes or other parts which might get out of order, and being of aluminum it is very light in weight. All of the details of design have been carefully developed, and as a machine milker, it is deserving of careful consideration.

As all dairymen know, refrigeration is an essential that they cannot do without. In many plants natural ice is still used, but the cost of harvesting, storing and handling ice is far greater than the operation of a power-driven refrigerating machine.

Artificial refrigeration is more sanitary and far more convenient. Figs. 19 and 20 show a refrigerating equipment which was recently installed in the dairy department at the College Farm of the New Jersey State College of Agriculture, New Brunswick, N. J.

In this refrigerator is the usual brine tank through which the ammonia coils pass. The cooling of the brine and of the refrigerator entirely takes the place of ice. In other words, it is not a combination refrigerator, but is cooled by the ammonia pumped by an electric motor. The same pump and motor conducts ammonia through the inner compartment of the milk cooler and aerator shown in Fig. 20.

The motor is set running just before the milk is started to flowing over the cooler and aerator. The milk by passing over it is cooled and aerated, and run into the bottler just below. As soon as the milk has all passed over, the motor is turned off; thus the power used is a minimum.

Some dairies without this equipment, resort to pumping of ice-water through the cooler. This, of course, can be done with the electric motor or any other power and even by gravity. This last method is most common, but in warm weather it does not cool the milk sufficiently. The cooling which the electric ammonia system provides makes it possible to almost freeze the milk, and thus keep down the bacteria content by reducing the natural multiplication of these organisms.

Small refrigerators are beneficial on all farms for storage of eggs, dressed poultry and for preserving the freshness of flowers, fruit or garden truck that cannot be immediately sent to market. They are also useful for keeping meats and other perishable supplies for home consumption.

Figs. 21 and 22 show an ice-carrying machine operated by electricity on the farm of Dr. Schuyler S. Wheeler, who states: " The outfit was eminently practical and satisfactory in every way and enabled me to fill my house with about 200 tons of ice, using five men and no teams, in four days. Previously it has been the custom to employ four to six teams, four to five days in addition to these men." When the bridge was fully elevated, 2.5 h.p. was required, current for which was supplied from the private generating plant, ordinarily used for lighting and small power devices.

Individual uses for electric power on the farm seem to be almost without end. Fig. 23 shows the method of electric clipping employed in the dairy barns of a milk farm, and cow grooming is accomplished in similar manner. When milk of the highest quality is to be produced, the farmer must put his stock through a careful preparation for cleanliness, and it has been determined at several experiment stations, as well as in practical commercial dairies, that it pays to groom cows daily, owing to the greater production of milk thus obtained. In some cases this practise has resulted in an average increased output per cow of 15 per cent, which of course, even at a low value of milk, would pay for the electric current, man's time, etc. Figs. 25 and 26 illustrate other applications of electric power which are in successful use at this same farm. It can be said of this plant that everything that makes for quality and efficiency has been employed, but nothing that would suggest an over-capitalization of equipment.

In all farming one realizes that the time incidental to covering distance is one of the greatest handicaps to rapid production and the accomplishment of quick results. The force of this statement is hard to realize until one has actually observed the distance a farmer and his men will travel in a day by team or on foot in going to and from their work, the house or barn buildings. Perhaps the farmer will desire merely to speak to his assistants about their work, but, nevertheless, he must travel the intervening distance, as, generally, no other means of communication is available to him.

In the western farm life, this is not so frequently the case, as the telephone has been used there for several years, but in the East, strange as it may seem, the telephone is only rarely found in the farming home and in the fields.

Some time ago, one of the electrical manufacturing companies designed a water-tight telephone, Fig. 27, for mine, police and railway service or other exposed use. The case is cast of heavy malleable iron, so shaped as to permit of attachment to a pole, post or side of building. The door closes against a rubber gasket, and when closed, the case is water-tight.

This form of local telephone station has been installed at some thirty different points on the farm of Mr. E. E. Ramsdell, Minot, Maine.

Mr. Ramsdell has introduced several electrical devices for saving labor on his form. The installation that has impressed me as being most worthy of especial mention, however, is his telephone equipment.

Fig. 28 shows the farm " central ", and from any outlying point on the farm the owner or his men may talk to the farm headquarters, the nearby town, or to any place whatever, by " long distance " if necessary.

Another form of telephone equipment which should be very useful for field work on the larger farms is shown in Fig. 29, consisting of a portable magneto telephone, which may be carried as part of the field worker's outfit, and by means of a pole jack, which is also shown in the illustration, it is possible to signal to, or converse with any other part of the farm. Telephone installations of the kind just described may also include a separate water-tight loud ringing extension bell that may be heard at a considerable distance from the fixed signal point. Such apparatus, and in fact any electrical devices for farm use, should be substantial in construction and built to withstand weather conditions.

That electricity on the farm makes for great economy, not only through convenience, cleanliness and safety, but also in actual cost of operation, can be proved over and over again in the case of those installations where the service is properly installed and where apparatus of suitable type and size has been selected. For example, in one instance where the monthly output was considerable, the cost for electric power averaged from one-half to one and one-half mills per pound of butter made, the rate of charge for current being 2½ cents per kilowatt-hour.

Considering the cleanliness, minimum upkeep and labor required, this cost becomes negligible. And the difference in cost of using electric illumination, compared with the full costs incidental to burning kerosene, while somewhat dependent upon the relative rates of charge, is actually in favor of electricity, when chimneys, wicks and time of trimming are considered.

It may, therefore, be accepted as a fact that on the farm, as elsewhere, electricity for lighting and power results in lower cost, but to make this statement so that it cannot be disputed, I would add that where electric service cannot be obtained from a public supply on a basis that will insure reasonable rates, it is entirely within the privilege of the farmer or rural dweller to equip his property with a private electric generating plant that will give him light and power at moderate cost, and the operation of such a plant should not be difficult for anyone to understand.

The plant illustrated by Figs. 30, 31 and 32 perhaps embodies a maximum of simplicity and minimum of operating expense, for which reasons I refer to it as an equipment within the reach of anyone desiring the benefit of electricity with very moderate outlay. In this instance, a small dynamo (6 amperes, 35 volts at 450 rev. per min) is belted to the vertical shaft of a windmill.

As the mill speed is not constant, an automatic cut-in is introduced in the electrical circuit between the dynamo and the storage battery, from which the lighting current is taken, the charging of this battery being the sole duty of the dynamo.

This plant, which is on the farm of J. F. Forrest, Poynette, Wisconsin, develops current for 24 15-watt, 25-volt tungsten lamps. Its whole cost was $250, exclusive of transportation, but including windmill, dynamo, storage battery, automatic cut-in, wire, porcelain insulators, sockets, switches and tungsten lamps. The owner did the complete wiring and arranging of the lights and switches. The two years of successful operation and the cleverness of the lighting scheme, which embodies several two-way and three-way switches for distant control of both exterior and interior lights, is certainly an indication that Mr. Forrest, who runs a farm of some hundred or more acres, has done for himself what many other farmers may also do by a little planning and some interesting labor.

To make this subject of electricity on the farm reasonably complete, there is shown Fig. 33, which illustrates a well-equipped generating plant where the dynamo is directly connected to a vertical type gasolene engine, the whole unit mounted together on one foundation. The storage battery is in the room adjoining, while the switchboard is built into a wall of the engine room.

In conclusion, I would state that the practicability and feasibility of utilizing electricity for both lighting and power on the farm has been demonstrated by many successful installations.

In some agricultural sections, central station operators are stimulating a general use of electricity in rural districts by following a far-sighted policy as to extension of service lines and rates for current.

Should one or more isolated farmers find it impracticable to obtain central station service, there is open the opportunity of establishing a cooperative generating station, utilizing waterpower, producer gas, steam, gasolene or fuel oil equipments, depending upon the conditions obtaining.

In conjunction with such cooperative electric generating stations, there could be operated community laundries, creameries, canneries, grist mills or other industries suggested by local needs.

Where neither public service nor cooperative plants are feasible, a farmer may, at a cost of approximately $250, install a private electric lighting plant, large enough for two dozen lights, and from this as a probable minimum, he may install an isolated plant at additional outlay that will provide current for as many lamps and as much power as he may desire.

The use of electricity on the farm makes for greater safety from fire risk, and for this reason especially, its use should be encouraged for lighting, heating and power.

And, finally, as our future land improvement in the East, as well as the South, will involve drainage and irrigation, we may expect to see here, as in the West, electricity taking a leading place in agricultural development. It should be remembered, too, that electric energy is greatly cheaper than man or horse power, and that nowhere else are man and horse labor wasted through periods of inactivity to an extent to be compared with the labor waste on the farm. Now, when it seems impossible to secure men on the farm, the turn of a switch brings electric energy, begetting production and wealth.

DISCUSSION ON "ELECTRICITY ON THE FARM" (BATES), BOSTON, MASS., JUNE 28, 1912.

J. D. Merrifield: Where I come from they sell electricity to the farmer at $50 a horse power, and he can use it for anything he pleases.

I want to speak of refrigeration. Mr. Bates states that every farmer can afford refrigeration. I will tell you of a refrigerating "plant" in use in my town. The humidity of the air there is very low. If you draw air through water and then pump air into the room by means of a fan, you will lower the temperature of the room six or eight or even ten degrees. Where I live the temperature goes up to 119 deg. fahr. in the shade, and I have known it higher. This may last a day or two. I know of a boy out there who rigged up a very successful device. It consisted of a rod from his wagon and the picket rope from the cow, and he made a little fan drive, put the fan on the kitchen window, hung wet cloths, and he cooled off both the kitchen and dining-room, and made it a very comfortable place to occupy. It is a very simple and yet a very effective method of accomplishing the result.

L. L. Elden: I hope before Mr. Bates leaves our country here in the East he won't fail to find out that at least one electric company is entering the field. The Edison Electric Illuminating Company of Boston has what is called an "Edison farm," about twenty miles from Boston, where all types of electrical machines and applications of electricity to these machines are on exhibition. The company is offering to extend its lines practically anywhere to get the business, and it is practically off-peak business. It is therefore very attractive to the company from both the capacity and income points of view. I do not know whether this exploitation has been attempted elsewhere, and we do not know exactly what the result of this effort is going to be, but so far there has been a marked interest displayed by the neighbors in the vicinity of the exhibit, and sales of several large motors have been made for farming purposes.

Putnam A. Bates: I have known something of the idea that this company was planning, and I am very glad to hear that the project has been put into actual operation this year. There is no question that it will take a little time before the additional expense of such an exhibit is brought back, but when it comes back it will come back strong and the companies that make their beginning now will be the ones that will profit the most. The sale of electric machinery among the farmers, as I have pointed out, is going to be tremendous. The sale of electrical energy is going to be even more tremendous, because in five or ten years at the outside, it will be a most unusual thing to see a farm without electric current in use for both lighting and power.

I can recollect when dentists used a hammer, to drive the filling into one's teeth, but they don't do that now. A little electric motor has been substituted for the hand method. I have worked my own garden with a hand wheel hoe, but why should I not attach an electric motor to this device and let the motor do the digging while I merely furnish the energy to move the tool along? That is what was done with the big grain harvesting machines. They required forty or fifty horses or mules to pull them, the greater part of this energy being necessary to do the cutting, threshing and binding. Some ingenious fellow said, " Why not leave a good many of those animals in the barn, or sell them to the neighbors? Put a little gasoline motor on the back of that threshing machine. It is heavy already. It won't add much to put on a few hundred pounds more. Let the gasoline motor do the threshing and binding, and let the animals pull the thing about." That was a great improvement in harvesting machinery.

J. A. Moyer: I would like to ask Mr. Bates one question, whether he has any figures regarding the proportion of the individual or isolated plants used in comparison to central station power, where the latter is available.

Putnam A. Bates: If I understand the question correctly my answer must be that the isolated plant and the central station service for the farmer very seldom conflict. We might think they would, because in the city we find such competition always. But out in the rural sections the conditions are different. The central stations seem to be either progressive or hopeless. The former follow a liberal policy and cultivate the farmers' business. They are solving the problem from his point of view. With the latter class, we find the plants generally are carrying tremendous overhead burdens and have to charge from ten to fifteen or more cents per kilowatt-hour, and they insist on the farmer paying for the pole line if he wants the current. It is a ridiculous proposition. The farmer simply buys an isolated plant instead. You can compete with a ten-cent service rate by having an independent plant.

You find that on the farm, labor conditions work out differently from in the factory. In the factory you can differentiate between your candidates for employment. You can pick out the skilled man. You can let the others who apply go. But on the farm it is the other way around. You are mighty lucky if you get an unskilled man, to say nothing of the skilled man. These farm hands are pretty good as farmers. They usually mean well, but they will go along with the load of corn stalks to put into the silo and if you have a gasoline motor of 12 h.p. that is supposed to be ample to drive an ensilage cutter and silo filler they will put two bundles of wet cornstalks on the platform, and they will jam them in so as to stall a 12- or 15-h.p. gasoline motor every time. So really you ought to have 20 h.p. in a gasoline engine if you want to do silage work and do it right. Now with electricity you can use a 10-h.p. motor. It will cost less than a 10- or 12-h.p. gasoline motor, and rough treatment such as I have described makes no difference to the motor. It has 100 per cent overload capacity for a short time, and it will go through the heavy momentary overload with no delay or injury. That is one of the great advantages of electricity on the farm, it is so easily and well adapted to the needs of the situation.

Mr. Sanford: I would like to ask whether in the course of the daily work there is what you ordinarily call a peak load on the generator, that is, on a farm running with a small isolated plant, and, supposing there is any peak load which would tend to bother the generator, would it not be economical to carry a storage battery which will be charging during the light load and when the peak load comes on will be running parallel with the generator?

Putnam A. Bates: That is a good point. The storage battery is of no little significance in connection with the equipment of the isolated plant on the farm. I never design an isolated plant for farm use without putting in a storage battery and a good big one because that is just the factor that you need in a small rural isolated plant—a good big balance wheel to carry you over the times when you don't want to run your engine.

Adolph Shane (by letter): This paper has proved of considerable interest to me for several reasons. In the first place I have had occasion to look into this subject under the conditions surrounding my section of the country (Iowa)* and I desired to ascertain the view-point of another who had also made a study of this important development. In the next place, Mr. Bates has given me a clearer idea of the extent to which electrical apparatus for farm purposes has been developed. Again, he has shown the possibilities inherent in farm electrification.

Under certain conditions these possibilities may prove to be desirabilities. And this is the phase of the subject I wish to consider. To what extent is it desirable to electrify a farm? Mr. Bates shows us how extensive irrigation schemes are successfully carried out in the semi-arid West by means of electricity. He has shown us the application of electric power in the dairy and in the harvesting of ice. But does a comprehensive scheme of electrification under our present conditions represent advantages to the majority of farmers over this broad land? I think not. Until central station men see that it will pay them to sell cheap power to the farmer and until the farmer sees that his returns in dollars and cents are greater by the use of electricity than without, electrically operated farms will not become general.

The greatest farming sections of the United States are in the Middle West. Because of the preponderance of farm production and wealth in this part of the country, the conditions as they obtain here should also fairly well represent the conditions over the country as a whole; and where other conditions exist elsewhere they might perhaps be taken as special and not typical.

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*See Bulletin No. 25, Engineering Experiment Station, Iowa State College, Ames, Iowa.

Let us then consider the farms of the Middle West and study the problem of electrification.

In looking over the field we find that the farms, generally speaking, are many and moderate in size rather than relatively few and great in extent. On the large farm the problem of electrification may be taken seriously, but on the small farm the owner will have to be convinced of definite profits before he commits himself to the expense, especially since the middle western farmer does not depend on irrigation for his crops. But suppose he is considering electrification, what is to be his source of power? It must either be a central station or he must manufacture the power himself. As a rule the central station does not find it profitable to supply farmers with power in this region. The uses to which the farmer may desire to apply electric power are light, a number of domestic utensils, several motors of small power, and a large motor of perhaps 25 h.p. with which to thresh and cut ensilage. This latter motor is used but a few days in each year, yet it is necessary to supply transformers to take this maximum load. The result is that the load factor for the year is so poor that the all-day efficiency on the average is low. The further result is that there is a considerable waste of power and the central station must charge more per kilowatt-hour for this reason, and because of the relatively heavy overhead charges in proportion to the amount of power used. The latter reason may not exist if the transmission line is primarily built to serve a neighboring town and the farmer is taken on incidentally.

If the farmer is to manufacture the power himself he must, under similar conditions again, install a plant capable of supplying the largest motor with power, namely the 25-h.p. motor. Thus he would again, excepting for a few days in the year, operate his plant at a ridiculously small load factor. This would be aggravated by the fact that there would be little excuse to drive the churn and cream separator by an electric motor, since the gasoline or oil engine could drive a line shaft, which connects the power room with the repair shop and dairy room, at the same time that it operates the generator. This would be no less convenient and cleanly than the motor drive, for under any circumstances all apparatus should be operated at as nearly the same time as possible for the sake of economy in power generation; and the line shaft and belting is not more prominent in one case than in the other. I refer now to the dairy room of the average farm. Accordingly the cost of plant is excessive for the amount of power produced and the cost of power is excessive because of the very small load factor.

We thus see that the average farmer is at present enabled to use electric power only in a limited fashion; but if he is properly advised he may reap considerable benefit from the use of such power in a conservative way. The farmer realizes the convenience and safety of the electric light, particularly in the barn. Hence, aside from its cost, he may desire electric light. So I believe the use of electric power on the farm centers at present in the farmer's desire for electric light. In most cases he will produce the power himself, using a small gasoline or oil engine, generator, and storage battery for lighting. This is the entering wedge. If planned beforehand, the generator may have sufficient capacity to supply power for the flat-iron, washing machine, fan, sewing machine, etc., as well as to charge the battery, without causing the plant to cost materially more. The farmer may be ambitious and desirous of doing his grinding and pumping by means of electric power. He may still do this with a small capacity plant. But this is perhaps the extent to which, it appears to me, electrification should be carried by the average farmer at present.

If a number of farms operated a plant in cooperation the above discussion would be subject to considerable revision. But because of the human equation entering, general cooperation has hardly proved a success among farmers.

In the future the following causes may extend the degree of profitable electrification:

a. The increase in value of farm products to such a point that it may pay to multiply machinery for the more efficient and rapid handling of them.

b. The general development of large central station systems for the economic production and distribution of power.

c. The increase in size of farms under single or corporate ownership.

Any of these causes or combination of causes may produce the desired end. The point I desire to make in this discussion is that the members of the electrical profession interested in exploiting electricity for the farm will gain greater and farther reaching results in the end if such exploitation is followed along careful and conservative lines. The confidence of the farmer will then be secured.

Putnam A. Bates (by letter): Mr. Adolph Shane in his discussion of my paper " Electricity on the Farm " states: " under certain conditions these possibilities may prove to be desirabilities." And he adds the question: " To what extent is it desirable to electrify a farm?"

In answering this question, I must first emphasize the fact that in my paper I have not described possibilities, but have recited actual conditions of electrification on farms, many of which have been thus successfully operating for several years, a sufficient length of time to demonstrate fully their desirability.

The purpose of Mr. Shane's argument, I take it, is to awaken the central station man to the importance of aggressive co-operation in this application of electricity landward, and while in a measure I can sympathize with Mr. Shane, as my own farm in New Jersey lies in a section of electrical supply where the operators of the local plants are many years behind the times, generally speaking, the central station men are now quite alive to this problem, and it is a notable fact that during the past two years the progressive central stations in the United States and Canada have been making rapid strides in extending service to the farm. In fact, almost coincidently with the presentation of my paper at the Boston convention of this Institute in June last, the National Electric Light Association during its convention in Seattle discussed this subject and many important data were presented.

A few years ago, Mr. Shane's statement that the greatest farming sections of the United States are in the Middle West would have gone unchallenged, but today reliable reports do not show this to be so.

Unquestionably, the Middle West is deserving of great credit as a section of immense agricultural wealth, but in basing an argument as to the best equipments to recommend for the proper development of our farms in all sections of this vast country on the practises that now obtain there, more credit is being given than is due the Middle West, or any other one locality, for that matter.

The very fact that the Middle West has for so many years been regarded as a leader, agriculturally, is, I think, a sufficient reason for us to regard with suspicion any suggestion of impracticability regarding the recommendations of those who wish to see the advancement of new ideas in this field. It is in the new sections that we are most apt to find the early adoption of improved methods and not, necessarily, in those districts where an industry has long been successfully established.

The older agricultural sections must not remain too wedded to the methods of the days during which their reputations were making, for it is only through a continual application of new ideas, improving upon the old methods, that supremacy can be maintained.

The increase in rural population during the past ten years has been decidedly in favor of sections other than our Middle West, and this is a straw that shows the way the wind is blowing. In Iowa, for example, the rural population has actually decreased and the same is true of Missouri, Indiana and Ohio, whereas in the other States of the middle western group the increase has been less than ten per cent. Against this, we find the increase in Washington, Oregon, Idaho, California, Nevada, Arizona, Colorado and other States to be 30 to 50 per cent, and in some cases even more than this. These figures are from the U. S. Government Census reports, 1900 to 1910.

A similar condition is indicated to us by a study of the acre crop yields of the middle western States compared with the old eastern States that are coming back into their own through the scientific treatment which these " worn-out " soils are now receiving and the passing of the farms from weaker to stronger hands. This fact is shown by the following figures taken from the reports of the Department of Agriculture of the United States for the year 1910 regarding the production of wheat, corn and oats since 1866. Reliable reports prior to 1866 are not available.

The production of wheat per acre in the following States was:

	1866 to 1875	1876 to 1885	1910
Maine	13.2 bushels	13.7 bushels	29.7 bushels
New York	14.1 "	15.5 "	23.7 "
Pennsylvania	13.3 "	13.4 "	17.8 "
Ohio	12. "	14.6 "	16.2 "
Illinois	11.9 "	13.1 "	15. "
Iowa	12.6 "	10.2 "	21. "
Kansas	15.7 "	13.9 "	14.0 "

The production of oats in the following States was:

	1866 to 1875	1876 to 1885	1910
Maine	21.6 bushels	26.8 bushels	42.4 bushels
New York	21.2 "	30.5 "	34.5 "
Pennsylvania	30.6 "	30.2 "	35.2 "
Ohio	29.6 "	30.6 "	37.2 "
Illinois	30.5 "	33.2 "	38. "
Iowa	35.8 "	33. "	37.8 "
Kansas	32.8 "	30.6 "	33.3 "

The production of corn in the following States was:

	1866 to 1875	1876 to 1885	1910
Maine	29.3 bushels	33.8 bushels	46.0 bushels
New York	31.6 "	30.4 "	38.3 "
Pennsylvania	35.1 "	32.6 "	41.0 "
Ohio	35.2 "	32.6 "	36.5 "
Illinois	29.9 "	27.2 "	39.1 "
Iowa	34.3 "	31.8 "	36.3 "

One very important feature of the now much discussed subject of " electricity on the farm " is that where this improvement is found, it is universally accompanied with better conditions generally. The farmers are of a different frame of mind from those where the less efficient forms of energy are used for power and lighting. This condition I have noticed many times in different localities, and it is in my opinion the most important condition of all, because this interest means better farming in all branches, and even if the electrical method were the most expensive, which it is not under a proper order of things, a comprehensive scheme of electrification would be justified on all farms worthy of the name and farmers will do well to adjust their present conditions so as to be not long delayed in the enjoyment of the advantages of electricity, no matter what agricultural section the farm is located in.

We would not think of recommending electric power for the textile mills of New Jersey and then advising against its use in the mills of Illinois. We would not say that the machine shop in New York State, where we will assume the power rate for electrical energy is from 5 to 10 cents per kw-hr., should be operated by hand-power whereas the shop in Colorado, where perhaps a 2- or 3-cent rate prevails, might indulge in electrification and the many resulting advantages therefrom.

Electric drive and electric lighting are too well understood for us to confuse in any way the importance of their advantages with the obstacles that are naturally encountered in the introduction of a new method into a new field.

Today, however, the farmer is independent of the central station, and yet where service is supplied at a fair rate with reasonable reliability, there may be advantages in some cases in not installing a private plant. In any event, the problem can be solved and the improvement well justifies the expense. This has been demonstrated in many places, under many conditions.

On all farms the problem of electrification should be taken seriously. On the small farm it may not pay to carry the idea as far as on the large farm, but again the reverse is sometimes true. In the small farm home, oftentimes it is nearly impossible to secure satisfactory labor, and it is under such conditions that electrical energy is most useful. On small farms a large amount of power is seldom, if ever, required. The feed is ground when bought and threshing and other heavy work can be contracted for.

On the larger farms a greater percentage of the operations involved in converting raw material into finished products is undertaken, the average daily power requirement is greater, and the business enterprise is of sufficient magnitude to justify a gradual improvement in equipment and an ultimate adoption of the most efficient methods. This is an economic problem and one which is more important to consider on our farms than in our factories or mills. And from the facts already presented we know that the increased rate of handling work, the decrease in labor required and the actual economy of electrical power commend this form of energy for favorable consideration on the farm as elsewhere.

I must also differ with Mr. Shane in what he says in reference to the character of plant that would be necessitated under certain conditions which he has named.

While a 25-h.p. motor would be running less than half loaded when operating an ensilage machine in reasonably good repair, and slightly more than this when driving a threshing unit of average size, let us take Mr. Shane's figure for the sake of argument. Manifestly it would not be good planning to load the entire year's service bills, where the ordinary day's electrical requirements are small, with the inefficiencies and overhead charges incidental to a service equipment that is out of all proportion to the average current demand. The idea of electrification of the farm should not be carried to this point.

The same principle is true in the designing of a private plant, but there the difficulty cited is more easily overcome through the introduction of a storage battery of sufficient capacity to carry large peak loads. In fact it is advantageous to have the battery of such size that it does not have to be charged every twenty-four hours, as here again we encounter the labor problem which is so difficult to arrange satisfactorily on the farm.

If the plant be so designed that the generating set is of sufficient size to carry the evening lighting load direct and to charge the storage battery during the daytime, and the battery is large enough for the heavy peak loads when unusual work is being undertaken, it is better, even if it takes several days to charge the battery fully, than it would be to have a generating set of sufficient capacity for the maximum demand and only a small battery or none at all.

Now one word about electricity in the dairy. Mr. Shane speaks of possibilities and desirabilities of electricity on the farm. Let me say that when clean milk is selling wholesale at from 7½ to 15 cents per quart net to the farmer, as it is today in New York State and New Jersey, Massachusetts, Connecticut, Pennsylvania, Maryland and doubtless elsewhere, there is little question of the desirability of using electricity for both lighting and power, no matter what may be the source of electrical supply. For the introduction of electric light and power devices in our high-class dairies has done more toward bringing down the bacterial count in milk than any one other feature of equipment, except sterilization facilities and proper means of cooling.

In the creamery, it is not a question of economic use of power that prompts the use of the direct-connected or closely belted motor-driven separator and similar sanitary devices, but the elimination of dust-stirring parts and vibrations and uneven speeds which reduce both the quantity and quality of creamery products.

To define the possibilities of electricity on the farm would be to design an ideal installation with an infinite number of uses for this form of energy. This I have not attempted to do in my paper, but instead have confined myself wholly to descriptions of actual installations and the submission of data from which all may benefit in dealing with this problem in individual cases.

In closing, I would, therefore, point out that the electrician must get his point of view in this matter from the needs of the farm in question and select his equipment on the basis of a proper economic treatment of the problem of the management of the farm as a whole. He must not reason from the standpoint of the farmer who is today poorly equipped with apparatus or knowledge as to scientific agriculture. The farm is a factory and in the profits of its output will be reflected the skill with which its operations are managed.

Electric light and power are used everywhere else in our industries and it is only through lack of confidence in the possibilities of success in farming as a business that anyone would be justified in denying this great improvement to the farmer.

The points which Mr. Shane raises come really under the heads of " farm management " and " plant design." And the answer as to whether any particular farm should be electrified or not must rest with the farmer himself. I need only add, as a guide to anyone in such a position, that the value of the farm as a producing proposition should be determined and its operating conditions noted. If then the business enterprise is of sufficient magnitude or of such character as to justify an important improvement for safety against fire risk, or for improved and increased production with greater economy of operation, then find a way to electrify and carry this as far as the state of the art may permit, or as far as one experienced in these matters would advise.

A paper presented at the 276th Meeting of the American Institute of Electrical Engineers, New York, October 11, 1912.

THE USE OF REACTANCE IN TRANSFORMERS

BY W. S. MOODY

Until recently, reactance in transformers was considered only as an objectionable characteristic. To this there was one minor exception, which will be referred to later on, in connection with transformers to furnish constant current for arc lighting; but in general, because of its detrimental effect on regulation, reactance in transformers has been considered something to be avoided, and the more it was avoided the better was the transformer supposed to be fitted to its use.

Recently, however, in connection with the use of larger units in generating stations, and higher voltages in transmission lines, reactance in other parts of electrical installations has become less and less, until a short circuit in such a system may result in such a tremendous flow of current, that some means of limiting the possible current rush through the system has become imperative. The most natural remedy is to replace in the system, by the transformer, some of the reactance that has been taken out.

Reactance has commonly been used as a means of obtaining a variable ratio of transformation between the source of supply and the collector rings of synchronous converters, but when more than 3 or 4 per cent reactance is desired for this purpose, it has been customary to use separate reactance coils between the transformers and the converter. A very satisfactory method of obtaining as high as 15 to 20 per cent reactance for this purpose in the transformer itself, has been recently developed.

It is the object of this paper to discuss in a general way how reactance can be introduced into transformers for the purposes mentioned above, to point out some of the difficulties and limitations which are met in obtaining the desired results, and to show

how effectively some of the problems connected therewith have been solved.

As all know, a transformer would have no reactance when under load if all the lines of force created by its primary threaded through the secondary and if all the lines linking the secondary also linked the primary. Such a complete interlocking of the primary and secondary fluxes is, of course, impossible, a portion of the fluxes always passing through the spaces between the primary and secondary coils.

The percentage of the total flux that links with the primary but does not link with the secondary coil, plus that which links with the secondary but does not link with the primary, is the per cent of reactance of the transformer. That is, when 99 per cent of the primary flux cuts both primary and secondary, the transformer is said to have 1 per cent reactance, and when 90 per cent, only, cuts both primary and secondary, it has 10 per cent reactance.

Calculations for reactance are made by an equation of the form:

Reactance volts =

$$\frac{(\text{Turns})^2 \times \text{Current} \times \text{Area of leakage path}}{\text{Length of leakage path} \times (\text{No. of groups})^2} \times \text{a constant} \quad (1)$$

From this formula, it is evident that reactance for a given size of transformer may be decreased,

a. By decreasing the total number of turns in primary and secondary.

b. By decreasing the length of turn, with a corresponding increase in the flux density in the core, or by decreasing the distance between primary and secondary windings.

c. By increasing the dimensions of the windings in the direction in which the leakage flux passes through the wire space.

d. By increasing the number of groups of intermixed primaries and secondaries, the number of turns in each group being correspondingly reduced.

So much effort has been put forth in designing transformers of the lowest possible reactance consistent with reasonable expense in the matter of insulation and efficient proportioning of the various parts, that one would naturally think that if low reactance was not desired, it would be a much easier problem to make a transformer.

Several difficulties are met, however, in the design of transformers with high reactance, principal among which are an extra loss in the conductors due to eddy currents, an increase in mechanical strains under overloads, and difficulties in multipling different sections of the windings. Some of the leakage flux between the primary and secondary windings must pass through the conductors of the windings themselves, resulting in an inequality of the e.m.fs. generated in different parts of the same conductor. This gives a distorted distribution of current, producing a copper loss, in addition to the calculated I^2R loss, which is roughly proportional to the square of the density of the leakage flux, and to the square of the width of the conductor in a direction at right angles to the leakage field. Unless the width of the conductors is small, therefore, high densities of leakage flux are not permissible, on account of the resulting abnormal copper loss, and the corresponding increase in heating, and decrease in efficiency.

Perhaps the first use of high reactance in transformers was that referred to above, to obtain in the secondary, constant current rather than constant potential for purposes of arc lighting. Here, however, not a constant reactance but a variable one was needed. High reactance was here obtained without high densities in the leakage flux, by providing a large cross-sectional area of the leakage field rather than many turns; and since the conductors were not large, no especial difficulty was experienced with eddy currents. The increased reactance for partial load conditions in these transformers is obtained by moving the primary farther and farther away from the secondary, so that the leakage flux is increased by increasing the area of cross-section of its field, the density remaining constant.

This method of obtaining high reactance is very expensive because of the great length of core that is necessary to surround this idle space, in addition to surrounding the copper and insulation, and is prohibitive in large units. The reactance that can be obtained economically, without a density of leakage flux which is not too high from the standpoint of eddy current loss, varies with the voltage of the transformer, for the higher the voltage the greater the distance that must necessarily exist between primary and secondary windings for insulation purposes, and therefore the greater the amount of flux that can be carried through this space without serious eddies in the copper. Thus it may be as easy to make a transformer with 10 per cent reactance when wound for 100,000 volts as for 5 per cent reactance when wound for

25,000 volts, due to the broader path that exists for the reactive flux in the high-voltage design.

As a general proposition, it may be said that it is usually impractical to get more than 8 per cent reactance in 60-cycle transformers without undue eddy current losses, and that the allowable maximum would be considerably less than this in low-voltage designs. For lower frequency, higher reactance may be practical, since eddy current losses are, of course, less at a given density.

It has recently become customary to specify that the transformer must not have less than, say 5 per cent reactance, for the protection of transformers, switches, generators, and in fact all parts of the system, against the high mechanical stresses due to excessive currents. It is not always appreciated, however, that limiting the current in this way, while protecting other apparatus, does not necessarily make the transformer any safer to withstand overload conditions.

Calculations for the mechanical stresses in the transformer may be made by the equation:
Mechanical stress =

$$\frac{(\text{Turns})^2 \times (\text{Current})^2}{(\text{Length of leakage path})^2 \times (\text{Number of groups})^2} \times \text{a constant} \qquad (2)$$

where the groups are all alike; or where the groups are not alike,
Mechanical stress =

$$\frac{(\text{Turns})^2 \times (\text{Currents})^2}{(\text{Length of leakage path})^2} \times \text{a constant,} \qquad (3)$$

where the turns considered are not the total of the transformer, but the turns in that group which has the maximum number.

From the above equations, it may be seen that when high reactance is obtained by massing the turns in a small number of groups, the " turns " factor of the expression for mechanical stress is increased, though the " current " factor at short circuit is reduced. If the groups are not kept equal to each other, the maximum stress, which occurs in the maximum group, and which produces the forces that are felt by the core and coil supports, is likely to be actually greater under short-circuit conditions for a high-reactance transformer than for a low-reactance one.

With equal numbers of turns in all the groups, the forces will be greater for the low-reactance transformer than for the high-reactance one at absolute short circuit with full voltage maintained on the primary terminals, although not enough greater to make a very serious difference in any case where the supports are designed to supply a proper factor of safety for the high-reactance transformer. Moreover, with a definite fixed current flowing, the force will be much smaller for the low-reactance transformer than for the high-reactance one, and with a comparatively small external impedance, in addition to the impedance of the transformer, the force due to short circuit becomes less for the low-reactance transformer than for the high-reactance one.

From the above it will be seen that very little is to be gained from the standpoint of safety to the transformer by the introduction of high reactance within the transformer itself. It is true that this would protect other parts of the system, but the additional reactance would be equally as effective for this purpose outside of the transformer as inside of it.

This is illustrated by Fig. 1, which shows the mechanical stresses under short-circuit conditions, in a transformer designed for 2 per cent reactance and in the same transformer when redesigned for 5 per cent reactance. It is assumed that constant voltage is maintained at the primary terminals. With normal current only flowing, the mechanical stresses in the high-reactance design are higher than in the low-reactance design, but when short circuit occurs at the secondary terminals, the stress is higher in the low-reactance design. This is shown on the curve for zero external reactance. With the addition of about 1 per cent external reactance, the curves cross, and with further increase in external reactance, the high-re-

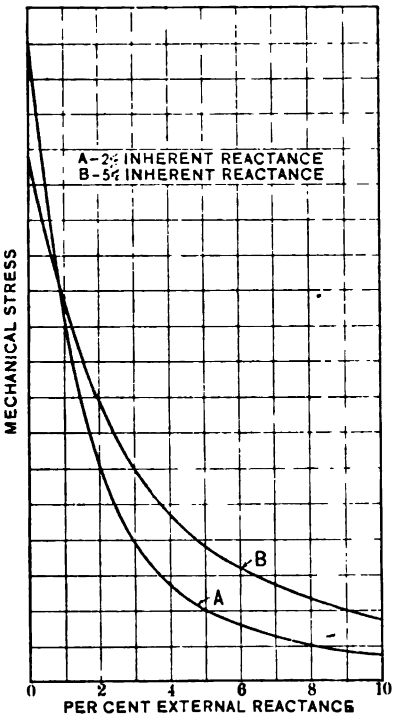

Fig. 1—Effect of External Reactance on Mechanical Forces in Transformers

actance transformer is subjected to the greatest strains. With 3 per cent external reactance added to the low-reactance design and none to the high-reactance design, thus making the total in both cases 5 per cent, the stress in the former is only about one-fourth as great as that in the latter.

When short circuit occurs at some distance from the transformer, the reactance of the lines adds to the transformer reactance and serves to reduce the stresses on the transformer. In fact, in this case the line resistance also assists, and a smaller value of external reactance will cause the two curves to cross and the stresses in the low-reactance design to become less than those in the high-reactance design.

The effort to obtain sufficient reactance for current limiting purposes in an auto-transformer is a more difficult problem. These are frequently used for a one-to-two ratio of transformation, as, for instance, in stepping up the voltage of a 10,000-volt generator to 20,000 volts. Here the auto-transformer has only half the rating of the generator, and the effect of its reactance on the system is only one-half that of its own inherent reactance. In some cases where it is necessary to get the equipment in the smallest possible space or keep to the lowest possible costs, it is necessary to be satisfied with what current-limiting reactance can be placed in the system by such an auto-transformer, but an exceedingly rigid design of coil supports then becomes necessary.

When greater amounts of reactance are desired for flexibility in ratio of transformation, as for use with synchronous converters, the result can be obtained by placing a laminated iron structure between primary and secondary in such a way as to form a path for the leakage flux. If this iron path is of such a section as to carry the flux corresponding to the desired reactance without approaching saturation, the copper will be entirely shielded from eddy currents, and the transformer's reactance may be increased almost without limit. It is evident, however, that the use of such a device does not extend the possibility of current-limiting reactance, as the amount of iron that would be necessary to carry the entire flux on short circuit would result in a prohibitive amount of reactance, from a regulation standpoint, at normal loads.

It is interesting to note that this use of an iron path for the reactive flux, as well as the high-reactance design in which the flux is entirely within the air space between primary and secondary, was first developed in connection with arc lighting apparatus, where transformers with a fixed high reactance were used to obtain regulation characteristics approaching constant current. The proportioning of these flux shunts for transformers with regulating reactance is an interesting and not altogether easy problem, and it may be of sufficient interest, in view of the fact that it has been so recently reduced to practise, to be worthy of comment here.

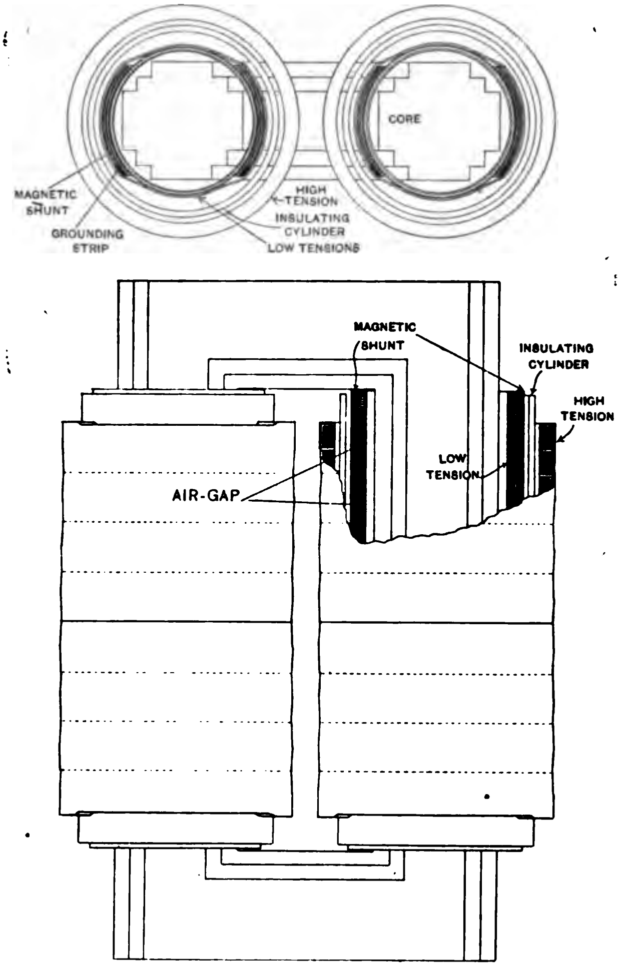

Fig. 2—Diagram of Core Type High-Resistance Transformer

Evidently there must be as many shunts as there are spaces between primary and secondary groups. Evidently, also, the section of these shunts must bear the same relation to the section of the core of the transformer as the reactance voltage bears to the full voltage of the transformer—this on the assumption that the density in the shunt at full load is to be the same as the normal density in the core at normal voltage. However, it is usually the case that if a straight line characteristic is to be obtained in the reactance, say, up to 50 per cent overload, the section of each of these shunts must be somewhat larger than this; that is, for 15 per cent reactance the section of the shunt will have to be perhaps 20 per cent of the section of the transformer core.

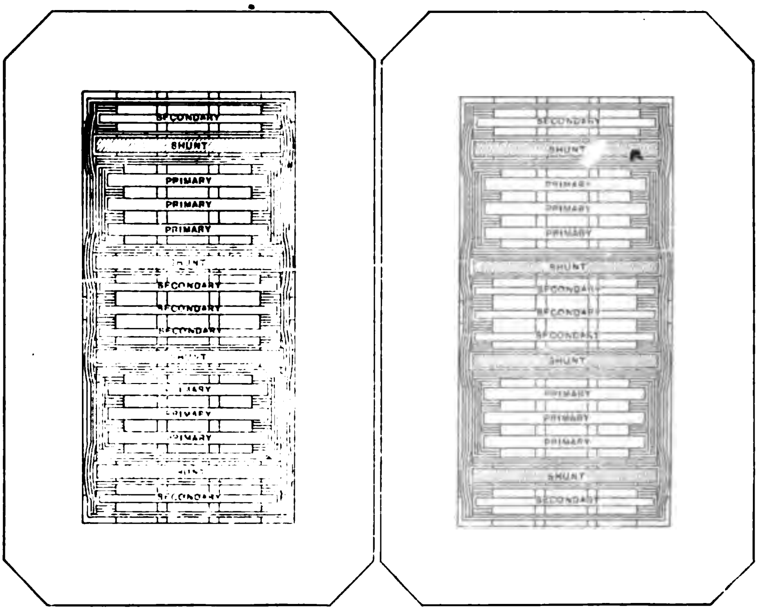

Fig. 3—Diagram of Shell Type High-Resistance Transformer

Again, it is necessary to have air gaps in this circuit: First, because a straight line characteristic can not be obtained with any magnetic circuit that is a closed iron circuit; and second, because in any group of ampere turns that would be practical, a sufficient magnetomotive force would be obtained to over-saturate the shunt circuit at full load if there were only the reluctance of the iron circuit to limit the flux. It should be noted

[MOODY]

FIG. 4--LARGE CONCRETE CORE CURRENT-LIMITING REACTANCE

[MOODY]

FIG. 5—CURRENT-LIMITING REACTANCE SHOWING ARRANGEMENT OF CORE, SUPPORTS AND WINDING

that the loss in these shunts is not a constant one like core loss, but varies with the load; consequently, it affects efficiency as if it were a copper loss. However, the loss in the shunts is small as their weight is very small compared with the weight of the core.

Figs. 2 and 3 illustrate the manner in which these flux shunts are placed in core type and shell type designs, respectively.

Figs. 4 and 5 show the general appearance of the concrete core external reactances which have been developed and successfully used in large power systems to limit the flow of current at short circuit.

A paper presented at the 276th Meeting of the American Institute of Electrical Engineers, New York, October 11, 1912.

THE EFFECT OF TEMPERATURE UPON THE HYSTERESIS LOSS IN SHEET STEEL

BY MALCOLM MAC LAREN

In the paper which the writer presented before the Institute last year upon this subject* it was shown that there was no apparent change in the law governing the variation of the hysteresis loss with the induction for all temperatures from atmospheric up to near the point where the steel became non-magnetic. The writer suggested at that time that the rate of heating the sample might affect the change in hysteresis loss with changing temperature and the measurements described below were carried out to investigate this point. It was thought also that some additional light might be thrown on this subject if hysteresis loops were obtained from the sample near the non-magnetic temperature. This had not been done in the previous tests as the samples had been prepared for the two-frequency method of measurement in order to obtain results quickly at any temperature over as wide a range of induction as possible. An attempt was made at that time to obtain a few characteristic loops at high temperatures, but the use of iron wire for the secondary winding on the sample introduced errors on account of variable thermal currents in the galvanometer circuit which could not be readily eliminated. It was also found that the insulation resistance between primary and secondary at high temperatures was not sufficiently good to permit measurements by the galvanometer method, although no error could be detected from this source with the two-frequency wattmeter method.

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*TRANSACTIONS A. I. E. E., 1911, Vol. XXX, I, page 761.

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cross-section was 6.585 square cm. and the weight was 3.989 kg. In each case the rings were separated at the center by U-shaped spacing strips to allow the introduction of thermocouples. The secondary was first wound on the sample and was insulated from it by sheet asbestos and mica. It was then covered with a thin layer of Portland cement, and a second layer of asbestos and mica. The primary was then wound over this and distributed as uniformly as possible around the ring. As the secondary covered only about ¼ of the ring, the inside surface of the remainder was padded with asbestos to the same thickness as the secondary in order to assist in obtaining an even spacing of the primary turns. The whole sample was then covered with a second layer of Portland cement. The use of copper wire for the secondary absolutely eliminated the thermal e.m.f. which had been present in the earlier samples. As anticipated, however, it did not prove to be durable for such high temperature work. After one heating oxidation increased the resistance about 25 per cent and the wire became so brittle that on one sample the terminal broke off upon removing it from the furnace. The change in resistance introduced no error in the observations as the resistance at start was only 0.3 ohm, and total resistance of the galvanometer circuit was 2450 ohms.

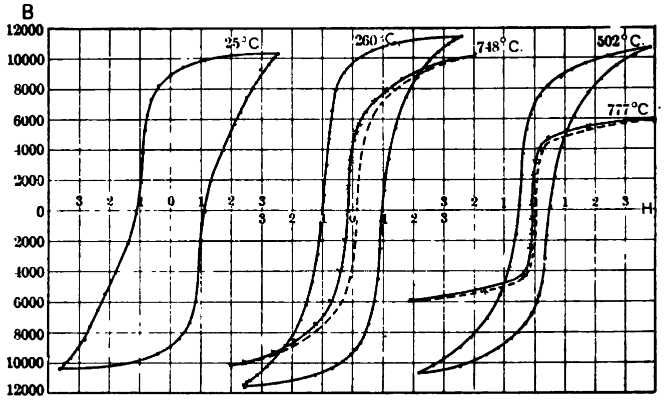

FIG. 2

The insulation resistance between primary and secondary was about 200 megohms when cold and fell to less than one megohm at the maximum temperature. At these extreme temperatures it was possible to detect a mere trace of leakage from primary to secondary, but this only occurred with high values of exciting current and was so small as to introduce no appreciable error in the results.

Electric Furnace. The same furnace was used as in the earlier experiments. This consisted of concentric heating coils arranged to give as uniform a temperature as possible in the heating chamber. The temperature was measured by platinum-iridium thermocouples, introduced into the sample through small holes cut in the walls of the furnace.

RESULTS

Sample No. 1. In this series of measurements the temperature was increased quickly and then held practically constant while a set of observations sufficient for one complete cycle was being made. During the earlier part of the run the temperature was held constant for an hour or more and then a second set of observations was made. When it was noted, however, that the losses did not change appreciably during such intervals, the later measurements were made without holding the temperature constant longer than was necessary for one set of observations. The effect of aging when a constant high temperature is maintained for a longer period was well illustrated during this run by keeping the sample at about 186 deg. cent. during one night.

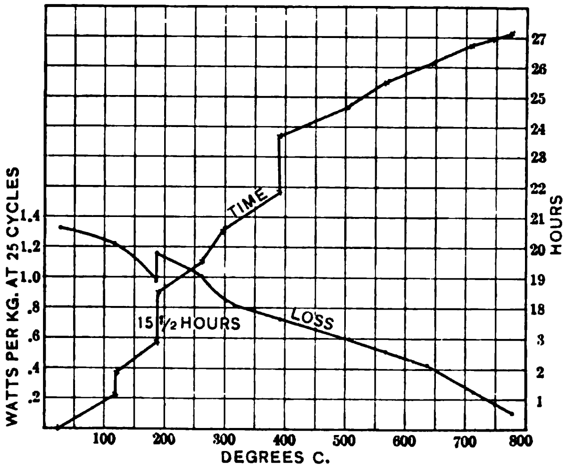

FIG. 3

Representative hysteresis loops taken during this run are shown in Fig. 2 and the results of the complete series are given in Table I. The losses are also plotted with reference to temperature in Fig. 3. These are reduced to a constant induction of

10,000, on the assumption that the loss will vary as the 1.6 power of the induction.

TABLE I

Time	Temperature	Induction	Magnetizing force	Watts per kg. at 25 cycles	Watts corrected for 10,000 B
2.45 p.m.	25 deg. cent.	10357 B	3.6 H	1.4	1.33
3.55 "	116 "	10686 "	3.6 "	1.355	1.23
5.40 "	186 "	11506 "	3.6 "	1.225	0.98
8.00 "	186 "	11473 "	3.6 "	1.235	0.99
9.15 a.m.	186 "	11428 "	3.6 "	1.43	1.16
10.15 "	260 "	11457 "	3.6 "	1.255	1.01
11.20 "	300 "	11379 "	3.6 "	1.037	0.841
12.35 p.m.	392 "	10936 "	3.6 "	0.85	0.738
2.25 "	389 "	10913 "	3.6 "	0.851	0.738
3.25 "	502 "	10676 "	3.85 "	0.662	0.598
4.15 "	562 "	11139 "	4.08 "	0.613	0.517
4.50 "	640 "	10986 "	4.08 "	0.489	0.421
5.30 "	708 "	10340 "	4.08 "	0.268	0.252
5.40 "	748 "	10149 "	4.08 "	0.1665	0.164
5.50 "	777 "	5952 "	4.08 "	0.0474	0.109

Sample No. 2. The observations were made upon this sample without holding the temperature constant for any extended period, except at noon, and the measurements immediately before and after this period were practically the same. Some of the hysteresis loops taken during this test are shown in Fig. 4 and the variation of the loss with the temperature is shown in Fig. 5. The results are given in detail in Table II.

TABLE II

Time	Temperature	Induction	Magnetizing force	Watts per kg. at 25 cycles	Watts corrected for 9000 B
8.00 a.m.	25 deg. cent.	9787 B	2.52 H	0.652	0.572
9.50 "	134 "	9270 "	2.52 "	0.584	0.556
10.40 "	225 "	8820 "	2.52 "	0.526	0.544
11.35 "	304 "	8719 "	2.77 "	0.488	0.511
12.20 p.m	408 "	8482 "	2.77 "	0.397	0.437
2.35 "	395 "	8472 "	2.77 "	0.397	0.438
3.40 "	542 "	8281 "	3.02 "	0.342	0.391
4.20 "	610 "	8651 "	3.30 "	0.228	0.243
5.45 "	725 "	6818 "	3.33 "	0.0525	0.082
5.55 "	735 "	4387 "	3.5 "	0.0185	0.058
6.05 "	745 "	1193 "	3.4 "	0.00	0.00

Comparing the results in the two cases it is seen that there are certain variations in the shape of the loss curves although the general trend is the same. These variations are quite as likely to be a function of the previous heat treatment of the samples as of their chemical composition. It will be seen that the high-silicon steel becomes non-magnetic at a lower temperature than the ordinary steel and also that its permeability falls with increasing temperature throughout the test, while with sample No. 1 the permeability first rises and then falls away with increasing temperature. No special significance should be attached to this last point, however, as an inspection of the hysteresis loops would indicate that if lower inductions had been used the permeability would have first increased with the temperature

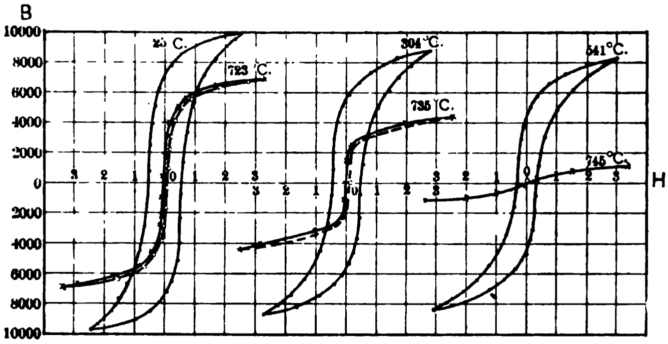

Fig. 4

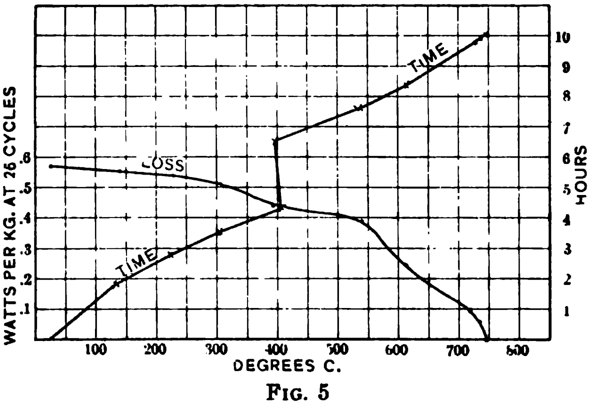

Fig. 5

in both cases. Both sets of experiments show that the temperature may be held constant for an hour or more at a time during the run without appreciably changing the hysteresis loss.

Cooling Curves. A series of observations made upon sample No. 1 as it was coming into the magnetic state is shown in Fig. 6. The temperature was falling slowly while these observations were being made and as the permeability varies rapidly with the temperature during this critical period it was apparent that magnetic changes were occurring in the sample while the test was being made, so that the value of B for the maximum H was not the same at the end as at the beginning of the reversal, and a true hysteresis loop could not be plotted. An attempt was made, however, to correct approximately for this in the second set of observations by considering the general shape of the curve, from which it appeared that the induction at start was about 2500 lines. This would mean that about 1430 lines were added to the circuit during the observations through change in temperature. Assuming that this change occurred fairly uniformly with the time, each observation may be corrected to show the approximate induction which would have existed with constant temperature by multiplying 1430 by the ratio of the time from the start to the time of the entire reversal and subtracting this from the observed value of B. In this way a complete loop, as shown in broken lines in Fig. 6, was obtained.

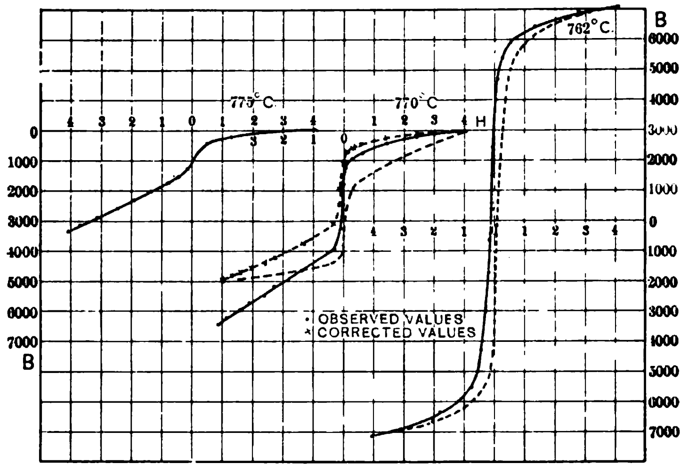

FIG. 6

Little importance could be attached to a single set of observations corrected in this way except as they are confirmed by tests upon sample No. 2. In this case the temperature fell very slowly and the time required for taking the observations for one reversal was about one minute, so that the slight changes occurring in the magnetic state during the reversal could not materially alter the shape of the hysteresis loop. Three such loops are shown in Fig. 7 and it is seen that they have much the same character as the loop shown in Fig. 6. The difference in the character of the reversal during heating and cooling is well illustrated by comparison with the dotted line which reproduces in the proper scale the last reversal with rising temperature as shown in Fig. 5. When the temperature fell to 735 deg. cent. the loops became normal. The writer regrets that he has been unable to make further investigations to verify these observations, for if these figures represent true magnetic cycles they show a peculiar molecular condition for the material near the critical temperature.

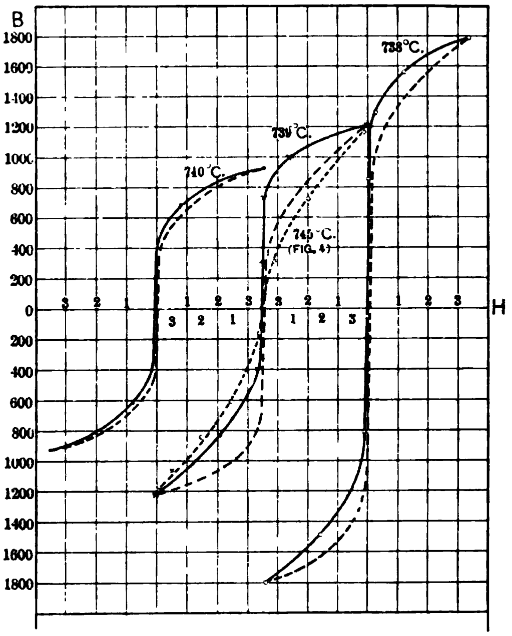

FIG. 7

Critical Temperature. In the earlier experiments with alternating current the temperature at which the material became non-magnetic was quite clearly defined, but in these tests with a sensitive galvanometer it was possible to detect a trace of magnetism in both samples eight or ten degrees above the temperature at which the induction ceased to be measurable. With alternating current it appeared that the material returned to magnetic state at the same temperature as it became non-magnetic, while in these later tests, at the lowest measurable induction the temperature was about 10 deg. lower upon cooling than for the same induction and magnetizing force with rising temperature. Such differences may be due to lack of uniform temperature throughout the sample in every case, or possibly the continued application of an alternating magnetizing force may assist the material in regaining its magnetic properties. This point was investigated further with sample No. 2 by maintaining a constant magnetizing current in the primary while the material was passing through the critical temperature during both heating and cooling. As the induction fell, through the loss in permeability, an e.m.f. was generated in the secondary which could be observed with the galvanometer. In order to get a measurable deflection under such conditions it was necessary to remove the external resistance from the galvanometer circuit and the leakage between the primary and secondary circuits then caused a deflection of several millimeters in the galvanometer, and it was not possible to sharply define the point at which the galvanometer deflection became zero due to the reduction of the permeability of the sample to unity, but with rising temperature, this occurred at approximately 750 deg. cent. and with falling temperature a reversal in the galvanometer deflection, indicating a rising permeability, could first be detected at 740 deg. cent. The maximum deflection corresponding to the point at which the permeability changed most quickly with the temperature occurred at 745 deg. cent. with rising temperature and 715 deg. cent. with falling temperature. This experiment is of further interest in showing a new, though scarcely a commercial, method, of producing an e.m.f. by magnetic induction in which there is no movement of conductors in the magnetic field nor change in magnetizing current. For if a continuous current is maintained in the primary circuit and the temperatures are successively raised and lowered through the critical point an alternating e.m.f. will be produced in the secondary.

At temperatures below the critical point the magnetic characteristics during heating and cooling soon coincide. In Fig. 7 it is seen that sample No. 2 has practically the same permeability for rising temperature at 745 deg. cent. as for falling at 739 deg. cent. At 725 deg. cent. no difference in either permeability or character of loop could be detected.

DISCUSSION ON " THE USE OF REACTANCE IN TRANSFORMERS " (MOODY) AND " THE EFFECT OF TEMPERATURE UPON THE HYSTERESIS LOSS IN SHEET STEEL" (MACLAREN). NEW YORK, OCTOBER 11, 1912.

Philip Torchio: Mr. Moody states that outside reactances are equally effective and in practise superior to reactance within the transformer. Different attempts have been made to obtain a design of such reactances that would give the best results as to economy and safety, and also meet with the operation and installation requirements in stations. Mr. Moody gives in Figs. 4 and 5 views of a drum-wound reactance of large capacity. I desire to describe a design of reactance which has certain important features that might be of interest to the Institute members.

These characteristic features are:

1. The adoption of the pancake winding instead of the drum winding.
2. The adoption of an enclosed case and supports of fireproof and insulating materials throughout.

By means of these two features several marked advantages are obtained.

The pancake-wound coil can be designed more efficiently, and for the same floor space, of considerably less height than an equivalent drum-wound reactance. This is due to the fact that windings and layers can be placed closer together for the same potential gradient between layers. It is also a well known fact that for the same outside diameter, the shorter the coil the greater the reactance for a given number of turns. These two facts combined make the drum-wound coil, for approximately the same per cent reactance and the same floor space, about twice as high as an equivalent pancake-wound coil. This causes a greater leakage of flux, which creates a greater tendency to eddy current losses and requires a greater length of conductor and consequently more heating and losses.

The adoption of a coil with porcelain supports and self-enclosed in a case made up of fireproof and insulating materials gives a greater factor of safety and other obvious practical advantages to the user.

These self-enclosed, self-cooled reactances are built of horizontally wound spirals supported and insulated by porcelain arms with suitable recesses for the windings; the arms are assembled radially as vertical walls between a center core of alberene stone and outer enclosing wall built up of special porcelain segments. These cellular compartments as formed allow natural ventilation for the coil. The whole is supported at the two ends by heavy concrete headers, securely fastened to the wall by a series of brass bolts passing through the heads and the special porcelain segments from top to bottom. Ventilating holes crorespond with each vertical cellular compartment of the coils.

FIG. 1 [TORCHIO]

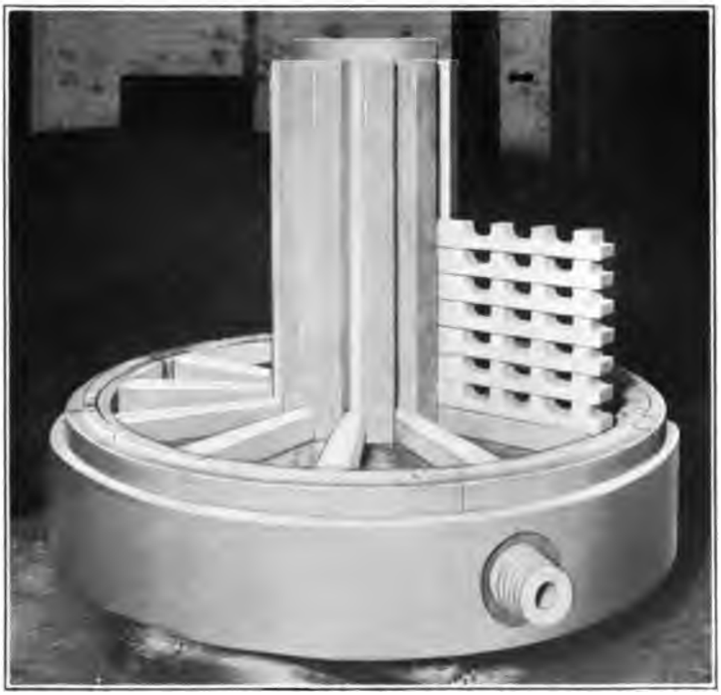

FIG. 2 [TORCHIO]

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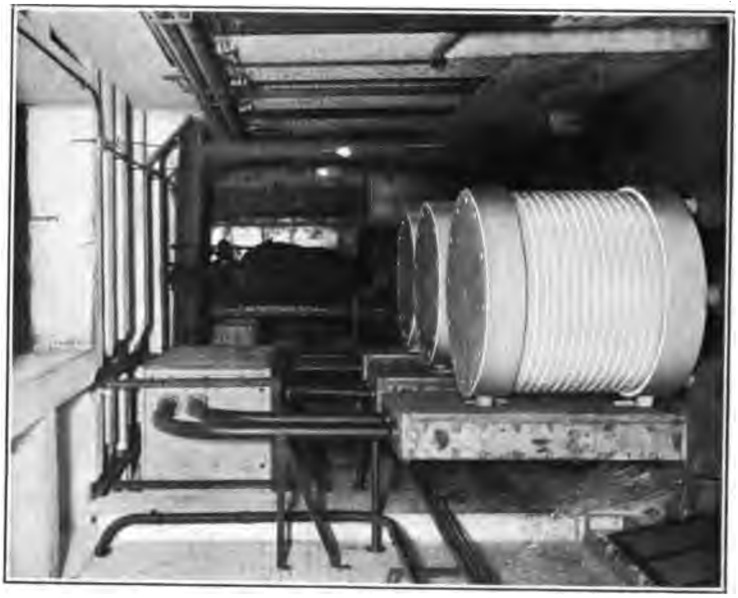

FIG. 4 [TORCHIO]

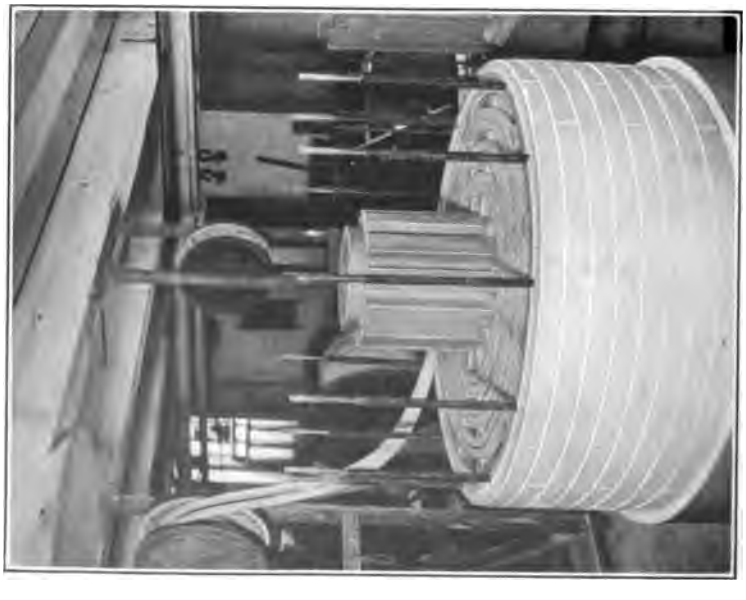

FIG. 3 [TORCHIO]

The heating is very small and considerably less than the heating of the generator itself, which was accomplished by a special treatment and design of the stranded conductors. These conductors are also insulated throughout to prevent short circuits from foreign objects falling or being drawn into the coil. Each coil is tested to ground at five times the working potential.

Figs. 1 and 2 show the separate pieces and an assembly section of the different insulating materials for encasing the coil. Fig. 3 shows a top view of a coil under construction, showing the way the winding is laid in the porcelain arms. The brass rods are insulated by mica tubes throughout their length. Fig. 4 is a photograph of a set of three coils in service. The coils are resting upon eight small concrete pillars and insulators to allow air space for natural ventilation. The over-all dimensions are 59 in. (1.5 m.) in diameter and 55 in. (1.4 m.) in height. The winding inside the case is 45 in. (1.14 m.) diameter and the height over copper is 30 in. (0.76 m.)

The same design is used for different sizes of generators and different frequencies, the only changes required being in the number, size and shape of slots in the radial arms, and the number of layers assembled in one coil.

The following table gives the constants of a set of reactances operating on three 20,000-kw., 6600-volt, 25-cycle generators installed by the New York Edison Company. The table also gives the results for the same coil at 62½ cycles; the latter to be used for a sectionalizing bus reactance in a large station.

	62½ Cycles	25 Cycles
Number of turns	34.	34.
Reactance in ohms	0.227	0.0914
Reactance in per cent	10.4 per cent	4.2 per cent
Equivalent resistance	0.00254	0.00204
Ohmic resistance	0.00197	0.00195
Calculated a-c. resistance	0.00215	0.00198
Current	1750. amps.	1750. amps.
I^2R losses	6.57 kw. per coil	6.05 kw. per coil
Foucault losses	1.17 kw. per coil	0.186 kw. per coil
Total losses	7.81 kw. per coil	6.236 kw. per coil
Temperature rise full load 3 hours	43.7 deg. cent.	33. deg. cent.

L. W. Chubb (by letter): Professor MacLaren's paper is certainly a valuable addition to the general knowledge of the influence of heat upon the magnetic properties of sheet steel. Such papers on magnetic phenomena not only add the data given but are unusually fruitful because of the suggestions for future work.

The paper by the same author last year was of great value because it showed that the law of variation between loss and magnetic induction was practically the same at all temperatures. The suggestion made that rate of heating probably affected the change in loss has been covered briefly by the paper under discussion, but the relation between loss and temperature, as a function of rate of temperature change, is too involved, and depends upon too many variables, to be disclosed by a few tests on a few samples of steel. The general trend of the curve is shown by the tests and some very interesting points have been brought out because the author not only gives results of the hysteresis or loop area, but has given the actual loops and thereby shown the relation between permeability and temperature. The changes in shape of the hysteresis loops and the odd shapes at the magnetic-point are very interesting.

In the work with which I have been connected, a limited number of experiments were made to find the effect of rate of change of temperature upon the loss at different temperatures, and to determine if any great change in the cycle of temperature would have its effect upon the losses. The results were too variable to be of value and it was necessary to study only the effect of the heat cycle upon the losses at atmospheric temperatures before and after heating. This of course is the familiar problem of annealing. Within certain limits of temperatures the rate of change in temperature has the opposite effect upon the instantaneous value of the loss. A pause in temperature at some values will have no effect on the loss, at others it will raise such loss, and at others it will lower the loss. Tests show that although such holding of temperature may not change the loss at the *given* temperature it will change the loss at *other* temperatures. Also at certain points a pause in temperature that will appreciably age the steel at the given point while held constant will cause a lowering of the intrinsic loss at other temperatures, other parts of the temperature cycle being the same.

The study of temperature cycles on the final losses at temperatures at which laminated cores operate is of the greatest importance and it is this study which will probably result in the greatest improvements in sheet steel in the near future.

The arrangement of samples which was used under test may be of interest. The first tests were made upon small shell-type punchings built into coils of asbestos-covered wire. The results were not accurate but were relative. The later tests were made by placing a ring sample around the leg of a large transformer core and heating it as a short-circuited secondary. The sample was taped with several layers of asbestos tape and wound with a primary and secondary of asbestos-covered wire. The temperature of the ring sample was very uniform and could easily be controlled by variation of flux in the transformer core. The sample was so well heat-insulated that the windings were relatively cool and gave no oxidation trouble. The wattmeter method was used in both cases.

Professor MacLaren's loops are certainly a recommendation for the method of " slow reversals " and the points plotted seem to show great accuracy. I believe that the results are worthy of careful analysis and that it is to be regretted that all of the loops were not reproduced in the paper so that the progressive changes in magnetizing components could be followed.

C. A. Adams: Mr. Moody's very interesting and instructive paper illustrates a not uncommon experience in the development of electrical plant and apparatus; namely, that when a certain size is reached, qualities which for smaller sizes were considered as objectionable and the reduction of which was considered of sufficient moment to warrant the partial sacrifice of other desirable qualities, pass through a critical stage and we suddenly find ourselves straining other points in design in order to increase this erstwhile objectionable feature.

The reason for this is usually the appearance of a new limitation, such as that of mechanical strength in the present instance. But why should this limitation appear in large rather than in small sizes, since the short-circuit current of a transformer in terms of its full load current, does not increase considerably with size beyond a comparatively low limit? Here is an interesting illustration of the operation of one of those laws connecting the quality of a physical organism or piece of apparatus with its linear dimensions. A large piece of stone will fall through the air without feeling appreciably the atmospheric resistance, but a sufficiently small piece of the same stone will float in the same air as a dust particle, because the weight decreases as the cube and the friction surface as the square of a linear dimension. A flea can jump hundreds of times his own length, but an elephant can't jump at all, because weight increases as the cube and muscle cross-section only as the square of a linear dimension. Numerous other illustrations of the most fundamental nature could be provided to explain other limitations and critical values.

The connection between the relative mechanical strength of a transformer coil under short-circuit and the size of the transformer, is not quite so obvious; but as it may be of interest to many here, I will attempt to explain it briefly.

Imagine every linear dimension of a transformer to be increased in a certain ratio, the current density in the copper and flux density in the core remaining the same; the cross-section of the magnetic leakage path will increase as the square, its length as the first power, and therefore its permanence as the first power of the linear increase. The current linked with this path will increase as the square and therefore the flux as the cube. The useful flux will increase as the square; therefore the per cent leakage flux and the per cent reactance will increase as the first power. To avoid this increase a larger number of interlacings between the primary and secondary coils is ordinarily employed in the larger sizes.

Assume first that the number of interlacings is not changed. The leakage flux density will increase as the first power, the current as the square, the length of current path as the first power. and the mechanical reaction of the two on each other as the fourth power of the linear dimension. Moreover the length of the coil extension and thus the lever arm of this force will increase as the first power, and the moment of the force about the coil support as the fifth power.

If the coil section were solid in each case, the moment of inertia of its cross-section and its stiffness would increase as the fourth power, and therefore its relative stiffness inversely as the first power. But if the coil is built up of wire, the linear dimension of whose cross-section does not increase as much as the linear dimension of the transformer, the stiffness will increase by less than the fourth power, and the relative strength be still less than inversely as the first power.

Assume now that for purposes of ventilation, the coils are kept at the same thickness, and that in order to keep down the reactance, the interlacings between the primary and secondary coils increases as the linear dimension. This approaches approximately to common practise. Then the leakage flux density will be the same, the current in a single coil will increase as the first power of the linear increase, the length of the current path as the first power, and the lever arm as the first power. Thus the bending moment will increase as the cube. But as the stiffness will increase as the first power only, the relative strength will be inversely as the square of the linear increase.

If, in order to increase the reactance, n of these same primary coils be grouped together in place of being interlaced with secondary coils, but are separated from each other for ventilation purposes, the density of the leakage flux adjacent to the outside coil will be n times as great and thus the relative strength $\frac{1}{n}$ times as great as for the completely interlaced arrangement of the same coils and the same short-circuit current; but the latter will be much less owing to the n^2 times as much reactance.

With the common method of construction there is thus a limit of size beyond which extraordinary methods of coil support, or some form of current limiting reactance, must be employed.

David B. Rushmore: The very interesting subject brought up by Mr. Moody, is, I think, indicative of one of the critical changes that are taking place in electrical development. In much of our historical work we alter and improve by very slow methods up to a certain point, and then we are apt to make very radical changes. As we all know, in the small apparatus which we have been using there was sufficient inherent reactance to furnish the desirable characteristics; but the very large power stations of the present day have brought into play such large concentrations of energy that the destructive effects are no longer controlled by the natural characteristics of the apparatus, and we have had to introduce artificially into such machines and into such systems qualities which previously we bent all our efforts towards keeping out.

When we think of what reactance is and why we introduce it, in general terms, or why we do not want it and why we have got to have it, the thought comes to us that reactance is comparable to inertia. In other words, it introduces inertia into electrical movement. It introduces into inertia a capacity for the storage of energy and also a capacity for the reflection of wave motion. Reactance is used in some places for one reason, and in other places for still another reason. The tremendous mechanical force brought into play by the short-circuit current, and especially the instantaneous short-circuit currents of apparatus and installation, is so great that it has to be lowered in some artificial way.

In introducing the reactance into machines, speaking now especially of the subject of alternators, we are confronted with the fact that in all designing a compromise has to be made. The desirable qualities of reaction when put into a machine introduce certain undesirable features of bad regulation, and also the fact that practically all voltage fluctuations that we get are across reactance. I shall always feel indebted to Prof. Rosa for an article which he wrote years ago, which expounded to my youthful mind how we could neutralize capacity in reactance and what actually happened.

Introducing reactance into transformers also introduces the possibility of a very serious rise of potential, especially with high-frequency currents. These are naturally guarded against in other ways, but still this is the reason why in generators, for example, it is one of a number of points which make it desirable to put the reactance outside of the machine rather than to introduce it all into the armature, and in that way sacrificing other qualities of manufacture, repair, and conditions of operation. Introducing it into the transformer, as Mr. Moody has explained, does not protect the transformer itself; and the reactance is now finding a considerably wider application in busbars, together with its introduction into machines.

Reactance is also used—and very likely in the future will be used to a much larger extent still—for another purpose which has been mentioned, namely, that of protection against high-frequency and high-voltage disturbances. A person naturally wonders why iron is not used with current-limiting reactances. Naturally one would think that it would be very much more efficient and thus reduce the size of the coils. The densities, however, that are employed, are so great that iron is of no benefit. It is quite startling when you think of magnetizing the surrounding air.

While it is rather difficult to add much that is new to the discussion without entering the field of speculation, I think it can well be said that the use of reactance both for current-limiting devices and self-protecting devices is undoubtedly to increase much in the future. It is one of the refinements of the art which is going to be studied; it is a new refinement of analysis, and I think the work of the engineer in the future is going to be very largely concerned with the proper use and application of such reactances.

W. M. McConahey (by letter): Mr. Moody's paper is very timely as it deals with a phase of transformer design that is of great importance in large power transformers and, generally speaking, is but imperfectly understood.

Low reactance has been considered desirable because of the good regulation it gives on inductive load. With large power transformers this is unimportant. What is of great importance, however, is that the reactance be of such a value that the mechanical stresses on short circuit will not be such as to make it difficult to prevent damage to the windings. There is a widespread impression that merely changing the design so as to increase the reactance will reduce the short-circuit stresses. This is true only within limits and in some cases an increase in the reactance will actually increase the stresses.

Formula (I) of Mr. Moody's paper shows the elements that enter in to determine the reactance of a transformer and formula (III) shows those that enter in to determine the short-circuit stresses, the current in the latter case being that which flows on short circuit and which is determined by the impedance of the transformer. An inspection of these formulas shows that practically the same elements enter into both, thus indicating the close relation between reactance and short-circuit stresses.

In large transformers of 50 or 60 cycles, particularly if they are for high voltage, it is not difficult so to proportion the design that they will stand up successfully under the most severe short-circuit conditions. For 25 cycles the problem is much more difficult and if the voltage is comparatively low, the difficulties are still further increased. However, by careful designing and the use of substantial mechanical construction, satisfactory low-frequency transformers can be built in moderate sizes without resorting to any special form of construction or the use of outside protective reactances, but in very large sizes, one of these special methods of protecting the windings against excessive mechanical stress may have to be employed.

As stated by Mr. Moody, in a 2:1 auto-transformer the effect of the reactance is reduced by one-half. In a recent case involving the design of some 2:1 auto-transformers for railway service, the short-circuit stresses were found to be so heavy that it was deemed advisable to reduce them by a mechanical separation of the primary and secondary parts of the winding. This of course increased the cost of the transformer, but it is cheaper than supplying outside reactances, which in this case would not have been acceptable.

Exceedingly low reactance, giving very close regulation on inductive load, not only makes it difficult to brace the coils securely but it also increases the cost.

The scheme of placing strips of laminated iron between the primary and secondary coils in order to increase the leakage flux and thus secure high reactance in transformers, particularly for operating synchronous converters, is one that the writer tried out as far back as 1899 and has used many times since with entire success. I cannot quite agree with Mr. Moody that by this scheme " the copper will be entirely shielded from eddy currents" because there will be leakage flux inside the coils themselves as well as in the space occupied by the laminated iron, and there will also be a fringing flux cutting into the coils around the air gaps in the iron. These fluxes will have an appreciable effect in producing eddy currents in the copper. With this scheme, however, high reactance can be secured with much less eddy current loss than with the ordinary type of design, because a comparatively small number of turns can be used in the windings, thus securing a low magnetomotive force and consequently a weak leakage field through the windings.

Charles F. Scott: Mr. Moody's paper presents the subject in a simple, clear and analytical way, and the author has made himself understood without very many differential equations.

In placing the iron shunts between the coils, he says that they can be used to modify the regulation of the transformer up to say 50 per cent overload, but that this is not a remedy for excessive current on short circuit.

In this connection I have been looking at Fig. 3, showing the cross-section of the transformer, and have been trying to imagine what the probable effect would be with a current on short circuit. As I understand the situation it is that as current is increased above normal the reactance continues to be very high until the saturation of the shunt prevents its becoming proportionately greater, so that the transformer on short circuit would probably give, say, three-quarters of the current that it would without the shunts. In order to make the shunts fully effective under conditions of short circuit it would be necessary to make them pretty large. If that were done in Fig. 3, the shunts would present a total area equal to a large fraction of the area of the main core of the transformer, which would introduce a number of difficulties and complications.

Prof. MacLaren's Fig. 1, in which he shows a ring with a primary and a secondary coil around it, leads me to remember that some seventeen or eighteen years ago he and I were associated together in some work of this kind. The diagram here represents very nearly the conditions which we had then. Our ring was some four in. (10 cm.) thick, something like five ft. (1.5 m.) high, and about 12 ft. (3.6 m.) in diameter. It was one of the large nickel steel rings used on the first of the Niagara generators. The interesting feature was that we got away from a delicate fiber suspension galvanometer, and could maintain a constant reading on a voltmeter, of a volt or two, for some time while the current through the primary was increased. Indeed, it was increased at such a rate as to keep the reading on the secondary constant. As I recall it now, a period of something like ten minutes could be occupied in keeping a constant voltage on the secondary by slowly increasing the current flowing around the big ring.

H. M. Hobart: Years ago we used to make alternators and transformers less satisfactory and more expensive than they otherwise need have been in order to keep the reactance very *low*. The present tendency is perhaps to make them still less satisfactory and more expensive than they otherwise need be in order to make the reactance somewhat ***higher*** than would conform to their natural characteristics.

My own opinion is that when we try to give a transformer or an alternator a high internal reactance, the result is a bad transformer or a bad alternator ***and a bad reactance***; and I think that generally the best economic solution of the problem is to make the transformer as good as it can possibly be from all standpoints and then if we need further reactance, put in a reactance as a separate external item. That seems to me to be substantially the conclusion at which Mr. Moody arrives, and I should be interested in hearing his comment on this summing up of the situation. Of course, as Mr. Moody has pointed out, the natural reactance will be higher, the higher the voltage of the transformer, and in the case of very high voltage transformers a considerable proportion of the desired reactance can be obtained in the transformer itself, without sacrifice of other characteristics. But the point to be emphasized, as it seems to me, is that we should design a transformer from the standpoint of heating and efficiency and mechanical strength, and let the reactance come whatever it will, and then put whatever further reactance we desire, ***outside*** of the transformer. The introduction of iron to increase reactance is a more undesirable means than it would appear at first thought. We usually estimate the efficiency of transformers or of alternators by summing up the segregated losses, and we do not take into account the so-called " parasitic " losses which we have at full load. These " parasitic " losses are liable to be considerably increased if we employ magnetic material in the leakage paths. Moreover the increased reactance obtained by the employment of magnetic material in this way, while present at moderate loads when we do not require it, (when, in fact, it is very undesirable), is not present to any appreciable extent under the conditions of short-circuit. This is because, for the enormous magnetomotive forces present in the leakage magnetic circuit at short-circuit, the permeability of iron is scarcely in excess of unity, the permeability of air.

M. V. Ayres: I would like to say a few words in regard to Mr. Moody's paper, more from the point of view of the designer of the substation than of the designer of the transformer. I would take issue with the last speaker in regard to the desirability of designing a transformer and then putting the reactance outside. It seems to me that in the case of the railway substation, where reactance is required for voltage regulation, the method of putting the reactance inside of the transformer fills a long-felt want. A separate reactance for the purpose is a great deal of a nuisance from the point of view of building and equipping a substation. It practically takes up a great deal more room then its mere floor area would seem to indicate, and requires arrangement and adjustment of other apparatus just on account of finding the space to put the reactance; and the wiring of the secondary is always rather awkward on account of the very heavy conductor used. Of course, it is true that the transformer with the reactance feature would not have as good efficiency at full load, but it would seem probable that it would have as good efficiency at full load as a transformer plus a separate reactance coil. If so, that is a sufficient answer to that objection.

As to the use of reactance in transformers for very high voltage circuits and in installations of very large kilowatt capacity, I do not feel able to speak definitely. I only wanted to make the point that for railway substations where reactance is required for voltage regulation, it seems to me that this would be a very great step in advance.

W. S. Moody: I am afraid that I was not very logical, in view of the title of my paper, in referring at all to these external reactances, and without cuts or illustrations it will be difficult for me to describe in detail any of the types that have been constructed.

Just what form it is best to use in a given case depends upon very many factors—the current that you have to handle, the voltage, whether they must be transported, and so forth. As yet there has not been much opportunity to test the relative advantages, for fortunately, short circuits do not occur every day, and so as yet we cannot say whether one form or another form will stand up best under such strains. It is well that more than one form is being tried out, and I hope that some time in the near future we will have enough data to show what particular form is the best for average conditions.

In the communication read from Mr. McConahey he pointed out something in my paper that was not stated as clearly as it should have been. He states that the magnetic shunts in transformers will not necessarily protect the windings from any eddy currents that would result from the flux passing through. I had reference in my remarks entirely to the extra flux that is created by the presence of iron. It is easy to see that the transformer must be designed so that if the iron was not there the flux would be sufficiently low so as to cause no appreciable eddy in the conductors. If that is so, then the addition of the shunts will create a much greater flux, and that additional flux will not cut through the copper, as the flux density in the air and the copper will remain constant, because the magnetomotive force causing them remains constant.

The reason why iron cannot be used advantageously in devices designed to limit current on short circuit is simply because you have in a large transformer, even when the primary and secondary are well subdivided, ampere turns enough so that you would over-saturate the iron, unless so large a cross-section be provided as to give too much reactance at time of normal load. Similarly in these current-limiting reactances that are external to the transformers, for, under the conditions of short circuit, the flux in the air is well above the saturation point of iron. So there would be practically no greater flux there if iron were present.

Ralph D. Mershon: Are the concrete forms, that you wind the resistance on, reinforced?

W. S. Moody: No. We have never felt that it was safe to reinforce them, as iron or any other metal that might be used to reinforce them might heat sufficiently from eddy currents to crack the cement.

Ralph D. Mershon: How do you insulate the coils on the concrete form?

W. S. Moody: The conductors are bare and insulated by treated wood, with asbestos as a heat insulation between the conductor and wood.

Malcolm Mac Laren: The only comment that I have to make is to emphasize what Mr. Chubb said about the extreme sensibility of steel to its heat treatment. Different samples taken from the same consignment may show widely different loss characteristics, if subjected to slightly different treatment, and the laws which govern the various factors entering into the problem are so complicated that it will probably be necessary to gather a great many additional data before any systematic attempt can be made to generalize on the subject.

W. L. Waters (communicated after adjournment): Mr. Moody's paper gives a complete resume of the present state of transformer design as affected by the presence of internal reactance. It is also interesting as indicating how early engineers understood the effect of reactances on the operation of transformers. The explanation given by Mr. S. Z. de Ferranti of the effect of internal self-induction in limiting the secondary current and influencing the regulation of a transformer is practically as complete as that given by Mr. Moody. Mr. Ferranti's explanation was given 20 years ago when he installed his first constant-current arc lighting transformer operated by the magnetic repulsion of the primary and secondary windings, this transformer being almost an exact duplicate of the series arc lighting transformer as used today. The development of distribution systems involving the parallel connection of transformers on a lighting network resulted in engineers reducing the self-induction of transformers to a minimum, in order to improve the regulation; and as Mr. Moody points out, it was only when synchronous converters came into extensive use—about 15 years ago—that it was recognized that the presence of self-induction in the circuit had other uses than that of producing a constant secondary current for arc lighting work. On account of the existence of patents covering the use of a special external reactance coil to obtain automatic compounding with a synchronous converter, the writer, together with other engineers of the smaller manufacturing companies, considered the possibility of building transformers with a high internal self-induction. It was soon found that with the comparatively small transformers then being used with converters, practically the only disadvantage of placing the required self-induction in the transformer itself, rather than in the separate external coil, was that it became impossible toad just the value of the reactance after installation. The transformers with high internal reactance were somewhat cheaper, and the over-all efficiency was about the same, as the increased eddy currents mentioned by Mr. Moody were offset by the reduction in the weight of iron in the transformer due to the modified arrangement of the coils, and by the absence of any losses in an external reactance coil. A large number of such high-reactance transformers was built and operated satisfactorily with synchronous converters, and it is only recently, when heavy compounding has been required in connection with large transformers, that the external reactance coil has again become a necessity.

The use of internal or external reactance for limiting the secondary current in a transformer on short circuit is merely a natural development of the Ferranti principle, which is now found to be advantageous on account of the increased size of power systems; and I think one of the most interesting features in Mr. Moody's paper is that it indicates how early the theory and principles of transformer design and operation were thoroughly understood. The great advance in transformer design and manufacture during the past 20 years has been in the details of construction and in the improved methods of manufacture which have made transformers for high voltage and large capacity a commercial possibility.

M. G. Lloyd (communicated after adjournment): The especial value of Professor MacLaren's paper lies in the fact that the observations have been carried up to the critical temperature, since the measurements of magnetic hysteresis with varying temperatures have been comparatively few and most of these have not been extended to so high a temperature. A large number of measurements have been made upon permeability, however, showing that iron and steel lose their ferromagnetic quality at this temperature, and that the hysteresis must therefore disappear at this point.

The results obtained by Professor MacLaren are quite similar to those obtained by Kunz[1], who in 1894 made experiments up to 800 deg. cent. with specimens in the form of long thin wires, the measurements being made by the magnetometric method. He made use of several varieties of soft iron and of steel, and one specimen of nickel. The results with soft iron showed a decrease of hysteresis with increasing temperature, the curve plotted between these quantities being a straight line. Very nearly the same result was obtained with steel when the temperature cycle was repeated often enough to obtain constant values. With nickel the hysteresis fell off rapidly at first with increasing temperature, and afterward decreased more slowly. As the author has made

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[1] W. Kunz, *E. T. Z.*, XV, 194 (1894.)

no reference to any of the previous work on this subject it may be of interest to note some of the other experiments which have been made.

Wills[2] found similar effects with iron and tungsten steel, and Thiessen[3] observed the same general trend for several materials between minus 70 deg. and plus 100 deg. Some of their results are shown in the following table.

EFFECT OF TEMPERATURE ON HYSTERESIS

Material	B*max*	Ergs per cu. cm. per cycle					Authority
		15°	100°	300°	500°	700°	
Iron	4000	1080	975	685	460	250	Wills
Iron	6000	2200	2200	1450	725	——	Wills
Tungsten steel (4.5%)	2000	9200	8900	5800	2200	——	Wills
Tungsten steel (4.5%)	6000	12000	11700	8000	3750	——	Wills
		−70°	20°	100°			
Soft wrought iron	2000	423	397	333	——	——	Thiessen
Soft wrought iron	5000	1720	1620	1520	——	——	Thiessen
Soft wrought iron	10000	5070	4600	4030	——	——	Thiessen
		−52°	17°	99°			
Crescent tool steel	14700	33850	31880	29600	——	——	Thiessen
		−65°	24°	100°			
Nickel steel (5%)	14900	43070	41860	39700	——	——	Thiessen

The work of Honda and Shimizu,[4] reaching down to the temperature of liquid air, is perhaps the most illuminating which has been done on this subject. They found that upon cooling Swedish iron the hysteresis decreases for low flux densities, but increases for high flux densities, and tungsten steel behaved in the same way. In nickel and cobalt, the hysteresis was always increased by cooling. A research by Waggoner[5] shows that low-carbon steel behaves as stated above for iron, while high-carbon steel behaves like nickel and cobalt. The change was least for a steel containing 1.1 per cent carbon. He also found that the ratio of hysteresis to coercive force was constant for varying temperature and varying carbon content.

The above results apply to hysteresis with alternating magnetization. Experiments in a rotating magnetic field were made by Fuller and Grace[6] and by Perrier.[7] Both sets of experiments show that the maximum hysteresis in the rotary field decreases with increasing temperature, and that this maximum is reached

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[2] R. L. Wills, *Phil. Mag.*, V., 117 (1903.)

[3] A. H. Thiessen, *Phys. Rev.*, VIII, 65 (1899.)

[4] K. Honda and S. Shimizu, *Proc. Tokyo Phys.-Math. Soc.* 2, III, 186 (1904.)

[5] C. W. Waggoner, *Phys. Rev.*, XXVIII, 393 (1909.)

[6] W. P. Fuller & H. Grace, *Phil. Mag.*, XVIII, 866 (1909.)

[7] A. Perrier, Thesis, Geneva, (1909.)

with a lower flux density. Thus for iron at 580 deg. this maximum occurs at 10,500 gausses, while at temperatures below 340 deg. it occurs at about 16,000 gausses. Since the saturation value is also reduced by increasing the temperature, it was to be expected that the hysteresis would decrease to zero for a lower magnetization, and this was found to be the case.

Perrier worked with nickel, magnetite and three kinds of iron and concluded that the ratio of the maximum values of the two kinds of hysteresis was characteristic of the material and independent of the temperature.

One of the most recent papers dealing with this subject was presented before the recent convention of the International Association for Testing Materials and presented results which had been obtained in the chemical laboratory of the Schneider works at Creusot. In this case an automatic registration was secured of the magnetic flux due to a constant magnetizing field with variable temperature. These experiments showed not only the critical point, mentioned above, at which magnetism disappears, but also another critical point between 200 and 300 degrees, at which point there is an irregular change in the curve in the case of many of the steels used. The changes at this critical point are not reversible. The authors connect this critical point with the disappearance of magnetism from the iron carbide or cementite. A highly oxidized steel probably containing occluded gases shows in the cold state abnormal hysteresis and coercive force. This anomaly disappears at about 250 degrees and appears at a slightly lower temperature on cooling.

I regret to note the misleading statement in the opening paragraph of this paper, where the author states in reference to the paper presented in April, 1911, that " It was shown that there was no apparent change in the law governing the variations of the hysteresis loss with the induction for all temperatures from atmospheric up to near the point where the steel became non-magnetic." In the discussion of that paper it was pointed out by both Mr. W. J. Wooldridge and the writer that this statement was not justified by the experimental results.

Malcolm MacLaren: If Dr. Lloyd will refer to the discussion of the author's paper of April, 1911, he will find that no results were presented to show that the law governing the change in hysteresis with the induction was affected by the temperature. The only point which was raised at that time was whether in the case of high silicon steel there should not be a greater variation from the 1.6th power law than was shown by the author's results, and it was pointed out at that time that the inconsistencies were largely due to the erroneous method which Dr. Lloyd used in deriving his exponents. Since the date of that paper the author had made further measurements upon the exponential values for high silicon steel which show a departure from 1.6 above 10,000 lines, but there was no indication that a change in temperature would affect these exponential values.

A paper presented at the 277th Meeting of the American Institute of Electrical Engineers, New York, November 8, 1912.

POWER REQUIREMENTS OF ROLLING MILLS

BY WILFRED SYKES

The increasing use of electric motors for driving the main rolls in modern steel works, makes the question of the power requirements of rolling mills of considerable importance to the industrial engineer engaged in designing such installations. An error in judgment due either to inexperience or to lack of accurate information, may involve the loss of a large sum of money in the installation itself, but what is of still greater importance, is the loss that is incurred indirectly, due to the time lost before the error can be remedied.

The subject is one of great complexity due to the various factors controlling the power requirements and also to the variation in operating conditions in different works. The subject of rolling mills is one on which it is hardly possible to obtain reliable information from published data and the whole rolling mill practise is based upon empirical knowledge gained by experience. During the last few years an attempt has been made in Europe to reduce the subject of rolling mill practise to some scientific basis but without very great success up to the present time.

It is not the object of this paper to attempt to give any set of rules for determining the correct size and characteristics of the motor required for driving any particular mill but rather to indicate the lines along which such problems must be studied and to give an idea of the factors controlling the size and equipment required. To cover the conditions met in modern steel mills would require a great deal more space than can be allowed in a paper before this Institute, and even with full knowledge of such conditions, considerable judgment is always required in working out such problems.

One of the most difficult features of this problem is to determine the set of conditions on which to design the equipment, for any particular mill, that will coincide with the actual practise. It is almost impossible to obtain accurate data, from the men responsible for the operation of such installations, as to operating conditions, on account of the changes that occur in practise after the mill has been installed, and for this reason any assumptions made when determining the size of machine required for driving it, may be altogether wrong in two or three years. A great many superintendents are of the opinion that it is impossible to obtain, within limits, an equipment too large. This is a mistaken idea, but has been based upon past experience which has shown that by improvements, mainly in organization, it has been possible to increase the output often as much as 100 to 200 per cent over the original estimate. With our present knowledge of rolling conditions and in view of what has been done in the past it should be possible to make a reasonable estimate as to how much the production of a mill may be increased in the future, by improvements in the auxiliary apparatus and organization, and this is a factor which must always be considered when designing an installation; and it is here that the electrical manufacturer must often take the responsibility for assumptions as to rolling conditions altogether different from those given by the steel mill engineers. Some of our most successful manufacturers of rolling mill engines have based their machines upon the size required to break some part of the mill, so that they are certain that the engine would carry any load that could be caused by the mill, independently of the method of operation. So long as efficiency is not considered and it is not necessary to meet competition as to price of the installation, such an arrangement is an ideal one from the standpoint of the manufacturer, as there is never any doubt as to the operation of his part of the plant, but under the conditions now existing in our steel mills, attention must be paid to the question of efficiency, and business conditions also necessitate attention being paid to the price of equipment.

In the first place it must be pointed out that the size of the mill as determined by the size of pinions, or the width and diameter of rolls, has comparatively little to do with the size of motor required for driving it, as the work performed by the same size mill may vary several hundred per cent. The fundamental basis on which the size of motor must be determined, is the product of the mill and the tonnage rolled. There are a great many factors entering into the proposition which must be considered, and dealing first with the product, the following are the principal in their usual order of importance:

1. Volume of metal displaced.
2. Method of displacement.
3. Temperature of metal.
4. Class of material.
5. Rate of displacement.
6. Size of roll.

This order is not fixed, and the importance of any of the factors will vary with the practise at the particular mill in question.

VOLUME OF METAL DISPLACED

It is of the greatest importance to have some method of comparing the actual work done on the metal in various mills and it must be admitted that such a comparison is extremely difficult. In comparing various tests, I have used as a unit of work, the h.p.-seconds required to displace one cubic inch of metal. The displaced volume is obtained as shown in Fig. 1. The area enclosed by the full lines, represents the original length of material with the original area *A* and length *L*. After rolling, the area has been reduced to *a* and the length increased to *l*. The shaded portion of the original section, it has been assumed, has been displaced so as to correspond with the shaded part of the metal after the pass. The displacement in practise is of course not as shown, but the illustration will show what is meant by displaced volume. From this sketch it is obvious that the volume displaced is equal to $(A - a)\ L$. If the inch is taken as a unit, this formula gives the cubic inches displaced.

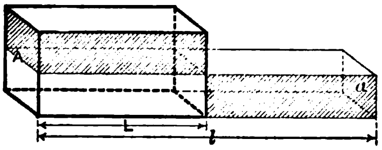


FIG. 1—DIAGRAM OF DISPLACED VOLUME

This unit of work takes into consideration only the volume displaced in the direction of rolling, and for simple work such as rolling plates, blooms, flats, etc., practically all of the metal is displaced in this way, as the displacement at right angles to the direction of rolling is negligible. In cases where the section of the pass is completely enclosed by the rolls, there is very often a side displacement which this unit does not take into consideration, nor is it my opinion that any simple unit of work can provide for this condition, as it is impossible to determine exactly how the metal flows. Fig. 2 shows a typical pass when rolling rounds from square billets. The full line shows the section after the pass, and the dotted line the section before the pass. These sections were obtained by cutting pieces from the bar before and after the pass. It will be seen that the width of the material has been appreciably increased, much more than would be natural if the pressure of the rolls were only perpendicular to the bars of the metal.

Attempts have been made to introduce a factor into the comparisons that would take this condition into consideration, it being considered that the metal covered by the area not shaded has not been displaced, but investigations have not yet reached the stage that would warrant any statement being made as to this method of comparing different passes. The instance given in Fig. 2 is a comparatively simple one, but in practise when rolling various sections such as angles, channels, rails, etc., this side displacement is often made under conditions that make it impossible to use anything else but empirical figures. Referring to Fig. 5, showing the sections after the various passes when rolling rails from billets, it will be seen in the case of pass one of the first series, that the metal has been displaced considerably to form the basis of the flange. In this case there has been a considerable distortion of the metal in addition to the increase in the length due to displacement in the direction of rolling, and it is obvious that no formula can take into consideration such distortion, even if an accurate knowledge were available as to the way that the metal flows. We have some information available as to how metal flows when rolling simple sections such as plates or blooms, but, even with this knowledge, theoretical calculations do not check up very well with practical test results. Various other units of work in addition to the power required to displace a cubic inch of metal, have been adopted by different investigators, but they all take into consideration only the displacement in the direction of rolling, and from what has been said, it is obvious that this is the only basis on which any comparison can be made, although it is admittedly open to objection and must be used in conjunction with empirical constants to provide for the distortion of the metal in other directions. I have adopted the unit of h.p.-seconds per cubic inch displaced as it appears to be the most simple and direct basis of comparison. For convenience it will be referred to as "specific power consumption," or S.P.C.

METHOD OF DISPLACEMENT

Reference has been made to the side flow of the metal, but it is also of the greatest importance to consider how the pressure is applied to the material rolled. When the pressure is vertical, or nearly so, to the surface being rolled, it may be referred to as " direct pressure " and it is obvious that under such conditions the power required will be a minimum. When finishing material such as flanged rail or channel, where the pressure is almost parallel to the surface being rolled, it is obvious that the actual displacement for a given pressure, may be very small. Such a condition is illustrated in Fig. 3, which shows the condition existing when finishing a rail flange and a channel section. Under such conditions, it is obvious that the component at right angles to the surface of the metal is very small, and consequently the pressure may be very large for a very small amount of work done. This condition may be referred to as " indirect pressure."

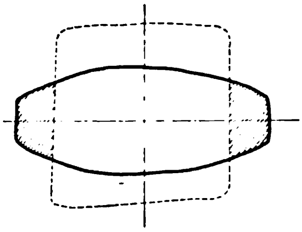


FIG. 2—PASS SECTIONS ROLLING ROUNDS FROM BILLETS

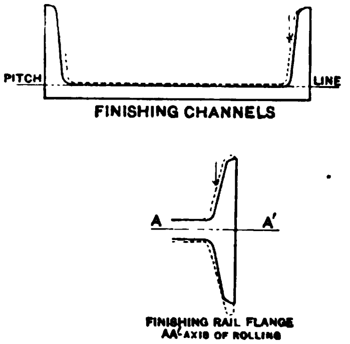


FIG. 3—EXAMPLES OF INDIRECT PRESSURE

In Fig. 4 is shown a number of sections illustrating what is meant by " direct " and " indirect pressure," which will make this point clear.

Referring to Fig. 5, a comparison is made of the various passes when rolling rails, and this figure illustrates the difference in practise met with in steel mill work. The second series of sections shows that the rolls are designed to have as direct pressure as possible, whereas in the first set of sections, a great deal of the work is done by indirect pressure. The first series of sections, however, has been laid out so that the axis of the rail, during the finishing passes, is not parallel to that of the rolls and in this way the surface of the metal is worked at a more favorable angle than in case of the finishing passes of the second set of sections. It would be reasonable to expect for such conditions that the second set of sections would require less power during the initial passes, but that the finishing passes would require somewhat greater power. This shows to some extent the local problem encountered in steel mills. In Fig. 6 are shown two methods of rolling channels, and it will be seen that in rolling the second set the direct pressure is used as much as possible and it is only in the last pass that the actual channel section forms. In this pass the volume displaced is negligible, so that the mill has only to straighten the sides of the channel which has already been formed by direct pressure or pressure at favorable angles. These two examples show the difference in practise in various mills and illustrate to some extent the necessity of studying the particular conditions in each mill before attempting to design an equipment for driving the rolls. The question of roll turning has been based in the past, more or less, upon empirical knowledge obtained by the roll turners from actual experience, but in Europe, some attempt has been made during the last few years to systematize the methods of reducing the metal for different sections, and when this is done the problem of comparing the results to be expected from various mills will be considerably simplified.

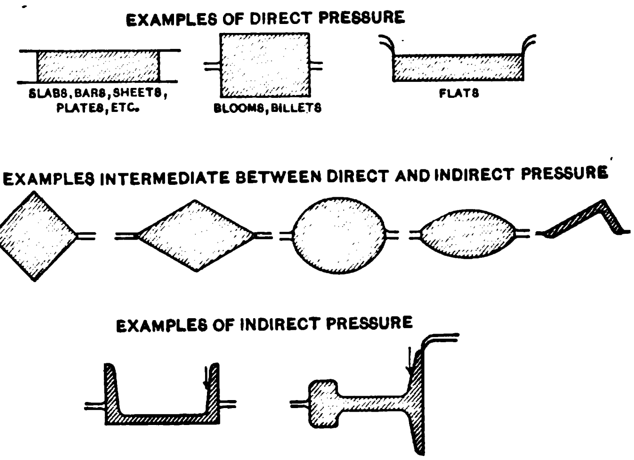
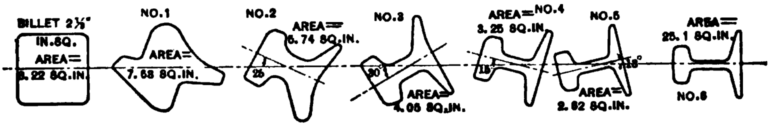
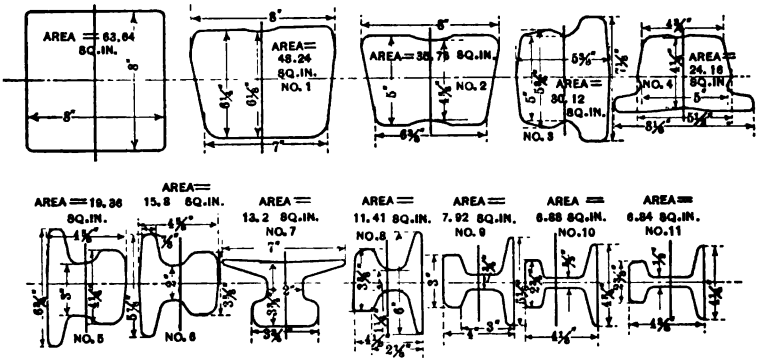


FIG. 4

The pressure on the rolls due to the metal introduces additional friction, but as this cannot be separated from the power actually required to displace the metal, it must be included in the specific power consumption. There is often considerable friction between the rolls and the metal due to the peripheral speeds of various parts of the section being different. On referring to Fig. 5 it is obvious that the speed of the portion of the roll in contact with the web is appreciably greater than that at the edge of the flange and therefore as the flange and the web are delivered at the same rate, there must be slippage somewhere between the metal and the roll. In cases where a rail flange, for instance, is being finished, there is a tendency to move the rolls laterally in relation to one another, which may be taken up by indirect pressure in the opposite direction or in roll collars, in which case the friction is of course increased. As we have no way of determining what the friction due to rolling may be, it must be included as part of the net rolling work, which is the actual input to the mill less the no-load friction. In the author's opinion, it is perfectly legitimate to consider the additional friction in the rolls, pinions and spindles as part of the net rolling



First Series—Pass Sections Rolling Rails



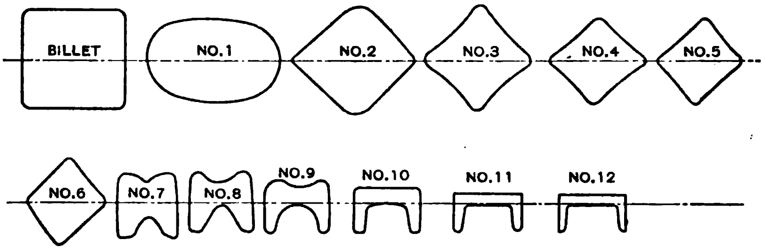
Second Series—Pass Sections Rolling Rails

Fig. 5

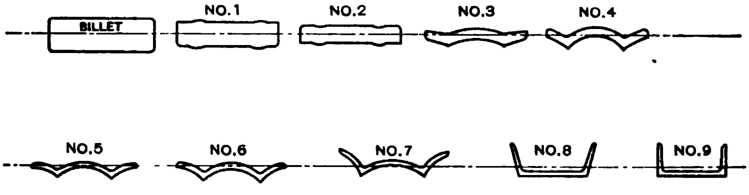
work, and I do not think we would be any better off if we had tests showing exactly how much power each item represented, as the problem is so complicated that I doubt if we would be able to make more accurate estimates than are now possible, although perhaps it might be possible to get along with a smaller number of tests.

TEMPERATURE OF METAL

The temperature of the metal plays a very important part in the power required for any mill. Tests made indicate that the power requirements, all other things being equal, vary practically as the tensile strength of the material. There is not a great deal of information available as to the tensile strength of steel at various temperatures and naturally such tests are rather difficult to make. In Fig. 7 is shown a curve of tensile strength of mild steel at various temperatures, this curve being made up from information that has been published of tests in the Watertown Arsenal and from various European publications, as well as from tests made by the writer. The curve varies somewhat from others that have been published as to the strength at high temperatures, as the tests made by the writer indicate that previous estimates as to the tensile strength have been too low and that, instead of the curve gradually tapering to zero at the melting



PASS SECTION ROLLING CHANNELS—FIRST SERIES



PASS SECTION ROLLING CHANNELS—SECOND SERIES

FIG. 6

point, there is a point somewhere between 1300 and 1400 deg. fahr. where the tensile strength rapidly decreases. Tests made at various temperatures when rolling plates, using only direct pressure, so that there are no other disturbing factors, indicate that this curve is approximately correct as indicating the relation between the power required to displace the metal and the temperature. It will be seen from this curve that the strength increases quite rapidly after the temperature drops below about 1400 deg. fahr., so that when rolling thin sheets, when the metal becomes almost black the power requirements increase at a very rapid rate. This curve shows that tensile strength about 100 deg. fahr. is about 18 times greater than at 2000 deg. fahr. Tests made when rolling sheets at 2000 deg. fahr. and rolling cold, showed a variation in the power consumption per cubic inch displaced varying from 17:1 to 20:1.

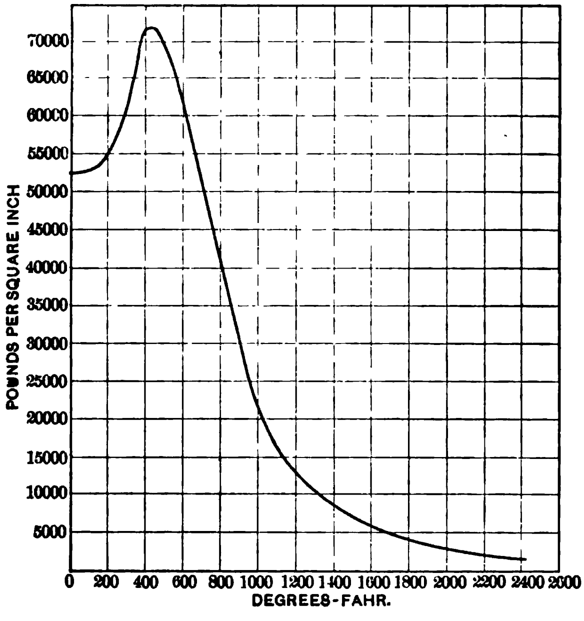


Fig. 7

The rate at which metal cools is obviously of the greatest importance and within the usual limits of rolling temperatures it may be said that the rate of cooling will be practically proportional to the area exposed in relation to the volume. In

Fig. 8 is shown the increase in exposed area of a particular slab as the cross-sectional area was reduced; and when the rate of cooling is taken into consideration, in conjunction with the curve shown in Fig. 7, it is obvious that the power required to displace the metal will increase very rapidly as the cross-section is decreased. This will be referred to later when discussing this point.

Class of Material

Tests made by the writer and by others indicate that, providing the temperature is the same, the power required to displace a given volume of metal is practically independent of the chemical composition of the steel. This of course applies only when rolling metal hot and within the usual rolling temperatures.

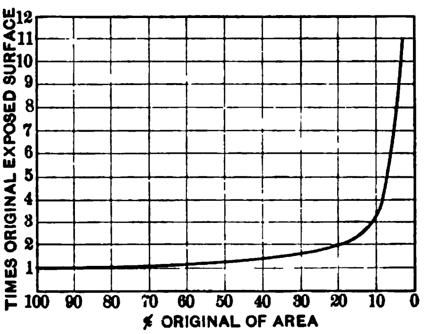


Fig. 8—Showing Increase in Exposed Area of Plate with Reduction in Cross-Section -

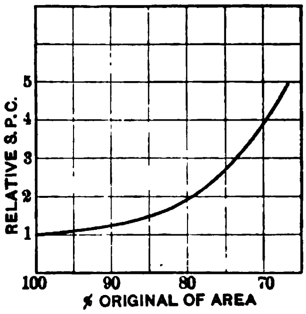


Fig. 9—Showing Increase in Relative Specific Power Consumption—Cold-Rolling Steel Plates

As the temperature approaches 1500 deg. fahr. the influence of the different chemical compositions can be noticed, but as metal is usually worked, except in the case of thin sheets or small sections, between 1800 and 2400 deg. fahr., it may be said that in practise, the composition of the material does not directly influence the power consumption. Indirectly, however, it has considerable influence, as it is necessary to roll high-carbon steels and some alloy steels at comparatively low temperatures, so that the power consumption for a given volume of displacement may be considerably higher than would be the case when rolling mild steel.

The density of the steel also has considerable influence upon the power requirements, and when rolling ingots, the first one or two passes made require comparatively little power per cubic inch displaced, as the steel is more or less porous. After the metal has had one or two passes through the rolls, the density when hot apparently does not enter further into the question. When rolling steel cold, there is a continual increase of the power required due to the increased density, and in Fig. 9 is shown a typical curve indicating the increase in power requirements as the cross-section area is decreased.

Rate of Displacement

Although little information is available, there are indications that the rate of displacement somewhat affects the power requirements. Tests made by the writer appear to show that a low rate of displacement requires less power than if metal is rolled quickly. In practise, however, metal is rolled as quickly as it can be handled, so that this feature is of comparatively little importance.

Size of Rolls

Theoretical investigations show that when rolling plates or blooms or such sections where direct pressure only is used, the size of roll has some effect upon power requirements. Small rolls should require somewhat less power than large rolls, but the writer has not been able to demonstrate the accuracy of these theoretical calculations owing to the great many other factors which influence the test results.

Practical Determination of Motor Size

The great majority of rolling mills are of the type running continuously in one direction, and to equalize the input to the motor, flywheels are used. It is of the greatest importance to determine the size of flywheel required in conjunction with the characteristics of the motor and control apparatus, as it is only by considering them as a unit that a satisfactory installation can be made. It is seldom that a mill is run at such a rate that it is discharging metal from the finishing pass for anything approaching 100 per cent of the running time. Depending upon the class of mill and the work performed, it is usual to find the mill actually rolling from 20 to 80 per cent of the total time. In the heavier mills, the percentage is naturally less than in the case of the mills rolling small sections, and it is therefore obvious that if the motor size is determined upon the basis of rolling so much material per hour, it may be altogether too small to perform the work while the metal is actually in the rolls, although it might be large enough to take care of the average conditions. With the ideal flywheel, a motor sufficiently large to carry the average load would be the right size to use, as all the peaks would be taken by the flywheel, and during the intervals between passes, energy would be stored in it. In practise it is not possible to use such flywheels, as they would be excessively large, and consequently a compromise must be made between motor and flywheel. It is usual to consider that the mill will run for short periods at its maximum capacity, that is, with the minimum interval necessary to handle the material, and on this basis the load diagram must be determined. The load diagram can be determined from curves showing the power requirements per cubic inch displaced, in conjunction with the volumes displaced and the rate of rolling. From this diagram, the average load, when the mill is rolling at the maximum rate, can be determined, and also the size of the flywheel. The average production of the mill must be taken into consideration in determining the size of motor so as to have an equipment which has suitable characteristics for the normal operating conditions. The curve showing the power required per cubic inch displacement shows a rapid increase as the cross-section area of the material rolled decreases. It is necessary to determine this curve from test data for practically every installation, as local conditions vary so greatly that it is not possible to take any set of curves as representing universal conditions. To illustrate the methods used in determining the size of motor, a load diagram when rolling plates is worked up in detail in Table I, which it is believed will show how this problem is handled when the proper data are available. It is of course obvious that this diagram is subject to appreciable variations in practise due to the variation in the condition of the material, temperature, etc., but as the curve for power consumption is based upon an average of a number of tests, the diagram is sufficiently accurate to enable the size of the motor and flywheel to be determined. The motor slip under actual operating conditions may be somewhat different from that calculated, but the flywheel will take care of these operating variations. From the load diagram, after allowing for friction, the average load on the motor during the period when the mill is rolling at its maximum rate, can be determined. For perfect operating conditions the flywheel should take all loads in excess of this average load. In practise this is not

TABLE I

Calculation of power required for rolling ¾-in. by 24-in. plate from 4 by 24 by 97.5-in. slab. Rolls 30 in. diameter. Average speed 90 rev. per min. Friction load of mill, 250 h.p. Interval between passes, 5 seconds. Interval between slabs, 20 seconds

Pass No.	Thickness after pass (inches)	Area		Length		Time of pass (sec.)	Vol. displaced $(A-a)\ L$ (cu. inches)	Percentage original area before pass	Specific power consumption-h.p.-sec. per cu. in. (Fig. 10)
		Before pass A (sq. inches)	After pass A (sq. inches)	Before pass L (inches)	After pass l (inches)				
1	3 9/16	96	85.5	97.5	109.7	0.78	1002	100	1.43
2	2 15/16	85.5	70.5	109.7	133.0	0.94	1643	89	1.57
3	2 7/16	70.5	58.5	133.0	160.0	1.13	1595	73.4	1.80
4	1 15/16	58.5	46.5	160.0	201.5	1.43	1920	60.9	2.05
5	1 7/16	46.5	34.5	201.5	271.5	1.92	2420	48.4	2.38
6	1 1/16	34.5	22.5	271.5	368.0	2.6	2440	35.9	2.83
7	15/16	25.5	22.5	368.0	416.0	2.94	1100	26.6	3.36
8	13/16	22.5	19.5	416.0	480.0	3.4	1250	23.4	3.65
9	12/16	19.5	18.0	480.0	520.0	3.68	720	20.3	4.00

Pass No.	Net rolling work during pass (h.p. sec.)	Total h.p.-sec. during pass, including friction	Horse power-seconds during interval	Output of fly-wheel excess peak above average h.p.-sec.	Returned to flywheel between passes (h.p.-sec.)	Net loss of flywheel energy during pass (h.p.-sec.)	Summation of energy from flywheel (h.p.-sec.)	Maximum output of flywheel after pass (h.p.-sec.)
1	1435	1630	1250	1092				
2	2580	2815	1250	2167				
3	2870	3152	1250	2374	2197	177	177	2374
4	3940	4298	1250	3313	2197	1116	1293	3490
5	5760	6240	1250	4917	2197	2720	4013	6210
6	6900	7550	1250	5758	2197	3561	7574	9771
7	3700	4435	1250	2410	2197	213	7787	9984
8	4560	5410	1250	3070	2197	873	8660	10857
9	2880	3800	5000	1263	8788	+ 7525	1135	9923

always feasible, but it must be remembered that the type of control also has considerable influence upon the input to the motor. If the speed of the motor is to be regulated in such a way that the motor takes only the average load, it is necessary to vary automatically the resistance of the rotor circuit. The usual method of control in rolling mills is to use a fixed rotor resistance, so that the speed falls as the load is increased. This gives a more or less satisfactory control of the flywheel, but in the majority of cases it leaves a great deal to be desired. Efficient control devices have been designed which will automatically regulate the rotor resistance quickly enough to meet rolling mill conditions, and a description of one successful type has been already given by the author.* In the table calculated, it has been assumed that automatic slip regulation is provided for, so that the flywheel will take all loads in excess of the average, and from the load diagram, the capacity of the flywheel can be readily determined. In Fig. 10 is shown the curve from which the S. P. C. has been obtained. This curve represents the average of a number of tests. In Fig. 11 is shown the load diagram corresponding to the table, which shows the work to be performed by the motor and flywheel. In practise it has been found that, al-

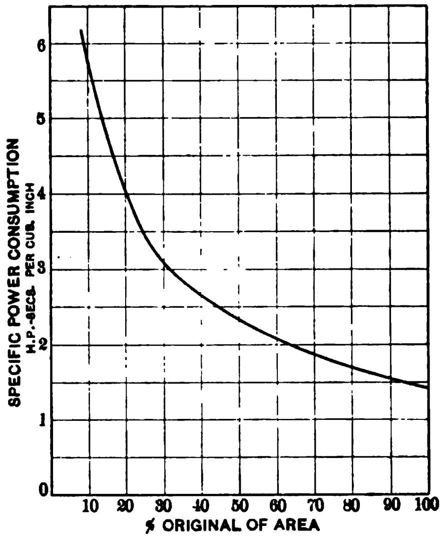


FIG. 10

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*TRANSACTIONS A. I. E. E., 1911, Vol. XXX, Part II, page 1587.

though the power required for the individual passes may vary quite appreciably from that calculated, the flywheel will have sufficient capacity to compensate for these individual variations, and that the general operating conditions of the motor can be fairly accurately determined. It has been pointed out that the daily or hourly capacity of a mill may be very much less than the maximum possible capacity, and it is necessary to compromise between the size of machine required to handle the maximum possible output and the actual hourly and daily output. For instance, in the example that has been worked out, the average load on the motor is 675 h.p. when the mill is run at its maximum rate of production. The actual hourly rate of production of this mill is only 80 per cent of this maximum, so that if the normal rating of the motor is such that it would carry the hourly average, it would be overloaded 25 per cent when working at the maximum rate of production.

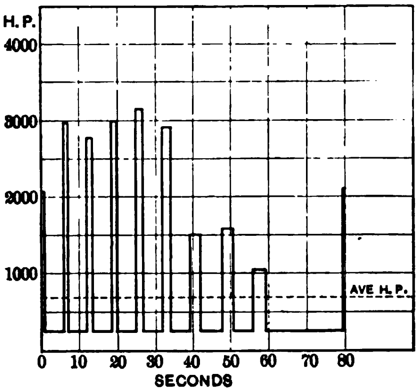

FIG. 11—LOAD DIAGRAM CORRESPONDING TO TABLE I

In practise it is advisable not to allow for an overload of more than 25 per cent when rolling at the maximum possible rate, so that there is always a certain reserve available in the motor for extraordinary conditions that may arise. Rolling mill motors are usually designed so that they can carry 25 per cent overload continuously with a 50 deg. cent. rise and 50 per cent for one hour with a 60 deg. cent. rise. With motors designed on this basis, it is quite permissible to allow for their being overloaded 25 per cent when the mill is run at its maximum capacity. If the hourly capacity of the mill is considerably less than the maximum that can be rolled, it is then necessary to investigate very closely the conditions existing so as to determine on what basis the compromise must be made.

In the foregoing, attention has been drawn to some of the features controlling the power requirements of rolling mills and it is hoped that at some future date it will be possible to discuss this problem more in detail when a fuller knowledge is available of the various constants that must be considered when dealing with this proposition. The examples given represent simple conditions and it will be readily appreciated that the great variety of shapes rolled makes the actual determination of power requirements very difficult. Curves showing the specific power consumption are not as a rule so regular as for plates, which represent the simplest condition met with and the one not interfered with by such items as indirect pressure, collar friction, etc.

A paper presented at the 277th Meeting of the American Institute of Electrical Engineers, New York, November 8, 1912.

THE ECONOMICAL SPEED CONTROL OF ALTERNATING-CURRENT MOTORS DRIVING ROLLING MILLS

BY F. W. MEYER AND WILFRED SYKES

For reasons which need not be discussed in this paper the induction motor has been adopted almost exclusively for driving rolling mills where electrical equipments have been installed. One of the most difficult problems to be solved with this type of motor when electrifying rolling mills is the speed regulation required for the merchant and hand mills, owing to the fact that this type of motor is normally a constant, speed machine. It is also one of the requirements on which it is almost impossible to obtain reliable information and one which invariably leads to a great deal of discussion, not only between the electrical engineers and the mill operator, but also amongst the operators themselves. Although the principal types of mills requiring adjustable speed are the merchant and hand mills, it is occasionally necessary to run the mills rolling heavy sections at various speeds. In the latter case, however, the problem is usually fairly simple because as a rule only two speeds are asked for.

The smaller mills generally call for a great number of speeds and it is in connection with motors of about 300 to 1000 h.p. that the principal difficulty occurs.

In referring to adjustable speed drives it is understood that this means mills that have to run at a number of definite speeds and that these speeds are maintained substantially constant, independent of the load variation.

To any one investigating the requirements of rolling mills, one of the most striking features is the diversity of opinion among mill operators, as to what speed regulation is necessary when rolling various sizes of material and different classes of work. To explain clearly the problem, it is necessary to divide the mills into three classes as follows:

1. Speed adjustment is required on account of the large range of material required.

2. The speed regulation is required to enable a mill to run in tandem with another mill which has a fixed speed and which rolls a variety of product.

3. Speed regulation is required to make it possible to obtain certain qualities, finish, and accuracy of section for different products.

As a rule it is not clearly understood, but it is a fact nevertheless, that in the first case, the speed regulation required depends greatly upon the class of labor operating the mill, and to the degree to which it have been organized for working this particular plant. A gang of men that has been working together for a considerable period at a particular mill can naturally handle the metal quicker than one that is not so well organized and familiar with its characteristics, and it is also possible when the men are thoroughly familiar with the work to handle a larger variety of sections at high speeds, than can be done by less skilful workmen. Where the range of material rolled is very great it is, of course, not possible to handle heavy sections properly at the same speed as the lighter sections, no matter how well the workmen may be trained. The rate at which it is possible for the workman to catch the metal with his tongs as it leaves the mill and return it to the roll, depends, within limits, entirely upon the skill he may have acquired through practise, and when rolling the smaller sections, it is the workman's capacity to handle the metal that limits the speed of the rolls. The more skill he has, the greater will be the range of material that he will be able to handle at the maximum speed of the mill, provided, of course, that the weight is not excessive, and this accounts to a very great extent for the difference in the practise of different mills when rolling the same material. It may be stated, therefore, that if the range of material rolled is not very great, the speed regulation required depends principally upon the skill of the workman. It is not unusual to find that after a mill has been installed with arrangements for speed regulation, and has been operating for a few months, that speeds lower than the maximum are not used at all.

As the greatest speed regulation is generally required by the smaller mills, due to the larger range of material that must be rolled with a given equipment, it is in such plants that the best results can usually be obtained by studying the operating conditions and the organization of the workmen.

In changing an existing installation from steam to electric drive, it is very often possible to materially increase the output, due to the fact that the speed limitations of the induction motor necessarily introduce changes in the method of operation. If, for instance, a mill is installed with say only two speeds where previously a greater number was possible, it is commonly found that after a short time, a much greater variety of sections is rolled at the higher speed than was formerly the case. As the operators have only one alternative, it is, therefore, necessary to study very closely the working conditions, and by comparing them with those of other plants, to arrive at conclusions independently of the statements of the operators. Such methods must not be pushed too far, of course, as the quality of the organization must also be taken into consideration. From investigations made as to the operating conditions in a great many mills driven by steam engines, it has been found that the operators usually have only a very vague notion of the speeds at which different materials are rolled. In Fig. 1 are shown some average figures for the delivery speed of hand-operated mills and it will be noted that the speed depends upon the maximum dimensions of the material rather than upon the area of the section.

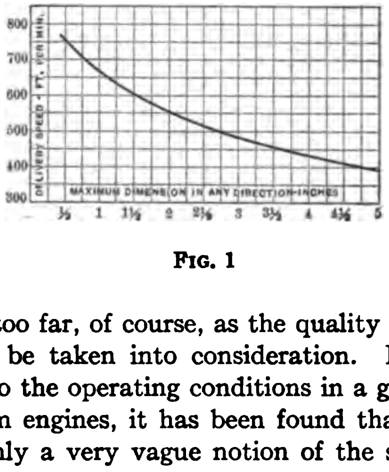

Fig. 1

It is occasionally necessary to roll certain kinds of steel at lower speeds than the maximum on account of the quality of the material or the temperature at which it is worked, and this must, of course, be taken into consideration.

It is obvious that if a mill is to roll a great variety of sections some speed regulation may be necessary, but as it is not uncommon to find material rolled at speeds varying as much as 100 ft.

(30.4 m.) per minute from the average figures given, it is obvious that a great number of speeds is not absolutely necessary, although very often asked for. The greatest speed adjustment is required in the case of jobbing mills where it is not unusual to find material varying from ¼ in. to 3 or 4 in. (0.63-cm. to 7.6 or 10.1-cm.) rounds rolled in the same mill, and a speed range of 2 to 1 may be required. With such a range of work it is necessary to finish the smaller sections at a higher speed than the larger ones, as otherwise the metal would cool too rapidly and could only be formed by the expenditure of a great deal of power, thereby increasing the liability of breakage of the mill, and the accuracy of sections and quality of product may also be affected. To obtain a reasonable production from the mill, the smaller sections must naturally be rolled at as high a speed as possible.

The second conditon to be met is where the finishing stands of a mill are driven by a separate motor, and the metal is in the two mills simultaneously. In this case the metal is usually delivered from the first mill at approximately constant speed and the speed of the finishing stands is dependent upon the reduction in area in the last passes. There is usually a loop between the two mills, but if the relative speeds are not approximately correct, the length of the loop may become excessive or the metal may be torn apart. In Fig. 2 is shown the layout of a mill of this type in which the smaller sections are finished in the separately driven rolls while the larger sizes of material are finished by the first mill. The delivery speed of the mill is approximately the same as the peripheral speed of the rolls, and consequently the intake speed will vary in proportion to the reduction in area in the pass. For instance, if there is a 30 per cent reduction in area, the ratio between the intake and delivery speeds will be the same as 70 to 100, or in other words the delivery speed will be 43 per cent

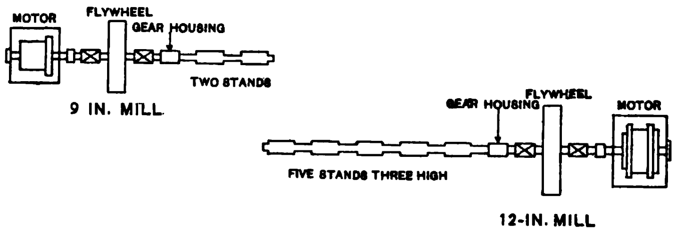

FIG. 2

faster than the intake. This relative speed, of course, varies with each section rolled. Another feature controlling the delivery and intake speeds is the size of the rolls. In practise, rolls will vary in size 10 per cent; they are usually about 10 per cent over size when new, and they will be turned until they are about this amount under size, before they are discarded. If it should happen that the first mill has new rolls, and the finishing mill old rolls, there may be a difference between the delivery and intake speeds of 20 per cent, independent of any other conditions that may exist.

The amount of variation from the correct speed of the finishing rolls depends upon the normal length of the loop, which should be as short as possible, the floor space available and the length of the material. It is, therefore, usually necessary with this arrangement to arrange for a fairly large speed regulation with a considerable number of steps.

The third condition is usually met with in mills rolling heavy and complicated sections. In such cases in order to roll some particular section accurately to size, a lower speed may be necessary than is required for normal operation, but in such cases only two speeds are usually wanted to meet operating conditions.

To meet these three conditions a number of arrangements have been used and suggested, and it is proposed to review some of these different schemes from a practical operating and commercial standpoint.

Rheostatic Control

The simplest method of reducing the speed of an induction motor is, of course, to insert resistance in the rotor circuit, by which means any speed required may be obtained for a certain definite load and with a corresponding loss of efficiency depending on the load and reduction in speed. With simple rheostatic control, we are limited by the speed variation which occurs with varying loads, as at light loads the motor speed will rise to approximately the maximum value, no matter what the full load speed may be. Within certain limits, where the regulation required does not exceed about 10 to 15 per cent from the synchronous speed, the rheostatic method of control is not only the simplest and most satisfactory, but under mill operating conditions probably the most economical. In the class of mill requiring speed regulation, the load is usually comparatively constant, due to the fact that there is often more than one piece going through the mill at a time, and the interval between passes is generally very short, so that the actual speed variations are not so great as it may be thought would be the case from the motor characteristics, especially if the flywheel effect of the rotating parts is at all appreciable. The effect of a flywheel is not only to lower the peak loads that come on the motor, but also to lengthen the time required for the motor to increase in speed after the load is reduced.

Without automatic regulation of the resistance, about 15 per cent regulation is about all that can be obtained under usual operating conditions, but sometimes a still greater range is practicable. With automatic resistance adjustment so as to vary it inversely with the load, it is usually possible to obtain a speed regulation up to about 30 per cent, provided the friction load of the mill is not less than about 20 per cent of full load capacity of the motor, and there is sufficient flywheel effect in the mill to compensate for the time element of the regulator. Beyond these limits it is hardly practical to use rheostatic speed regulation, but up to about 30 per cent it is possible to obtain fairly satisfactory operation by rheostatic control under the above conditions. The accuracy of the regulation will depend somewhat upon the flywheel effect of the system and if it is very great even a greater range than given above may be obtained satisfactorily. Although at first sight rheostatic control may not appear to be economical, where the speed range is as large as mentioned above, there are many cases where it is more economical than some auxiliary arrangement for obtaining speed regulation, due to the fact that at light load the rheostatic losses are not great and that the proportion of the time that the motor is operating at full load may be comparatively small.

If we consider, for instance, a jobbing mill which runs continuously, but which has a very small production, the no-load losses of any auxiliary arrangement may mean an appreciable reduction of the all-day efficiency. Take for example a mill requiring 500 h.p. average when rolling and 100 h.p. running light, the motor losses being 10 per cent of the average output at full load, and 5 per cent at the friction load. If the mill carries full load 20 per cent of the running time, and the regulation from synchronous speed required is 25 per cent, the additional loss due to the resistance will be about 22 per cent at full load, and at light load the rheostatic loss will be about 24.4 per cent. The total input to the motor under these conditions will be for one hour:

Useful output, 500 h.p., 12 minutes	100 h.p-hr.
Motor loss, 50 h.p., 12 minutes	10 " "
Rheostatic loss, 140 h.p., 12 minutes	28 " "
Friction output, 100 h.p., 48 minutes	80 " "
Motor loss, 25 h.p., 48 minutes	20 " "
Rheostatic loss	32 " "
	270 h.p-hr.

The 25 per cent speed regulation has been obtained at the expense of an additional input of 60 h.p-hours. If, instead of rheostatic control, the alternating current were converted to direct current by means of a synchronous converter, the efficiency of the converting equipment, including transformers, would be about 90 per cent at full load and about 83 per cent at light load. In this case an adjustable speed motor would be used for the mill, so the efficiency would be about the same as the induction motor. With this arrangement the input would be as follows:

Useful output, 500 h.p., 12 minutes	100 h.p-hr.
Motor loss, 50 h.p., 12 minutes	10 " "
Conversion loss 60 h.p., 12 minutes	12 " "
Friction output, 400 h.p., 48 minutes	80 " "
Motor loss, 25 h.p., 48 minutes	20 " "
Conversion loss, 25 h.p., 48 minutes	20 " "
	242 h.p-hr.

The over-all efficiency with the rheostatic control would be

$$\frac{(100 + 80) \times 100}{270} = 66.6 \text{ per cent.}$$

and with the direct-current system,

$$\frac{(100 + 80) \times 100}{242} = 74.3 \text{ per cent.}$$

An improvement of 7.7 per cent in the over-all efficiency has been gained with a capital expenditure about 100 per cent greater than that of the simple induction motor. The fixed charges will be appreciably increased due to the greater outlay and the greater maintenance of the additional apparatus. Actually, the gain will be considerably less, as the mill will operate only a part of the time at the reduced speed. If, for instance, it runs half the time at the reduced speed, the over-all efficiency of the induction motor drive would be 75 per cent, and the direct-current drive 74.3 per cent, so there would be no saving in a year's operation.

This is not representative of the class of work usually met with, but such cases are not uncommon and it will be seen that although rheostatic control is inherently inefficient, yet in certain instances it might be better than some of the arrangements that are at present operating. In the example taken, the obvious solution of the problem would be to use a two-speed motor and to obtain intermediate speeds by rheostatic control, in which case the economy would be very much better than shown, and superior to the direct-current arrangement. With some of the newer methods of speed regulation which will be referred to later, much more economical regulation can be obtained than with any arrangement requiring the conversion of the energy to direct current, so that the field for rheostatic control will be reduced in the future, but the difference between full-load and the yearly efficiency with rheostatic control, should be clearly understood.

Multi-Speed Motors

Theoretically it is possible to obtain practically any number of speeds required from a single motor by using one or more windings and suitably grouping the coils. In practise, however, we are limited to one or two combinations, not only on account, of the complexity of the motor design and the uneconomical use of the material, but also because of the complication of the control equipment. Four speeds is about the maximum that can be obtained with multi-speed motors in practise and even this range requires an extremely complicated control, especially if the motor has a wound rotor. Two of the speeds need not have any definite relation to each other, but the other speeds in each case must be half of the corresponding higher speeds. This arrangement requires two windings on the stator, and in the case of a wound-rotor motor, two windings on the rotor, each winding being grouped to give double the number of poles for the lower speed. To obtain the various combinations, such a motor must have at least nine slip rings, and 12 leads must be brought out from the stator.

The usual type of motor used in steel mills has not more than three speeds, one speed being half of the maximum and the third speed intermediate between these two. This motor also has two windings, one of which must be re-connected to give a 2 to 1 ratio. Such arrangements are seldom met with and a great majority of cases, up to the present, have been taken care of by two-speed motors, intermediate regulation being obtained by rheostatic control. The simplest type has a speed ratio of 2 to 1 and has only one winding which is re-connected, requiring six stator and six rotor leads. The second type has two windings that are absolutely independent of each other, but has the same number of leads as the motor with the 2 to 1 ratio. The complication of the control is one of the disadvantages of the multi-speed motor and it is one of the limiting features of the number of speeds that it is feasible to obtain. In the motor with two separate windings the control is very simple, as it is only necessary to change from one winding to the other by means of double-throw switches.

With an arrangement giving two synchronous speeds, one approximately 70 per cent of the other, it is possible to obtain a speed regulation by rheostatic control of about 2 to 1, giving any number of intermediate steps that may be required. This arrangement in a great many cases where comparatively close regulation may be necessary, such as when mills are worked in tandem, may work out to be the best and cheapest installation.

A number of papers have been read before this Institute on the possible combinations for obtaining a number of synchronous speeds, but in all the discussion little attention has been given to the switching arrangements required to make up such combinations. From the standpoint of the operator, the control equipment is usually a greater worry than the motor, and an arrangement that may be technically very interesting and ingenious will probably be so complicated from a control standpoint that satisfactory operation is impossible. The motor is usually the simplest and most reliable part of the equipment and, therefore, it must not be considered alone. The order in which the switching must be done, when changing from one speed to another, to prevent short circuits, is such that it is almost imperative to use automatic control with the class of labor usually operating such machines, and, to obtain the proper combinations the wiring becomes extremely complicated if more than two speeds are required.

The efficiency and power factor of the multi-speed motor is not very much lower than a single-speed machine of the same characteristics and from a practical operating standpoint, the difference is not appreciable.

MOTORS IN CASCADE

With motors in cascade it is possible to obtain practically any number of speeds that may be required. Actually, the number of speeds that it is possible to obtain is limited by the cost of the equipment and the complication of control apparatus more than by any limitations of the system. This arrangement has been used to a slight extent here, and to a greater extent abroad for rolling mill work, but on account of its high cost and rather unsatisfactory operating conditions it has not found many advocates.

The possible combinations have been brought out to some extent in the discussion of Reist and Maxwell's paper before this Institute,* and practically the only limitation is the number of steps that can be obtained with an even number of poles. Such combinations, however, could not be used in practise on account of the complexity of the switching devices, which would be such that they would be necessarily very unreliable. The combinations that are really practicable do not give any greater range than can be obtained by multi-speed motors, and the efficiency and power factor are not as good. The low power factor of the cascade arrangement is one of the most undesirable features of this arrangement, and in steel mills where induction motors are so largely used the addition of such apparatus is very undesirable. The work that has been done in the study of the speed requirements of the mills by electrical engineers has shown that it is not necessary to have such a wide range of speeds as can be obtained with the cascade arrangement even leaving the practical side of the question out altogether, and, therefore, the multi-speed motor has been used almost exclusively in this country, wherever different speeds have been necessary.

INDUCTION MOTORS IN CONJUNCTION WITH THREE-PHASE COMMUTATOR REGULATING MACHINES

In the types of machines that have been referred to, the characteristics are generally well known. In the case of rheostatic control, the resistance losses are such that this system is not efficient if the amount of regulation required is large, as the energy from the rotor circuit is dissipated in the resistance. If, instead, the energy from the rotor circuit is absorbed by an auxiliary machine or machines, which in turn delivers power to the system, it will be possible to obtain speed regulation below

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*TRANSACTIONS A.I.E.E., 1909, XXVIII, I, page 610.

synchronism economically. If energy is delivered to the rotor circuit by an auxiliary machine or machines, regulation above synchronism can be obtained. With such arrangements it is possible to combine many of the advantages of the induction motors with those of the adjustable-speed direct-current motors. The desirability of such regulating systems cannot be questioned, but under the conditions existing in this country there are at present certain difficulties standing in the way of the general adoption of the various methods which will be described. The problem of adapting these various systems to American conditions presents considerable difficulty and consequently they cannot be generally used at the present time.

The various systems that have been developed enable speed regulation over a considerable range to be obtained, and in addition to their use in connection with rolling mill motors they have been largely adopted in Europe for the speed control of compressors, blowers, etc., as well as for the driving of machine tools requiring adjustable speed, thereby supplanting the adjustable-speed direct-current motor, and making possible the use of alternating current for all purposes.

The desirability of obtaining a greater speed range, economically, than is possible with the multi-speed motor and cascade systems that have been previously described, caused some of the European manufacturers to experiment at an early date with the various arrangements involving three-phase commutator machines. In spite of the favorable results obtained under test conditions the development of these arrangements progressed rather slowly, due to the fact that this type of machine introduced new problems from an operating standpoint, and consequently, practical experience had first to be obtained before confidence was established. Originally, there was considerable doubt as to the possibility of obtaining satisfactory commutation, but the development of the single-phase commutator motor for railway work, operating under most severe conditions, paved the way for the introduction of a three-phase commutator motor. One of the difficulties that had to be overcome in the introduction of this type of motor was the education of the operators. In Europe, the experience that had been gained with the single-phase motor showed that the three-phase machine did not present any greater difficulties, as far as commutation is concerned, and in certain features had advantages over the single-phase, and in some respects even over direct-current machines, in spite of other drawbacks.

How far it is possible to use the systems that have been developed in Europe, in this country, is a question that can only be demonstrated by experience, but in view of the inferior class of labor that we have in a great many of our plants for attending to the machines, it will be necessary to exercise considerable care in the early installations. As will be seen from the following descriptions of the various systems, some of them are quite simple, and when the preliminary difficulties have been overcome, we may expect that such arrangements will find considerable application. In a paper before this Institute, Mr. G. A. Maier* described some of the systems that have been developed in Europe, and in the discussion another system was mentioned. It is proposed in this paper to describe some of the newer developments with this type of machine and for the sake of comparison, the principal features of the systems already described will be mentioned. Most of the main characteristics of the new systems that will be described have been already tested, but at the present time it is not possible to discuss operating experience.

One characteristic of the three-phase commutator regulating machine is that it is possible, with suitable arrangements, to compensate for the power factor of the main motor and overcome the objections that are raised as to the use of induction motors, on account of their low average power factor. This characteristic has not been taken full advantage of in all systems that have been developed, but it is one of the important advantages of this method of regulation, if properly worked out.

One of the first systems developed had the commutator machine direct-connected to an induction motor shaft. This system has worked satisfactorily, but the question is sometimes asked why the three-phase motor is not used directly instead of in combination with the induction motor. The reason is that it is desired as much as possible to employ the simple induction motor for performing the work and that the commutator machine is only used as an auxiliary to obtain the speed regulation, and consequently it may be smaller in most cases than would be the case if it were used directly.

In Fig. 3, the system referred to above is shown diagrammatically. The induction motor *A* is designed for the full load to be carried. When the main motor is operating at its full speed the auxiliary motor *B* is not loaded and may be disconnected altogether. In order to obtain a reduction in speed, the transformer

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*TRANSACTIONS A.I.E.E., 1911, XXX, III, page 2455.

C is so regulated that the auxiliary motor *B* develops a back e.m.f. which can only be overcome by an increase in the rotor voltage and a consequent drop in speed, and consequently, the energy from the rotor circuit, instead of being lost in resistance as with rheostatic control, is absorbed by the auxiliary motor, which assists the main motor in carrying the load. So long as the speed range of the main motor is not large, the auxiliary motor is comparatively small, but its capacity is determined by the percentage of speed regulation required, or, for instance, if the speed must be reduced 30 per cent, it must have 30 per cent of the capacity of the induction motor. This is important, as previously it was not possible to build three-phase commutator motors for large capacities. The limit of size was fixed by the fact that satisfactory means were not available to obtain good commutation, and the arrangements for obtaining power factor regulation, by means of moving the brushes, made it extremely difficult to use auxiliary commutating fields in the motor. The movement of the brushes was necessary to avoid the use of an expensive combined phase and voltage regulator in place of the simple regulating transformer. Due to later developments, the limit placed upon the size of machine by the commutation has been removed by the use of commutating fields, which makes it necessary with the ordinary phase winding to use a constant brush lead to obtain good power factor compensation for the average operating conditions; or it is possible to obtain the same results by a special phase combination in the motor itself. The latter arrangement has certain advantages, especially where the field form is not favorable to good commutation, which is not possessed by the system of varying the brush position.

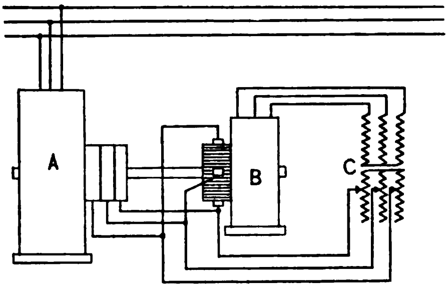

Fig. 3

This system of speed regulation has the advantage that as the speed of the set is reduced, the available torque for the same line current is increased as the work done by the commutator machine increases, directly in proportion with the decrease of speed. The disadvantage of this system is that the direct connection of the commutator motor necessitates its being designed for the same speed as the induction motor, which as a rule, in the case of machines of large capacities in rolling mills, is comparatively low, and this introduces difficulties in the construction. In the case of high-speed induction motors, driving turbo-compressors, blowers, etc., it is generally quite impossible to build the commutator motor for the same speed as the main motor. It is, of course, possible to connect the commutator motor to the main motor through some form of gearing, but such arrangements should be avoided if possible.

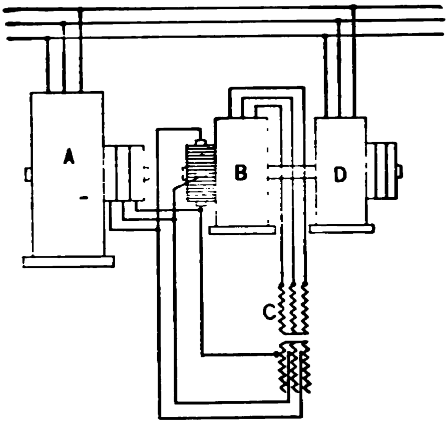

Fig. 4

The well-known system shown in Fig. 4 presents advantages in this respect. In this figure the commutator motor *B* is not connected to the main motor *A* mechanically, but is coupled to an induction machine *D* which is connected to the line. This makes it possible to build the auxiliary machines for the most desirable speed, from a designing standpoint. The energy from the rotor circuit is not transmitted to the shaft of the main motor, but is transmitted through the auxiliary machines and is returned to the line in the form of electrical energy, and consequently this arrangement is better adapted for cases where constant torque is required. The commutator motors of such regulating sets are nearly always provided with a compensating winding on the stator which counteracts the rotor field and makes it possible to regulate the speed by varying the magnetizing current. Consequently, the regulating transformer C and the necessary controller can be smaller. It would be possible to avoid the use of a regulating transformer altogether if the commutator machine were provided with an auto-transformer winding, which has been done in a number of cases with the system first described.

The power factor compensation with this system is obtained by a special phase combination some what different from that used with the arrangement previously described, but such an arrangement provides correct compensation for only one definite speed and load, which are chosen so as to approximate, as closely as possible, the average working conditions.

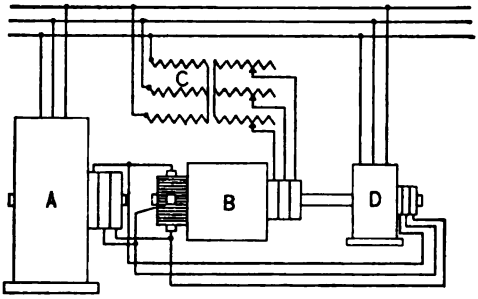

FIG. 5

In the system just described the commutator machine has been in some cases furnished with a series pole for obtaining the characteristics of a compound motor, which is an advantage, for instance, if this arrangement is used in conjunction with the motor driving a rolling mill requiring a drooping speed characteristic to enable the flywheel to take the proper proportion of the load.

The principal disadvantage of this system is that it requires two auxiliary machines to obtain regulation and it will be shown later that it is possible with suitable arrangements to avoid this feature.

In Fig. 5 is shown diagrammatically a system that has been used to some extent in Europe and which has been mentioned in the discussion of G. A. Maier's paper before this Institute. In this arrangement the second auxiliary machine D is a small motor which drives the frequency changer B and only has to overcome the mechanical losses. The commutator machine B consists of a wound rotor which has on one side a commutator and on the other, slip rings. On the stator there is only an auxiliary winding for improving the commutation of the machine. This machine cannot develop any torque and it is, therefore, necessary to use the small driving machine D to rotate it relatively in synchronism with the main motor. The regulating transformer C must in this case be designed for the whole of the rotor energy, which flows through the frequency changer and the transformer to the line. In the frequency changer the copper losses are comparable with those of a synchronous converter and are consequently very small.

With this system, as it has been pointed out, it is necessary for the frequency changer to run relatively in synchronism with the main motor, and consequently if the number of poles of the auxiliary machine D and the main motor were the same, which, however, is generally not the case, both would have to run at exactly the same speed. The rotor connections between the motor A and the auxiliary driving motor D insure that the machines remain relatively in synchronism and any slight difference will cause the exchange of synchronizing energy in the same way as with synchronous machines. The power factor of this system is fairly good on account of the favorable distribution of the magnetizing current, but it is not possible to obtain regulation. The advantage of this system over the arrangement previously described is that it is possible to supply energy to the rotor circuit so as to regulate above synchronous speed. With the previously described arrangements it is extremely difficult to cause the main motor to pass through synchronism. As it is possible to divide the regulating range above and below synchronous speeds of the main motor, the auxiliary machine need only be designed for half the capacity that would be necessary if the whole of the regulation was done below synchronism. This arrangement presents certain advantages when a higher speed than normal is occasionally required; for instance, in the case of blowers, where a higher pressure than normal may be required for a short period, the motor being run above synchronism when this necessary. To make it possible to obtain a definite speed variation between no-load and full load a compounding transformer has been used which gives such a characteristic.

Suggestions have been made for the simplification of this system by modifying the frequency changer, but they introduce undesirable characteristics such as poor power factor. The power factor might be sometimes improved by such arrangements as brush moving or phase combinations, but in such modified arrangements, the range of regulation required is greater than is necessary with the types of machines previously described, and consequently, it is more difficult to obtain a phase combination or to set the brushes in such a position as to obtain an average power factor that will be satisfactory under operating conditions. It is possible to simplify the arrangement somewhat by coupling the frequency changer to the main motor, which obviates the use of the auxiliary driving machine, or the frequency changer may be geared to the main motor so as to obtain favorable construction speed, and as the power to be transmitted is trifling, the gearing can be of small dimensions. If the gearing is so arranged as to make it possible to change the relative rotor position of the motor and the frequency changer, power factor regulation can be obtained, and it is also possible to use a phase and voltage regulator for the same purpose. Such arrangements for connecting the two machines together are not very desirable and although possible, should be avoided.

From what has already been described it will be seen that there are many desirable features not covered by the systems hitherto in use, and it is, therefore, not astonishing that even recently arrangements have been used by which the rotor energy is converted into direct current and then to alternating current and returned to the line. For American conditions where 25 cycles is standard for heavy power work, such a system presents many disadvantages, not only on account of constructive difficulties, but also on account of the high cost compared with other arrangements, although it has the advantage of using machines that are familiar to the attendants.

Although it is not possible in this paper to discuss all of the improvements that have been made, some of the latest developments may be described. It is not proposed to discuss the theoretical features of the various machines and systems, as these will be given in another publication. The arrangement shown in Fig. 6 is one that is particularly suitable for rolling mill and mining applications and it will be seen that it is very simple. There is only a single auxiliary machine, the frequency changer *B*, which has a simple three-phase winding on the stator which need only be designed for a comparatively small current and which is connected to a small regulating resistance. In addition, an auxiliary winding is provided to improve the commutation. As in addition to this regulating resistance there is also provided the regulating transformer *C*, it is possible to regulate the whole system in two ways, which are necessary to control independently the power factor and the speed. The operation of this system can be understood from the following: Let us suppose the motor *A* is started as an ordinary induction motor, with rotor resistance, and the connection to the frequency changer being open. The frequency changer may be also started as follows: Rotor *R* of the frequency changer *B* is supplied through the regulating transformer *C* with voltage to correspond to the desired voltage on the rotor of the main motor, and the stator winding of the frequency changer *B S*, which in this case is the secondary, is regulated by the resistance *D* until it runs relatively in synchronism with the main motor *A*. If, for instance, both the main motor and the auxiliary machine have the same number of poles, which, however, is generally not the case, then both machines must run at exactly the same speed. As for example, if the voltage of the rotor of the main motor at standstill is 200 volts, and the speed is to be regulated to half the normal, the rotor voltage will be 100 volts, which must also be the case of the voltage on the commutator and

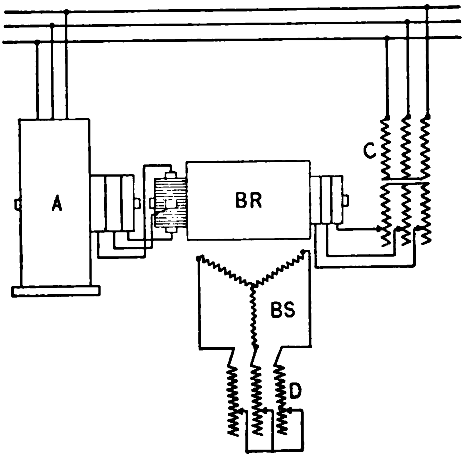

FIG. 6

slip rings of the frequency changer. If the ratio of the secondary and primary windings of the frequency changer is 1 to 1 then the voltage across the stator winding of the frequency changer must be regulated for 50 volts. The frequency of the induction motor rotor circuit is the same as that on the commutator and the stator of the frequency changer. By means of synchronizing lamps between the commutator of the frequency changer and the slip rings of the main motor, the two machines can be synchronized. If the starting resistance of the main motor is disconnected, the rotor energy will flow through the frequency changer and the regulating transformer to the line. The current in the stator of the frequency changer can be comparatively small, as the field generated by the current flowing through the commutator is counteracted by the current flowing to the transformer through the slip rings, with the exception of that necessary for the magnetizing of the working field, which is only sufficient to give enough torque to enable the machine to run at the proper speed. The method mentioned for synchronizing the frequency changer and the main motor is in practise unnecessary and is only used to illustrate the process.

An interesting question is what happens when the stator winding only is regulated by means of the resistance *D*, or only the transformer is regulated. It has been held that under such conditions stability of operation is questionable. The whole question of relative synchronous operation in general is interesting and difficult to solve, which occasionally has led to a misunderstanding of the whole problem, as for instance in the newly published book of Arnold* on single-phase and three-phase commutator motors. Practical results, however, have settled all doubts on this question and have confirmed the theoretical foundations for this system. The theory shows that by such regulation, power factor compensation of the whole power circuit is possible as far as may be desirable. If, for example, the resistance *D* is decreased without changing the regulation of the transformer *C*, the frequency changer has a tendency to run faster, but this is impossible on account of its connection to the main motor, and the only result is that an equalizing current will flow between the two rotors, therefore, causing a synchronizing force. It is consequently the case that by suitable regulation of this current, the power factor to the whole system can be set at any desired value. This result can be somewhat explained by

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*Volume 5-A, "Wechelstromtechnik."

means of the vector diagram in Fig. 7. The uncompensated induction motor with resistance regulation will take the current I' which will be behind the voltage E. In operation with the auxiliary machine, there flows the current I_a in the stator of the motor which leads the voltage E and at the transformer we have the current I_b which lags very much behind the voltage component. The resultant of both these currents gives the current I, which is more or less in the direction of the vector E and consequently the power factor can be brought to the desired value. As a diagram of the internal action of the commutator machine would show, the regulating transformer supplies a strong wattless component of the current I_b which produces the field of the auxiliary machine and also that of the induction motor. However, by the regulation of the stator winding of the frequency changer a greater wattless component is produced than is necessary for the production of these fields and this has the effect that the main motor current can be made leading so that the resulting current comes into the right phase relation. It should be kept in mind that, although at the transformer there is an increase in the magnetizing current, there is not a corresponding decrease in the induction motor. If we assume a ratio of 1 to 1 between rotor and stator in the induction motor, there will be the same leading component in the primary as there is a surplus lagging component in the secondary, which is independent of the voltages of the rotor and stator, and also of the speed. It is questionable whether it is advisable to compensate for the power factor of other machines on the line by such methods, but if this is done, it will have practically no effect on

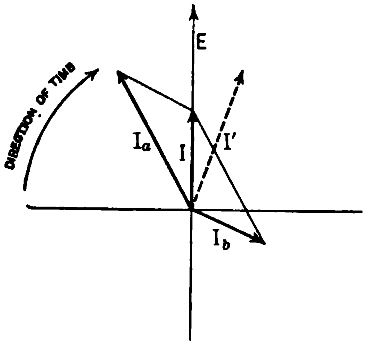


FIG. 7

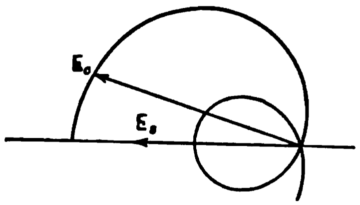


FIG. 8

the stability of the machines, as good machines are capable of standing two or three times the normal torque, and oscillation between the machines seldom occurs, even if no particular efforts are made to avoid it. The main motor and the regulating machine operate only relatively in synchronism and not in synchronism with the line.

The speed of the sets varies somewhat when the power factor is regulated, being caused by the fact that the voltage drop in the machines varies somewhat when the wattless current is changed. In a simple case, with constant torque on the motor and other conditions remaining unchanged, we obtain from a detailed investigation of the characteristics, the curve shown in Fig. 8, which shows the variation of the commutator voltage E_c in comparison with the assumed constant slip ring voltage E_s. This variation is the reason why the speed changes somewhat when the power factor is regulated. When there is an improvement in the power factor, the speed increases. If the load is varied, we also have variation in the speed of the set which decreases as the load increases, and this characteristic can be taken advantage of in case of motors driving rolling mills to enable the flywheel to take its proper proportion of the load. The drop in speed is naturally dependent upon the resistance and self-induction of the frequency changer, leaving out of the question the characteristics of the main motor, and if the set is regulated for a certain speed, the speed characteristic is similar to that of a shunt motor. It should be noted that on account of the interaction of the machines, even if the frequency changer were non-inductive, it would be possible to obtain satisfactory operation, which is an important difference from the characteristics of synchronous machines. Even with such a condition, it would still be possible to compensate for power factor, but in view of the fact that it is desired to obtain a good power factor, as constant as possible without regulation over a wide range of load, it is desirable to have some induction in the rotor circuit. By varying the self-induction in the rotor circuit, it is possible to change the speed characteristics from no-load to full load and this may be done without interfering with the capacity of the machine to regulate the power factor. If variations in the power factor are permissible, it is possible to obtain a very fine speed regulation by regulating it, and consequently the regulating transformer need not have so many steps. The inner part of the voltage curve, Fig. 8, corresponds to the operation of the set above synchronism, and as is clear from theoretical consideration of the effect of regulating the machine, the speed must eventually rise above synchronism, although with the constant voltage E_s there would be heavy current flowing at the synchronous speed. It is a very interesting question as to how it is possible to obtain such a curve practically; as also is the whole subject of operation above synchronous speed. It might be mentioned in this connection that by means of phase transposition, the frequency changer can run as much below synchronism as the main rotor is to run above synchronism. The necessity for the transposition of the phases can be avoided by modifying the system somewhat, and the whole operation ofthe set at and above synchronous speed can be improved by such modification, but this point cannot be discussed at the present time. The system that has just been described is very simple on account of the fact that we have only a single regulating machine instead of a number of machines, and it is easily regulated as it is only necessary to regulate the transformer in any way that may be convenient, or an induction regulator might be used which would avoid handling the regulating current altogether. On account of the fact that the current in the stator is very small and need not be regulated in fine steps there is no difficulty whatever in controlling this circuit.

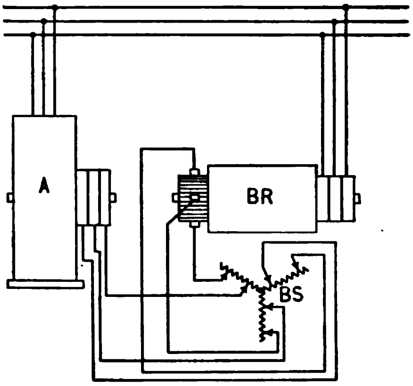


FIG. 9

It is possible to avoid the use of the regulating transformer in the case of low-voltage circuits as shown in Fig. 9. In this case, we have also the main motor *A* and the frequency changer *B* with the rotor *R* and the stator *S*. The stator is provided with an auto-transformer winding and the function of the regulating transformer is combined in the machine. It will be seen, however, that the stator winding can be regulated in two ways, and this makes it possible to regulate both speed and power factor as in the system previously described. If we suppose the frequency changer is running relatively in synchronism with the main motor and also has the right voltage, the two machines can be connected together. If the stator is now regulated in such a way that the transformer ratio remains the same, but at the same time, the absolute number of active turns is varied and consequently the field, the wattless current will change and the power factor can be regulated. The whole of the regulation can be taken care of by a single controller which can be very simple, as it is unnecessary to regulate the power factor in fine steps. All of the characteristics required of the motors driving the mills or machines can be readily met by interlocking the various elements of the controller. This arrangement does not require any changes in the windings of the machines, nor is it necessary to move the brushes, or to have any variable gearing between the main motor and the auxiliary machine to obtain power factor regulation. The auxiliary machine combines in itself all of the regulating requirements and is, therefore,

Voltage regulator,
Frequency changer,
Power factor regulator,
Motor for driving itself.

By various arrangements it is possible to obtain entirely satisfactory operation above synchronism, and in fact, it is just as easy to operate above synchronism as below and the passing through synchronous speed of the main motor does not present any particular difficulties.

When it is necessary to work near or at synchronism it is far better, however, to use such an arrangement as is shown in Fig. 10, although it is possible in the system just described to obtain a working field and the possibility of regulating at the synchronous speed. The system shown by Fig. 10 provides for an almost constant working field under all conditions. The system shown in Fig. 9 is more suitable for regulating the speed in fairly large steps, and when the motor is running at such a speed as not to require the use of the auxiliary machine it can be disconnected and used for regulating the power factor of the line. The arrangement shown in Fig. 10, on the other hand, is more suitable for regulation in fine steps near the synchronous speed, but the auxiliary machine is somewhat more expensive. This system is desirable where speed regulation is required, where the size of machine does not determine the type, but other technical reasons make it desirable to use such a regulating system. This is, for instance, the case with turbo-compressors or blowers, which generally run at very high speeds, and even with comparatively small equipments it would be impossible to use any type of commutator machine directly. Consequently it is necessary to use an induction motor, and to obtain necessary speed regulation by some such system as has been described. The characteristics of blowers and compressors are such that only comparatively small speed changes are required to cause a considerable difference in the output, as the power varies practically as the cube of the speed. The regulation of the system shown in Fig. 10 is obtained in a way similar to that described in the previous system, and to obtain operation above synchronous speed it is possible to use a continuation of the phase winding through the star of the stator. A further development of the three-phase commutator machine for the purpose of obtaining motors for main drives as well as for regulating induction motors, however, makes it possible to avoid the use of such an unsymmetrical phase arrangement.

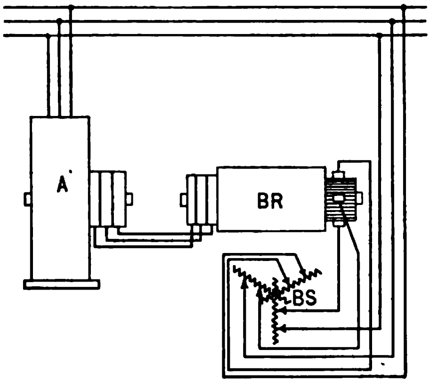


FIG. 10

It is sometimes the case that the requirements of such systems are severe and that high momentary overloads or severe overloads for a comparatively short time must be carried, such as, for instance, in the case of rolling mills, blowers, compressors, etc. These characteristics can be obtained with such a combination, either at starting or at high speeds, under or above synchronism. In some cases it would be advantageous if the frequency changer could be used as a motor, at the same time retaining the function of the frequency changer, which would give a good combination for running above or below synchronism. Such an arrangement would present a number of advantages in some cases, but is only possible if the auxiliary machine is mechanically connected in some way with the main motor. It may be also desirable to use a mechanical connection on account of the quickness of the speed variation required. To obtain such characteristics and to keep the advantages already mentioned, new arrangements are necessary, and it might be mentioned that such a system has been already worked out, but it cannot be described at present.

Three-Phase Commutator Motors

Operating difficulties exist when a very large speed range is required when the speed is reduced practically to zero, and in such a case a regulating auxiliary machine presents no advantages, as it would have to be designed for practically the same capacity as the main motor. In such a case the commutator motor can be used for direct drive except when it is necessary to regulate the speed very much above synchronism, when it may be desirable on account of the commutator speed to use an induction motor and to operate the regulating commutator machine correspondingly below synchronism. In the case of drives of small power, the commutator motor used directly is quite satisfactory, but even in the case of motors of large capacity, there is no particular constructive difficulty in the way so long as care is taken to provide good commutating fields and such devices as brush moving are avoided. Some method of providing a good commutating field is, however, necessary, as, for instance, with an eight-pole motor designed without commutating poles or other means of helping commutation, for 50 cycles, the limit of construction is about 150 to 200 h.p. In the United States the conditions in the steel plants are favorable for such machines on account of the almost universal adoption of 25 cycles. Until recently only one type of such machine with shunt characteristics was in use in Europe. This type has at present such characteristics that the voltage for the rotor is supplied by an auto-transformer winding from the stator with a special phase combination or an arrangement with auxiliary phases. This design makes it possible to obtain power factor compensation for one particular load and speed which is chosen so as to approximate the average operating conditions. To give power factor correction over a wide range of load and speed when this is desirable, such a system becomes so complicated as to be impracticable. In the following there is described a system which avoids all of these phase combinations and auxiliary phases as well as fixed phase relations at all, and also the necessity of brush moving. This machine is constructed not only with a rotor similar to that of a direct-current machine, but also with a field of the same type, which enables the speed, power factor and starting torque to be regulated. It should be noted that the machine with such a winding usually prevents the formation of excessive disturbing fields for the commutation. The newer developments of the winding have made it possible to regulate, even over a very large range, without introducing disturbing fields. Such machines have, however, in every case, a simple continuous winding without auxiliary phases. The diagram shown in Fig. 11 illustrates the principles involved for all cases, as far as regulation is concerned. This diagram

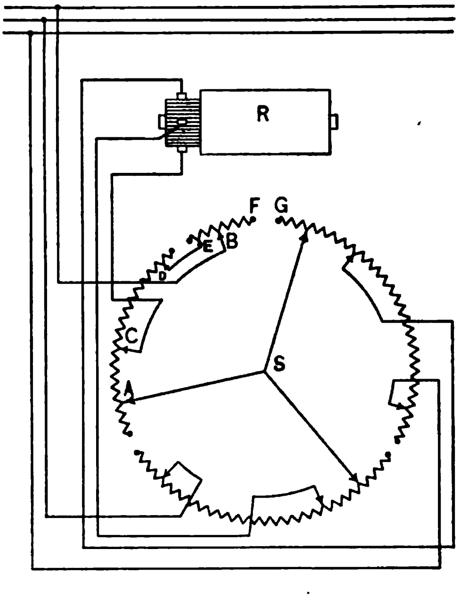


FIG. 11

shows most of the possible variations, but it is necessary when designing such machines to determine how far the different possibilities can be taken advantage of. The same results as shown in the vector diagram, Fig. 7, are here obtained by the use of a single machine giving the phase regulation. From Fig. 11 it will be seen that it is possible to obtain the phase regulation by shifting the connections, and at the same time to vary the field and the voltage, or in other words, this arrangement allows of a direct regulation of the vectors. For this purpose the stator winding has a number of divisions as shown by the spaces *D E* and *F G*. How many divisions are necessary in the stator winding is a question which depends upon the amount of copper in the winding. In any case, however, there must be at least three in these phase segments, which it will be understood can be displaced if required. From this diagram it can be seen that it is possible to shift the field and at the same time to vary its strength. The line voltage is applied between *B* and *A*. On the segment *A B* the voltage vector for the rotor can be set between *A C*. It will be, of course, understood that the rotor circuit can also be supplied from a special winding which is independent of the main winding. This circuit need only be designed to carry the regulating power, which arrangement is particularly advantageous when the machine is designed for higher voltages. In this way, we obtain another possibility of varying the vector displacements which can be partly substituted for the other vector regulation. The whole question of such winding combinations, which is connected with the question of the maintenance of the field form, and the reduction of the current to be handled by the controlling devices, as well as the type of winding, is too complicated to be discussed in this paper. The speed of the motor can be varied, for instance, either by varying the position of the point *B*, thereby changing the field, or by varying the position of the point *C* which changes the rotor voltage, and in either case the phase connection *A* can be so regulated as to give good power factor. This system has the advantage that the necessary commutating field can be supplied directly in the correct phase relation on the stator winding by proper connections. Fig. 12 shows how this same arrangement can be used for a motor with series characteristics. This diagram shows the phase connections *A* and *B* and the division points *C D*, *E F*, etc., and it is believed that no further explanation is necessary. In this paper, which describes some of the latest developments in this class of work and only mentions the well-known other systems for the sake of comparison, we have avoided, altogether, any reference to the names of the various arrangements and also to the historical development, but it is generally known that the series three-phase motor is very old. As originally built it had the disadvantage that the speed could only be regulated by shifting the brushes, which caused the machine to operate with very poor power factor. The newly developed machines with brush-shifting arrangements also have the same disadvantage even when the operating characteristics are favorable. Such an arrangement also has the disadvantage of high cost on account of the lack of a good commutating field. If in addition to shifting the brushes the number of turns on the stator is also regulated, the whole machine becomes very complicated. The arrangement shown in Fig. 12 offers a better solution of the problem, as it avoids these disadvantages and presents a number of other desirable features. The combination of the series and shunt systems gives the characteristics of a compound-wound motor, which is of special importance where it is necessary to use a fly-wheel.

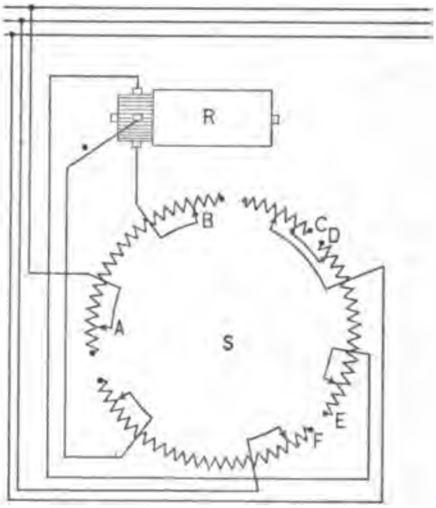


FIG. 12

The combination of such an arrangement with the regulating sets previously described gives a series of possibilities that can be obtained with standard construction of commutator machine which may at times be useful. Further discussion of such special applications, as for instance, arrangements to avoid the use of the expensive and rather inefficient flywheel motor-generator sets, must be left for another occasion.

The various arrangements involving the use of three-phase commutator machines make possible the efficient regulation of induction motors, but they introduce a new problem in the use of the commutator machine itself. The results obtained in Europe, where the class of attendants is usually very much better than here, have been very favorable, but under American conditions any attempt to simply follow European practise would probably give disastrous results. As it has been pointed out, considerable care must be exercised in the first installations, and we may expect difficulties which can only be overcome by a sympathetic cooperation between the user and the manufacturer. The use of a regulating machine in conjunction with an induction motor offers many advantages over the direct use of the commutator motor when the speed range is not large, not the least being the comparatively low frequency of the rotor circuit. The extensive use of this type of machine may be looked for in the future, but in any case, to insure success careful application is absolutely necessary.

DISCUSSION ON "POWER REQUIREMENTS OF ROLLING MILLS" (SYKES), AND "THE ECONOMICAL SPEED CONTROL OF ALTERNATING-CURRENT MOTORS DRIVING ROLLING MILLS" (MEYER AND SYKES), NEW YORK, NOVEMBER 8, 1912.

John M. Hipple: The general tendency in industrial engineering is towards refinement in methods and apparatus. Only an exact knowledge of those requirements enables us to meet them successfully. The steel industry is a notable example of this condition. The making of steel requires high-power substantial machinery, the first demand on the machinery being continuity of service.

When the application of electricity to steel mills was first taken up, the first motor that was available which the steel mill engineer thought by any chance would do the work, was put in service. If it broke down, a larger one was put in service, and this was continued, until a motor was secured which would stand up to the service. The same was true of control apparatus. The tendency was for many years, after reaching that point, to duplicate that application, unless the new application required more power, in which case a larger motor was used. More experience and more exacting requirements have indicated the necessity for investigations such as the one which has been undertaken and reported upon in Mr. Sykes's paper.

Such investigations are sure to advance the cause of industrial electrical engineering, and, further, to increase the economy of production, and these are the things that the members of the Institute who are interested in industrial engineering are particularly anxious to see forwarded.

J. H. Wilson: In looking over this paper by Mr. Sykes, I feel that considerable credit is due the author for the clear and comprehensive manner in which he has subdivided and explained the various elements entering into the determination of the amount of power required to roll steel in its various forms and shapes. Concerning this part of the paper there is not much to be added of a general nature. The only thing that might be added would be more complete data concerning some actual installations.

Referring to the paragraph under the heading "Practical Determination of Motor Size," in this paragraph Mr. Sykes fails to bring out clearly the fact that the utilization of flywheel energy is more or less of a necessary evil. The use of a flywheel is made necessary in most cases, by considerations external to the motor equipment, such as the supply of electrical energy or the arrangement of the mill drive. For example, a sheet mill with rope drive between the motor and mill must necessarily have flywheel effect on the mill side of the ropes, as the power required for rolling varies so greatly that with the flywheel on the motor side the ropes would jump, run unevenly and be subjected to such variations in pull as to increase materially the maintenance cost. The necessary flywheel effect is usually obtained from the large rope sheave wheel.

The following facts should be noted:

First.—In order to obtain energy from a flywheel we must permit the slowing down of the equipment. This means the adding of external resistance to the rotor of the induction motor, which in turn results in decreasing the efficiency of the motor at heavy loads where efficiency is most important from a power consumption point of view.

Second.—The slowing down of the flywheel in turn slows down the rolls and decreases the amount of material which can pass through them in a given time.

Third.—Additional power is required, due to the friction load caused by the flywheel. This power becomes of considerable importance, as it must be expended all the time, when the mill is running idle as well as when rolling steel.

Fourth.—The use of a flywheel adds expense, due to the necessity of maintaining large heavy bearings, keeping them properly lubricated and in good mechanical condition.

The load diagram, Fig. 11 of this paper, is fairly ideal for the use of flywheel equipment. The passes are of short duration and the interval between passes is sufficiently long to allow the motor to re-accelerate the flywheel from a very low speed to nearly synchronism.

In an installation such as this the additional first cost of a larger motor would probably offset the savings which would result from the elimination of the items shown above as being objectionable in the case of flywheels. In case, however, we consider a load curve in which the average load is, say, twice the average load shown in this curve and the peaks remain the same as shown on this curve, the flywheel would probably not be warranted, this heavier average load being assumed to have resulted from a decrease in the interval between passes.

The above argument is based entirely on a consideration of the power conditions at the mill. If, however, other conditions, such as power station capacity and arrangement of the mill drive, are allowed to enter into this matter the question assumes an altogether different aspect. Assuming that the power supply for a rolling mill is of sufficient size so that the maximum fluctuation obtainable from one driving motor or the accumulated fluctuation from a number of driving motors is small as compared to the total station load, then these questions of economies in operation are of first importance. In other words, these economies might well be sufficient to cover the increase of a motor size as much as 50 per cent, which increase would not affect the efficiency at light load but would greatly benefit from the elimination of flywheel expenses. On the other hand, if the power station is comparatively small and an individual motor is large in comparison to the total average load, then flywheels and automatic regulators are necessary, as the economies referred to could not possibly offset the additional cost due to the operation of the power station under the extreme variations of load which would be met with. These economies could not, of course, offset additional cost which would result from the operation of power station machinery below its normal capacity, as the efficiency of the generators and driving units would be of considerable importance.

The equipment of individual mills determines the power station load curve and the flywheel is more often made necessary on account of the fluctuation here than on account of the power requirements of the individual mill.

The electrolytic regulator referred to by Mr. Sykes makes the use of flywheels more economical than does any other type of induction motor regulator with which I am familiar. This regulator permits the operation of the motor and flywheel at the highest possible average speed and will cause the motor to re-accelerate the flywheel much more quickly than will any resistance stepping device on the market.

This question of motor and flywheel sizes is one which presents different phases in each installation and necessarily must be figured to meet local conditions.

Selby Haar: All engineers who are called upon to become familiar with the power requirements of rolling mills will owe their thanks to Mr. Sykes, because he has collected facts which heretofore have been scattered in a great many places. As long as the known laws of the subject are largely empirical, the collection of data for generalization will be restricted to the few who are able to conduct the very expensive and extraordinarily difficult tests. As an instance of the meagerness of our knowledge, it may be pointed out that practically all the available data relate to iron and steel.

Mechanical engineers interested in roll driving contented themselves generally with measuring the fuel and water consumption of the engines, so that the electrical engineer entering the field was compelled to exercise imagination as well as judgment in recommending motors. Even in the present state of our knowledge, it is still advisable to make a minute study of local conditions before recommending a motor equipment, because the steady operation of the motor frequently increases the output of a mill beyond all expectation; and an electric motor does not, like a steam engine, deliver its maximum capacity continuously without injurious heating. As soon as electric motors began to displace steam engines, however, precise testing began; a German manufacturing firm collected a complete set of measuring instruments for this purpose alone, with which a committee of the Society of German Foundrymen (Verein deutscher Eisenhuettenleute) conducted the extensive series of tests which is the nucleus of the published data.

It was fortunate for the testing engineer that reversing mills were among the first to be electrified, because direct-current motors were used, which simplified the design of graphic meters. Even with the present refined testing apparatus, however, it is not clear why there should be such a difference in the nature of the results obtained by different experienced engineers, such as, for example, results published in *Stahl und Eisen*, June 9, 1909, and *Iron Age*, January 4, 1912. Both sets of tests show a fluctuating torque for a constant reduction of the thickness of a piece during a pass, which is contrary to the usual assumption.

In the construction of load diagrams for mill cycles, I have found it easier to deal with the elongation of the piece rather than the actual volume of metal displaced as has been done by Mr. Sykes in Table I of his paper, because this method lends itself readily to wide changes in ingot or billet sizes, and also fits in well with the working range of the slide rule.

In regard to the automatic regulation of resistance mentioned on page 2064, it should not be overlooked that a regulator which can perform its function during passes, the duration of which is a few tenths of a second, must be exceedingly rapid.

In conclusion, however, I wish to express my thanks to Mr. Sykes for the preparation of this paper, which must have entailed a large amount of work; and it is to be hoped that it will stimulate the publishing of more data on this important subject.

Edward J. Cheney: With the application of electric motors to main roll trains there has arisen the necessity of determining with as much accuracy as possible the power requirements for rolling steel. With engine drives the size of the engine was rarely, if ever, calculated, but was determined almost solely from judgment and experience. If it was known that a certain mill was running satisfactorily with a certain size of engine, and a similar mill was to be installed, the same size engine would probably be used, or, perhaps, a trifle larger for safety. The result of these methods is that most rolling mill engines are too large and very few are of the proper size. It is not an uncommon sight to see engines running which take steam for only one or two strokes at occasional intervals.

Mistakes in engine size are not attended with serious results except as regards efficiency and possible handicaps on production. If the engine is too small the mill stalls. The rollers then judge that the capacity of the mill has been reached and ease up on the work. Most engines have heavy flywheels which will carry them over the peak loads and, with steam-driven mills, speed variations are tolerated which would not be considered with motor drive.

In determining the size of motors, such haphazard methods are not, or should not be, used. If the motor is too large a low power factor results, to say nothing of lower efficiency and increased first cost. It should be noted that the latter items apply equally well to engines, but are not so much considered in their case because the error in capacity is not so easily noticed.

If the motor is too small the mill will not stop and so compel mercy from the rollers, but the over-willing motor will continue to turn the rolls until it overheats, and perhaps burns out and is cursed for being inadequate.

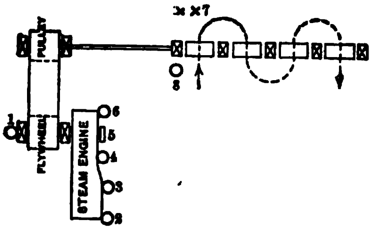
This quality of the electric motor, which causes it to take enormous overloads without any appreciable change in speed, has resulted in a large increase in production in nearly every instance where mills have been changed over from steam to electric drive, merely because the rollers are then enabled to crowd the material through, absolutely regardless of the driving motor. For this reason engine tests must always be used with caution as a basis for determining motor sizes.

The electrical engineer must have at hand all of the information possible and needs much more than is now available. Mr. Sykes has well pointed out the difficulties which are encountered in this work, probably the greatest one of which is the ignorance of what any mill will ultimately be called upon to do. Considerable progress has been made in determining the power actually required for rolling under various conditions, and, particularly in the case of mills used simply for reductions in section without much distortion of shape, fairly reliable data are available. This includes blooming, billet, slabbing, and plate mills, and mills for rolling simple shapes, such as rods and bars. It is on merchant mills that the greatest uncertainty exists. Here a great part of the work is used not in elongating the piece, but for distorting its shape, or is consumed in friction, as shown by the author. For such mills there is no reliable information except from actual tests under the exact conditions. This is a laborious task but apparently a necessary one. Much has already been done, enough to afford approximately correct information for most conditions, but much more remains to be done before complete data are obtained for all cases.

While not strictly pertaining to this subject, it may be remarked in this connection that the ease with which power is measured in the case of electrically driven mills is really one of the greatest advantages which they possess. This fact not only makes possible the accurate determination of power for future installations, but is a constant check and guide to rolling methods in the mills already equipped. With engine drive little attention is paid to the setting of valves or the condition of the rolls, because there is no direct way of determining the power consumption. But with electric drive the indicating wattmeter faithfully points out and the watt-hour meter relentlessly records the power input to the motor, and the influence of various factors is readily seen. The mill superintendent soon learns to watch the meter. He knows what has been the record for any section and any increase in power over that record causes an immediate investigation to determine the cause. This stimulates activity in searching for further possibilities of reduction. Instances have been known where over 25 per cent saving in power has been accomplished by slight modifications in roll shapes without in any way affecting the quality of the product.

Bayse N. Westcott: I was very much interested in Mr. Sykes's paper, because I have encountered the same troubles in testing that he has. Mr. Sykes mentioned the difficulties in getting accurate speed measurements on mills. With an induction motor of the slip ring type, you can get very accurate speed measurements, because the slip of the motor with a given resistance in the secondary is, within reasonable limits, inversely proportional to the input, so that if you know the characteristics of the motor, or if you can make an experimental determination, all that is necessary is to record the input with a sufficiently sensitive curve-drawing wattmeter and you can determine the speed of the motor at any instant from the record of kilowatts input.

Mr. Sykes did not say anything about steam-engine-driven mills. They are the most difficult mills to test and also very important, because it is the present steam-driven mills which are largely being electrified and which mean business to the electrical manufacturer.



1—Liquid tachometer and contact maker.
2 and 3—Continuous steam-engine indicators.
4—Reducing motion
5—Stroke counter.
6—Recording instrument
7—Mill observers.
8—Electric gong.

FIG. 1

In steam-driven mills, one of the first essentials is to secure a good record of the horse power developed by the driving engine while the steel is being rolled, and the best way to do this is to use a continuous drum steam engine indicator. This differs from the ordinary steam engine indicator in that the paper on which the indicator card is made is a long strip, which is reeled inside the drum and feeds around the drum a quarter of an inch (6.35 mm.) at each stroke of the engine. Fig. 1 shows the general layout used in testing steam-driven mills.

Fig. 2 shows details of recording instruments for speed, time and general information regarding work in the mill. These have pens actuated by magnets, which mark on a strip of paper which is moved at a uniform rate beneath the pens by a spring motor. In most cases three pens are used, marked *A*, *B* and *C* in the figure. *A* is actuated by a contact maker, which is driven from the engine shaft or other convenient place so as to complete the circuit of magnet *A* several times for each revolution of the engine. The number of contacts per revolution depends on whether the engine is of high or low speed. Pen *B* is controlled by a contact-making clock, which is regulated to close the circuit of *B* once in every five seconds, or at shorter intervals if preferred. In addition to actuating *B*, the contact-making clock also closes the circuit of an electric bell, or in some cases, that of an electrically operated whistle. The third pen *C* is controlled by a manually operated key located at the rolls.

In addition to the foregoing, a liquid tachometer, consisting of a small centrifugal pump which raises a column of colored alcohol to a height depending on the speed at which the pump is driven, is used to indicate speed variations of the engine. A stroke counter is connected to the engine to record strokes and furnish a check on the graphic instrument.

The equipment described will secure an accurate record of the power that is furnished the mill.

Speaking of graphic meters, Mr. Sykes said that in using the graphic meter the pen should not touch the paper. We used successfully a high-speed graphic meter, with a pen which used ink, and which did rest on the paper. We used a paper speed of about 30 in. (76 cm.) per min., which is only half the speed used by Mr. Sykes, which was one in. per sec., or 60 in. (152 cm.) per min. I suppose the paper in the tests referred to by Mr. Sykes was driven by an electric motor. On our graphic meters we had spring motors, which, of course, are not as good as an electric motor drive for the paper.

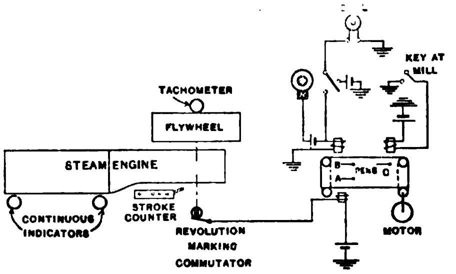


FIG. 2

The chief thing about instruments for use in steel mill testing, especially in commercial testing, is that they must be reliable. They must be hardy, as they have to be shipped around the country by express to various mills and they are liable to rough treatment.

David M. Petty: I would ask Mr. Sykes if he has any figures which show the relative kilowatt-hours necessary, for a given reduction, with a fast or slow rate of displacement. I refer to the paragraph in his paper headed "Rate of Displacement."

Fred Bickford Crosby: Messrs. Meyer and Sykes have presented for our consideration a problem of especial interest to every engineer concerned with the application of mechanical power. In the manufacture of steel the introduction of the direct-current motor brought about revolutionary changes in established methods. With the advent of the polyphase induction motor the superior advantages of alternating current were quickly seized upon, particularly where power in large quantities must be distributed over a considerable area. Today, even for the largest drives where only a single constant speed is required, the high efficiency and substantial simplicity of the induction motor leaves it practically without a competitor in new installations. With all its good qualities, however, the induction motor for certain classes of service possesses two undesirable characteristics—power factor and inability to secure adjustable speed regulation.

Multispeed induction motors with changeable pole connection to give a 2 : 1 speed ratio or with separate independent windings to give some third speed, have in many instances proved a satisfactory compromise for adjustable speed control. The efficiency of such a machine may be fairly high for each of the several synchronous speeds, but the power factor is invariably poor at the lower speeds. With rheostatic control the power factor is reasonably high at all speeds, but, since with constant h.p. output the slip energy dissipated is directly proportional to the reduction in speed, the low efficiency encountered renders continuous operation at reduced speeds prohibitive. Furthermore, the induction motor with rheostatic control has an unfortunate tendency to accelerate automatically as the load falls off. Direct or differential concatenation of two single motors or of a multiple-wound induction motor has been employed to secure as many as six independent synchronous speeds for a single set, but only at a heavy sacrifice in simplicity and other desirable features.

Until recently it has been practically necessary to resort to direct-current motors to obtain strictly adjustable speeds, that is, several independent speeds, each constant under variable loads.

Recently there has been a steadily increasing demand for an adjustable-speed alternating-current motor. In recognition of this demand the company with which the writer is connected has for nearly two years been carrying on a series of very thorough investigations, both theoretical and experimental, to determine which of the numerous schemes suggested for obtaining shunt speed characteristics is commercially feasible. The company is now prepared to furnish speed-regulating sets for use with standard phase wound induction motors. The form which these sets will take depends very largely upon the requirements of the installation in question. Of all the schemes suggested two have successfully withstood the test of actual installation. Either of these methods will give a uniformly high efficiency and, if desired, unity power factor throughout the speed range for which the set is designed. In general, power factor correction above 95 per cent is not recommended, since the higher percentage correction is obtained at an expense wholly disproportionate to the benefits resulting.

The first of the two methods advocated employs a compensated commutator motor which transforms the slip energy of the main motor into mechanical energy and drives a high-speed induction motor connected to the supply main, slightly above synchronism, thus causing it to operate as an induction generator and return electrical energy to the system. This scheme has proved especially satisfactory for 25-cycle systems and speed regulation not exceeding 30 to 40 per cent. These sets are also practicable for 60-cycle service, provided the regulation required is not too great.

For regulation in excess of 50 per cent where the slip frequency is high and the output large, the second method is usually preferable. In this case a special synchronous converter is used which transforms the slip energy to direct current. This in turn is used to drive either a high-speed d-c.-a-c. motor-generator set for returning energy to the system electrically, or to drive an adjustable-speed d-c. motor mounted on a shaft extension of the main motor.

It should be distinctly understood, however, that these sets are not a universal panacea for chronic speed difficulties. Each is subject to limitations, but of all the various schemes proposed the two which I have mentioned appear to be by far the most satisfactory from the viewpoints of practical design and economic operation. Some of the other schemes appear more simple in diagram, but I believe will be found to involve serious difficulties both in electrical and mechanical design, particularly in those cases where it is proposed to pass the entire slip energy through the regulating transformer.

In spite of the very real advantages which these regulating sets possess for the various classes of service mentioned, there are still occasions when sound engineering will warrant only the use of direct-current motors to meet the requirements of adjustable speeds.

I recently had occasion to investigate the comparative characteristics of a 350-h.p. mine fan motor with rheostatic control and with commutator motor regulating set arranged to give 20 per cent speed reduction, with the following interesting results:

Per cent regulation	Regulating set		Rheostatic control	
	Efficiency	Power factor	Efficiency	Power factor
0.5	88	100	84	91
10	87	100	82	91
15	86	100	77	91
20	84.5	100	72.5	91
25	84.5	100	68	91

On the basis of 0.6 cent per kw-hr. the saving per annum effected by the higher efficiency of the regulating set would be approximately $2700.

Another interesting case involving a 6500-h.p. motor with the synchronous converter and motor-generator designed for 40 per cent speed regulation gave the following results:

Rev. per min.	Over-all efficiency	
Main motor	Regulating set	Rheostatic control
85.6	87.0	73.5
75.0	83.7	64.0
64.3	80.0	55.0
53.5	75.0	46.0

The arguments of complex control often used against the speed-regulating set lose much of their weight in view of the present excellence of automatic magnetic control and the increasing tendency among steel mill engineers to place the motor with all accessory control in a room separate from the mill.

L. T. Robinson: I wish to make one general remark, and to refer specifically to one point in Mr. Sykes's paper. The general remark is that I think we have been much benefited by the discussion of methods of measurement, together with the general subjects to which they are related. There is very seldom an engineering problem that does not involve some problem of measurement, and to get the most good out of the whole thing it is well to take them up together, as they have been in this discussion.

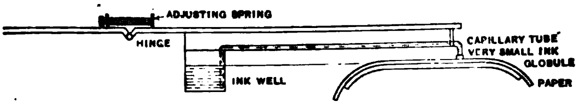


FIG. 3

The specific point I wish to raise is in connection with the spark method of recording. I was much interested in the reference to that method—it brings out the fact that one thing, although it may be good, is not always useful to cover every condition that comes up. The advantages of this spark method of recording are quite obvious, but, in my experience, it has some disadvantages.

The paper which is used for the record is somewhat irregular in thickness, and in getting a difference of potential between plate and pointer that will strike through in a satisfactory manner, you encounter two troubles—first, if you use a high potential that will strike through rather definitely, you are likely to run into trouble with electrostatic effect between the pointer and the frame of the instrument; second, sometimes there is a tendency to puncture at a point not directly underneath the needle, especially if a comparatively low difference of potential is used. This means that you must develop a considerable difference of potential, and guard successfully against the electrostatic effects by using a considerable torque, to get the same degree of precision that you can get in other ways.

I will show what means have been employed in the instruments that have been referred to by some of the previous speakers, to overcome the effect of friction on the paper, etc. (See Fig. 3.) Friction is minimized by an arrangement to feed the ink by capillary action, leakage on to the paper being prevented by surface tension at the recording point. The arrangement will not leak, and the ink will flow freely, and it can be adjusted to the paper so that it is in very light contact, and after the pen starts, it is simply the contact of the ink and paper and not of the pen point.

H. L. Barnholdt (by letter): When determining the motor size during the early stages of introducing electric rolling mill drives, the tendency was to follow the steam engine practise in many cases, *i.e.*, to use a motor large enough so that the first thing to break would be some part of the mill rather than the motor. This, no doubt, was good practise with the meager data then on hand in regard to the power requirements, as it would have been poor policy to run much risk of the motor breaking down when endeavoring to introduce the electric drive. Although at the present time the economy of electric rolling mill drives in general, as compared with steam drives, has been fully established, competition has made the question of further increasing the economy of these drives one of great importance. Not only can the initial investment be made low by selecting a motor of proper capacity to handle the requirements, but the performance of such a motor will be superior to that of a larger motor running underloaded. The ease and accuracy with which the electric power consumption of these fluctuating loads can be determined, as compared with steam, has done much to bring the subject of rolling mill practise to a more scientific basis. It also enables the motor manufacturer to work closer on the design and still be within limits of safety.

G. E. Stoltz (by letter): Mr. Sykes has mentioned the difficulty in obtaining the tonnage output of a mill from the operators. It seems to me that by knowing the peripheral speed at which the metal is rolled and the method of handling the material, an engineer who is acquainted with this phase of steel mill work should be able to estimate very closely the output which the mill is capable of rolling.

It has been stated that it is the practise of some engine builders to supply an engine large enough to break some part of the mill. This seems to be rather an expensive method of playing safe. Of course, in the absence of the necessary data to make an intelligent calculation of the power required, it is easy to see why the engine builder is willing to install an unusually large engine, provided the customer can be persuaded to pay for apparatus of such abnormal capacity. By the use of such a method for determining the size of engine, it would be only natural to simply guess at the size of flywheel. Supposing the flywheel should be too small, the engine must take more than its share of the peaks. With this condition the engine builder may be misled into believing that his engine is none too large. Very comprehensive data are necessary to determine definitely the size of motor and flywheel required, considering the two as a unit, their relation to each other depending to a large extent upon the type of control used. Almost any engineer can specify the drive of a mill if he is allowed a large factor of safety, but good engineering and commercialism demand accurate knowledge of the subject.

It is stated that a low rate of displacement probably requires less power than if the metal were rolled quickly. Could this be attributed to greater slippage between the metal and rolls at high speeds, which would introduce greater friction?

One of the advantages of automatic speed control is that the losses in the external resistance of a motor are reduced to a minimum. It is well known that very often rolling mills run idle a fairly large percentage of the time. During light load the secondary resistance is automatically short-circuited, which, with no losses occurring in external resistance, gives the best possible efficiency. With fixed resistance in secondary, energy is dissipated in this resistance, which makes it impossible to obtain a high efficiency even at light load.

I note that in Table I of Mr. Sykes's paper the last four columns of passes one and two have been left blank. This has probably been done not to complicate the calculations too much. It is evident that the motor can return 2197 h.p-sec. during the five seconds interval, but during the intervals after the first and second passes, only 1092 and 2167 h.p-sec. are required, respectively, to bring the flywheel up to speed. This is true only of the first slab put through the mill after the motor has been running idle long enough to come up to light-load speed, but if the schedule is followed as shown in Fig. 11 when the second slab enters, 1135 h.p-sec. are still required to bring the flywheel up to light load speed. This shortage is made up during the intervals after the first and second passes by the motor returning 2197 h.p-sec. to the flywheel in each case, instead of 1092 and 2167, respectively.

Wilfred Sykes: In Mr. Wilson's discussion of the first paper he refers to the use of flywheels being a necessary evil. That is quite true. But the flywheel makes it commercially feasible to drive rolling mills electrically, which, in the majority of cases, would otherwise not be possible. The diagram referred to in the discussion, that is, the one given in the paper, is actually made up from tests on a plate mill, in fact, it is the result of the test, modified somewhat to give it in round figures, but for all practical purposes they are the test figures obtained.

Mr. Wilson refers to the possibility of carrying the peak loads to the power station. The universal complaint that one hears from the operators in steel mills is that their power stations are all fully loaded, and they never have enough generator capacity to carry the load, and anything that produces a peak is about the most undesirable thing they can think of, next to something that will give them a bad power factor.

Mr. Haar in his discussion referred to the differences that exist in tests that have been published. I have studied some of these tests rather closely, and I believe a good deal of the difference is due to the method of testing. Some years ago, I had some work to do, involving such testing, and as we did not know before starting what the difficulties were, we got all sorts of results, and exactly the same thing occurred in tests referred to in this discussion. That is why it was necessary to make a preliminary test extending over about two months. It took that time to train the people so that they would operate the instruments properly and get the information accurately. One of the most difficult things was to get all the information, in the first place, and after we had the observers trained properly so that they would get all the information, the next difficulty was to get the information correctly. The preliminary results which were obtained varied several hundred per cent and were wholly unreliable. It was after the people had been trained for a couple of months to work together that they reached such a state of perfection in their operations that they could go into a mill and make tests which would be reliable from the beginning.

A great deal of this trouble was due to the fact that we did not appreciate the necessity of calibrating our apparatus often enough. We thought if we calibrated it once a day it was all right. Actually, we found we had to calibrate the apparatus after every test, and that is not an easy proposition, and involved the employment of a great many instruments.

Mr. Cheney has brought out very well the subject of power factor. It is often asked, " Why don't you put in a motor that is big enough to carry the load, so that there will be no doubt about it?" In some cases they have such machines, and they do not know how to run the generating stations on account of the low power factor.

Mr. Westcott referred to the tests on steam-driven mills. In that connection I think it might be well to refer to a type of steam indicator that has been developed in Europe by Rosenkranz. This indicator has been used in Europe, and to some extent in this country. When you make a test with an ordinary closed diagram the lines get so mixed up that in many cases you cannot make out where one diagram begins and the other ends, and under such circumstances it is difficult to get accurate results. Instead of using a closed diagram Rosenkranz brought out an arrangement of diagrams which has the appearance of an ordinary graphic recording meter chart. This indicator makes it possible to make fairly reliable tests and secure reliable results from steam mills, where it was not possible to obtain very consistent results with the ordinary closed indicator diagram.

Regarding the method used for obtaining the section when rolling heavy materials, such as angles, channels, etc., we have managed to persuade the mill people in a great many cases to run out a piece after a pass so that we got a section of it. We did not always succeed in doing this. If they were not very busy we managed to get them to do it, but it was not always easy.

The paper was driven from a countershaft, all instruments being driven by the same countershaft, and the whole thing driven by a little motor, from a storage battery, or sometimes directly from the lighting circuit. The speed stated in the paper, of one inch (25.4 mm.) per second, was not always used. We arranged the speed according to the class of mill with which we were dealing. If we had a rapidly fluctuating load the high paper speed was employed. If the load did not fluctuate, then a lower speed was used. In all of these tests we never succeeded in getting the people to slow down their mills to accommodate us. All the tests were made while the mills were running at their normal rate of production, and that complicated the matter a good deal.

Mr. Petty asked if any information was available as to the effect of the rate of displacement. The effect of the rate of displacement is not very great, so far as I can determine, and the whole thing is so covered up with other factors, that I am doubtful, without making a series of investigations especially with that object in view, if it is possible to say definitely what effect it has upon the power requirements.

Referring to Mr. Crosby's discussion, there is no doubt that the separation of the electrical equipment from the mill is an important factor in insuring satisfactory operation and this is practically the universal custom, but this does not obviate a number of difficulties that occur with complicated control apparatus.

Regarding the use of three-phase commutator regulating machines, it has been pointed out that such schemes have the general drawback that they require good attention, more so than is usually given apparatus in steel mills in this country. However, the general use of 25 cycles in our mills makes it easier to design good machines than is the case in Europe, where 50 cycles is nearly always used. This is especially true of the revolving field type. The regulating schemes involving the use of a synchronous converter in the rotor circuit are, on the other hand, placed at a considerable disadvantage on account of the lower frequency, compared with European plants, and it is hardly to be anticipated that they will be used to any appreciable extent, on account of the high cost. In discussing such a subject it is desirable to give particular attention to the difficulties that may be met with, so that the problem may be fully understood before installations are made. Mr. Crosby's anticipation that some of the schemes described will present difficulties is rather hard to answer, as he has not stated just what he fears. Machines built along the lines of the newer types described have given very good results under severe conditions and it is difficult to understand just what troubles he has in mind. We fail to see where any difficulty exists in passing the slip energy through a transformer, as surely this is preferable to using a rotating machine, such as shown in Fig. 4, and also more efficient. The system shown in Fig. 5, which is in commercial use in Europe, has this feature. The arrangements shown in Figs. 9 and 10 avoid the use of a transformer, but, of course, they can only be used on comparatively low-voltage circuits.

It is important, however, to avoid energy transformations as much as possible, or, in other words, to return the rotor energy as directly as possible to the line. The systems referred to by Mr. Crosby are generally well known, the one using a three-phase commutator motor being shown by Fig. 4 of our paper. The speed regulation requires the transformation of energy from the primary to rotor circuit, then into mechanical energy by the commutator motor, and again into electrical energy by the inductive machine.

That such an arrangement is not the limit of development, is clear, and other systems were described in our paper which avoid at least one of these transformations. Even the arrangement shown in Fig. 5, using a transformer, has the advantage over the older systems that both power factor and speed can be regulated without shifting the brushes, or the use of complicated auxiliary phase combinations. The newer arrangement described can be readily designed to operate from below to above synchronism, which, however, is not the case with the systems mentioned by Mr. Crosby, due to the difficulty of obtaining current in the commutator machine when passing through synchronism. The possibility of regulating above and below synchronism reduces the maximum energy to be handled by the commutator motor to one-half of what is necessary for a certain speed range compared with arrangements regulating only below synchronism. It also reduces the frequency of the current to be handled, which is particularly desirable for commutator machines. With the system shown in Fig. 3, even if arrangements could be made to run above synchronism, the commutator machines would have to be driven by the main motor as a generator, and the available torque is correspondingly reduced, whereas generally the reverse is required.

We believe it can be safely said that the limit of development of such schemes has not been reached, and we have indicated in our paper some of the lines along which improvements can be made. Other systems promising further improvements are receiving attention, but cannot be discussed at present.

This brings up the point, in connection with mining work, especially in this country, that you must look out very carefully for anything that introduces complication. The more machinery or control apparatus you have, the more trouble you will have with the system.

The point brought out by Mr. Robinson covers one of the difficulties we ran into. It is quite true that the spark has a tendency to jump around, and we found it was necessary to make pretty careful arrangements to insure that the paper went evenly over the board in which the plate was recessed. Then, in addition to that, we had to use a special paper, to avoid spreading of the spark. We also found out that the material used for the spark point had a great deal to do with the matter. If we used platinum and shaped it properly we got good results. We used rather a light spark, which did not burn the paper, but the puncture could be distinctly seen by holding the paper to the light. After the test was made, the sheet of paper was placed on a plate of glass and the curve drawn in by hand. In that way it was possible to avoid the difficulty of the spreading of the spark, and I do not think in any case the mark of the spark was more than 0.01 in. (0.25 mm.) wide in the tests we made after the preliminary experiments were made.

A. Dyckerhoff (communicated after adjournment): In going over the paper on *The Economical Speed Control of Alternating-Current Motors Driving Rolling Mills*, it occurs to me that some statements made in this paper are misleading, and also that many points are not brought out which should be mentioned. While I do not wish to invade the territory of the rolling mill engineer, whose task it is to find out the best rolling methods, and to whose needs the electrical manufacturer has to adapt his machinery in ways consistent with the best engineering practise, I wish to make a few remarks as an electrical engineer connected with steel and rolling mills. I feel myself the more qualified to speak since I had a very good opportunity during the past summer to study in Germany the question of economical speed regulation of a-c. motors, and its reliability in practical application under severe conditions.

The objection may be made that the rolling mill practise in this country is more severe than in Europe, and requires also, on account of the more or less unskilled labor, machinery of the most heavy construction and with practically fool-proof control. It will be seen, however, from the following statements, that all such objections to the adaptation of similar devices can be easily overcome. These devices are selected for their value in giving more definite speed control as a refinement in the art of rolling steel, and for cheapening the cost of producing rolled steel through more efficient operation.

The statement is made that speed regulation on merchant mills depends greatly on the class of labor operating the mill. Naturally a certain gang will have to be trained for a particular mill or class of work, but the lack of skilled labor should not impose the necessity of providing arrangements for speed regulation which would otherwise be unnecessary. In the case of merchant mills of the continuous type for high production the rolling process is almost automatic, and when steel is being rolled at very high speed, *e.g.*, in three-high rod mills, unskilled manual labor can be almost entirely dispensed with by using " guides " leading the metal from one pass to another.

It is the nature of the rolling process that merchant mills with a wide range of work require speed adjustment, particularly mills rolling refined material such as tool steel, spring steel, etc., where accuracy of section is necessary. This applies especially to mills running at low speed and rolling higher grade sheet and tin plate, stampings for electric machinery, etc. In most of these cases speed adjustment is essential for reasons of quality of metal and finish of product. Metal of this kind is often worked at low temperatures, thus requiring more power. Since many firms rolling such material do not own electric power plants, but have to buy electric power, they are particularly concerned with putting in the most economical speed adjustment devices they can get.

There are certain other applications where speed regulating devices are desirable in order to secure better operating conditions. Continous mills, a type much in evidence in this country, may offer possibilities for great improvement in conditions, due to their large output. Where the range of product of an existing mill is increased by adding several roll stands, a small regulating set attached to the roll motor may increase its output sufficiently to carry the entire load under the new conditions, whereas a larger motor would be otherwise required.

Rheostatic Control. It is pointed out above that in many cases a steady speed regulation is required, for rolling reasons. It follows that a resistance control cannot, for inherent reasons, give as good results as can be obtained by the new speed regulation devices, even if an automatic regulation of the resistance is applied so as to vary it inversely with the load. In ordinary merchant mills a speed regulation of from 10 to 15 per cent of synchronous speed, obtained by rheostatic control, may be just as economical under certain conditions as that obtained by regulating sets, and being more practicable is therefore more desirable. That a rheostatic speed regulation of 25 to 30 per cent can be just as economical as that obtained with any other auxiliary arrangement, not considering the question of satisfactory operation, is an assertion that will not hold true in ordinary practise. In the example cited of a jobbing mill carrying full load only 20 per cent of the running time, a condition is illustrated that is rarely met with, as it means bad mill practise and excessive costs due to light running. Furthermore, several points are omitted which should be taken into account. First of all, the power factor on the motor decreases with the rheostatic regulation considerably; further, the efficiency of the converting equipment, including transformer, is rather low (about two per cent higher could be obtained at full load and three per cent higher at light load with a proper arrangement). I assume that the transformer mentioned was connected between the rotor ring and the converter, but the transformer, however, can be entirely dispensed with, since it does not assist in the cheapening and improving of the arrangement in any way. There is also an improvement of the power factor on the motor to approximately 100 per cent over almost the entire range of regulation, which means that a motor of a smaller rating could eventually be chosen. Any of these points should be fully taken into account; however, none has been mentioned. It is nothing but fair to consider the efficiencies of the different regulating sets and rheostatic regulation under equal conditions as found in ordinary practise, and to leave out entirely exceptions due to certain local conditions. This assumption of general conditions is illustrated by the curves in Fig. 4 of this discussion, which are based on actual tests representing present-day practise. It will be noted that the best result has been obtained by the converter d-c. motor system, and therefore the statement remains to be proved that some of the newer methods, referred to on page 2074 of the paper by Messrs. Meyer and Sykes, give more economical regulation than an arrangement requiring the conversion of the energy to direct current.

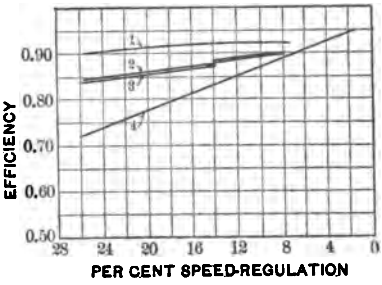


FIG. 4—EFFICIENCIES OF VARIOUS REGULATING SYSTEMS IN RELATION TO SPEED REGULATION

(1) Synchronous converter—d-c. motor system (Kramer). Main motor—1150 h.p., 270 rev. per min.
(2) Frequency changer system (Heyland). Motor—950 h. p., 300 rev. per min.
(3) Scherbius system. Main motor—1000 h. p., 363 rev. per min.
(4) Rheostatic control. Motor—1200 h. p., 248 rev. per min.

Multi-Speed Motors and Motors in Cascade. It is a matter of fact that the control of those motors is rather complicated. When dealing with a motor arranged for pole changing, this arrangement provides for a few speed steps only, the intermediate steps being obtained by inserting resistance. The power factor of such a motor is poor, consequently the generators and lines are loaded unnecessarily with current. In the case of two motors in cascade this feature of a low power factor is still more doubtful, the cascade motor forming a high inductive resistance for the main motor,, thus resulting in high wattless current in the system. If there is a choice between a multi-speed motor and motors in cascade, the former is preferable. The latter arrangement is used in very few installations in this country as well as in Europe, where they have been using d-c. roll motors, which are so ideal as to speed regulation, to a greater extent than in this country.

Regulating Sets. There are four different kinds of regulating systems in successful operation:

1. Induction motor with synchronous converter, feeding d-c. motor, connected mechanically to shaft of induction motor, known as the Krāmer set.
2. Induction motor with three-phase commutator motor coupled to same.
3. Induction motor connected electrically to three-phase commutator motor which drives induction machine feeding back to the line, known as the Scherbius set.
4. Induction motor with frequency changer feeding its secondary energy back to the line, known as the Heyland system.

Application. The nature of rolling processes generally requires high torque and low speed for heavy stock, and low torque and high speed for light sections, and also, when rolling a certain section, high torque at low speed is necessary for the first passes and light torque and high speed for the last passes. The rolling mill is therefore entirely a constant output proposition, *i.e.*, the torque increases with decreasing speed, whereas in the case of fans, blowers, and pumps, low torque is wanted at low speed. From this it follows that the d-c. motor system (set No. 1) and the three-phase commutator motor cascade (set No. 2) are in their nature more adaptable for roll trains than any other system, of which two the latter is preferable on account of requiring only one additional machine and converting the secondary energy of the induction motor directly into mechanical power. I know of installations where such sets, arranged for a regulation of more than 30 per cent on merchant mills, are operating very satisfactorily. This country is more fortunate than Europe in using 25-cycle circuits for steel mills, which makes the design of three-phase commutator motors easier, although the output is limited. The maximum speed regulation in operation with the Krāmer system is somewhat more than 60 per cent in connection with an induction motor of 1000 h.p. There is under construction a set calling for the regulation of a 2000-h.p. motor over a range of 55 per cent. The two systems, Krāmer and d-c. commutator motor cascade, thus respond, to a great extent, to the needs of rolling practise, but this does not do away with the great usefulness and adaptability of the other systems. Some of the merits of the remaining systems are as follows: (1) they are very suitable for a high range of regulation; (2) they can be designed for their most suitable speed; (3) they can be placed independently of the mill itself; (4) they possess certain other advantages mentioned in the course of the discussion. Thus far a Scherbius set is operating in connection with a roll motor of 1800 h.p. with a speed regulation of 50 per cent, and a Heyland frequency changer in connection with a 900-h.p. motor for approximately 45 per cent regulation. If a choice is to be made between the three-phase commutator motor cascade and the Krämer set, the former is preferable for a roll motor running at high speed for a limited range of speed regulation, and for motors at medium speed and speed regulation usually met with, say, up to 65 per cent, the Krämer set is preferable; and for low-speed motors with wide range separate regulating sets should be chosen. Thus far the Krämer set seems very adaptable for this country, as the design of the synchronous converter has reached a higher stage of development in the United States than in Europe; its reliability is proved by its extended use in power stations and railroad service, and its operation is familiar to attendants. Also, the three-phase commutator motor cascade promises, from its successful operation as single-phase motor in railroad service, to be a reliable asset in steel mill drives.

Number in Operation. It is interesting to note that approximately 57 motors with a total rating of approximately 64,000 h.p. (continuous rating at high speed of main motor only) are equipped with economical speed regulating devices, of systems 1, 2, 3, or 4. Of this 64,000 h.p., motors totalling approximately 17,000 h.p. are under construction or are intended for speed regulation. The total amount of 64,000 h.p. is distributed among the different systems approximately as follows:

Synchronous converter-d-c. motor system	57 per cent.
Scherbius system	19 per cent.
Three-phase commutator motor cascade	18 per cent.
Frequency changer system	6 per cent.

Of this 64,000 h.p. approximately 12,000 h.p. is driving fans, blowers and pumps, and 45,000 h.p. is driving roll trains, the distribution of which on the various systems amounts approximately to:

Synchronous converter-d-c. motor system	75 per cent.
Scherbius system	13 per cent.
Three-phase commutator motor cascade	9 per cent.
Frequency changer system	3 per cent.

From these statistics it will be seen to what a great extent (about 70 per cent) the roll train motors share in the total amount, and to what a great percentage (75 per cent) the synchronous converter-d-c. motor system is represented. The latter system is also supplied for a great amount of the 17,000 h.p.

under construction. The frequency changer system was brought out only about two years ago, which accounts for its small share.

Efficiency. Besides having a reliable operation it is of the greatest interest to learn what efficiencies have been obtained in actual service. Fig. 4 (see *Electrische Kraftbetriebe und Bahnen*, 1912, No. 21) shows the over-all efficiencies of three systems with their respective motors compared with rheostatic control. These motors are driving fans, are approximately of the same output, and therefore permit the direct comparison as shown. From this it will be seen that the synchronous converter-d-c. system gives the best efficiencies, followed by the frequency changer system and the Scherbius system, which operate practically at the same efficiency. I understand that the efficiencies of the latter two have been increased lately. Further, the curves show that the efficiencies of the Krämer set and rheostatic control are approximately the same at 4.5 per cent speed regulation, and those of the frequency changer and Scherbius system and rheostatic control the same at approximately 7 per cent. This means that a speed regulation above 4.5 per cent and 7 per cent, respectively, in these particular cases, is therefore more economical with regulating sets than with rheostatic control. The synchronous converter requires approximately at least two cycles for operation free from hunting,

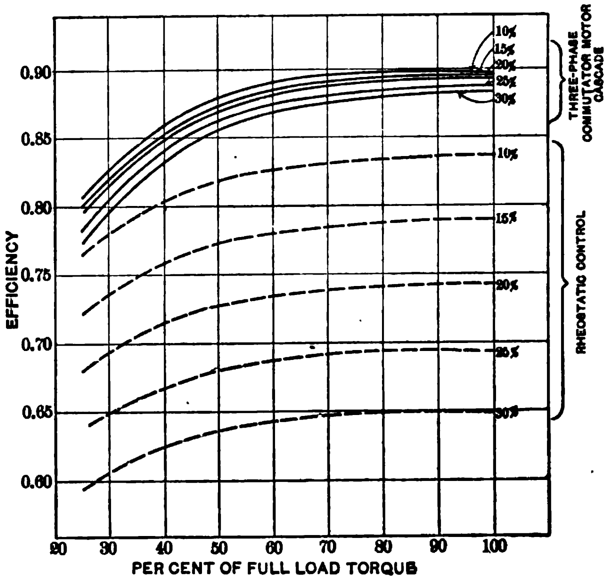


FIG. 5—EFFICIENCY CURVES FOR SPEED REGULATION BY MEANS OF THREE-PHASE COMMUTATOR MOTOR ON ROLL MOTOR SHAFT COMPARED WITH RHEOSTATIC CONTROL. MAIN MOTOR 1000 H.P., 360 REV. PER MIN.

which means that with a frequency of 25 cycles, as used in steel mills, operation for less than about 8 per cent speed regulation will not be very satisfactory.

Fig. 4 does not give the efficiency of a three-phase commutator motor cascade set; this, however, can be taken from Fig. 5 (see *Electrische Kraftbetriebe und Bahnen*, 1910, Nos. 6 and 7), showing efficiencies of such a cascade set compared with rheostatic control. It will be noted that such a set has an efficiency approximately two to three per cent less than the synchronous converter-d-c. motor system.

For comparison of a three-phase commutator motor cascade set with a Scherbius set Fig. 6 (see *Electrische Kraftbetriebe und Bahnen*, 1910) has been prepared, and it will readily be seen that the three-phase commutator motor cascade is superior in efficiency to a Scherbius set by several per cent, depending on the amount of regulation and on the torque. The efficiency of the Scherbius set is better than if there is a roll motor and a three-phase commutator motor operating at a very low speed. How far the efficiency is affected by a speed drop of 5 per cent from no load to full load, so as to obtain energy from the flywheel, is shown by the dotted lines. This disadvantage of a lower efficiency of the Scherbius set, however, is rather compensated by other advantages. In connection therewith, I would mention that by means of such a set 18 to 20 per cent of the energy taken by a roll motor of 1800 h.p. at 375 rev. per min. driving a rod mill was actually returned to the line, this being the average over several months and measured by actual readings of integrating wattmeters.

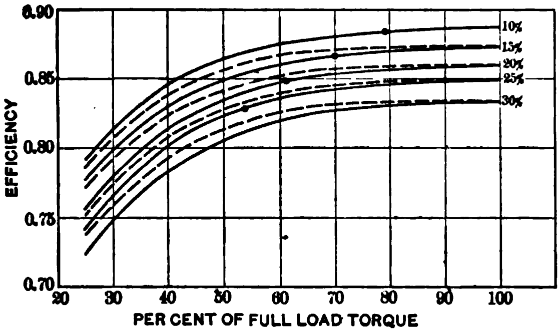


Fig. 6—Efficiency Curves for Speed Regulation by means of Scherbius Set, with and without 5 per cent Speed Drop from No Load to Full Load for 10, 15, 20 and 25 per cent of Normal Speed. Main Motor—1000 h. p., 360 rev. per min.

Power Factor. With any of the regulating sets mentioned, the power factor of the circuit has been brought to unity and the sets operate usually under this condition. A high power factor is the more important since the output of an existing motor can be increased, or in a new plant a main motor of smaller output can be chosen, under proper conditions, by adding are gulating set or a three-phase commutator machine as a phase compensator. Fig. 7 shows that unity power factor has been obtained with the synchronous converter-d-c. motor, the Scherbius and the Heyland frequency changer systems. The same result can also be obtained with a three-phase commutator motor cascade, but not, however, with such a simple device as with a Krämer set, where merely the excitation of the synchronous converter is regulated till unity power factor is obtained on the motor. The same effect can very easily be secured with a frequency changer; first, either by shifting the stator of the motor driving the frequency changer or, second, by means of double induction regulators if the frequency changer is connected to the main motor by means of a gear. Both of these methods are in successful operation. The disadvantage of the rheostatic control as compared with regulating sets is borne out by curve 4 of Fig. 7 of this discussion.

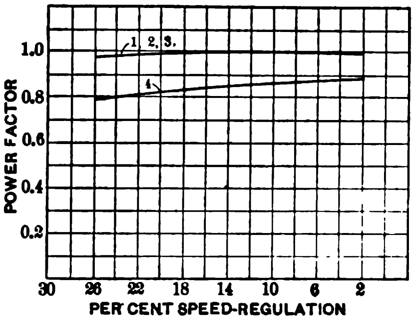


FIG. 7—POWER FACTOR OF VARIOUS REGULATING SYSTEMS IN RELATION TO SPEED REGULATION

Control. A word may be said as to control, which is of such importance for successful operation. In most cases it is required to arrange the control so that it is fool-proof. Comparing the control for any regulating system with, for instance, that of a multi-speed roll motor, it will readily be seen that one is practically no more complex than the other. The sequence of switching operations in connection with regulating sets is very simple, and in all instances mechanical or electrical interlocks can be provided. Under certain conditions, *e.g.*, with a frequency changer, synchronizing is necessary, and this can be done by automatic synchronizers.

In a great many installations phase-potential regulators have been used successfully, although this arrangement involves higher cost. The potential regulator has also been used in conjunction with the synchronous converter-d-c. motor system, connected between the rotor of the main motor and the converter, but not to the advantage of the regulating system, because of such drawbacks as additional high cost, large converter, lower efficiency, etc.

There is another important field of application of the three-phase commutator motor in connection with an induction motor and flywheel. This application is the more important in this country as the three-phase induction motor is being much used in connection with roll trains, whereas in Europe, due to other conditions, a great number of reversing mills are in operation which require a flywheel motor-generator set interposed between the line and the roll motor. This arrangement involves a triple conversion of energy from the switchboard in the motor room to the roll necks, and accordingly heavy losses. The tendency in this country is mostly to use the electric energy directly in the roll motors, thus requiring from the switchboard to the roll necks only one conversion of energy and saving the losses imposed by two more conversions.

It may be desirable to smooth out the peaks on the line where a motor drives the roll train directly, and in such cases a flywheel set with induction motor and three-phase commutator motor can give very good service. It is mainly the task of the three-phase commutator motor to enable the three-phase induction motor to act as a generator below synchronous speed, taking its energy from the flywheel and supplying current to the line. At the same time, the three-phase commutator motor takes care of the economical speed regulation of the induction motor. The whole arrangement can be made automatic.

A similar application of a three-phase commutator motor may also be useful in connection with an Ilgner set for the purpose of improving its efficiency.

The above points rectify some erroneous statements made in the paper and outline what really has been obtained under actual operating conditions in Europe, which same conditions hold true to a great extent in this country.

In regard to the systems described on page 2084 and following, I would say that the above statements of a general nature which I have made hold true also for the new regulating arrangements, especially as to the adaptation of frequency changers to roll trains. These systems apparently represent some simple features, but so far are not yet proven by practical application, as far as I know, and the results will be awaited with interest. If there are any such installations I should like to know where they are located, also the output of the motor and the amount of regulation. I would further like to know for what theoretical reasons synchronizing of the frequency changers is not necessary, although I can anticipate the means for synchronizing which might be applied.

The main part of the switching arrangement of the frequency changer, as shown in Fig. 9 and Fig. 10 of the paper, and also of the three-phase commutator motor, Fig. 11 and Fig. 12, will consist of the control of the stator winding. These windings will have to have many taps in order to obtain a sufficient number of steps and thereby fine speed regulation. Furthermore, resistance steps or similar arrangements will have to be provided in order to avoid short-circuiting of part of the winding when switching from one tap to another. In connection therewith, I wish to say that the operation of three-phase commutator motors arranged for control by means of brush shifting has proved very satisfactory, and I learn that in consequence of this many are under construction.

Ford W. Harris (communicated after adjournment): It seems to me that the authors have made a little too much of a bugbear of the complexity of control and of control wiring. The latter may be eliminated at once as a matter of first cost only. That is, the control wiring can be so installed that it is absolutely no trouble to maintain. This is reasonable enough, as it is simply stationary material that may be protected against external injury. The multiplicity of switches is another matter, but even here a good word may be said for the simpler motors that may be used if a little switch complexity is allowed.

Further, it will be found that, by a little care in laying out the sequence of switching operations, all the maintenance will fall on one or two switches and the remainder will be more or less free from arcing and wear. As to making them operate automatically, the writer has become convinced that there is really no question that, by suitable arrangements of interlocks and contacts, automatic control can be made practically infallible. The only requirement is good switches in the first place and a moderate amount of attention. It is my opinion that either a cascade or rheostatic control would probably work out more cheaply and be more satisfactory to maintain than either of the several commutator type systems shown. The item of economy is, of course, getting to be of importance, as the steel mill engineers are fast getting to a point where they can get absolutely satisfactory service and they are more and more bending their energies to the refinements that tend toward lower fixed charges and lower operating expense.

A paper presented at the 278th Meeting of the American Institute of Electrical Engineers, New York, December 13, 1912.

HIGH-FREQUENCY TESTS OF LINE INSULATORS

BY L. E. IMLAY AND PERCY H. THOMAS

The object of this paper is to present for consideration certain very interesting and suggestive high-frequency insulator tests recently made by the authors. These tests were undertaken to determine the availability of a certain insulator for use on a projected 38,000-volt line and resulted in a radical modification of the design. Having a strictly utilitarian purpose in view, these tests were not expanded to the point that would be desirable from a scientific point of view, although the nature of the results shows the great desirability of further research in this same field. With this explanation the plan of the tests will be understood.

A certain transmission system* has used three parallel circuits operating at 22,000 volts to transmit a rather large amount of power some 16 miles for a number of years. The demand for more power has rendered a new line necessary, which is being installed for 38,000-volt operation. The insulators on the old lines are made of electrose, having an umbrella petticoat about 12 in. (30.4 cm.) in diameter, and a second smaller petticoat about 6 in. (15.2 cm.) in diameter. They were originally intended to be used on 38,000 volts when the rise of the load should require. Experience showed that these insulators occasionally punctured through the head from lightning, such failures being very difficult to find. The insulators are mounted on grounded steel pins. This sort of failure was very surprising in view of the fact that these insulators had never been punctured in testing, though they would arc over when wet at about 90,000 volts, as indicated on the primary side of a 25-cycle testing transformer.

It was this discrepancy between the repeated punctures through the head from the conductor to the pin due to lightning, and the steady refusal of the insulators to puncture on a 25-cycle

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*Canadian Niagara Power Co.

testing set, that led to the high-frequency, high-voltage tests described below.

These tests were made to determine directly whether any difference in the behavior of the insulators could be determined between the use of high frequency and 60 cycles, both produced in the laboratory.

The circuits for the high-frequency tests are shown in Fig. 11.

In this figure is indicated a 500-kw., 750,000-volt transformer. One side of this transformer is grounded and the other side connected to the discharge apparatus. The " plate " shown was a sheet iron plate approximately eight by nine ft. (2.4 by 2.7 m.), estimated capacity 0.0001 microfarad, suspended by a cord approximately 3.5 ft. (1.06 m.) from a large transformer tank, which served as a ground plate. The coils marked *A*, *B* and *C* were three air-core choke coils intended to protect the transformer. The coil *A* was a helix having a diameter of 18 in. (45.6 cm.), and had approximately 22 turns of wire, the turns being spaced approximately three in. (7.6 cm.) apart. The coil *B* was circular and approximately 24 in. (60.9 cm.) in diameter and had 10 turns. The coil *C* was a pancake coil and had approximately 200 turns with a mean length of turn of 37.7 in. (95.8 cm.) This coil *C* was shunted by a graphite resistance of about 125,000 ohms.

The insulator to be tested was mounted on a wooden box some four ft. (1.22 m.) from the floor and had a half-inch (12.7-mm.) brass rod tied in the groove by a band of small size copper wires. The pin carrying this insulator was grounded through a wire approximately six ft. (1.8 m.) long. The length of the lead from the transformer terminal to the condenser plate was approximately 50 ft. (15.2 m.)

A series discharge gap was made by approaching a second brass rod mounted on a wooden stand to one end of the ½-in. (1.27-cm.) rod tied to the insulator, the second rod being connected to the sheet iron condenser plate by a wire two or three ft. (60 or 90 cm.) long.

Where a measuring gap was used, as recorded in the reports below, this consisted of a needle point gap mounted on hard rubber pedestals located some six ft. (1.8 m.) from the insulator under test. One side of this gap was connected, either with or without resistance, to the conductor on the insulator under test, and the other side was connected to the insulator pin or to the ground.

The general method of test was to raise the voltage of the generator feeding the primary until a discharge occurred across the series gap onto the insulator. With the adjustment of generator voltage and transformer ratio used, the result of the breakdown of the gap was in most cases to so reduce the applied voltage that the arc proper would drop out, at least partially, leaving the series gap nearly intact, and thus the return of voltage on the next alternation would be obliged to nearly reproduce the original breakdown voltage on the gap. The effect of this arrangement was to give a continuous succession of static sparks lasting as long as voltage remained on, that is, one or two seconds, as distinguished from the holding of a continuous arc over the gap. In the tests of June 24th, however, the opposite effect was secured, that is, a single static spark each time the voltage was raised, followed by a mild arc.

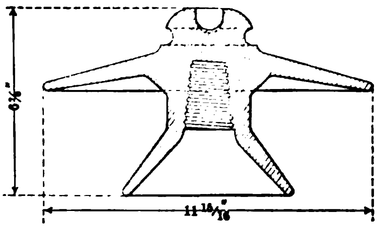


FIG. 1—ORIGINAL INSULATOR

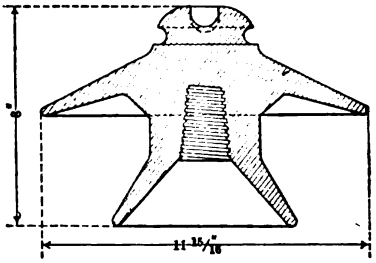


FIG. 2—PROPOSED 38,000-VOLT INSULATOR

The terms "application of voltage" and "trial" used hereinafter mean the raising of voltage to the breakdown point and the cutting off of voltage one or two seconds later.

The results of the various tests have been tabulated as follows, and the tests will be considered briefly in groups.

First Group. (*Tests* 1-2) *Normal Flash-Over Test, Dry, in Air, 60 Cycles.*

This group of tests was preliminary and was made in the usual manner, the voltage being measured by a spark gap checked approximately by a voltmeter reading on the low-tension winding of the raising transformer.

In no case did an insulator puncture. An insulator of the type shown in Fig. 1, that now in use in the three existing lines, flashed over at 122,000 on the second trial; the insulator of the type shown in Fig. 2 flashed over at 150,000 volts. The insulator of Fig. 2 is a new design that was intended to replace the insulator of Fig. 1 and to resist lightning stresses better. The two insulators are the same except that the later design has a head nearly two

HIGH-FREQUENCY TESTS OF LINE INSULATORS

TABLE OF ACTUAL TESTS

Test No.	Date 1912	Insulator No.	Description of insulator	Type of test	Series gap	Transformer voltage on spark gap	Result of the test
1	June 24	1	Same as Fig. 1.	60 cycles, dry	—	122,000	Flashed over surface, no arc.
2	" "	2	Same as Fig. 2.	" " "	—	150,000	" " "
3	" "	2	" " " 2.	" " wet	—	95,000	" " " , some preliminary sparks.
4	" 25	12	" " " 1.	" " oil	—	205,000	Punctured through head.
5	" "	11	" " " 2.	" " "	—	240,000	Flashed over surface.
6	" "	13	" " " 2.	" " "	—	250,000	Flashed over surface, except for puncture in middle of lower petticoat.
6½	" "	15	" " " 1.	High frequency	25"	342,000	Punctured through head, 14th trial.
7	" 24	3	" " " 2.	High frequency	27"	300,000	Punctured through head after 10–15 trials making a hole approx. 1/32 in.-1/64 in. diam.†
8	" "	4	" " " 2.	" "	"	"	Punctured through head after 10 trials as in test 7.
9	" 25	5	" " " 2.	" "	25"	342,000	Punctured through head the second trial.
10	" "	14	Same as Fig. 2, except for ¼" hole through base of lower petticoat.	" "	"	338,000	Punctured through head 24th trial.
11	" 29	20	Same as Fig. 2, except that 1¼" is cut off the upper petticoat all around. (Previously flashed over surface on 60 cycles dry at 130,000 volts.)	" "	"	328,000	" " " 6th "
12	" "	23	Same as Fig. 2, except for 4 holes drilled in upper petticoat 2½" in. from edge.	" "	"	335,000	" " " 28th " about. Examined from time to time before a puncture but showed no incipient injury.
13	" "	28	" " " 2, except top petticoat was cut off at base. (Previously flashed over surface on 60 cycles dry at 90,000 volts.)	" "	"	"	Punctured through head 15th trial.

†This insulator was not hot to the touch after puncture.

HIGH-FREQUENCY TESTS OF LINE INSULATORS—Continued

Test No.	Date 1912	Insulator No.	Description of insulator	Type of test	Series gap	Transformer voltage on spark gap	Result of the test
14	June 29	25	Same as Fig. 2, except both petticoats were cut off at base, leaving a stump 5 in. high to the tie wire groove and a little over 5" maximum diameter (Previously flashed over surface on 60 cycles dry at 94,000 volts and wet at 33,500 volts.)	High frequency	"	330,000	No puncture in 150 trials.
15	" "	21	Same as Fig. 1, except that 1¼" was cut off top petticoat. (Previously flashed over surface on 60 cycles at 120,000, dry.)	" "	25"	"	Punctured through head, 14th trial.
16	" 25	7	No. 3007 22,000-volt porcelain insulator, see Fig. 6. (Previously flashed over surface on 60 cycles dry at 87,000 volts.)	" "	"	235,000	Puncture bottom petticoat 2nd trial; no further punctures in 65 trials.
17	" "	6	No. 3012 35,000-volt porcelain insulator, see Fig. 7. (Previously flashed over surface on 60 cycles dry at 130,000-140,000 volts.)	" "	"	"	Punctured lower petticoat, then through middle petticoat, then through head under tie wire, hot at puncture, 20 trials.
18	" "	8	No. 3002, 45,000-volt porcelain insulator, see Fig. 8. (Previously flashed over surface on 60 cycles dry, at 125,000-129,000 volts.)	" "	25"	335,000	Punctured through two lower petticoats, 2nd or 3d trial; then punctured through head under tie wire in a few more trials, puncture not very hot.
19	" 29	24	Same as Fig. 2, except that a belt of lead foil was placed around the waist of insulator as in Fig. 3. (Previously flashed over surface on 60 cycles dry at over 138,000 volts.)	" "	"	330,000	Punctured through head on 59th trial. This insulator was examined from time to time but no signs of heating or injury were found prior to the failure.
20	" "	26	Same as Fig. 2 except that 4" metal cap was used in head. (Previously flashed over surface on 60 cycles dry at 130,000 volts.)	" "	"	"	Punctured through head, 2nd trial.
21	" "	27	Same as Fig. 1, except that 4" metal cap was used on head. (Previously flashed over surface on 60 cycles dry at 124,000 volts.)	" "	"	"	Punctured through head, 17th trial.

HIGH-FREQUENCY TESTS OF LINE INSULATORS—Continued

Test No.	Date 1912	Insulator No.	Description of insulator	Type of test	Series gap	Transformer voltage on spark gap	Result of the test
22	June 25	9	Same as Fig. 1, but had been long exposed to weather, surface grey, and checked, especially on lower petticoat.	60 cycles, dry	—	105,000	Flashed over surface, sparks passing through checks on lower petticoat.
23	" "	10	Same as Fig. 1, but exposed as in test No. 9.	" "	—	120,000	Flashed over surface, sparks passing through checks on lower petticoat.
24	" 29	22	Same as Fig. 1, but had been long exposed to weather, surface grey, and checked, especially on lower petticoats; also 1½" cut off upper petticoat all around.	60 cycles, dry	—	108,000	Flashed over surface, passing through checks in lower petticoat.
25	July 8	31	Same as Fig. 2. (Previously flashed over at 156,000 volts on 60 cycles, dry.)	High frequency	22½	315,000	Punctured through head, 9th trial. Pin was warm when examined after test and threads were blackened and split on one side.
26	" "	33	Same as Fig. 2, except that 1½" was cut off the upper petticoat. (Previously flashed over surface on 60 cycles dry at 129,000 volts, wet at at 103,000 volts.)	" "	"	302,000	Punctured through head, 113th trial.
27	" "	34	Same as Fig. 2, except that 2½" was cut off the upper petticoat. (Previously flashed over surface on 60 cycles dry at 119,000 volts, wet at 81,000 volts)	" "	"	306,000	No puncture in 150 trials.
28	" "	30	Same as Fig. 4, electrose. (Previously flashed over surface on 60 cycles at 115,000 volts, dry, and 76,000 volts, wet.)	" "	21½	310,000	No puncture in 150 trials. Insulator was warm when tests were discontinued.
29	" "	29	Same as Fig. 5, porcelain. (Previously flashed over on 60 cycles at 95,000 volts, dry. Insul. 35, same type as 29, flashed over surface on 60 cycles at 118,500 volts, dry, and 70,000 volts, wet.)	" "	"	"	Punctured under tie wire on 3rd trial.
30	" "	32	Same as Fig. 5, porcelain.	" "	"	"	Punctured under tie wire in 2nd trial.

in. (5 cm.) thick in comparison with a head thickness of one in. (2.5 cm.) in the old insulator of Fig. 1.

Second Group. (*Test* 3) *Normal Flash-Over Test, Wet, in Air,* 60 *Cycles.*

These tests were made with the same electrical apparatus as the first group. Water was thrown on the insulator from three spray nozzles at one side, giving a very heavy " scotch mist." The water dripped very rapidly from the petticoats during the tests, but no direct measurement was made of the amount of water sprayed. The water was relatively pure river water.

The insulator of Fig. 2 flashed over at approximately 95,000 volts.

Third Group. (*Tests* 4-6) *Normal Test Under Oil,* 60 *Cycles.*

The insulators were immersed in good " transil " oil, bubbles under the petticoats and in the pinhole being carefully eliminated. The insulator of Fig. 1 punctured through the head at 205,000 volts, and that of Fig. 2 flashed over the surface, once at 240,000 volts and once at 250,000, except that the lower petticoat was punctured at a point intermediate between the edge and the central portion in the latter test.

Fourth Group. (*Tests* 6½-9) *High-Frequency Test: apparatus as shown in Fig.* 11.

The insulator of Fig. 2, that is, the new insulator with the 2-in. (5-cm.) thickness of head, punctured from the conductor to the pin. The first two insulators tested failed on the tenth to fifteenth applications of voltage, and the third insulator on the second trial.

This result was most surprising, since insulators of this type had flashed over the surface even *under oil* rather than puncture through the head at 60 cycles. The unusual character of this behavior made a furthur investigation imperative, and the following tests were made.

Fifth Group. (*Tests* 10-15) *High-Frequency Tests as in Fig.* 11. (*continued.*)

Insulators of the type of Fig. 2 were altered in various ways and subjected to the same test. As electrose can be sawed and drilled such alterations could be easily made. The results were as follows:

a. With ¼-in. (6.3 mm.) hole drilled at the base of the lower petticoat, the insulator failed by puncture through the head on the twenty-fourth trial.

b. With 1¼-in. (31.7-mm.) turned off the edge of the upper petticoat, the head failed as before on the sixth trial. This insulator had previously flashed over, as altered, at 60 cycles on 130,000 volts, dry.

c. With four equally spaced ¼-in (6.3-mm.) holes drilled through the upper petticoat 2¼ in. (5.7 cm.) from the edge, this insulator punctured in the head on the twenty-eighth trial.

d. With the top petticoat entirely cut off, an insulator punctured in the head on the eighteenth trial. This insulator, as altered, had previously arced over on 60 cycles at 90,000 volts, dry.

e. An insulator with both petticoats sawed off as closely as practicable, leaving a stump about 5 in. (12.7 cm.) high to the tie wire groove and a little over 5 in. (12.7 cm.) maximum diameter, showed no failure in over 150 trials. Apparently this insulator was capable of standing this application of high frequency at 340,000 volts indefinitely.

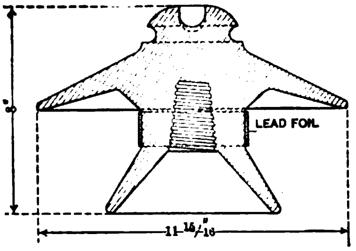


Fig. 3—Electrose Insulator of Fig. 2, with Band of Lead Foil about Waist

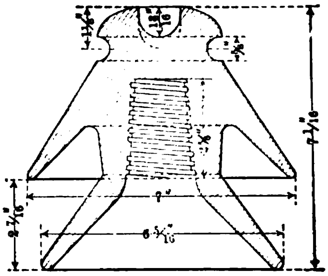


Fig. 4—Type E Insulator—Electrose—22,000 Volts

f. A similar test was made on an insulator as shown in Fig. 1 with 1¼ in. (3.1 cm.) turned off the upper petticoat. This punctured the head as usual on the fourteenth trial. Previously this insulator had flashed over the surface on 60 cycles at 130,000 volts.

These results, which were all on electrose insulators, showed most plainly that the resistance to high-frequency stress, in this sort of apparatus at least, bore little relation to its strength against the normal 60-cycle stress. The question naturally arose, were these results peculiar to electrose? Some porcelain insulators were then obtained and high-frequency tests made upon them, as follows:

Sixth Group. (*Tests* 16-18) *High-Frequency Tests, as Shown in Fig.* 11.

a. A porcelain insulator, No. 3007, recommended for 22,000 volts, showed a puncture in the lower petticoat on the second trial, but suffered no further damage in 65 trials. This insulator had previously flashed over at 87,000 volts, dry, 60 cycles.

b. A porcelain insulator, No. 3012, recommended for 35,000 volts, showed a puncture first on the lower petticoat, then in the middle petticoat and then through the top under the tie wire. This insulator had previously flashed over on 127,000-135,000 volts, dry, 60 cycles.

c. A porcelain insulator, No. 3002, recommended for 45,000 volts, showed a puncture in the two lower petticoats on the first or second trial and a puncture under the tie wire in a few more trials. This insulator had previously flashed over at 125,000-129,000 volts on 60 cycles.

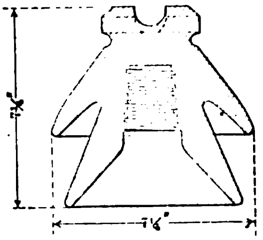


FIG. 5—TYPE E INSULATOR—PORCELAIN—22,000 VOLTS

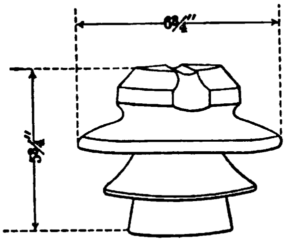


FIG. 6—PORCELAIN INSULATOR No. 3012

From these tests on porcelain insulators it appeared that this feature of failure on high frequency was not peculiar to electrose.

It was surmised that the peculiar effect of high frequency was due to a different distribution of electric stresses produced under this condition, which distribution may be assumed to cause a concentration of potential at certain points. Some tests were therefore devised to verify this assumption.

Seventh Group. (*Tests* 19-21) *High-Frequency Tests, as Shown in Fig.* 11.

a. A new insulator of the type of Fig. 2 was covered with lead foil about the waist as shown in Fig. 3. This foil was entirely disconnected from any metal parts; but, in view of its electrostatic capacity to the pin, it would change the distribution of potential during the high-frequency attack. Its effect would obviously be toward increasing the effective size of the pin top. This insulator punctured through the head on the 59th trial. It had previously flashed over the surface at 138,000 volts on 60 cycles. While this insulator was not proof against the high frequency, it stood up longer than any of the other electrose insulators, even longer than those with reduced petticoats, except the one without any petticoat. This result is very illuminating, as this insulator had all its petticoats intact.

b. A test was made with a new Fig. 2 insulator with a metal cap, about 4 in. (10 cm.) across, on the top of the insulator. The electrical effect of this should be opposite to that of the lead foil of *a* above. This insulator showed a puncture in the head on the second trial. This insulator with cap had previously flashed over at 130,000 volts on 60 cycles, dry.

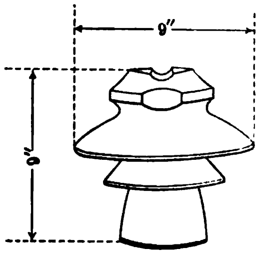


FIG. 7—PORCELAIN INSULATOR
No. 3007

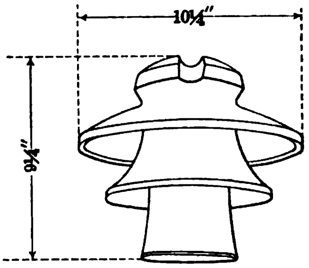


FIG. 8—PORCELAIN INSULATOR
No. 3002

c. The same test as "b" was made on a Fig. 1 new insulator and the insulator showed a puncture in the top on the seventeenth trial. This insulator with cap had previously flashed over at 124,000 volts on 60 cycles, dry.

These last three results, while few, indicate pretty clearly the cause of the weakness as well as the nature of experiments required to clarify this matter further.

Those electrose insulators of the type of Fig. 1 which had been in service for some years showed a roughening and a bleaching of the surface to a light gray from the effects of exposure to the weather. Some of these old insulators further showed checks on the surface extending to various depths, mostly on the lower petticoat. Tests were made to get the effect of the weathering on the behavior of the insulator.

Eighth Group. (*Tests* 22-24) *Weathering Tests,* 60 *Cycles, Dry.*

a. Two old insulators showed a dry flash-over on 60 cycles on 105,000 and on 120,000 volts, respectively, a loss of insulating power of perhaps 10,000 volts, which was undoubtedly due to the arc passing through checks in the lower petticoat. The insulating power of these insulators was thus hardly lessened by the weathering, per se; at least as far as it had then progressed.

b. A third weathered insulator with 1¼ in. (3.1 cm.) turned off the edge of the top petticoat flashed over at 108,000 volts, the arc passing through a check on the lower petticoat.

A few days after the completion of those tests, to try still other conditions, a further series of tests was made with results as follows:

Ninth Group. (*Tests* 25-27) *High-Frequency Tests.*

These were similar to the previous high-frequency tests, but with the insulator mounted on a wooden pin with tin foil wrapped around the pin up to a point ½ in. (12.7 mm.) below the insulator and grounded.

a. An insulator of the type of Fig. 2 punctured through the head, as before, on the ninth trial. This design of insulator (which insulator was newly made for this last set of tests) had previously flashed over the surface at 156,000 volts, dry, 60 cycles.

b. An insulator similar to Fig. 2 but with 1½ in. (3.7 cm.) turned off the outer edge of the upper petticoat, punctured through the head, but only after 113 trials. This insulator was nearly at the safety point. This insulator previously flashed over at 129,000 volts, dry, at 60 cycles or at 103,000 volts, wet.

c. An insulator similar to Fig. 2, but with 2¼ in. (5.7 cm.) turned off the edge of the upper petticoat, resisted 150 trials without puncture. This insulator was found to flash over at 119,000 volts, dry, at 60 cycles and at 81,000 volts, wet, under the rain test already described.

Tenth Group. (*Test* 28).

The same high-frequency test on electrose insulators of the type shown in Fig. 4 showed no puncture in 150 trials. This insulator flashed over at 115,000 volts, dry, on 60 cycles and 76,000 volts, wet.

Eleventh Group. (*Tests* 29-30).

The same high-frequency test on a porcelain insulator of the type shown in Fig. 5 showed a puncture from the tie wire groove to the pin top, on the third trial in the case of one insulator, and on the second trial on another insulator. This type showed a flash-over at 118,500 volts, dry, at 60 cycles, in one case, and at 95,000 volts in a second case, and a flash-over of 70,000 volts, wet, on the first insulator.

These tests of groups 9 to 11 show that the use of a wooden pin, extending only a short distance out from the threaded portion of the insulator, considerably increased its power to resist the high-frequency stress.

This result must be due to the prevention of the ground potential from getting up inside the insulator, so to speak. Its effectiveness is, however, somewhat limited by the fact that extremely severe potential shocks, such as were here produced, tend to cause a discharge over the surface of the pin into the insulator pin recess. If this pin were cemented air-tight into the insulator the result would presumably be to increase the power of the insulator to stand high-frequency tests.

Certain other tests which are of interest were made to measure the actual voltages reached on the insulator during discharge. Measurements were made by noting the voltages that were required to jump the spark gap marked "measuring gap" in Fig. 11, under certain discharge conditions.

a. During the high-frequency test on a Fig. 2 insulator, (test 8), sparks were observed in the measuring gap when it was set at 10 in. (25.4 cm.), 104,000 volts, (needle points) but no sparks occurred when it was at 11 in. (27.9 cm.), 112,000 volts. There were 125,000 ohms (seven composition sticks) in the shunt measuring gap circuit when these readings were taken. This indicates a maximum voltage during the high-frequency attack of slightly over 100,000 volts. This result, which should be compared with the 150,000 (15-in. or 38-cm. gap) necessary to make the insulator flash over at 60 cycles, shows that there must have been a great local concentration of voltage on portions of the insulator at the high frequency. This is an important point in connection with surges produced by internal causes. If a 100,000-volt static voltage will pass over or through an insulator which flashes over at normal frequency only on 150,000 volts, this fact should be recognized.

b. With the same arrangement as in "a" above, except that the insulator was short-circuited by a No. 18 copper wire, drawn tight between pin and tie wire groove, a voltage sufficient to jump a needle gap corresponding to 15,000 volts was noted, and no spark occurred over the gap when set for 20,000 volts. No resistance was used in the measuring gap circuit in this test.

c. With the conditions of test "b" above, except that five separate No. 18 wires were used to short-circuit the insulator, located at points equally spaced around its circumference, a spark gap of ½ in., (12.7 mm.), corresponding to 10,000 volts, was jumped, but no spark was found with the spark gap set at a value to indicate 15,000 volts. No resistance was used in the measuring gap circuit in these tests.

Discussion of Tests

The obvious meaning of these tests is of great import. Unless there is some reason for believing that the tests are only of limited application or are rendered misleading by some unobserved condition, they mean that many of the line insulators now in service may be expected to break down by puncturing under the attack of lightning rather than by discharge over the surface, which latter is recognized as the desired characteristic. And this in spite of the fact that these insulators may have been thoroughly tested on normal frequencies in the usual way and may have then always flashed over the petticoats as intended. The fact shown in these tests, that an insulator which did not puncture at 250,000 volts on 60 cycles (under oil), punctured after a comparatively few shocks of high-frequency discharge, and without apparently opposing a resistance of much over 100,000 volts (10-in. (25.4-cm.) spark gap), shows how little can be determined from the 60-cycle tests, as to the lightning-resisting capacity of an insulator.

While none of the tests were on trains of suspension insulators, the question immediately arises whether the same effects, that is, local concentration of voltage with high-frequency shocks, will not cause these insulator trains to puncture relatively easily from lightning even when withstanding satisfactorily the most severe tests of the usual sort. Such failure is very likely to be expected. High-frequency tests on such insulator trains should be made by all means, and without delay.

The conclusion also is forced upon us, that if high-tension line insulators are to be adapted to resist lightning to the best advantage, the design of many of them should be radically changed. Such a design study will require much patient investigation. In view of the importance of these conclusions, a critical examination of our tests was made for the purpose of discovering any improper methods or errors that might account for the great weakness of the insulators under high-frequency shocks; nothing, however, so far has been found to explain more than a very small portion of the very great discrepancy between the results of the two types of tests.

Considering the material of the insulators, most of which were electrose, we should say that insulators made in at least four different lots, distributed over a period of several years, showed the same consistent behavior. Further than this, four different types of porcelain insulators were tested and all showed this effect, although the lower-voltage insulators showed it in a less degree than the higher-tension insulators. In the case of the insulators of Fig. 4 and Fig. 5 the shape of the insulator was the same and only the material was different. Of these, the electrose insulator behaved best on the high-frequency test.

One very significant point is that no insulator failed on high frequency on the very first shock. In fact the strain of repeated shocks seemed to be far more severe than that of a few. Probably there is a progressive hammering out of a path through the solid material of the insulator. It will be immediately suggested that this effect may be due to a progressive heating of the material by conduction or dielectric hysteresis, but we are inclined to doubt this. Investigations were made by exploring with the finger during the tests, and, while after a puncture, which would of course be followed by some arcing, there was often a very noticeable rise of temperature at the puncture, exploration before an actual puncture but after the occurrence of many shocks showed no detectable preliminary heating. Furthermore, there seemed to be no difference in the behavior of electrose and porcelain. This matter of dielectric loss and heating is of course one of the matters that should be carefully followed up in future tests along these lines. If the effect of the greatly increased severity of many shocks was due to the heating effect, it is not likely that the cutting off of the petticoats would be so effective in increasing the resisting power.

It has been suggested by some that porcelain deteriorates in quality with time or exposure to the weather. This hypothesis is supposed to explain the fact that insulators which stand up under tests and during the initial months of actual service then seem to fail far more readily at a later time. It is suggested by the behavior of the insulators of our tests that there was progressive deterioration under the intense stresses of these experiments (or under the attack of lightning in actual service), which, while due to electrical forces, are of a physical nature. This would be somewhat analogous to the well-known mechanical disintegration of the surface of glass under repeated surface sparking. In this view, the repeated attacks of these tests represent the anticipated effect of several seasons of lightning storms; to put it another way, the tests serve as a measure of the service durability of an insulator, as far as lightning and static are concerned.

These tests were made in a large transformer testing pit, but it is not likely that the presence of the grounded sides of the pit several feet away could have had any material effect on the results.

While the 60-cycle tests and the high-frequency tests were made on different testing outfits, there can be no great error here. The 60-cycle tests were made on a 300,000-volt transformer, regularly and frequently used for such testing, and the ratio and spark gap methods of measuring the high-tension voltages were about five per cent apart, the voltage actually reported being the spark gap voltage as recommended by the Standardization Rules of the A. I. E. E. The character of the high-frequency tests was of course determined by the series spark gap and the constants of the plate condenser discharge gap. The high-tension condenser had approximately 72 sq. ft. (6.7 sq. m.) surface and a dielectric thickness of 42 in. (1.06 m.) of air. The discharge path of the condenser was roughly rectangular in form, 5 by 7 ft. (1.5 by 2.1 m.), including the series gap and the insulator itself.

An estimate of the natural oscillation frequency of this discharge circuit would be, roughly that it was of the order of 1,000,000 cycles per second or higher. The noise of the discharge during the tests was very loud and some of the observers used cotton in their ears to avoid the disagreeable physiological effect. While the highest voltage of the high-frequency tests was in the neighborhood of 300,000-350,000 volts, and the quantity of the discharge great for laboratory tests, it was of course far short of lightning conditions in both particulars. The frequency, however, may have been comparable with that of lightning.

The probability of the trustworthiness of these tests is greatly increased by the behavior of insulators in actual service, where punctures of a surprising character have occurred at the time of lightning or other disturbance of a static nature. We are informed that trains of suspension insulators and also pin type high-tension insulators which are carefully designed and shown by test at normal frequency to flash over before they puncture, still do in practise actually puncture under lightning strains. It is a fact, however, that many of these insulators at other times do actually flash over in actual service instead of puncturing under static stress, showing that either all insulators or all stress conditions are not the same. This matter cannot be finally cleared up without much experiment and research.

Cause of the Peculiar High-Frequency Effects. Of the most interest and importance is of course the explanation of the cause of the great observed discrepancy between the effect of high-frequency tests and commercial frequency tests. It is too early to speak with certainty, but there is little doubt that the principal cause is the concentration of potential with high frequency upon some local part of the insulating material, with the result of the breaking down of this portion and the throwing of the potential on some other part which is then also broken down. This general phenomenon is well known in related situations; for example, in the behavior of trains of small air gaps in high-tension lightning arresters.

If a resistance and a capacity are connected in series and so adjusted that a given voltage at 60 cycles is evenly divided between the two, and the same voltage at a much higher frequency is impressed on the two, it will be found that the resistance then receives nearly all the voltage and the condenser practically none at all. The same would be true to an even greater extent were an inductance substituted for the resistance. An adjustment may easily be arranged in which at 60 cycles the condenser will take all the voltage and at the high frequency the resistance would take all the voltage. In applying this principle to insulator service, it must be remembered that the change in frequency between 60 cycles and the frequency of lightning is enormous, the ratio being somewhere of the order of 1 to 1000 or 10,000, which gives range enough to permit even a small tendency of 60 cycles to be transformed into a dominating effect on the lightning frequency.

Consider Fig. 9; the small condensers indicate the capacity of various parts of the insulator surface to which the potential of these parts is due, and the small resistances indicate the insulation resistance of the corresponding dielectric material of the insulator. At 60 cycles, the charging current for the several small condensers, 1, 2, 3, can easily flow through the several resistances, 4, 6, etc., without the impressing of any very great potential upon these resistances. With a high frequency, however, as just explained, the full potential may be impressed on the resistance for the moment, or, in fact, for as long as the high frequency lasts. Thus the resistance 4 which charges the surface capacity 1, which is a relatively large capacity, may on high frequency have to support nearly the full voltage of the attack, which it is evidently not adapted to do. But there is also a leakage of current toward the tie wire and conductor which will flow over part of the path of the resistance 4. Since the surface of the pin is much smaller than that of the surface of the insulator, the concentration of leakage current will be greatest at the former and the first break or failure of the insulating material will occur at this point. When this occurs the voltage on the conductor and tie wire will tend to cause a puncture through this weakened material and thus make a puncture from the conductor to the edge of the top of the pin. This is what was actually observed. This explanation is, however, given rather as illustrative of the general tendency of the distribution of force, than as a correct picturing of the action in detail, for this would be very hard to establish directly.

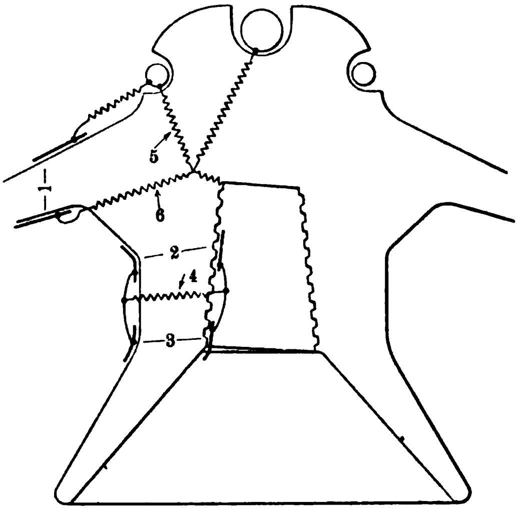


FIG. 9—ILLUSTRATION OF ELECTROSTATIC CAPACITY OF SURFACE AND INSULATION RESISTANCE OF THE VARIOUS PARTS OF THE INSULATOR

According to this view the effect of the lead foil of test 24, which showed a great strengthening of the insulator's resistance, was to permit the charging of the small condenser 1 through the foil in virtue of the capacity of the foil to the pin and in virtue of the fact that a free charge of opposite sign could be repelled to the lower end of the foil. So far as it goes, then, the foil test tends to confirm the distribution of potential assumed above in connection with the discussion of Fig. 9.

Looking at this matter from another point of view, which, however, in substance is much the same, it is evident that the conductor and the wire on the top of the insulator form the electric equivalent of a hemisphere, and that the pin top is in effect a small discharge point near the center of the hemisphere. This form is one in which the distribution of electric field is most uneven, for its intensity is greatly concentrated at the center on the pin top, and much less intensity exists at the conductor and the tie wire. This condition is somewhat similar to that of a cable with a lead sheath and a relatively small conductor inside. It is found, in such a cable, that if the diameter of the conductor is smaller than that of the sheath by more than a certain ratio, little gain in insulation strength is made by increasing the thickness of the insulation and the diameter of the sheath. This is because the potential becomes more and more concentrated at the center and this part fails first, so that the added insulation is later broken down by itself. However, in the case of the tests here described, the effect of resistance and capacity in series, assumed in the discussion of Fig. 9, is probably present, for this sort of concentration comes from high frequency only, while that described in connection with cables occurs at all frequencies. It is significant that the use of a metal cap only weakens the insulators in the tests (see tests 20 and 21), as would be expected from these explanations.

High-Frequency Tests. It will naturally follow from the conditions indicated by these tests, assuming that they are confirmed by later investigators, that it will be desirable to modify our methods of testing insulators for practical work by adding tests of their behavior on high frequency. Such tests presumably need not be made on all the insulators entering into a plant, but on each type, to show that the design is satisfactory. Such tests will be difficult to make, in the first place, because very high voltage and large capacity are necessary for making the tests, and second, because these tests are dangerous to the testing apparatus used and because so far there is no knowledge as to what limits of frequency, voltage, electrostatic capacity or number of repetitions of attack are necessary to give a proper measure of the conditions of actual service. These service conditions will undoubtedly vary greatly in different localities. It can only be suggested here that further study of these phenomena be made as speedily and as exhaustively as practicable.

Design of Insulators. In the matter of new designs of insulators to resist high-frequency discharges, much research should be done, but there are some guiding principles already clear. First, the more widely the live conducting parts of an insulator are separated from the pin, the less will be the stress. Second, the more nearly uniform the electrostatic field between these elements is, the better the condition. Third, wide and thin petticoats add very little strength to the high-tension insulator, for the electrostatic capacity of the surfaces of the outer parts is very great with regard to capacity of the parts nearer to the pin. It is very likely that the capacity of the wide petticoat of the insulator of Fig. 1 or Fig. 2 plays little part in its behavior on high frequency, since the potential stresses may be transmitted through the petticoat by virtue of the capacity of the lower surface in relation to that of the upper surface. This would account to some extent for the behavior observed. It is significant that the type which stood best, that of Figs. 4 and 5, had short and thick petticoats placed low down with regard to the pin top. The heavy ball of insulating material at and around the head of the pin is very likely the chief reliance of the insulator on high frequency.

It will be noted that the design of the present suspension insulator has some points of disadvantage from the point of view of static stresses, if these tests are to be relied upon.

Effect of High Frequency on Lead-Covered Cables. From the analysis of the necessary effects of applying very high frequency to structures having electrostatic capacity and high resistance in series, it is suggested that these high-frequency strains may have a very trying effect on lead-covered cables. Here the layers of the insulating material next to the conductor may receive a far greater concentration of potential from high-frequency stresses than from 60-cycle stresses, for example; in which case static disturbances may break them down at a lower voltage than under normal conditions. As the great susceptibility of cables to static disturbances has been frequently observed in actual service, a series of cable tests after the type of those here reported would be of the greatest interest.

The great difficulty in such tests would be to get some reliable measure of the equivalence of voltages at high frequency and low frequency.

Fig. 10 shows the insulator and pin finally adopted by the power company. The pin consists of an iron base for attachment to crossarm, and metal sleeve with conical bore to receive a wooden pin, which is secured in place by the pressure produced in screwing the sleeve and base together. The wooden pin is impregnated with bakelite to prevent absorption of moisture.

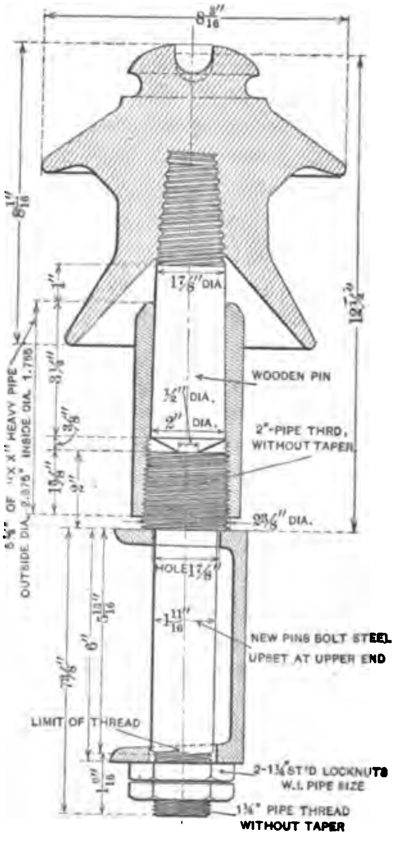


FIG. 10—SECTION OF INSULATOR FINALLY ADOPTED

No attempt was made to cement the pin in the insulator, but this can readily be done if experience indicates that it is desirable. The insulator thus mounted on the combination wood and iron pin will withstand a breakdown test at 60 cycles between a conductor in the tie-wire groove and the iron pin, of 120,000 volts, dry, and 85,000 volts, wet. It is highly probable that if time had permitted, a better design of insulator could have been developed, but the construction of a new line was under way and the order for insulators had to be placed. The design selected was that which our tests had shown to be best able to resist the high-frequency discharges which we were able to obtain in the laboratory. It remains to be shown by experience whether these insulators will resist puncture from all lightning discharges to which they will doubtless be subjected.

Suggestions for Investigations. We would make the following suggestions, the application of which will be clear from what has been said above.

a. Those who wish to get an idea of the behavior of their insulators on high frequency without waiting until a generally accepted test is developed, should utilize the arrangement of apparatus of the tests here described, which has been found very satisfactory and as practicable as any is likely to be.

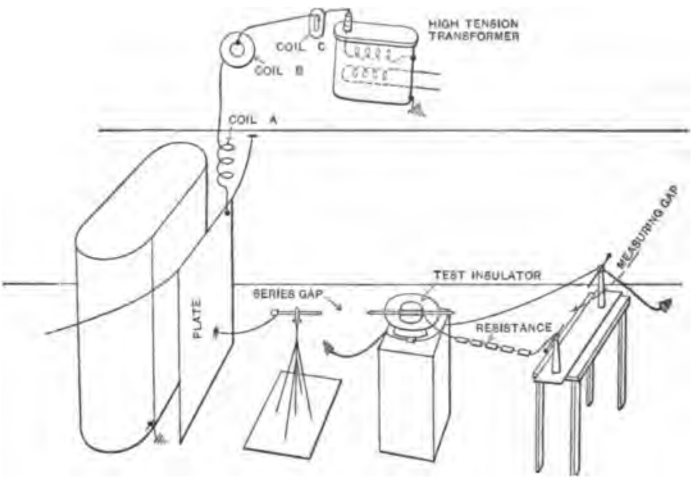


Fig. 11—View of High-Frequency Testing Arrangements

b. Those who wish to do research work on this line of investigation, should study:

1. The effect of frequency itself on some standard type of test insulator, by varying the constants of the high-frequency discharge circuit.

2. The effect of high frequency on trains of suspension insulators.

3. The effect of the distribution and size of petticoats and

the control of the potentials of various parts of the surface of the insulators, for example, by the use of conductors distributed on the surface, as in the above lead-foil test, and especially the location of the petticoats with regard to the top of the pin and the thickness of the base of the petticoats.

4. The effect of a wooden or other insulating pin. Especially the effect of cementing the pin air-tight in the socket. With a wooden-topped pin and an insulator so mounted and shaped that any discharge would take place to the *crossarm* and not to the pin, many of the electrical advantages of a metal pin would be obtained, with probably greatly increased possibilities of resisting puncture by lightning.

5. The high-frequency test as a test, to determine the effect, on the behavior of any insulator, of variations of *test frequency*, of the amount of the *excess series gap voltage* over and above the *flash-over voltage* of the insulator, of the amount of *static capacity* connected with the high-frequency discharge circuit, of the *length* and character of the *discharge* path, and the effect of the method of securing the actual conductor and tie wire during the test.

In conclusion we would state these tests are reported to the Institute for their great interest and suggestiveness, but with the full consciousness that they are far from complete from the broad point of view of the effect of high-frequency voltages on high-tension insulators.

A paper presented at the 278th Meeting of the American Institute of Electrical Engineers, New York, December 13, 1912.

COMPARATIVE TESTS ON HIGH-TENSION SUSPENSION INSULATORS

BY P. W. SOTHMAN

This paper presents an account of work done in connection with the selection of a suitable high-tension insulator for a transmission line operated at 110,000 volts. It is a report of an investigation giving a faithful account of the motives calling for the same, the method adopted and used to carry out the work, and the line of reasoning followed in classifying the results obtained. It is not intended to be a criticism of any individual design or of the valuable work which has been done by others in the same direction. The problem which had to be solved was well defined, requiring no more difficult task than to select from a number of insulators the one best suited for certain predetermined conditions. From the first to the last, the question was one concerned with engineering only, in which biased opinion or partiality was to be absolutely absent. How well this problem has been solved may be judged from the following account and perhaps more so by the tangible results obtained in the years following, during actual operation.

When it was found that the line losses of the proposed power transmission could not be kept at a reasonably low figure unless the system was operated at 110,000 volts between conductors, the question of insulation became at once of greatest importance. Unfortunately, at that time, very few reliable data were available with regard to the operating experience with potentials above 60,000 or 80,000 volts. Notwithstanding the lack of such practical experience, every manufacturer was ready to offer and guarantee an insulator for a transmission line operating at 110,000 volts. Before an attempt was made to draw up specifications for these insulators, a thorough canvass of the situation was made. The different insulator factories were visited to ascertain the manufacturing facilities of the firms and their ability to turn out a rather large order within a specified time. Tests on the proposed insulators were witnessed at the works of the manufacturers and all available information and data bearing on the subject were collected.

While visiting these factories, one could not help being most peculiarly impressed by the widely varying methods of testing employed by the manufacturers to demonstrate the merits of their insulators. This applies especially to the application of artificial rain and to the facilities afforded for observing the effect of the test. As a matter of fact, every manufacturer had his own way of applying rain, and of interpreting the effects observed. It can easily be understood why tests on one and the same type of insulator would show two entirely different results, depending upon where and by whom they were tested.

In view of the seemingly erratic behavior of the insulators during these manufacturers' tests, it was impossible to arrive at a definite conclusion. It became apparent that tests of this character should be performed under absolutely unvarying conditions in order to arrive at reliable figures; and arrangements were at once made to duplicate and elaborate these tests under conditions which could be controlled and changed at will to suit certain predetermined requirements.

The testing equipment of which use was made in the following tests, consisted of a large platform over which was placed a gas pipe, resting at each end upon 60,000-volt pin-type insulators. The insulators were tested one at a time, the small trolley from which they were suspended being moved opposite a mark made in the pipe midway between the supporting insulators, while all other insulators were crowded to one side and out of the way. The test on one insulator completed, it was moved to one side, and the next insulator placed in the proper position. This method proved to work out very well, especially in connection with the rain test described later.

The electrical apparatus consisted of two 50-kw. 2200/150,000-volt transformers in series, fed from a 25-kw. 220/2200-volt transformer.

The maximum voltage which could be safely obtained with this combination was slightly above 330,000 volts, with the two transformers in series, the neutral point being grounded, and

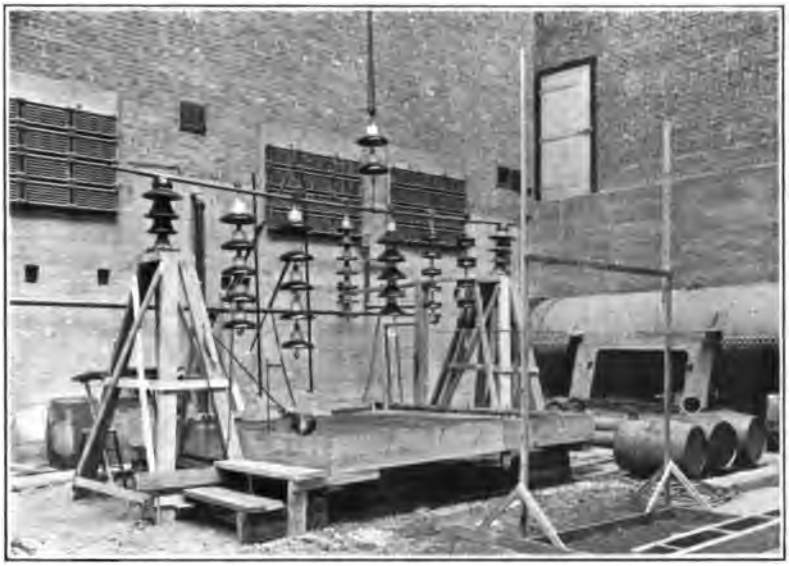


FIG. 1—TESTING PLATFORM FOR SUSPENSION INSULATORS [SOTHMAN]

Insulators supported from insulated pipe on small trolleys—Note groups of nozzles in background for wet tests—Also spark gap in front—Rain gage is shown on left of platform.

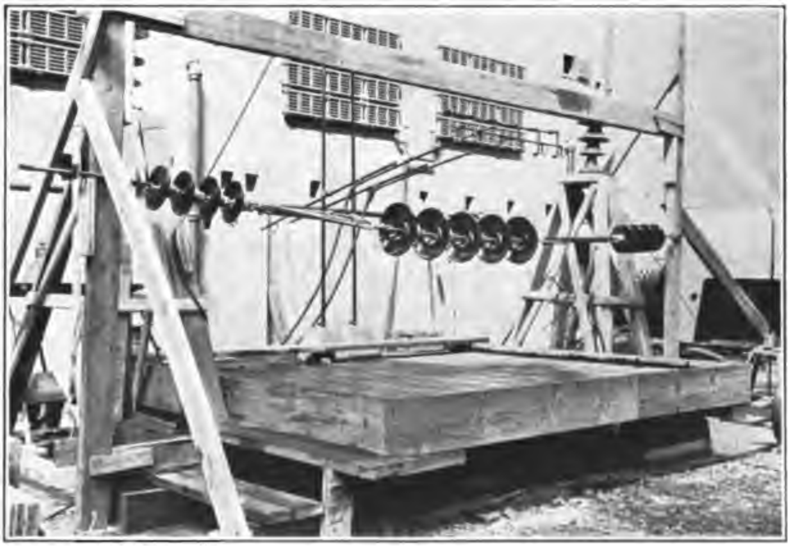
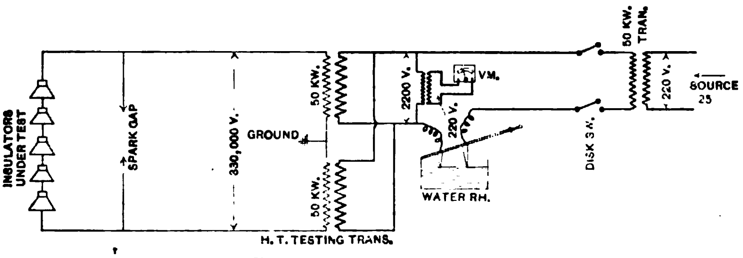


FIG. 5—TESTING PLATFORM FOR STRAIN INSULATORS [SOTHMAN]

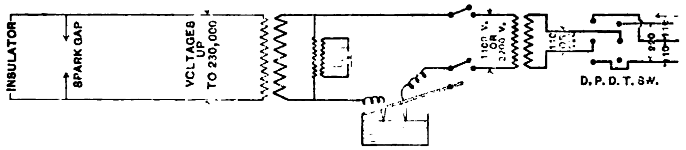
Insulator sections at either end of insulators under test are inserted to prevent leakage to ground. Nozzles are located directly above insulator.

225,000 volts with one transformer alone and ungrounded. The voltage was controlled by means of a water rheostat in the low-tension circuit of the high-tension transformer. The readings were taken on an alternating-current voltmeter previously calibrated with spark gap in accordance with the Standardization Rules of the A. I. E. E. (1907). The voltmeter was connected across the low-tension side of a one-kw., 2200/110-volt transformer, the latter being connected across the low-tension side of the high-tension transformer.

All tests were performed at night in complete darkness. In order to have a permanent record for comparison, photographs were taken of each insulator during the several tests. The time on the clock dial appearing in the illustrations was used as a means of identification.



CONNECTIONS OF TWO TRANSFORMERS FOR 330,000 VOLTS



CONNECTIONS OF SINGLE TRANSFORMERS FOR 230,000 VOLTS

FIG. 2—DIAGRAM OF CIRCUITS OF HIGH-TENSION TRANSFORMERS

The tests were applied in the following order:

1. Dry test.
2. Wet test.
3. Parallel test, dry and wet.
4. Puncture test, under oil.
5. Mechanical test.

The Dry Test consisted of

a. Flash-over test on each section in order to exclude weak or punctured units.

b. Potential test on each complete insulator, also on smaller number of sections. Voltage was applied and raised by successive steps and photographic records were taken while the test was progressing.

Records were kept of the time on the clock dial, which was set for each new test, voltage applied, time of exposure, number of sections, and such other observations as were made during the test which could not be recorded on the photograph.

In this manner, each type of insulators submitted was subjected to the same series of tests under exactly like conditions.

The Wet Tests consisted of applying rain at 45 deg., the precipitation varying from 0.25 to 0.35 in. (6.35 to 8.39 mm.) and finally to 0.53 in. (13.46 mm.) of water per minute. Accordingly each insulator was subjected to three series of tests, in which voltage and precipitation were the variable quantities. The execution of these wet tests was very similar to that of dry tests. Photographs were taken and records made of each test and observations were carefully noted.

For these rain tests, which were the most important of all, the following method was adopted. A number of nozzles of the type used for spraying trees were secured to the ends of pipes cut to suitable length, and these, in turn, were connected to the water mains by means of a rubber hose and arranged to slide along a vertical post. Two groups of nozzles were used, and by means of this arrangement, it was possible to adjust the angle of precipitation, and by moving the nozzles closer or further away from the insulators, to adjust the amount of rain supplied per minute. It was found more expedient to entirely open the valve in the mains, thus operating with full pressure of the standpipe, and to regulate the amount of water by adjusting the number of working nozzles, their heights and distance away from the insulator under test. The amount of precipitation was determined by means of a specially constructed rain gage, consisting of a funnel-shaped vessel with a cover, provided with an aperture five in. (12.7 cm.) in diameter. The edges of the opening were slightly raised to prevent the water from spilling and splashing over the top of the funnel when striking it at an angle of 45 deg.

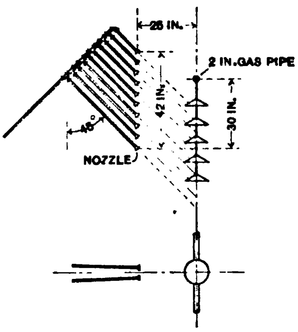


FIG. 3—ARRANGEMENT OF NOZZLES FOR 0.53 IN. PRECIPITATION PER MINUTE

The gage was held in the rain at the points where the several sections of the insulators would be located, and the quantity of water was measured with a graduated glass. As a rule the gage was operated for four minutes and the fall of water determined from the amount gathered during that time. By setting the nozzles and adjusting the spacing, the correct amount of precipitation could be obtained, and this setting was left undisturbed during each series of tests. One insulator after the other was moved to the mark on the pipe and voltage applied, beginning low and increasing by successive steps.

It was found that although water flowed freely over all the sections, wetting an area of 7 ft. (2.13 m.) in diameter, on the platform, and thoroughly flooding the top of the sections, the inside of the insulators remained practically dry except for a few drops. For those reasons, it was necessary to apply the rain for some time before voltage was applied in order to arrive at reliable and unvarying results. The water was turned off when insulators were changed and turned on again when ready for test. A long series of check tests showed that the precipitation was constant within the error of observation after turning water on and off, provided the valve was always turned on wide open.

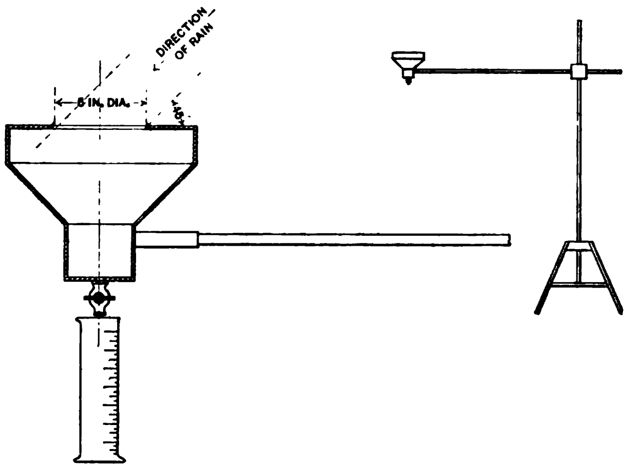


Fig. 4—Rain Gage and Stand Used for Determining Fall of Water

In most cases, the same underhung suspension insulators, strung horizontally, were subjected to a series of rain tests to ascertain their performance when used as strain insulators, but on account of this horizontal position, required a somewhat different method of supporting. The insulator was strung between two well-braced upright wooden posts. In order to prevent leakage to ground, a number of units were inserted between the posts and the insulator under test. The nozzles, twelve in number, were located directly above at a distance of 25 in. (63.5 cm.) from the center of the insulators, directing the spray of water, which could be raised from 0.22 to 0.5 in. (5.58 to 12.7 mm.) and even 0.75 in. (19 mm.) per minute at an angle of 45 deg. either toward the inside or the outside of the sections. The water was measured with the same rain gage used in previous tests, at eight different points within the space occupied by the insulator when in place, allowing the gage to remain thirty seconds in each of the eight positions.

Parallel Test. A most interesting series of tests with all insulators connected in parallel was made later, in order closely to follow their performance simultaneously at different voltages. The insulators, composed of a proportionately smaller number of sections, were supported from the pipe, equally spaced, their lower ends connected by a common bus. Voltage was applied and gradually raised as in previous tests. As soon as a voltage was reached at which one of the insulators would show signs of distress, a photographic record was taken of the whole set, after which the failing insulator was disconnected from the bus and the voltage increased until one of the remaining insulators would fail, and so on. A similar series of tests was performed with the insulators subjected to rain. Each insulator had its own set of nozzles and the flow of water was regulated to be the same for every string. The test was made with 0.15 in. (3.8 mm.) of water per minute at 45 deg.

Puncture Test. Under ordinary conditions, it is almost impossible to puncture an insulator, in dry air, since a well-proportioned insulator will flashover at a voltage well below its puncture voltage. To obtain values for the puncture voltage, it is necessary to immerse the insulator under oil and to take a number of other precautions, like the protection of leads, etc. Following this plan, a series of tests was performed in which this voltage was determined for all the different types of insulators.

Mechanical Tests. The testing device used to determine the breaking strength of suspension insulators, consisted of a frame-work in which the insulator was fastened by links and steel cables and the tension applied by means of a screw acting on a lever. A robust dynamometer indicated the maximum pull exerted by the screw and that pull multiplied by three, the ratio of the lever arms, gave the actual tension on the hook of the insulator. Voltage was applied across the insulator while pulling, but it was found that the insulator punctured always at the moment of fracture, so this method was discontinued on subsequent tests. A number of tests were made with each type to arrive at a fair average figure, and photographs were taken of the appearance of the fractures.

The above is a brief outline of the apparatus and methods used in making the tests on high-tension suspension and strain insulators. A number of post type insulators were also tested in a similar manner. As there were but two types offered, neither of which met the specified tests, considerable development work was necessary until fairly satisfactory types were evolved.

After completion of all design tests and before the final selection of the insulator best fitted to fulfil the specified requirements, one week was set aside for witness tests. This was done to demonstrate to the manufacturers and their engineers the method which was followed in making these tests and to give them an opportunity to make their own observations with regard to the results obtained under conditions controlled in accordance with the tests specified. These conditions, as mentioned before, were kept unaltered during all tests and were constantly checked and adjusted, if this was found necessary.

The tests performed in the presence of the manufacturers were really nothing else but a repetition of the tests already made, and incidentally, served the purpose of furnishing an additional set of confirming results. In every case, these results checked closely with those obtained during previous tests, as the conditions under which each test was made could easily be duplicated.

TEST RESULTS

SUSPENSION INSULATORS

As to the method of comparing the performance of the different types of insulators under test, it became apparent from the start that no standards existed which could be followed or used as a guide. From an academic standpoint it would, perhaps, have been of importance to measure the watts lost for each type of insulator under varying conditions. This method may give results which would allow of direct comparison, but the difficulty of measuring power accurately under the conditions imposed by the test, and at such high voltages, appears to be out of proportion with the expected accuracy of the results. It was, therefore, decided to compare qualitative rather than quantitative results. Under the assumption, which should not be far from correct, that the power loss of an insulator would make itself manifest in a proportionate display mostly of luminous character, the direct comparison of this visual display with the voltage required to create it should give a fair means of judging the relative insulating value of two insulators, provided all other conditions remained the same and unaltered. In applying this method in practise, there are, of course, a number of other considerations requiring attention. For instance, the display of luminosity may appear gradually in direct proportion with the voltage applied, or it may appear rather suddenly after a certain limit of voltage has been reached; or else, the display may appear to be localized at some parts or points, which, though a portion of the insulators, are of no value to its insulating quality and merely show faulty design. As will be explained later, the presence of such parts is always the cause of failure, regardless of the quality and design of the porcelain parts themselves. Taking into consideration the many sources which contribute towards the discharge of an insulator under potential, and by following the system of comparison outlined above, it was possible to classify the insulators according to certain well-defined merits and demerits. After balancing all merits of an insulator against all its demerits and by successively eliminating those insulators possessing the greatest number of demerits, it was possible to arrive at one type which had the least number of disadvantages and the most of the advantages.

In the discussion of the actual test results obtained, the different types of insulators are designated with the letters *A*, *B*, *C*, *D*, *E*, and *F*, in accordance with the half-tone illustrations representing the different makes. From the results of the dry test, it can safely be said that all insulators with the exception of types *A* and *B* withstood the tests of three times line voltage more or less satisfactorily. The following table gives the actual results in condensed form:

Type	Number of units	Brush discharge becomes visible at	Heavy static discharge but no flash-over
A	5	150 kv.	330 kv.
C	5	250 "	330 " on top
D	5	250 " on hook	330 " at point of hook
E	7	200 " on cotter-pin	Not excessive at 330 kv.
F	5	250 "	" " " "

From the wet tests, which were the most significant of all, the final results of the series executed with 0.5 in. (12.7 mm.) water per minute are given below:

Type	Sections	Discharge becomes visible below	Failure occurs at
A	5	150 kw.	160 kw.
C	5	225 "	265 "
D	5	250 "	280 "
E	7	225 "	260 "
E	8	250 "	300—310
F	5	250 "	300 "

The first visible discharge occurs invariably around the top section, in the form of streamers radiating in a more or less oblique direction away from the edge of the top skirt. The subsequent breakdown of the insulator appears to grow gradually with increasing voltage. This is especially noticeable on type *A*, whereas it is less prominent on other types; *i. e.*, they may hold out fairly well until a critical voltage is reached. Above this voltage, the insulator will fail rapidly with relatively slight increase of voltage.

As a rule, more or less active discharge always takes place around the pin of the insulator within the hollow of the petticoat on all insulators designed along the orthodox lines of a pin insulator like types *C*, *D*, and *F*. This discharge is practically absent in the one-piece insulator *E*, which is not provided with an inner petticoat. Any discharge which occurs at the point where the pin issues from the porcelain disk is effectively broken up and confined within a small, concentric corrugation.

The character of the breakdown is different for each type of insulator. Type *A* breaks down on account of the excessive leakage; the whole insulator becoming conducting, as it were. The breakdowns of the other types have more the character of a flash-over from one section to the next, the moment the voltage is high enough to break through the wet and conducting air enveloping the sections. This breakdown voltage could be ascertained with fair accuracy, and these figures were used as merits or demerits in accordance with their relative values.

From these records one feature is especially worthy of note. Almost in every case the discharge of the insulator was started by a sharp corner or point of the metal fittings by means of which the sections were held together. In all cases except *A*, *B* and *D*, the static field around the insulator sections was uniformly distributed in consequence of the almost symmetrically arranged parts occupying a space within this field. The word " almost " is used, as the presence of even slight projections like the head of a cotter-pin in the bolt linking the two sections together was enough to break up the air at that point after a certain voltage was reached. In case *D* this phenomenon was particularly noticeable. The metal parts in the shape of two prominent hooks were so large that the field was excessively distorted, creating highly uneven stresses in the air. The highest stresses are localized at the sharp point of the hook, as is apparent the moment the voltage is raised above a critical value. That this distortion of the field is always accompanied by a premature failure of the insulator can be proved by eliminating those unsymmetrical iron parts, covering them, for instance, as was done in some experiments, with a cylindrical metal shield. Although the striking distance is thereby somewhat reduced, the insulator is capable of withstanding a voltage at least 10 per cent over and above that which it was able to withstand with the hooks bare. In case of *A* the distortion of the field is especially prominent. As beautiful as the link feature appears from a purely mechanical viewpoint, it creates most unfavorable stresses in the air between the disks, likewise in the holes within the disks. The stresses in the porcelain cap are more uniformly distributed in all cases except *A* and *B*. In these latter, the dielectric is strained the most at that point where the interlinking metal parts have their least separation from each other. In all other cases in which use is made of a metal cap and pin, the stresses in the porcelain are higher closer to the pin, and decrease gradually and uniformly towards the cap. As long as the highest value of this stress is well below the safe working limit the insulator is not endangered. But in every case, the diameter of the pin, together with the voltage it assumes, remain the determining factors for the highest stress of the porcelain within the cap. For this reason, it seems that no advantage is gained by the use of a two-piece insulator. Theoretically correct. the idea of using two thicknesses of porcelain would appear to offer a larger margin of safety. In practise, the idea cannot be worked out to its full efficiency, for the size of the pin cannot be increased without correspondingly increasing the size of the cap, making an insulator of this sort too bulky and altogether impractical.

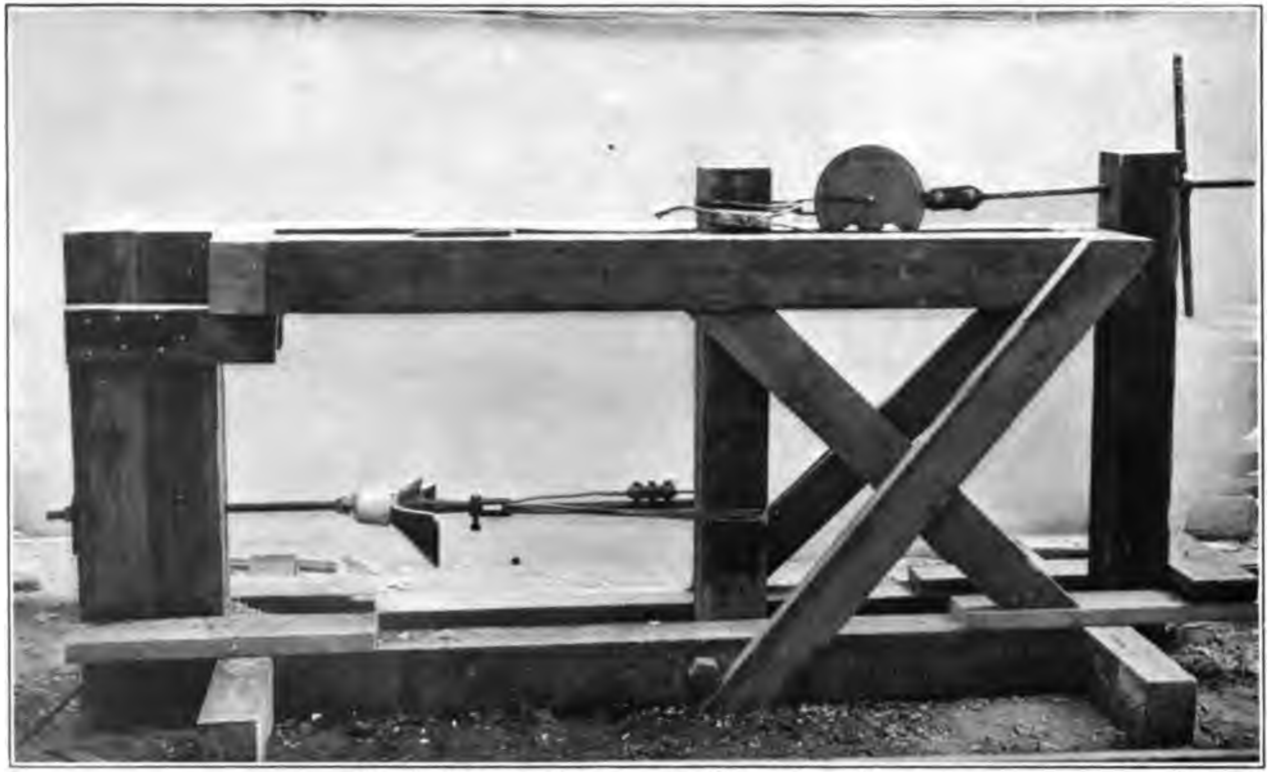
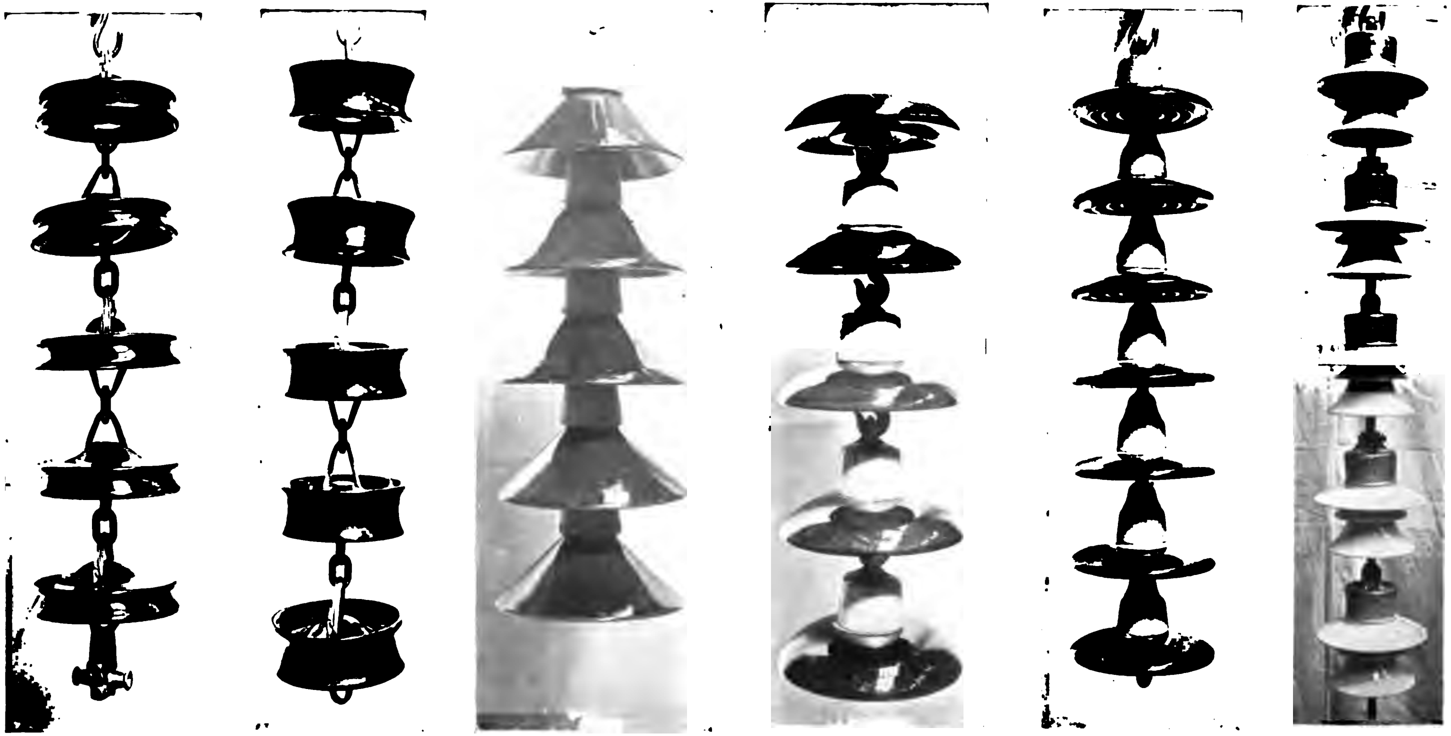


FIG. 6—PULLING MACHINE FOR MECHANICAL TESTS [SOTHMAN]

Insulator section is fastened by means of cable and links to lever, operated by screw arrangement on the right—Dynamometer indicates maximum pull



Type A Type B Type C Type D Type E Type F [SOTHMAN]

FIG. 7—SUSPENSION INSULATORS SUBMITTED FOR TEST

Types A, C, D, E, and F are regular suspension insulators—Type B is a proposed strain insulator.

FIG. 8a—TYPE A—160 KV.-½ IN. WATER PER MIN.—45 DEG.

Under side of each section is flaming due to excessive leakage.

[SOTHMAN]

FIG. 8b—TYPE C—265 KV.-½ IN. WATER PER MIN.—45 DEG.

Breakdown of insulator in consequence of flash-over—Note the point of discharge on left side of cap of second section.

FIG 8*c*—TYPE D—280 KV.—½ IN. WATER PER MIN.—45 DEG.

Breakdown of insulator in consequence of flash-over—Note localized discharges from point and back of hooks

[SOTHMAN]

FIG. 8*d*—TYPE E—SEVEN SECTIONS—260 KV.—½ IN. WATER PER MIN.—45 DEG.

Breakdown of insulator in consequence of strong leakage from section to section—Note discharges from points (cotter pins) on cap.

FIG 8e—TYPE E—EIGHT SECTIONS—310 KV.—½ IN. WATER PER MIN.—45 DEG.

Breakdown of insulator in consequence of strong leakage from section to section—Note discharge from points (cotter pins) on cap.

[SOTHMAN]

FIG. 8f—TYPE F—300 KV.-½ IN. WATER PER MIN.—45 DEG.

Breakdown of insulator in consequence of flash-over from section to section—Note heavy firing inside petticoat in first and second sections—Also point discharges (cotter pins.)

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[SOTHMAN]

FIG. 9*a*—TYPE D—ONE SECTION AT 117 KV.
Note discharge localized at point of hook.


[SOTHMAN]

FIG. 9*b*—SAME SECTION (*a*) AT 117 KV., BUT WITH HOOK PROTECTED BY BOTTLE-SHAPED METAL SHIELD.
Note absence of static over top umbrella, but strong discharge over petticoat.

FIG. 10*a*—TYPE D—FIVE SECTIONS—280 KV.—½ IN. WATER PER MIN.—45 DEG.

Note discharge localized at point and back of hooks.

[SOTHMAN]

FIG. 10*b*—TYPE D—SAME AS PREVIOUS TEST (*a*) EXCEPT HOOKS PROTECTED BY BOTTLE-SHAPED SHIELDS

Note absence of distress.

[SOTHMAN]

FIG. 10c—SAME AS PRECEDING TEST (*b*) EXCEPT VOLTAGE RAISED TO 300 KV.

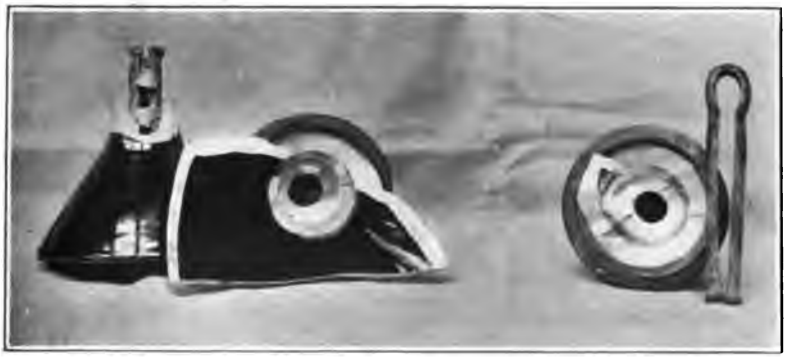
Note uniformly distributed discharge.

FIG. 11*a*—TYPE B—FRACTURE OCCURRED AT 8000 LB.

[SOTHMAN]

FIG. 11*c*—TYPE D—HOOK PULLED OUT AT 9000 LB.

Poor mechanical design—holding power of hook reduced to the shearing strength of cement.



[SOTHMAN]

FIG. 11*b*—TYPE C—FRACTURES OCCURRED AT 15,000 LB.

Note distortion of U-shaped eye-bolt indicating excellent holding power of construction.

[SOTHMAN]

FIG. 11*d*—TYPE E—FAILURE OCCURRED AT 7500 LB.

Note sound fracture—eye-bolt pulled out at 10,800 lb. The latter was cemented with litharge and glycerine which had remained soft.

[SOTHMAN]

FIG. 11*e*—TYPE F—AVERAGE BREAKING LOAD 6900 LB.

Holding power of lips cut in eye-bolt very limited—Plaster of paris not suitable for cementing.

From all these considerations it was found advisable to have the metal parts of the insulators as symmetrical as possible, presenting a smooth and even surface void of any projection whatever. In accordance with this suggestion the ball and socket type connection was subsequently devised by one manufacturer to meet this contingency.

Another feature which militates against the use of a two-piece insulator is the fact that it is impossible to equalize the stresses in the two pieces under all and any conditions. In a dry condition, the porcelain of the inner petticoat is far less strained than when the top section is wet and conducting. The working efficiency of the material is bad and the cost of a two-piece insulator is necessarily high.

Outside of the design determining the electrical efficiency of the insulator, the method of mechanically connecting the different units to a string is of no little importance. The practise of cementing a pin into a porcelain shell and subjecting the pin to a strain may, at first sight, be regarded by many engineers as a doubtful proposition, and it was in that light that the interlinking feature of types *A* and *B* was devised. As already mentioned, this link feature has proved to be a failure, at least electrically, and the cemented pin has so far given no cause for complaint. The breaking strength of the cemented pin, on the other hand, had been found to be far superior to the wire link type, in some cases being nearly twice as strong. The device of type *C* is unquestionably a most splendid solution of the problem, as for an actual holding power, this type can hardly be excelled.

As stated elsewhere, it was possible to tabulate the test results and to classify the insulators according to their merits and demerits. How this was done will appear from the two following tables. The first table contains a summary of characteristics, *i. e.*, a tabulation of all features which can be measured and expressed in one or another unit. The first column of this table contains characteristics like diameter, spacing, number of sections, length over-all, open spacing between sections, widths, etc. A number of other characteristics relating to design are also added, like number of pieces, method of connecting the sections, material, etc., and finally, characteristics bearing directly on their electrical efficiency, like leakage distance, thickness of shell, dry surface, etc. Opposite each column representing the actual figures corresponding to each type of insulator were placed certain comments, indicating observations or deductions with regard to those particular characteristics.

Summary of characteristics of 110,000-Volt Suspension Insulators

Characteristics	Type *A*	Comments	Type *C*	Comments	Type *D*	Comments	Type *E*	Comments	Type *F*	Comments	Remark
MECHANICAL											
Size:											
Largest diameter.	10½ in.		14 in.		14½ in.	Too large	10 in.		8¾ in.		
Spacing.........	8 "		8 "	Too close	10 "		6 "		10½ "	Too far	Large number of sections of advantage electrically, not mechanically.
No. of sections...	5 "		5 "		5 "		7 "	good	5 "		
Total length.....	40 "		40 "		50 "		42 "		52½ "	Too long	
Open space between sections..	5 "	Small	5 "	Too small	8 "	Good	5½ "	good	6 "		
Weight:											
Per section (lb.).	9¾		22	High	24	Too high	10		12¾		
Total (lb.).......	48¾		110	High	120		70		64		
Strength.........											
Breakage in handling..........	None	Good	High	Very bad	None	Good	None	Very good	Low	Bad	
Mechanical design											
Number of shells.	One		Two		Two		One		One		Two piece insulator theoretically better than one piece but proper proportions are not obtained in practise. Should present perfectly symmetrical and smooth surface to prevent premature discharge ....
Cement used......	None		Portland		Portland		Litharge, also Portland		Alabaster plaster		
Connection between sections	Brass wire and links	Poor	*U* bolt and pin	Good	Drop forged hook	Bad	eye bolt & pin	Good	Eye-bolt & pin	good	
Renewal of sections..........	Difficult	Very bad	Simple		Simple		Simple		Simple		
Manufacture:											
Porcelain........	Bad		Good		Fair		Good & tough		Good		
Glaze...........	Rough	Bad	Rough	Bad	Glossy	Good	Glossy, poor finish	Fair	Glossy	Good	
Color...........	Chocolate		Brown		Yellow brown		reddish brown		White		
ELECTRICAL											
Design:											
Leakage distance per section....	11½ in.	Too small	24 in.	Good	20 in.	Good	13 in.	Sufficient	14½ in.	Good	
Dielectric thickness..........	1 × ¾ in.	Sufficient	2 × ⅝ in.	Sufficient	2 × 9/16 in.	Sufficient	1 × ¾ in.	Sufficient	1 × ¾ in.	Sufficient	
Premature discharge......	None		None		Point of hook	Very bad	Point of cotter pin	rather bad	Practically none	Good	
Brush discharge appears	In and around cavities of porcelain	Very bad	Lower edge of cap and base of U-bolt		Base of hook and lower edge of cap		Lower edge of cap and base of eye-bolt		Between top and middle petticoat & base of eye-bolt		
Dry surface......	One flange	Poor	Petticoat	Good	Petticoat	Good	Three concentric flanges	Sufficient	Two petticoats	Good	

The second table is really a condensed statement of all results from actual tests, both electrical and mechanical. The table also contains the specification requirements. In compiling this table, a certain assumption was made which, although not absolutely correct, was justifiable in the light of the present comparison. For instance, in reference to the number of sections used, it was assumed that the share of line voltage per section was in direct proportion with the line voltage and number of sections.

According to the values given in the table, each section of insulator is subject to a voltage of approximately 22 kv. in all cases, except in type *E*, where this voltage drops to 15.7 and even 13.8 kv. per section, according to whether a complete insulator is made up of seven or eight sections, respectively. With the flash-over voltage per section known, the ratio of flash-over voltage to share of line voltage can be determined, this figure being equivalent to a safety factor against flash-over for the individual section. From the table it becomes at once apparent that type *E* has a very high ratio in comparison to type *A*, which has the lowest. Likewise, with the puncture voltage per section known, the ratio of puncture voltage to share of line voltage represents another safety factor against puncture, which, as in the former case, is the highest for type *E* and lowest for type *C*. The voltage per inch leakage distance has been found to be highest with type *A*, and lowest with type *C*, type *E* being next highest.

The table also gives the approximate percentage of sections puncturing. During the long run of the test it was found that insulator sections would puncture for no apparent cause and a record was kept of all these failures. At the end of the test it was considered of importance enough to compare these percentages with each other, assuming that these values could be taken as a fair indication of the superiority of one insulator above the other, with reference to its dielectric strength. From the table it will be found that types *F* and *A* both had exceptionally high percentage of puncture as compared with the low percentage of type *E*.

The average breaking strength of the different types of insulators as found from numerous tests are tabulated in the last-named table under " Mechanical Tests." The highest values were obtained with type *C*, the lowest with types *E* and *F*, all three types being cemented insulators. It must be said in d -

RESULTS OF TESTS ON 110,000-VOLT SUSPENSION INSULATORS

	Specification requirements	Type *A*	Type *C*	Type *D*	Type *E*		Type *F*
MECHANICAL							
Strength:		lb.	lb.	lb.	lb.		lb.
Breaking strain	8000 lb.	Average 9430	14000	10700	7650		7200
		Lowest, 8700	9600	7800	5100		5100
		Highest 10200	16200	12600	10800		8700
ELECTRICAL							
Dry tests:					7 sections	8 sections	
Share of line voltage per section		22 kv.	22 kv.	22 kv.	15.7 kv.	13.8 kv.	22 kv.
Flash-over " " "	3 times share of line voltage	65—70 kv.	85 "	90 "	75—80 kv.		105 "
Puncture " " "		135 "	130 "	above 140 kv.	135 kv.		above 135 kv.
Approximate per cent of sections puncturing		75 per cent	33 per cent	30 per cent	10 per cent		85 per cent
Brush discharge becomes visible below (on complete insulator)		150 kv.	225 kv.	250 kv.	225 kv.	250 kv.	250 kv.
Ratio flash-over voltage to share of line voltage (safety factor)		3.0	3.8	4.1	5.	5.7	4.75
Ratio puncture voltage to share of line voltage (safety factor)		6.1	5.9	6.5	8.6	9.7	6.1
Voltage per one-in. leakage distance in kv.		1.9	0.91	1.1	1.2	1.06	1.5
Wet tests:							
(One-half in. water per minute at 45°, complete insulator.)							
Failure at approximately		160 kv.	265 kv.	280 kv.	260 kv.	300 kv.	300 kv.
Nature of failure		Excessive leakage	Flash-over	Flash-over	Flash-over and leakage		Flash-over
Flash-over occurs		Gradually	Suddenly	Suddenly	Suddenly		Suddenly
Recommended working limit	220 kv.	80 kv.	200 kv.	220 kv.	200 kv.	225 kv.	225 kv.

fense of the last two types, that subsequent tests on regular stock insulators showed a breaking strength of not less than 8000 lb. (3628 kg.), the relatively poor results obtained by the former tests being due solely to the cement which had not properly set.

From all observations and test results, the following conclusions were drawn up on which a classification of the various types of insulators, in the following order, was based:

1. *Type F.* This type meets electrical requirements but not the mechanical tests. Design, however, can be readily modified to meet mechanical tests and incidentally, improve the insulator electrically. Percentage of puncture can be kept down by rigid inspection. Insulator shows high class of workmanship and material.
2. *Type E.* This type meets electrical tests with eight sections, but not the mechanical tests. Insulator should, without material modification of design, be able to come up to the required mechanical tests. Slight increase in diameter should also increase electrical efficiency of insulator. Large number of open spaces between units is of advantage. Insulator is strong, durable, light and compact. Method of connecting units should be modified so as to present symmetrical and smooth surface to prevent premature discharge.
3. *Type D.* This type meets electrical and mechanical tests. Insulator has, however, very faulty design. Diameter too large; weight and bulk too high. Inefficient cementing of hook. Hook feature to be condemned, causing distortion of field and premature discharge. As a two-piece insulator, electrical stresses of petticoats are not balanced.
4. *Type C.* This type meets the mechanical but not electrical requirements. The insulator is far too fragile, causing excessive breakage in ordinary handling. Sections are too close upon each other, leaving too small a clearance between units. As a two-piece insulator, electrical stresses of petticoats are unbalanced.
5. *Type A.* This type meets mechanical but not the electrical requirements.

Final selection of the type *E* insulator was made in consequence of various favorable considerations. Type *F* is of European design and manufacture, and its selection would have entailed several difficulties, especially in regard to delivery. Next to type *F*, type *E* was found to be the most suitable and practical insulator, both from an engineering and a commercial point of view, and this consideration, together with the outlook for better deliveries, determined its adoption. It must be mentioned that the diameter of the insulator was subsequently changed from 10 in. (25.4 cm.) to 11 in. (28 cm.), and that the ball and socket type connection was universally adopted.

STRAIN INSULATORS

No special insulators were offered for use as strain insulators excepting the one designated as type *B*, which is but a variation of type *A*. In order to increase the efficiency of the suspension insulator for use as a strain insulator, one or two additional sections were added by the manufacturers. From numerous tests similar in character to those performed on suspension insulators, it was found that none of the different types recommended by the manufacturer met the requirements of the specifications for wet test. Excessive leakage at voltages below the standard fixed in the specification (220 kv.) made their use as strain insulators prohibitive. As one exception, type *E*, using as many as ten sections instead of seven, showed some advantage over the others, but even at its best was found to be not entirely satisfactory. In every case, failure of the insulator did not occur suddenly, but very gradually. Distress begins to be visible at voltages as low as 110 kv., this distress increasing in almost direct proportion with the voltage.

After considerable experimenting with new designs and numerous combinations, it was found that the use of ten sections of the adopted insulator type *E* gave the least unsatisfactory results of all. With a modification of the design of the cap, increasing the breaking strength of the insulator, this type was finally adopted for use as strain insulators.

The preceding sections of this paper dealt with the investigation only in so far as it covered the selection of a suitable insulator. With this question settled, there remained one not less important part of the work, viz.: the supervision of the factory tests on some 140,000 insulator sections. The specifications called for distinct electrical and mechanical tests on each unit, and the acceptance of the insulators was based on their ability to pass these tests. Outside of these specified tests, the insulators had to conform to certain well-defined standards as to shape, quality, finish, etc. The whole inspection and supervision of tests was comparable to a weeding-out process, and it was the duty of the inspectors to see that this process was carried out in conformity with the specifications. After successful completion of all factory tests, the insulators were packed and shipped to the nearest railroad siding where they were delivered to the contractors.

Even though the specifications were drawn up with the utmost care, taking into consideration every phase of the work involved, it was found during the course of this investigation, and especially during the subsequent work at the factories, that they did not meet every contingency. In a number of instances it was found almost impossible to hold the manufacturer down to the terms of the specification, but that he had to be allowed a considerable margin in his favor. Although the manufacturer guaranteed to furnish insulators in accordance with samples submitted and approved, in the regular course of manufacture it was found to be a commercial impossibility to keep the standard at par with the hand-picked samples. In prescribing limits between which variances were allowable, both mechanically and electrically, it proved to be a very difficult matter to draw a distinct line. After the contract was let and the manufacture was progressing, difficulties were encountered in determining when an insulator had successfully passed certain inspection or tests, requiring several conferences between manufacturer and engineers in order to come to a definite understanding. From all these experiences and observations, it was found that specifications for high-tension insulators were susceptible of a number of amendments, which, if properly worked out, would go far towards minimizing possible misinterpretations and misunderstandings.

In viewing this work now, after a number of years rich in experience have passed, and in the light of all after events, it must be admitted that the problem of insulating high-tension transmission lines is yet far from being solved. Much valuable experience has been gained which in the course of time will undoubtedly be utilized to improve methods and means of effectively insulating and protecting a transmission line. With special reference to the question of insulators and their future development, it will be understood by all, that work in this direction can be carried out successfully only with a close co-operation between the ceramic and operating engineers. The question of properly designing and loading an insulator is one which presumes a thorough knowledge of transient phenomena occurring on a transmission line and their proper interpretation with regard to the effect on the insulators. Once these phenomena are known and their effect thoroughly understood, the drawing up of specifications for high-tension insulators will become a matter less open for conjecture. For it is quite probable that precautions, now taken in one direction, are often unwarranted and uncalled for, whereas, on the other hand, liberal allowances made in other directions may be of the greatest detriment to the line and insulators.

In summing up the experience gained during the foregoing investigations, especially with regard to testing, the following points are presented as worthy of future consideration and discussion.

They are given in the form of an itemized list of headings or questions to which are added a few remarks, commenting on certain experiences gained either in the field, in the factory, or in the testing room.

Design Test.

What design test should be specified for insulators intended to work at a certain voltage?

In the present case a dry test of three times line voltage was specified. Experience, however, seems to indicate that even though the insulator may meet this arbitrary condition, its safety against failure in actual operation is not thereby assured. It is a well-known fact that an insulator is never endangered by the steady static forces but rather by those sudden and transient movements appearing in a system and caused either by external or internal disturbances. It is not the steady dead-load which is dangerous to a bridge or structure, even though it may assume a value two or three times higher than the load for which it was designed, but those moving loads which will set up vibrations and surges in the structure, especially if they are rhythmical in character and coincide with the natural swing of the bridge. For this reason, soldiers are generally not permitted to cross a bridge while marching in step. Although the actual forces coming into play are insignificant in such cases, their effect may, under certain conditions, become disastrous. It is without doubt that the insulators of a transmission line are very susceptible to similar phenomena, and to guard against failure from these causes, it will be necessary to impose tests of an entirely different character.

Method of supporting insulator during test. Should insulator support be grounded and voltage applied to groove, or should voltage be applied between groove and pin, both ungrounded?

At first sight, it may appear as if the manner in which the insulator is supported during tests is of no importance. As a matter of fact, the proximity of large grounded or ungrounded bodies close to the insulator under test will materially affect the distribution of the static field around the insulator, especially when these tests are performed with one side of the potential grounded; the best method of supporting an insulator and applying a test would undoubtedly be the one which closely approximates conditions under which the insulator works in actual operation.

> Capacity of testing transformer and generator. Method of regulation of voltage. Determination of correct voltage during test at any time. Should spark gap be used or static voltmeter, or should step-down transformers in connection with voltmeters be used?

The kilowatt capacity of the testing outfit cannot be too large, for the puncture of a weak insulator may never be discovered but for the power back of the transformer.

As to the method of regulating the voltage: It must be accomplished by means which do not alter the shape of the alternating-current wave form and the latter should be a true sine curve. From the different means employed today, like water rheostat, induction regulators, auto-transformers, etc., the method of regulating the voltage of the alternator by controlling its field current seems to offer the most advantages.

In reference to the determination of the voltage, several methods are at present in vogue. The most common of these methods involves the use of a properly calibrated spark gap. An ordinary voltmeter in connection with a step-down transformer is also used, and finally, in some instances, static voltmeters have given excellent satisfaction. Each of these methods, however, has its drawbacks. The spark gap setting is susceptible to atmospheric conditions. It may also introduce undesirable oscillations at the instant of discharge. The breakdown voltage of an insulator cannot be determined by means of spark gap alone, which in this case must be supplemented by a voltmeter reading. Another feature is the burning off of the points, each time the gap discharges, a matter which cannot always be avoided. The method employing step-down transformers is not altogether reliable and should be used in connection with a gap from which the voltmeter readings are calibrated. Undoubtedly the best method to ascertain the value of the testing potential is by means of a static voltmeter of suitable design.

Frequency, permissible distortion of wave form, effect of harmonics and high frequencies.

The effect of the frequency upon the results is a matter which is very seldom fully appreciated. The value of the charging current increases in direct proportion with the frequency, and the effect of this current will naturally follow a similar law. An insulator tested at 60 cycles will show different results than when tested at 25 cycles, the potential being the same in both cases. If for any reason, the wave form of the alternator is not a true sine curve, the results may become extremely misleading, to say the least. In one case which is on record, a porcelain transformer bushing was tested at two different places under apparently identical conditions, and yet the results differed by nearly 40 per cent. The tests were checked and repeated several times with no better results until, finally, the wave form of one of the alternators was found to have a very pronounced 13th harmonic. Immediately this harmonic was suppressed, the tests could be duplicated at both places without difficulty. The smaller the number of insulators tested, the smaller also the capacity of these insulators, the more pronounced will be any effect caused by higher frequencies appearing in the electrical system used for such tests. With a large number of insulators, and consequently, with a large capacity available, these higher frequencies will cause relatively little trouble, provided the amount of energy they represent is small. But in all cases where the capacity of the insulator tested is small, the wave form of the alternating current should be a pure sine wave.

As to the number of insulators which should be tested in order to arrive at a fair average value, this is a matter left open for discussion.

Effect of power factor upon test.

The effect of the power factor on insulator tests is also left open for discussion. When a large number of insulators are tested simultaneously, the available load of the transformer is utilized to charge that large capacity and there will exist considerable lead between this charging current and the impressed e.m.f. Whether or not this power factor has any influence on the test results is left open for discussion.

What wet test should be specified? Should it be artificial rain, dew, salt water spray, etc.? Amount of precipitation per minute? Character of precipitation and means for applying the same? Angle at which this precipitation should be applied?

Several means for approximating the conditions found in the open air are used at the present time. Artificial rain is applied which may vary between wide limits from a downpour to a mist; it may be applied vertically or at an angle, usually 45 deg. Or else the insulators may be confined within an air-tight room in which steam is left to escape until the insulators are completely enveloped in an atmosphere of steam and covered with a film of condensed vapor. Each test will yield certain results, but no two tests can be compared unless the conditions governing the tests are the same in both cases. Which of these methods is the most effective remains to be determined. It should always be chosen with regard to the facility for duplicating it at any time. In the present instance, the specifications called for 250 kv. with 0.5 in. (12.7 mm.) rain per minute vertically applied, or 220 kv. applied at 45 deg. These figures may seem arbitrary, and far above the standards commonly used, but on the other hand, they also include a safety factor higher than it is customary to allow. The above rain tests are easily made or duplicated, which is a great advantage. On the other hand, the distribution of the water needs considerable improvement to approximate more closely real rain.

> What should determine the failure or the success of insulator under test? Should it be the luminous display when test is performed in absolute darkness, and if so, what should be the limit of intensity? Or, should the ratio of flash-over or breakdown voltage to voltage at which first sign of luminosity appears, be considered?

With all conditions of test fully determined, and agreed upon, there remains the most difficult task of all; namely, to judge the performance of the insulator under test. The method followed and described elsewhere in this paper was the only one which promised to yield comparable results. This method, however, has the disadvantage of being a purely subjective matter. Even the comparing of photographic records is susceptible to that personal element always present. That the method is not free from objections has been realized from the start, but in the absence of some better way, it had, at least, the advantage of simplicity. It is quite evident that there must be other ways of determining the efficiency of insulators than by merely comparing their luminous display either among themselves or with that of a standard. What this method should be, is an open question. Undoubtedly, the determining of watts lost would yield results free from the personal element if a reliable method could be devised. In regard to the other method mentioned, in which the ratio of breakdown voltage to voltage at which first brush discharge becomes visible, is made the basis of comparison, it is likewise not always an easy matter to determine the exact value of this voltage. The breakdown voltage of an insulator, as a rule, is fairly constant, but the voltage at which the brush discharges become visible depends largely upon various accidental conditions and eventualities which render its determination extremely difficult. Consequently, this method should be viewed with the utmost caution.

Puncture Test.

Method of applying and performing test. Method of applying electrodes. Number of samples to be tested in order to arrive at a fair average value.

As a well-proportioned insulator will flash over before its puncture voltage is reached, it becomes necessary to test the insulator under oil. In this test, the most important feature is the application of electrodes. Unless the area presented is of sufficient size, erratic and unreliable results are obtained. The cemented cap and pin of sections of the suspension-type insulator form ideal electrodes in a test of this character, inasmuch as they distribute the stresses in the porcelain evenly and uniformly, also in exactly the same manner as obtains in actual use.

Mechanical Test.

What should this test be? Method of subjecting insulator to mechanical test according to whether pin insulator, suspension or strain insulator is tested. Method of applying load. Method of recording load at any instant. Should mechanical test be performed with insulator under voltage?

Routine Test and Inspection.

Inspections for physical defects. What are the limits to be observed in rejecting insulators on account of mechanical imperfections?

There naturally exists considerable difference of opinion between manufacturers and engineers as to the insulators which should be rejected. In most instances, the porcelain manufactured in this country will show an imperfect surface. This imperfection is caused by warping of body, discoloration, small cracks, flaws, grooves and foreign material adhering to glaze, bubbles underneath the glaze, etc. As a rule, foreign and especially German porcelain is faultless in those repects and there is never the slightest difficulty in rejecting insulators in these factories.

What routine tests should be specified? Method of applying such tests. Number of insulators tested simultaneously. Method of applying voltage. Should these tests be continuous or should test be executed in stages, allowing for the removal of insulators failing during test? If insulators are subjected to time test, should the test be continuous? Is it good practise to subject insulators to flash-over test for any length of time, with regard to possible deterioration or fatigue of the porcelain? What conditions will determine the success or failure of test? Should insulators failing, be cut off automatically from the rest of the insulators under test?

Two-Piece Insulators.

Where insulators are made up of several parts, cemented together, should cement preparation and method of cementing be specified? Length of time allowed for setting? Should insulator be tested over electrically after cementing is done?

Considerable difficulties were experienced in Germany with cemented insulators. The cement used in that country is either plaster of paris prepared in a special way, or litharge and glycerine and several other cements of secret composition. It has been found that after some time, the shells would crack, due—as was inferred—to the working of the cement used, and for that reason the cemented type insulator has been abandoned in favor of the single-piece type.

While the insulators which were selected as a result of these tests have proved to be highly satisfactory throughout a period of two years' operation, there have been nevertheless a few characteristic failures. In most cases the ultimate failure of these insulators was due to puncturing, although there exists strong evidence that this failure was preceded by the cracking of the petticoats, through no apparent cause. In most cases when puncturing takes place, it affects all sections of the insulators, with the curious but nevertheless logical result that holes are burned through the insulator cap opposite the point of puncture in the porcelain and fusing the metal surrounding it. The size of the hole in the cap depends to a great extent upon the time setting of the circuit breakers at the power station. If the circuit breakers trip out instantaneously after puncture has occurred, there may be no burning of the cap whatsoever. On the other hand, if the circuit breaker holds on for three or four seconds or even longer, the current to ground, which is limited through a resistance of large heat capacity connected between the neutral point of the transformers and ground, fuses the porcelain and adjacent metal parts. In one of these cases, where the holes through the caps were quite large, the circuit breaker did not trip out at all and one of the insulator sections, under the excessive heating action of the current to ground, finally came apart, thus automatically interrupting the circuit.

It is a rather difficult matter to determine the primary source of these failures. It may be due to cracks in one or two of the sections, which naturally tend to lower greatly the total insulating capacity of the insulator. If then, during a lightning storm, or during switching, surges are set up in the line, the weakened insulator becomes punctured as a direct result of any discharge occurring in the vicinity along the line. Considering the large capacity involved in the system and the power back of the transformers, this localized discharge in the insulator may immediately set up powerful commotions and oscillations which may affect the adjacent insulator and finally puncture one after the other in rapid succession.

The cracks inside the insulator cap and also the falling apart of the insulator sections with no apparent cause may have been due to faulty insulators having accidentally passed inspection, or it may have been brought about by the subsequent expansion which takes place in the cement within the cap and around the pin. This cracking of the cemented insulator has been experienced in Germany, as mentioned elsewhere in this paper, although in these cases the insulators in question were pin insulators only. It is almost impossible to determine whether the cracking of the porcelain within the cap is actually due to the uneven expansion of the porcelain, cement, or metal cap under temperature changes, or whether they were a result of the puncturing of the insulators. The inspection of some 140,000 sections of insulators was a task requiring much endurance, and although the work was carried out with great conscientiousness, it is quite possible that a few sections with a weakness in the porcelain cap which would not be detected by the ordinary routine test, may have passed by. There is also to be considered the theory of electrical and mechanical fatigue in the porcelain and cement respectively, which has already been discussed by several authorities. There seems to be no doubt that some such effect takes place, but the data which have been collected so far on the subject are not sufficient to permit of definite conclusions being drawn. To be able to insure absolutely continuous service over any transmission system may necessitate the sectionalizing of the line, where each section can be periodically tested at much higher voltage, or else it may be necessary to remove the insulators in batches and test them individually, as has already been done by one of the large operating companies.

At the present time there appears to be a rather unwarranted competition by the different manufacturers and operating companies to use excessively high voltages. There is a system already in operation at 145,000 volts and quite recently another company has contemplated the use of 180,000 volts. In view of the fact that operation at 110,000 volts has not yet reached a stage of maturity, and the fact that phenomena which were not anticipated, occur on such lines, and which, even now, are far from being fully understood, considerable caution should be displayed before attempting the use of still higher voltages. A few years ago the suspension type of insulator was heralded as the solution for line insulation up to any voltage at which it would be practicable to operate for many years to come. The factor limiting the use of high voltages so far as the line was concerned was then considered to be the effect of corona and leakage into the atmosphere. But from past experience it is almost certain that these views will need revision and that a systematic and thorough study of the properties of insulators is urgently required.

Examples of the rather uncertain conditions manifesting themselves in a high-voltage power transmission system are mainly the behavior of oil circuit breakers when large amounts of power have to be handled, the lightning arrester problem, and even the high-tension transformers. Most all of this apparatus, as will be admitted by the manufacturing companies, is yet in the stage of development, and it is very gratifying to see that a large amount of study is being devoted at the present time to rendering these devices more reliable in service.

The above criticism should not be taken as an indication of extreme conservatism or as tending to block the way to progress, but under the prevailing conditions, it is almost imperative that a word of caution should be spoken to prevent the somewhat extravagant use of the higher voltages when the use of lower voltages would answer the purpose equally well, and especially when the difficulties which are encountered with these extreme voltages may endanger the financial prospects of a particular power proposition.

I cannot close this paper without mentioning the Ontario Power Company at Niagara Falls, in whose plant these tests were made. The president of the company, Mr. J. J. Albright, and vice-president, General F. V. Greene, and their engineer in charge, Mr. V. G. Converse, have given their heartiest support and assistance to the furtherance of this work in gratuitously supplying all necessary testing equipment, power and the help of their personnel for these tests. I welcome this opportunity to personally and publicly thank these gentlemen for the interest they have taken in this work, for their generous help and friendly coöperation.

DISCUSSION ON " HIGH-FREQUENCY TESTS OF LINE INSULATORS" (IMLAY AND THOMAS), AND " COMPARATIVE TESTS ON HIGH-TENSION SUSPENSION INSULATORS " (SOTHMAN), NEW YORK, DECEMBER 13, 1912.

Ralph D. Mershon: There are a number of things in connection with the paper by Messrs. Imlay and Thomas that are not clear to me, and which I would like to have Mr. Thomas elucidate. For instance, in Fig. 3 of their paper there is shown a metal band around the insulator, and it is said that the effect of that metal band is equivalent to increasing the diameter of the pin. That is not quite clear, neither is it quite clear that putting a cap on the insulator is equivalent to reducing the diameter of the pin, the opposite effect of the band.

As to the change in voltage distribution over an insulator with change of frequency, I think there is no doubt about that, both from theoretical considerations and from measurements in connection with some high-voltage tests made at Niagara on which I reported to the Institute some time ago. These measurements were of the losses on insulators. The losses varied with the frequency. Inasmuch as other measurements made at that time indicated there was little, if any, loss in the porcelain of the insulator, it appeared that the losses measured were mainly confined to the surface of the insulator. And the only acceptable explanation for the variation of these losses with frequency was, that as the charging current of the insulator changed with the different frequencies, the amount of charging current that had to flow over the surface changed, resulting in the change in the values of the losses. That change in loss would indicate a change in distribution similar to the one of which Mr. Thomas speaks, because change of loss, due to a change of charging current, means a change in the voltage absorbed on those parts of the surface over which the current has to flow in order to charge other portions of surface.

There can be little question in the mind of any one who has to do with transmission lines that the main point brought out in this paper is correct; namely, that the behavior of insulators under high frequency is not the same as their behavior under commercial frequencies. Again and again insulators are punctured in service, which under test at commercial frequencies would flash over rather than puncture. This happens with wooden as well as metal pins, although it happens more frequently with metal pins. But you do not have to go to insulators to see there is a difference between action of high and low frequencies. You have seen a dry transmission line pole struck by lightning and shattered. Instead of taking the perfectly easy path through the air alongside the pole, the lightning preferred to go through the pole and smash it to pieces. I could understand how the lightning might choose a green tree with the sap in it, rather than the air alongside of it, but it is difficult to understand why it should prefer to go through a dry pole, which we have reason to believe would, if tested at commercial frequencies, flash over before it would pass any serious amount of current.

High-frequency tests should be continued further, and the endeavor should be made, when more knowledge as to these phenomena has been obtained, to connect up the effect of high-frequency tests with the results of tests at commercial frequencies. In other words, the endeavor should be made to determine what tests at commercial frequencies (either as to voltage or time, or both) would constitute an equivalent of high-frequency tests, so that tests can be made under ordinarily available conditions, equivalent to tests at high frequency.

In Mr. Sothman's paper rather undue emphasis seems to be laid upon factors of safety relative to the line voltage. It would seem that our experience, extending over a number of years, has shown that the problem of insulating a transmission line is not so much a problem of insulating it against the line voltage—that is comparatively easy—but the problem of insulating or protecting it against lightning or lightning effects.

On the last page of his paper Mr. Sothman has spoken in a rather discouraged way in regard to higher voltages. Now, while I agree with him that in some cases it would seem that higher voltages have been adopted than were justifiable, I think them unjustifiable on the score of economics rather than on the score of difficulties to be met with in operation. There is no particular reason to believe that the percentage of electrical troubles will be any greater with higher voltages, requiring an increased number of units in the suspension insulator, than there are now, though I can see some chance for a considerable increase in mechanical troubles.

There is one other point I desire to take up that bears on both these papers, and on other work that has been done and papers that have been read before the Institute in regard to suspension insulators.

The term "string efficiency" has been used, presumably as being indicative of the way in which the impressed voltage distributes itself over a string of insulators. As I understand that, it is the ratio between the voltage required to flash over a string of *n* units and *n* times the flash-over voltage of one unit. In the first place I protest against the term "efficiency" as applied to an insulator. In engineering work the term efficiency is used to designate the ratio of output to input. It cannot, though, be properly applied to an insulator. Some such term as "string ratio" would be better, and would fit the case, and with your permission I will use it.

The term "string ratio" is not necessarily indicative of the distribution of voltage over a suspension insulator. It would appear that in the adoption and use of this ratio as an indication of the voltage distribution, a point has been overlooked that is of considerable importance, especially where the suspension insulator is made up of units closely spaced. What I have in mind will appear from what follows.

In order to simplify the discussion consider the very elementary form of insulating unit shown in Figs. 1 and 2, consisting of an insulating disk on each side of which is a metal hub representing the metal parts of the insulating unit usually employed. Also, for the sake of simplicity, assume that the flash-over value of any given distance is directly proportional to that distance. This, as we all know, is not strictly true, so that the following discussion will be in error quantitatively, to the extent that this assumption is wrong, although, as you will see, the assumption does not affect the discussion qualitatively, and does not therefore introduce any error in the general conclusion arrived at.

In the figures the upper and lower surfaces of the units are designated by *a* and *b*, respectively. Let *a* and *b* also stand for such numerical values as will represent the flash-over values of these surfaces. Then the flash-over value of one of the units, say No. 1 of either of the figures, will, when tested singly, be $a_1 + b_1$. Let *c*, the distance between the edges of the disks, be such that its flashing value is *c*.

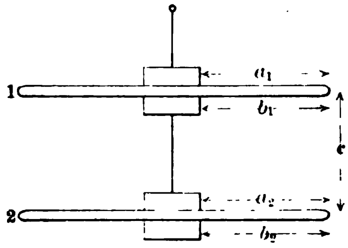


FIG. 1

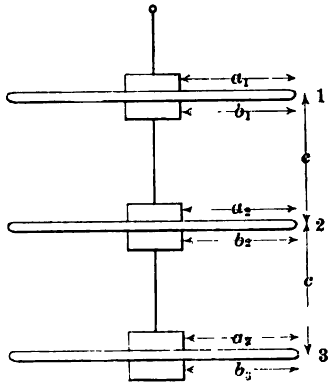


FIG. 2

Suppose a ***direct current*** voltage be impressed upon the two insulating units of Fig. 1, the value of the voltage being just under that at which the insulator will flash over. There will be a leakage over the surface of the units, and as the result of it the voltage impressed will distribute itself between the two units 1 and 2.

Now if the flashing value of *c*, the spacing of the insulator units, exceeds the value of $b_1 + a_2$ the tendency will be for the current to flash around from metal to metal of each individual unit, making use of the metal connection between the units in traveling from one unit to the other, instead of flashing around the whole string of units from the metal of the upper one to the metal of the bottom one. Under this condition the actual distribution of voltage over the insulator will be uniform, and the string ratio of the insulator will be unity. So, also, will the distribution of the voltage be uniform and the string ratio unity if the value of c is just equal to $b_1 + a_2$; *i.e.* if the flash-over is just as likely to occur around individual units as it is over the combination. In both these cases, therefore, the indication of the string ratio agrees with the actual condition.

If the flashing value of c be less than that of $b_1 + a_2$ the tendency will be for the current to flash through the path $a_1 + c + b_2$, and if the impressed voltage be of a value just under the flash-over the impressed voltage will be distributed over the distance $a_1 + c + b_2$. Let us assume that c is of a sufficiently low value so that the latter condition holds. Then the string ratio of the insulator will be

$$R = \frac{a_1+c+b_2}{2\,(a_1 + b_1)}$$

Or, since in exactly similar units b_1 and b_2 will be identical,

$$R = \frac{1}{2} + \frac{c}{2\,(a_1 + b_1)}$$

Or, more generally,

$$R = \frac{1}{2} + \frac{c}{2\,(a + b)} \qquad (1)$$

Similarly, for three units, as in Fig. 2, the string ratio is:

$$R = \frac{a_1 + c + c + b_3}{3\,(a_1 + b_1)} = \frac{1}{3} + \frac{2\,c}{3\,(a_1 + b_1)} = \frac{1}{3} + \frac{2\,c}{3\,(a + b)}$$

And for n units the string ratio is

$$R = \frac{1}{n} + \frac{(n-1)\,c}{n\,(a + b)} \qquad (2)$$

Now let us examine equation (**1**) applying to Fig. 1. We see from the last term that if c is equal to $(a + b)$ the value of R is unity, which agrees with what has just been stated. If c is less than $(a + b)$ the value of R is less than unity. But suppose the values of a and b were exactly identical, as would be the case if the upper and lower surfaces were exactly similar and in exactly the same condition. Then, in that case, the distribution over the complete insulator when subjected to a direct-current voltage must of necessity be uniform, because the leakage over the insulator will equalize the voltage over it and cause each unit to take up its share of the voltage. It follows, therefore, that in this case the string ratio is no criterion of the distribution of voltage over the suspension insulator, because if c is less than $(a + b)$ the string ratio will be less than unity, and therefore indicate a non-uniform distribution; whereas, as a matter of fact, no matter what the value of c may be, the distribution will be uniform.

Let us examine the case of Fig. 2. As previously stated for Fig. 1, if c has a value sufficiently high, the string ratio of the insulator will be unity because the individual units will always flash around; and, also, if c has a value just equal to the flash-around value of a single unit, the string ratio will be unity. But if c has a value less than the flash-over value of one unit so that the voltage will flash over the insulator by way of the path $a_1 + c + c + b_3$, instead of around the individual units, then the distribution over the insulator will not be uniform. Instead, each of the intermediate units will have impressed upon it the voltage c, while the upper and lower units will each have impressed upon it some voltage higher than c. This is due to the fact that in the case of the upper unit, for instance, the voltage upon it will be equal to a_1, plus that proportion of c received by the surface b_1. That is to say, the voltage impressed on the upper unit will be

$$a_1 + \frac{b_1}{b_1 + a_2} c$$

and the voltage impressed on the lower unit will be

$$\frac{a_3}{b_2 + a_3} c + b_3$$

The middle unit will have impressed upon it a voltage

$$\frac{a_2}{b_1 + a_2} c + \frac{b_2}{b_2 + a_3} c$$

which, (since the insulators are all similar, and therefore the a surfaces all identical and equivalent, and the b surfaces all identical and equivalent) reduces to the value of c, as previously stated. It is evident from this that if another unit be introduced into Fig. 2, making four units in all, and the impressed voltage raised accordingly, the voltage on each of the end units will be the same as before, and the two intermediate units will be subjected to the voltage c. It is evident also that any number of units thus introduced will lead to a similar result. That is to say, the two end units will each be subjected to a higher voltage than each of the intermediate units; and the voltages on each of the intermediate units will be uniformly the same. But on referring to equation (**2**) we see that as n is indefinitely increased, R approaches the value

$$R = \frac{c}{a + b}$$

In other words, the value of R would continually change, approaching more and more closely to the value $\frac{c}{a+b}$ which, if the units were closely spaced, would be a small value, perhaps as low as $R = 0.5$, indicating a very bad distribution. Whereas, as a matter of fact, the actual distribution would not change at all, and might not be anything like as bad as indicated by this ratio. As a matter of fact, as previously explained, with the exception of the two end units, all the units of the system would each have impressed upon it the same voltage (the voltage corresponding to the distance c), while the end units would have impressed upon them somewhat higher voltages.

We have assumed so far that the flashing values of the upper and lower surfaces, a and b, of the insulator are not widely different.

Suppose, however, that the upper or a surfaces of all the units were wet and the lower or b surfaces all dry, as might be the case in a rain storm. Then, as will be apparent on following the thing out, unit No. 1 of the string will receive less voltage than each intermediate unit, and the last unit of the string will receive more. It would appear, therefore, that even in the case of direct current one or both (depending on whether or not the upper surfaces are wet) of the end units will receive more voltage than will the intermediate units, if the spacing c is such as to have a flash-over value less than the flash-over value of a single unit.

It would appear from the above considerations, therefore, that the string ratio may or may not be indicative of the distribution of voltage over a series of insulating units. If the spacing of the units is such that the flash-over value of the spacing distance c is equal to or greater than that of a single unit, the string ratio will be indicative of the voltage distribution over the string. But if the spacing of the units is such that the flash-over value of the spacing distance is less than that of a single unit, the string ratio will not be indicative of the voltage distribution over the string.

Now let us consider the conditions with alternating current. With alternating current we are, in addition to the above considerations, concerned with the question of capacity—the capacity of the individual units, each within itself (which I will refer to as the " internal capacity ") and the capacity of each unit to earth (which I will refer to as the " external capacity "). So long as we consider direct current only, and we assume that there is leakage over the unit, the question of capacity does not enter, because the leakage will ultimately determine the distribution of voltage over the string. When, however, we come to alternating current we are concerned with leakage, internal capacity, and external capacity. Of these three elements, leakage and internal capacity tend towards a uniform distribution, whereas external capacity tends toward a non-uniform distribution. If the spacing of the units is such that the flash-over value of the spacing distance *c* is greater than that of a single unit, then the string ratio will be a measure of the unequal distribution of voltage due to the effect of external capacity. But if the spacing of the units is such that the flash-over value of the spacing distance *c* is less than that of a single unit, then the string ratio will be indicative of a distribution which is the result of the combined effect of external capacity and the end unit effect discussed above for direct current.

That this is true will be apparent on examining some of the curves obtained on suspension insulators in which the number of units is plotted against the flash-over voltages. Not infrequently we have the following condition. With the units all dry, the curve is one having a bend in it, showing that added units are of less and less value. If, however, the insulator be subjected to a spray of water and another curve plotted, the curve will be practically a straight line. This straight line will not, however, if extended, pass through zero, but will cut the axis of voltage at a certain value. If now the spray be increased sufficiently and another curve taken, this third curve will be a straight line passing through zero. The reason for this condition is that the spray under which the second curve is obtained introduces enough leakage to mask, and practically do away with, the effect of the external capacity, thus producing a practically uniform distribution over all but the end units. The fact that the second curve when extended cuts the voltage axis instead of passing through zero is evidence of the existence of the end unit effect discussed above for direct current. That is, it is evidence that the distribution of voltage is substantially uniform over all of the units, except the end ones. When, however, the spray is further increased so that the flash-over value of each unit has been reduced so much that it is less than the flash-over value of the spacing distance between units, then the distribution is uniform over *all* the units, and the line passes through zero. Curves similar to those described above will be found in Fig. 2 of the paper* by Mr. Peek read before the Institute May 17, 1912.

It would seem, therefore, that in considering the voltage distribution over a string of insulating units, the end unit condition previously discussed with reference to direct current must be taken into consideration, especially if the insulating units are placed close together. It is even more important when one comes to consider an insulator with more than one petticoat, because in this case the two or more petticoats give a result very similar to that of insulating units very closely spaced.

I believe, however, that the matter of string ratio and voltage distribution over the string is of a great deal less importance than that of the relation between the dry flash-over value and the puncture value of the unit. As previously stated, the problem

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**Electrical Characteristics of the Suspension Insulator*, TRANSACTIONS A. I. E. E., 1912, XXXI, Part I, page 911.

of insulating the line against the voltage of the line is a comparatively easy one. The difficult part is to insulate the line against lightning. It is easy enough to put enough insulating units together to hold the voltage of the line. It is not so easy to get insulating units of such characteristics as will insure that there will always be a flash-over rather than a puncture. And while it is desirable to have as good voltage distribution as possible, I consider voltage distribution entirely secondary in importance to a high puncture value of the units relative to the dry flash-over value of the unit. In this connection it is well to remember that a good voltage distribution with commercial frequencies does not necessarily mean a good one with frequencies equivalent to lightning, and that therefore the endeavor for a good voltage distribution at commercial frequencies is, beyond a certain point, a waste of time which might be much better devoted to the endeavor to increase the ratio of puncture value to flash-over value of the individual units.

Paul M. Lincoln: Some of the deductions made by Messrs. Imlay and Thomas from the facts presented in their paper are deductions with which I cannot agree. In the first place, they use throughout this whole discussion the term " high-frequency tests." Now, they may be high-frequency tests or they may not be. There is not one iota of *proof* that the tests which they have described really do produce high frequency upon the insulator. The fact, if it is a fact, that high frequency exists on that insulator, is one that must be deduced entirely by inference. When a condenser discharges through a given circuit, if proper assumptions are made, one may infer that the discharge is alternating and of high frequency. Whether it is high frequency and alternating, or not, depends upon the amount of energy stored in the condenser as related to the rate at which this energy is dissipated once the discharge starts. It is my idea that if the discharge is alternating, the rate of decadence is so great that it is questionable whether the actual discharge is governed by the laws which govern alternating currents. When the rate of decadence is high, it requires only a relatively small number of alternations before the value of the voltage has dropped practically to zero.

It is admitted, however, that the method of testing as described in this paper does produce an exceedingly sudden application of voltage to the insulator, and one that exists for a very brief length of time. I believe it is due to the fact that the voltage exists on the insulator for such a very brief period of time, that we find the unexpected results which have been described by the authors.

There is one thing which has been omitted by the authors, and that is a minute description of just how the voltage is applied. The authors state that the " application " exists for a period of one to two seconds, but there is no way of telling how many shocks the insulator receives during a single " application." It may receive one shock every alternation, in which event there will be some 200 or 300 shocks per application, or it may be that there is a shock only every tenth alternation, or some such matter, or it may be that there is a shock on the insulator a good many times per alternation. It would be interesting if we could have some data to settle this question.

The authors have submitted some "speculations," as Mr. Thomas has called them, by which they attempt to explain the results of the tests. They assume that in an insulator the distribution of voltage across its parts is determined by the fact that there is a resistance in series with a capacity, and that the very high frequency to which the insulator is subjected during the tests gives an entirely different distribution of potential over the insulator from what takes place when a frequency of 60 cycles is used. I have my doubts as to whether an analysis will show much weight to this contention. Suppose we have an insulator to which we apply a voltage. The voltage is brought by metallic conductors up to the material of the insulator itself. (Fig. 3). This voltage appearing on the metallic parts of the insulator causes a current to flow. This current will flow, due to two causes, first, because there is a capacity present, and consequently there will be a capacity current flowing through the insulator, and second, because the insulator is not a perfect insulator, but is to a slight extent a resistance, and consequently the voltage which appears will cause current to flow through that resistance. It is apparent that these two paths are not in series, but in parallel, so that any deductions which the authors make on the basis that the paths are in series will not apply. It is perfectly true that the current which flows through the capacity has a 90-degree lead over that which flows through the resistance, but I do not see that that has any particular bearing upon the case.

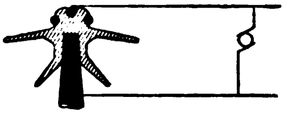

FIG. 3

The tables given in the fourth, fifth and sixth pages of the paper by Messrs. Imlay and Thomas indicate that these so-called high-frequency tests were made with a transformer voltage which ranged between 300,000 and 350,000. Furthermore, the test on insulator "No. 1" indicated that the solid part of that insulator would break down at a voltage somewhere around 200,000. They could not obtain a breakdown on No. 2 insulator, since it flashed over under oil, before breaking down, but it is fair to suppose that the solid dielectric of insulator No. 2 would break down at somewhere around 300,000 to 350,000 volts, because it is a well-known fact that the dielectric strength of a solid dielectric does not go up in proportion to its thickness, and a dielectric two inches thick will not stand twice the voltage of a dielectric one inch thick. If the No. 1 insulator would stand 200,000 volts, it is fair to suppose that the No. 2 would break down at 300,000 or 350,000.

That is about the voltage actually in the transformer during the so-called "high-frequency" tests, and it is my opinion that the only thing which is observed in this breaking down on the "high-frequency" test is simply the result of a voltage of somewhere around 300,000 to 350,000 volts applied to the insulator, and that 300,000 to 350,000 volts is what breaks down the solid dielectric of that insulator. You may ask why it does not break down the air path, as when a 60-cycle current is applied. My answer, as suggested early in my discussion, is that the *time of application* is so short that the air does not have time to break down. Dielectrics break down in two separate and distinct manners. The first way may be likened to the breaking down of an oak plank by the penetration of a rifle bullet. That is the manner in which all solid dielectrics break down, and in which the air breaks down under certain conditions. It is my belief, from certain tests which I have seen made, that the breakdown strength of air from the "rifle bullet" method is not so far different from that of solid dielectrics as many suppose. Air, however, may break down in another way, that is, by ionization, but that method requires time. It does not act instantaneously. Ionization occurs by collision and is necessarily a *progressive* action, and it requires a certain appreciable amount of time for these collisions to extend from one terminal to another. Therefore, if the voltage is applied to the insulator with extreme suddenness, it may break down by the "rifle bullet" method before the parallel air path breaks down by ionization.

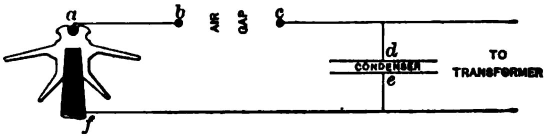

FIG. 4

I think the statement by the authors that during the "high-frequency" tests not more than 100,000 volts was applied to these insulators, as indicated by the air gap, fails for the same reason. It requires time for the measuring air gap to break down, and even if the air-gap separation indicates only 100,000 volts, I do not believe it follows necessarily that there was a pressure of only 100,000 volts present. It may have been a much higher voltage.

Another point which should be explained is the manner of determining the frequency of the attack upon these insulators. As I understand it, there is a condenser (*d e*, Fig. 4) connected in series with an air gap, *c b*, and the opposite terminal of the air gap is attached to the insulator, the pin *f* of which is attached to the other side of the condenser. It is my understanding that the million cycles per second which the authors have given as the approximate frequency of the voltage applications to the insulator, is that which will take place when the path is completed through the insulator; that is, the frequency is that determined by the condenser *d e* discharging through the inductance of the circuit *d c b a f e*. It should be noted that the current cannot flow through this path until the breakdown actually occurs. Until that breakdown occurs the frequency is determined simply by static capacity of the insulator discharging into the condenser *d e* through the path *a b c d*. In this case the frequency will be governed by this static capacity of the insulator and the inductance of the circuit *a b c d*. Since the static capacity of the insulator is exceedingly small compared to that of the condenser *d e*, the theoretical frequency is largely increased. Consequently, instead of a million cycles per second, we may have a theoretical frequency of many times that, possibly a factor of one hundred to one thousand. It is evident, therefore, that the duration of time of strain upon that insulator is exceedingly short, and, according to my conception, this does not give time for the air to ionize between terminals.

I agree with the conclusion of the authors that their tests have opened an exceedingly interesting line of investigation, and one which certainly ought to be followed up.

F. W. Peek, Jr.: The term " line insulator " is rather a misnomer. The real line insulation is the air in which the conductors are immersed. At present the " line insulator " is, at best, an electrically weak point which must be used for mechanically supporting the conductors. Fortunately, however, although the properties of the air cannot be changed, and a uniform gradient distribution not even approximated on the conductors in the air, the stresses can be very nearly balanced in the insulator by proper design or a proper understanding of the dielectric circuit. The development of the high-voltage insulator has been extremely rapid, and it was at first an overgrown telegraph insulator. When the voltage was doubled, the insulation thickness was doubled. By this method of design an insulator may be actually weakened by the addition of perfectly good porcelain. The configuration of the parts is generally of as great importance as the quality of material entering into the parts. In general, that insulator would be best in which, when under voltage, the gradients were in all parts, internal and external or surface, in proportion to the strength of the parts; that is, everywhere equal, in a one-material insulator. The greatest advance in high-voltage insulators was the suspension insulator invented by Hewlett.

Energy is necessary to smash insulators and to destroy insulation. The reason for the suddenly magnified importance of phenomena once negligible is increased energy. The energy stored in the dielectric is

$$\omega = \frac{e^2 C}{2}$$

Thus stored energy increases as the square of the voltage. It is the transfer of this energy from one form to another, dielectric to magnetic, that causes excessive voltage rises, etc. Incidentally, this is a good argument against the interconnection on the high-voltage side of several parallel transmission lines from the same station, as such interconnection not only transfers high-frequency insulator discharges from one line to the others, but also requires high-tension switching, which is in itself a source of trouble.

The subject of insulator design and testing is of the utmost importance, as a single broken insulator may eat up the profits of an investment by causing thousands of dollars' damage to other apparatus.

In a paper presented on May 17, 1912, at Schenectady, on *Electrical Characteristics of the Suspension Insulator*, I made the following statement:* "Hence, it seems that the arc-over (voltage) would not always indicate the best insulators for all conditions of service. As, for instance, with surge, sudden impulse, lightning, or transient voltages, a bad operating distribution would probably mean not flash-over, but punctured porcelain, or the porcelain would puncture before corona could form to distribute the stress better." The object was to bring out the great importance in insulator design of well balanced or distributed stresses which the flash-over tests at low frequencies do not necessarily indicate. To illustrate the necessity of good balance, and as an explanation of failures at high frequencies, let us take an extreme case. Suppose an insulator is constructed as in Fig. 5. If voltage is gradually applied at low frequency the air on the surface breaks down as corona, becomes conducting and distributes the stress, or becomes, in effect, Fig. 7. Arc-over takes place before puncture. If, now, the whole is placed in oil or a drop of oil is placed at each point, the flux density is not distributed, as the air does not break down and even-up the high points, so to speak—no conducting path is formed, and the stress is localized and puncture occurs.

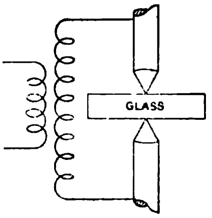

FIG. 5

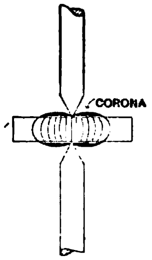

FIG. 6

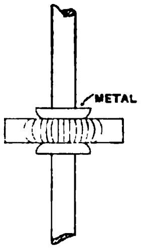

FIG. 7

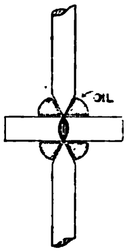

FIG. 8

It takes a very short time, but an appreciable time, for air to become conducting, or for an arc to form. If the applied potential and frequency are very high, or if high voltage is suddenly

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*Part I, page 926.

applied—that is, with steep wave front—this high potential is across the insulator during the time that the arc is forming, or the air is becoming conducting to relieve the stress. The time interval may be sufficient for the porcelain to become shattered. High-frequency puncture should occur at about the same voltage as puncture under oil at low frequency where the arc-over is prevented by the oil.

Let us now see if this applies to the interesting data presented by Messrs. Imlay and Thomas.

Fig. 9 shows the connections used in these tests. At the moment before high-frequency discharge, or arc-over, the insulator is practically at zero potential. When arc-over occurs, the insulator is thus raised very suddenly from zero potential to 325,000 volts, or possibly double this, above zero. This is well above the puncture voltage, as shown by the test under oil, and if this voltage had been *gradually* applied, the stress at high points would have been gradually evened up by conducting air until arc-over occurred and the voltage across the insulator was reduced to zero. With the voltage *suddenly* applied the air does not become conducting to a great enough extent over the surface in time to relieve the insulators—hence, the porcelain is punctured. Complete puncture may not occur at the first application, but at first only cracks or chips in the porcelain, which gradually develop into puncture. If the petticoat is reduced as in the tests, the time lag for flash-over is reduced and less punctures should occur. There is still another effect which I have noted and which may have a bearing. If potential at low frequency is applied between electrodes, and gradually increased, arc-over occurs and the potential across the gap drops to zero, as indicated by a voltmeter placed across the gap. In other words, the low-frequency arc " resistance " is practically zero. If, however, at a frequency of say 50,000 cycles from a generator, the potential is gradually increased until arc-over occurs, the potential does not drop to zero, but may remain near the applied voltage, that is, the high-frequency arc seems in effect to have a very high resistance, or the high-frequency arc may play over an insulator surface without considerably reducing its potential below the applied value,

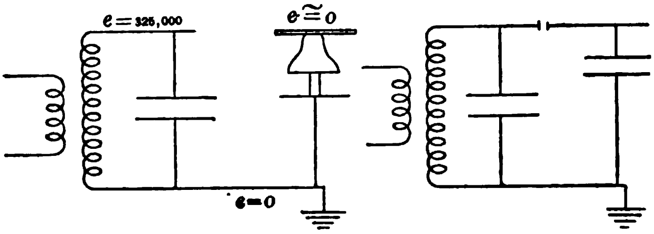

FIG. 9

which may still remain above the voltage at which puncture would occur at any frequency, as under oil where arc-over is prevented.

The effect of the time lag of corona means that a good insulator under transient voltages must have a good balance. The suspension insulator should have high string efficiency, as brought out in my paper, previously referred to. This applied also to the parts that makes up the pin type insulator. There must also be ample margin between the low-frequency flash-over voltage in air and the puncture voltage under oil.

An interesting point is here brought up in design, or spacing of disks. If potential is gradually applied across a string of say five insulators (as usually spaced) and gradually increased, flash-over takes place first on the unit nearest the line, then over the second, third, and so forth. As there is a time lag for flash-over at each insulator this means that a gradually increasing potential is suddenly applied on the units, just as in the Thomas-Imlay tests. When the last insulator is reached the full applied voltage is for a short time before arc-over across, the insulator. This is far above puncture voltage. I have observed insulators punctured in this way during arc-over tests. Thus with low-frequency surge the insulator nearest the tower may puncture. This shows the importance of good string balance, or of having the design such that all insulators will arc over at the same instant. Perfect balance is in the present design hardly possible, so, after designing for the best possible balance, the insulators should be so spaced that arc-over voltage from line to tower is just below the arc-over voltage around one unit.

Referring to Mr. Mershon's remarks on string efficiency, we believed this to be a proper term*, as it is the ratio of the actual flash-over voltage to the maximum possible flash-over voltage. The question brought up by Mr. Mershon in regard to the method of obtaining the string efficiency is answered in the paper (p. 911).

The question of the comparative voltage values of a given spark gap at low and high frequencies is of great interest.

We have made some tests on spheres and needle gaps up to 50,000 cycles sine wave. At this frequency both the sphere and needle types spark over a given gap at lower voltages than at 60 cycles. The difference is not great, however, for spheres, where corona does not form before spark-over and heat the air in the gap. At very high frequencies or very suddenly applied potentials where the time element enters, it is probable that higher voltages are required for a given gap.

Mr. Sothman in his paper has brought up many interesting questions. Regarding the question of test precautions, method of voltage control, power required, etc., I would refer to what I have said in the paper previously cited. I should like to add that while the needle gap has long been useful, we have about out-

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* See *Electrical Characteristics of the Suspension Insulator*, in Part I of this volume of the TRANSACTIONS, page 911.

grown it, and it is not reliable above 100 kv. Unless proper corrections are made for humidity the variation is very great, and the voltages indicated are generally too high. This effect is not noticeable where the electrode is such that spark-over takes place before corona forms. Such an electrode should be standardized.

DESIRABLE TESTS AND SPECIFICATIONS.

In closing my discussion I will summarize the test conditions which I believe should exist in order that uniform and reliable results may be obtained, and also additions which I believe should be made to specifications.

Generators—Voltage Control and Power. 1. Generator wave free from high harmonics and reasonably close to sine wave.

2. Control of potential by generator field over short range (never below half field) in combination with potentiometer method.

3. Power sufficient to allow a true dynamic arc to start before an appreciable change can take place in the voltage or wave form.

Transformers. A properly designed transformer, the ratio of which should remain practically constant. The iron should never be too highly saturated. For careful measurements the voltmeter coil is recommended.

Spark Gap. 1. Fairly reliable results can be obtained with the needle gap if correction is made for all of the variables, as humidity, etc.

2. The sphere gap is recommended—always using a sphere large enough so that spark-over takes place before corona can form. Correction should be made for temperature and barometric pressure.

3. Water tube resistances should be placed in series with the gap, limiting the current to about 0.5 amperes.

Insulator Tests. 1. The top of insulator string should be grounded.

2. In determining flash-over tests, insulators must not be allowed to become overheated by arc.

3. Temperature, barometric readings, frequency, and humidity should be recorded.

4. The impulse test by transformer as made by Messrs. Imlay and Thomas seems better than the Tesla coil method, as in the former the maximum applied voltage is known. This is an extremely important test, as it will indicate the life of an insulator due to lightning, high frequency, etc., and uniformity of porcelain.

Specifications. 1. Good string efficiency in the suspension insulator, and high efficiency between parts of pin type insulator. This can be determined in various ways. This test will determine the relative values of various insulators at high frequency.

2. Ratio of the puncture voltage under oil to the arc-over voltage will determine approximately the relative value of insulators under high frequency. This ratio should be specified. The

oil test may also be made to indicate the uniformity of the porcelain.

3. Possibly electrical test while insulator is under mechanical strain.

4. Resistance of rain water should be specified or standardized.

J. A. Sandford, Jr.: I believe that there is no one who has gone more carefully into comparative testing of suspension insulators from all points of view than Mr. Sothman. He realized at the time of taking up this work what most engineers have since acknowledged, that good comparative results can be obtained only when all tests are made with the same equipment and with as few variables in the test conditions as possible.

Turning to the observations made by Mr. Sothman and particularly to the remarks on the type of insulators using the so-called hook and loop connection as compared with the others, it is useless to dispute the fact that from the point of view of the electrical performance of the insulator this type does not show up as well under test as others, due to the discharge at the point of the hook. It is well to bear in mind, however, that this type of connection is very largely in use, both with the two-piece and one-piece suspension units, and has given entire satisfaction in competition on the same lines with two other styles of unit. The simplicity of the connection will appeal to many engineers, no tools being required to connect or disconnect the units when making renewals.

Referring to the subject of mechanical strength, I believe there is no difficulty at the present time in producing single-piece units of short spacing and reasonable design and cost, that will have an average ultimate strength of 12,000 to 13,000 lb. (about 5500 to 5900 kg.), and this may be increased to 15,000 lb. (about 6800 kg.) by a slight increase in spacing.

Passing now to the summary of Mr. Sothman's paper and the questions raised therein for our consideration, I believe the author has come quite close to the reason why insulators fail on the line even after the most thorough test possible at the factory, when he says: " For it is quite probable that precautions now taken in one direction are often unwarranted and uncalled for, whereas, on the other hand, liberal allowances made in other directions may be of the greatest detriment to line and insulators." This seems to be forcibly brought out by the findings of Messrs. Imlay and Thomas as given in their paper. I will discuss some of these points, taking up the various headings in the order given in the summary of Mr. Sothman's paper.

Design Tests. The specifying of very high flash-over tests, wet and dry, necessitates in suspension insulators either a few units having a high flash-over value and long spacing, or a greater number of smaller units with shorter spacing, each unit having a relatively low flash-over. The latter is a step in the right direction, judging from the observations by Messrs. Imlay and Thomas, but up to the present it has not been carried far enough.

The ratio of puncture voltage of the unit to its flash-over value, and the ratio of flash-over of entire insulator to flash-over of single unit, should be increased. In order to accomplish this the flash-over of single units, must be reduced. Incidentally the flash-over values of the entire string will be slightly lowered, but an insulator will have been produced that is better able to withstand the effects of high-frequency disturbances, while sufficient factor of safety will still be obtained to take care of the steady application of static forces impressed by normal line potential and frequency.

In pin type insulators we have to use large flaring parts in order to take care of the flash-over requirements. Judging from the tests of Messrs. Imlay and Thomas, the insulators could better stand the high-frequency disturbances if the diameters were reduced, thereby changing the capacity of the insulator, and thus, as in the case of the suspension insulator, giving a greater factor of safety against puncture.

Method of Supporting Insulator under Test. For the comparatively small number of tests necessary to demonstrate the performance of various insulators and their suitability for certain requirements, the best method is undoubtedly to support the insulators as nearly as possible in the manner in which they will be installed on the line; that is, with one end grounded. This method, however, necessitates a very large and expensive transformer, and inasmuch as the tests are comparative only, it is my opinion that the tests can as well be made using a transformer with middle grounded. The latter method is preferable for the routine tests that have to be conducted in the regular testing racks, on account of having to insulate for only half of the total voltage. There is also less trouble from static, etc. (This is important, owing to the presence of lighting circuits, watchman's clock circuits, sprinkler, water and gas systems. The company with which the writer is connected has recently installed 300-volt lightning arrester cells to protect the lighting circuits, but we have had insufficient experience to say whether or not they will eliminate the burning out of lamps.) No resistance should be used in series with the insulators under test. Other means than this should be employed to protect the transformer.

Capacity of Testing Transformer and Generator. I agree with the author that the greater the kilovolt-ampere rating of the transformer and generator used for testing, the better will be the results. It is surprising to see the difference in appearance of the same insulator under test with first one equipment and then another.

Means should be provided for changing the low-voltage connections of the transformer in order that the generator may be worked at all times with a fairly strong field excitation, if this method of control is used. It is my belief that field control offers fewer objections than any of the other methods that have been proposed. It is convenient to be able to vary both the exciter and alternator fields, as very slow and gradual changes may be made by using the alternator field control for say 97 or 98 per cent of the desired range and then using the exciter field control for the balance.

The determination of the voltage present at any time during test, is the most important element of the results obtained and is, unfortunately, very difficult to obtain accurately unless careful laboratory methods are resorted to.

Inasmuch as we cannot hope to duplicate exactly our line operating conditions, the tests resolve themselves, as before stated, into comparative ones. It is probable that errors may be found in any method of measurement that might be introduced. However, I believe that, given a transformer of good design and sufficient capacity, grounded at the middle point, and supplied with power from a single-phase generator giving a sine wave at all loads, the generator having been designed in connection with the transformer with full knowledge of the service to which the equipment is to be put, the most convenient method of measurement of voltage is by the use of a voltmeter coil at the grounded neutral of the transformer, using the ratio of transformation. If the equipment has sufficient kilovolt-ampere capacity and is properly designed, the error in using this method should be small, and in tests where all work is comparative, would be eliminated. This is certainly the ideal way for regular factory testing where an unskilled man is used to operate the testing equipment. The needle-point spark gap is subject to considerable error, and the resistance which should be used with it should theoretically vary with voltage at which tests are being made. It is not practically possible, however, to vary the resistance with the voltage. I tried water, but have come to the use of resistance rods. Frequent discharges of the gap ionize the air and distort the results; also the method of operating the gap itself may introduce considerable error.

With reference to the effect of frequency, the paper by Messrs. Imlay and Thomas brings out this point so strongly that I can add nothing further. I believe, however, that no appreciable difference in results will be obtained at any of the normal frequencies; that is, 25 to 133 cycles.

Concerning distortion of wave form, the table herewith gives a comparison of results obtained by using first an old smooth core single-phase machine, and second a 200-kw., three-phase, Y-wound generator running single-phase to excite a 250-kw., 60-cycle, 2300/4600/400,000-volt transformer.

Single-phase Generator.			Three-phase Generator.		
Primary volts	Secondary volts (spark gap)	Transformer ratio	Primary volts	Secondary volts (spark gap)	Transformer ratio
458.0	80.5 kv.	175.7	467.3	85.8 kv.	183.6
519.2	90.0 kv.	173.3	517.5	99.5 kv.	192.2
572.7	99.0 kv.	172.8	575.0	107.5 kv.	186.95
631.0	111.7 kv.	177.0	632.5	123.5 kv.	195.2

The designed ratio of transformation of this transformer was 173.9:1. The ratio as found under test before shipment was 176:1. The only load on the transformer during the above tests was the spark gap. This goes to show how important a part is played by the wave form in the final results. The wave form of the single-phase machine referred to, is as nearly a sine curve as can be produced. Note how closely the transformer kept to its ratio.

Wet Test. The best wet test to apply is the one which has the least number of variable elements connected with it. The greatest variable is the quality of the water itself. All others may be controlled with more or less accuracy. Figs. 10 and 11 reproduce a set of curves drawn from results of rain tests made on a number of 10-in. (254 mm.) corrugated suspension units first at Lisbon, Ohio, and then at Pittsfield, Mass. The same spray nozzles and insulator units were used in both cases. Plenty of power was at hand and the frequency was the same. Both generators had good wave forms. The specific resistance of the water at Lisbon was 880; that at Pittsfield was 7000. Also note the effect of throwing salt into the spray. It is my belief that condensed water should be specified, as it would not have such variable characteristics. Water of this character may have a specific resistance of 30,000 ohms per cu. cm. The quantity of water sprayed on the insulator is of secondary importance, as it can be varied through quite a large range without changing the results appreciably. I have found that four Mistry nozzles supported at an angle of 45 deg. with the horizontal and supplied with water at 45 lb. (20.4-kg.) pressure if placed about three ft. (91.4 cm.) from the insulator give very good results. As to what is to determine the failure of an insulator, I believe the only way is to use what the author has called a parallel test, putting all styles of insulators to be compared under test simultaneously and selecting the one which shows up the best. All other methods are unsatisfactory, owing to the absence of any correct measure of the various phenomena

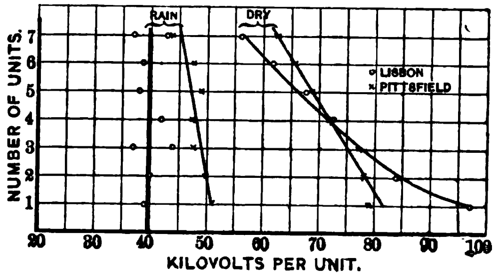

FIG. 10—COMPARATIVE TESTS ON INSULATOR NO. 1113; LISBON VS. PITTSFIELD

to be observed. The formation of corona or luminosity is particularly indefinite.

The puncture test under oil as conducted in the past amounts to little, and will continue to be of little value until the method of applying it has been standardized. The time element plays a most important part as the voltage is raised. A choice of two methods of handling the time and voltage elements may be suggested:

First—Gradual and steady increase of voltage until puncture occurs.

Second—Voltage increased by stated amounts at stated intervals, noting when puncture occurs.

Further, a certain requirement should be set forth in a set of specifications to cover this item, based upon a certain per cent of line voltage. In every case the potential should be applied using as nearly as possible the same style of fittings as are to be used on the insulator in service. At least ten samples should be tested to give a fair average.

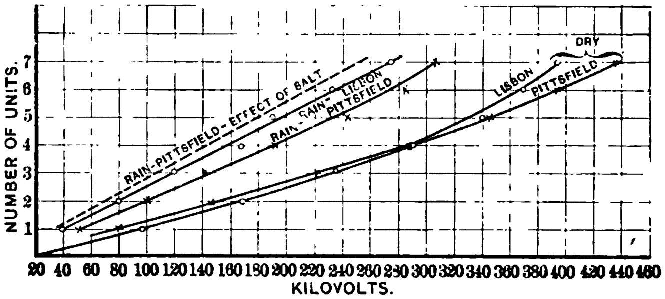

Fig. 11—Comparative Tests on Insulator No. 1113

The usual methods of applying mechanical tests to pin type insulators might more properly be called pin tests, as I know of no insulator pin made that will stand nearly the amount that is required to break the insulator with load applied at the tie wire groove and perpendicular to the axis of the insulator. The test value to be specified depends largely on how great a factor of safety the purchaser is willing to pay for.

All the above has to do with the selection of a proper type or size of insulator for a specified set of conditions.

The inspection of the porcelain parts of insulators for physical defects and the agreement between the purchaser and manufacturer as to what constitutes sufficient cause for rejection is often the most difficult problem of all. Mr. Sothman has hinted at this, and I believe many others have had a like experience. Personally, I believe that insulators showing cracks, blisters, large amounts of sagger deposit, pieces that show plainly that they are either over- or under-fired, or having crazed glaze, should be rejected. On the other hand, insulators showing discoloration—if not due to over- or under-firing—slight warping, or slight unevenness caused by small pieces being chipped from the ware before glazing, should be accepted. However, no matter what lines are drawn, it will finally boil down to the judgment of the inspector, who can easily work a hardship on both the purchaser and manufacturer.

The company with which the writer is connected has drawn up standard specifications for routine tests, which are used in all cases where specifications are not supplied by the purchaser. Voltages used of course depend on the insulator in question. The periods of time of test, so far as suspension units are concerned, we have fixed, as the variation in size of different insulators is not great; therefore the expense of testing is nearly the same for all styles we make. With reference to pin type, however, the sizes vary greatly, requiring voltages varying from 45,000 to 180,000 volts. The smaller insulators, particularly below 22,000 volts, do not need to be tested so long as the larger sizes, as each porcelain part in the smaller insulator is often as thick as in the larger, and the voltage per part very much less. Furthermore, a long time test on a very small insulator makes the cost of testing out of proportion to the price of the insulator.

The specifications which we have adopted are the result of our experience in testing porcelain insulators, combined with what we find is being asked for in specifications issued by different engineers. They are not as voluminous nor as exacting as some, nor as short and indefinite as others. We feel, however, that they are so drawn as to insure the purchaser against receiving defective material, without imposing undue hardships on the manufacturer.

In regard to two-piece insulators, I believe that the specifications may properly contain a statement as to the kind of cement to be used, and if Portland is specified, a statement as to the time of setting. As to the method of cementing, I believe this should be left entirely to the manufacturer, as it is right to suppose that if the manufacturer is following up his methods closely with a view to turning out the best possible product in the most economical manner, and at the same time fulfilling all guarantees made, he is in better position than the purchaser to say how the details of the work shall be carried out. This applies to all other parts of the work as well as the cementing, and will be found to vary in the different factories.

All insulators, whether pin or suspension type, should be tested after having been assembled and the cement is sufficiently set to allow of safe handling. There is a possible exception to this rule in the case of the very small two-part pin type insulators, as it is sometimes found advantageous to test these to flash-over when they come from the kilns, assembling the parts in the test pans without cement, thus testing both parts at once. Water is placed between the parts for this test. In the case of these small insulators it is then safe to cement the parts together and pack the complete insulators without further testing.

The paper by Messrs. Imlay and Thomas at once suggests that it may be desirable to introduce some sort of high-frequency test into the list of tests to be applied in order to make a selection of the proper insulator for a given set of conditions. However, I do not believe there are sufficient data at hand, at present, to allow us to say just what this test should be or how it should be applied. Further, I doubt the advisability of using the same apparatus for this test as is used for the commercial routine tests at the insulator factory.

Since it is coming to be generally acknowledged that the parallel test is the only good way to determine what is the most suitable insulator to meet a set of specified conditions, it seems to me that there should be available some place where such work could be done, using the same equipment and conditions of test at all times. At present non-interested companies that are equipped, so far as apparatus is concerned, to make such tests, do not like to go to this trouble to set aside a space and rig up for the various tests, as such work does not pay them, and not having arrangements especially for it, there is more or less danger of injuring the apparatus.

If arrangements could be made with some laboratory or factory having the equipment and not directly interested in the sale or purchase of the insulators, in accordance with which this apparatus in a suitably equipped room could be available at all times, I believe that with proper use of such advantages there would be fewer mistakes made in insulating our transmission lines, and incidentally the owner of the equipment could derive considerable revenue from the making of comparative tests preliminary to the purchase of insulators for a transmission line, and from the use of such equipment for experimental and research work at very high voltages not at present possible except for experimenters connected with our large manufacturing companies.

We will be glad to give anyone copies of the specifications used by the company with which the writer is connected, or in any way to help in a movement for the standardizing of the specifications and the methods of tests on high-tension insulators.

A. O. Austin: There are a number of important points brought up in the papers by Mr. Sothman and Messrs. Imlay and Thomas, which deserve careful consideration, but the scope of these papers is such that it will be possible to discuss them only in a general way. I hope, however, that a few words in regard to the methods of testing and their discrepancies may be of interest, for I find that tests are only too often misinterpreted.

The character of the testing apparatus has been given very careful consideration, so that in testing at flash-over, severe surges would be thrown upon the insulator in order to make the weeding-out process as effective as possible. This practise has been followed for a long time on pin type insulators and carried even farther in the case of suspension insulators. By providing the proper regulation of testing apparatus, the picking up of power arc is prevented when insulators flash-over under test.

For over four years, suspension insulators have been given routine tests under conditions similar to those outlined in the paper by Messrs. Imlay and Thomas. The insulators are given this routine test one at a time under conditions much more severe than those at normal frequency and flash-over. This test is very much more severe than a long time test, and more nearly approaches high-frequency conditions under which the insulator must operate.

In general, too much attention is given the wet flash-over values obtained on insulators, and not enough attention paid to surface stress and dielectric strength to meet line conditions.

Several years ago the fad of designing insulators for high wet flash-over was responsible for many poor designs. While many of these gave fairly good results when mounted upon wooden pins, trouble was sure to follow when they were mounted on metal pins under severe conditions. In at least one instance these commercial designs were discontinued and the dielectric factor of safety increased in the other types. There will always be a considerable variation in tests under rain conditions made by different persons, but as the dry tests are very much more important this should give but little trouble.

Dry tests on the better types of insulators may be checked very closely on widely varying types of apparatus. It is of course recognized that insulators which have high surface stress or charging current, such as low-voltage bushings and the poorer types of insulators, will be greatly affected by frequency or wave form. This class of material, however, is rapidly becoming obsolete.

The design of an insulator is necessarily a compromise of the elements producing dielectric strength, surface resistance, flashing capacity, and mechanical strength, and since the operating conditions on different lines may call for widely different relative proportions of these elements, it is very difficult to draw up general specifications. Lines operating at the same voltage but under different conditions may require a difference of several hundred per cent in the factor of safety of one of these elements, in order to produce the same degree of reliability. The relative numerical values involved are all-important. and the design of two insulators may be radically different in appearance but the same for operating conditions. There are some commercial insulators which have been in use for several years, which were designed to meet the severe conditions of the high-frequency surges, and which involved the use of the screen shown in the paper by Messrs. Imlay and Thomas. These insulators have the further advantage of multipart construction, enabling a redistribution of stress between the outer and inner surface, by making use of the cement zone. The relative diameter of the several parts was given very careful consideration, also the striking distance between conductor and pin.

Some experiments were performed several years ago which show that there is a redistribution of stress in insulators through an air discharge, which is not visible to the eye. A discussion of this point would be too lengthy, but would throw considerable light on some of the tests performed by Messrs. Imlay and Thomas.

I may add that the performance of these insulators has been more than gratifying and furnishes strong proof that the tests performed by Messrs. Imlay and Thomas imposed conditions similar to those found on the line.

In a rather wide experience in investigating operating conditions, I have found that the information as regards insulator failure is only too often very misleading. An investigation usually shows that much valuable evidence which cannot be replaced has been lost or destroyed.

It may be interesting to know that type *E* insulator tested by Mr. Sothman was the only insulator in the series which provided a thickness of material purposely to provide dielectric strength for high-frequency line surges. Operation showed that under the most severe conditions a still further increase in this regard was warranted. The insulator was further improved in this regard and this has been the only marked improvement in the suspension insulator since the tests made by Mr. Sothman.

Before writing up a set of specifications to be used for inspection it is of the utmost importance for the engineer to investigate as far as possible, so that his inspection will produce an increase in reliability in the product.

Good appearance should be maintained, but there are other essentials not apparent on the face of the insulator which are very much more important for reliability in line operation.

The methods in process of manufacture should be such as to produce the greatest degree of reliability.

In general the insulators of foreign manufacture are superior to ours in appearance, but very inferior as regards reliability. Certain processes are used which have a very bad effect upon the insulator; the dielectric strength is sacrificed for appearances, and it has been found that serious cracking occurs after a short period of installation. This, of course, has been particularly noticeable where the multipart insulators were made up, and was pointed out by Mr. Sothman.

The designs in use in this country are very much ahead of those of foreign manufacture when it comes to line conditions. Most of the large pin type lines in use in foreign countries are being supplied by American manufacturers.

There is much to be said in regard to static puncture, for an investigation carried on in 1904 showed conclusively that a static puncture could be in the nature of a partial breakdown.

This was effected by a low voltage for mechanical stress, for the resulting failure was of a physical nature.

F. M. Farmer: These papers are valuable contributions to a phase of electrical engineering activity which has been very much neglected in the deliberations of the Institute. Although matters pertaining to the transmission of electrical energy form a conspicuous part of the transactions of the Institute, practically nothing will be found about the testing of high-tension insulators, despite the importance which all engineers attach to the proper inspection and testing of insulators to be used for transmission line purposes. Contributions to this neglected subject are, therefore, very welcome, and those of us who are especially concerned with the testing side of engineering work will be particularly glad to see attention drawn to the need for improvements in, and the standardizing of, testing methods.

The standardization of methods of testing not only insulators, but all classes of insulating materials, is very urgently needed. It is probably safe to say that no two testing engineers, whether representing manufacturers, consulting engineers, or testing laboratories, will have the same ideas as to just how a high-tension test should be carried out, although it is well known that such details as the method of controlling voltage, the amount of resistance and inductance in series with the specimen, and the arrangement of the spray in an artificial rain test, may have a marked effect on the results. We have available more or less standardized methods of testing other materials used in transmission lines. Methods have been fairly well standardized for physical tests of the tower members, for galvanizing tests, and for physical and electrical tests of the conductor materials, but practically nothing has been done on insulators, although they are the most important element in the transmission line.

While the standardization of testing methods is very important, the definition of the terms used in connection with insulators should receive first attention. Different manufacturers and engineers use, in their catalogues and specifications, different terms for the same thing and describe the same phenomenon in different ways. For instance, the parts of a pin type insulator are called shells and petticoats; the components of a complete suspension insulator are called units, sections and parts; and the corrugations on a suspension insulator unit are called corrugations and petticoats. Also, what is static arcing and what is a power arc? Is flash-over voltage the potential at which the first intermittent static arcing, or continuous static arcing, or power arcing, occurs? The suggestion is offered that the attention of the Standards Committee be drawn to the desirability of having some of these things officially defined.

Referring to Mr. Sothman's paper, it seems to me that it would have been advisable to separate the data pertaining strictly to types or designs from those which may be affected by variations in quality or methods of manufacture. For instance while it is true that the ultimate dielectric strength, the tensile strength, and the number of punctures which occurred during the tests, will be affected by the design, it is also true that the quality of the material and the methods of manufacturing may affect the results to a greater extent, so that a poorer design of superior manufacture might show up more favorably than a better design of inferior manufacture. Therefore, when comparing the results of an investigation made for the purpose of selecting a type, this should be carefully borne in mind. Of course, the ideal methods of making such comparison would be to have various designs made by the same manufacturer and then the results would be affected in a similar manner by the inherent variations in clay composition, firing, cooling, etc.

No figures are given in the various tables showing the number of insulators or insulator sections tested. This information would be valuable in connection with those tests which involve variations in the individual specimens of the same design and manufacture, such as dielectric strength, tensile strength, punctures during the various tests, etc. These data should be taken on a considerable number of specimens before definite conclusions can be drawn.

Mr. Sothman refers to factory inspection of insulators and his statements emphasize the importance of careful and conscientious work at this stage. Porcelain insulators are inherently a variable product and the only method of determining whether an insulator is a good one or a poor one is by inspection and test of each and every one. A large factor in the success of an operating company is continuity of service, and this depends very largely upon the line insulators. It is apparent, therefore, that the inspection and testing cannot be too carefully or thoroughly done, and that the inspectors should be experienced men competent not only to make the electrical test but to judge accurately the quality of porcelain. With the present methods of manufacture, the quality of porcelain will vary from day to day and even in the same kiln, for it is extremely difficult to " fire " porcelain just right—it may be "over-fired" or it may be "under-fired". Insulators that are not properly fired are inferior, but the high-voltage test cannot always be relied upon to weed them out. The operating company cannot afford to take any chances, no matter how small they may appear to be, therefore the inspector should be competent to detect such insulators and reject them without test. It is also desirable that the inspector have some experience in miscellaneous high-voltage testing of all classes of materials and apparatus in order that he may intelligently interpret the performance of insulators during the routine factory test.

Referring to the points which Mr. Sothman suggests should be given consideration in the future discussions, the writer would propose that the item referring to generator and transformer capacity include the amount of resistance and inductance in the high-tension circuit of the testing transformer. It is customary to use an impedance of some kind in this circuit to protect the transformer and obviously it may be sufficient to decrease the power available at the specimen under test and thus have an effect upon the results.

Referring to specifications for wet tests, it is suggested that the minimum period of precipitation before the voltage is applied be stated.

Routine tests and inspections on the product as it is being manufactured may be divided into two classes. One class includes the preliminary inspection, the preliminary electrical test, the final inspection and test after assembling and the mechanical tests. These tests and inspections are made on each insulator and insulator part. The second class includes those tests which would only be made at occasional intervals to check up the quality of the product and insure that the standard originally established is being maintained, as for example, the determination of the dielectric strength under oil, the effect of immersion in water for a considerable period, the effect of application of potential for a long period, and ultimate tensile strength tests.

Referring to the manner of making the routine electrical tests at the factory, the writer feels that such tests should be made as severe as possible, consistent with reasonable cost and fairness to the manufacturer. The operating company is very dependent upon the insulators on its transmission line in reducing interruptions of service to a minimum. While it cannot eliminate all chances of interruption, it is justified in taking precautions at every stage in the construction of the line to eliminate sources of possible failure. Therefore, the inspection and test at the factory should be as severe as expense will permit and the electrical tests should include a long time test at continuous flash-over voltage after all insulators giving any signs of physical weakness have been eliminated. Of course the imposition of severe conditions on the manufacturer may mean a higher cost, but in view of the great investment in modern transmission lines and the importance of continuity of service, a slight additional cost in the insulator item would seem to be entirely justified. Experience has shown that a continuous static flash-over test is more severe than a test at voltage just under continuous flash-over. This is probably due to the high-frequency oscillations set up under such conditions, which produce the effects noted by Messrs. Imlay and Thomas in their paper.

Ralph W. Pope: The relative merits of different materials and different forms of insulators have been a fruitful topic of controversy since the construction of the first telegraph line. Fluted porcelain insulators (then known as " white flint ") were used on the House telegraph line between Albany, N. Y., and Springfield, Mass., in the fifties. They were superseded by glass, which, so far as telegraph and telephone service is concerned, has appeared to be a " survival of the fittest." After reading these two papers, it appeared that glass for high-tension work had been overlooked, as no tests of that material are included. In seeking for information upon the subject, I learned that glass insulators, although extensively used on the Pacific coast of the United States, have not always received the consideration which their merits deserve.

Glass was the first material to be used for insulators on transmission lines in the United States, and it has shared with porcelain this application. In France glass is extensively used for transmission lines, we understand, up to 100,000 volts, while in Italy many power lines are similarly equipped. There are 5,000-000 glass insulators giving good satisfaction over high-tension lines today in the United States. The question is one both of material and of construction. Fundamentally, glass is superior because, being of homogeneous character and a single material, the entire body of the glass acts uniformly as the insulating medium, whereas in porcelain the glaze appears to be the main factor of insulation resistance and differs in composition from the body of the substance, which is far inferior to glass in this respect. Now, when it is recalled that this glaze may be but a thousandth of an inch or so in thickness, it is obvious that any imperfections or unevenness in its texture are sure to be fraught with danger. This is further emphasized by recent improvements in glass manufacture which result today in a material, uniform in character, of greater strength and specific gravity, where increased mechanical efficiency and strength are combined with the desired insulating properties. This improvement has followed technical developments in glass-making just as in steel and other industries, and is due primarily to a better understanding of the chemical and physical questions involved. In the first place, the raw material is now rigidly controlled by test and analysis and the substances entering into the batch are selected with due regard to the resulting product. For example, the elimination of all iron is considered of prime importance, and in the best factories, magnetic separators are used to remove such impurities from the raw material. Then again, the proportioning of the materials can now be done with great accuracy and by mechanical weighing and mixing, the composition can be controlled within narrow limits, so that the product is not only uniform and homogeneous, but conforms closely to the desired specifications. In this respect modern glass, as used in insulators, shows great strides over the product of fifteen years ago, which was too often uneven in composition and texture. Today not only are the materials carefully selected, weighed and mixed, but they are melted in large open-hearth Siemens tanks where the molten material, being in motion, is kept from separating into layers of varying density, which, in former days, too often produced not only uneven, but cordy or stringy glass that failed to give the best results either electrically or mechanically. Modern methods of manufacture have done away with this, and at least one large and well known glass factory has had no cordy glass for ten years.

Unfortunately, glass manufacturers in the United States have failed to realize adequately the availability of their product for high-tension work. In the first place, for the new and unusual shapes required they at first demanded prices that, if not prohibitive, plainly suggested an unduc profit. Secondly, the manufacturers have failed to consider sufficiently the electrical side of the problem and have not shown a progressive spirit in arranging testing plants and methods of test and experiment. Furthermore, such concerns as have developed improved methods of manufacture have failed to publish the results of their improvements, so that to many engineers the merits and relative economy of glass as compared with other materials, have never been made apparent. For these reasons, chiefly, porcelain has achieved a position in this field which modern glass insulators are now in a position to dispute. Just as the problem of a high-tension insulator was solved in porcelain by the suspension insulator, so similar designs have been developed for glass, which are now gaining wide vogue. It will be remembered that a porcelain pin insulator required for a 100,000-volt transmission line could be built only of such size and form as to cost the prohibitive amount of about $30, but that by combining a number of insulators by cementing to malleable iron fittings and suspending the cable, high-tension insulators of such capacity could be supplied at a cost of about five or six dollars. Likewise for glass, the suspension insulator has also been developed for high-tension lines, and types now in use meet all conditions in a most satisfactory manner and often more advantageously than porcelain. Instead of making the glass about three inches (76 mm.) thick as has been done with a pin type insulator, where stresses are almost unavoidable, the same result can be secured with glass three-quarters of an inch (19 mm.) thick. This permits of perfect annealing and the development of a glass with practically the same strength as porcelain. In such disks corrugations of the necessary shape can be molded so that the cement holding the various segments together will have a firm hold and afford an insulator of strength equal to a solid piece. Today these composite insulators of glass have been developed to a point where samples of suspension insulators are supplied by glass manufacturers for comparative tests with those of porcelain, irrespective of the voltage for which the line is to be used. For long-distance telephone communication, comparative tests have been made of glass insulators and those of other materials along parallel lines and the practical results, as shown in more distinct enunciation, have coincided with the reports from the testing laboratory, while the power lines on the Pacific coast where glass has been used all return satisfactory reports. One objection to glass insulators has been that they could only be used with wooden pins. The more perfectly annealed glass insulators have been used with iron pins dipped in pitch and stand up as well as the porcelain. Another objection has been that internal stresses are caused in the piece, due to poor annealing. This has been eliminated by flash-over tests of say five minutes and by the more perfect methods of annealing.

But, for the present consideration, we can take up in some detail a test of some glass suspension insulators which shows their present condition and possibilities. These were ten units of glass, all of the same size and style, sent to the testing laboratory without previous tests or inspection. These samples were ten in. (254 mm.) in diameter, fitted with malleable caps and eyebolts. The record of the tests given herewith is a factory laboratory test designed to show the general run of manufacture so that the samples showing defects of manufacture would not figure in engineers' or contract tests. These tests follow the standard methods usual with high-tension insulators and imitated as nearly as practicable the conditions of service.

A test of ten insulators follows. The test speaks for itself.

Flash-Over Voltage, Dry

Specimen number	Voltage at first intermittent flash-over	Voltage at continuous flash-over
1	76,600	83,650
2	78,600	84,650
3	78,600	83,650
4	79,650	86,700
5	75,600	83,650
6	Punctured through head at 60,500 volts	
7	78,600	88,700
8	Punctured at bottom of cap at 76,600 volts	
9	78,600	88,700
10	Punctured through head at 78,600 volts	

Test at Continuous Flash-over for Five Minutes

Specimen number	Voltage applied	Remarks
9	88,700	Heated slightly.
7	88,700	" "
5	86,700	Punctured through head after 4 min. 45 sec. Considerable heating noted.
4	86,700	Heated slightly.
3	86,700	Punctured through head after 1 min. 5 sec.

Flash-over Voltage Under Spray of 0.2 in. (5 mm.) per Minute (Approximate)

Specimen number	Voltage at first intermittent flash-over	Voltage at continuous flash-over
1	46,350	50,400
2	43,350	48,400
4	45,350	49,450
7	45,350	49,450
9	44,350	48,400

Maximum Dielectric Strength—Punctured Under Oil

Specimen number	Volts at puncture
1	184,650
2	110,900
4	114,900
7	88,700
9	114,900

E. E. F. Creighton: The importance of the study of line insulators is obvious to the engineer of electrical transmissions. The paper of Mr. Sothman is of a different nature from the one by Messrs. Imlay and Thomas. They are both valuable contributions to a subject to which more attention is needed and has been needed for some time past.

Instead of commenting directly on these papers it is the intention of the writer to look at the subject from still another view point, in an endeavor to explain the theory of the phenomena. A correct explanation and analysis is needed to aid in the solution of the problem of insulator design. Much of the following analysis is, however, of the nature of hypothesis based on observations of experiments extending over a period of several years.

Measurement of High-Frequency Potentials. Because of its prominence, and furthermore, because of the great ignorance concerning the factors entering into the designs and tests of high-tension line insulators, it is, probably, the most important element today in the successful transmission of power. The known factors which cause a line insulator to fail are diversified. They range through successive steps from choice of material, to the nature of the applied strains. There are, probably, factors to which we have not given name or even recognition. Furthermore, we have a number of fixed ideas, taken from standardized practise, which have led us somewhat astray. The most important of these false ideas is that a spark gap necessarily represents the voltage given in the Institute rules. Spark gaps have been checked many times since Dr. Steinmetz made the original curves and have been often used at generator frequency. No one, so far as the writer knows, has made a systematic study of the relation of gap length to voltage, at high frequencies. There is a difference. In general, one can say that the higher the frequency the lower the potential that is necessary to produce a spark across any definite spark gap. There is, possibly, an upper limit of frequency above which the reverse law holds: that is to say, with any further increase in frequency the potential to produce a spark across any definite gap may actually be on the increase. The foregoing conclusion is based on reasoning from the standpoint of dielectric spark-lag. There can be no question as to the reality of spark-lag. It has been measured indirectly[1]. Under particular conditions the writer has been able to so magnify it as to measure it with an oscillograph and even with a stop watch.[2]

A possible explanation of how the potential to cause a spark is increased, as the *time* of alternation of the high-frequency oscillations becomes less than the time of the dielectric spark-lag, follows.

As an hypothesis, it is assumed that if, in a given brief time,

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[1] *Disruptive Strength with Transient Voltages.* J. L. R. Hayden and C. P. Steinmetz, TRANSACTIONS A. I. E. E., 1910, XXIX, II, p. 1125.

[2] See Discussion, TRANSACTIONS A. I. E. E., 1910, XXIX, II, p. 1214.

ionization has taken place over only a limited zone around an electrode, this ionization may be more or less destroyed by each reversal of potential. With less total ionization between two electrodes it may require an increased potential to produce a discharge.

It seems probable that local de-ionization around a spark accounts for the fact that successive sparks in air between electrodes or around an insulator choose new paths. Each high-frequency spark has an opportunity to cool below the conducting temperature, before the next one appears. The spark relieves the potential strains in its immediate neighborhood. The successive spark naturally follows a path that is left partly ionized by the previous application of potential. This is some new path.

Some Problems Relating to Standardization. To the experimenter, the very natural question arises in the course of his work —what constitutes a discharge as a basis of measurement? In the development of lightning arresters in one protective apparatus laboratory the engineers have found it expedient to measure the current and potential of discharges ranging gradually from a few billionths of an ampere up to a thousand amperes.

The discharge of lowest current is the invisible conduction with which we have been made familiar by the writings and work of J. J. Thomson and others. This ionization can not be ignored while we are in search of a stable foundation for measurement. Under certain conditions this ionization, which is for convenience, in testing lightning arresters, termed " cold " ionization, may affect the spark potential for seconds or even minutes after it has been produced.

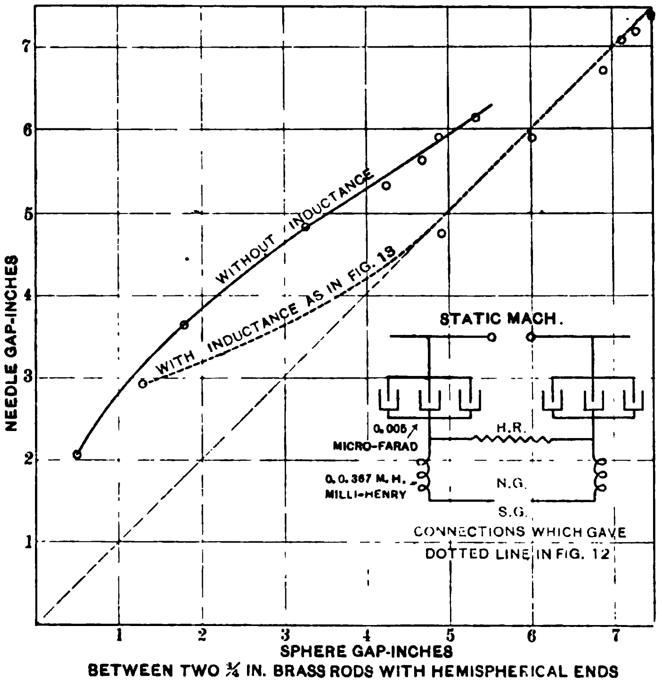
As the current is further increased there appears at the electrodes the faintest blue brush discharge, sometimes called the " silent discharge." This blue brush discharge grows into a dense blue discharge and becomes noisy. As the current is still further increased there appear little white threads of light in the denser parts of the brush discharge. In the next stage the blue discharge has disappeared and there is nothing seen but the whitish spark. The spark is apparently more highly conducting than the brush discharge. Further increases in current increase the brilliancy of the spark. In the next stage a crater is formed in an electrode which furnishes arc vapor. As the current density increases the resistance of the arc decreases.

During these different stages of discharge the potential across the electrodes has risen and fallen irregularly—sometimes gradually and in a few points abruptly.

What potential of discharge is to be used as a basis of measurement? I see no answer at present.

At normal frequencies the potential that will cause a short-circuit arc is the one chosen. Everyone who has tested the dielectric strength of oil is familiar with the " b.d.s.i. " spark (b.d.s.i. = break down at short intervals). It is customary to neglect these small preliminary sparks which occur before the final potential of complete failure is reached.

We are all familiar with the curves of spark potential of needle gaps and sphere gaps. At low values of gap length it requires more potential to spark the sphere gap than the needle gap. But as the gap lengths become greater these two values of spark potential gradually approach each other. For very large gaps there is very little difference in spark potential between needles and small spheres used as electrodes. In the measurement of high-frequency discharges, however, the conditions of test may be adjusted to give practically identical curves for both the sphere and needle gaps. (See Figs. 12 and 13.)



FIGS. 12 AND 13

The curves in Fig. 12 show the relation of spark potential of a needle gap and a sphere gap at frequencies of about 4,000,000 cycles per second and somewhat less.

Fig. 13 shows the general connections of the circuit. With no inductance in series with the spark gap under test, the relation between the sphere gap and the needle gap is given by the upper curve. This curve shows the same general relations as the tests at 60 cycles. When, however, the inductance is placed in series, as shown in Fig. 13, the needle gap and sphere gap become equal in length for the same potential. The dotted line shows the relation. The broken line, drawn in at 45 degrees for reference, shows the position of the curve for equality between the needle gap length and the sphere gap length.

In the measurement of the discharge potential of a multigap lightning arrester, as shown in the circuit connection of Fig. 14, the potential indicated by the needle gap is always much higher than the potential by transformation. Although the actual potential may be greater than the value given by the ratio of transformation of the transformer, there is evidence to show that it is not as high as indicated by the needle gap.

The difference between the two values of potential is really due to the oscillations set up by the sparks between the cylinders nearest the line terminals. As the potential of the transformer is increased, more and more of these arrester-gaps spark over, until finally the spark runs entirely across from terminal to terminal. Since it requires only about 2000 volts to spark over a single gap, and since each successive gap breaks down like the fall of a " card-house," it is reasonable to conclude that the oscillations set up by the sparks on the end gaps do not raise the potential by more than a few per cent. Since the indications of the needle gap may easily be 50 to 100 per cent above the potential by transformation, one must necessarily conclude that the high frequency causes the spark across the needle gap to form more easily. Other examples could be given, but the foregoing is sufficient to cast doubt on the needle gap as a device for measuring potentials at high frequency.

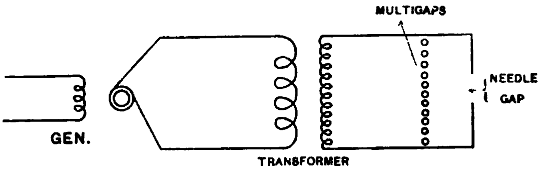


FIG. 14

Circuit connections for showing the variations in needle gap when local high frequencies are superimposed on the 60-cycle wave of potential.

Let us look next to the use of the electrostatic voltmeter. First of all, the electrostatic voltmeter measures effective but not maximum values of potential at normal frequencies. At high frequencies the usual type of electrostatic voltmeter does not seem to measure anything. To illustrate: an electrostatic voltmeter was calibrated on 60 cycles and found approximately correct. It was then attached to a 200,000-cycle Alexanderson generator through a small step-up transformer. At three-quarters of the full scale deflection it sparked over and thus short-circuited. Two questions arise—did the lower potential, as indicated by the deflection, cause an internal spark due to the better conduction of the air under high-frequency stresses? Or, did the excessive value of brush discharge which, due to high frequency, occurred at the edges of the vane, cause an erroneous deflection? The mechanical repulsion of the brush discharge on the edges of the vane might naturally prevent the vane from moving up to the position corresponding to the impressed potential. Thus the standard electrostatic voltmeter fails in its application to high-frequency measurements.

In all these measurements, it may incidentally be noted, there is always the possibility of the occurrence of localized resonance. A stationary wave might raise the potential locally to nearly double value.

THEORY OF DISCHARGE AT AN INSULATOR

The electrostatic strains on an insulator under test cause two well-known distinct phenomena:

1. A direct stress through the porcelain.
2. Corona streamers over the surface.

1. *The Stress through the Porcelain.* This presents no especial difficulty in its analysis, so long as we do not insist on knowing too intimately the sub-atomic processes. There are two metal surfaces separated by solid porcelain. In the intense field the potential gradient between the metal parts is fairly uniform. At the sharp edges of the metal, such as, for example, the pin of an insulator, there is a local concentration of static stress, which may be the cause of the beginning of a failure by puncture.

If there is a flaw in the porcelain in the strong part of the electrostatic field, naturally, this locates the path of puncture. If the flaw is outside the strong part of the field, puncture is a matter of accident. The probabilities of puncture under this condition will be discussed later, as it comes under the category of superficial discharge.

What is a flaw in the porcelain? What produces flaws? How are flaws to be distinguished from universally weak porcelain? These are questions that should be answered by the manufacturer of porcelain for electrical purposes. My understanding of the situation at present is that they are all too busy manufacturing porcelain to spare the time for anything else. The possibility of studying this subject carefully is not given to many engineers. The man who should know is the operator of a furnace. The processes have been developed by cut and try methods and even at the scientific " best " the temperature throughout a furnace in practise may vary from top to bottom and from center to edge. The problem, it seems, in firing porcelain is to raise the temperature to a point such as to soften the porcelain and sinter it into a solid mass and yet not go so far above this temperature as to make the porcelain melt down. " Under-firing " produces weak porcelain containing flaws, and the insulators are punctured in subsequent test. " Over-firing " allows the insulator to warp out of shape and it is scrapped before it comes to test.

Flaws may come also from local impurities, insufficient curing before firing, improper dimensions, or improper rate of firing.

Irrespective of other factors, there is a marked effect resulting from the periodicity of the potential of test. Our tests have not shown directly that dielectric hysteresis in porcelain is a factor, because there is no method of predetermining the presence of a flaw. The fact that puncture is most liable to occur in spots that are not initially at the maximum electrostatic stress would lead one to believe that it is most frequently the accidental flaw or locally weak spot that fails, rather than a damage to the good porcelain resulting from the rapid alternation of potential. However, on the other hand, in using a battery of glass Leyden jars, the evidence seems conclusive that when a high-frequency discharge takes place it is the heating effect of hysteresis or at least the alternating effect of the high frequency which causes puncture. Leyden jars have withstood more than five times as much undirected potential as alternating potential. The frequency was about a million cycles per second. These statements have reference specifically to very high frequencies. The difference between 25 cycles and 60 cycles is relatively negligible.

By inductive reasoning from experiment it seems certain that high frequency is more severe on the flaws in porcelain than low frequency. At the surface checks and flaws the possibility of damage, then, is increased not only by the greater potential gradient due to the depth of the flaw but also by any increase in the frequency of oscillation.

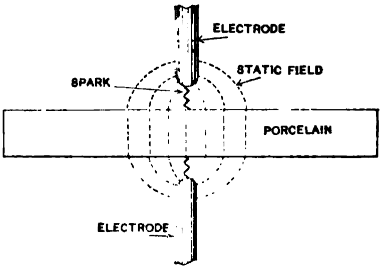


FIG. 15

Illustration of the spark which takes place when the air is over-stressed. The arc is prevented by the fact that the porcelain has a greater dielectric strength than air.

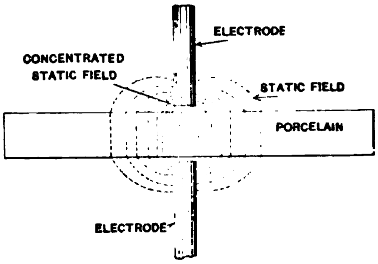


FIG. 16

This illustrates at the corner of the electrode the dense field which has a component parallel to the surface of the porcelain. When the potential gradient reaches the critical value for air a horizontal spark starts along the porcelain.

2. *Corona Streamers over the Surface of an Insulator.* It is evident that if an insulator must fail, it should do so by sparking around through the air rather than by puncture. There are two important questions: What makes the arc go around?—and, what forms or designs favor this? Mr. A. O. Austin, as stated in his paper* at the Chicago convention, 1911, used a working theory of surface resistance to aid in improving the design. Where the surfaces are wet, and they are usually more or less

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******The High-Efficiency Suspension Insulator,* TRANSACTIONS A. I. E. E., 1911, XXX, III, p. 2303.**

moist, there is a real surface resistance that must be taken into account. Putting aside the matter of rain tests, there is a phenomenon of discharge over the surface which I think can be distinguished from conduction by "surface resistance." This is shown in several gradations in Figs. 15, 16 and 17. The requisite parts to give this phenomenon are two electrodes in air and a sheet of insulation separating them. A primary requisite of the insulation is a dielectric strength greater than air. If at the same time the insulation has a dielectric constant greater than air, this greater constant will also tend to magnify the surface corona on the sheet of insulation. In Fig. 15, it is assumed that the insulation is of porcelain which has a dielectric strength seven times as great as air and a dielectric constant four times that of air. As the difference of potential on the electrodes is gradually increased, the air breaks into a conducting spark, but there is no damage to the porcelain as it is at only one-seventh of its dielectric strength.

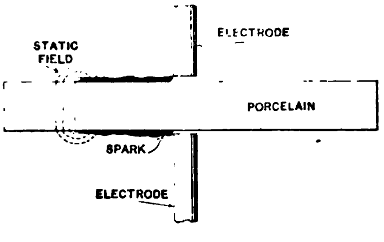

FIG. 17

This represents a single spark running out from the electrodes along the surface of the porcelain and the electrostatic field at the advance points of the spark which causes it to continue to move forward along the surface of the porcelain.

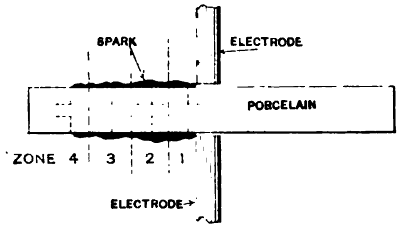

FIG. 18

This shows, for the purpose of analysis, an artificial separation of the capacity between two electric sparks into four zones. The use of this figure is explained in the text.

As the potential gradient at the edges of the electrodes rises (Fig. 16), the air will be put under more and more stress. Since the porcelain conducts the displacement current four times as readily as air, it tends to draw the electrostatic lines in air closer to the edge of the electrodes and thus increase the density there.

Fig. 17 represents the condition when the horizontal electrostatic forces at the surface of the electrode reach a gradient above 30 kv. per cm. This causes a spark to run out along the porcelain on each surface, in the same relative position. Since the spark is more or less of a conductor of electricity, the electrostatic lines will extend beyond its outermost point and thus will continue to overstrain the air, in advance of the extending spark. This overstrain turns into a brush discharge and then a spark discharge. Thus the spark length gradually but rapidly grows. As a distinguishing mark this surface spark will be called ***creeping spark***. If there were no losses of energy to weaken the spark it might be possible to spark over an indefinitely extended surface merely by raising the potential gradient of the electrodes above the dielectric strength of the air.

What gives the spark its volume or intensity of current? The growth of the corona spark consists in supplying new electrostatic condensers with electric charge. The sparks on opposite sides of the porcelain form the plates of a condenser.

For the sake of convenience the length of a given spark (Fig. 18) is divided into four arbitrary zones and so numbered. When the spark first reached the capacity of zone 1 it was carrying current to charge condenser 1. As soon as condenser 1 became charged, the current in the spark would have dropped to zero if it had ceased to move forward toward the next zone. Its movement into a new zone necessitated a further supply of electricity to the capacity of that zone.

When the spark reaches zone 4 it may be that the condenser of zone 3 has not yet received its full charge, due to the drop in potential, along the spark, from the electrodes to zone 3. If the spark increases in conductivity zone 3 will get more potential, and therefore, more charge. As a result of this condition the spark tends to attenuate as its length increases. One might say that the attenuation is due principally to the drop of potential along the spark.

So far, we have considered only the first impulse that starts the spark—the equivalent of applying a constant direct potential to the electrodes. The lag in the formation of the spark at the point gives a limit to the current that is drawn through the spark. If, however, the applied potential is rapidly alternated, then the condensers formed by the sparks as electrodes must be supplied with new charges of opposite sign at each alternation. When the electric charge changes from positive to negative (or vice versa) the current supplying the charges does not change in direction. For this reason, and others, the current in the second impulse will be much greater than in the first.

If the alternations are sufficiently rapid to prevent complete de-ionization of the spark streak, each subsequent alternation will find a spark path already partially made and consequently the re-establishment of the spark will be facilitated. Since the creeping spark forms with less obstruction it will be able to extend itself farther from the electrode than it would at a lower frequency.

If we knew that the spark-lag was located mostly in the initial dark discharge rather than in the subsequent blue brush discharge, we would be in a position, at this stage of the hypothesis, to state that the higher frequency would lessen the spark-lag. Further studies of creeping spark-lag are needed to understand the details of the discharge over insulators.

As the frequency of oscillation increases, there is no doubt that the creeping sparks are magnified in intensity and in length. Furthermore, their location is somewhat determined by the frequency.

Does this magnification of the creeping spark always increase as the frequency increases? Exact experimental data are lacking. Since, however, we are launched into an hypothesis it may be extended to cover the condition of extremely high frequency. So far, frequencies of the order of only 100,000 cycles per sec. have been considered (wave lengths about ½ mile long). The matter hinges on two factors, the rate of creeping of the spark, and the possibility of having a wave length less than the length of the creeping spark.

We do not know the rate of creeping of the spark, but if the wave length is less than the distance to the edge of the porcelain it is highly improbable that the creeping spark could extend beyond a half wave length. The energy loss in the spark is so great relatively to the energy stored in the capacity of the creeping spark that probably little of the energy returned from this local condenser would be available to extend the spark. (A spark wave 6 in. (152.4 mm.) long has a frequency of the order of 24 million cycles per sec.).

Furthermore, with such high frequencies the decrement due to the resistance of skin effect in the conductor must be very high and may need to be taken into account. Although it can not be considered as settled, it seems tenable to assume that beyond a certain very high frequency of unknown value the creeping sparks begin to lessen, but at the same time the danger of puncture may also lessen.

The Effect of Surface Conduction as Distinct from the Effect which Causes the Creeping Spark. If the top surface of the porcelain shown in Fig. 17 is covered with rain water the electrostatic forces will be distributed over the surface by the conduction of the water. This will change the electrostatic field on the under side of the porcelain. The current in the creeping spark on the lower side must be drawn through the water on the upper side. This brings into effect the surface resistance.

The general effect of placing a good conductor over one surface of the porcelain is to facilitate the formation of creeping sparks from a narrower electrode on the other side.

Impressed Potential, Creeping Spark-Lag, and Dielectric Spark-Lag. In these three factors is the crux of the problem. To assist in establishing the relations, a specific hypothetical problem is assumed. A gradually increasing potential applied to an insulator makes it spark around at 100,000 volts, at 60 cycles. Under oil the head of the insulator punctures at 130,000 volts at 60 cycles. Under oil, again, an identical insulator tested at high frequency punctures at 120,000 volts, due to the more energetic effect of high frequency in puncturing. (We have no standard for measuring high-frequency potential and we do not know what frequency will cause a decrease in the puncture potential from 130,000 volts to 120,000 volts, but the equivalent condition exists.)

Now, with the insulator in air, if any potential between 100,000 and 130,000 volts at 60 cycles is applied, the creeping spark will, in due time, cause the insulator to " arc around." If a certain high frequency between 100,000 and 120,000 volts is applied the result will be the same.

But if more than 130,000 volts at 60 cycles is applied, the insulator will puncture if the dielectric spark-lag of the porcelain is less than the lag of the creeping spark. The same relation should hold for the high-frequency test. Herein are four factors to be determined: 1. The law of decrease in creepage spark-lag with potential.

2. The law of decrease of creepage spark-lag with increase of frequency.

3. The law of decrease of dielectric spark-lag in the porcelain for increase in potential.

4. The law of decrease of dielectric spark-lag in the porcelain for increase in frequency.

A design must be made which gives a low value of lag to the creeping spark.

METHODS OF TESTING INSULATORS

1. Generator at 25--60 cycles, step-up transformer, and increase of potential by variable excitation.
2. Generator at 100,000 cycles, step-up transformer, and increase of potential by variable excitation.
3. Single sudden disruptive discharge from Leyden jars (or equivalent). Source of power a static machine or other direct current.
4. Oscillating transformer supplied with power at 60 cycles.
5. Multiple disruptive discharges from a condenser charged by potential from a transformer at 60 cycles.

The choice of a method has been dictated at times by its availability. Among the five there are some which give equivalent effects. From the analysis of the problem already given, there are certain characteristics that are desirable to give the insulators certain kinds of strains. These are:

1. Gradually increasing potential at 60 cycles.
2. Gradually increasing potential at high frequency.
3. Suddenly applied potential (*less* than puncture value) at high frequency.
4. Suddenly applied potential (*greater* than puncture value) at high frequency.

The test for puncture of an insulator under oil is not one to be included as a standard test. Although it has a value in investigations of the dielectric strength of porcelain, it has no practical value for general use, due simply to the artificial condition it imposes. The oil cuts off the natural relief path over the surface of the insulator which it is desirable that the discharge should take. The criterion of quality in an insulator depends exactly on this relation, namely, that the insulator shall spark around rather than puncture under the application of sudden excessive potentials of high frequency.

What Value of High Frequency should be Used? This is an open question. It may be regarded from three standpoints:

First (the present-day standpoint), the insulators are made to withstand gradually applied potential at 60 cycles with a resultant flash around the insulator through the air. They have sometimes a further imposed test. This is an endurance run at a potential somewhat below the potential which causes a "flash-around." The fairness or need of this test might well be questioned. The insulator is never subjected to such a strain in practise. So far, then, it is not a fair test. If the test, however, is equivalent to some strain that actually occurs, such as the oscillation of an arcing ground, or if the test is necessary at the factory to eliminate weak porcelain, it must be proved so.

The assumption is made in the above test, wittingly or otherwise, that lightning occurs very infrequently and cannot be allowed for in the construction of the insulator.

Second, from the standpoint of protection, the insulators should be made to withstand the sudden high-frequency potentials of lightning. What are these conditions exactly? Nobody knows and no one is willing to undertake the expense of the investigation. A little is known, but the imposition, blindly, of any arbitrary high-frequency test may be unfair.

Third, from the manufacturers' standpoint, it is a question of production. How many insulators will be left after the high-frequency test is made? One answer is, it depends on the design. Many insulators, however, of a design particularly adapted to high frequency may even be punctured if the imposed test is sufficiently severe. What potential in excess of the average puncture potential of the porcelain is to be applied? How long is the application to be made? How sudden must be the application of potential?

Known and Speculative Conditions of Strain on Line Insulators. Putting aside normal conditions of potential as being so safe to the insulator as to require no comment, there are left two types of abnormal strains: namely, lightning, and surges from arcing grounds.

In the extreme, the value of potential and suddenness of application of a direct stroke of lightning may be said to be greater than anything we can produce in test. In other words, the most severe potential test of the laboratory is permissible. On the other hand, the time of application is short. It is usual to have several successive lightning discharges in a fraction of a second. The frequency is unknown. Dr. Steinmetz's calculations and our uncertain tests put the value at perhaps a half-million cycles. This frequency, for other reasons, may be higher than should be used in test.

The surges from arcing grounds are, fundamentally, of more moderate values, although they may have superimposed upon them ripples of much higher frequencies. For the oscillation of a line one may find 1000 to 20,000 cycles per sec.; for the oscillation of a transformer, frequencies of the order of 20,000 cycles; for the oscillation of a coil of a transformer, frequencies of the order of 100,000 cycles per sec. Except for the particular condition of resonance, the potential of these surges may be considered, tentatively, at least, as double the delta potential; the time of application as ½ sec., where the arcing ground suppressor is used, and several minutes, otherwise. How to measure in test the potential of this high frequency is yet to be determined.

General Effects Found in High-Frequency Tests of Insulators. As the frequency of the applied potential increases there is an increased tendency for sparks in the air to cling to the surface of the porcelain in the form of creeping sparks. For example, a pin type insulator consisting of several pieces, when tested on 60 cycles, had a spark formed over the upper surface of the top skirt, but at the edge the spark jumped straight to the pin. When the same insulator was tested on 200,000 cycles the spark followed every surface on the three skirts.

On other insulators of the suspension type having several concentric rings of petticoats under the skirt the very high frequency would cause the spark to follow the long path over the surfaces of these petticoats rather than jump from edge to edge as it does when a lower frequency is applied.

There is, fundamentally, a great difference between the tests at 60 cycles and the high-frequency tests, not yet brought out. This comes from the nature of the circuits. In the 60-cycle test the first spark is usually followed by an arc which necessitates opening the circuit. The arc potential is always much less than the spark potential, so the instant the arc forms the potential strain on the insulator is relieved. Furthermore, there is usually but a single streak or spark for each test. In the high-frequency tests, successive sparks are being rapidly formed and extinguished. If the parts are symmetrical this spark forms continually in new positions. It follows the surfaces. The insulator is literally bathed in a succession of sparks which feel for weak spots everywhere in the porcelain. One test of this kind may be made the equivalent of a thousand tests at 60 cycles—everything else in the comparison being neglected. (This bathing of the insulator in sparks was shown in the demonstration tests made at the meeting by Mr. Stewart Thomson and Mr. H. E. Nichols.)

SUMMARY AND SOME CONCLUSIONS

The probable relation of spark potential to gap length may perhaps be expressed as follows: With a given length of gap, the potential to cause a spark *decreases* as the frequency increases, up to a limited value of high frequency. Above this critical frequency the potential to cause a spark *increases* with a further increase in frequency. This change in the law probably comes from dielectric spark-lag.

Neither the needle gap nor the usual electrostatic voltmeter

FIG. 19 [CREIGHTON]

An illustration of the application of potential to an insulator from an oscillating transformer. The frequency was about 120,000 cycles. For frequencies above this value the spark has a greater tendency to cling to the surface; for frequencies below this value the spark has a greater tendency to jump from the edges of the skirts to the pin. At this particular frequency, both creepage sparks and jump sparks are illustrated.

In viewing these sparks, the real spark must be distinguished from its reflection from the smooth surface of the porcelain. For example, on the smallest skirt of the insulator a number of sparks, ending apparently about 1 in. (25.4 mm.) from the edge, are the reflections from the spark from the inner surface of the middle skirt.

FIG. 20 [CREIGHTON]

This photograph is reproduced primarily to illustrate the bathing effect of the static sparks of high frequency around the skirts of a suspension type insulator. Some of the sparks pass over the surface around the petticoats, while others jump straight from petticoat to petticoat, as may be seen from the middle disk. The upper disk of these three insulators is shown punctured by the test.

measures high potential at high frequencies. Furthermore, due to resonant effects in a transformer, the ratio of the transformer is also unreliable.

The subject of insulator tests is divided, primarily, into: first, the direct strains on the molecular structure of the porcelain, with a consideration of the weakening effect of flaws, and, second, the creeping spark which forms over the skirts of the insulator. A jump spark 10 cm. long will easily turn into a creeping spark 50 cm. long.

There are four factors of importance to be considered in connection with the testing of an insulator. First, there is the actual value of potential. It must be above the puncture value to have any possibility of causing puncture. The frequency must herein be taken into account. The second important factor is the suddenness of application of potential. The third important factor is the spark-lag of the creeping spark, and the fourth, the dielectric spark-lag of the porcelain to puncture.

Assuming that the application of super-spark-potential is suddenly made in a time less than the time of spark lags, then there are two possible results. If the dielectric spark-lag of the porcelain is less than the lag in the formation of the creeping spark, the porcelain punctures. If, on the other hand, it is greater, the spark passes around the skirts and relieves the potential strains.

There are five different methods of test given. When the design of insulators makes it practicable, these tests can be reduced to one. If a porcelain insulator will stand a sudden application of high-frequency potential above the puncture value (for short, a *super-spark-potential*) without puncturing the porcelain, it will withstand any of the other tests. No standardization of test is possible at the present time. More experimental work must be done.

The most severe strain is that of lightning. Heating by the dynamic arc which follows the lightning stroke may break an insulator but there is, in general, no necessity of allowing the arc to play long enough to do this.

The high-frequency test has the advantage of giving many successive strokes which cause shifting creeping sparks. These shifting creeping sparks search out the flaws in the skirts.

In the demonstration tests made by Mr. Thomson and Mr. Nichols, a frequency of 180,000 cycles from an oscillation transformer was applied successively to several pin insulators and to a pair of suspension insulators. The usual result of the test on the pin type was to puncture one skirt after another, until the last one was left. A single skirt withstands the high-frequency strains better than two or more. The suspension type insulators in test refused to puncture, although the discharges were passed over them for nearly a minute. In every case most of the sparks crept over the surface of the porcelain. These effects are shown in Figs. 19 and 20.

H. Winfield Secor (by letter): This paper on the high-frequency testing of high-voltage insulators seems of prime importance, and it is a matter that should be followed up closely by both manufacturers and engineers.

Referring to Mr. Lincoln's remarks, in regard to whether the current applied to the insulator under such high-frequency test as described, really was impressed at a potential of as great a periodicity as mentioned by Mr. Thomas, I would say that in accordance with Thompson's well-known equations, applying to an oscillation circuit such as employed by Mr. Thomas, which is not greatly different from the ordinary wireless transmitting circuit, the following holds true:

Mr. Thomas' arrangement of the high-frequency test comprises a closed oscillating circuit, and whether or not an alternating—or, if you please, an oscillating—surge is caused to be set up in that circuit and to act on the insulator under test depends upon whether or not the resistance, squared, of the closed oscillation circuit is smaller than four times the inductance divided by the capacity of the circuit. In case it is smaller the condenser discharge is oscillatory or alternating in character, but if

$$R^2 > \frac{4\,L}{C}$$

then the condenser discharge is not alternating or oscillating in character. In view of this it seems quite probable that the insulator is not always subjected to a high-frequency alternating-current test, as the oscillation period of this circuit is a function partly of the capacity of the insulator being tested, and partly of its resistance.

Having these conditions under which to work, the number of shocks in a given time to which the insulator is subjected can be found by means of a wave-meter calibrated to read frequency per second, instead of wave length, provided, of course, that the circuit conforms to the above-mentioned rule so that the condenser discharge is oscillatory or alternating. In this connection I believe the new direct-reading wave-meter, developed by Dr. Seibt of Germany, would be of service, indicating in a similar manner to the ordinary direct-reading instruments, by means of a pivoted needle moving over a graduated scale, the wave length at any instant, and conversely the frequency of the alternations, or, also, the number of shocks applied in a given time to the insulator being tested. As suggested by Mr. Lincoln, a decrease in each train of waves or oscillations takes place, and the peaks of the decreasing waves, equivalent to each half-cycle of transformer primary current, follow a logarithmic curve, and the logarithmic decrement may easily be determined by means of a Marconi decremeter. At the frequency mentioned in Mr. Thomas's paper, *viz.:* 1,000,000 cycles per second, the wave length is 300 m., as the velocity of ether waves is 300,000,000 m. per sec., and this wave length is easily read on any ordinary wave-meter, or on Dr. Seibt's instrument, also much lower wave lengths corresponding to several million cycles per second. Lightning discharges have a very high frequency, generally, and a varying potential that is enormous, and in view of this it does not seem that insulators will ever be built that can be guaranteed to stand any lightning, but these high-frequency tests are certainly a long step in advance and are to be highly commended, in my mind.

E. S. Lincoln (by letter): I noticed with particular interest Mr. Sandford's remarks relative to a laboratory for high-voltage investigations, and I wish to state at this time that such a laboratory is under construction. It will be fitted for both testing and research work, with a special department for high-voltage investigations. The maximum potential will be 1,000,000 volts at 60 cycles with a capacity of 1000 kv-a. Details of this laboratory will be furnished to the Institute in the near future, but I wish to mention the fact at this time so as to inform those who are interested in this subject that they will have the facilities for making any test that they may desire.

Ford W. Harris (by letter): I should like to ask if it is possible to add to Mr. Sothman's paper, or rather to the tabulation, a column showing the number of sections tested. That is, the number of different insulators actually tested. This is important, as, if all the insulation tests were made on a single string, a considerable error might be involved due to peculiarities of the insulators involved. In dealing with a problem of this nature average results are sought after and the only way to get average results is to test a considerable number of sections.

The second point that would seem to me to be pertinent is the question of the costs of the various types involved. For example the insulator " type A " would appear to be materially cheaper than those having a metal cap, and it might be that, by using a larger number, the same or better protection could be obtained at lower cost. In considering this phase of the matter the additional cost of structure to accommodate the longer length of string would also have to be considered. What the power user is really buying is insulation, and a little additional information from Mr. Sothman would be interesting.

I have not had any considerable experience with transmission lines but have used a considerable number of insulators that were originally designed for such lines in various types of switching devices. When used for such purposes the question of mechanical strength is a critical one. I have come to two conclusions. First, that for cementing insulators together and cementing on caps and cementing in pins, there is nothing better than neat Portland cement. Such cementing must, however, be watched very closely and the parts kept wet. A good method in the case of pins is to invert the insulator and fill the petticoats with water. Portland is a hydraulic cement and needs lots of water. The second point is that the use of line insulators in disconnecting switches and the like is poor economy. It is true that most operators prefer to use the same insulator on disconnecting switches and the line on account of ease of carrying spare parts, but the average insulator is entirely too weak for such use and much better results may be obtained by the skilful design of special porcelains with larger fastenings. I have often wondered if the characteristics of ordinary line insulators could not be materially improved by applying the same analysis that we have applied to those for disconnecting switches.

The photographs reproduced are very interesting, but photographs of discharges are somewhat likely to be misleading, due to the unfortunate characteristic they have of integrating the discharges. That is, they photograph discharges that occur at different times and the result is the sum of all the discharges that occur during exposure. Even if the exposures are made absolutely the same there is an accidental factor to be considered in that such discharges are more or less intermittent and vary greatly in their violence from second to second, even with the conditions maintained absolutely constant. This is quite generally understood, however, and Mr. Sothman has doubtless given them for their value as qualitative measures rather than as quantitative. They certainly show just what we may expect during the time of stress on an insulator.

Charles Rufus Harte (by letter): The determination of Messrs. Imlay and Thomas that a grounded pin tends to concentrate stresses upon an insulator and thus reduce its factor of safety is particularly interesting to the writer, who for some years has taken exception to the desired practise, first of the telephone companies, and now of the joint committee specifications for high-tension crossing protection, in calling indiscriminately for grounding pins and grounded strips on crossarms at these crossings.

Where a transmission line has such construction throughout its length there is no distinction, but it has always seemed to the writer, and a number of instances had confirmed that belief prior to the evidence of this paper, that to ground the pins at the crossings alone, takes away a considerable proportion of the protection it is intended to create by the use of higher safety factors for insulators at this point.

Edward Bennett (by letter): In the "Discussion of Tests" in the paper by Messrs. Imlay and Thomas, great importance is attached to the fact that the potentials causing puncture of the insulators were of high frequency. The implication is that the puncture of the insulators is to be attributed either to some difference in the nature of 60-cycle and high-frequency stresses or to some difference in the distribution of the stresses throughout the body of the insulating material at high and at low frequencies. It is further stated that the insulators which did not puncture at 250,000 volts on 60 cycles under oil, punctured after a comparatively few shocks of high-frequency discharge and without apparently opposing a resistance of much over 100,000 volts (10-in. (25.4 cm.) spark gap).

It would seem, however, that under the conditions of test shown in Fig. 11 of the paper, the breakdown of a 10-in. measuring gap would indicate the application between line-wire and pin of a potential far in excess of 100,000 volts during the interval of time required to bridge across the 10-in. gap or, in general, to establish a conducting flash-over path.

The breakdown of a spark gap is not an instantaneous phenomenon; our knowledge of the rates of breakdown of the series gap and of the flash-over path does not permit of the formation of an estimate of the value to which the potential between the line-wire and pin might build up during the interval of breakdown. It is conceivable, however, that with a 25-in. (63.5-cm.) series gap and the transformer adjusted as stated, the potential across the insulator might build up to 500,000 volts.

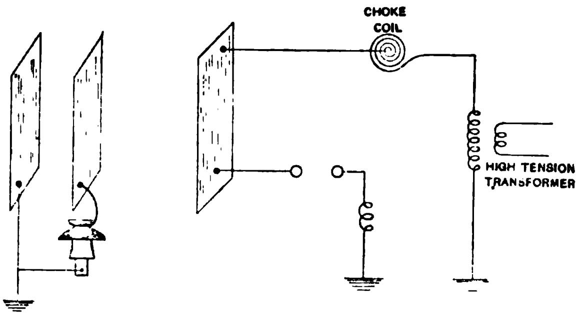

FIG. 21

If this is the case, the puncture of the insulators is not to be attributed to the high-frequency stresses alone, but partly, or possibly largely, to the application of extremely high potentials for short intervals; that is, the interval of the "spark-lag" of the protective path—the flash-over path. To eliminate from the tests an unknown high potential, a third plate might be used, as indicated in Fig. 21 of this discussion, with the insulators connected by extremely short wires between two of the plates, as shown.

Whatever the explanation, the paper emphasizes the fact that the insulators puncture in service which are protected by flash-over under prevailing testing conditions. The paper is of great importance because it brings this out so clearly, and emphasizes the need of tests, such as those described, more nearly representing service conditions.

F. F. Brand (by letter): The high-frequency tests outlined by Messrs. Imlay and Thomas are, I believe, the first recorded in which an attempt was made to subject insulators to a definite test similar to a lightning disturbance.

There are one or two points I wish to raise with reference to the statement that the potential drop across the insulator was apparently only 100,000 volts. The method of measurement was to connect a spark gap in multiple with the insulator, and in series with this spark gap was a high non-inductive resistance. At a frequency of approximately 1,000,000 cycles per second the charging current from the line side would be considerable, and the radiation current also would be appreciable, therefore the voltage drop across this resistance might be quite high. Furthermore, the spark gap was some 5 or 6 ft. (1.5 to 2 m.) from the insulator, so that the inductance was appreciable. Therefore, we do not know that the voltage indicated by the spark gap represented the actual voltage across the insulator when it arced over. Furthermore, we do not know whether the spark gap is accurate at a high frequency.

The explanation the authors give of the cause of breakdown is quite feasible. It may also be possible that, while the energy required to disrupt that small part of the dielectric which represents the resistance which is in series with the capacity of the insulator, is greater than the energy required to disrupt the air around the insulator, due to the inductance of the path around the insulator, and to the fact that the air usually breaks down by corona which requires time to form, the air does not have time to break down before the dielectric adjacent to the pin is disrupted. Each further impulse produces this failure until the whole insulator head is punctured.

It would appear that a more careful study of the gradient around the sharp edges of the pin would solve this difficulty. In an electrose insulator we might mold a sphere of metal into the insulation and screw the pin into it.

In regard to suspension insulators, if the potential balance over the string depends to any great extent on the leakage current, at high frequency this would be obliterated by the larger charging current through both the shunt and mutual capacity, and thus the voltage required to arc over the string would decrease. Also, if the potential balance is dependent to any extent on corona formation, with a sudden application of voltage, as by a wave with a steep front, the potential rises to a high value before corona forms and thus the distribution of potential is not the same.

Furthermore, the links connecting the units have an inductance which is not negligible, and as the frequency increases, the voltage drop across this inductance increases by the frequency times the increased current through the insulators to ground. This voltage is in opposition to the voltage across the insulators; thus the sum of the voltages across the insulators no longer equals the total voltage across the string, but is higher, thus causing the insulators to arc over at a less total voltage across the string. The puncture of the line unit would not necessarily occur unless the potential gradient is excessive at some point.

Since the above tests were made, I have tried with the same apparatus and voltage the effect of high frequency on a small string of suspension insulators, but did not succeed in breaking them in 150 flashes, possibly due to the fact that the excess voltage over the arcing voltage of the string was not proportionately as great as in the tests described in the paper.

Mr. P. M. Lincoln has raised the point that the frequency of oscillation as given by the authors is not correct, but that the insulator reflects the wave of potential—this is not exactly correct. The frequency of oscillation given by the authors was calculated from the constants of the circuit when the insulator had arced over. The oscillation before this is the oscillation with the capacity of the insulator in series with the inductance of the connections and the main capacity. Inasmuch as the low-voltage capacity of the insulator, that is, before corona forms, was less than one-tenth of the main capacity, the insulator would be subjected to an oscillation practically at a frequency equal to that caused by its capacity only with the inductance of the circuit, and the potential across the main condenser would be sustained until the insulator punctured or had time to arc over.

Mr. Peek has suggested that the reason why the insulators punctured is due to the sudden application of a voltage in excess of the puncture voltage at normal frequency, and is not due primarily to the high frequency of the oscillation. This can readily be tried by applying an impulse test at a voltage less than the low-frequency puncture voltage.

Turning now to a consideration of the paper by Mr. Sothman, I wish to call attention to the errors in results which arise if the method of testing does not correspond to service conditions.

Practically all line insulators are used between line and ground, therefore the grounded end of the insulator string should be grounded during test. Due to the fact that each insulator has a capacity to ground, as well as a mutual capacity with reference to the other insulators, the voltage is not divided uniformly over the total string. The arcing voltage of the string usually occurs when the line unit reaches the arcing point, thus the arcing voltage of the string is not equal to the arcing voltage of one unit multiplied by the number of units. This discrepancy is increased the greater the number of units from line to ground, and the greater the ratio of the shunt to mutual capacity. Thus in testing with the neutral of the testing system grounded, as apparently was done by Mr. Sothman, the number of units between line and ground is one-half the total number in the string, and the voltage from line unit to ground is one-half the total voltage on the string.

Neglecting the change of potential balance due to corona and the leakage current, for a string of five insulators, similar to the type A shown, the dry arcing voltage with one terminal grounded is 281 kv. The arcing voltage with the neutral grounded, calculated from the ratio of shunt to mutual capacity, would be 332 kv. Seven units similar to the type E shown should arc over at 357 kv. with one end grounded, and at 450 kv. with the neutral grounded. Five units of the type D shown should arc over at 308 kv. with one end grounded, and 368 kv. with the neutral grounded.

Thus we see that we do not even get a correct comparison between the types, as the ratio of shunt to mutual capacity is not the same for different types, also the number of units used in the string is not the same. In practise this difference is not so great as the calculations show, due to the potential balance being changed by corona formation, but there is liability of serious error in results with the neutral of the testing system grounded.

Regarding the author's list of specifications and tests I would make the following suggestions regarding some of the points raised.

Method of Support. The insulator should be supported as nearly as possible as in service. Normally the top of the insulator string should be grounded in suspension insulators, and the pin in pin type insulators. Tests thus should always be made with one terminal of the testing transformer grounded. The insulator should be supported by approximately the same size apparatus as the service crossarm. The voltage should be applied to a conductor the same size as the line conductor, of a length sufficient to prevent concentration of stress on the ends affecting the test. The insulator should not approach closely any large bodies, and in a string of suspension insulators the line should probably not be closer than twice the length of the string from the ground surface.

Capacity of Testing Transformer and Generator. These should be large enough to give a fairly heavy dynamic arc, and to prevent very great distortion of the wave shape, also to prevent the regulation of the testing system being changed by the insulator load. In general, a testing transformer with a normal rating of 0.5 to 1 ampere, high-tension winding, with a generator of equal rating to the transformer, is sufficient.

Method of Determining Voltage. This should be by a device which indicates the maximum of the voltage wave, such as a spark gap. The ratio of the transformer should be checked against the spark gap when connected to the insulators, and this ratio used as a final means of determining the exact voltage.

Method of Regulating the Voltage. This should be one which avoids distortion of the wave shape. The potentiometer method is undoubtedly the best, that is, with shunt and series resistance or reactance. In large power outfits this, however, is both bulky and wasteful of power, and a method using generator field control within small limits and a multiple-circuit generator or low-tension winding on the testing transformer is very satisfactory.

Effect of Frequency. Commercial tests are usually made at 60 cycles, the variation between results at this frequency and other operating frequencies being small. High-frequency tests are particularly a design test and should be made only on a few sample insulators or a specified small percentage of the insulators. These tests are difficult to execute, to duplicate, and are at present destructive to the insulators. The impulse test outlined by Messrs. Imlay and Thomas is probably more definite than the sustained oscillations produced by an oscillation circuit, in which the maximum voltage is unknown. Also a sustained test is probably unfair to the insulator by reason of the heating of the dielectric under sustained high-frequency voltage.

Wet Test. Two conditions of artificial rain are required for a general wet test, depending on the climate the insulators are to be used in. One is precipitation in large drops as in a thunder storm, the other being more nearly a mist. A precipitation of 0.5 in. (12.7 mm.) per minute for the large drops and about 0.25 to 0.3 in. (6.35 to 7.62 mm.) per minute for the mist gives severe enough results. The mist can be readily produced by sprays in which compressed air is used to atomize the water. In this way the mist is blown up under a shallow petticoat of an insulator. The specific resistance of the rain plays a very important part in the results. In general a fairly high specific resistance should be used to approximate rain conditions. In Pittsfield, Mass., the city water has an average specific resistance per cu. cm. of 7500 ohms. The rain should be at an angle of 45 deg. to the horizontal for vertical insulators, and 45 deg. to the inside of horizontal or strain insulators.

Corona. The insulator should certainly show no corona at normal operating voltage, and an insulator which does not show corona until practically the arc-over point is best, as such an insulator is less likely to be disrupted by sudden impulses of potential which may rise to a very high voltage before corona has time to form.

Design Test. A design test of twice the line voltage under wet conditions should be a good value, the value of the dry arc-over not being so important, provided it is not less than the wet test, which can occur in badly proportioned strings of suspension insulators. The test should be made at a barometric pressure equal to the mean pressure at the maximum altitude at which the insulator string is to operate. If this test is not feasible as a regular test the results should be corrected for altitude from experimental tests on certain of the insulators.

Max H. Collbohm (by letter): The subject treated in the two papers on testing of insulators, particularly the high-frequency test, is of considerable importance to the transmission engineer for the reason that practically all insulator breakdowns are caused by external or internal lightning strokes of inherent high frequency, while hardly any insulator is damaged under normal operating conditions.

The writer has observed on two transmission systems—44,000-volt and 66,000-volt, 65 mi. (104.6 km.)—that breakdowns occurred most frequently on the strain insulators on dead-ends along the line, although these were composed of more units than the ordinary suspension. In one instance practically every strain insulator on the whole line was damaged by a single inductive stroke caused by accidentally closing a short-circuited line under full potential. This was very likely due to a high-frequency surge finding an easier path through the insulator in direct line with the power cables than over the loop connecting the two dead-ended lines and offering probably a high impedance under high frequency on account of its curved form.

The writer has previously suggested a high-frequency insulator test at extremely high voltage and sudden application in order to determine the capacity effect of the insulator under lightning stresses. He believes that the inherent fatigue of the insulator material is an important factor in the self-protecting qualities of the insulator against the very short lightning strokes. This is again a point in favor of a grounded system (over resistance) as against an ungrounded system, on account of the absence of the probability of continuous arcing grounds producing high frequency.

The puncture between pin and top of insulator is probably due to the high potential gradient at the pin with its small dimensions and sharp corners, and improvements could be effected, as indicated in the papers under discussion, by carefully avoiding sharp corners and small curvature on the pin, and by increasing the thickness of the material around the pin. As a further means for protection the writer would suggest the adaptation of a fairly large metal disk on the pin of each insulator in the row, as close as permissible to the head of the pin without reducing materially the flash-over resistance by approaching the petticoats too closely, and also equipping the insulator cap likewise with an extension of its lower rim in the form of a horizontal disk. This would serve, for one thing, to obtain a more even distribution of static stresses by shielding the pin as far as practicable, and it may furthermore have the more important function of a condenser, the action of which may eventually be sufficient to pass to ground any high-frequency charge, thus being similar in operation to the high-frequency arrester of recent European development.

Another protection to the insulator may be available in the installation of arcing rods, both above and below the insulator, the comparatively sharp end points of these rods tending to break down sooner than arcing rings would, on account of the higher potential gradient at the ends. The writer is completing the erection of a 66,000-volt line equipped with these arcing rods and awaits with great interest the effect of this arrangement during the coming lightning season.

The installation of arcing rods seems to have had a beneficial effect on one 6600-volt line put into service a year ago which has gone through a number of very severe storms, the effect of which was shown by the burning up of an outdoor fuse box and by the almost continuous operation of the electrolytic arrester, with final damage, without having caused the slightest injury to even a single insulator.

It is the writer's opinion that ideal conditions can only be obtained by developing each insulator so as to act as its own arrester, either by giving it sufficient conductance under high-frequency conditions by means of additional condenser capacity, probably arranged as mentioned above, or by preventing the passage of high-frequency energy over the insulator proper by providing a suitable choke coil between the power conductor and insulator (which in case of suspension insulators could be arranged with comparative ease and cheapness between wire clamp and suspension hook by a few turns of iron wire) and letting the arcing rods take care of the main discharge (preventing service interruption by the use of a grounding rheostat of lowest permissible current-carrying capacity to avoid opening of switch).

Regarding the insulator test as a test, the writer believes that it ought to be made under conditions closely approaching those under which the insulators have to operate:

All insulators intended for steel towers should be placed on steel crossarms with cable attached, to get exact static stress distribution.

All insulator wet tests should be made with a strong air current directed horizontally against the insulators to get the effect of a wind carrying the rain into the insulators.

All insulators for service along the coast should be tested with salt water.

Strain insulators should be tested horizontally with rain applied alternately, or perhaps simultaneously, from both sides.

All high-voltage tests to be made under mechanical loading.

With these points considered, the test itself (as for the buyer's interest only) should otherwise be conducted about as follows:

1. Mechanical test (continued throughout the entire test).
2. Wet test on completed unit with hardware attached.
3. Wet test on string of units with cable attached.
4. High-frequency high-voltage test (wet) on string of units with cable attached.
5. Dry test on single unit.
6. High-frequency test (dry) on string of units with cable attached.
7. (Optional). Tests Nos. 3, 4 and 6 repeated with arcing rods attached, to determine proper dimensions for the latter in combination with the particular insulator pattern.

P. W. Sothman (by letter): Referring to Mr. Mershon's criticism that rather undue emphasis has been laid upon factors of safety relative to the line voltage, it must be borne in mind that owing to the lack of operating experience with potentials as high as 110 or 120 kv., the question of line insulation was, at the time, obviously one of paramount importance, and the tests were conducted with the end in view to ascertain first of all the insulator best suited to work safely at a voltage arbitrarily placed at twice the operating voltage under the worst condition. The fact that insulators may fail owing to suddenly applied excess voltages or surges along the line due to lightning discharges or other disturbances was even then pretty well appreciated and the records show that the selection of the type E insulator was made mainly because of its superiority in resisting puncture as compared with other insulators which stood up equally well with regard to the double line voltage test.

The use of still higher voltages appears to encounter certain limitations, and although it is now fully realized that the problem of insulating the line against lightning disturbances is one quite different from that of insulating against line voltage only, it is nevertheless apparent that a radical departure from the method employed at the present time for insulating the line must be adopted, if transmission voltages much above 130 or 150 kv. are to be used in future. A mere increasing of units of the present suspension insulator will not afford the insulating value which could be expected from the amount of porcelain and space employed. An increase in insulation simply by increasing the dimensions of the material either in linear or in cubic direction proportionately to increased line voltage, will not work out satisfactorily with the present methods of insulator design, and unless a more scientific method is devised the use of higher voltages should be considered with more conservatism than has been displayed in some cases.

L. E. Imlay (by letter): We set out to develop a pin type insulator adapted for use on 44,000-volt circuits which would not puncture with lightning discharges. The plan we adopted was to take an insulator already designed for 44,000-volt service, subject it to the stresses which it would receive in actual service, and vary its size and shape until the desired result was secured. The nearest approximation to lightning that we could obtain was the discharge from a 750,000-volt, 500-kw. transformer.

In the course of the tests we found that the most effective way to secure the desired results was to reduce the width of the petticoats. When these were entirely removed the desired result was obtained, so far as resisting puncture was concerned. This is shown by test No. 14, in which the insulator consisted of a cylinder of electrose about 5 in. (12.7 cm.) high and 5 in. in diameter. This insulator, however, would not answer our requirements, as it flashed over the surface on 60 cycles wet at 33,500 volts. It is highly probable, however, that the insulator, even in this form, would have been adequate for 44,000-volt service in places where its surface would not become covered with dust from chemical works and where rain water only could get on it.

The idea of a high-tension line insulator without petticoats was so novel that we could not make up our minds to go any further in this direction, although the next logical step would have been to increase the height of the cylinder until the required leakage surface was obtained. We finally adopted a compromise design involving the use of a wooden pin which was equivalent to lengthening the cylinder. We retained considerable of the petticoat feature, but a plain cylinder without these projections would probably have been better.

Transmission lines can be adequately protected from lightning by the installation of a sufficient number of overhead guard wires. If the system is of sufficient importance to warrant the expense necessary to provide this method of protection, insulators we already have available are adequate. If, however, this expense is not justified, insulators should be provided which will not be injured by lightning and which will remain in condition after lightning discharges and the arcs consequent thereto have passed over their surfaces, so that the line can be placed in service immediately after an interruption. Such an insulator will perform the functions of a lightning arrester. I believe each line insulator should be an adequate lightning arrester and a system equipped with such insulators should have no need of an elaborate lightning arrester equipment at the stations to protect the generating and transforming apparatus. I trust the slight amount of work which we have done in beginning this investigation will lead to the development of a reliable insulator which will answer these requirements.

P. H. Thomas (by letter): By the expression "high frequency," in our paper, is meant an abrupt or steep wave-front rather than a sustained high-frequency vibration. It is very unlikely that anything more than a very few rapidly decreasing waves would be produced by the high-potential discharge of this apparatus.

Care should be taken to distinguish between the breakdown of insulating material by *constantly applied* sustained high-frequency potentials, and the tests of this paper. The former may cause the failure of very strong insulators in virtue of the rapid cumulative heating due to the dielectric losses produced by the alternating high-intensity static field, while in the tests described in our paper the high-frequency shocks were not sustained and a space of time occurred between each application and the next. No evidence of heating could be found either inside or outside the insulator until after an arc had passed.

Perhaps the most interesting question raised during the discussion is that of the cause or nature of the marked preference of the high-frequency discharge for puncturing the insulator instead of flashing over. It has been argued that an air gap requires a certain amount of time to break down, which time is greater than the amount of time required for the solid material to break down, and consequently that if the time of application of voltage were too short to permit the air gap to break down when its normal breakdown voltage limit was reached by the rising wave, the impressed voltage would go on rising above this limit until the breakdown limit of the solid material was reached. This explanation seems plausible enough and will explain the phenomenon, ***provided*** it be true that the spark gap in air does require a longer time to break down than the solid material, and ***provided***, further, that the actual minimum limit of time required for such a breakdown in air is actually greater than the time required for the potential to rise to its maximum in these tests, and at the same time, that the time required for the breakdown of the solid material is less than the time required to reach full potential. If all of these conditions are true it is a rather remarkable coincidence.

It does not seem probable to the writer that there is any such length of time required to start a discharge across an air gap as is required for the potential to rise in the present case. It is true, as pointed out by Mr. P. M. Lincoln, and more in detail by Mr. Brand, that the initial discharge to the insulator top before breakdown will be at a higher frequency than the main discharge (perhaps four to six times as high), yet the period is so long compared with the numerous known instances of sparks from far higher frequency, that its likelihood seems very small.

If an air gap could not break down as rapidly as the voltage was impressed on the air gap in this case, it would not be possible to operate Tesla coils as they are operated, for the voltage on the terminals of the coil secondaries would be reversed before a spark could occur. Similarly with the famous Hertz researches, where far, far higher frequencies were used than in these tests. Hertz could not have gotten sparks from his ***very high*** frequencies if a spark gap could not break down in a period as short as that of these tests.

It may be argued that a short gap would break down more readily than a long one, but this would not seem to be the case, since the longer gap will have a proportionally higher voltage. In the case of the present tests the available voltage was far higher than the normal resistance of the spark gap, and further, there was immediately available a very large amount of stored energy from the condenser. Another point should be considered, that it is not necessary, in order to relieve the potential strain on the solid material, that a spark be established all the way across the gap, but merely that the charge be able to escape from the live metal parts into the air.

Finally, if the air cannot break down quickly and a potential of 300,000 volts is thus impressed upon the solid material of the insulator head, those insulators having a head only 1 in. (25.4 mm.) thick should have invariably broken down, for they failed under oil at 200,000 volts. As a matter of fact there was little difference in their behavior from that of those with 2-in. (50.8 mm.) heads.

Mr. Peek has suggested that in the normal tests of insulators the formation of corona at 60 cycles permits a redistribution of stress over the surface of the insulator and enables it to stand a higher applied voltage than would otherwise be the case. This action is very similar to the explanation given in the paper, except that the effect is there attributed to insulation resistance rather than corona. In Fig. 9 of our paper the insulation leakage paths are illustrated as through solid material, but the same effect would be produced if they were over the surface of the insulator.

Mr. Brand's discussion is much to the point, and is especially valuable as he was present at the tests and was familiar with all the apparatus.

Mr. Mershon has asked why we consider that the effect of the metal foil band is to increase the effective size of the pin, as shown in Fig. 3 of the paper. This is because the band tends to take the same potential as the pin on account of its superior electrostatic capacity to the pin and hence acts electrically as part of the pin.

Referring more broadly to the testing and inspection of high-tension insulators, I wish to say that Mr. Sothman's paper gives an excellent treatment of the subject and fulfills the plan of the High-Tension Transmission Committee that this meeting should give a foundation or a text for a thorough general discussion of the subject, with the hope that at some later meeting it may be possible to arrive at some concrete agreement as to the essentials of a satisfactory test.

While many thoughts are suggested by Mr. Sothman's paper and the discussion thereon, I wish to call attention only to the point made by Mr. Brand, viz., that when a string of suspension insulators is used, its test strength will be greatly altered by a grounding of one end of the string. This effect will be the more marked the greater the number of units in the string and the greater the capacity of the individual insulators to ground, as compared with their internal capacity. Mr. Peek's admirable paper treating of string efficiency* makes this clear.

I would here suggest as a probable explanation of the apparent relative weakness of a string of insulators when used as strain insulators, the fact that the units will have a larger capacity to ground when in a nearly horizontal position than when vertical, and will therefore have a less string efficiency. If this be true, some designs should suffer more than others from being used in an inclined position, and the strings composed of many units should be the most affected.

R. F. Hayward (communicated after adjournment): It is probably safe to say that no long-distance transmission line that has been equipped with insulators designed on any reasonable basis has ever experienced the slightest difficulty from rain or snow. This is absolutely true, at least, in the writer's experience.

**Electrical Characteristics of the Suspension Insulator,* in Part I, p. 907.

Consequently all tests of insulators for breakdown under artificial rain conditions, with ordinary frequencies, while being important, should be looked at more in the light of standard tests for strength of iron or steel or cement; in other words, something that has got down to more or less settled conditions.

In the writer's experience with high-tension transmission at 50 and 60 cycles over long distances and wide areas in Utah and Mexico, after eliminating breakdowns due to the mechanical destruction of insulators from outside sources, the only brea downs of insulators that have passed through the standard tests have occurred in cases where there has undoubtedly been a high-frequency discharge of some kind or other, whether from lightning or as the result of some sudden surge, as from a heavy short-circuit.

I do not think that people interested in high-tension transmission can have the importance of high-frequency tests too strongly brought before their attention, and I look forward to any investigations that may throw additional light on this matter.

CODE OF PRINCIPLES OF PROFESSIONAL CONDUCT
OF THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

ADOPTED BY THE BOARD OF DIRECTORS, March 8, 1912.

A. General Principles.
B. The Engineer's Relations to Client or Employer.
C. Ownership of Engineering Records and Data.
D. The Engineer's Relations to the Public.
E. The Engineer's Relations to the Engineering Fraternity.
F. Amendments.

While the following principles express, generally, the engineer's relations to client, employer, the public, and the engineering fraternity, it is not presumed that they define all of the engineer's duties and obligations.

A. GENERAL PRINCIPLES

1. In all of his relations the engineer should be guided by the highest principles of honor.

2. It is the duty of the engineer to satisfy himself to the best of his ability that the enterprises with which he becomes identified are of legitimate character. If after becoming associated with an enterprise he finds it to be of questionable character, he should sever his connection with it as soon as practicable.

B. THE ENGINEER'S RELATIONS TO CLIENT OR EMPLOYER

3. The engineer should consider the protection of a client's or employer's interests his first professional obligation, and therefore should avoid every act contrary to this duty. If any other considerations, such as professional obligations or restrictions, interfere with his meeting the legitimate expectation of a client or employer, the engineer should inform him of the situation.

4. An engineer can not honorably accept compensation, financial or otherwise, from more than one interested party, without the consent of all parties. The engineer, whether consulting, designing installing or operating, must not accept commissions, directly or indirectly, from parties dealing with his client or employer.

5. An engineer called upon to decide on the use of inventions, apparatus, or anything in which he has a financial interest, should make his status in the matter clearly understood before engagement.

6. An engineer in independent practise may be employed by more than one party, when the interests of the several parties do not conflict; and it should be understood that he is not expected to devote his entire time to the work of one, but is free to carry out other engagements. A consulting

engineer permanently retained by a party, should notify others of this affiliation before entering into relations with them, if, in his opinion, the interests might conflict.

7. An engineer should consider it his duty to make every effort to remedy dangerous defects in apparatus or structures or dangerous conditions of operation, and should bring these to the attention of his client or employer.

C. Ownership Of Engineering Records And Data

8. It is desirable that an engineer undertaking for others work in connection with which he may make improvements, inventions, plans, designs, or other records, should enter into an agreement regarding their ownership.

9. If an engineer uses information which is not common knowledge or public property, but which he obtains from a client or employer, the results in the form of plans, designs, or other records, should not be regarded as his property, but the property of his client or employer.

10. If an engineer uses only his own knowledge, or information which by prior publication, or otherwise, is public property and obtains no engineering data from a client or employer, except performance specifications or routine information; then in the absence of an agreement to the contrary the results in the form of inventions, plans, designs, or other records, should be regarded as the property of the engineer, and the client or employer should be entitled to their use only in the case for which the engineer was retained.

11. All work and results accomplished by the engineer in the form of inventions, plans, designs, or other records, that are outside of the field of engineering for which a client or employer has retained him, should be regarded as the engineer's property unless there is an agreement to the contrary.

12. When an engineer or manufacturer builds apparatus from designs supplied to him by a customer, the designs remain the property of the customer and should not be duplicated by the engineer or manufacturer for others without express permission. When the engineer or manufacturer and a customer jointly work out designs and plans or develop inventions a clear understanding should be reached before the beginning of the work regarding the respective rights of ownership in any inventions, designs, or matters of similar character, that may result.

13. Any engineering data or information which an engineer obtains from his client or employer, or which he creates as a result of such information, must be considered confidential by the engineer; and while he is justified in using such data or information in his own practise as forming part of his professional experience, its publication without express permission is improper.

14. Designs, data, records and notes made by an employee and referring exclusively to his employer's work, should be regarded as his employer's property.

15. A customer, in buying apparatus, does not acquire any right in its design but only the use of the apparatus purchased. A client does not

acquire any right to the plans made by a consulting engineer except for the specific case for which they were made.

D. The Engineer's Relations To The Public

16. The engineer should endeavor to assist the public to a fair and correct general understanding of engineering matters, to extend the general knowledge of engineering, and to discourage the appearance of untrue, unfair or exaggerated statements on engineering subjects in the press or elsewhere, especially if these statements may lead to, or are made for the purpose of, inducing the public to participate in unworthy enterprises.

17. Technical discussions and criticisms of engineering subjects should not be conducted in the public press, but before engineering societies, or in the technical press.

18. It is desirable that first publication concerning inventions or other engineering advances should not be made through the public press, but before engineering societies or through technical publications.

19. It is unprofessional to give an opinion on a subject without being fully informed as to all the facts relating thereto and as to the purposes for which the information is asked. The opinion should contain a full statement of the conditions under which it applies.

E. The Engineer's Relations To The Engineering Fraternity

20. The engineer should take an interest in and assist his fellow engineers by exchange of general information and experience, by instruction and similar aid, through the engineering societies or by other means. He should endeavor to protect all reputable engineers from misrepresentation.

21. The engineer should take care that credit for engineering work is attributed to those who, so far as his knowledge of the matter goes, are the real authors of such work.

22. An engineer in responsible charge of work should not permit non-technical persons to overrule his engineering judgments on purely engineering grounds.

F. Amendments

Additions to, or modifications in, this Code may be made by the Board of Directors under the procedure applying to a by-law.

HISTORY OF THE CODE

At the Milwaukee Convention in May, 1906, Dr. Schuyler Skaats Wheeler delivered his presidential address on "Engineering Honor." It was the sense of the Convention that the ideas contained in this address should be embodied in a Code of Ethics for the electrical engineering profession, and to this end the following committee was appointed in October, 1906:

Schuyler Skaats Wheeler, *Chairman.*
H. W. Buck Charles P. Steinmetz

In May, 1907, the committee reported a code to the President and Board of Directors for discussion at the June Convention at Niagara Falls. It was discussed and adopted by the Convention but later the adoption had to be set aside on account of the provisions of the Constitution prohibiting

Conventions from acting upon questions affecting the Institute's organization or policy.

It was taken up by the Board of Directors on August 30, 1907, revised, printed and submitted to the membership for suggestions to be sent to a new committee appointed by President Stott.

It lay dormant until June, 1911, when, in accordance with a resolution of the Board of Directors, President Jackson appointed a committee. The personnel of this committee, as reappointed by President Dunn in August, 1911, is as follows:

GEORGE F. SEVER, *Chairman.*

H. W. BUCK	CHARLES P. STEINMETZ
SAMUEL REBER	HENRY G. STOTT

SCHUYLER SKAATS WHEELER

This committee's work was presented in a report to the Board of Directors on February 9, 1912, when the code was tentatively adopted. After a month's careful analysis and consideration of numerous suggestions from the advisory members of the committee and others, the completed code was adopted at the meeting of the Board of Directors on March 8, 1912.

At the meeting of February 9, the title of the committee and of the code was changed from that of Code of Ethics to Code of Principles of Professional Conduct.

The committee was assisted by eighteen advisory members appointed by the President. Their names are appended.

WILLIAM S. BARSTOW
LOUIS BELL
JOHN J. CARTY
FRANCIS B. CROCKER
DUGALD C. JACKSON
A. E. KENNELLY
JOHN W. LIEB, JR.
C. O. MAILLOUX
RALPH D. MERSHON
HENRY H. NORRIS
RALPH W. POPE
HARRIS J. RYAN
CHARLES F. SCOTT
SAMUEL SHELDON
WILLIAM STANLEY
LEWIS B. STILLWELL
ELIHU THOMSON
W. D. WEAVER

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1912

The Board of Directors of the American Institute of Electrical Engineers herewith presents to the members of the Institute its annual report for the fiscal year ending April 30, 1912.

Brief summaries of the work of the various standing and special committees are included in the report, and also a detailed financial statement showing the condition of the respective funds of the Institute, the receipts and disbursements for the year, the assets and liabilities, and a condensed cash statement.

Notwithstanding the fact that the disbursements for the year far exceed those of all previous years, as a result of the constantly increasing activity and scope of the Institute, there is an excess in the receipts over the disbursements of $5,574.35.

Upon recommendation of the Finance Committee, the Institute purchased for investment,, in June 1911, $15,000 par value Wilmington Del., 4½ per cent. registered bonds.

The Board of Directors has held nine regular monthly meetings at Institute headquarters during the year, and one meeting at the Chicago Convention in June 1911.

The Annual Convention was held in Chicago June 26-30, 1911. The registered attendance was 578 members and 386 guests, a total of 964, which was the largest convention attendance in the history of the Institute.

The Pacific Coast Meeting was held in Portland, Oregon, April 16-20, 1912, and was attended by 210 members and guests, including delegations from all the principal Pacific Coast cities.

A three day meeting under the auspices of the Pittsburgh Section and the Industrial Power Committee, in conjunction with the Association of Iron and Steel Electrical Engineers, was held in Pittsburgh April 25-28, 1912. The attendance at this meeting was 265.

At the Chicago, Portland and Pittsburgh meetings, in addition to the large number of excellent papers presented and discussed, the programs included inspection trips and other interesting features arranged by local committees, which were both enjoyable and profitable to all who participated.

During the year President Dunn presided at the Pittsburgh meeting and at the Pacific Coast meeting at Portland. He also visited the Sections at Ithaca, Cleveland, Boston, San Francisco, Los Angeles, St. Louis and Lynn.

At the Chicago Convention the resignation of Mr. Ralph W. Pope as Secretary of the Institute, was tendered and accepted, and the Board of Directors, in recognition of Mr. Pope's long and loyal services to the Institute, appointed him to the position of Honorary Secretary, in which capacity the Institute still has the benefit of his long experience in its affairs.

Mr. Pope devotes his time principally to the welfare of the Sections and Branches, and during the year he has visited the following Sections: Ithaca, Schenectady, Chicago, Cleveland, Toledo, Washington, Minnesota, Indianapolis-Lafayette, Los Angeles, San Francisco, Portland, Seattle, and Vancouver; also the Branches at Armour Institute and Lewis Institute, Chicago, and Throop Polytechnic Institute, Pasadena. Upon his return trip from the Pacific Coast Convention at Portland he also addressed a meeting of members at Spokane, Wash., where a movement is on foot to establish a Section.

At the first meeting of the Board of Directors in the present administrative year, held on August 22, 1911, there was inaugurated a policy of publicity in Institute affairs, and accordingly a resumé of the actions of the Board has been sent to the technical press and all Directors and members of committees immediately after each meeting.

Mr. S. Z. de Ferranti, President of the Institution of Electrical Engineers, of Great Britian, visited this country in September, 1911, in company with several other prominent engineers. A luncheon in honor of the distinguished guest was given by the Institute officers and past-presidents in New York on September 29th.

A delegation of Institute members attended the International Electrical Congress and the meeting of the International Electrotechnical Commission held in Turin, Italy, in September, 1911. Reports of both meetings were published in the November, 1911, issue of the Institute PROCEEDINGS.

At the October meeting of the Board of Directors, the President was requested, in view of the cordial hospitality shown by the Italian authorities and members of the Associazione Elettrotecnica Italiana to the representatives of the United States and the American Institute of Electrical Engineers attending the Congress at Turin, to appoint a committee to draft suitable resolutions expressing the appreciation of the Institute for the honors and distinctions the American representatives had received. In reporting these resolutions at the November Board meeting the committee suggested that in the case of the Associazione Elettrotecnica Italiana a more substantial evidence of appreciation and good will would be fitting and desirable, and recommended the presentation to the Associazione of a bust of Joseph Henry. Arrangements have been made for the formal presentation of the bust at the Annual Meeting on May 21.

A bronze bust of the distinguished German scientist, Hermann von Helmholtz, was presented to the Institute last fall by Mr. Edward D. Adams, to whom the Institute is indebted for many benefactions in the past. The formal presentation of the bust to the Institute was the feature of the Institute meeting held in New York in November 1911. The Verband Deutscher Elektrotechniker was represented at the meeting by Dr. Adolf Franke of Berlin.

On October 13, 1911, resolutions were adopted by the Board directing the Editing Committee to regard as standard practise and to continue the insertion in its publications of metric equivalents, after each expression of values in English measures; also that the Institute adopt the standard international symbology decided upon by the International Electrotechnical Commission; also that the Institute adopt as the standard direction for expressing advancement of phase in graphic diagrams of alternating-current quantities the counter-clockwise direction standardized by the International Electrotechnical Commission.

The President was also authorized to correspond with the officers of the leading European societies of electrical engineers with a view to establishing reciprocal visiting member privileges for the mutual advantage of European electrical engineers visiting the United States and American engineers visiting the various countries of Europe.

At the November 1911 meeting of the Board a new By-law was adopted providing for preliminary nominations of officers of the Institute by petition. This has met with general approval, as was evidenced in the recent nominations for officers for 1912–1913.

On January 12, 1912, Mr. F. L. Hutchinson, formerly Assistant Secretary, and Acting Secretary since Mr. Pope's resignation, was appointed by the Board of Directors as Secretary of the Institute, to fill the unexpired term of Mr. Ralph W. Pope.

The Board also unanimously approved the proposed amendment to the Constitution providing for the appointment of the Secretary by the Board instead of his election by the membership, and directed that this amendment be submitted to the membership for a vote.

At the same meeting, in accordance with the provision of the Constitution by which Honorary Members may be chosen from among those who have rendered acknowledged eminent service to electrical engineering, Professor Andre Blondel, of Paris, Mr. C. E. L. Brown, of Baden, Switzerland, Dr. Emil Budde, of Berlin, Mr. Sebastian Z. de Ferranti, of London, and Professor Antonio Pacinotti, of Pisa, Italy, were elected Honorary Members. These were the first names to receive the distinction of honorary membership since 1892.

A trip to the Panama Canal for members and their guests was authorized by the Board last fall, and on January 17, 1912, a party of 59 members and guests sailed from New York on the steamer Almirante. Another party of 51 members and guests left New Orleans on the steamer Cartago on January 20. The parties combined at Panama, and were afforded unusual facilities for inspecting the engineering features of the great canal. A report of the trip was published on page 283 of the March PROCEEDINGS.

On February 9, the Board adopted a resolution recognizing the propriety of permitting the use to the members of the columns of the PROCEEDINGS for the expression of their criticisms and views on Institute affairs. Since the passage of this resolution " The Forum " has been used to a considerable extent for the discussion of various questions, particularly the constitutional amendments.

In addition to the work mentioned in this report, much has been accomplished by the various permanent and special committees as reported from time to time in the Institute PROCEEDINGS. From the foregoing statements and the following brief reports of the work of many of the committees, it will be seen that the Institute's field of activity is constantly broadening, and that a vast amount of useful work has been accomplished during the past year.

Sections Committee.—The Sections Committee is able to report an increased activity in its work during the past year. In line with similar statements of previous years, the activities of the Sections Committee are summarized in the following table.

	Year Ending				
	May 1 1908	May 1 1909	May 1 1910	May 1 1911	May 1 1912
SECTIONS					
Number of Sections..........	21	24	25	25	28
Number of Section meetings held......................	141	169	187	208	231
Total attendance............	7,476	16,427	16,694	15,243	19,800
BRANCHES					
Number of Branches.........	22	26	31	36	42
Number of Branch meetings held......................	143	198	237	255	281
Attendance.................	4,128	8,443	10,255	10,714	10,255

The foregoing table does not show by any means all of the increased activities of our various Sections. Not only has the amount of work increased as indicated in the foregoing table, but the character has during the last year or two shown a marked improvement. The number of original papers which is being produced by our various Sections is increasing to an astonishing degree. Practically every Section now has presented at its meetings original papers of a value which is comparable to that of the papers presented at the regular Institute meetings. Not only have the Section meetings themselves shown increased activity and improved character, but the recent movement to hold regular Institute meetings in various parts of the country has done much to stimulate Section activity. In addition to the regular Section meetings shown in the preceding summary, regular Institute meetings have been held in Boston, Mass., Portland, Oregon, Pittsburgh, Pa., and in Schenectady, N. Y. Some of these meetings have occupied a period of three days.

As indicated in the summary, three new Sections have been added during the past year; namely, at Lynn, Mass., Indianapolis-Lafayette, and Vancouver, B. C. These new Sections have taken hold well, and already 20 meetings, with a total attendance of 2,249, have been held by these three new Sections.

Six new Branches have been added during the year as follows: University of California, Ohio Northern University, Oklahoma Agricultural and Mechanical College, Rose Polytechnic Institute, University of Virginia, and Yale University.

The uniform basis of Section expenditures which was adopted a year ago is working to the satisfaction of all concerned.

In brief, the Sections Committee reports a satisfactory year.

Meetings and Papers Committee.—During the year this committee has arranged for eight regular meetings in New York, and has co-operated in and approved the programs for the Pacific Coast Meeting held in Portland, Ore., April 16th to 20th, 1912, and the Industrial Power Meeting held in Pittsburgh, April 25th to 27th, 1912. A total of thirty technical papers were presented and discussed at these meetings. The committee has also approved the plans and program for the meeting to be held in Schenectady, N. Y., on May 17th. At this meeting, which is under the auspices of the Schenectady Section, ten papers will be presented.

At the 1911 Annual Convention held in Chicago under the auspices of last year's committee, 35 technical papers were presented. Preparations are now being made for the 1912 Annual Convention to be held in Boston, June 24th to 28th, at which about 35 papers upon a wide variety of subjects will be presented. The program will include joint sessions with the Illuminating Engineering Society and the Society for the Promotion of Engineering Education.

New York Reception Committee.—This committee was established by the Board of Directors in December, 1911, to raise funds for and to take charge of the smokers which have been held in the Institute rooms immediately after the technical sessions at the New York meetings. These smokers have enjoyed an increasing popularity very greatly increasing the attendance at the meetings and affording an excellent opportunity for social intercourse of members and their guests. The finances to defray the expenses of the smokers have been collected by the Reception Committee in the form of voluntary contributions.

This committee also arranged for a dinner which was attended by members of the Board of Directors and several Past-Presidents on April 1st, 1912, in honor of Mr. C. E. L. Brown, of Switzerland, who had recently been elected an Honorary Member of the Institute.

Railway Committee—The committee avoided any efforts to obtain papers which would not add materially to electric railway information, or which might be in the nature of duplication of other papers.

One notable contribution along a new line was arranged for by the committee; that by President Samuel Insull of the Commonwealth Edison Company, on the general subject of consolidating power plants, and treating the railway demands, whether urban, interurban or trunk line, simply as large customers in a general system. On the presentation of this paper it was decided to have it revised and printed for presentation at the Annual Convention in Boston in June for discussion.

Realizing that much of the opposition to the electrification of trunk line railways is due to lack of detailed operative information, as well as figures of first cost of installation, a series of blanks have been prepared by a sub-committee which it is hoped may be filled up by the various important steam railways operating electrical sections so that there may be strictly comparative information at hand.

High-Tension Transmission Committee.—Every Section and Branch has held a special meeting on high-tension transmission work, and there has been an extremely broad and general discussion of all active high-tension subjects. There is to be a regular Institute meeting at Schenectady in May, half of which will be devoted to high-tension transmission work, and a session will also be devoted to the subject at the Annual Convention at Boston in June. There has been a great deal of correspondence with different Sections and Branches, and in many cases speakers have been arranged for by the committee.

Electric Lighting Committee.—The Electric Lighting Committee has obtained five papers during the year on electric lighting subjects. One of these was presented at the Pacific Coast Meeting held in Portland, Oregon, in April, and the other four will be presented at the Institute's Boston Convention in June.

Industrial Power Committee.—The Industrial Power Committee organized in Pittsburgh, in connection with the Pittsburgh Section, a joint meeting with the Association of Iron and Steel Electrical Engineers. The meeting was held April 25–27, and 10 papers on various subjects relating to industrial power were presented. The committee has also obtained a number of papers for presentation at the Annual Convention.

Telegraphy and Telephony Committee.—This committee has held one meeting during the year, and has carried on considerable correspondence. The committee has obtained a number of valuable papers dealing with telegraphy and telephony. Some of these were presented at the Pacific Coast Meeting in Portland, Oregon, in April, and others will be presented at the Annual Convention in Boston in June.

Power Station Committee.—It was the intention of the Power Station Committee to have a meeting under its auspices at which would be presented a number of brief papers descriptive of the latest developments in the constituent parts of a typical large power station. As the season advanced, however, it was found that the amount and variety of material offered made it unnecessary to set aside a meeting for this specific purpose but the main items were covered in other meetings during the year.

Electrochemical Committee.—At the beginning of the season the Electrochemical Committee endeavored to get a sufficient number of papers on electrochemical subjects to devote one of the regular monthly meetings of the Institute in New York to electrochemistry. It was not possible to obtain the papers in time for such a meeting, and the committee therefore decided to postpone the presentation of the papers until the Annual Convention. The committee has succeeded in obtaining for the convention six papers, and a session will be devoted to the subject.

Electrophysics Committee.—This new committee was created by the Board in recognition of the fact that Electrophysics has ceased to be solely science and has become an important practical factor in electrical engineering. It was appointed late in the year and therefore has not been able to accomplish as much as it might have done if appointed at the usual time. No meetings have been held during the few months that elapsed since the committee was appointed, but it has secured a number of papers on various subjects included within the field of electrophysics for the Boston Convention, and it is believed that next year's committee on electrophysics will find it possible to secure a larger number of valuable papers on this subject.

Educational Committee.—The Educational Committee was reorganized on account of the resignation of the original chairman and the appointment of his successor last October. At the first meeting thereafter, it was decided to take up the consideration and study of vocational and industrial education in the United States. The subject was divided into parts, as follows:

A study of the present schools now established in which distinction is made between those maintained by industrial corporations for their own purposes, those maintained by public taxes, and those maintained by private benevolences; the second part, a study of the laws in existence for the establishment and maintenance of vocational schools; third, from the data gathered, the presentation of such elementary principles as appear from experience to be wise in the development of this particular form of education.

The committee divided the country into several sections and members were assigned to sections for gathering data and information with regard to existent schools. A member of the committee was assigned for the project of gathering together all laws on vocational education at present existent in the United States. Much work has been done by the committee as above outlined and arrangements have been made with the Meetings and Papers Committee to have the results presented at the Annual Convention.

Editing Committee.—Since April 30, 1911, there have been edited and published 12 numbers of the PROCEEDINGS. The total number of pages contained in these PROCEEDINGS is 2,582. Of these, 404 pages have appeared in Section I, and 2,178 in Section II. Volume XXX of the TRANSACTIONS, consisting of the papers and discussions presented during the calendar year 1911 and the report of the Board of Directors for the fiscal year ending April 30, 1911, will be issued in three parts, and will contain about 2,700 pages, more than any previous volume of the Institute TRANSACTIONS. With the third part still to be printed, the first two parts contain 1,742 pages, only six pages less than the whole of Volume XXIX.

The reports and discussions submitted by the Sections and Branches, and the discussions presented at the regular Institute meetings, have been edited and published under the supervision of the Editing Committee.

Standards Committee.—The Standards Committee has held monthly meetings in New York. It was voted that no new edition of the Standardization Rules should be issued this year. A sub-committee was, however, appointed to collect material for a complete revision of the Rules.

A post-card invitation was issued from the Institute office to all Members and Associates requesting that suggestions for amendments and modifications in the Rules should be forwarded to the secretary of the committee, with a view of being included, if approved, at the next revision.

A special sub-committee was also appointed to consider the modifications in the Rules for the rating of machinery.

The following subjects have occupied the attention of other special sub-committees during the year: electric cable terminology, definitions for the Committee on Code of Principles of Professional Conduct, co-operation with like committees of other societies, international copper resistivity standards, questions of international nomenclature and international rating. Action was taken on some of the above subjects, as well as on others not included in the list.

Communications have been held with the Bureau of Standards, and also with the American Society for Testing Materials, in regard to the preparation of a new electrical table of copper wires.

Communications have also been exchanged with the U. S. National Committee of the International Electrotechnical Commission.

Code Committee.—The Code Committee held a meeting on March 12, 1912, with representatives of the National Electric Light Association, the Association of Edison Illuminating Companies, and the National Inspectors Association, and concurred in a joint recommendation to the National Fire Protection Association in regard to the grounding of secondaries.

On March 27, 1912, Mr. Farley Osgood, representing the A. I. E. E., attended the annual conference of the Electricity Committee of the National Fire Protection Association. Mr. Osgood's report is printed in full in the May PROCEEDINGS.

Law Committee.—The Law Committee, in its advisory capacity, has during the year presented its views with reference to the provisions of the Constitution bearing upon actions of the Sections; the publication of the names of candidates for nomination, and the management of the library; also upon certain proposed amendments of the Constitution with reference to the appointment of the Secretary by the Board of Directors, and providing for an additional grade of membership. The committee has also presented its opinion with reference to the Code of Principles of Professional Conduct.

Under the Constitution, the Law Committee, being an advisory committee, has undertaken no constructive work other than such as may be involved in the consideration of the subjects brought to its attention.

Library Committee.—In accordance with Section 24 of the By-Laws of the Institute we beg leave to submit herewith our annual report for the year ending April 30, 1912, showing the state of the library and including the names of all donors to it.

During the year a mezzanine floor with shelving capable of holding about 15,000 volumes has been erected at a cost of $6,196. The additional shelves have been filled with the books most frequently referred to; they are reached by a low staircase and the books are accessible to all readers. The appearance of the main room has been much improved by this addition and the efficiency of the service of the attendants has been increased thereby considerably. A number of additions have been made to the library furniture and a new system of illumination has been installed at a cost of $1,481.

A system of compilation of references to engineering literature, by special search through the publications in the library, has been inaugurated, the searches being made by the regular library attendants. Since its inauguration 181 such investigations have been made, most of them at the request of members residing outside of New York City. Duplicates of the related reports are kept on file and it has already been disclosed that several requests are likely to refer to the same subject matter.

The subject card catalogue of the Schuyler Skaats Wheeler collection is practically completed, a few minor items remaining to be entered.

The attendance has increased over the previous years, even though the main library room was closed for three months during the alterations and evening admission was prohibited during September, 1911.

The joint library of the Founder Societies now contains 50,000 volumes, receives currently 650 periodicals, and has over 1100 sets of periodicals and transactions. The growth amounts to about 3000 volumes per annum in all languages and this includes nearly all the worthy books issued in the restricted field which the library represents.

Statistical information concerning the library and its use during the year, including a list of donors, is given in the following tables:

Donors

May 1, 1911—April 30, 1912

ADAMS, E. D.	8
ADAMSON, D.	2
A. E. G. ZEITUNG	1
ALLGEMEINE ELEKTRICITAT GESELLSCHAFT	1
AMERICAN ELECTRIC RAILWAY ASSOCIATION	5
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS	8
AMERICAN SCHOOL OF CORRESPONDENCE	5
ARNOLD, BION J.	7
BENEDICT, V. L.	3
BERLINER ELECKTRICITATS WERKE	1
BLAKISTON'S SON & COMPANY	1
CALDWELL, EDWARD	1
CANADA. COMMISSION OF CONSERVATION	1
CENTRAL STATION	1
DAVID WILLIAMS COMPANY	1
DIXON CRUCIBLE COMPANY	7
IOWA ELECTRICAL ASSOCIATION	1
IOWA ENGINEERING SOCIETY	1
ITALY. MINISTERIO DI AGRICOLTURA	1
KENNELLY, A. E.	2
MACMILLAN COMPANY	2
MAILLOUX, C. O.	63
MARYLAND. PUBLIC SERVICE COMMISSION	2
MASSACHUSETTS GAS & ELECTRIC LIGHT COMPANY	1
MCGRAW PUBLISHING COMPANY	1
NATIONAL ELECTRIC LIGHT ASSOCIATION	1
NATIONAL FIRE PROTECTION ASSOCIATION	1
NATIONAL FIRE PROTECTION ASSOCIATION	1
NEW ENGLAND WATER WORKS ASSOCIATION	1
NEW YORK STATE. DEPARTMENT OF LABOR	4
NEW YORK STATE LIBRARY	1
ONTARIO. HYDROELECTRIC POWER COMPANY	1
RUGBY ENGINEERING SOCIETY	2
SPON & CHAMBERLAIN	2
STONE & WEBSTER	1
U. S. DEPARTMENT OF AGRICULTURE	1
U. S. NATIONAL WATERWAYS COMMISSION	1
UNIVERSITY OF LONDON PRESS	1
UNIVERSITY OF MISSOURI	1

VAN NOSTRAND, D. COMPANY	9	
VILLARS, G.	3	
WEAVER, W. D.	3	
DONOR UNKNOWN	1	
OLD MATERIAL	30	
		191

Exchanges	108	
Purchases and old material accessioned	191	
		299
Total accessions		490

The following tabulation gives the state of the accounts from which the Library Committee is entitled to draw.

Donations (General Library Fund)

Dr.		Cr.	
Balance May 1, 1911	$264.52		
Interest May 1, 1912	6.63	Unexpended	$271.15
	$271.15		$271.15

Mailloux Endowment Fund ($1000)

(Proceeds for the maintenance of certain sets of periodical publications)

Balance May 1, 1911	$41.35	Expended	$7.80
Interest	45.00	Unexpended	78.55
	$86.35		$86.35

International Electrical Congress of St. Louis, 1904, Fund

(Proceeds available for the purchase of non-American international electrical literature)

Invested in New York City 4½% bonds	$2268.00
Additions to the fund	63.60
Total fund	$2331.60

Balance on hand May 1, 1911	$219.12		
Interest to May 1, 1912	90.00	Unexpended	$309.12
	$309.12		$309.12

Weaver Donation

(Available for the purchase of early electrical literature)

Balance on hand May 1, 1911	$65.44	Expended	$58.75
		Unexpended	6.69
	$65.44		$65.44

INSTITUTE APPROPRIATION ACCOUNT

Appropriation for the year	$4500.00	Salary (one-third) of librarian, assistants, cataloguer and desk attendant May 1, 1911-April 30, 1912	$2700.00
		One-third running expenses of library May 1, 1911 to April 30, 1912	257.98
		Books	555.16
		Subscriptions	62.80
		Insurance	88.21
		Binding	181.42
		Miscellaneous	2.25
			$3847.82
		Unexpended balance	652.18
			$4500.00

STATISTICS OF LIBRARY MAY 1, 1912

Source	Volumes	Pamphlets	Valuation
Report of May 1, 1912	15,293	1343	$28,035.28
Purchase	181	10	604.37
Gifts and exchanges	267	2	569.50
Old material accessioned	10	20	25.00
	15,751	1375	$29,234.15

In the following table are given the figures for the total valuation of the Library property:

Books	$29,234.15
Stacks	1,761.05
Furniture, catalogues, cases, etc	376.00
	$31,371.20

LIBRARY ATTENDANCE

	Day	Night	Total
May, 1911	833	375	1208
June, "	637	310	947
July, "	610	Closed	610
August, "	550	"	550
September, "	608	"	608
October, "	661	252	913
November, "	720	283	1003
December, "	853	287	1140
January, 1912	728	298	1026
February, "	813	273	1086
March, "	869	326	1195
April, "	719	343	1062
Total May, 1911-April, 1912	8601	2747	11,348
Total May, 1910-April, 1911	7473	3041	10,514

The income from the C. O. Mailloux Fund of $1000 has again been used to maintain the four important periodical sets which were originally presented to the library by Mr. Mailloux.

Respectfully submitted,
FREDERICK BEDELL
MORGAN BROOKS
ALBERT F. GANZ
OTIS ALLEN KENYON
SAMUEL SHELDON, *chairman.*
Library Committee.

Public Policy Committee.—One of the first acts of the Board was to create a Public Policy Committee to which could be referred the increasing number of important issues affecting the Institute's public relations.

On November 10, 1911, the Board referred to this committee an invitation to the Institute from the National Waterways Commission of the U. S. Congress, to take part in a hearing at Washington, D. C. on November 21, 1911.

A sub-committee of the Public Policy Committee consisting of President Gano Dunn and Mr. H. W. Buck prepared a preliminary report of its views on the development of water powers, which draft was modified by the Public Policy Committee and its Advisory Members to conform to and represent their joint opinion. President Dunn and Messrs. H. G. Stott, chairman, Calvert Townley, Lewis B. Stillwell, and John H. Finney, members of the committee, represented the Institute at the hearing in Washington. The brief presented by the Institute delegation and a report of the hearing were published in the December, 1911, PROCEEDINGS.

The Institute representatives were given the first hearing on the afternoon of November 21 and the entire morning of November 22, and through them the thanks of Chairman Burton and other members of the Commission were transmitted to the Institute for the information given in the printed brief and for its representation at the hearing.

Patent Committee.—The Patent Committee was appointed but recently and is not yet prepared to make a final report. Thus far the work of the committee has been accomplished by correspondence between the chairman and the members of the committee. Four members of the committee acted as conferees at an important conference on patent matters held in Washington on April 15 and 16 at the call of the Patent Law Association of Washington.

This committee was established by the Board of Directors as a result of the initiative of the St. Louis Section in urging improvements in the patent laws of the United States.

Code of Principles of Professional Conduct.—Originally this committee was known as the Committee on a Code of Ethics. Its appointment was the result of a discussion at the Milwaukee Convention, held in May 1906, following the presidential address of Dr. Schuyler Skaats Wheeler, on " Engineering Honor." It was the sense of the convention at that time that the ideas expressed in Dr. Wheeler's address should be embodied in a code of ethics for the electrical engineering profession. A code was prepared and discussed at the Niagara Falls

Convention held in June 1907. Later in the same year the code was revised, printed and submitted to the membership for suggestions.

No further action was taken on the code until June 1911, when in accordance with a resolution of the Board of Directors, President Jackson appointed a committee to take up the question. The committee was reappointed by President Dunn the following August on his accession to office.

This committee's work was presented in a report to the Board of Directors on February 9, 1912, when a code of principles was tentatively adopted. After a month's careful analysis and consideration of numerous suggestions from the advisory members of the committee and others the present code as printed in the April PROCEEDINGS was adopted at the meeting of the Board of Directors on March 8, 1912.

The name of the committee was changed on February 9, 1912, to the Committee on Code of Principles of Professional Conduct.

The committee is now considering suggestions which have been submitted to it since the adoption of the code.

Relations of Consulting Engineers.—The Committee on Relations of Consulting Engineers has considered at its several meetings the matters referred to it, also the proper procedure and general scope of its work. The committee expects to be able to formulate its recommendations after further conferences with the representatives of other societies and of the various interests concerned.

United States National Committee of International Electrochemical Commission.—The president and secretary of the Committee, with President Dunn of the Institute, attended the meeting of the I. E. C. at Turin (September 7–13, 1911) as delegates from the United States. A provisional report of the meeting was submitted by the secretary of the committee to the Institute's Board of Directors, in October, and was published, by their direction, in the November issue of the PROCEEDINGS, Vol. XXX, No. 11, pages 2437–2448.

A brief official resumé of the Turin meeting, in French and English, was printed and issued by the central office of the I. E. C., in London, in November, 1911, marked Publication 12.

At that meeting the U. S. National Committee communicated, through President Dunn, to the I. E. C., a cordial invitation from the American Institute of Electrical Engineers to hold a meeting in San Francisco in 1915. This proposal was formally adopted.

Under the instructions of the Board of Directors, the last edition of the Standardization Rules, issued by the Institute this year, contains a brief resume of the decisions of the Turin meeting, and also a slightly abridged copy of the Central Office's publication No. 9, on "Rating of Electrical Machinery," being extracts from the rules of various countries.

At the Turin meeting the I. E. C. appointed three international special committees on the subjects of "Nomenclature," "Symbols," and "Rating of Machinery," respectively, to report at the next plenary meeting in Berlin in 1913.

The United States Committee endeavored to have delegates attend meetings of the two latter special committees. After some delays, President C. O. Mailloux left New York on April 24, to attend, as U. S. delegate, the meeting of the "Committee on Rating of Machinery" at Paris, set for May 8.

The committee has secured from the Treasury Department at Washington an order that all official reports of the I. E. C. may be admitted free of duty into the United States, as scientific publications, under paragraph 517 of the Tariff Act.

The committee has held monthly meetings in New York City. It has carried on a considerable amount of correspondence with the Central Office and of communication with the Standards Committee.

International Electrical Congress, San Francisco, 1915.—The project of holding an International Electrical Congress during the Panama Exposition at San Francisco in 1915, first took shape in the Spring of 1911 when a group of Pacific Coast members organized and sent Mr. H. A. Lardner as a delegate to bring it to the attention of the Institute officers in New York. This matter was first brought to the attention of the Board at the June, 1911, meeting, at which a committee was appointed to consider the matter. Upon the recommendation of this committee the Board adopted resolutions in August, 1911, to the effect that the Institute should initiate and organize such a congress under the authority of the International Electrotechnical Commission. The desired authority was granted by the latter body at its meeting in Turin in September, 1911.

The following officers of the Committee on Organization of the Congress have been appointed by the President: Dr. Charles P. Steinmetz, President; Dr. A. E. Kennelly, Vice-President in Charge of Program; Mr. C. O. Mailloux, Vice-President in Charge of International Relations; Mr. W. D. Weaver, Vice-President in Charge of Organization; Mr. Henry A. Lardner, Vice-President in Charge of Pacific Coast Relations; Dr. E. B. Rosa, Secretary; Mr. Preston S. Millar, Treasurer and Business Manager.

John Fritz Medal.—The John Fritz Medal for 1911 was awarded to Sir William Henry White, for " notable achievements in naval architecture. " The presentation was made at a dinner of the Society of Naval Architects and Marine Engineers at the Waldorf-Astoria Hotel, New York, on Friday evening, November 17, 1911. The attendance included representatives of the principal engineering societies of the United States.

Edison Medal.—The Edison Medal Committee, at its meeting held on November 20, 1911, selected from the names of the candidates submitted for consideration in accordance with its by-laws, the name of George Westinghouse, to be voted upon in December following.

At the meeting of the committee on December 15, 1911, a vote taken in accordance with its by-laws resulted in the award of the Edison Medal to Mr. George Westinghouse, " for meritorious achievement in connection with the development of the alternating-current system for light and power. " The presentation of the medal is to be made at the Annual Convention to be held in Boston in June.

Indexing Transactions Committee.—The Indexing Transactions Committee has had prepared during the year synopses of all papers presented before the Institute up to and including the year 1910, and index cards have been prepared covering, in detail, the contents of these papers.

The papers and cards have been largely classified and samples of typographical arrangement have been obtained. The entire index will be ready for the printer this coming summer and should appear in the fall. There will be two parts to the index; one part covering papers up to and including 1900, and the second part, papers from 1901 to 1910 inclusive. The index for the year 1911 will appear in the volume for that year.

Additional Grade of Membership.—The Additional Grade of Membership Committee (originally appointed under the name of the Intermediate Grade of Membership Committee) has considered during the present administration the data collected by the committees of previous years, and, after further investigation and discussion, prepared a draft of amendments to the constitution for consideration by the Board of Directors at its December meeting. This report was then revised in the light of criticisms and suggestions obtained from members of the Board and others, and resubmitted at the January meeting of the Board. At this meeting, the last draft with slight modification was unanimously adopted by the Board and recommended for submission to the membership as a constitutional amendment.

The final form of the report was of the nature of a compromise between the rather widely varying views of the committee arrived at by vote at numerous meetings held. The substance of the amendments has been so fully set forth in various explanatory statements published in the PROCEEDINGS that no further explanation is here required. The duties of the committee, with the exception of assisting in expounding the amendments for the benefit of the membership, were practically completed with the acceptance of the amendments at the Board's January meeting.

Board of Examiners.—The Board of Examiners has held 10 meetings during the year. It has considered and recommended for action by the Board of Directors a total of 1616 applications of all classes. A summary of these applications is as follows:

Recommended for election as Associates	808
Not recommended for election as Associates	2
Recommended for transfer to the grade of Member	60
Not recommended for transfer to the grade of Member.	25
Transfer applications considered but held for additional information	7
Recommended for enrolment as students	714
Total	1616

In addition to applications for admission and transfer, the Board has considered and reported upon a number of questions that have been submitted to it by the Board of Directors during the year.

Membership.—A circular letter was mailed to each member of the Institute on November 28, 1911, asking for names of desirable candidates for admission to membership. The co-operation of Section officers was also enlisted. As a result, over 1,200 names were received at Institute headquarters. Each of these candidates was communicated with promptly and supplied with literature relating to the Institute and the advantages of membership.

The total number of applications received during the year is 1,025.

A complete report showing the total membership, the additions and deductions, and the net increase for the year is given below.

	Hon. Mem.	Mem.	Assoc.	Total
Membership, April 30, 1911.	1	689	6,427	7,117
Additions:				
Honorary Members	4			
New Associates..............			855	
Transferred.................	1	49		
Reinstated..................		1	27	
Deductions:				
Died........................	1	3	29	
Resigned....................		6	150	
Dropped.....................		5	351	
Transferred.................		1	- 49	
Membership, April 30, 1912........	5	724	6,730	7,459

Net increase during the year in membership......................342

Deaths.—The following deaths have occurred during the year:

Honorary Member.—Antonio Pacinotti.

Members.—Caryl D. Haskins, E. W. Mix, W. D. Sargent.

Associates.—E. H. Anderson, Edwin H. Bennett, E. H. Berry, D. E. Black, E. B. Boor, W. R. Brixey, Lon D. Caldwell, F. T. Clarke, C. C. Cokefair, E. Copley, F. S. Davenport, I. T. Dyer, H. W. Fellows, J. B. Fleming, L. A. Freudenberg, W. C. Getz, H. L. Hart, Junzo Itoh, W. S. Johnson, E. M. Kenly, M. McIntyre, O. C. Poste, Roger P. Stebbins, H. H. Sykes, R. H. Thomas, E. G. Tracy, R. A. Turner, G. A. Wilson, Chas. I. Young.

Total deaths, 33.

Resignations.—Resigned during the year in good standing: Members, 6; Associates, 150; total 156.

Delinquents.—Dropped as delinquent during the year, 356.

Finance Committee.—The following correspondence and financial statements form a complete summary of the work of the Finance Committee for the year.

New York, May 14, 1912.

Board of Directors,
American Institute of Electrical Engineers.

Gentlemen: Your Finance Committee respectfully submits the following report for the year ending April 30, 1912.

During the past 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. Peirce, Struss and Company, chartered accountants, have audited the Institute books and their certification of the Institute finances follows.

In company with your Secretary and a member of the firm of chartered accountants, the committee has examined the securities held by the Institute and find them to be as stated in the accountants' report.

In accordance with the authority of the Board an investment from the surplus funds of the Institute was made during the past year amounting to $15,000.00 par value Wilmington City 4½ per cent registered bonds.

The expenditures of the Institute during the past year have been considerably increased due to the constantly broadening scope and activity of the organization, and particularly due to the increased amount of technical material published in the PROCEEDINGS and TRANSACTIONS resulting from the extension of the policy inaugurated a few years ago of holding Institute meetings in various parts of the country. Notwithstanding the increased budget of expenditures made necessary by reason of these extended activities, it is gratifying to note that the accompanying increase in income has resulted in a comfortable surplus for the fiscal year.

Respectfully submitted,
A. W. BERRESFORD
Chairman, Finance Committee.

MR. A. W. BERRESFORD,
Chairman Finance Committee.

NEW YORK, May 10, 1912.

Dear Sir: In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30th, 1912.

The results of this examination are presented in four exhibits, attached hereto, as follows:

Exhibit "A" Balance Sheet, April 30th, 1912.
Exhibit "B" Receipts and Disbursements for general purposes for year ended April 30th, 1912.
Exhibit "C" Receipts and Donations for designated purposes, also expenditures for year ended April 30th, 1912.
Exhibit "D" Condensed Cash Statement.

We beg to present, attached hereto, our certificate to the aforesaid exhibits.

Yours very truly,
(Signed) PEIRCE, STRUSS & CO.
Certified Public Accountants.

MR. A. W. BERRESFORD,
Chairman Finance Committee.

NEW YORK, May 10, 1912.

Dear Sir: Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1912, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30th, 1912, and that the accompanying statements of Cash Receipts and Disbursements are correct.

(Signed) PEIRCE, STRUSS & CO.
Certified Public Accountants.

AMERICAN INSTITUTE OF
BALANCE SHEET,

EXHIBIT A

ASSETS

CASH:		
Land, Building and Endowment Fund	$5,307.53	
General Library Fund	271.15	
Life Membership Fund	4,827.28	
		10,405.96
General Cash in Bank	9,277.02	
Mailloux Fund, Interest	78.55	
Weaver Donation	6.69	
International Electrical Congress of St. Louis Library Fund, interest	372.72	
Total Cash deposit	9,734.98	
Secretary's Petty Cash on hand	750.00	
		10,484.98
Land, Building and Endowment Fund, accrued interest	55.28	
General Library Fund, accrued interest	2.82	
Mailloux Fund, accrued interest	22.50	
International Electrical Congress of St. Louis Library Fund, accrued interest	45.00	
Life Membership Fund, accrued interest	40.00	
		165.60
Mailloux Fund, principal (Bond)		1,000.00
International Electrical Congress of St. Louis Library Fund, N. Y. City 4½% Bonds, due 1917		2,268.00
New York City 4½% Gold Bonds, due 1957, par	30,000.00	
Premium on N. Y. 4½% Gold Bonds	1,952.50	
Chicago, Burlington & Quincy 4% Bonds, due 1958 (par value $15,000)	14,606 25	
City of Wilmington, Del. 4½% Bonds, due 1934	15,000.00	
Premium on City of Wilmington, Del. Bonds	997.50	
Westinghouse Elec. & Mfg. Co's stock	50.00	62,606.25
Equity in Engineering Societies Building (25 to 33 West 39th Street)	353,346.61	
One-third cost of land (25 to 33 West 39th Street)	180,000.00	
		533,346.61
Library Volumes and Fixtures	30,905.78	
Transactions	9,008.50	
Office Furniture and Fixtures	7,915.64	
Works of Art, Paintings, etc.	2,656.35	
Badges	463.35	
		50,949.62
ACCOUNTS RECEIVABLE:		
Members for current dues	240.00	
Members for past dues, suspense account	8,132.00	
Members for entrance fees	115.00	
Special	76.32	
Miscellaneous	265.65	
Advertising	2,016.25	
Accrued interest on bonds	831.25	
Accrued interest on bank balance	132.19	
		11,808.66
Total		$683,035.68

ELECTRICAL ENGINEERS
April 30, 1912

Liabilities and Surplus

Funds:		
Land, Building and Endowment Fund	$5,362.81	
General Library Fund	273.97	
Life Membership Fund	4,867.28	
Mailloux Fund	1,101.05	
International Electrical Congress of St. Louis Library Fund:		
Bonds	2,268.00	
Cash on deposit	372.72	
Accrued interest	45.00	
		$14,290.83
Reserve for Furniture and Fixtures		2,946.39
Accounts Payable, subject to approval by the Finance Committee		6,984.68
United Engineering Society (for cost of land)		54,000.00
Total Liabilities		78,221.90
Surplus:		
In Cash	9,277.02	
New York City Bonds	31,952.50	
C. B. & Q. Bonds	14,606.25	
City of Wilmington, Del. Bonds	15,997.50	
In property and accounts receivable	532,980.51	
		604,813.78
Total Liabilities and surplus		$683,035.68

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1912

EXHIBIT B

RECEIPTS		
Entrance Fees	4,303.00	
Current Dues	66,879.00	
Past Dues	4,102.50	
Advance Dues	450.00	
Students Dues	4,113.00	
Transfer Fees	500.00	
Badges	1,740.00	
		$82,087.50
Sales, Transactions etc.	1,347.43	
Subscriptions, Proceedings	2,084.50	
Advertising	9,513.41	
Binding	138.00	
Exchange	19.31	
		13,102.65
INTEREST:		
Bonds	2,625.00	
Bank Balance	597.48	
		3,222.48
Total		$98,412.63

DISBURSEMENTS		
Stationery and Printing	4,425.85	
Postage	2,849.85	
General Expense	2,582.27	
Meeting Expense	5.034.21	
Section Meetings	9,271.33	
Badges purchased	1,643.72	
Salaries	11,821.00	
Indexing Transactions	822.20	
Interest on Mortgage	2,160.00	
Office Furniture and Fixtures	981.04	
Adver. Expense	3,339.41	
Year Book and Catalogue	2,896.86	
Express	220.87	
Interest refunded	71.25	
		$48,119.86
PROCEEDINGS:		
Printing	7,934.32	
Paper and Envelopes	6,002.84	
Engraving	1,663.34	
Binding and Mailing	4,137.31	
Salaries	4,084.00	
		23,821.81
TRANSACTIONS:		
Vol. 29	8,135.76	
Vol. 30	4,413.03	
		12,548.79
LIBRARY (including salaries)		3,847.82
UNITED ENGINEERING SOCIETY Assessments for office space		4,500.00
Total		$92,838.28
Excess of Receipts over Disbursements		5,574.35
		$98,412.63

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES, ALSO EXPENDITURES FOR YEAR ENDED APRIL 30, 1912

EXHIBIT C

RECEIPTS	
Land, Building and Endowment Fund, Donations, Interest, etc.	316.16
General Library Fund, Interest	6.63
Compounded Membership Fund	504.29
International Electrical Congress of St. Louis, Library Fund, Donations and interest	103.95
Mailloux Fund, interest	45.00
Certificate of Deposit	1,000.00
Total	1,976.03

EXPENDITURES	
Mailloux Fund	7.80
Life Membership Fund	420.00
City of Wilmington, Del. Bonds and interest	16,087.50
Weaver Donation	58.75
Special Library Account	76.32
Total	16,650.37

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CONDENSED CASH STATEMENT

EXHIBIT D

Cash on deposit April 30, 1911	$29,240.93	
Secretary's Petty Cash, April 30, 1911	750.00	
		$29,990.93
Receipts for general purposes, Exhibit " B "	98,412.63	
Receipts for designated purposes, Exhibit " C "	1,976.03	
		100,388.66
		130,379.59
Disbursements for general purposes, Exhibit " B "	92,838.28	
Expenditures for designated purposes, Exhibit " C "	16,650.37	
		109,488.65
Balance on hand April 30, 1912		20,890.94
On deposit for designated purposes, Exhibit " A "	10,405.96	
* On deposit in General cash, Exhibit " A '	9,734.98	
Secretary's Petty Cash, Exhibit " A "	750.00	
		20,890.94
Property acquired during the year, Office Furniture and Fixtures	981.04	
* This includes the following unexpended balances:		
Mailloux Fund	78.55	
Weaver Donation	6.69	
Int. Elec. Congress of St. Louis Library Fund	372.72	
		457.96

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER

During each fiscal year for the past seven years.

Year	**1906**	**1907**	**1908**	**1909**	**1910**	**1911**	**1912**
Membership, April 30, each year	3870	4521	5674	6400	6681	7117	7459
Receipts per Member	$12.77	$12.21	$13.01	$13.21	$13.35	13.37	$13.19
Disbursements per Member	10.48	11.62	11.73	10.49	12.03	11.03	12.44
Credit Balance per Member	$2.29	$.59	$1.28	$2.72	$1.32	$2.34	$.75

Respectfully submitted for the Board of Directors,

F. L. HUTCHINSON, Secretary

New York, May 21, 1912.

INDEX

PAPERS AND DISCUSSIONS

INDEX OF AUTHORS

SYNOPTICAL AND TOPICAL

INDEX

OF

A. I. E. E. TRANSACTIONS

Vol. XXXI, Parts I and II

The main headings under which these synopses are classified were arrived at by a careful study of all the papers contributed since the organization of the Institute.

The method of making this classification may be called the automatic method, since it is created by sorting the papers themselves into groups and then naming the groups.

Many papers fall naturally into several different groups and in such cases they are inserted under as many different heads as it is thought they rightfully belong.

The classified synopses are designed for those searching for comprehensive information on any given topic, while the subject index is intended for those looking up specific and definite data or information.

MAIN SECTIONS OF SYNOPTICAL INDEX

1. EDUCATION

INDUSTRIAL EDUCATION

Preliminary Report by the Educational Committee

Vol. xxxi—1912, pp. 1309-1347

Part I. Introduction. Comparison of American and European laborers. Outline of purpose of the investigation, suggesting a classification of industrial schools and mentioning conditions desirable in the organization of such schools.

Part II. Provision by law for vocational training in the United States, being a survey of the educational enactments of the various states, that of Massachusetts being given in detail.

Part III. Description of typical vocational and industrial schools, conducted by the Government, private individuals, electric corporations and railroads, giving many statistics in tabular form covering the character of the students and the courses.

Discussion, pages 1348-1366, by Messrs. Henry G. Stott, J. P. Jackson, A. L. Williston, Albert L. Rohrer, W. S. Franklin, Henry H. Norris, J. W. L. Hale, W. I. Slichter, William McClellan, Professor Diemer, Comfort A. Adams, F. C. Caldwell, M. J. McGowan, Jr., W. G. Raymond and Harry Barker. Need of industrial education from economical and humanistic standpoints. Data on the Bridgeport Industrial School. Functions of corporation schools. Use of existing industrial equipment for educational purposes. Plan of Fitchburg co-operative school system. Definition of professional work. Application of natural selection vs. artificial selection in education. Defects in modern educational systems. Basis of organization of Land Grant Colleges.

2. GENERAL THEORY

ELECTROLYTIC CORROSION OF IRON BY DIRECT CURRENT IN STREET SOIL

Albert F. Ganz **Vol. xxxi—1912, pp. 1167-1176**

Experimental investigation of the relative corrosion of different kinds of iron in two typical street soils. Comparison of actual electrolytic corrosion with that calculated by Faraday's law.

Discussion, pages 1177-1178, by Messrs. Carl Hering, Edward B. Rosa, Irving Langmuir, C. H. Sharp and Albert F. Ganz. Corrosion of iron in cinders. Voltage of electrolytic corrosion of iron.

SIMPLIFICATION OF ELECTROTHERMAL CALCULATIONS, THE WATT AND THERMAL OHM

Carl Hering **Vol. xxxi—1912, pp. 1191-1201**

Advantages of absolute systems of units. Energy factors in heat transmission and selection of units for measuring such factors. Factors for converting the new units into those already in use.

Discussion, pages 1202-1205, by Messrs. H. B. Gale, Carl Hering, Alfred H. Cowles. Definitions of factors of heat energy.

VACUA

W. R. Whitney **Vol. xxxi—1912, pp. 1207-1216**

Improvement of vacuum by condensing vapors. Blackening of inside of vacuum tubes and lamp bulbs. Edison effect. Crookes radiometer for measuring pressure in a vacuum. Effect of temperature on life of vacuum lamps.

Discussion, page 1217, By Messrs. W. R. Whitney and Alfred H. Cowles. Gases held within glass containers.

THE CONVECTION AND CONDUCTION OF HEAT IN GASES

Irving Langmuir **Vol. xxxi—1912, pp. 1229-1240**

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Discussion, including that of paper by W. D. Coolidge on "Metallic Tungsten and Some of Its Applications," pages 1241-1242, by Messrs C. M. Green, William J. Hammer, Carl Hering, W. D. Coolidge, H. M. Hobart and Irving Langmuir. Plating tungsten. Relation of external temperature to temperature rise of electrical machinery.

THE VIBRATIONS OF TELEPHONE DIAPHRAGMS

Charles F. Meyer and J. B. Whitehead **Vol. xxxi—1912, pp. 1397-1418**

Experimental study of vibrations of telephone receivers and transmitters at different frequencies and currents. Relation between frequency, current and amplitude of vibration, shown graphically. Resonance curves, curves for receiver and transmitter.

Discussion, pages 1419-1428, by Messrs. George D. Shepardson, George W. Pierce, Alan E. Flowers, A. E. Kennelly, John B. Taylor, John B. Whitehead, Frank Wenner and Charles F. Meyer. Effect of temperature on vibration of telephone diaphragms. Variation of inductance and resistance of telephone transmitters and receivers when vibrating.

3. MEASUREMENT AND INSTRUMENTS

MEASUREMENTS OF VOLTAGE AND CURRENT OVER A LONG ARTIFICIAL POWER-TRANSMISSION LINE AT 25 AND 60 CYCLES PER SECOND

A. E. Kennelly and F. W. Lieberknecht **Vol. xxxi—1912, pp. 1131-1163**

Design and construction of an artificial transmission line. Methods of measuring e.m.f. and current distribution in artificial equivalent of very long transmission line. Results of test, giving space distribution of current and e.m.f. both as to magnitude and phase. Results in tabular and curve form. *Appendix*—Method of measuring line impedance.

Discussion, pages 1164-1165, by Messrs. Charles P. Steinmetz, John Price Jackson, Charles F. Scott, John B. Taylor and A. E. Kennelly. Praise of experimental investigation.

SIMPLIFICATION OF ELECTROTHERMAL CALCULATIONS, THE WATT AND THERMAL OHM

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Discussion, pages 1202-1205, by Messrs. H. B. Gale, Carl Hering, Alfred H. Cowles. Definitions of factors of heat energy.

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Frank Wenner **Vol. xxxi—1912, pp. 1243-1254**

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Carl Hering **Vol. xxxi—1912, pp. 1449-1463**

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A TUBULAR ELECTRODYNAMOMETER FOR HEAVY CURRENTS

P. G. Agnew **Vol. xxxi—1912, pp. 1483-1488**

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MEASUREMENT OF ALTERNATING CURRENT OF LOW VALUE

M. G. Newman **Vol. xxxi—1912, pp. 1489-1499**

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TO MEASURE AN ALTERNATING-CURRENT RESISTANCE AND COMPARE IT WITH THE DIRECT-CURRENT RESISTANCE—ELECTRO-DYNAMOMETER METHOD

Edwin F. Northrup **Vol. xxxi—1912, pp. 1501-1510**

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ELECTRICAL MEASUREMENTS WITH SPECIAL REFERENCE TO LAMP TESTING

Evan J. Edwards **Vol. xxxi—1912, pp. 1517-1523**

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INCANDESCENT LAMPS AS RESISTANCES

T. H. Amrine **Vol. xxxi—1912, pp. 1525-1531**

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F. V. Magalhaes **Vol. xxxi—1912, pp. 1541-1544**

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Alexander Maxwell **Vol. xxxi—1912, pp 1545-1550**

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Paul MacGahan **Vol. xxxi—1912, pp. 1565-1577**

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Discussion incorporated with that of paper by W. H. Pratt and D. R. Price on "Resonant Circuit Frequency Indicator."

COMPENSATING WATTMETERS

A. L. Ellis **Vol. xxxi—1912, pp. 1579-1590**

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Discussion incorporated with that of paper by W. H. Pratt and D. R. Price on "Resonant Circuit Frequency Indicator."

HOT-WIRE INSTRUMENTS

A. W. Pierce and M. E. Tressler **Vol. xxxi—1912, pp. 1591-1593**

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RESONANT CIRCUIT FREQUENCY INDICATOR

W. H. Pratt and D. R. Price **Vol. xxxi—1912, pp. 1595-1598**

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L. T. Robinson and J. D. Ball **Vol. xxxi—1912, pp. 1609-1615**

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MEASUREMENTS OF MAXIMUM VALUES IN HIGH-VOLTAGE TESTING

C. H. Sharp and F. M. Farmer **Vol. xxxi—1912, pp. 1617-1622**

Use of electrostatic voltmeter with synchronous reversing commutator across one section of a series of condensers. Introduction of the term "peak-factor."

Discussion, including that of paper by L. T. Robinson and J. D. Ball on "Permeability Measurements with Alternating Current," pages 1623-1626, by Messrs. E. D. Doyle, M. G. Lloyd, Clayton H. Sharp, T. W. Varley, L. T. Robinson and Elihu Thomson. Leakage loss with electrostatic voltmeter. Limitations in the use of alternating current for permeability measurements. Comments on "peak-factor."

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J. R. Craighead **Vol. xxxi—1912, pp. 1627-1633**

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THE TESTING OF INSTRUMENT TRANSFORMERS

P. G. Agnew and F. B. Silsbee **Vol. xxxi—1912, pp. 1635-1638**

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E. M. Olin **Vol. xxxi—1912, pp. 1695-1718**

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HIGH-FREQUENCY TESTS OF LINE INSULATORS

L. E. Imlay and Percy H. Thomas **Vol. xxxi—1912, pp. 2121-2142**

Account of method of testing line insulators with high-frequency, high potential e.m.f. to determine their behavior under lighting stresses. Discussion of the design of insulators for lighting stresses. Comparative test on electrose and porcelain. Suggested outline for future investigation along the same line.

Discussion, incorporated with that of paper by P. W. Sothman on "Comparative Tests of High-Tension Suspension Insulators."

COMPARATIVE TESTS ON HIGH-TENSION SUSPENSION INSULATORS

P. W. Sothman **Vol. xxxi—1912, pp. 2143-2168**

Account of experimental study of various types of line insulators to determine the specifications to be adopted by the Ontario Power Company in equipping a 110,000-volt line. Description of tests and summary of results.

Discussion including that of paper by L. E. Imlay and Percy H. Thomas on "High-Frequency Tests of Line Insulators." pages 2169-2226, by Ralph D. Mershon, Paul M. Lincoln, F. W. Peek, Jr., A. O. Austin, F. M. Farmer, Ralph W. Pope, E. E. F. Creighton, H. Winfield Secor, E. S. Lincoln, Ford W. Harris, Charles Rufus Harte, Edward Bennett, F. F. Brand, Max H. Collbohm, P. W. Sothman, L. E. Imlay, P. H. Thomas and R. F. Hayward. Analysis of e.m.f. distribution and string ratio in strings of suspension insulators. Effect of high-frequency stresses on insulators. Nature of high-frequency stresses. Points to be observed in testing insulators and outline of standard specification for tests. Properties of glass insulators for very high-tension work.

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F. W. Peek, Jr. **Vol. xxxi—1912, pp. 907-930**

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C. Francis Harding **Vol. xxxi—1912, pp. 1035-1050**

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THE LAW OF CORONA AND THE DIELECTRIC STRENGTH OF AIR

F. W. Peek, Jr. **Vol. xxxi—1912, pp. 1051-1092**

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Discussion incorporated with that of paper by J. B. Whitehead on "The Electric Strength of Air."

THE ELECTRIC STRENGTH OF AIR

J. B. Whitehead **Vol. xxxi—1912, pp. 1093-1118**

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MEASUREMENTS OF MAXIMUM VALUES IN HIGH-VOLTAGE TESTING

C. H. Sharp and F. M. Farmer **Vol. xxxi—1912, pp. 1617-1622**

Use of electrostatic voltmeter with synchronous reversing commutator across one section of a series of condensers. Introduction of the term "peak-factor."

Discussion, including that of paper by L. T. Robinson and J. D. Ball on " Permeability Measurements with Alternating Current," pages 1625-1626, by Messrs. E. D. Doyle, M. G. Lloyd, Clayton H. Sharp, T. W. Varley, L. T. Robinson and Elihu Thomson. Leakage loss with electrostatic voltmeter. Limitations in the use of alternating current for permeability measurements. Comments on "peak-factor."

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L. E. Imlay and Percy H. Thomas **Vol. xxxi—1912, pp. 2121-2142**

Account of method of testing line insulators with high-frequency, high potential e.m.f. to determine their behavior under lightning stresses. Discussion of the design of insulators for lightning stresses. Comparative test on electrose and porcelain. Suggested outline for future investigation along the same line.

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P. W. Sothman **Vol. xxxi—1912, pp. 2143-2168**

Account of experimental study of various types of line insulators to determine the specifications to be adopted by the Ontario Power Company in equipping a 110,000-volt line. Description of tests and summary of results.

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5. ELECTRIC CONDUCTORS

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C. T. Mosman **Vol. xxxi—1912, pp. 755-781**

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Discussion, pp. 782-809, by Messrs. A. E. Kennelly, L. L. Elden, William L. Puffer, William Clark, E. N. Lake, G. A. Burnham, David Harrington, George W. Palmer, Jr., Philip Torchio, C. T. Mosman, and R. W. Atkinson. Generalization of author's results. Results of other tests on the heating and carrying capacity of underground cables. Practice of various central stations in underground cable operation. Ventilation of conduits. Observed sheath currents, e.m.fs. and losses. Calculation of induced current and e.m.f. in lead sheath of single conductor cables.

LOCALIZERS, SUPPRESSORS, AND EXPERIMENTS

E. E. F. Creighton and J. T. Whittlesey **Vol. xxxi—1912, pp. 1881-1910**

Experimental study of effect of grounding upon e. m. fs. in three phase system. followed by oscillographic tests made to determine the applicability of localizers and arcing ground surpressors to the distribution systems of the Public Service Electric Company of New Jersey. Detailed discussion of oscillograms of current and e.m.f. in the system under various grounding conditions. Charts of insulation resistance of system of underground and overhead conductors under various weather conditions.

Discussion, incorporated with that of paper by L. L. Elden on " Relay Protective Systems."

6. MAGNETIC PROPERTIES AND TESTING OF IRON

PERMEABILITY MEASUREMENTS WITH ALTERNATING CURRENT

L. T. Robinson and J. D. Ball **Vol. xxxi—1912, pp. 1609-1616**

Study of general relations between maximum flux density, maximum exciting current and magnetizing current.

Discussion incorporated with that of paper by C. H. Sharp and F. M. Farmer on " Measurements of Maximum Values in High-Voltage Testing."

MEASUREMENTS OF MAXIMUM VALUES IN HIGH-VOLTAGE TESTING

C. H. Sharp and F. M. Farmer **Vol. xxxi—1912, pp. 1617-1622**

Use of electrostatic voltmeter with synchronous reversing commutator across one section of a series of condensers. Introduction of the term " peak-factor."

Discussion, including that of paper by L. T. Robinson and J. D. Ball on " Permeability Measurements with Alternating Current," pages 1623-1626, by Messrs. E. D. Doyle, M. G. Lloyd, Clayton H. Sharp, T. W. Varley, L. T. Robinson and Elihu Thomson. Leakage loss with electrostatic voltmeter. Limitations in the use of alternating current for permeability measurements. Comments on " peak-factor."

THE EFFECT OF TEMPERATURE UPON THE HYSTERESIS LOSS IN SHEET STEEL

Malcolm MacLaren **Vol. xxxi—1912, pp. 2025-2035**

Experimental investigation of the rate of heating upon hysteresis losses and permeability of iron. Hysteresis loops obtained at non-magnetic temperature.

Discussion, pp. 2036-2049 by Messrs. Philip Torchio, L. W. Chubb, C. A. Adams, David B. Rushmore, W. M. McConahey; Charles F. Scott, H. M. Hobart, M. V. Ayres, W. S. Moody, Ralph D. Mershon, Malcolm MacLaren, W. L. Waters, and M. G. Lloyd. Construction and electrical constants for external reactance built for 20,000-kw. generator of New York Edison Company. Relation between relative mechanical strength under short circuit and the size of a transformer. Disadvantages of transformers and alternators designed to have high reactance. References and results from investigations made by various experimentors on iron and other magnetic materials at extremely high and low temperatures.

7. BATTERIES

ELECTRICITY ON THE FARM

Putnam A. Bates **Vol. xxxi—1912, pp. 1985-2003**

Review of the present state of the art of applying electricity in agricultural undertakings. Specific data from irrigated farms, stock farms and others, covering central station and isolated plant practise. Power requirements of such enterprises and rates changed by central stations, use of storage batteries.

Discussion, pp. 2004-2013 by Messrs. J. D. Merrifield, L. L. Elden, Putnam A. Bates, J. A. Moyer, Sanford, and Adolph Shane.

8. TRANSFORMERS

SOME FEATURES OF THE OUTDOOR ELECTRICAL INSTALLATION

F. C. Green **Vol. xxxi—1912, pp. 323-327**

Brief description of the requirements of apparatus for outdoor substations. List of transformers now in operation. Data on moisture contained in air, effect of heat on insulation strength of oil, etc.

No discussion.

MEASUREMENT OF ENERGY WITH INSTRUMENT TRANSFORMERS

Alexander Maxwell **Vol. xxxi—1912, pp. 1545-1550**

Effect of ratio and phase angle upon the accuracy of watt-hour meters under various load conditions.

Discussion incorporated with that of paper by C. H. Ingalls on " Wheatstone Bridge-Rotating Standard Method of Testing Large Capacity Watt-hour Meters.

POTENTIAL TRANSFORMER TESTING

J. R. Craighead **Vol. xxxi—1912, pp. 1627-1633**

Analysis of errors resulting from resistance of the detector circuit when making ratio and phase angle test by the balance method.

Discussion incorporated with that of paper by P. G. Agnew and F. B. Silsbee on " The Testing of Instrument Transformers."

THE TESTING OF INSTRUMENT TRANSFORMERS

P. G. Agnew and F. B. Silsbee **Vol. xxxi—1912, pp. 1635-1638**

Bureau of Standards modification of potentiometer or balance method of testing shunt and series instrument transformers.

Discussion including that of paper by J. R. Craighead on " Potential Transformer Testing," pages 1639-1644. Relative merits of vibration galvanometer and reversing key as detector in balance method of testing instrument transformers.

THE USE OF REACTANCE IN TRANSFORMERS

W. S. Moody **Vol. xxxi—1912, pp. 2015-2023**

Analytical discussion of transformer design with reference to the production of high internal reactance. Description of magnetic shunt method of transformer construction. Effect of high internal reactance on mechanical stresses.

Discussion, incorporated with that of paper by Malcolm MacLaren on " The Effect of Temperature Upon the Hysteresis Loss in Sheet Steel."

9. ELECTRIC MACHINERY AND APPARATUS

OPERATION OF TWO ALTERNATING-CURRENT STATIONS THROUGH PARALLEL CIRCUITS, AND THE DISTRIBUTION OF LOAD AND WATTLESS CURRENTS BETWEEN THEM

J. W. Welsh **Vol. xxxi—1912, pp. 449-457**

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AIR GAP FLUX DISTRIBUTION IN DIRECT-CURRENT MACHINES

Charles R. Moore **Vol. xxxi—1912, pp. 509-525**

Account of experiments made on a d. c. machine to develop an accurate and rational method of calculating a full-load flux distribution from design data. Description of test apparatus and methods. Discussion of results. Development of method of calculating permeance, m.m.f. and flux for both full and no load conditions.

Discussion, pp. 526-528 by H. Weichsel. Effect of armature flux on flux distribution.

SELF-STARTING SYNCHRONOUS MOTORS

Carl J. Fechheimer **Vol. xxxi—1912, pp. 529-585**

Analytical and experimental study of the starting characteristics of synchronous motors with revolving field structure. Discussion of effects of various factors upon the starting characteristics at standstill and during acceleration. Results of tests plotted as curves to determine the quantitative effect of various operating and design factors upon the starting and accelerating characteristics. Starting characteristics of various types of load, such as fans, centrifugal pumps, motor-generator sets, etc. Mathematical predetermination of the starting characteristics of synchronous motors. Appendix giving mathematical development of formulas.

Discussion, pp. 586-604, by Messrs. R. B. Williamson, F. D. Newbury, H. M. Gassman, A. M. Dudley, W. J. Foster, B. G. Lamme, Francis B. Crocker, C. P. Steinmetz, Bradley T. McCormick and C. J. Fechheimer.

General remarks on design of synchronous motors for favorable starting characteristics. Explanation of half-speed running of synchronous motors.

DIRECT-CURRENT AND ALTERNATING-CURRENT MILL MOTORS FOR AUXILIARY DRIVES

Brent Wiley **Vol. xxxi—1912, pp. 605-618**

Analytical discussion of the design requirements of d. c. and a. c. motors for steel mill service. Characteristics of series and compound d. c. motors and induction motors with wound secondary.

Discussion, pp. 619-626, by Messrs. Alexander C. Lanier, M. A. Whiting, R. B. Treat, Gano Dunn, F. R. Fishback, A. G. Ahrens and Brent Wiley. General remarks on choice of motor for steel mill auxiliaries; a. c. vs. d. c. motors. Method of rating motors for intermittent service.

ELECTRIC BRAKING OF INDUCTION MOTORS

H. C. Specht **Vol. xxxi—1912, pp. 627-640**

Theoretical, mathematical analysis of induction motor performance with a. c. and d. c. braking. Development of equations for design of such systems.

Discussion, pp. 641-643, by Messrs. H. E. White, H. F. Stratton, Gano Dunn, John C. Reed, Clark S. Lankton and H. C. Specht. Advantages of electric braking of d. c. motors.

ELECTRIFICATION OF A REVERSING MILL OF THE ALGOMA STEEL COMPANY

Bradley T. McCormick **Vol. xxxi—1912, pp. 645-652**

Description of flywheel motor-generator set and equipment for reversing mill plant giving general design data for the generators, motors, controllers, etc.

Discussion, pp. 653-658, by Messrs. David Hall, B. T. McCormick, Wilfred Sykes, R. A. Black, H. C. Specht, R. B. Treat and H. W. Cheney. Effect upon inertia of dividing units. European practice in rolling mill drives. Time required to reverse Algoma mill, test.

THE OPERATION OF A LARGE ELECTRICALLY DRIVEN REVERSING ROLLING MILL

Wilfred Sykes **Vol. xxxi—1912, pp. 659-681**

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Discussion, pp. 682-684, by Messrs. R. A. Black, H. C. Specht, R. Tschentscher, James Farrington, Bradley T. McCormick and E. Friedlaender. Relative economy of two-high and three-high rolling mills.

ELECTRICAL CONTROL OF A LARGE MINE HOIST

H. W. Cheney **Vol. xxxi—1912, pp. 685-699**

General description of induction motor hoist in No. 5 mine of the Woodward Iron Company, Birmingham, Alabama. Detailed description of design and performance of water rheostat. Experimental data for rational design of water rheostats.

Discussion, pp. 700-708, by H. M. Gassman, W. O. Oschmann, H. E White, Wilfred Sykes, F. L. Stone, E. Friedlaender, H. W. Cheney and M. A. Whiting. Data on the design of water rheostats; general remarks and experience in their operation.

FREQUENCY

D. B. Rushmore **Vol. xxxi—1912, pp. 955-972**

Comprehensive review of the quantitative relations between frequency and the operative characteristics of electrical apparatus and distribution circuits showing the difficulty of fixing a universal standard frequency for commercial circuits. The effect of frequencies upon the design and operation of electrical systems as to cost and satisfactory service. Table of frequencies used in various typical systems covering central stations, railways and many industrial plants.

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THE TRANSIENT REACTIONS OF ALTERNATORS

William A. Durgin and R. H. Whitehead **Vol. xxxi—1912, pp. 1657-1680**

Demonstration of the existence of transient impedance in alternators and experimental study of its effect upon the performance of large turbo-generators under short-circuit conditions, alone and connected in parallel with others to a distribution system; also its influence upon cross currents in paralleling such generators. Tests showing the effects of external reactance and resistance on short-circuit currents and resulting torques. Results plotted as curves.

Discussion, including that of paper by A. B. Field on "Operating Characteristics of Large Turbo-Generators," pp. 1681-1693, by Messrs. H. M. Hobart, B. G. Lamme, P. M. Lincoln, Henry G. Reist, Comfort A. Adams, A. B. Field, Sanford A. Moss, H. R. Woodrow, W. L. Walters, and William A. Durgin. Relative advantages of external and self-contained blowers for cooling of turbo-alternators. Desirability of cleaning air for cooling purposes. Use of dampers to prevent potential rise in the field circuit caused by short circuits. Value of maximum torques under short circuits. Value of external resistance in protecting turbo-alternators.

DETERMINATION OF POWER EFFICIENCY OF ROTATING ELECTRIC MACHINES

E. M. Olin **Vol. xxxi—1912, pp. 1695-1718**

Detailed analysis of the summation-of-losses method as applied to the various types of rotary electric machinery. Methods of determining the various losses and tabulated results of numerous tests on all classes of machines discussed. Correction factors for load losses that can not be separated are tabulated for different types of machines operating at different loads. Disadvantages of input-out-put method and actual comparison of this method with summation-of-losses method.

Discussion pp. 1719-1720, by C. M. Green, B. G. Lamme and E. M. Olin.

THE SQUIRREL-CAGE INDUCTION GENERATOR

H. M. Hobart and E. Knowlton **Vol. xxxi—1912, pp. 1721-1747**

Analytical discussion of the design of induction generators for operation at very high speeds and in large units. Some results of studies made on induction generators in the Interborough Rapid Transit Power House. Comparison of the design, operation and economic features of synchronous and induction generators.

Discussion, incorporated with that of paper by P. M. Lincoln on " Motor Starting Currents as Affecting Large Transmission Systems."

SINGLE-PHASE INDUCTION MOTORS

W. J. Branson **Vol. xxxi—1912, pp. 1749-1787**

Development of complete vector analysis of single-phase induction motors applicable even to the smallest commercial sizes. Method compared with actual tests. Formulas for secondary no-load current as reflected in the primary, for the construction of the current circle and for the speed of single-phase induction motors developed from the transformer theory.

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MOTOR STARTING CURRENTS AS AFFECTING LARGE TRANSMISSION SYSTEMS

P. M. Lincoln **Vol. xxxi—1912, pp. 1789-1800**

Reason for limiting the size of motors connected to a given system. Account of extensive investigation of starting conditions found in a certain system where a number of cotton mills are connected to a transmission net work. Recording wattmeter records on mills and transmission line. Starting data on different types and sizes of induction motors.

Discussion, including that of paper by H. M. Hobart and E. Knowlton on " The Squirrel Cage Induction Generator " and W. J. Branson on " Single-Phase Induction Motors," pp. 1801-1810, by Lee Hagood, Comfort A. Adams, E. F. W. Alexanderson, Lester McKenney, H. M. Hobart, E. Knowlton and W. L. Waters. Use of synchronous condenser in connection with a system fed by induction generators and synchronous generators, operating in parallel. General remarks on calculation of core losses and eddy currents in induction generators.

DEVELOPMENT OF A SUCCESSFUL DIRECT-CURRENT 2000-KW. UNIPOLAR GENERATOR

B. G. Lamme **Vol. xxxi—1912, pp. 1811-1835**

Account of the experiences obtained and difficulties overcome in the practical development of a large unipolar machine. Description of original construction and subsequent modifications giving reasons therefore. Overcoming of troubles incident to current collection, ventilation and insulation with very high speed operation in an extremely dirty atmosphere.

Discussion, pp. 1836-1840 by Messrs. J. E. Noeggerath, Elihu Thomson, and W. L. Waters. Comparison of another solution of a similar problem with that described in the paper. Very early experience in the design of unipolar machines.

EXCITATION OF ALTERNATING-CURRENT GENERATORS

D. B. Rushmore **Vol. xxxi—1911, pp. 1841-1876**

Excitation requirements of alternators and characteristics of various types of exciters. Brief description of different methods of alternator excitation and voltage regulation. Circuit diagrams and principles of operation of various types of voltage regulators, including the booster system, and systems developed by Tirrill, Thury and Chapman. Choice of exciter arrangements together with collection of circuit diagrams, showing typical arrangements used in modern practice.

Discussion, pp. 1877-1880 by Messrs. B. G. Lamme, H. M. Hobart, J. Lester Woodbridge, E. A. Lof, and Lester McKenney. General remarks on the choice of excitation system.

THE ECONOMICAL SPEED CONTROL OF ALTERNATING-CURRENT MOTORS DRIVING ROLLING MILLS

F. W. Meyer and Wilfred Sykes **Vol. xxxi—1912, pp. 2067-2095**

Classification of speed requirements of rolling mills followed by analytical discussion of various methods of induction motor control including rheostatic, multi-winding, cascade and regulating machines of various types with special reference to the last named. Late developments in the use of frequency changers as regulating machines, three-phase commutator motors for direct drive.

Discussion, including that of paper by Wilfred Sykes on " Power Requirements of Rolling Mills "pp. 2096-2120 by Messrs. John M. Hipple, J. H. Wilson, Selby Haar, Edward J. Cheney, Bayse N. Westcott, David M. Petty, Fred Bickford Crosby, L. T. Robinson, H. L. Barnholdt, G. E. Stoltz, Wilfred Sykes and Ford W. Harris. General remarks and experience in the choice of motor equipments for rolling mill drives. Method of testing steam driven mills relative merits of different methods of speed control. Notes on recording instruments for tests.

10. PRIME MOVERS AND STEAM BOILERS

PLANT EFFICIENCY

An Analysis of the Losses of a Hydroelectric System.

J. D. Ross **Vol. xxxi—1912, pp. 471-484**

Description of plant and analytical discussion of the losses in the generating and distributing system of the Seattle Municipal Light and Power Company. Efficiency-load characteristics and losses of different elements of the hydraulic and electric systems. Tables and curves.

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OPERATING CHARACTERISTICS OF LARGE TURBO-GENERATORS

A. B. Field **Vol. xxxi—1912, pp. 1645-1656**

Trend of modern practice in the choice of size, speed, ventilation and regulation of large turbo-generators. Benefits derived from allowing poorer regulation.

Discussion, incorporated with that of paper by William A. Durgin and R. H. Whitehead on " The Transient Reactions of Alternators."

THE RUNAWAY SPEED OF WATERWHEELS AND ITS EFFECT ON CONNECTED ROTARY MACHINERY

Daniel W. Mead **Vol. xxxi—1912, pp. 1937-1968**

Elementary principles for turbine governing followed by brief review of the hydraulics of impulse and reaction wheels with special reference to the determination of the runaway speed. Practical example of calculation. Fundamental data given for various commercial types of impulse and reaction wheels.

No discussion.

11. POWER PLANTS

SOME NOTES ON ISOLATED PLANTS

Percival R. Moses **Vol. xxxi—1912, pp. 15-45**

Brief analytical discussion of the interdependence of the various factors in the design of isolated plants for the production and utilization of energy for heating, lighting, refrigeration, driving machinery, etc., Actual load requirements in different types of plants, together with costs, equipment used, log sheets and load curves. Cost of electric energy production in different types of isolated plants.

Discussion, pp. 46-68, by Messrs. R. P. Bolton, John C. Parker, Arthur Williams, George W. Martin, Charles K. Nichols, John W. Lieb, Jr., S. N. Clarkson and Clarence P. Fowler. Criticism and defense of author's figures and methods of analysis.

CENTRAL STATION ELECTRIC POWER FOR RAILROAD OPERATION

Frederick Darlington **Vol. xxxi—1912, pp. 69-79**

Advantages of electric energy over steam in railway operation. Reasons for purchasing electric energy from central stations. Gain in economy due to larged mixed loads.

Discussion, incorporated with paper by George I. Rhodes on " A Method of Studying Power Costs with Reference to the Load Curve and Overload Economies."

A METHOD OF STUDYING POWER COSTS WITH REFERENCE TO THE LOAD CURVE AND OVERLOAD ECONOMIES

George I. Rhodes **Vol. xxxi—1912, pp. 81-100**

Mathematical analysis of the cost of producing electric energy, based on assumption of certain relations between load and losses in steam-electric plants. Effect of load-factor and overload capacity on cost of energy production. Relation between first cost and operating charges on overload.

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THE RELATIVE COSTS AND OPERATING EFFICIENCIES OF POLYPHASE AND SINGLE-PHASE GENERATING AND TRANSMITTING SYSTEMS

H. M. Hobart **Vol. xxxi—1912, pp. 115-147**

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THE RELATION OF CENTRAL STATION GENERATION TO RAILWAY ELECTRIFICATION

Samuel Insull **Vol. xxxi—1912, pp. 231-282**

Comprehensive analytical discussion of the advantages and savings to be derived by combining all electrical power plants in Greater New York into one unified system. Results attained by unification in Chicago compared with group systems in New York and Boston. Load curves and characteristics of different classes of service in New York, Boston and Chicago. Much well-digested, statistical information on industrial power, lighting and railway service. Appendix on power requirements of Chicago electrified steam roads showing saving of unified energy supply system over independent group system.

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OPERATION OF TWO ALTERNATING-CURRENT STATIONS THROUGH PARALLEL CIRCUITS, AND THE DISTRIBUTION OF LOAD AND WATTLESS CURRENTS BETWEEN THEM

J. W. Welsh **Vol. xxxi—1912, pp. 449-467**

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DOES IT PAY THE AVERAGE COAL MINE TO PURCHASE CENTRAL STATION POWER

Graham Bright **Vol. xxxi—1912, pp. 737-747**

Detailed analysis of the cost of producing electric energy at the coal mine and cost of changing over for central station service for requirements of coal mines. Cost data from actual practice in coal mine power plants.

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FREQUENCY

D. B. Rushmore **Vol. xxxi—1912, pp. 955-972**

Comprehensive review of the quantitative relations between frequency and the operative characteristics of electrical apparatus and distribution circuits showing the difficulty of fixing a universal standard frequency for commercial circuits. The effect of frequencies upon the design and operation of electrical systems as to cost and satisfactory service. Table of frequencies used in various typical systems covering central stations, railways and many industrial plants.

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12. PARALLEL OPERATION

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William A. Durgin and R. H. Whitehead **Vol. xxxi—1912, pp. 1657-1680**

Demonstration of the existence of transient impedance in alternators and experimental study of its effect upon the performance of large turbo-generators under short-circuit conditions, alone and connected in parallel with others to a distribution system, also its influence upon cross currents in paralleling such generators. Tests showing the effect of external reactance and resistance on short-circuit currents and resulting torques. Results plotted as curves.

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13. TRANSMISSION LINES

SOME PROBLEMS OF HIGH-VOLTAGE TRANSMISSIONS

Charles P. Steinmetz **Vol. xxxi—1912, pp. 167-173**

Brief description of the factors most prominent in limiting extremely high-voltage transmissions, insulators, capacity, corona, transformer capacity; transformer connections, etc.

Discussion, incorporated with that of E. M. Hewlett on " Characteristics of Protective Relays."

CHARACTERISTICS OF PROTECTIVE RELAYS

E. M. Hewlett **Vol. xxxi—1912, pp. 175-184**

General advice concerning selection of relay characteristics for protection of various apparatus assembled in different types of distribution systems.

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DESIGN OF TELEPHONE POLE LINES FOR CONDITIONS WEST OF THE ROCKY MOUNTAINS

A. H. Griswold **Vol. xxxi—1912, pp. 427-443**

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OPERATION OF TWO ALTERNATING-CURRENT STATIONS THROUGH PARALLEL CIRCUITS, AND THE DISTRIBUTION OF LOAD AND WATTLESS CURRENTS BETWEEN THEM

J. W. Welsh **Vol. xxxi—1912, pp. 449-457**

General analytical discussion of parallel operation of alternators and alternating-current stations. Division of load and current under various conditions of connecting circuits and of speed and voltage adjustment. Vector diagrams illustrating effect of different conditions upon magnitude and phase of currents and e.m.fs.

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PRACTICAL JOINT POLE CONSTRUCTION

J. E. Macdonald **Vol. xxxi—1912, pp. 491-500**

Description of the Los Angeles system of joint pole construction and operation. Outline of joint agreement between operating companies. Illustrations of different types of contruction.

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PROPAGATION OF IMPULSES OVER TRANSMISSION LINE

J. H. Cunningham and C. M. Davis **Vol. xxxi—1912, pp. 887-896**

Description and analysis of tests on artificial transmission line to determine the e.m.f. and current impulses traveling along the line when switching under various conditions.

Discussion incorporated with that of paper by F. W. Peek,Jr., on "Electrical Characteristics of the Suspension Insulator."

SOME MECHANICAL CONSIDERATIONS OF TRANSMISSION SYSTEMS

T. A. Worcester **Vol. xxxi—1912, pp. 897-906**

Analysis of factors that cause mechanical stresses in transmission towers bringing out the economical advantages of the flexible tower. Cost of transmission tower line construction.

Discussion incorporated with that of paper by F. W. Peek, Jr., on "Electrical Characteristics of the Suspension Insulator."

ELECTRICAL CHARACTERISTICS OF THE SUSPENSION INSULATOR

F. W. Peek, Jr. **Vol. xxxi—1912, pp. 907-930**

Experimental investigation of the operative characteristics of suspension insulators connected in series. Development of equations for calculations of the arc-over e.m.f. The string efficiency, the e.m.f. distribution and the capacity of strings of suspension insulators of various types. Comparison of theoretical results with actual tests.

Discussion, including that of papers by Messrs. E. E. F. Creighton and F. R. Shavor on " Compression Chamber Lightning Arrester and the Protection of Distribution Circuits;" E. E. F. Creighton, H. E. Nichols and P. E. Hosegood on " Human Accuracy: Multi-Recorder for Lightning Phenomena and Switching," E. E. F. Creighton, F. R. Shavor and R. P. Clark on " Studies of Protection and Protective Apparatus for Electric Railways " and J. H. Cunningham and C. M. Davis on " Propagation of Impulses over Transmission Line " and T. A. Worcester on " Some Mechanical Considerations of Transmission Systems," pages 931-954, by Messrs. E. M. Hewlett, Paul M. Lincoln, R. J. McClelland, C. Edward Magnusson, Andrew McNaughton, Harris J. Ryan, R. P. Jackson, Charles P. Steinmetz, Charles F. Scott, R. Philip Clark, Cassius M. Davis, T. A. Worcester, and F. W. Peek, Jr. Method of calculating the e.m.f. distribution in a string of suspension insulators. Comparison of test data with results calculated by the Peek formulas. Effect of ground wire on strength of transmission structure. Inherent self-protective characteristics of a.c. railway circuits. Care of aluminum d.c. arrester.

CORONA LOSSES BETWEEN WIRES AT HIGH VOLTAGES

C. Francis Harding **Vol. xxxi—1912, pp. 1035-1050**

Account of experimental investigation on a transmission line at Purdue University. Comparison of experimental results with formulas of various investigators. Results plotted as curves.

Discussion, incorporated with that of paper by J. B. Whitehead on ' The Electric Strength of Air."

THE LAW OF CORONA AND THE DIELECTRIC STRENGTH OF AIR

F. W. Peek, Jr. **Vol. xxxi—1912, pp. 1051-1092**

Summary of equations and laws of corona covering previous and present investigations. Tests of effects, of temperature, frequency, spacing, wire diameter, water, oil, etc. upon corona phenomena. Also tests and calculations of disruptive energy of air. Relation between power loss and surface gradient. Stroboscopic examination of corona. Mechanical vibration of electrified lines.

Discussion incorporated with that of paper by J. B. Whitehead on " The Electric Strength of Air."

THE ELECTRIC STRENGTH OF AIR

J. B. Whitehead **Vol. xxxi—1912, pp. 1093-1118**

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Discussion, including that of papers by C. Francis Harding on " Corona Losses Between Wires at High Voltages " and F. W. Peek, Jr. on " The Law of Corona and the Dielectric Strength of Air," pp. 1119-1130, by Messrs. John B. Taylor, A. E. Kennelly, C. P. Steinmetz, C. Francis Harding, F. W. Peek, Jr., J. B. Whitehead and A. S. Langsdorf. General remarks on corona. Comparison of tests on actual line with calculated results for corona loss and critical gradient. Observed vibration or swinging of high-tension lines.

MEASUREMENTS OF VOLTAGE AND CURRENT OVER A LONG ARTIFICIAL POWER-TRANSMISSION LINE AT 25 AND 60 CYCLES PER SECOND

A. E. Kennelly and F. W. Lieberknecht **Vol. xxxi—1912, pp. 1131-1163**

Design and construction of an artificial transmission line. Methods of measuring e.m.f. and current distribution in artificial equivalent of very long transmission line. Results of test, giving space distribution of current and e.m.f. both as to magnitude and phase. Results in tabular and curve form. *Appendix*—Method of measuring line impedance.

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MOTOR STARTING CURRENTS AS AFFECTING LARGE TRANSMISSION SYSTEMS

P. M. Lincoln **Vol. xxxi—1912, pp. 1789-1800**

Reason for limiting the size of motors connected to a given system. Account of extensive investigation of starting conditions found in a certain system where a number of cotton mills are connected to a transmission net work. Recording wattmeter records on mills and transmission line. Starting data on different types and sizes of induction motors.

Discussion, including that of paper by H. M. Hobart and E. Knowlton on " The Squirrel-Cage Induction Generator " and W. J. Branson on " Single-Phase Induction Motors," pages 1801-1810 by Lee Hagood, Comfort A. Adams, E. F. W. Alexanderson, Lester McKenney, H. M.

Hobart, E. Knowlton and W. L. Waters. Use of synchronous condenser in connection with a system fed by induction generators and synchronous generators, operating in parallel. General remarks on calculation of core losses and eddy currents in induction generators.

HIGH-FREQUENCY TESTS OF LINE INSULATORS

L. E. Imlay and Percy H. Thomas **Vol. xxxi—1912, pp. 2121-2142**

Account of method of testing line insulators with high-frequency, high-potential e.m.f. to determine their behavior under lightning stresses. Discussion of the design of insulators for lightning stresses. Comparative test on electrose and porcelain. Suggested outline for future investigations along the same line.

Discussion, incorporated with that of paper by P. W. Sothman on " Comparative Tests of High-Tension Suspension Insulators."

COMPARATIVE TESTS ON HIGH-TENSION SUSPENSION INSULATORS

P. W. Sothman **Vol. xxxi—1912, pp. 2143-2168**

Account of experimental study of various types of line insulators to determine the specifications to be adopted by the Ontario Power Company in equipping a 110,000-volt line. Description of tests and summary of results.

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14. ELECTRIC SERVICE, DISTURBANCES AND PROTECTION

CHARACTERISTICS OF PROTECTIVE RELAYS

E. M. Hewlett **Vol. xxxi—1912, pp. 175-184**

General advice concerning selection of relay characteristics for protection of various apparatus assembled in different types of distribution systems.

Discussion, pp. 185-202, by Messrs. David B. Rushmore, C. S. Ruffner, F. W. Peek, Jr., Percy H. Thomas, A. E. Kennelly, A. S. McAllister Farley Osgood, C. O. Mailloux, C. C. Badeau, Charles W. Stone, E. M. Hewlett, G. A. Burnham and E. A. Lof. General remarks on high-tension transmission problems. Advantages, disadvantages and requirements of protective relays for use on large systems.

COMPRESSION CHAMBER LIGHTNING ARRESTER AND THE PROTECTION OF DISTRIBUTION CIRCUITS

E. E. F. Creighton and F. R. Shavor **Vol. xxxi—1912, pp. 811-824**

Description of the construction and operative characteristics of a low-priced lightning arrester for medium potential circuits. Tests made to determine the practical merits of this lightning arrester. Specifications for protection of pole transformers and directions for installation of lightning arresters for this purpose. Outline of actual method pursued in experimentally developing this type of arrester.

Discussion, incorporated with that of paper by F. W. Peek, Jr., on "Electrical Characteristics of the Suspension Insulator."

HUMAN ACCURACY: MULTI-RECORDER FOR LIGHTNING PHENOMENA AND SWITCHING

E. E. F. Creighton, H. E. Nichols and P. E. Hosegood **Vol. xxxi—1912, pp. 825-850**

Examples of unreliability of human impression when observer is under stress of excitement. Use of multi-recorder in diagnosing conditions which produce an accident. Description of the construction and operation, of several types of multi-recorders which are capable of recording the time of occurrence of any phenomenon that can be made to close an electrical contact.

Discussion incorporated with that of paper by F. W. Peek, Jr., on " Electrical Characteristics of the Suspension Insulator."

STUDIES OF PROTECTION AND PROTECTIVE APPARATUS FOR ELECTRIC RAILWAYS

E. E. F. Creighton, F. R. Shavor and R. P. Clark **Vol. xxxi—1912, pp. 851-886**

Experimental investigation of effects of high frequency on car wiring. Experience with the aluminum arrester in the protection of railway circuits. Additional devices used with d.c. aluminum arresters to increase their durability. Comprehensive study of magnetic blow-out type of arrester with oscillograph to determine the quantitative value of the various factors entering into the design of the gap and the circuit to which it is connected. Many oscillograms of current and e.m.f. in a metallic arc.

Discussion incorporated with that of paper by F. W. Peek, Jr., on " Electrical Characteristics of the Suspension Insulator."

PROPAGATION OF IMPULSES OVER TRANSMISSION LINE

J. H. Cunningham and C. M. Davis **Vol. xxxi—1912, pp. 887-896**

Description and analysis of tests on artificial transmission line to determine the e.m.f. and current impulses traveling along the line when switching under various conditions.

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ELECTRICAL CHARACTERISTICS OF THE SUSPENSION INSULATOR

F. W. Peek, Jr. **Vol. xxxi—1912, pp. 907-930**

Experimental investigation of the operative characteristics of suspension insulators connected in series. Development of equations for calculations of the arc-over e.m.f. The string efficiency, the e.m.f. distribution and the capacity of strings of suspension insulators of various types. Comparison of theoretical results with actual tests.

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THE TRANSIENT REACTIONS OF ALTERNATORS

William A. Durgin and R. H. Whitehead **Vol. xxxi—1912, pp. 1657-1680**

Demonstration of the existence of transient impedance in alternators and experimental study of its effect upon the performance of large turbo-generators under short-circuit conditions alone and connected in parallel with others to a distribution system, also, its influence upon cross currents in paralleling such generators. Tests showing the effect of external reactance and resistance on short-circuit currents and resulting torques. Results plotted as curves.

Discussion, including that of paper by A. B. Field on "Operating Characteristics of Large Turbo-Generators," pp. 1681-1693, by Messrs. H. M. Hobart, B. G. Lamme, P. M. Lincoln, Henry G. Reist, Comfort A. Adams, A. B. Field, Sanford A. Moss, H. R. Woodrow, W. L. Walters and William A. Durgin. Relative advantages of external and self-contained blowers for cooling of turbo-alternators. Desirability of cleaning air for cooling purposes. Use of dampers to prevent potential rises in the field circuit caused by short-circuits. Calculation of maximum torques under short-circuit. Value of external resistance in protecting turbo-alternators.

LOCALIZERS, SUPPRESSORS, AND EXPERIMENTS

E. E. F. Creighton and J. T. Whittlesey **Vol. xxxi—1912, pp. 1881-1910**

Experimental study of effect of grounding upon e.m.fs. in three-phase system, followed by oscillographic tests made to determine the applicability of localizers and arcing ground suppressors to the distribution systems of the Public Service Electric Company of New Jersey. Detailed discussion of oscillograms of current and e.m.f. in the system under various grounding conditions. Charts of insulation resistance of system of underground and overhead conductors under various weather conditions.

Discussion, incorporated with that of paper by L. L. Elden on "Relay Protective Systems."

RELAY PROTECTIVE SYSTEMS

L. L. Elden **Vol. xxxi—1912, pp. 1911-1931**

Review of present practice in the use of balanced protective relays, based on the Merz-Price (England) systems as applied to high-tension a.c. distribution system. Typical installation of the system also brief description of similar system by Höchstädter in Cologne and Faye-Hansen and Harlow in England.

Discussion, including that of paper by E. E. F. Creighton and J. T. Whittlesey on " Localizers, Suppressors, and Experiments," pp. 1932-1935 by Messrs. D. W. Roper, Harold Osborn, L. C. Nicholson, E E. F. Creighton, L. L. Elden and L. N. Crichton.

THE USE OF REACTANCE IN TRANSFORMERS

W. S. Moody **Vol. xxxi—1912, pp. 2015-2023**

Analytical discussion of transformer design with reference to the production of high internal reactance. Description of magnetic shunt method of transformer construction. Effect of high internal reactance on mechanical stresses.

Discussion, incorporated with that of paper by Malcolm MacLaren on " The Effect of Temperature Upon the Hysteresis Loss in Sheet Steel."

15. DISTRIBUTION SYSTEMS

SOME FEATURES OF THE OUTDOOR ELECTRICAL INSTALLATION

F. C. Green **Vol. xxxi—1912, pp. 323-327**

Brief description of the requirements of apparatus for outdoor substations. List of transformers now in operation. Data on moisture contained in air, effect of heat on insulation strength of oil, etc.

No discussion.

PRACTICAL JOINT POLE CONSTRUCTION

J. E. Macdonald **Vol. xxxi—1912, pp. 491-500**

Description of the Los Angeles system of joint pole construction and operation. Outline of joint agreement between operating companies. Illustrations of different types of construction.

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NOTES ON UNDERGROUND CONDUITS AND CABLES

C. T. Mosman **Vol. xxxi—1912, pp. 755-781**

Exhaustive experimental investigation of a certain underground conduit single-conductor alternating-current installation to determine the temperature distribution in the conduit ducts and cables under various conditions of ventilation and load. Results plotted in the form of curves.

Discussion, pp. 782-809, by Messrs. A. E. Kennelly, L. L. Elden, William L. Puffer, William Clark, E. N. Lake, G. A. Burnham, David

Harrington, George W. Palmer, Jr., Philip Torchio, C. T. Mosman, and R. W. Atkinson. Generalization of author's results. Results of other tests on the heating and carrying capacity of underground cables. Practice of various central stations in underground cable operation. Ventilation of conduits. Observed sheath currents, e.m.fs and losses. Calculation of induced current and e.m.f. in lead sheath of single-conductor cables.

FREQUENCY

D. B. Rushmore **Vol. xxxi—1912, pp. 955-972**

Comprehensive review of the quantitative relations between frequency and the operative characteristics of electrical apparatus and distribution circuits showing the difficulty of fixing a universal standard frequency for commercial circuits. The effect of frequencies upon the design and operation of electrical systems as to cost and satisfactory service. Table of frequencies used is various typical systems covering central stations, railways and many industrial plants.

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MOTOR STARTING CURRENTS AS AFFECTING LARGE TRANSMISSION SYSTEMS

P. M. Lincoln **Vol. xxxi—1912, pp. 1789-1800**

Reason for limiting the size of motors connected to a given system. Account of extensive investigation of starting conditions found in a certain system where a number of cotton mills are connected to a transmission net work. Recording wattmeter records on mills and transmission line. Starting data on different types and sizes of induction motors.

Discussion, including that of paper by H. M. Hobart and E. Knowlton on " The Squirrel-Cage Induction Generator " and W. J. Branson on " Single-Phase Induction Motors," pp. 1801-1810 by Lee Hagood, Comfort A. Adams, E. F. W. Alexanderson, Lester McKenney, H. M. Hobart, E. Knowlton and W. L. Waters. Use of synchronous condenser in connection with a system fed by induction generators and synchronous generators, operating in parallel. General remarks on calculation of core losses and eddy currents in induction generators.

16. CONTROL, REGULATION AND SWITCHING

ECONOMIES IN RAILWAY OPERATION

F. E. Wynne **Vol. xxxi—1912, pp. 203-229**

Analytical discussion of the effects produced by various factors involved in the reduction of dead weight and energy consumption. Selection of gear ratio and armature speed for given service. Relative merits of field control and standard series rheostat method, substantiated by tests.

No discussion.

SOME FEATURES OF THE OUTDOOR ELECTRICAL INSTALLATION

F. C. Green **Vol. xxxi—1912, pp. 623-627**

Brief description of the requirements of apparatus for outdoor substations. List of transformers now in operation. Data on moisture contained in air, effect of heat on insulation strength of oil, etc.

No discussion.

ELECTRIC BRAKING OF INDUCTION MOTORS

H. C. Specht **Vol. xxxi—1912, pp. 627-640**

Theoretical, mathematical analysis of induction motor performance with a.c. and d.c. braking. Development of equations for design of such systems.

Discussion, pp. 641-643, by Messrs. H. E. White, H. F. Stratton, Gano Dunn, John C. Reed, Clark S. Lankton and H. C. Specht. Advantages of electric braking of d.c. motors.

ELECTRIFICATION OF A REVERSING MILL OF THE ALGOMA STEEL COMPANY

Bradley T. McCormick **Vol. xxxi—1912, pp. 645-652**

Description of flywheel motor-generator set and equipment for reversing mill plant giving general design data for the generators, motors, controllers, etc.

Discussion, pp. 653-658, by Messrs. David Hall, B. T. McCormick, Wilfred Sykes, R. A. Black, H. C. Specht, R. B. Treat and H. W. Cheney. Effect upon inertia of dividing units. European practise in rolling mill drives. Time required to reverse Algoma mill, test.

THE OPERATION OF A LARGE ELECTRICALLY DRIVEN REVERSING ROLLING MILL

Wilfred Sykes **Vol. xxxi—1912, pp. 659-681**

General description of electrically driven universal mill of the Illinois Steel Company. Detailed description of the flywheel motor-generator plant and controlling equipment with design data, performance characteristics and test results. Power required to operate mill and load characteristics.

Discussion, pp. 682-684, by Messrs. R. A. Black, H. C. Specht. R. Tschentscher, James Farrington, Bradley T. McCormick and E. Friedlaender. Relative economy of two-high and three-high rolling mills.

ELECTRICAL CONTROL OF A LARGE MINE HOIST

H. W. Cheney **Vol. xxxi—1912, pp. 685-699**

General description of induction motor hoist in No. 3 mine of the Woodward Iron Company, Birmingham, Alabama. Detailed description of design and performance of water rheostat. Experimental data for rational design of water rheostats.

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HUMAN ACCURACY: MULTI-RECORDER FOR LIGHTNING PHENOMENA AND SWITCHING

E. E. F. Creighton, H. E. Nichols and P. S. Hoseegood **Vol. xxxi—1912, pp. 826-850**

Examples of unreliability of human impression when observer is under stress of excitement. Use of multi-recorder in diagnosing conditions which produce an accident. Description of the construction and operation of several types of multi-recorders which are capable of recording the time of occurrence of any phenomenon that can be made to close an electrical contact.

Discussion incorporated with that of paper by F. W. Peek, Jr. on "Electrical Characteristics of the Suspension Insulator."

PROPAGATION OF IMPULSES OVER TRANSMISSION LINE

J. H. Cunningham and C. M. Davis **Vol. xxxi—1912, pp. 857-896**

Description and analysis of tests on artificial transmission line to determine the e.m.f. and current impulses traveling along the line when switching under various conditions.

Discussion incorporated with that of paper by F. W. Peek, Jr. on "Electrical Characteristics of the Suspension Insulator."

EXCITATION OF ALTERNATING-CURRENT GENERATORS

D. B. Rushmore **Vol. xxxi—1912, pp. 1841-1876**

Excitation requirements of alternators and characteristics of various types of exciters. Brief description of different methods of alternator excitation and voltage regulation. Circuit diagrams and principles of operation of various types of voltage regulators, including the booster system and systems developed by Tirrill, Thury and Chapman. Choice of exciter arrangements together with collection of circuit diagrams. showing typical arrangements used in modern practise.

Discussion, pp. 1877-1880 by Messrs. B. G. Lamme, H. M. Hobart, J. Lester Woodbridge, E. A. Lof, and Lester McKenney. General remarks on the choice of excitation system.

THE RUNAWAY SPEED OF WATERWHEELS AND ITS EFFECT ON CONNECTED ROTARY MACHINERY

Daniel W. Mead **Vol. xxxi—1912, pp. 1937-1958**

Elementary principles for turbine governing followed by brief review of the hydraulics of impulse and reaction wheels with special reference. to the determination of the runaway speed. Practical example of calculation. Fundamental data given for various commercial types of impulse and reaction wheels.

No discussion.

THE ECONOMICAL SPEED CONTROL OF ALTERNATING-CURRENT MOTORS DRIVING ROLLING MILLS

F. W. Meyer and Wilfred Sykes **Vol. xxxi—1912, pp. 2067-2095**

Classification of speed requirements of rolling mills followed by analytical discussion of various methods of induction motor control including rheostatic, multi-winding, cascade, and regulating machines of various types, with special reference to the last named. Late developments in the use of frequency changers as regulating machines, three-phase commutator motors for direct drive.

Discussion, including that of paper by Wilfred Sykes on " Power Requirements of Rolling Mills," pp. 2096-2120 by Messrs. John M. Hipple, J. H. Wilson, Selby Haar, Edward J. Cheney, Bayse N. Westcott, David M. Petty, Fred Bickford Crosby, L. T. Robinson, H. L. Barnholdt, G. E. Stoltz, Wilfred Sykes and Ford W. Harris. General remarks and experience in the choice of motor equipments for rolling mill drives. Method of testing steam driven mills. Relative merits of different methods of speed control. Notes on recording instruments for tests.

17. TRACTION

CENTRAL STATION ELECTRIC POWER FOR RAILROAD OPERATION

Frederick Darlington **Vol. xxxi—1912, pp. 69-79**

Advantages of electric energy over steam in railway operation. Reasons for purchasing electric energy from central stations. Gain in economy due to large mixed loads.

Discussion, incorporated with paper by George I. Rhodes on " A Method of Studying Power Costs with Reference to the Load Curve and Overload Economies."

RELATIVE COSTS AND OPERATING EFFICIENCIES OF POLYPHASE AND SINGLE-PHASE GENERATING AND TRANSMITTING SYSTEMS

H. M. Hobart **Vol. xxxi—1912, pp. 115-147**

Details and comprehensive analysis of the cost of producing electric energy, transmitting it and delivering it to the working conductors of a railway system, by the straight single-phase system, and by the three-phase synchronous converter substation system.

Discussion, pp. 142-166, by Messrs. W. C. Smith, C. M. Green, H. M. Hobart, B. A. Behrend, Dugald C. Jackson, A. E. Kennelly, C. T. Mosman, W. S. Murray, Edgar Knowlton, John B. Sparks and Roger T. Smith. Relative merits of single-phase and d.c. railway systems. Costs and efficiencies from actual practise.

ECONOMIES IN RAILWAY OPERATION

F. E. Wynne **Vol. xxxi—1912, pp. 203-229**

Analytical discussion of the effects produced by various factors involved in the reduction of dead weight and energy consumption. Selection of gear ratio and armature speed for given service. Relative merits of field control and standard series rheostat method, substantiated by tests.

No discussion.

THE RELATION OF CENTRAL STATION GENERATION TO RAILWAY ELECTRIFICATION

Samuel Insull **Vol. xxxi—1912, pp. 231-282**

Comprehensive analytical discussion of the advantages and savings to be derived by combining all electrical power plants in Greater New York into one unified system. Results attained by unification in Chicago compared with group systems in New York and Boston. Load curves and characteristics of different classes of service in New York, Boston and Chicago. Much well-digested, statistical information on industrial power, lighting and railway service. *Appendix* on power requirements of Chicago electrified steam roads, showing saving of unified energy supply over independent group system.

Discussion, pp. 283-322, by Messrs. John W. Lieb, Jr., Dugald C. Jackson, Charles P. Steinmetz, Lewis B. Stillwell, Benjamin F. Wood, Cary T. Hutchinson, Bion J. Arnold, Samuel Insull, Frank J. Sprague, Hans Lippelt, William McClellan, Percy H. Thomas, W. G. Carlton, Calvert Townley, S. D. Sprong, W. S. Lee, William B. Jackson, Lee H. Parker, C. O. Mailloux, P. W. Sothman, C. L. de Muralt, N. W. Storer and Edward N. Lake. General remarks on feasibility and desirability of supplying electric railways from unified systems of electric energy production. Advantages of unified system in organization, economy and favorable operating conditions. Defense of separate power plants for railways.

FREIGHT TRAIN TESTS ON AN ELECTRIC INTERURBAN RAILWAY

S. T. Dodd **Vol. xxxi—1912, pp. 1001-1017**

General description of the electric freight equipment of the Fort Dodge, Des Moines and Southern Railway, followed by an account of the method and results of tests made to determine the power and energy requirements of freight trains under regular service conditions. Graphic and tabular records of results.

No discussion.

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THE PROBLEMS OF INTERIOR ILLUMINATION

Bassett Jones, Jr. **Vol. xxxi—1912, pp. 1273-1292**

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