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MEETING AT NEW YORK, SEPTEMBER 22, 1905.

APPENDIX.

A paper presented at the 193d Meeting of the American Institute of Electrical Engineers, New York, Jan. 27, 1905.

ACYCLIC (HOMOPOLAR) DYNAMOS.

BY J. E. NOEGGERATH.

Except for very low pressures, the so-called homopolar dynamo has so far been a failure from a commercial point of view. This failure is principally due to two conditions: first, the uncertainty as to the magnetic and electrical conditions prevailing in this type of generator; secondly, the difficulties encountered in collecting large currents from a generator running at a high rate of speed. These conditions will be discussed in this paper, and in order that their import may be grasped there will be described in outline the design of, and some results obtained with, a 300-kw. 500-volt turbine-driven acyclic (homopolar) generator built in the shops of one of the large electrical manufacturing companies. The question dealt with is a broad one, too broad to be discussed at length in this paper; the main points only will be taken up and a more thorough discussion left for a later date.

Classifying acyclic generators according to the position of the armature conductors, we find two prevailing types:

1. The radial type; single disc, Fig. 1; double disc, Fig. 2.
2. The axial type; single cylinder, Fig. 3; double cylinder, Fig. 5.

(The cylinders being solid or hollow—Fig. 4). Combinations of these types are, of course, also practicable.

The armature of the cylinder-type acyclic dynamo here under consideration, Fig. 5, consists chiefly of a solid cast-steel cylinder carrying a small number of straight conductors on its surface; these conductors are connected at both ends to sets of collector rings.

The field, Fig. 5, consists chiefly of a cast-steel structure extending towards the shaft in three polar projections that enclose the armature in complete cylinders. Field coils, *F*1 and *F*2, are wound concentrically around the shaft.

There are also mounted two sets of brushes and a number of stationary conductors (frame conductors). Eight openings give access to the brushes and field spools.

The field spools set up two primary fluxes shown in Fig. 5 as dotted lines, and in Fig. 6 as dotted lines diverging radially.

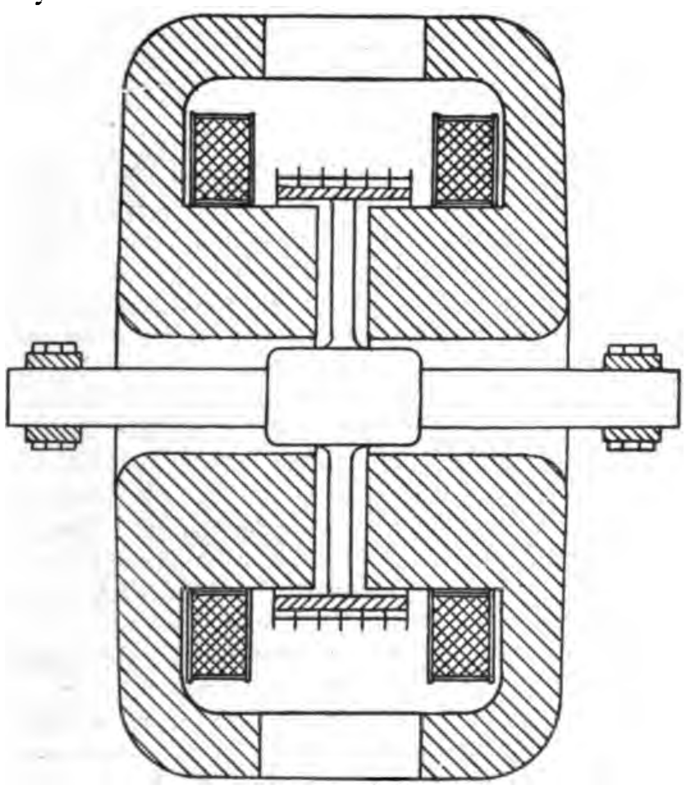


Fig. 1.

As the armature revolves in this uniform field, electromotive forces are generated in the armature conductors; Figs. 5 and 6*C*; these electromotive forces are constant as to magnitude and direction. Single conductors or groups are connected in series by means of collector rings or commutator segments and the frame conductors.

The induced electromotive force $= \dfrac{\phi\ N\ n\ 10^{-8}}{60}$

$$= 1.66\ \phi\ N\ n\ 10^{-10}$$

Where ϕ = Total flux
N = Revolutions per minute
n = Armature conductors in series.

Fig. 7 shows diagramatically the simplest form of an electric circuit in a cylinder type of generator, C and R representing armature and frame conductors, $C\ r$ and B representing

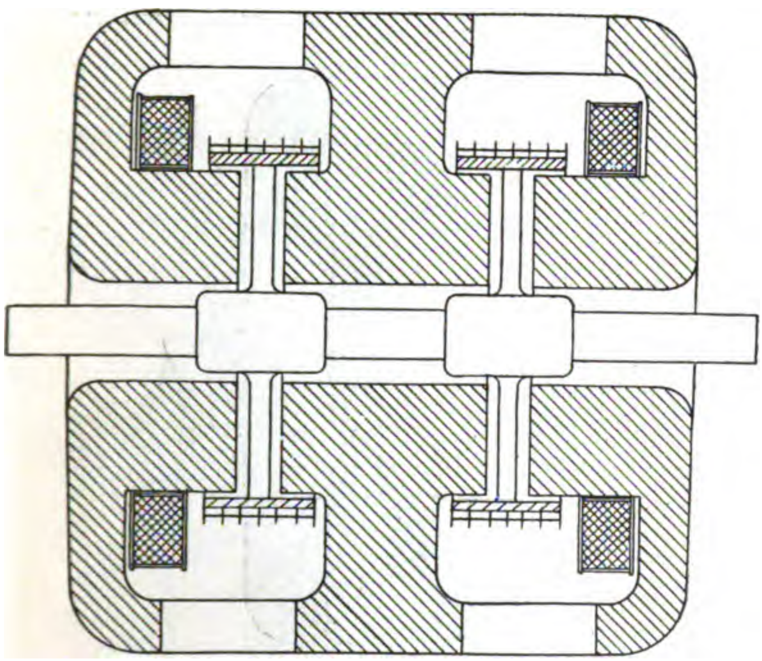


FIG. 2.

collector rings, and brushes respectively. The currents passing through this system set up secondary fields which affect the primary flux. Of these, the ones created by the currents flowing in the collector rings (ring reactions) are of great interest from a practical point of view.

For a given time the connection point between armature conductors and collector ring passes through P_1. At this moment currents flow from P_1 to B_1 through both sections of the ring, the currents being inversely proportional to the ohmic resistance of the ring-sections. The currents set up fields in the magnetic material in which they are completely embedded.

As the armature revolves, the connection point P_1 moves on, changing magnitude and direction of the magnetomotive force. These periodical changes of magnetization create hysteresis and eddy losses in the solid material. They also weaken the primary flux, since, due to saturation, the increase in density is considerably smaller than the decrease. This means bad regulation.

There are various means of counteracting ring reactions. One consists of placing brushes all around the ring, practically covering its surface. For commercial pressures this

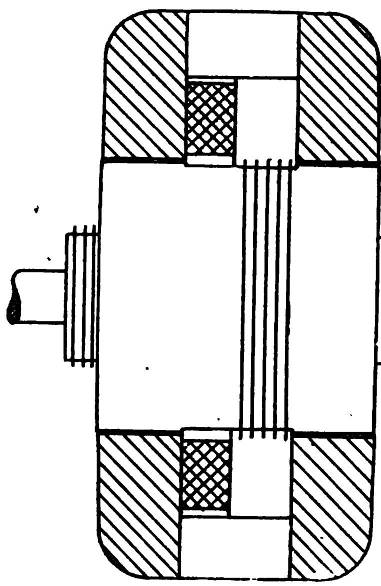


Fig. 3.

method is out of consideration because of the great number of collector rings. It would be impracticable to adjust and watch the very large number of brushes required in this case. The question of friction losses also limits the number of contacts

Satisfactory results were obtained with a method which is diagramatically shown in Fig. 8. R_1, R_2, etc., B_1, B_2, etc., and P_1, P_2, etc., represent rings, brushes, and connection points of the collecting system on one side of the armature of one collector. The connection points form a spiral of one complete turn, while the contact points of the brushes form one or more turns of a spiral running in the opposite direction. The brushes are arranged in groups that can be inspected from the openings in the frame. In this case Σ magnetomotive force $= 0$ for each section of the collector periphery and for any position of the armature.

As to the armature reaction, reference is made to Figs. 5 and 6. The currents flowing in the armature conductors C set up secondary fluxes as indicated by the curved lines. These secondary fluxes cut the frame as the armature revolves, causing hysteresis and eddy losses. They also increase the primary

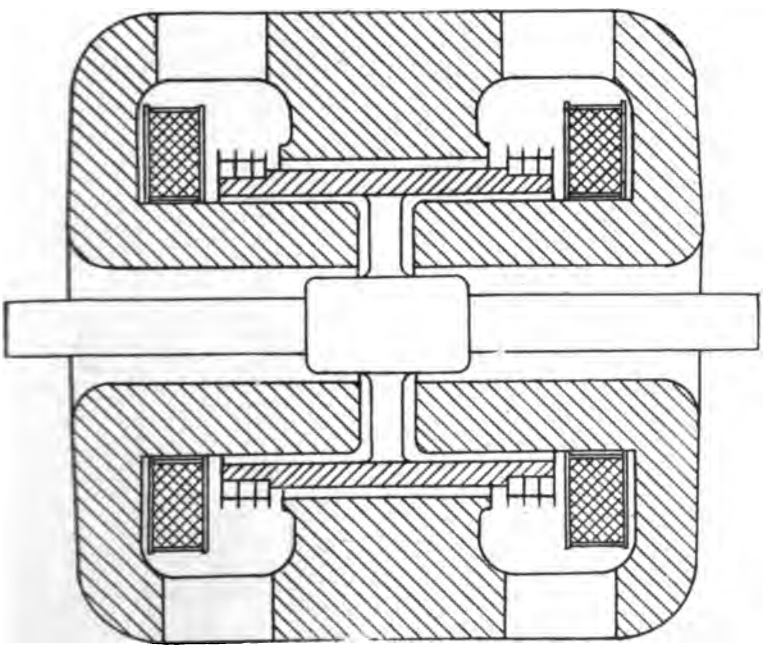


FIG. 4.

flux at α and decrease it at β. On account of saturation, the weakening effect will again be considerably augmented, affecting the regulation. When the conductors are placed close together, that is, in approaching the equation

$$\frac{di}{dl} = C$$

where i = amperes, l = unit length of armature periphery. The radial components of these secondary fluxes at α and β

are neutralized. Similar considerations are valid for the stationary conductors.

The most efficient means of conforming to this equation consists of using flat conductors mounted close together. They may be assembled inside of the armature body or on its surface, Fig. 6*b*. The remaining components of all the local fluxes form one circular field that intersects at right angles with the

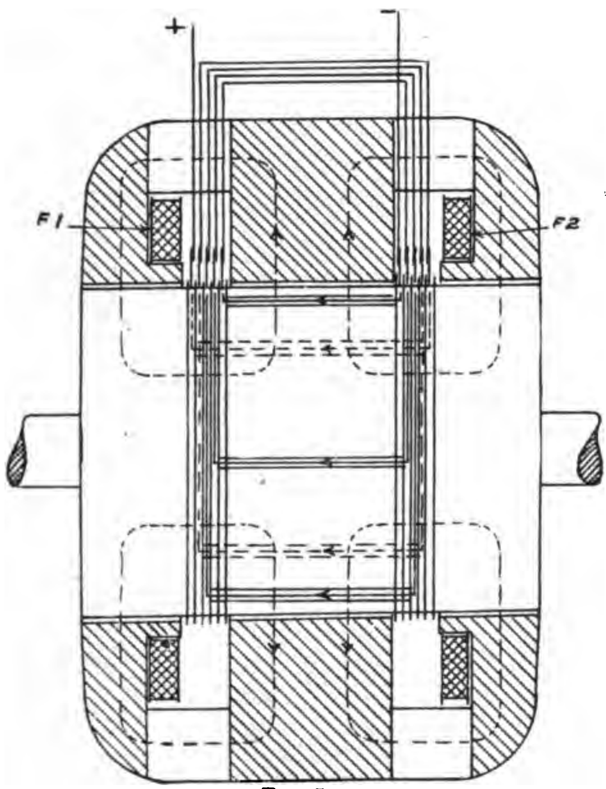


FIG. 5.

primary flux, Fig. 6. Considering the influence of these magnetizations upon each other, two conditions are of importance.

1. The medium between armature and frame conductors consists of non-magnetic material, air; that is, the conductors are mounted on the surface of armature and frame respectively, Fig. 9*A*.

If in Fig. 10, $M1$ and $B1$ represent magnetomotive force and density of the primary, M_2 B_2 the magnetomotive force and

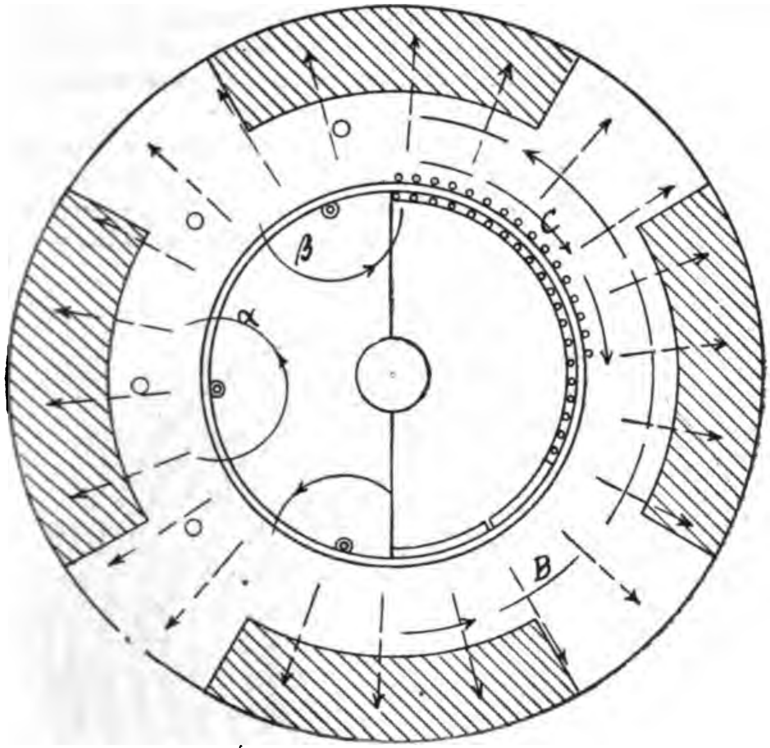


Fig. 6.

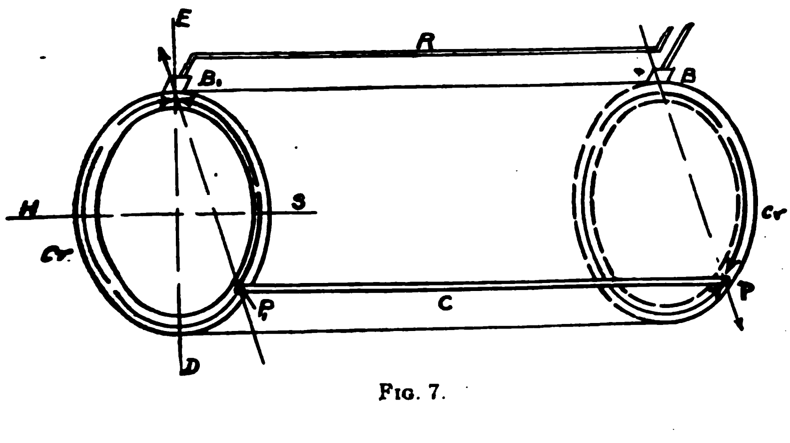


Fig. 7.

density of the secondary flux produced by the armature turns, then M_3B_3 will designate the resulting flux, provided the reluctance is the same in all directions. It is evident that the component of the flux in direction of the primary magnetization remains unchanged.

In an air-gap the length of the path of the resulting flux will actually be somewhat greater than that of the primary flux. But on account of the very high reluctance in the path of the armature reaction, the secondary flux is so small that direction

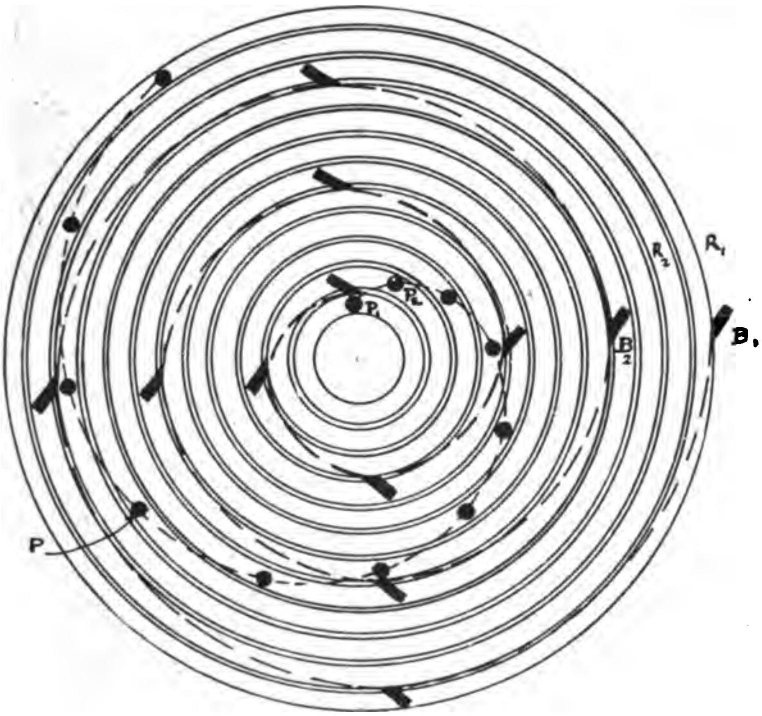


Fig. 8.

and magnitude of the resulting field does not differ appreciably from the primary.

2. The magnetic medium between the stationary and revolving parts of the winding consists of iron Fig. 9 *B*, *C*; Fig. 11. Principally due to saturation, the density of the resulting flux will be considerably smaller than $\sqrt{B_1^2 + B^2_2}$, and its component in direction of the primary magnetization appreciably weaker than B_1. But to restore the flux to its original value only so

many ampere-turns have to be added as are required for the increase in density along that part of its path that is affected by the secondary magnetization. The influence of a given armature reaction on regulation is therefore determined by the relation between the reluctance of the primary magnetic circuit in that area and the total primary reluctance. It can be kept very low.

While for the circuits *B* and *C*, Fig. 9, the main secondary magnetizations are practically of the same order, the local fluxes

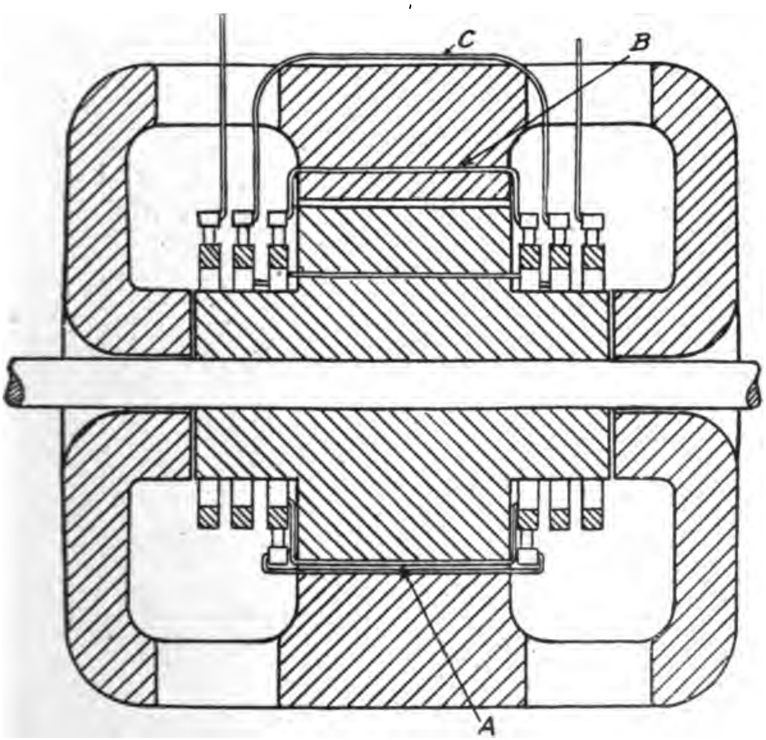


FIG. 9.

produced by the part of circuit *C* that runs parallel to the shaft are much smaller than in *B*, because of the high reluctance. They are, in fact, negligible. The neutralization of the ring and armature reactions as discussed above is very complete.

Tests on the 300-kw. generator show that the difference in pressure between full load and no load is only slightly higher than the drop, due to the total resistance of the armature circuit; that is, regulation is good.

While the armature windings of acyclic dynamos will not be discussed in detail, yet the points that have to be considered in laying out these windings would better be indicated here; they are:

1. Neutralization of ring reactions.
2. Magnetizing effect of end connections.
3. Minimum pressure between rings.
4. Assembling of brushes in groups for accessibility.
5. Equal resistance of armature circuits.
6. Minimum pressure between adjoining conductors.

Point 5 is to be considered if it is desired to run the machines at different pressures, Fig. 16.

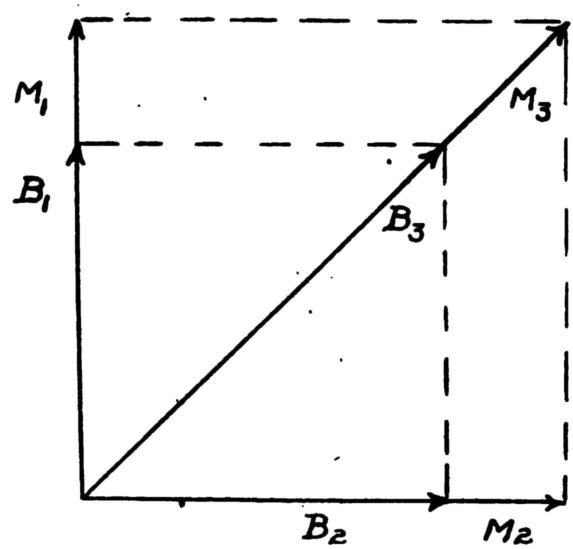


Fig. 10.

Accumulative or differential compounding of acyclic motors or generators can be effected either by means of a series coil, or by giving an angular displacement either between the contacts and the frame conductors or between the connection points and the armature conductors, Fig. 13. For instance, Fig. 12, the currents flowing in the leads that connect the frame conductors and brushes partly or totally enclose the armature. The circular component of the magnetomotive force of these currents acts in the same or opposite directions as the magnetomotive force of the field-coils. By shifting the

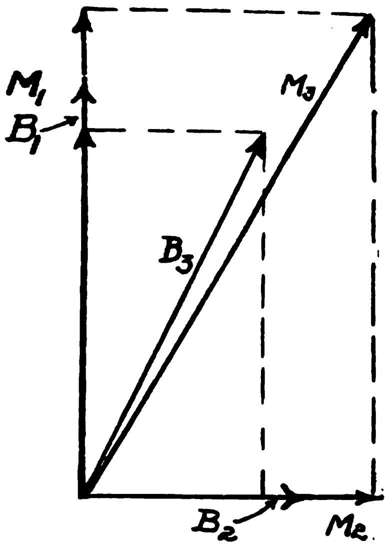


Fig. 11.

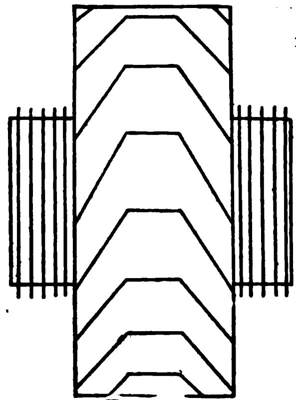


Fig. 13.

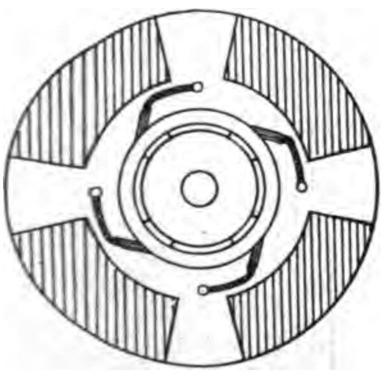
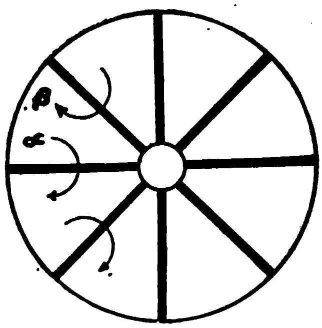


Fig. 12.



Fig, 14.

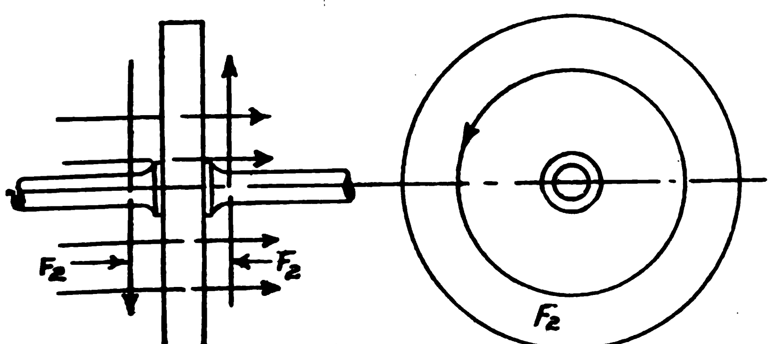


Fig. 15.

brushes it is possible to adjust the compounding. By moving them against the direction of rotation accumulative compounding is effected in generators; for motors, the result is the reverse.

It is obvious that series generators and motors can be built without field coils. In such generators the intensity and direction of magnetization can be changed by shifting the brushes and, consequently, the electromotive force of generators as to direction and magnitude can be influenced as well as the speed, torque, and direction of rotation of motors. Acyclic generators are self-exciting.

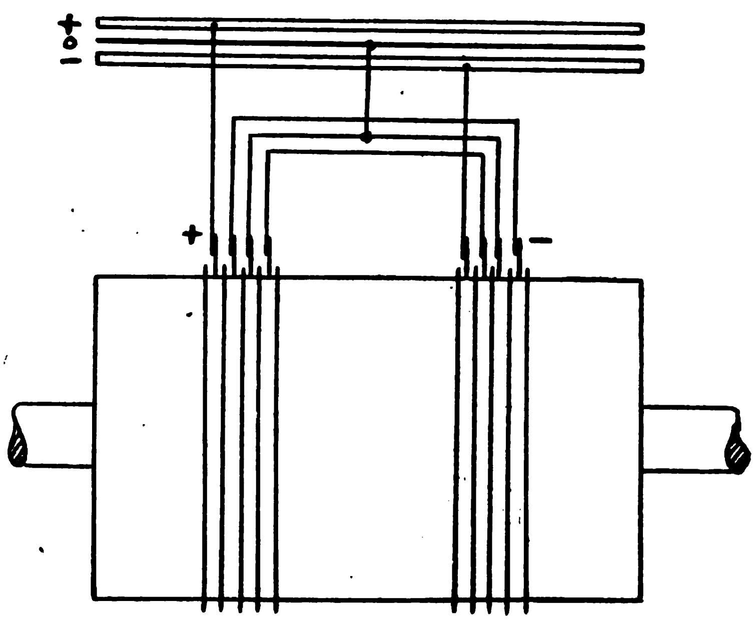


FIG. 16.

The considerations of the electrical and magnetic quantities discussed above for an axial-type acyclic generator hold good also for the radial type, with the exception of a modification in regard to the armature reactions. The currents flowing in the armature of the radial type set up fields that enclose the conductors. These secondary magnetizations disturb the primary flux in a way similar to that discussed for the axial type, resulting in core loss and affecting regulation. By placing the conductors close together, that is, in conforming with the equation,

$$\frac{d\,i}{d,l} = C,$$

the components at α and β are neutralized, leaving a resultant magnetization which may consist of two circular fluxes, $F2$ Figs. 14, 15.

In this case i = Current, l^1 = Unit length of a circular section taken concentrically around the axis.

The secondary flux $F2$ intersects at right angles with the primary. Their influence upon each other can be modified as was discussed for the axial type.

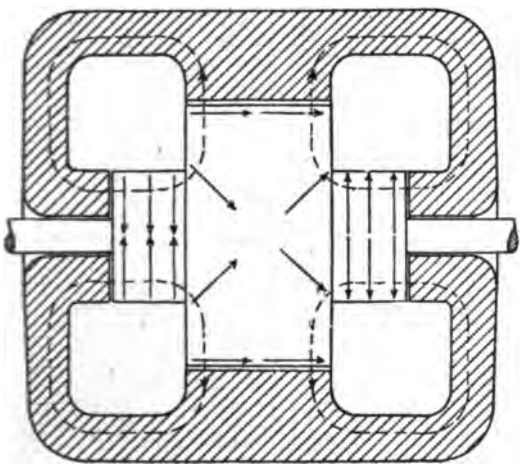


FIG. 17.

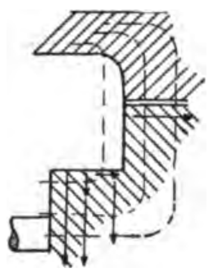


FIG. 18.

The efficiency of a high-speed acyclic generator about equals that of a turbine-driven commutator generator, but the distribution of the losses is very different. As windage and bearing friction depend on the mechanical design only and not on the type, they can be made to have the same value for both machines.

The $I^2 R$ field loss is somewhat smaller in acyclic machines principally because the length of the air-gap is limited by mechanical requirements and not by the armature reaction.

The $I^2 R$ armature loss is almost negligible on account of the small number of turns. In the generator under consideration there are 12 armature conductors and 12 frame conductors in series.

It is obvious that in a field of uniform and constant density there should be no hysteretic loss. As to eddy currents, reference is made to Fig. 17 where uniform distribution without stray fields is assumed. No electromotive forces are induced in the field. The arrows represent value and direction of the electromotive forces induced in the armature body. It is evident that Σ electromotive force $= 0$ for any closed circuit inside the armature, as well as in any circuit including armature, bearings, and field. From Fig. 18 it will be seen that this is true even if there is a stray field, provided it is uniform.

In general, the distribution of the flux in acyclic dynamos that eliminates core loss is expressed by the equation $\frac{d B}{d L} = C$

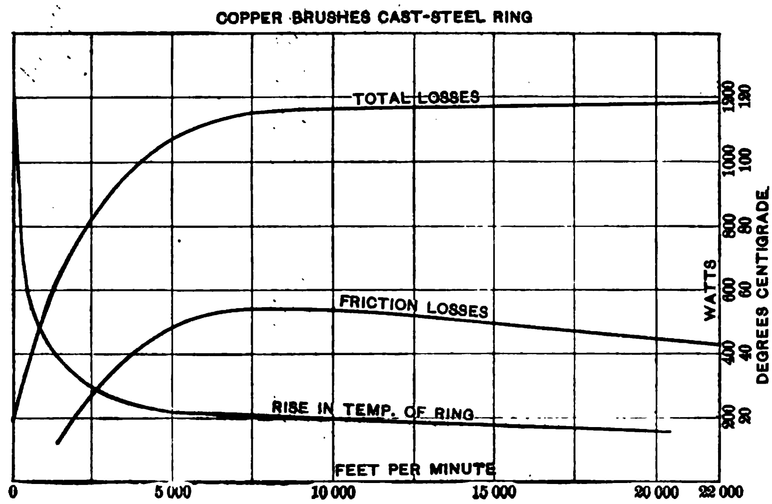


FIG. 19.

Where L = unit length of any circle concentric with the axis; that is, the flux must have a constant specific linear distribution in the direction of rotation.

The variation of the air-gap length and of permeability, the openings in frame and armature, as well as the secondary fields, disturb this ideal condition. In other words, the flux densities in symmetrical points are not actually equal.

One-half of this difference in density $B\, d$ represents the B in the hysteresis and eddy current formulas. Its value depends, except on the magnitude of the disturbing elements mentioned above, on the relation of the reluctance in and close to the air-gap to the total reluctance. It is possible to keep this $B\ d$ and, consequently, the core loss very low. The main losses are encountered in the brush contacts.

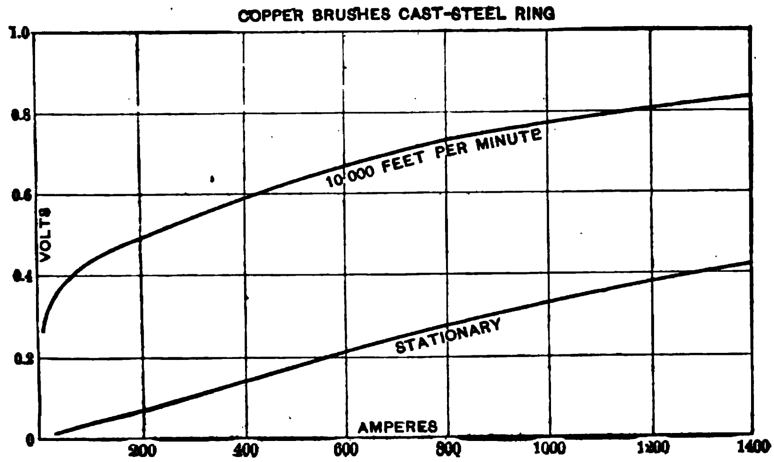


FIG. 20.

From a series of investigations the following conclusions are drawn:

1. *As to speed.* Fig. 19.

There is a steady but small increase of pressure drop at the

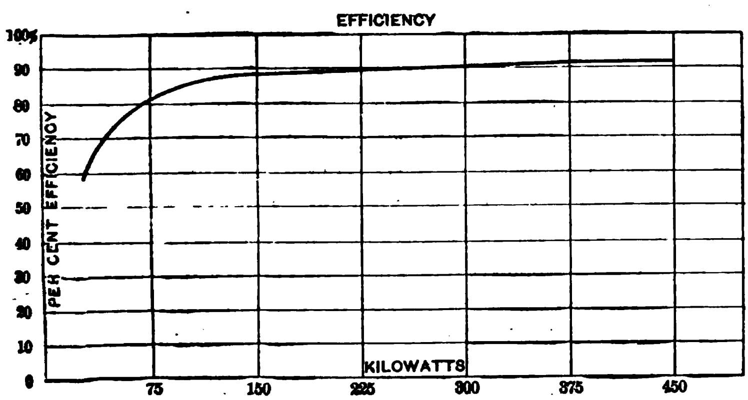


FIG. 21.

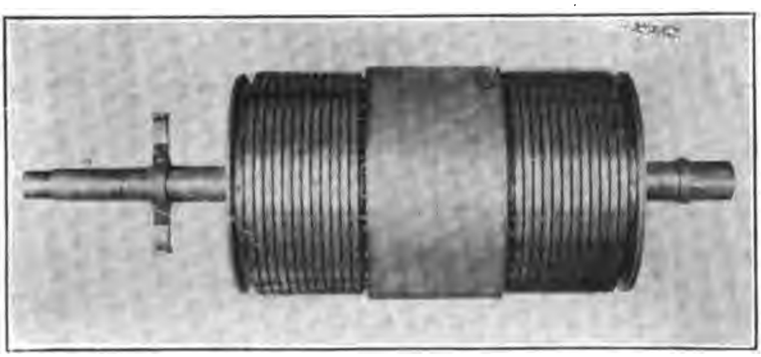
brush-contacts with increasing speed. The friction loss, declining somewhat, practically remains constant for high velocity. The total losses also remain practically constant above these speeds. The improved ventilation inherent to greater velocity allows a higher current capacity to be used in the collecting system.

2. *Current density.*

While the relation between current and pressure drop in stationary contacts of metal brushes and metal rings is similar to that in a solid resistance, the conditions in moving contacts are of the character of those prevailing in an electric arc, the apparent resistance falling off rapidly with increasing densities Fig. 20. The similarity is furthermore illustrated by the fact that in frequent instances, pressures 10 to 20 times higher than normal were required to start the flow of current.

3. *Brush pressure.*

The increase of brush pressure does not decrease the drop

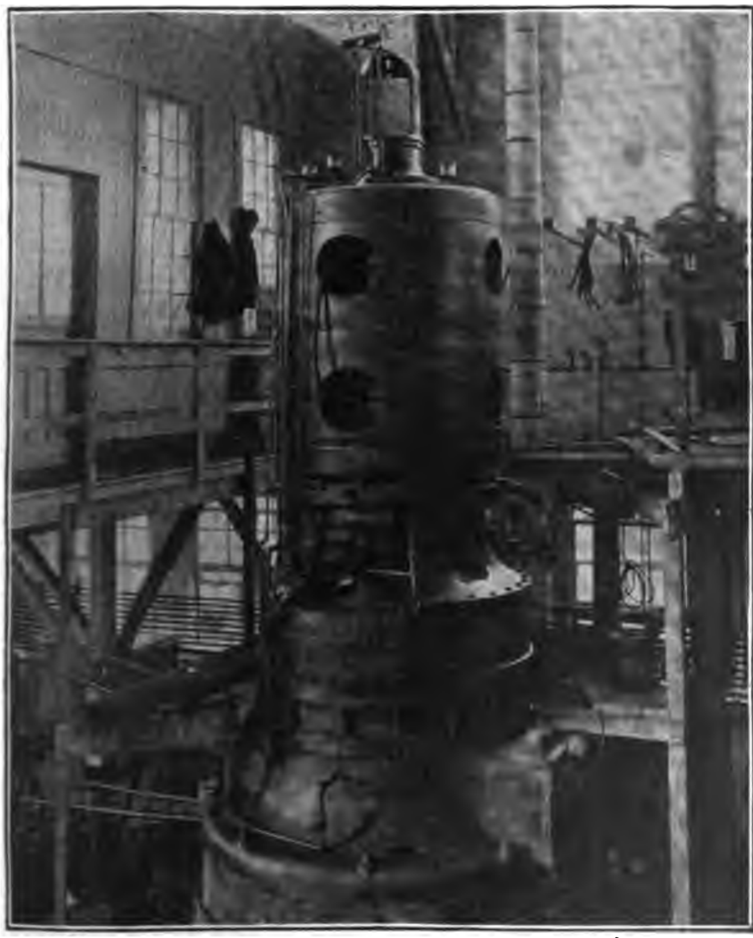


considerably, but the sparking tendency at high speeds and densities necessitates high pressures.

In the 300-kw. 500-volt turbo-generator, the full-load losses equalled 28 kw. without windage and bearing friction. The efficiency curve, Fig. 21, is flat, due to the small core and brush-friction loss. Regulation = 6 to 12 per cent.

Considering now the mechanical design, as mentioned above, the generator consists chiefly of a cast-steel armature and a cast-steel frame. On the smooth armature surface 24 conductors are mounted, flat sheets bent on the radius of the periphery. The torque is taken up by lugs projecting axially from the armature body and the centrifugal stress by means of steel binding wire.

The 12 collector rings on either side of the armature are assembled close together and mounted on a shell. Eight large-size openings in the frame give access to three brushes each, making a total of 24 contacts. The main objection raised against a large number of rings in series is based on the assumption that, consequently, many brushes are required, rendering inspection difficult. It seems that 24 contacts would be a moderate figure



even for a commutator machine of that rating. The stationary circuit consists of 12 cables. Without interfering with other parts, the armature or the stationary winding and either set of collector rings may be removed.

In comparing commutator and acyclic direct-current machines as to inherent conditions from a commercial point of view, the latter is essentially a high-speed machine, its field being limited in general to large turbo-generators, high-speed motors, direct connected to rotary pumps and blowers, and motor-generators.

While the total weights of both types are about equal, even for moderate turbine speeds, the very low copper weight, simple construction—less labor and smaller total cost—combined with the elimination of commutating problems, should speak favorably for the new type.

Discussion on Acyclic (Homopolar) Dynamos.

F. B. Crocker: At the Philadelphia meeting of the Institute in May, 1894, the speaker read a paper entitled " Unipolar Dynamos for Electric Light and Power." It received little encouragement then and there has been very little since that time. The present paper is therefore welcome, as it is the first ray of hope in 11 years for the successful development of a machine of this type. This paper gives evidence of real progress; the machine is not experimental—not a one-kilowatt machine generating one volt, but one that gives 300 kilowatts at 500 volts.

As a matter of fact it is the original Faraday type. Faraday also proposed to multiply the pressure by connecting discs in series; he suggested the revolving of discs in opposite directions in the same field and connecting their peripheries by brushes or mercury, thus causing the current to flow outward in one disc and inward in the other, the current being taken from the two shafts. There are still other methods of multiplying the pressure besides the one which the author uses. One way is to have concentric cylinders revolving in the same field, the current entering one end of the first cylinder, passing out at the other end, then passing through the second cylinder in the same direction, and so on—a series connection threading through the field repeatedly in the same general way as in the machine described by the author, the inductors however being concentric cylinders instead of elements of a cylinder.

The author has adopted a plan of splitting the cylinders longitudinally into strips, like the staves of a barrel, and then connecting these strips in series. The speaker understands that there are 12 of these strips and 24 brushes, one brush at each end of each of these elements of the cylinder. This type of machine is one in which the inductor, whether an element or the whole cylinder, revolves in an annular space, in which the field is always in one direction and, as nearly as possible, of uniform strength throughout. Therefore, the electromotive force is simply the number of lines of force cut per second divided by 10^8. A conductor one foot long moving 12 000 feet per minute or 200 feet per second in a field of 90 000 lines per square inch, would generate 26 volts.

The fact that the armature reaction *in the air-gap* does not materially affect the flux is interesting, but is what we might expect from the fact that cross ampere-turns do not materially reduce the flux in ordinary dynamos. It is the back ampere-turns that have that effect. In the present case there are cross ampere-turns but no back ampere-turns. On the other hand *in the iron*, as shown in Figs. 10 and 11, because it becomes partly saturated, the resultant flux due to two magnetomotive forces acting at right angles, is not equal to the square root of the sum of the squares, because that implies that the reluctivity is constant, whereas we know it increases with the density, consequently in that case the flux is not so great.. Nevertheless

Mr. Noeggerath says at the bottom of page 9, that the regulation is good, and that the difference between full-load and no-load pressure is only slightly higher than the drop; in other words, armature reaction is not excessive, only slightly greater than the resistance drop. He said, during the presentation of his paper, that it was only 6 or 8%. It is very interesting to see, in one of the diagrams given, that by merely moving the brushes forward or backward; the conductors connecting these brushes with the circuit had the effect of compound winding or differential winding; and that you might even have a series machine, without any field winding, because the current going into the armature, and out again, as it were, had the effect of a field coil.

The limitation of this machine is of course the speed at which the current can be taken off. At the speeds adopted by the author, one element which might be a plain cylinder of the old-fashioned unipolar type generates 1/12 of 500 volts, a commendable pressure for a unipolar machine. Though he uses the term, the speaker thinks that "unipolar" is not a happy expression. There are, in fact, two poles, the flux passing across the air-gap from one pole to the other. The term "unipolar" is therefore not appropriate, though it has been in use for a very long time. Acyclic or non-cyclic is much more appropriate.

Regarding eddy currents in the armature: if there is a blowhole in the casting there is practically no electromotive force generated in the area covered by the blow-hole; the current therefore tends to flow backward in that area, being supplied from the adjoining portions of the inductor. It is evident that a casting which is not uniform or a mechanical construction which is not uniform will involve eddy currents, because the current can flow back whenever the electromotive force is less in one part than in other parts of the armature.

A. E. Kennelly: An interesting point brought out by this paper is that the direct-current machine shows distinct advantages over the alternating-current machine. The ordinary direct-current machine is in reality an alternating-current machine with the alternating current rectified for external use by a commutator. A telephone will sing when connected to the terminals of the ordinary direct-current generator, whereas we may expect it to remain mute when connected to the terminals of a true direct-current generator, the homopolar generator.

Electrical engineers have always regretted not being able to get a magnetic material that could be cast, a material that would conduct magnetically but not electrically. Heretofore it has usually been necessary to laminate the iron in order to destroy eddy currents in the body of the revolving armature of a high-pressure direct-current generator; this laminating is quite expensive. But in an arrangement of this kind we can obtain a revolving solid mass, in which there will be no sensible production of eddy currents or hysteresis.

The secret of the success arrived at in a machine of the type described by the author is the relatively enormous speed obtainable in comparison with machinery that existed before the introduction of steam-turbine; and it is by reason of this enormous speed that the high electromotive forces of 30 volts per foot can be obtained. The result ought to be a great reduction in the weight of the active parts, after the weight of the material which is purely structural has been deducted. Owing to this electromotive force produced per foot of active conductor, accounting of course for the small ohmic drop in the active conductors themselves, we arrive at a type of machine in which the surface of the collector, which takes the part of the commutator, is nearly double the surface of the armature core. This is shown clearly on the diagram on page 16.

It is worthy of note that the designer has been able to reduce the brush frictions as low as they appear to be. Even though the main losses in the machine seem to be frictional losses, hysteresis losses, and eddy-current losses, still one would suppose that the friction losses of the brushes would have been the limiting losses which might have interfered with the success of the machine. The fact that they are reduced to so low a quantity is surely a matter for congratulation.

C. Cartwright: The advantage of this type of machine over the ordinary direct-current commutator type should, it seems to the speaker, be emphasized; this advantage is most apparent in comparing machines designed for railway purposes. The insulation of this machine is of a mechanical rather than of an electrical nature, and there is an absence of commutator troubles due to overloading—these conditions, it would seem, combine to make this type of machine especially desirable. Other most desirable features are its simplicity of design and cheapness of construction. It is constructed so that only the simplest machining is required such as can be done on a lathe or boring-mill. Also, there are no complicated parts, and the machine can be easily assembled.

F. V. Henshaw: Any designer who has tried to solve the problem of building a direct-current generator for connection to a steam-turbine is greatly interested in the development of this unipolar type of machine. It seems to the speaker that the reduction of the surface speed of contact rings is of much importance. Of course, in a machine of this kind, there being no commutation, the bad effects of this high speed are chiefly due to mechanical causes. The large size of the collector rings impresses one, and Fig. 20 shows clearly the effect of high speed on the contact drop.

Another feature is the location of the brushes. If the brushes could be placed outside of the frame it would be most desirable. The speaker presumes that these details have been carefully considered; possibly inherent conditions have caused the designers not to attempt to place the contact rings outside of the frame.

J. E. NOEGGERATH: A few words explaining why the speaker used the terms "axial" and "radial" types. Classification into cylinder type and disk type relates solely to the mechanical construction; it does not give an idea of the condition prevailing in the machine itself. The speaker knows of a low-pressure machine, now in operation in a New England town, in which the electromotive forces are induced in a radial direction, but from a mechanical point of view it is a cylinder machine. To avoid possible confusion, then, the speaker adopted the terms "axial" and "radial."

Regarding armature reaction, it is true that a comparison with the effect of the cross ampere-turns of multipolar machines

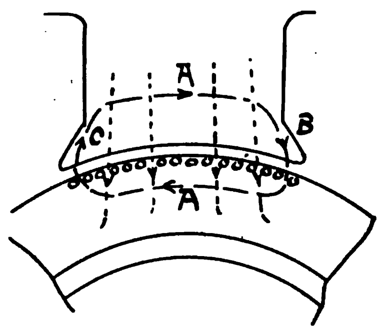


FIG. 1.

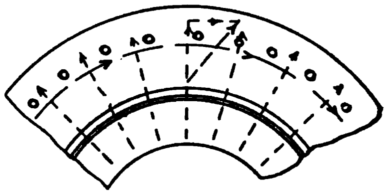


FIG. 2.

apparently justifies the conclusion that the difference in pressure between no load and full load should be greater than is indicated in the paper; but there is a considerable difference in the action of the cross ampere-turns in multipolar and acyclic dynamos. In the former type the effect of the secondary flux produced by the cross ampere-turns is threefold: first, there is a rectangular intersection of primary and secondary fluxes at A; secondly, there is an action in the direction of the primary flux at B; thirdly, an action in direction opposite to the primary flux at C. The first one is of the least influence and corresponds to the armature reaction in acyclic dynamos. As far as total primary flux is concerned, actions B and C would neutralize each other if there were no saturation. But since there is saturation, the loss in density at C overbalances the gain in B and thus affects the regulation. In acyclic machines where the pole encloses the armature in a complete cylinder there is no such crowding of lines but a plain rectangular intersection of fluxes as discussed in the paper. Its influence on regulation can, by the way, become very strong if the densities are not properly chosen.

As far as core losses are concerned, blow-holes in the armature are not really a very serious matter. The speaker has bored holes in both the armature and fields for purposes of ventilation and still the core loss is not high. The openings in the frame produce core loss chiefly in the armature and the openings in the armature produce core loss chiefly in the field. If these openings are sufficiently removed from the air-gap, the influence is not very strong; more serious is the unevneness of the air-gap.

For theoretical reasons it is impossible to put collector rings insiae of the frame. As far as the relation of ring speeds to losses is concerned, the curve in Fig. 19 indicates that while tne $I R$ drop rises with increasing speed, yet the friction iosses decrease so that the total losses remain practically constant above certain high speeds.

The collector rings are of cast-steel, although for mechanical reasons it would be better to have them of nickel-steel. There is, of course, wear on the brushes but not more wear than on the carbon brushes generally used with turbine machines.

Discussion on "Acyclic (Homopolar) Dynamos," at Boston, February 1, 1905.

A. E. Kennelly: A curious feature about this machine is that although we have discarded smooth-core armatures for years, and thought they had been scrapped, here comes once more a smooth-core armature with the conductors lying on the top and tied on with a binding wire. This shows that one cannot be sure that when a piece of apparatus has been discarded and laid on the junk-heap, that it will not come to life again. Now the query arises; is the extra expense of drilling the solid armature core at sufficient depth to permit of the conductors going in without producing eddy currents in the pole pieces as they go round, such that the improved mechanism of a toothed-core armature would be not worth while? The speaker thinks that although a machine could be made solid and sound by binding the conductors on the surface, yet at high speeds one would feel less uneasy if the conductors were embedded in the solid metal.

As regards the question of stationary or rotating field, the speaker thinks that on any hypothesis—in this machine at least—the field should be looked upon as stationary, and the armature as cutting through that field. Most people who have entered this contest—it has been a theoretical contest for many years—would concede this case. There are other structures, however, different from this one, where there would be more discussion as to what takes place, although the speaker believes it is conceded now that flux-lines have in a certain sense a physical existence. The speaker does not know whether any conclusion has been reached in some cases as to whether the flux in particular types of unipolar machines remains stationary or is rotating.

J. E. Noeggerath: The wires were not embedded on account of reaction. As far as the size of the machine is concerned, the length of the armature conductors is somewhat over one foot, not much more than that.

A. E. Kennelly: It is extremely interesting to note that out of a machine with 12 conductors one foot long one can get 300 kilowatts and 500 volts.

H. E. Heath: The difficulty of compounding depends on the type of machine. Take for instance the same type, but with five volts and 15 000 amperes or something of that sort; it is readily seen that it would be rather difficult to put in series coils and get satisfactory compounding action. That would require large conductor and would be rather difficult to handle. There are also some other forms that are extremely similar.

W. H. Pratt: Further remarks on the matter of compounding are asked for: the speaker does not quite gather the arrangement of compounding by shifting the brush position in connection with the armature conductors.

J. E. Noeggerath: The field coils are wound cylindrically around the shaft. If there is circumferentially a space between the brushes and stationary conductors, a current flows, in the same or opposite direction as the current in the field coil, and therefore there is a compound reaction. Since there are 12 conductors in series, if all of them are shifted there is 12 times as much reaction; in other words the compounding is effected by the length of the brush leads.

H. E. Heath: There is a bare possibility that one or two people may not quite understand what Mr. Noeggerath meant by compounding action. His armature is really a cylinder of iron carrying 12 conductors; these conductors cutting the magnetic circuit when the armature is revolved, with a consequent generation of electromotive force. The collector rings and leads embrace portions of the magnetic circuit. If the leads from collectors to conductors are straight and parallel to the lines of force, no addition to the magnetomotive force is produced when current flows in them, the magnetomotive force due to this current tending to produce distortion only. But if the leads are carried spirally around the armature (and therefore the magnetic flux) then, when a current passes between collectors and conductors, we get a magnetomotive force which either assists or opposes the main magnetomotive force, the strength of this magnetomotive force in ampere-turns being the fraction of a turn taken by the lead multiplied by the current.

Now speaking of a type about which there can be no doubt as to where the cutting takes place. Let us take a hollow iron cylinder as an armature, supported at one end and surrounding a cylindrical magnetic pole from which it is separated by the usual air-gap. The supporting shaft passes through the center of this pole, or is in line with it. A magnet pole in the form of a ring surrounds the cylinder and the magnetic circuit is completed through an exciting coil at any convenient point away from and outside of the armature, the material being assumed to be so distributed as to give uniform flux density in the air-gap. Then we have the magnetic circuit through the cylinder from one pole to the other and the electrical circuit lengthwise of the cylinder through the flux. We have then possibly as simple a form as you can conceive, and there is no doubt about the cutting. You do not imagine for a moment that the lines of force are going to cut out through the sides of the exciting coil, nor do you expect any coiling of them, so the action must take place in the cylinder.

Roughly, this is the type mentioned by the speaker as the heavier form that it might pay to use for very low pressures and comparatively low currents. Instead of the external-ring pole we may use another internal pole in the opposite end of the armature cylinder with the armature support between the two poles and the shaft running through their centers.

The magnetic path will then be through the cylinder from pole to pole, and the electrical path from outside of armature to shaft. In both of these forms we have the same maximum collector surface velocity for same pressure and speed. If we now make both the internal poles of the same magnetic pressure and use the ring for the opposite pole, we shall be able to get double the electromotive force for same collector surface velocity and revolutions per minute, as this electromotive force is determined by the polar section at the entrance of the cylinder and now the flux enters at both ends; that is, we have a double magnetic circuit type with series armature.

All the above refer to single elements; there is of course the possibility of much modification, but they are all accessible. There is no doubt that the less accessible forms will be considerably lighter than those which are more accessible.

One thing more with regard to these types — there is no doubt about where the action takes place; for if we could hold the armature still the cutting would take place just the same. There is a case where the flux actually revolves, because the reluctance revolves. It is the speaker's opinion that a revolution in a case of this kind is a purely relative matter in the machine itself; it makes little difference which part moves, the action would be just the same.

G. H. STICKNEY: Is there any possibility of reducing the collector velocity?

H. E. HEATH: Not in a machine of that kind, and for the reason that the collector rings have got to be outside the magnetic flux; it is merely a matter of how much density can be carried through there.

As to core loss, the speaker will not say there is none, but it will be so small that it will require considerable care to detect it. On one machine we had—we were driving the machine as a motor, and were unable to detect whether the field was on or not by the reading of the instrument—there was no variation at all in the motor readings when one excited the field or cut it out.

C. M. GREEN: That also enables you to run at a very high density?

H. E. HEATH: At high density, yes; but there is a limit to the density. The speaker would not hesitate to run at as high a density as 100 000 or 115 000 per square inch, but running at that density costs money.

As long as the armature is centred there will be no pull; if the machine is running at extremely high density there will be very little pull. Fairly large shafts are used, something that has no spring.

C. M. GREEN: There is no magnetism on that shaft?

J. E. NOEGGERATH: There is no or very little stray field in the shaft. There is considerable side pull to a machine of that construction, and it is not possible to increase the densities up above a certain point, because the core loss will be detrimental. As pointed out in the paper, it is necessary to have a certain relation of density near the air-gap to the total flux and to the density in the remaining part, but there are certainly limitations as to the density. If the air-gap is uniform the machine could be run at very high density; but while this is true at the start it is not the case afterward. The machines now vary from 0.0625 in. up to 0.4375 in. air-gap.

A paper presented at the 193d Meeting of the American Institute of Electrical Engineers, New York, January 27, 1905.

MODERN CENTRAL STATION DESIGN AS EXEMPLIFIED BY THE NEW TURBO-GENERATOR STATION OF THE EDISON ELECTRIC ILLUMINATING COMPANY OF BOSTON.

BY I. E. MOULTROP.

The design of most of the central stations in this country can hardly be said to be ideal; first, on account of the handicaps and limitations imposed by the location and environment of the selected site; secondly, because usually the cost of the land to be built upon renders it imperative that the area covered be made as small as possible.

In selecting the site for a large power station, three main problems confront the engineer: first, a satisfactory location with a low valuation must be found which is reasonably near to the bulk of the business; secondly, the location must be so situated that the fuel can be brought to it with the least expense for freight and handling; that is, it should be somewhere on a main ship-channel below all drawbridges with ample depth of water and docking facilities for coal-carrying vessels up to seven or eight thousand tons burden. Also there should be ample ground adjacent to both the dock and the proposed station site to permit the storing of at least six months' supply of fuel, and so situated that the minimum amount of coal-handling and conveying machinery is required. Thirdly, an unlimited supply of suitable cooling water must be provided for the condensers, this should be such that the temperature will not be excessive during the summer time. The water should be free from sewage, seaweed, and other debris; and the proposed location for the station should be such that the distance the water has to be lifted from the level of the supply to the top of the condensers is as small as possible; and the length of pipes or tunnels employed to take the water from the supply to the farthest condenser is as short as possible.

The location of the L Street station of the Boston Edison Company fulfils these conditions admirably. The ground consists of two city lots of about 25 acres, two-thirds of which is solid ground. It is situated at the corner of L and East First streets, South Boston. Measured by an air-line it is about two miles from the centre of the business section of Boston. It has a water front of 815 feet on the so-called "Reserved Channel," is one-half mile from the main ship-channel of Boston Harbor, and is so located that no bridges will ever be built between it and the main ship-channel.

The solid ground consists principally of gravel with a bed of clay underneath so that the heaviest construction called for in the building of the station can be carried on ordinary footings without the use of piles. The area of the solid ground is more than double that required for the ultimate size of the station under consideration, consequently there is ample room for the storage of fuel close to the boiler-house.

Before taking up in detail the design of the station, a brief description of the company's territory will be given. The Boston Edison Company's system supplies electricity to a heavily-loaded business section of the city, which covers a comparatively small area located within a mile of the water-front. This business is supplied by a direct-current station on the water front having 10 500 kw. of machinery, with room to increase the capacity to 14 500 kw. Surrounding this business section is a city residential district where the load is considerable, although much lighter than in the business part. Here the customer receives direct current from sub-stations supplied, through motor-generator sets, from the existing alternating-current station of 9 000 kw. capacity, located on the L Street property. The output of these sub-stations being direct current, they are, with one exception, equipped with storage-batteries.

Many of the business people of Boston live in the surrounding cities and towns. Up to a few years ago most of these suburban places had their own local electric-light companies, usually operating small uneconomical steam-generating stations equipped with more or less obsolete forms of machinery.

Within the last two years the Boston Edison Company have purchased the property of many of these local companies, and

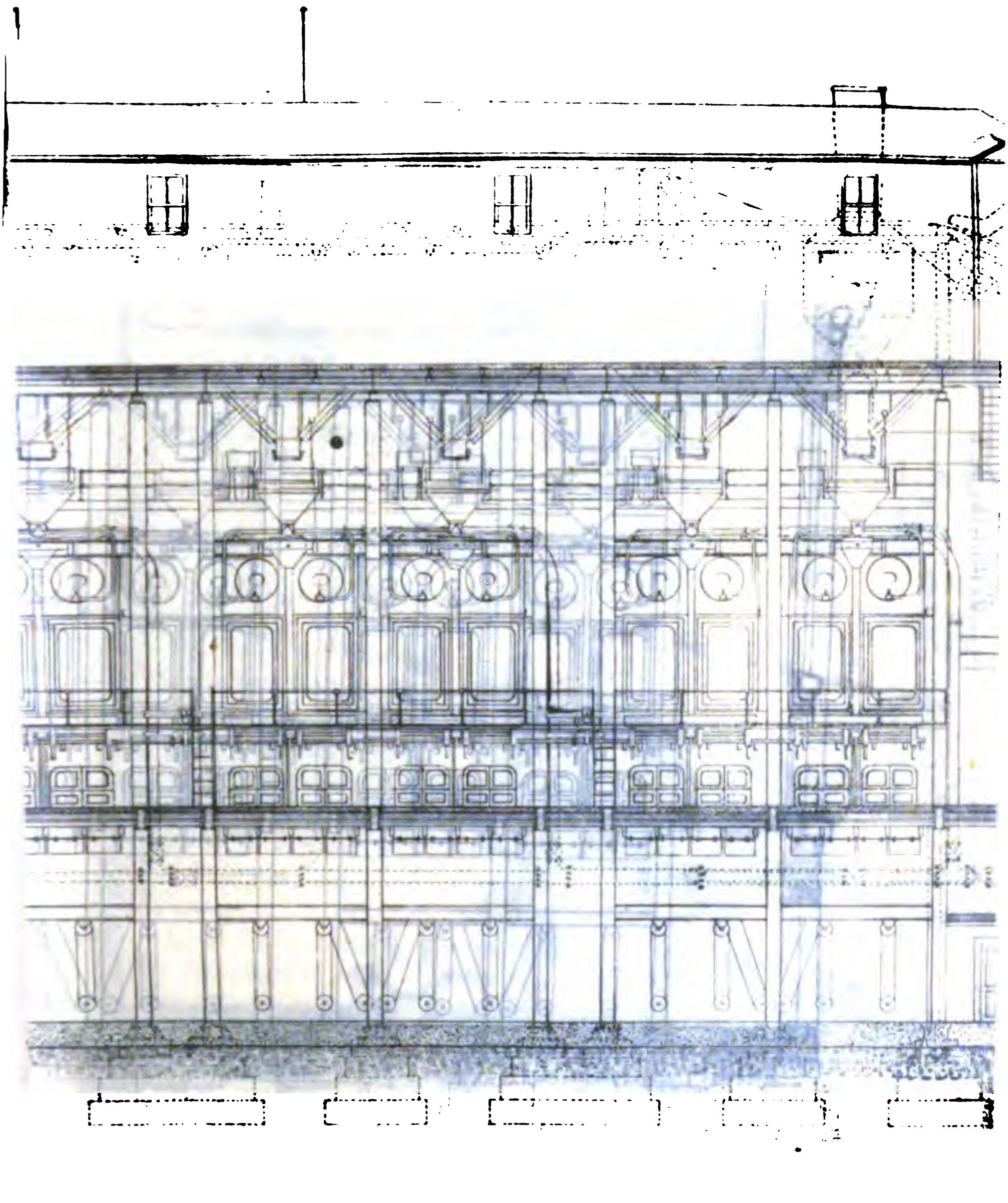
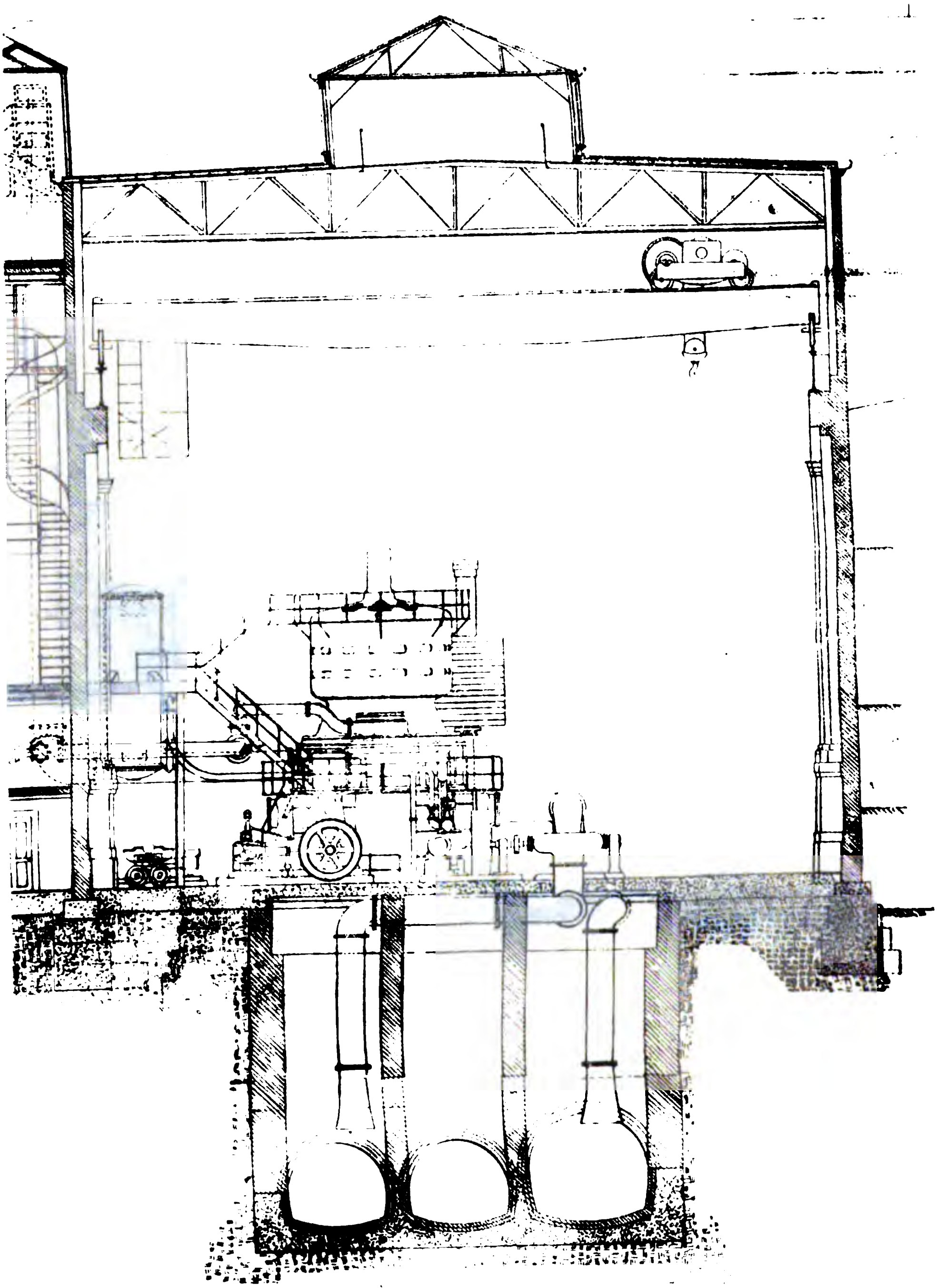


Fig. 1. Sectional Elevation through Turbine and Boiler House.



in most instances are changing the stations to modern alternating current sub-stations, making a suburban business which extends in various directions from 12 to 30 miles outside of the city.

This large increase in suburban territory together with the rapidly growing city business called for an immediate enlargement of the alternating-current station which was already loaded to its full capacity. A new station was therefore planned with an ultimate capacity of 60 000 kw. to be built on the L Street property alongside the existing station. The first installation of 10 000 kw. is just being completed. The position of the existing station on the property was fortunately such that it was no handicap in the location and arrangement of the new station. As a matter of fact, the old station naturally merges into and becomes a part of the new station, and had it not existed it is doubtful if any change would have been made in the design of the latter.

The value of the real estate is very small and will doubtless so continue for many years to come. Therefore the station buildings could spread out over the land as much as desired, and no attempt was made to build additional stories for the sake of saving ground area. Under these conditions, it is cheaper to spread out the buildings on the ground than to carry them up in the air to an equivalent area, and liberal room for and around the apparatus facilitates the operating, cheapens the cost of making repairs, and renders it easy to keep the stations clean.

The shape of the property was such as to make it desirable to erect the station with the end toward the water front, which naturally brought the building of that end of the station first.

The turbine-room will be 650 feet long, 68 feet wide, 56.5 feet high, and without a basement. It has no side windows. A liberal monitor with glass sides and roof gives a better distribution of daylight than do side windows and in connection with windows in the end walls provides good ventilation.

The boiler-house will be 640 feet long, 149.5 feet wide and of same height as the turbine-room. The arrangement of the boilers practically divides this building into seven fire-rooms. The lighting and ventilating is done from the roof similarly to the turbine-room.

The switch-house will be 605 feet long, 30 feet wide, and several stories high. The buildings for the installation of 60 000 kw. of machinery cover about 160 000 square feet, which is equivalent to about 2.67 square feet per kilowatt.

The ends of the buildings facing the water have been made the front of the station; with an entrance through offices located in the front end of the switch-house. The buildings are set back 136 feet from the sea-wall; the intervening space is covered with a fine lawn and planted with shrubbery. Through the centre of this lawn a paved driveway leads from the ornamental entrance gates on L Street to the office entrance, making a well-finished and attractive environment in keeping with the interior.

In designing this station the grouping of the apparatus has been given special attention and care has been taken so to arrange them that they naturally come under the charge of the class of operators best fitted to care for them.

The turbine-room has received all of the machinery in the station; even the boiler feed-pumps usually considered an adjunct of the boiler-house are treated as part of the turbine auxiliaries, and are placed in charge of the turbine operators, The boiler-house contains only the boilers with the necessary piping, etc., so that the work in this room is to burn coal properly and maintain the steam pressure.

All of the electrical apparatus has been grouped together and installed in a separate building adjoining the turbine-room, isolated from the noise and dirt of the latter and free from liability of damage by accidents to any of the turbine-room machinery.

The electrical operating, a matter of brain work, is done under as favorable conditions as are found in any office building, with no duplication of apparatus, and the operators cannot be disturbed by anything going on in the turbine-room. Escaping steam can neither damage the apparatus nor interfere with the work of the operators, while they can oversee any of the generating rooms by stepping through doors in the side walls on to observation galleries.

To add to the architectural appearance of the interior of the turbine-room, and also to facilitate the work of keeping the room neat and clean, it is finished with tile and enameled brick. The floor is tiled in dark red with black borders arranged in the form of a simple design to relieve the monotony of one color. The walls have a wainscot of two-colored green tile about ten feet high, and above they are paneled with a light-colored tile and

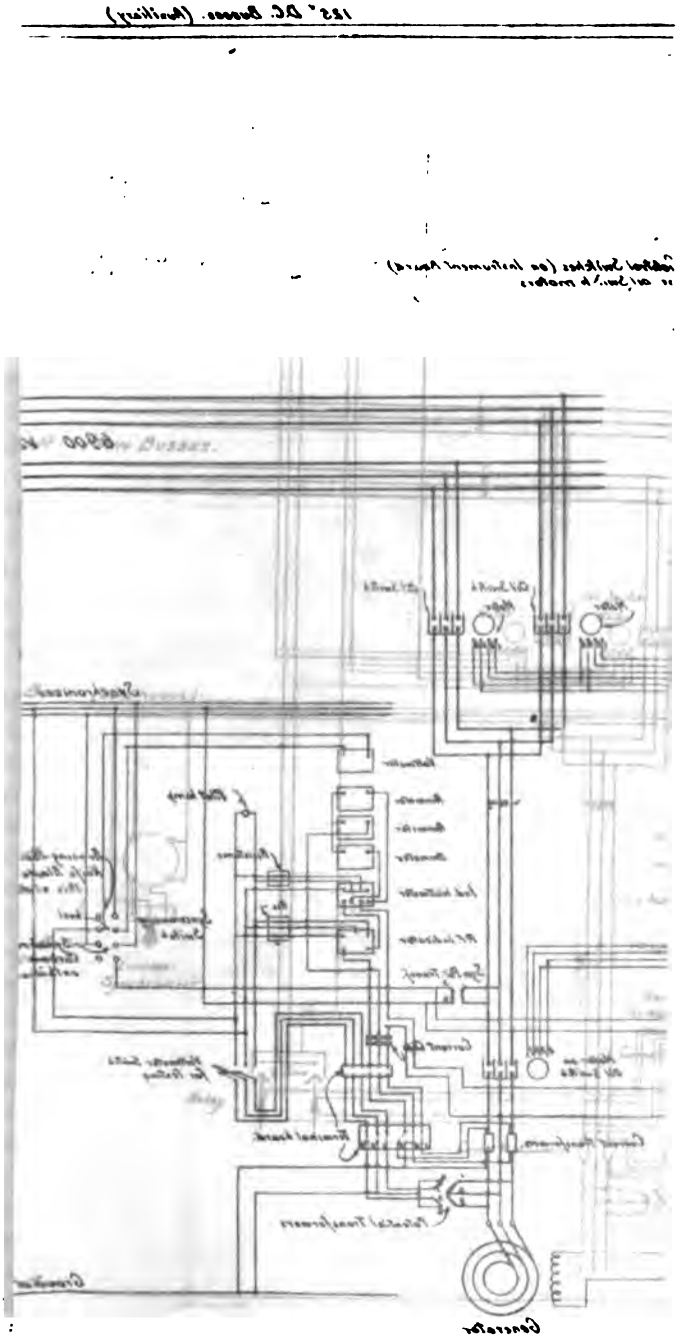
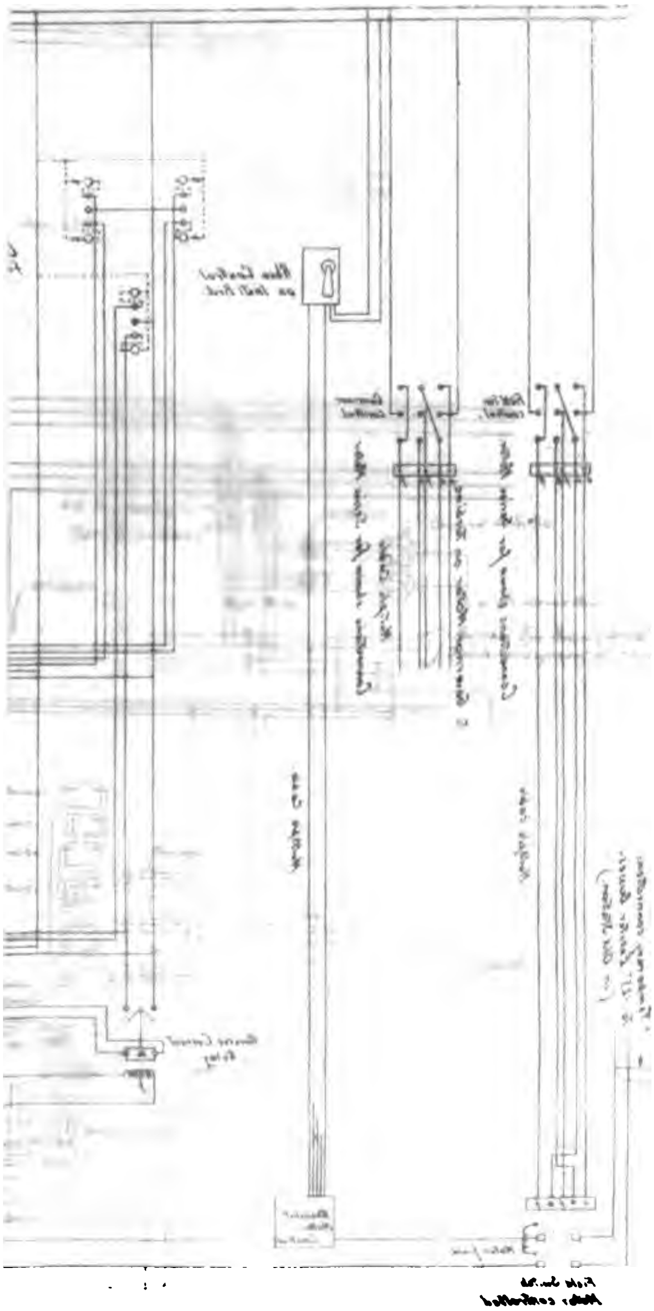


FIG. 2r—Typical Connecti



enameled brick. The crane track is concealed by the wall finish. The room is divided into three parts by permanent division-walls in which are large doors at the floor level, and large windows above, all equipped for quick closing. Ordinarily these will be opened, giving practically one long room, but in case of a serious accident in any room the openings can be quickly closed, isolating the trouble and leaving the other rooms free to operate without any interruption. The boiler-room has walls finished in tile similar to the turbine-room, but the floor is not tiled. The result is that these rooms are ornamental in character and are easily kept clean, while at the same time the cost of the decoration is quite moderate. Before the finish was determined upon, cost estimates were made on the various possible methods of satisfactorily finishing the rooms, including the up-keep for an extended period of years, and the finish employed was found to be the cheapest that could be adopted, being even less expensive than painting.

The exterior of the station buildings is simple and massive in character. Cut granite underpinning is used and the prominent walls are faced with a dark paving brick trimmed with terra-cotta.

The apparatus is installed on the unit system. In the turbine-room all the auxiliaries required for a generating unit are grouped around that unit and are generally of sufficient capacity to serve that unit alone. The boilers necessary to supply the generating unit are in one row directly behind the turbine. In this way each generating unit is a small central station in itself. Practically no cross-connections are installed between the various units except that between each pair of units the steam mains are joined by a small-sized tie so that a generating unit can be run temporarily from the boilers of its mate, should an emergency require. In this way a very simple piping system is sufficient, reducing the cost of installation and maintenance, and simplifying the manipulation of the station under emergencies when the engineer has to think quickly, and when he must be sure that the manipulations are made rapidly and correctly. The duplication of auxiliaries is eliminated, and should a generating unit be put out of commission by the failure of any one of its essential parts, it is intended that the entire unit will be shut down and another one started in its place.

Before determining upon the apparatus to be installed in the station, careful consideration was given to the respective merits of turbines and reciprocating engines as prime movers. The advantages of the turbine over the engine in first cost, the lesser amount of help required to operate, the ability to use condensed steam with safety for feed in the boilers, together with the fact that the apparatus takes very much less room decided the question in the favor of the turbine. These considerations were held to justify the decision without regard to the water consumption, and the decision will be considered wise even though the water consumption proves to be no better than that of a good engine, although it is expected to be better. Another important feature is the ability to start an idle unit quickly. The earlier turbines were open to improvement in this respect, but the later machines have been safely started and brought up to full load with remarkable speed.

The turbines used in the first installation are of the Curtis type with a rated capacity of 5 000 kilowatts on a conservative temperature rise in the generator. They are four-stage machines with surface condensers built in their bases and are equipped with mechanical brakes for bringing the machine to rest for an emergency stop. In these features they are the first machines of their kind to be installed. The base condenser was adopted because it will give a somewhat better vacuum in the turbine, which is an important consideration in turbine work. It also considerably reduces the floor space required for the installation, somewhat simplifies the piping, and makes possible a more symmetrical and pleasing grouping of the machinery. Its disadvantage is that it increases the height of the turbine a few feet, which is, however, of little moment. Its first cost is somewhat more than an independent condenser, which may be partly balanced by the saving in piping; it also requires special arrangement for filling the condenser tubes with water when the turbine is to be run non-condensing.

The brake is very useful for emergency shut-downs, because the turbine will run for some hours with no load and no field, while with the brake it is possible to bring the machine to rest in about five minutes. It also facilitates the overhauling of the step bearing by sustaining the weight of the rotating parts.

The generator is a three-phase, Y-connected, 60-cycle machine, generating at 6 900 volts. This number of cycles was determined upon because the bulk of the alternating-current business is lighting, and also for the reason that the existing alternating-current apparatus has the same number of cycles.

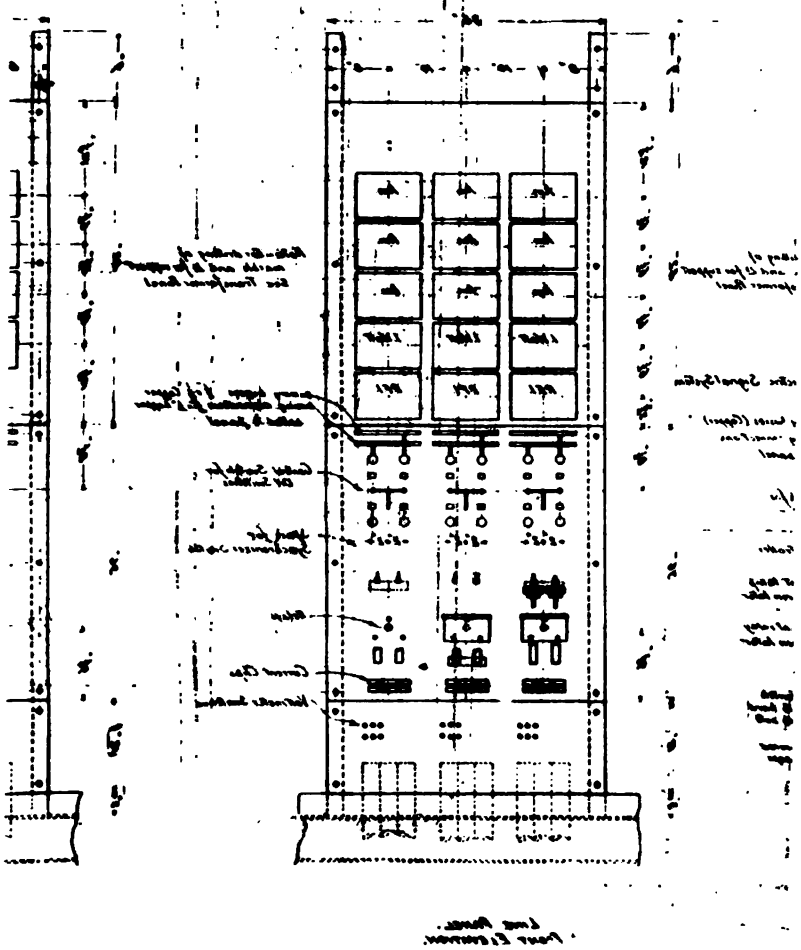
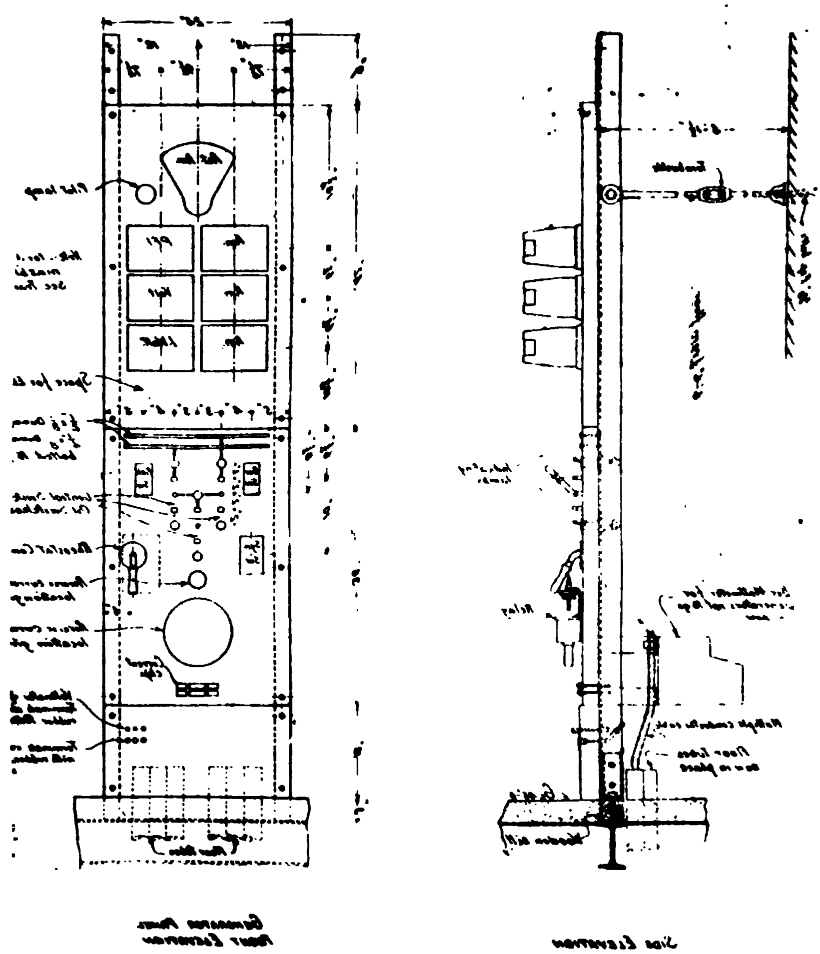


Fig. 3. Typical Control Panels.



The auxiliaries for each turbine consist of a circulating-pump, a wet and a dry vacuum-pump, a step-pump, a hydraulic-accumulator, and a boiler feed-pump for the group of boilers connected to the turbine. All these machines are steam driven with the exception of the wet vacuum-pump which is motor driven because its speed is too high to be conveniently handled by an engine. Careful consideration was given to the subject of steam- versus electrically-driven auxiliaries, and steam was determined upon because it gives better station economy. All the exhaust steam from the auxiliaries is carried to the feed-water heater and is condensed in heating the boiler-feed. The condensation is then discharged to the sewer as it contains too much cylinder oil to warrant trying to purify it. As all the exhaust from the auxiliaries can be condensed in heating the feed-water, the greatest possible use is made of the heat originally put into this water in the boilers, for practically all that is not taken up in the form of work in the engine cylinder is returned to the boiler in the feed. Moreover the first cost of steam-driven auxiliaries is less than electric drives, and speed regulation over wide ranges is much more easily accomplished.

The circulating-water pump consists of a centrifugal-pump driven by a simple high-speed engine with a throttle governor. The quantity of water to be handled is very great, and the head very low, so that a centrifugal-pump is well adapted for this duty. It also makes a very much smaller machine than a piston-pump, is much less expensive, and at the same time it is very simple and requires almost no attention.

The distinctive feature of the dry vacuum-pump is that the air-cylinder is placed at a right angle to the steam-cylinder, thus giving a better turning moment on the crank, and it takes less room. The air end is built single stage, and will maintain a vacuum on a closed tank within one-half inch of absolute. The steam end is throttle governed to permit of speed variations while running. The wet vacuum-pump consists of a two-stage centrifugal-pump, motor driven. This pump will maintain a vacuum in the condenser equal to that of the dry vacuum-pump without the use of either suction- or discharge-valves; thus requiring a minimum amount of repairs and almost no operating attention. The boiler feed-pump is an ordinary duplex, center-packed plunger-pump, selected because it is easier and quicker to repack, and a casual inspection will show if there be leakage from the plungers.

The step on the turbine is lubricated by water instead of oil, because the water is as good a lubricant for this purpose, is cheaper, and the lubricating system simpler. The water is forced into the step under a pressure of about 900 lb. by a steam pump of similar design to the boiler feed-pump. As even a momentary stoppage of the water supply to the step would result in damage to the bearings, a motor-driven triplex-pump, which can be started much quicker than a steam-pump, is installed as a relay to the main step-pump. To obviate fluctuations in the pressure due to the pump's reversing its stroke, a weighted hydraulic accumulator is used. This is made of sufficient capacity to keep the step supplied with water for ten minutes, thus giving time either to shut down the turbine by means of the brake or to put the relay-pump in service, should the steam-pump fail.

The condensing apparatus is designed to condense 153 000 lb. of steam per hour and maintain a 28-in. vacuum in the condenser, with the cooling water at summer temperature of 70 degrees Fahrenheit. The same apparatus under winter conditions and when the heaviest loads occur on the station, will give a vacuum within about three-quarters of an inch of the barometer.

Brick tunnels running under the center of the turbine-room, at such a grade that they are always flooded, convey the cooling water to the pumps. They are constructed within the building, so that the machinery can be installed above them. For additional insurance, two tunnels are provided for the incoming water, each supplying one-half the station. The notable feature of this system is the intake construction at the sea wall. Racks and screens, provided to keep out all floating material, are so installed that they require very little cleaning, and the screens are arranged to be easily removed and cleaned without permitting debris to pass into the tunnels. Where the tunnels join the screen chamber, heavy timber gates are provided so that the tunnels may be pumped dry for inspection of repairs. The water-front construction is of concrete with a wing-dam so designed that, while the warm discharge-water empties into the harbor alongside of the incoming tunnels, thus simplifying the construction, at the same time the latter tunnels get the coldest water available, without danger of taking any of the warm discharge-water.

The rows of boilers are placed in pairs alternately face to face and back to back, with a chimney for each pair midway of the row and between them. Thus six chimneys in all are required, each being 230 feet high above the level of the grates, this height dispensing with forced draft. Building the chimneys between the rows of boilers, considerably increases the ground area of the boiler-house, but the additional space is very useful for work-room, toilet-rooms, etc. The boilers are elevated from the ground to provide liberal space beneath for the ash handling. Large brick chambers immediately below the boiler furnaces collect the ashes, and discharge through valves in their bottoms into carts or cars on the ground floor. Other distinctive features of the boiler-room are the provisions for bringing air to the furnaces, the location of the piping mains, and the small capacity of the coal-bunkers.

The ash-room has a free circulation of air at all times through openings in the exterior walls which are without doors and are provided with grilles. In the front wall of each ash-chamber, close to the fire-room floor, are openings equipped with dampers admitting air directly to the ash-pits and maintaining an adequate supply to the furnaces, while permitting the windows and doors in the fire-room to be closed, during extreme weather conditions.

A portion of the basement under each two rows of boilers is separated from the ash-room by partitions forming the pipe-room. Immediately under each row of boilers in this pipe-room are installed all the various pipe-mains which connect with them, and only branch pipes to each battery of boilers are taken into the fire-room. This puts the most of the boiler-room piping into a warm, clean room by itself where it is accessible, free from cold drafts which would tend to start leaks, and where it can be carried upon substantial supports.

The grouping of boilers and turbines which has been adopted gives a smaller amount of piping than would be the case were the boilers placed in the usual manner in two rows, parallel to the turbine-room, and makes a very short smoke-flue with a minimum amount of reduction in the draft.

Supplying each row of boilers is a line of coal-bunkers built in monitors above the roof. As there is practically no piping on top of the boilers, little space is needed above them, and building the coal-bunkers in the monitors enables the boiler-house to be made quite low, saving considerable expense in the cost of the structure, and also making a small waste space above the boilers to be heated. As there is always a large amount of coal stored alongside the station, the capacity of the bunkers is made small, being sufficient to last during the time of making routine repairs in the coal-conveying system. This reduces the cost of the building very materially. The boilers are equipped with the attached type of superheaters and automatic stokers. They are higher by two rows of tubes than is the usual practice, which provides for additional storage of hot water, and in such form that it will also serve as additional heating surface.

The amount of superheating, 150° fahr., was made conservative to be sure that the temperature would not cause trouble with flanged joints and in the steam-cylinders of the auxiliaries. The attached type was selected because they took no additional room and are self-regulating. Use of superheaters at the direct-current station shows a gain of about 9% per 100° fahr. of superheating in the engine economy, and while with the attached type it is impossible to make comparative tests with and without superheaters upon the same apparatus, the station economy indicates a substantial net gain by moderate superheating.

Stokers were selected that seemed to give the best results with the high-grade fuel used in New England, and with a minimum amount of repairs; the labor required to operate them is small, and very little combustible fuel is wasted in the ash pits.

Beneath the coal-bunkers small non-automatic weighing hoppers are installed. Direct-reading beam-scales are used because they are reasonably accurate, cheap in first cost, and are easily tested.

No economizers have been installed because of their doubtful value under the operating conditions of this station and of their effect on the chimney draft, which is liable to cause a reduction in the capacity of the boiler plant at the time when the maximum is needed, or else make it necessary to cut the economizers out of commission at a time when they would be most useful.

The storage of coal is a very essential feature of a large central station, and is seldom adequately taken care of. Alongside of this station and adjacent to the water front an open-air storage of from 60 000 to 70 000 tons of coal is provided where the coal is stored without any shelter and immediately on the ground. The winter's supply of coal can therefore be purchased while the freight rates are low during the summer time, even including the loss from weathering coal, this reduces the cost of fuel delivered in the fire-room.

The coal-wharf is equipped with an electric tower, operating a one-ton clam-shell bucket and one electrohydraulic tower operating a similar bucket of 1.5 tons. The electrohydraulic tower is of a new design in which vertical hydraulic-elevator cylinders furnish the power for operating the bucket. The water pressure is obtained by a three-stage centrifugal-pump driven by an induction motor. This pump is automatic in its action, and when the water pressure reaches the maximum point the pump continues running and maintains that pressure without delivering any water until the pressure drops. The tower is operated by one man, with a minimum amount of physical exertion.

The coal is conveyed from the wharf to the storage-yard by a system of conveying belts, the conveyors from the wharf to the yard having a maximum capacity of 700 tons of coal per hour. This conveying system was adopted because it was possible to obtain a very large capacity when desired, with a minimum amount of attendance and repairs.

The storage-yard is equipped with an electric reclaiming-bridge which operates a clam-shell bucket of the usual type and of two tons' capacity. This bridge is so installed that it will cover the entire storage-yard, and besides taking coal from the field and putting it on to the conveyor running into the station, it is very useful to turn over the coal quickly should it show signs of heating.

The distinctive feature of this reclaiming-bridge is the fact that all the machinery for operating the bucket is installed on a trolley car running on the deck of the bridge. The operator riding on this trolley is always immediately over his work, and can control the motions of the bridge at the same time he is operating the bucket.

The water-supply for the boilers is of equal importance to that of the fuel. Water-service pipes of ample capacity for the total station are brought into it from large mains in the two adjacent streets. These will shortly be fed from separate trunk mains. For a further safeguard to the water-supply, a system of storage-tanks, with a combined capacity of 50 000 cubic feet of water, or sufficient to run one turbine on the condenser for about ten days, is installed on the ground alongside the station building and at an elevation considerably above that of the feed-pumps.

An inspection of the wiring-diagram will show the general arrangement of the switching. There are of necessity three bus-bar pressures, the excitation, and the possibility of a fourth pressure being required later. The engine-driven alternators generate, as stated above, at 2 300 volts, and the turbine-driven alternators at 6 900 volts. This latter was fixed upon after careful consideration of the location of the present business with reference to the station and of its probable growth. There is also a certain amount of 4 600-volt business which crept into the system some time previous because a considerable amount of business developed at a distance too far away for the economical use of 2 300 volts, and the standard cables on the system would safely carry only 5 000 volts. Therefore, the simplest expedient at that time was to install two-to-one transformers and supply them from the old station bus-bar. This business which started in a small way long before a turbine station was considered had grown to a considerable size at the time the turbine was installed, and the loss in the underground cables and other apparatus—which would have no commercial value in case this pressure was changed—prohibits making any change at the present time. The turbine pressure of 6 900 volts promises to be ample for the present needs of the company, but it can be easily foreseen should the lines be extended beyond their present limits or should the business at the end of some of the transmission lines materially increase, that this pressure might be too low. If this happens, it is planned to double the pressure on the transmission lines in question and transmit in these instances at 13 800 volts. All transformers installed on these lines are built with 13 800-volt taps.

The bus-bars in each system are installed in duplicate, and so arranged that they can be cut into short sections of no more than 10 000 kw. each by tie-switches, and any transmission line or generator can be isolated if it is desired to do so. Transmission lines are grouped with the generators on a section of bus-bar so that this bus-bar does not have to carry much current any distance lengthwise. The generator is connected to the bus-bars through one main-switch and two selector-switches. These switches are designed to open under the full station capacity, should emergency ever demand it. The transmission lines have selector-switches but no main-switches at present, space being reserved for the installation of main-switches should they prove desirable later.

The switches are all installed on the third floor of the switch-house. The selector-switches are in two rows. Each row consists of two groups of switches (placed back to back) running through the center of the building and immediately over the bus-bars to which they connect. The main-switches are installed in two single rows, one on each side of the switch-house and against the side walls. On the floor below, the bus-bar compartments are arranged similarly to the selector-switches, two rows of two through the center of the room. In two single rows on each side wall immediately under the main-switches are grouped the instrument transformers in special compartments.

The oil-switch cells, the bus-bar chambers, and the instrument transformer chambers are all built of a light-yellow brick with a fine cement joint, the brick being selected for its low absorption properties. The barriers in the bus-bar compartments and also in the instrument compartments are of reinforced concrete with a fine, close-grained finish. These are all made in moulds and set in place as is done with alberene; they have as good insulating qualities as alberene with less absorption, are much cheaper, and furthermore are less liable to break. The bus-bar chambers are fully enclosed, small doors being left in the wall for access to the connections only. The instrument transformer cells are left open. The front of each switch-cell is enclosed with a wooden frame filled with a pane of glass which permits an inspection of the pot; at the upper part of the frame there are a few slats for ventilation, and for vents in case of an explosion.

The transmission lines and also the turbine-leads and transformer-leads enter the basement of the switch-house in duct-lines which terminate in this room and at a point nearly underneath the selector-switches that they connect with on the upper floor. The lead-sheathed cables terminate in end-bells as close to the end of the ducts as possible, from which points cable with flame-proof braiding is carried on glass insulators and through porcelain tubes to the switches overhead. From the end of the ducts, the cable is taken in air-runs and they are so grouped throughout the basement that there is ample air-space between all cables. Provision has been made for the installation of static-discharge apparatus in this basement but at present none has been installed.

The electrical operating-room is on the top floor of the switch-house in about the center of the building and contains nothing but the operating apparatus. Convenient stairways leading down from this room through the switch-house bring the operator in close touch with all the switching apparatus. A signal system similar to that used on board ship enables him quickly to communicate his orders to any of the generating rooms, doing this with a certainty that the order will not be misunderstood. This system also provides for an acknowledgment indicating when the order has been carried out.

All the switching apparatus with the exception of the excitation system is remote-controlled. The controller panels with all the necessary instruments are grouped in the operating-room in the form of a rectangle, facing inward so that the operator can see at a glance any panel in the room. The excitation switching is hand-controlled. The bus-bar for this is brought into the operating-room and placed between the two groups of switches controlling the engine-driven alternators and the turbine-driven alternators. The panels for the ground-detectors are installed alongside the excitation bus-bar so that the operator has grouped at one end of the room all the apparatus which requires constant attention. The transmission-line panels, transformer panels and others are scattered along down the room in the order that is most convenient for their installation, without reference to the sequence of the switches themselves down stairs.

The excitation is furnished by one small steam-driven set of sufficient capacity to start up an engine-driven alternator in case the entire station should be shut down, three small motor-generator sets located in the old engine-room having a capacity sufficient for all the engine-driven alternators, and three large motor-generator sets, one in each of the individual turbine-rooms with sufficient capacity to supply the turbines. In addition to the motor-generator sets there is a storage-battery with capacity of 1 000 amperes for an hour, floating on the excitation bus-bar. Besides the generator fields, there are fed from the excitation bus-bar a few other pieces of apparatus which are particularly necessary to the operating of the station, such as the motors operating the oil-switches, the relay-pumps for the step-bearings, and a few lights around the station which would be essential in case the general lighting system should give out.

Unfortunately no test or station-economy figures can be given at this time. The turbines are still in the builder's hands and while the first machine has been in commercial service for about three months, the conditions under which it has been operated make the station-economy figures of little value.

Much more could be written upon this subject if space permitted, but so many distinctive engineering features in the station call for special mention that this paper is of necessity rather long and unfortunately seems to have an appearance of being merely descriptive rather than technical.

Simplicity and reliability have been the aim of the engineers throughout the work. Experimenting and the use of untried devices have been avoided. Special care has been taken to install apparatus which would operate continuously with a minimum cost of attendance and repairs, notwithstanding the fact that this would oftentimes largely increase the cost of the installation.

DISCUSSION ON "MODERN CENTRAL STATION DESIGN AS EXEMPLIFIED BY THE NEW TURBO-GENERATOR STATION OF THE EDISON ELECTRIC ILLUMINATING COMPANY OF BOSTON."

PRESIDENT LIEB: The paper by Mr. Moultrop on "Modern Central Station Design," brings us face to face with a problem which has been before us these 20 odd years. It will not be a loss of time to consider for a moment the progress which has taken place in central station development, and in order to place this before you the speaker will abstract some of the data and some of the conclusions drawn therefrom as they appear in the last United States census report.

In the last census report, covering the operations up to June 30, 1902, there were in operation in the United States 3620 central electric light stations, of which the cost of construction and equipment was $504 740 352. The income from light and power distribution was $85 700 605 and the total expenses of operation $68 081 375. It was also estimated at that time that the power required for the central stations was 1 379 941 i.h.p., with an additional 438 472 h.p. in water wheels. The current output from lighting stations alone has been estimated at 2 453 502 652 kw-hr., and there were connected to these stations 385 698 arc lamps and 18 194 044 incandescent lamps, or including the electric light service operated from railway power plants, the total income for 1902 becomes $90 458 420, the total number of arc lamps 419 561, and the total incandescent lamps 19 636 729; these figures do not include the installations in isolated plants. It will be seen, therefore, that the central station industry has made remarkable strides, particularly when it is recalled that the industry is only 23 years old, whereas the gas industry dates from 1806. A brief comparison between the progress of these rivals in the business of artificial lighting may be of interest.

We find in 1902 that while there were in operation 3620 electric light stations, the number of gas plants was 877. The income from electric light plants was in excess of $85 000 000 and from gas plants approximately $75 000 000. It is interesting to note that whereas there were 2714 electric light stations in cities of 5000 inhabitants and less, there were in the same class of cities only 200 gas plants. Of the total income from the central lighting stations 29.7% was from arc lighting, 52.1% from incandescent lighting, 16.4% miscellaneous electric service and 1.8% from outside sources.

The design and construction of the power-house is influenced not only by the local conditions but also to a large extent by the personality of the designing engineer. One of the main features influencing the design which is perhaps not duly appreciated in the selection of the equipment of boilers, engines, and dynamos, is the effect which the load-factor should have in the selection of the apparatus, and the extent to which the maximum and part loads on the power-house are distributed throughout the hours of the year. In one of the largest electric lighting stations of this country it is found that of the total generating capacity, 10% of it is used only during 25 hours of the whole year, and these 25 hours come within the range of one month's operations; 25% of the capacity of the plant is used but 75 hours in the whole year, and practically all within two months; one-half of the plant capacity is used not over 500 hours of the whole year, all within seven months. It can be seen, therefore, that this factor is well worthy of consideration in the selection of the generating equipment, and it does not follow necessarily that for the part of the equipment to be used for such short periods the highest efficiency represents also the highest commercial economy when investment costs are considered.

H. G. Stott: A matter of great importance in central station design is the ratio of the interest charges plus depreciation to the operating cost. This ratio is, of course, largely dependent upon the load-factor, which, in a lighting plant, is extremely low; as an example, 50% of the machinery in a lighting plant operates only about 300 hours per annum, so that it becomes most important to keep down the first cost; for assuming that a plant costs $125 per kilowatt capacity, then the interest and depreciation charges upon the portion of it used for peak load would amount to 5.2 cents per kilowatt-hour, or probably five times as much as the operating cost. Upon the same basis an extra investment of $12.50 per kilowatt would mean 0.5 cents extra per kilowatt-hour of fixed charges. From a consideration of the above it is evident that it is more important to keep down the investment on that portion of a plant which is only used on peak load, than it is to make it highly efficient.

The ideal plant is one in which the fixed charges are equal to the operating and maintenance cost. In this connection, the adoption of the steam-turbine is undoubtedly a step in the right direction, as the investment is probably 30% less than for reciprocating-engine units. In the same direction a material decrease in the cost of plant can be obtained by purchasing machinery with a large overload capacity for two hours, 50% overload capacity for that time being readily obtainable, and at a slightly greater increase of cost, as much as 75% overload capacity.

Apparatus operated at this overload will not and need not be so efficient as at normal load, as a comparison of the operating cost and the fixed charges shows that the former is relatively of no importance on peak loads.

The speaker questions the wisdom of omitting the cross connection between the various units, referred to by the author on page 33. The absence of these cross connections is a mistake from every point of view; this absence might cause the shutting down of a 5000-kw. unit on account of the breakdown of a 10-h.p.

pump. The same criticism applies to the cross connections of the steam mains, because if one unit is shut down suddenly and another unit is needed, it will be necessary to use six or eight boilers that have been banked. This process requires the use of coal, whereas if there were sufficient steam cross connection it would not be necessary to fire any more boilers.

In any lighting station with large one- or two-hour peaks, the banking of boilers will require almost as much coal as the actual operation of the peak-load part of the plant. The speaker does not agree with the author that a turbine-driven unit can be started more quickly than an ordinary engine-driven unit. He has seen 5000-kw. engine-driven units started in less than two minutes.

The cost of condensers, relatively to the cost of the entire plant, is a matter of some interest. A large surface condenser with extremely high vacuum will probably cost $8 per kilowatt. A barometric condenser which will give equally high vacuum can probably be had for $2 a kilowatt. Here is a difference of $6 per kilowatt in an investment and that $6 means, for 300 hours' use a year, one-quarter of a cent per kilowatt-hour in fixed charges. The extra cost of water due to the use of a barometric type condenser would be less than 0.01 per kilowatt-hour. It seems then that there would be a saving of 0.24 of a cent per kilowatt-hour by putting in the cheaper condenser, without taking into account the fact that water cannot be used over again more than about 75% of the time, due to leaky condenser tubes where salt water is used for circulating water.

F. C. Bates: On page 34, Mr. Moultrop mentions "the inability to use condensed steam with safety for feed in the boilers." In this connection the speaker wishes to mention the results of a recent investigation. In a large central station in New York City, approximately $6000 per annum is paid for boiler water for a 5000-kw. unit. Assuming that 90% can be saved by the elimination of oil from the turbine, we have a net saving of $5400, which sum represents 10% on an investment of $54 000. This sum of $5400 may also be said to equal approximately two pounds of water per kilowatt-hour on the following basis of calculation, which agrees within a few dollars with the actual records.

8 lb. water evaporated	1 lb. coal
Capacity of unit in kilowatts	5000
Load factor (hours per year)	4000
Kilowatt-hours per year	20 000 000
Tons of coal per year	1250
Cost of coal per ton	$2.25
One pound water per kilowatt-hour	$2812

Philip Torchio: One of the points which occurs to the speaker is that Fig. 1 illustrates one characteristic of the new station design, and that is, on account of the reduced space taken up by the engines, the boilers have been put at right angles to the engine room, contrary to the usual standard station layout, where the engine room and boiler room run in parallel. The speaker has been connected with an operating company and has given some consideration to the layout of the electrical operating room and has had it entirely separated from the engine room, but he finds there are some drawbacks to that plan, as the operator in charge of a station of that kind should have nothing to interfere with his seeing all that goes on, but when he is confined in a room entirely separated from the place where the current is generated, he cannot keep in touch with the plant. The operating of a station of that kind is so important, that even small sounds mean a lot to the operator, which he detects, and which would be unnoticed by another man.

As to surface condensers being put in the base of a machine of the Curtiss type, to economize space, it seems somewhat unwarranted, as the turbine itself takes so little space there would be plenty of space available for the condenser outside and perhaps make the condenser more accessible and more roomy. The author says that careful consideration was given to the subject of steam- versus electrically-driven auxiliaries, and steam was determined upon because it gives better station economy. In general this would be found correct in American practice, though eventually there may be the possibility, with the further development of the turbine, of using steam turbine-driven auxiliaries, driven with electric motors and driven from the current generated by the turbine at a higher efficiency. Theoretically, in such a case you would get perhaps as good an efficiency as from the steam-driven reciprocating-engine units, which are necessarily of very poor efficiency.

The author says they have not used forced draught in Boston. Probably they do not use the small coal which is used in some parts of the country, in which case the forced draught would be a necessity. What is the draught of the chimney in inches? The superheat has been limited to 150 degrees fahr., which is probably a sufficient limit and one which is a commercial limit. If the auxiliary should be driven by the steam-turbine the superheat could perhaps be increased somewhat without running into the danger of getting into trouble with reciprocating-engine steam auxiliaries.

As to what Mr. Bates has said about the saving of water, which would compensate to a large extent for the poorer economy of steam turbines, equivalent to about two pounds of steam in favor of the steam-turbine, the speaker does not think that the figure would be so much for commercial load-factors in lighting stations because that figure can be anywhere from perhaps one-tenth of a pound to two pounds. It depends on the number of hours the turbine is run in the course of the year. The speaker agrees with Mr. Stott that cross-connection of steam mains would be desirable in a station of this character. He does not agree with Mr. Stott in the statement that surface condensers are undesirable in connection with steam-turbines, but he certainly thinks that the point is well taken if it applies to steam-engine units.

J. H. HALLBERG: The speaker reminds Mr. Torchio that recently public attention was called to the fact that the jet condenser has been used successfully at the Atlantic Mills in Providence, on a 750-h.p. Parsons turbine, with 28-in., or better vacuum. It has been entirely satisfactory.

C. O. MAILLOUX: The author's comments on steam turbine-driven auxiliaries are interesting. In Europe the speaker has seen places where steam-turbines are used to drive feed-water pumps successfully. There are great possibilities ahead for this kind of auxiliary apparatus, as soon as the pump is sufficiently developed and made cheap enough; but there is danger of getting our steam auxiliaries too efficient in the use of steam. On page 38 the author gives sufficient reasons for leaving out the economizers. In the absence of economizers, means must be provided for heating the feed-water, and usually the heat from the exhaust of the auxiliaries is used for this purpose. When the steam consumption of the auxiliaries is small, there is danger of not getting exhaust enough properly and adequately to heat the feed-water.

The speaker thought a case might arise where live steam would have to be used to heat the feed-water to a point where it would be sufficiently warm to feed it into the boiler without producing troubles from contraction due to insufficient heat. All needs considered, perhaps it is just as well not to attempt too much in the way of undue economy in steam-driven auxiliaries. The speaker has had to deal with this problem in a practical way recently, and he is more worried about not having enough steam from these auxiliaries than he is from having too much; he fears that he will have to resort to some means other than the auxiliaries to heat the feed-water sufficiently. He knows of cases where it has been proposed that a connection may be made at the second or third stage of the Curtiss turbine so as to furnish live steam—steam which has done some work and is partly expanded—for the purpose of supplementing the action of the feed-water heater.

The condensing tunnels of this station are particularly interesting to the speaker. The fact that there are three tunnels, giving a spare one for emergencies so that normally while each one of the intake tunnels may take only one-half the water, yet it might, in emergencies, serve for the whole at a slightly increased velocity, is particularly interesting. In a large plant with which the speaker is closely identified, he has endeavored to go one step farther; that is, to utilize the other tunnel so that in case of necessity it could be used as an intake or discharge tunnel. This can easily be done by modifying the design.

The speaker agrees with Mr. Torchio and others that favor the surface condenser. The speaker's experience with a jet condenser is that it fails entirely for steam-turbine work, and does not give anything like full vacuum especially on overload. The speaker has investigated the barometric condenser carefully; he found that while there was undoubtedly much better prospects of getting satisfactory vacuum, yet there seemed to be an element of chance in it.

Perhaps it will be of interest to note that the vacuum obtained in this country is considerably more than that obtained in Europe. In Europe they are quite satisfied when they approach 27 in.; in many places 26 in. seem to be considered fairly good. The speaker found a few places where it was thought that nothing better than 28 in. could be obtained.

The matter of placing the condenser in the base of the turbine is important from considerations other than that of space; the importance of having little loss of pressure due to the flow of the steam in the condenser pipe itself must be considered. In order to get as good a vacuum as possible, the fall of pressure in the steam pipe of the condenser itself must be reduced as much as possible. By placing the condenser in the base of the turbine the condenser is installed practically without any piping.

W. F. White: Mr. Stott's contention in behalf of the jet condenser is based on the difference in cost between the surface and the jet types of condenser; he distributes this difference over a comparatively few hours of the year, which is unfair because a large portion of the plant operates many hours per day. It follows that comparisons based on a few hours' operation per year do not hold good for that portion which operates constantly, because peak conditions are not average conditions. The surface condenser, due to the ability of turbines to utilize greater expansion and to benefit from higher vacuums than reciprocating engines, is undoubtedly preferable to the jet condenser. The decision as to the character of condenser to be adopted is not determined alone by the merits of the condenser itself, because the character of other parts of the station design will depend upon the type of condenser used.

With the jet condenser, outside feed-water must be used and no benefit is derived from the re-use of condensation. This condition affects not only the economy of the station in the cost of feed-water, but also materially affects the reliability of the boiler plant and the length of time during which the boiler can be operated continuously, and the cost of boiler repairs. This is an important matter in turbine station economy, because with surface condensers not only will boiler repairs and the fuel consumption be decreased, but the life of the boiler plant will be increased.

The decision as to the type of condenser also influences the use or non-use of economizers. With surface condensers, and using the condensation for feed-water, there is not the same need for economizers as with jet condensers. The exclusion of economizers may also mean the exclusion of forced or induced draft equipment. It is thus seen that the use of surface condensers in a turbine station may effect economies outweighing many times over the advantages of lower first cost of jet condensers and may easily reduce the cost of the station as much as $5 to $10 per kilowatt.

The absence of economizers in the Boston plant should be emphasized, as should also the arranging of all auxiliary apparatus under the immediate eye of the engineer, eliminating engine-room basement and otherwise reducing the total cost of the station. This Boston plant seems to have provided what most stations do not have, a sufficient coal-storage capacity. Most stations have their entire capacity in coal bunkers above the boiler room. It is impossible with reasonable cost of building to put an adequate supply in such coal bunkers. Most large stations, notwithstanding their expensive coal bunkers, have an inadequate storage. Every large station should have outside storage in addition to the bunker capacity above the boilers. If outside storage is necessary, then why make the coal bunkers overhead as large as is customary practice? A considerable saving in cost of building could be effected, without introducing any disadvantage, by reducing the capacity of the coal bunkers overhead, as the Boston company has done, and its example in this direction is to be commended.

H. G. Stott: The speaker takes issue with Mr. Mailloux on the question of the inability of the barometric tube condenser to maintain vacuum. The speaker can show this condenser operating with an average vacuum of 27.5 in. without the use of a dry-air pump; with the use of a dry-air pump attached there is no difficulty in maintaining 29-in. vacuum. This is within 1.5 inches of the barometer.

Mr. White has apparently overlooked one feature connected with the coal supply; that is, the possibility of bituminous coal taking fire when exposed to the air. Bituminous coal when warmed perceptibly will lose from 25 to 30% of its heat units.

I. E. Moultrop: Owing to the lateness of the hour the speaker will only take time to touch upon a few of the principal points brought out in the discussion. He would request the privilege of replying by letter to some of the other speakers after their remarks have been revised.

The speaker agrees with Mr. Stott that an engineer may be criticised for installing expensive apparatus to carry a peak load which exists for only a few hours during the year. This criticism does not apply to the station referred to in the paper, a station built to care for the increase in business of a large company. As the demand for power increases new apparatus of the very best quality is installed. The latest and most economical apparatus is used for the steady load and the older apparatus is retained for the peaks. The engineers of this company believe this to be the most economical method of equipping and operating their central stations.

Attention should be given to the cost of repairs as well as to the first cost of the apparatus. In the plant under discussion, special care was taken to install apparatus which would run continuously and overloaded when necessary, with a minimum cost of repairs.

The speaker does not agree with Mr. Stott that many cross connections are essential. The Atlantic Avenue station of the Boston Edison Company was originally built with many cross-connections; they finally became too complicated for practical use. Some were never used, and it is doubtful if the engineers would have been able to avail themselves of many of them in emergency. Most of these cross-connections were then removed and the station was operated just as well with much less apparatus to maintain. Possibly, in the station under discussion, the engineers have gone to the other extreme, but it must be remembered that this is the beginning of a large station and in such a station simplicity is essential. A very few cross-connections have been used, but generally each piece of apparatus, each line of pipe, and each cable or wire is put in to do only one thing. This reduces to a minimum the possibility of the operators making mistakes, which in a large station supplying a considerable territory by alternating-current transmission through sub-stations, might result seriously.

In the matter of condensing apparatus it should be remembered that this station was designed more than two years ago and that the apparatus is virtually two years old, although it has been in use only a short time. The speaker is quite sure that to-day this condensing apparatus can be improved upon and doubtless simplified. The form of the condensing apparatus should, in a measure, be determined by the location of the station and whether or not the supply of cooling water is suitable for feeding into boilers.

The speaker believes that it is very desirable to put the electrical apparatus and the electrical operating room in a separate building. This can usually be done with a very small increased cost. The men in the turbine-room generate the current and deliver it to the switch-house. The electrical operators maintain the pressure and distribute the current to the sub-stations and the outside system; they do not necessarily need to know what is going on in the turbine-room and do require a quiet room where there is nothing to distract attention from their work. In the station under discussion, the electrical operators can at any time see what is transpiring in the turbine-room by stepping through a doorway in the side wall of the switch-house.

The chimney is designed to give an adequate draft to burn an ample quantity of soft coal under any atmospheric condition. If mechanical draft were used the height of the chimney could be somewhat reduced, but the products of combustion, which will be considerable when the station reaches its ultimate size, have to be removed in such a way that they will not be obnoxious to the neighborhood. The chimneys would have to be built quite high for this purpose, even if some form of mechanical draft had been installed.

Replying to Mr. Mailloux, the speaker would state that an effort was made to install turbine-driven auxiliaries, but at the time the auxiliaries were purchased, no manufacturer cared to build slow-speed turbines for this purpose.

P. JUNKERSFELD (by letter): Mr. Stott says that the steam turbine has reduced somewhat the fixed charges of the station. In central stations of recent design, such as the one described by the author, the steam turbine has also reduced the so-called operating costs, particularly the labor item.

The writer now desires to call attention to the necessity of improving the quality as well as reducing the cost of the central-station product. The seriousness of the widespread and simultaneous effect of interruption in power and lighting, or transportation service, and the possible consequence can not usually be measured by any monetary standards. The quality of service or rather the degree of reliability which it is possible to furnish is necessarily circumscribed by commercial limits. In other words it is possible to provide for a greater degree of reliability than the income from the business will warrant.

Continuous service is dependent upon the efficiency of operating men as well as on the reliability of apparatus. Simplification of apparatus is always desirable, but a certain additional simplification in arrangement of apparatus and in methods of operation, even at extra expense, is often warranted in order to minimize the chances of error in operating and to localize trouble if it should start from any cause whatsoever.

The author's paper describes a type of station in which much attention has been given to these considerations. The selection and arrangement of proper apparatus for the particular conditions is of prime importance; it fixes largely the ultimate results to be obtained. However, a little extra care and thoroughness in construction which are not items of great expense, are often considerable factors in the results obtained after the station is in regular service. In addition to good workmanship on all apparatus, careful and conscientious detail work, and rigid inspection of all piping will do much to minimize future troubles and repairs. There is no part of the station which is more vulnerable than the high-pressure connections and auxiliary apparatus between the generators and the cable in the street. Such items as insulation and isolation of conductors in high-pressure apparatus and connections, the proper installation of cable terminals, and the provision for unfailing control of oil-switches—all these are worthy of much more attention than is ordinarily given.

Proper consideration of these and many other important details of construction, coupled with good design of the greatest simplicity which the commercial limits will allow are essentials in providing reliable service. The development of men and methods of operation needs unceasing attention to minimize the disputed ground between preventable and unpreventable troubles, troubles which will persist as long as we are dependent on the brain and hand of men to direct the design and operation of the station.

The central-station engineer in his efforts for economic results must strike balances between fixed charges and operating costs; for reliability of service he must strike balances between error of men and failure of apparatus.

A paper presented at a Meeting of the Chicago Branch of the American Institute of Electrical Engineers, Chicago, Feb. 28, 1905.

CEMENT IN CENTRAL STATION DESIGN.

BY EUGENE B. CLARK.

The Illinois Steel Company has just completed and placed in operation at its plant in South Chicago, a new power-house for the supply of power to its various mills at South Chicago, and at Buffington, 10 miles distant. This station contains, at the present time, two units, each consisting of a 2000-kw., 25-cycle, 2200-volt, three-phase generator, direct driven by a 24-in. by 60-in. by 48-in. horizontal-vertical, cross-compound engine. The addition of two more generating units, of a capacity of 4000 kw. each, is contemplated in the near future. This alternating-current station operates in conjunction with a direct-current station which has been in operation for some time. The two power-houses are connected by means of synchronous converters. Both stations take steam from blast-furnace boiler-houses, in which the fuel is excess blast-furnace gas. The supply of this excess gas is quite variable at times, and it is desirable under such conditions to be able to shift the load from one station to the other, as desired. Such an arrangement gives the opportunity of utilizing completely all excess blast-furnace gas at either point. The principal points of interest with which we are concerned to-night, deal entirely with the use of cement in the building of this and other power-houses.

The foundations for the machinery and the building rest upon piles and are made of slag concrete, consisting of one part cement, three parts torpedo sand, and seven parts crushed slag. The cement used for those parts of the foundations which are not exposed was of the brand known as "Puzzolan;" for those parts which are exposed, Universal Portland cement was used. The foundations were started in the coldest weather of last winter, and the concrete, which had to be mixed with warm water and warm sand, to keep from freezing in the mixer, did freeze immediately after being tamped into place. Filling was used to follow up the foundations as rapidly as they were put in place, so that the concrete was not permitted alternately to freeze and thaw as the warmer weather came on. The result was to obtain a thoroughly solid foundation, the concrete setting up firmly as it gradually thawed during the spring months. About the middle of summer the foundation was tested by drilling a hole several feet deep into that part which had originally been frozen. It was found that it had set up to make an extremely solid and strong concrete.

A considerable amount of time and attention was devoted to determining the most desirable method of floor construction. The power-house apparatus is controlled by electrically-operated switching devices. The electrically-operated switches, together with the bus-bars, control-pedestals, instrument-posts and feeder-panels, required for their accommodation the construction of galleries at one end of the engine-room. Two of these galleries were built, and the engine-room floor was used as another gallery. On the engine-room floor were located the generator-switches; on the first gallery were located the bus-bars, the instrument-posts, generator-control pedestals, feeder-panels, etc.; on the third gallery were located the feeder-switches and the lightning-arresters. A transmission line, carrying a pressure of 20 000 volts, was necessary to transmit the required amount of power to Buffington, located 10 miles south of South Chicago. At least 4500 kw. of transformers had to be located in the power-house. It was decided best to place these on the engine-room floor, under the first gallery, constructing an isolated transformer-room for that purpose. The transformer-room was isolated from the rest of the apparatus on the engine-room floor, by means of a wall about three inches thick and 17 feet high, built of reinforced concrete, in accordance with the method to be described later. This wall proved, after erection, to be thoroughly solid and substantial; as rigid, in fact, as would have been a masonry wall 12-in. or 14-in. thick. It then became necessary to take wires carrying a pressure of 20 000 volts through the operator's position on the first gallery. In order to harmonize these various requirements, it soon became evident that much additional space would be required if it should prove necessary to have the usual steel beams in the gallery floors, inasmuch as the beams would be in the way of the many wires which it would be necessary to take through these floors. These conditions pointed to the advisability of using a floor construction of concrete slabs or of fire-proof tile. Careful consideration of the subject proved that, even with the comparatively long spans for such heavy loads, the concrete construction would be far preferable, both from the standpoint of cost and from the standpoint of fire-proofing. Experience at the Baltimore fire had shown that properly constructed concrete floors had withstood the test of fire and water better than any other kind of floors.

To make certain of the safety and conservatism of the proposed design, a section of the floor, as proposed, was built and tested prior to the final decision as to the construction of the floor for the building and galleries. After being allowed to set 21 days, this section of floor was tested by piling pig iron upon it, to the extent of 500 lb. per square foot. The test slab was 7-in. thick and 15-ft. span, made of concrete, consisting of one part Universal cement, two parts Torpedo sand, and four parts 0.5 to one inch crushed limestone, reinforced with 0.5-in. steel rods, spaced five in. apart and laid on top of No. 10 gauge expanded metal placed one inch from the bottom of the slab. Upon test, the slab collapsed under a load of 550 lb. per square foot. An even distribution of the load over the surface was obtained by covering the top of the slab with about four inches of sand, upon which was piled the pig iron. Deflections were measured as the load increased. The deflection at the center had risen to about 1.5 inches by the time the slab failed. It was determined that the expanded metal was comparatively valueless for purposes of reinforcement when used in conjunction with the 0.5 in. round rods, as all the tension was taken by the rods. These rods were bent at the ends for a distance of about 10 or 12 inches through an angle of 180°, thereby insuring that they would not pull out at these points. It was found necessary to bend the rod through 180°, and not through 90°; for those which were bent only 90° showed a very decided tendency to crack the concrete at the corners and then to pull out. Round rods were used in preference to twisted or notched, or any other form of rods designed to prevent slipping or pulling out of the concrete, and for two reasons: first, the round rods are far cheaper; secondly, it was decided that nothing was gained by preventing the rods from pulling out of the concrete, provided they were properly fastened at each end. The mixture used in all the floor construction was one part Universal Portland cement, two parts Torpedo sand, and four parts crushed limestone, 0.5- to 1-in. mesh. The shoring under all floors was permitted to remain 28 days before removal. In the engine-room floor, for the very long spans, some floor beams were used, but in all cases they were entirely covered with concrete, to give thorough fireproofing.

Wherever generator-pits or fly-wheel pits were to be covered, such covers were made of cement castings, reinforced with expanded metal, rather than of cast iron. These cover plates were made to exact fit for each place as the work progressed, no drawings being necessary. The carpenter made a small mould of the correct size, in which the cement worker cast his floor plate and finished it exactly as the rest of the floor. The gallery floors were completed and the shoring removed before any work was done on the installation of the electrical control apparatus or the supports therefor. Each gallery was treated as independent of the one under it, so far as support was concerned, though, in building up the switch-cells, the bus-bar construction, and the barriers, the practical result was to give additional support to each floor from the one under it. The switch structure was also constructed in such a way as practically to be a beam in itself. Round iron rods were cast into the lower part of the structure and allowed to extend through from the first switch in the row to the last. The result was to provide a construction of the switch-cells which, being in itself a beam, would distribute the load to those points where the load might best be taken. In addition to this fact, the barrier which rose from the switch-cell to the ceiling above, taken in conjunction with the lateral barriers—all of which were built monolithic with the wall rising from the switch structure—formed a column of great strength. It would probably not be poor engineering to depend, in a measure, upon the strength of this column to support the floor above it; but in the case which is being described this was not done. Even though no attempt were made to utilize the switch structure as a column, still, the fact was taken into consideration that there would be a natural tendency, by reason of the presence of the switch structure, to transmit load from one floor to the one under it, and therefore to impose a greater load upon the lower floor than would be accounted for by the weight actually upon that floor. This effect was compensated for by giving the lowest floor additional supporting columns, which were placed between the basement and the engine-room floor. These columns were covered with expanded metal and a cement plaster to insure against failure, in case a fire should occur, due to the storing of inflammable materials. It had not been contemplated that such materials should be stored in the basement, but it was thought wise to provide against this contingency.

The roof of the engine-house was constructed of concrete laid in place as is usual for sidewalks. In each bay a removable wooden frame was secured to the structural roof cords in such a way as to permit of ready removal by knocking out wedges after the roof was in place. A thin layer of cement mortar, consisting of cement and sand, was placed on the top of this woodwork support. The function of this thin layer was to give a smooth coat for the finished interior of the roof. The expanded metal reinforcement was laid immediately on top of this preliminary coat, and was covered with about two inches of concrete of about the same mixture as was used for the floors. On top of this was placed a thin layer of rich mixture, which was given a sidewalk finish on the side exposed to the weather. After 28 days, the wooden supports were removed from the inside, by knocking out wedges, and were lowered to the engine room floor. The roof, made in this way, developed cracks after drying out. These cracks were filled by pouring into them a thin grout consisting of cement and sand. The result was to stop all leaks and insure a roof which was cheap and thoroughly fireproof. It has the disadvantage of being heavy and requires rather heavier roof-trusses than does a tile or slate roof; it is very strong and is not damaged by men walking upon it, or by falling pieces of stone or other materials. The latter consideration is an important one in the case described, because the station is located near blast furnaces, which, unfortunately, have the habit of throwing stone and ore out of the top at times. The advantage of using expanded metal on such a place as a roof, rested entirely in the economy of labor in handling the material. The writer believes the disposition of material in expanded metal to be uneconomical and, at times, disadvantageous. All of that material which lies transversely to the strain is wasted, and furthermore it is the speaker's belief that there is a tendency on the part of expanded metal, when subjected to strain, to elongate the diamond-shaped meshes and to shear off the concrete between the meshes. The tendency to shear the concrete would be trifling and unimportant if, in addition to this, there were not a tendency to break the concrete which is always placed below the expanded metal for fireproofing purposes. This lower section of concrete is generally about one inch thick; being in tension, it is apt to crack when the floor is heavily loaded. After the lower section of concrete cracks, there is a tendency for the expanded metal to shift in position, and therefore become ineffective. This belief of the writer's arises from observations of heavy beams reinforced with concrete and tested to the breaking point. He does not mean to convey the impression that for light beams, loaded comparatively lightly, expanded metal is not a desirable reinforcing material.

The electrically operated oil-switches which are usually mounted in a brickwork cell structure, were mounted in a cell structure built up of concrete. A collapsable wooden mould was made, set up in the proper position for the switch, and filled with concrete from the top. This mould was built similarly to a hinged flask standing on end, and was made large enough to allow of casting two switches at one setting. The mould was properly lined up, leveled, and braced to prevent moving while tamping the concrete. The bolts for holding the switches in place were set in the concrete of the cell structure by means of a template on top of the mould, just as foundation posts for engines are set. The concrete mixture was one part Universal cement, two parts Torpedo sand, and three parts screened limestone, which would go through a ⅜-in. mesh. After the mould was constructed, the only skilled labor required was that of the carpenter, who lined up the mould each time it was moved into a new position. After the concrete had set for approximately 48 hours, the mould was stripped and again set up for the next two switches. After all the switches of a row had been cast, and the moulds removed, the cement worker went over them to point up any voids which might have occurred in the corners, and to give the whole structure a finished appearance. The result was a pleasing one. It was decided that the mould—which in this case was built of dressed lumber, in the attempt to give a smooth and finished appearance to the concrete work—might better have been of rough lumber, in which case it could have been built for about $50. In case a large number of switches were to be built, however, the speaker would recommend the construction of a metal mould, which perhaps would cost $100. A mould constructed of metal would be free from liability to warp, which always exists in the case of a wooden mould. The wires leading from the oil-switches were separated from each other by means of barriers built up of thin slabs of concrete. The method of construction of these barriers was simple and effective. Pipes, or 0.5-in. rods, were set up and tied together with wire in the form of the proposed compartment construction. A light metal lath, such as is used for plaster partitions in building construction, was then wired to the light framework. A cement mortar was then applied, in the same way as the plaster. The cement worker became so expert in doing this class of work that he could build these compartments more rapidly than a draughtsman could make the drawings for them. The bus-bar structure was built up in the same way as was the cell structure for the oil-switches. Where lines left the building, or where they were run in any horizontal position, barriers were suspended from the ceiling by allowing a piece of metal lath to project down at the time the floors were put in. The barrier was plastered to this piece of lath in the same way as just described. Where conductor wires were taken through the floor, which, of course, was frequently necessary, the insulators were set into the concrete as the floor construction progressed; therefore, when the floor and switch construction was completed the wiremen had the insulators through which the wires were to be run properly located. One great advantage of this form of construction rests in the economy of space which it makes possible. Any brick wall must necessarily be four inches thick, whereas a concrete wall may be put up only two inches thick, provided it is reinforced. In case brick construction is employed, where thin partitions are desired, they must be built of soapstone or marble. The concrete is just as effective in most cases, and is much cheaper.

In constructing the switch-cells and bus-bar structures, an attempt was made to obtain a perfectly smooth finish by dressing the mould smooth and coating it with shellac, as is customary for patterns. This was found to be a mistake, as the bubbles of excess water contained in the wet mixture tended to gather on the smooth surface and make a rough finish to the work. It was found preferable to leave the mould rough and to finish the work with a final float-coat.

The generator leads were brought from the machines in three-inch bituminized fibre conduits, laid in the cement floor of the basement. Under the generator switches, they were brought from the basement floor to the engine room floor in a solid concrete wall. The lead sheathing was removed from the cables, and additional coating consisting of paper and shellac was provided. After allowing a few days for this to dry, the cables were built into a wall of concrete. Inasmuch as the wall was only a few inches thick, little difficulty would be encountered in cutting the cables out, if necessary; in fact, three cables were cut out, under the mistaken impression that they were improperly connected. Little difficulty and slight expense were involved in the operation; and the cables were found to be in perfect condition. In the basement, no important wire or cable was permitted to be exposed. The result is that if a fire should start in any material which might be stored there it could not affect the connections to the generators or instruments, nor could it cause the collapse of the structure, due to the failure of exposed steel columns. The instrument leads and the control wires for the switches were buried in cement. It was originally intended to use for this purpose lead-covered cable run in an iron-armored conduit, the latter being imbedded in the floors. It was decided later, however, to do without the iron-armored conduit, and to lay the lead-covered cables directly in the cement floor. For this purpose, a top coat of 2.5 in. of cement on the floor was allowed, in addition to the original cement floor which was designed to support the full loads. Of this top dressing, two inches consisted of a mixture of cement, sand, and sawdust, in the proportions of one of cement, one of sand, and two of sawdust. The method of installation consisted of laying the conductor cables on the top of the original supporting floor. When all the instrument wiring was completed and tested, the cables were covered and imbedded in this mixture of sawdust-cement, and on top of all was laid a 0.5-in. finishing coat for the floor. The mixture of sawdust-cement is soft enough to permit of chopping a cable out at any time without damage to the cable, or to surrounding cables. The repair of the floor is very simple, and the floor is perfectly solid and to all intents and purposes the same as if constructed wholly of concrete. The necessity for chopping out cables is very remote, because, once properly installed, there is no chance for movement or damaging of the cables. The item of labor saved by making it unnecessary to draw into the conduit the very great number of cables which are required for the installation of electrically-controlled switching apparatus is very considerable.

The 20 000 volt wires which were led from the transformer room on the first floor to the lightning-arresters and building outlets on the top gallery were provided with thorough protection where they passed through the operator's gallery. For each wire a chimney was built of 10-in. bituminized fibre conduit. The three chimneys carrying the three wires of a circuit were placed close together and were surrounded with a construction of expanded metal lath, covered with cement plaster. The result was, to outward appearance, a rectangular column. In effect, there was a thoroughly-insulated duct provided for the conveyance of each high-pressure wire, which entirely prevented an operator coming into contact with these wires.

After the installation of all apparatus and connections thereto, the cement work was given a final finishing wash of whiting, glue, and a slight amount of dark coloring matter, producing a uniform natural cement color over the whole job. It is impossible to produce this without some such wash, since all cement work will discolor more or less as it dries out.

The final result is most pleasing from both engineering and artistic standpoints. Not much effort was taken at the start to lay out the work with a view to insuring good architectural lines, but even though this was not looked to as it might have been, it was possible, by adding a touch here and there, to get some very satisfactory effects from the standpoint of appearance. Of recent years, most large power-houses are designed with a view to obtaining good architectural lines on the exterior, whereas the interior is generally designed from an engineering standpoint only. The possibilities of cement construction in insuring artistic and decorative interior effects, with very slight increased cost, and without sacrificing engineering requirements, have so far received too little consideration.

A paper presented at the 194th Meeting of the American Institute of Electrical Engineers, New York, Feb. 24, 1905.

TWO-MOTOR VERSUS FOUR-MOTOR EQUIPMENTS

BY N. MC D. CRAWFORD.

It is manifestly impossible to consider judiciously the relative commercial efficiency of two-motor versus four-motor equipments, or to reach any absolute conclusion unless certain conditions under which the equipments are to be operated have first been determined. For the purpose of this paper a line was selected having light grades and reasonably small line losses, a line passing through the business center of a city and reaching the residential section, thus at all hours of the day calling for a fair average number of stops and therefore reasonably rapid acceleration, in order to make the time schedule.

Four types of equipment were selected for this service, as follows: car 169, having a 20-ft. body, single trucks, two 25-h.p. motors, and a gear-ratio of 1 to 4.87; car 138, having a 26-ft. body, two trucks, two 35-h.p. motors, and a gear-ratio of 1 to 2.82; car 101, having the same length of body and number of trucks as car 138, but having four 35-h.p. motors and a gear-ratio of 1 to 2.82; car 480, having a 29-ft. body, two trucks, four 40-h.p. motors, and a gear-ratio of 1 to 3.67.

The service required of these four equipments was exactly the same, namely, 136.5 miles per day at an average schedule speed of 8.45 miles per hour. The runs were made on succeeding days and during the same relative hours. Each car was equipped with a wattmeter, an ammeter, and a voltmeter; the wattmeter readings at the end of each half trip were recorded, and at the end of the run checked by the ammeter and voltmeter readings. The wattmeter was also carefully calibrated with a standard meter, using a water rheostat as a load. The peaks were noted at times of acceleration and on grades. These tests have been tabulated as follows:

Fig. 1, the average watt-hours per ton-mi
Fig. 2, kilowatts at peaks during day's run.
Fig. 3, passengers and kilowatt-hours per half trip.
Fig. 4, passengers and kilowatt-hours per half trip.
Fig. 5, passengers and kilowatt-hours per half trip.
Fig. 6, passengers and kilowatt-hours per half trip.
Table 1 has been deduced from the sheets given.

TABLE 1.

Car No.	Capacity seats	Horse power motors	Gear-ratio	Total tons	Total cost	Cost per Seat	Cost per Ton	Commercial efficiency
169	26	two 25	1:4.87	9.075	$2710	$104.23	$298.62	17%
138	34	two 35	1:2.82	12.425	3275	96.38	263.59	13.11%
101	34	four 35	1:2.82	14.675	4360	128.23	297.10	12.53%
480	42	four 40	1:3.67	20.680	5040	120:00	243.71	10.66%

The commercial efficiency, E, was obtained as follows: $A+B+C+D = E$, and $\frac{H}{E} =$ commercial efficiency.

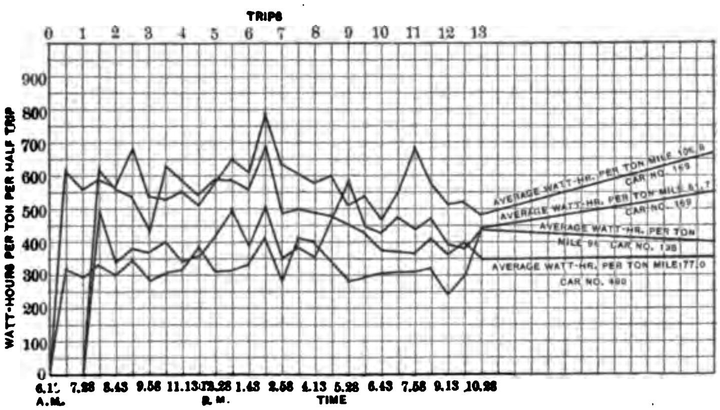


FIG. 1.

The same formula, substituting B for H, will give the greatest commercial efficiency. The letters used in the above formula represent the following:

A Cost of current per watt-hour at station switchboard.

B Value of seated load.

C Platform labor per mile run.

D Interest and depreciation per mile run, figured at eight per cent.

H Value of actual passengers carried per mile.

In obtaining the commercial efficiency, line losses and repairs of equipments and track have purposely been omitted, because it is almost impossible to determine what these values should be; the value of the standing load has been omitted for the same reason.

Applying the above formula and substituting values obtained during the test, the results are as follows:

CAR No. 169.

$$0.0006787+1.30+0.0475+0.0043 = 1.3525$$

$$\frac{0.23}{1.3525} = 0.1698\%$$

$$0.0006787+1.30+0.0475+0.0043 = 1.3525$$

$$\frac{1.30}{1.3525} = 0.96\%$$

CAR No. 138.

$$0.001056+1.70+0.0475+0.0056 = 1.7542$$

$$\frac{0.23}{1.7542} = 0.1310\%$$

$$0.001056+1.70+0.0475+0.0056 = 1.7542$$

$$\frac{1.70}{1.7542} = 0.96\%$$

CAR No. 101.

$$0.001174+1.70+0.0475+0.0070 = 1.7557$$

$$\frac{0.22}{1.7557} = 0.1253\%$$

$$0.001174+1.70+0.0475+0.0070 = 1.7557$$

$$\frac{1.70}{1.7557} = 0.97\%$$

CAR No. 480.

$$0.000847+2.10+0.0475+0.0087 = 2.1570$$

$$\frac{0.23}{2.1570} = 0.1065\%$$

$$0.000847+2.10+0.0475+0.0087 = 2.1570$$

$$\frac{2.10}{2.1570} = 0.97\%$$

An examination of Table 1, readily shows that car 169 is the most efficient for the service selected. This apparent efficiency must, however, be modified when the number of passengers carried, as shown in Fig. 3, is considered, because it will

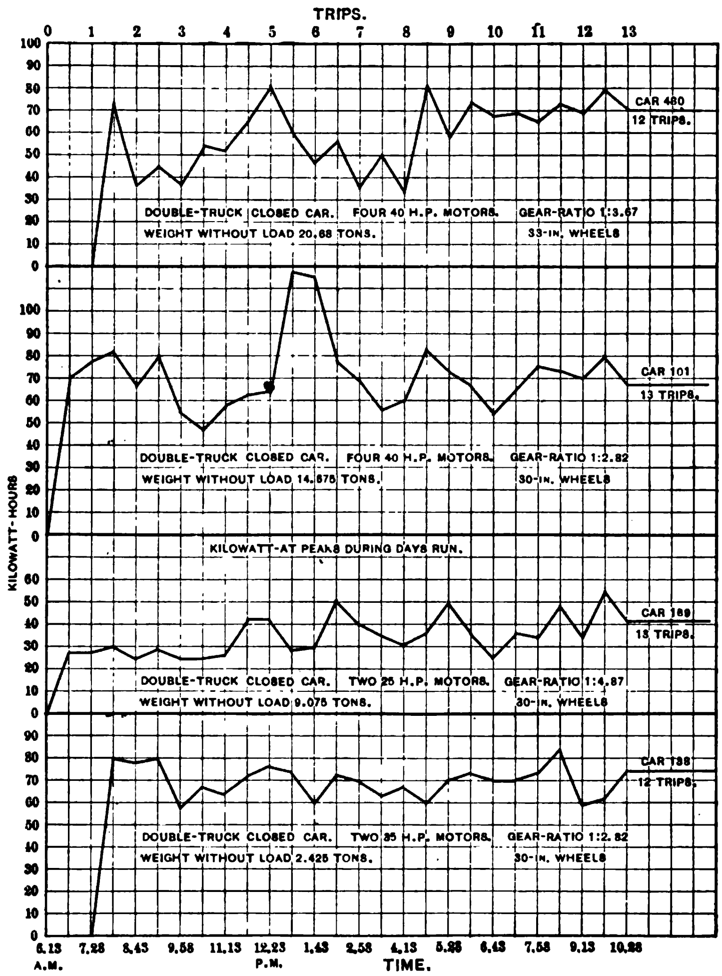


FIG. 2.

be seen that many times during the day's run the number of passengers was greater than 26, the excess constituting a standing load.

Car 138, although showing a lower commercial efficiency, probably on account of its greater weight, yet accommodates the passengers much better throughout the entire day.

Car 480 was the least efficient of those tried, although there

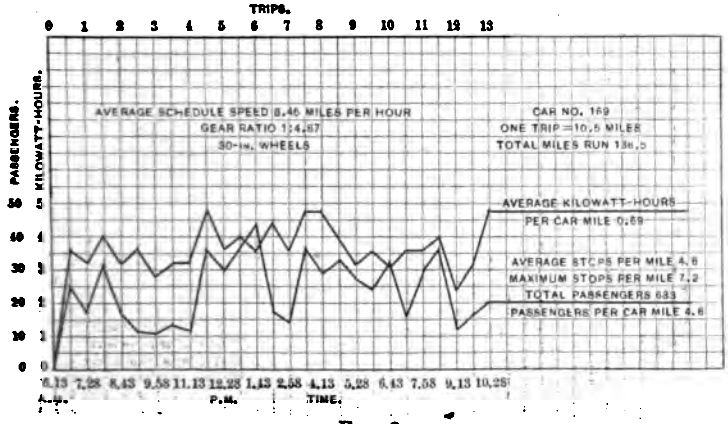


FIG 3.

was only a short time when all the passengers could not be seated. This car was provided with 33-in. wheels and could have made the time schedule easily with a lower gear-ratio.

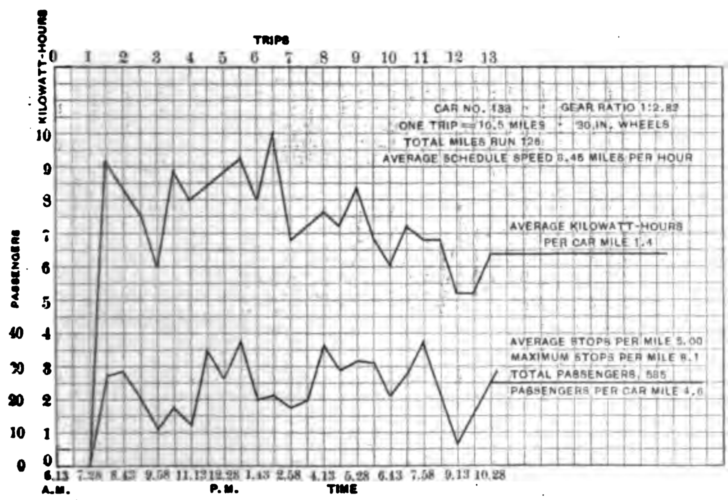


FIG 4.

Temperatures were taken at the end of each day's run; these were not excessive except possibly in the case of car 138, due no doubt to the weight of the equipment and the greater

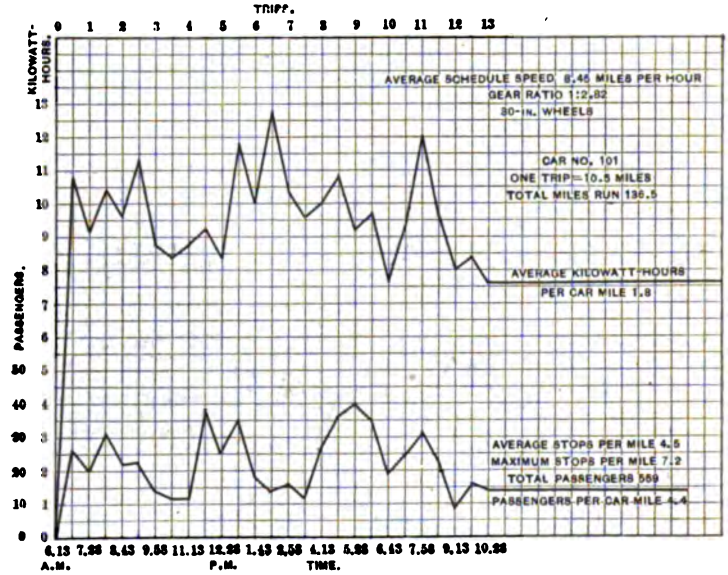

TRIPS.
KILOWATT-HOURS.
PASSENGERS.
AVERAGE SCHEDULE SPEED 8.45 MILES PER HOUR
GEAR RATIO 1:2.82
30-IN. WHEELS
CAR NO. 101
ONE TRIP = 10.5 MILES
TOTAL MILES RUN 136.5
AVERAGE KILOWATT-HOURS
PER CAR MILE 1.8
AVERAGE STOPS PER MILE 4.5
MAXIMUM STOPS PER MILE 7.2
TOTAL PASSENGERS 559
PASSENGERS PER CAR MILE 4.4
A.M.
P.M.
TIME.

Fig. 5.

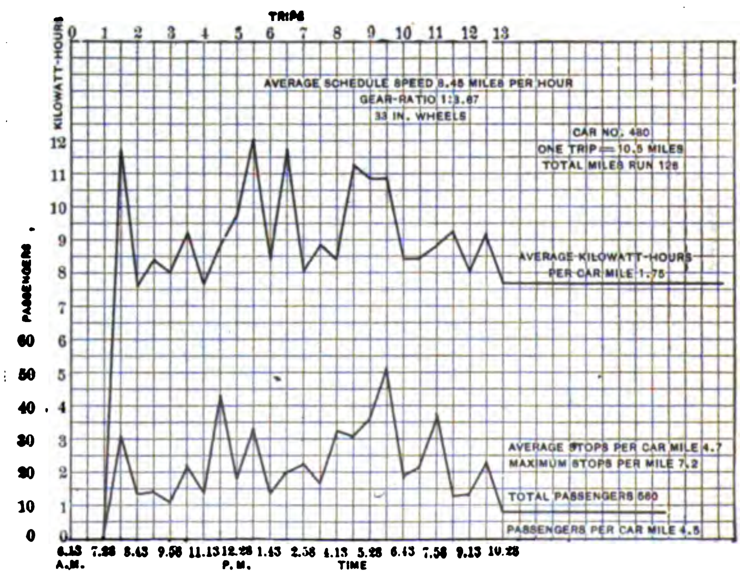

TRIPS
KILOWATT-HOURS
PASSENGERS
AVERAGE SCHEDULE SPEED 8.45 MILES PER HOUR
GEAR-RATIO 1:3.67
33 IN. WHEELS
CAR NO. 480
ONE TRIP = 10.5 MILES
TOTAL MILES RUN 126
AVERAGE KILOWATT-HOURS
PER CAR MILE 1.75
AVERAGE STOPS PER CAR MILE 4.7
MAXIMUM STOPS PER MILE 7.2
TOTAL PASSENGERS 560
PASSENGERS PER CAR MILE 4.5
A.M.
P.M.
TIME

Fig. 6.

number of stops to the mile as shown on Fig. 4. (See appendix for record of temperatures.)

The tabulated records point to the superiority of the light two-motor, single-truck equipments for service on the line and under the conditions selected. With longer trips, heavier grades, greater speed in miles per hour, and greater density of population, requiring more rapid acceleration, there is no doubt but that a car of the 480 type would show the greatest efficiency.

The operating manager is looking not only for an equipment that will fulfil all the requirements of any particular service with the least cost for repairs, and the minimum demand on the power station, but also for one that will combine these ad-

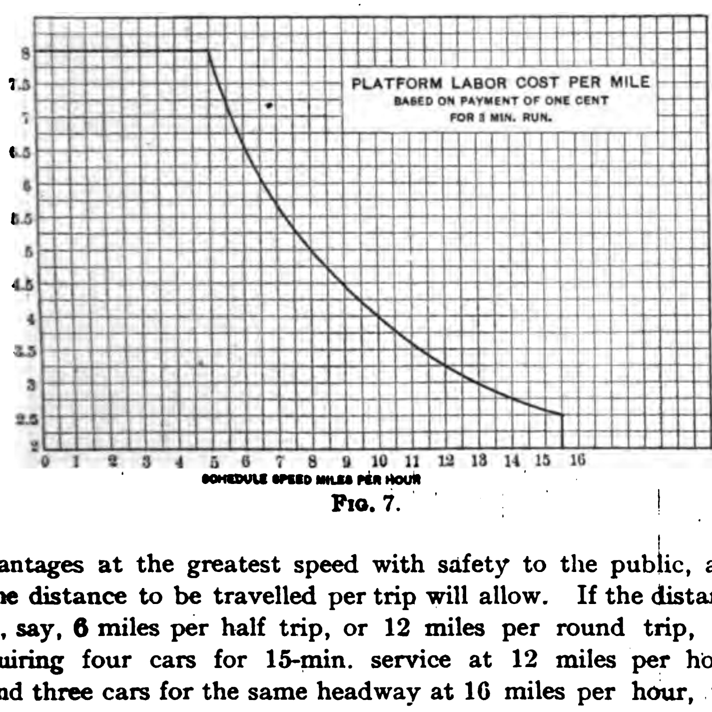


Fig. 7.

vantages at the greatest speed with safety to the public, and the distance to be travelled per trip will allow. If the distance is, say, 6 miles per half trip, or 12 miles per round trip, requiring four cars for 15-min. service at 12 miles per hour, and three cars for the same headway at 16 miles per hour, the platform labor per mile in the first instance will be $0.0335 \times 4 = 0.1340$, and in the second instance $0.025 \times 3 = 0.075$, a saving in labor of 0.059 per mile, and 0.0085 per car mile. This great saving in cost of operation appeals to the operator, but not so greatly if the operating costs are increased by excessive demand on power-station equipment and by added interest charges due to increased line copper and rail bonds. In selecting motors and cars for a given run, it will be found necessary to consider the following:

Density of population, as governing the size and seating capacity of the car body; the number of stops per mile, and con-

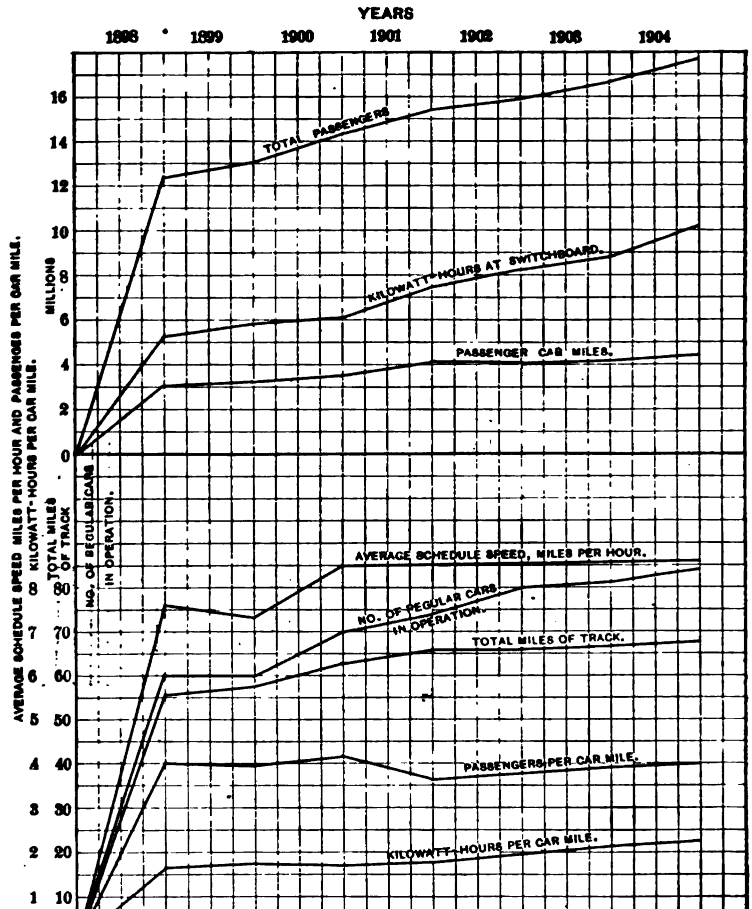


FIG. 8.

sequently the acceleration; the frequency of service; and the speed in miles per hour.

The number of trucks and *motors*, as determining the size and weight of cars selected; the tractive effort; and the acceleration

The speed in miles per hour, as determining the number of

TABLE "I"

	1899	1900	1901	1902	1903	1904
Passenger-car miles, per cent. increase	0.07	0.082	0.171	—0.0122	0.0247	0.051
Total passengers, per cent. increase	0.06	0.021	0.0772	0.031	0.052	0.065
Passengers per car mile, per cent. increase	—0.009	0.058	—0.112	0.0375	0.0154	0.035
Kilowatt-hours at switchboard, per cent. increase	0.012	0.051	0.222	0.094	0.081	0.146
Kilowatt-hours per car mile, per cent. increase	0.038	0.028	0.0462	0.105	0.085	0.06
Total miles of track, per cent. increase	0.016	0.096	0.0408	0.0	0.0142	0.0153
Number regular cars operated, per cent. increase	0.0	0.167	0.058	0.081	0.0125	0.037
Schedule speed, per cent. increase	—0.021	0.142	0.0058	0.0	0.0116	0.0

TABLE "J"

	1904	1903	1902	1901	1900	1899	1898
Passenger-car miles	4 420 873	4 206 435	4 104 488	4 155 414	3 541 564	3 278 314	3 063 765
Total passengers	17 726 397	16 735 071	15 900 325	15 434 068	14 319 252	13 043 728	12 304 639
Passengers per car mile	4.00	3.96	3.87	3.73	4.2	3.97	4.007
Kilowatt-hours, switchboard	10 204 480	8 896 924	8 226 905	7 520 852	6 148 588	5 849 584	5 225 010
Kilowatt-hours per car mile	2.3	2.17	2.00	1.81	1.73	1.78	1.715
Total miles of track	67.573	66.546	65.614	65.614	63.045	57.533	56.638
Number regular cars operated	84	81	80	74	70	60	60

cars in service; the platform labor; the demand upon power-plant equipment; the increased interest charge for line and power plant.

The gear-ratio, as determining the size of motors; the acceleration; the number of stops per mile; the heating of motors, and consequent repairs; and additional power-station and line requirements.

Too much care cannot be exercised in determining the gear-ratio for given service; for there can be no doubt that in many cases lack of power-station equipment and excessive motor repairs can be traced to the use of wrong gear-ratio. In the first place, cars should be selected of ample capacity for the service requirements, and then motors should be selected with a rating only slightly greater than the service requires, and with a gear-ratio so designed that the schedule may be made without resorting to rapid acceleration on starting, and, as a consequence, running the motors on low-efficiency points in order to kill time. The additional tables contained in this report show the various conditions existing in Hartford, and may be of general interest.

Average Schedule Speed Miles per Hour.

1898	7.6
1899	7.44
1900	8.5
1901	8.55
1902	8.55
1903	8.56
1904	8.56

APPENDIX.

CAR 138. Jan. 16.

MOTOR 1:

Car in at 10:35 p.m.

Temperatures are in degrees centigrade.

Temperature of air: 0.

Temperature of armature iron: 68°.

Temperature of field: 63°.

NOTE: Nearly 10 minutes were lost in getting thermometers in place on this motor.

CAR 101. Jan. 17.

MOTOR 1:

Car in at 10:35 p.m.
Temperatures are in degrees centigrade.
Temperature of air: 1°.
Temperature of armature iron: 70°.
Temperature of field: 46°.
Temperature of air in car barn at 6 a.m.: 17°.

CAR 480. Jan. 18.

MOTOR 4:

Car in at 10:35 p.m.
Temperatures in degrees centigrade.
Temperature of air: 1.5°.
Temperature of armature iron: 29°.
Temperature of field: 25°.
Temperature in barn at 6 a.m.: 23°.

CAR 169. Jan. 19.

MOTOR 1:

Car in at 10:35 p.m.
Temperatures in degrees centigrade.
Temperature of air: 5°.
Temperature of armature iron: 41.5°.
Temperature of field: 27.5°.
Temperature in barn at 6 a.m.: 20°.

In all the above temperature readings the temperature of the field coil was obtained by placing a thermometer on the top right-hand field coil at about the same point. The armature temperature was obtained by placing the thermometer on the iron core.

DISCUSSION ON "TWO-MOTOR VS. FOUR-MOTOR EQUIPMENTS."

N. McD. CRAWFORD (by letter): I desire to explain more fully the term "A" in the efficiency formula given in my paper. The definition of the term, as given, may be misleading; its value is obtained by multiplying the average watt-hours per ton-mile by tons weight of car, and this result by the cost of power per watt-hour at the switchboard.

I have named the efficiency obtained "commercial efficiency." It has been suggested that possibly "load factor" or "earning efficiency" would be better. But I have looked at the matter from the standpoint of the street railway manager rather than from that of the engineer.

A. H. ARMSTRONG: The contest between two- and four-motor equipments is of long standing, but of late years it seems to have settled itself rather definitely in a majority of cases in favor of the four-motor equipment. As Mr. Crawford brought out in his paper, no general ruling will apply in all cases, and each traction problem will have to be solved according to the local conditions. Perhaps the fundamental reason for adopting the four-motor equipment is the need felt for increased traction, due partly to climatic conditions in the north, partly to the presence of excessive grades on many roads, and partly in some cases to an exacting schedule, calling for a more rapid rate of acceleration than can be obtained by a two-motor equipment. In the latter class of roads may be included surface lines in cities of considerable size. On elevated, subway, or other city roads on which the surface condition of the rails is particularly good, the adoption of two-motor equipment is permissible so far as the question of traction is concerned, and this practically constitutes the legitimate field of the two-motor equipment.

In suburban and interurban service somewhat different conditions apply, cars are usually run singly at infrequent intervals, in many cases over excessive grades; because of the infrequency of the headway snow and ice accumulate, thus calling for as large a tractive effort as can be obtained even with four motors.

Referring to the paper, there are several assumptions made which perhaps can be looked at in a different way. In arriving at the efficiency of operation of the different cars cited, the author assumes that at the end of every mile an entirely new set of passengers is taken on board. Thus, if instead of a one-mile basis a two-mile basis had been taken, the 17% efficiency of operation noted in the case of car 169 would have been nearly doubled, without in any way changing the factors entering into the case. It would seem, therefore, that the method of the author is somewhat misleading, in that the commercial efficiencies obtained are arbitrary and do not necessarily represent the true prevailing conditions.

Again, on pages 69 and 70, the energy consumption of the two-motor equipment is given as somewhat less per car than that of the four-motor equipment. This brings up another point which has been the subject of discussion at previous meetings of the INSTITUTE; that is, the relative amount of energy consumed by two-motor and four-motor equipments. If one car is equipped with two motors, and a similar car is equipped with four motors, both cars having the same aggregate horse power capacity, there is no reason why the energy consumption in one case should be different from that in the other, provided the car weights, schedules, frequency of stops, and general conditions, are similar in each case. The method of comparing two- and four-motor equipments adopted by the author is somewhat unfair, as the operation of two 35-h.p. motors is compared with that of four 35-h.p. motors placed upon a similar type of car; obviously, in one case the motors are overloaded; in the other they are underloaded. Of course the four-motor equipment will weigh more and the energy consumption will be increased on account of the increase in weight. It would have been fairer to compare the operation of two 75-h.p. motors with the operation of four 35-h.p. motors. The watt-hours per ton-mile assumed for any given service is practically independent of the subdivision of power on the car inasmuch as the railway motors of the same manufacturer are all designed along the same general lines and offer about the same efficiency curve as expressed in per cent. at full load.

Perhaps one reason why results given by the author are more favorable to two motors than to four motors is that an insufficient number of tests has been taken. The average of a large number of tests is necessary in order to arrive at a correct understanding of the operation of a car under any given conditions. There is no reason why, with the conditions in the two cases the same, the four-motor equipment should not show as small, if not a smaller, energy consumption per ton-mile than the two-motor equipment.

S. T. DODD: In attempting to express the commercial value of different cars, the author has included both their operating expense and seated-load value in one term which he has called "commercial efficiency." Apparently it would have been clearer to have separated this term into two different expressions. I have tried to indicate my idea of this method of expression in a table, in which the items of "interest" and "platform labor" are taken directly from the values given on page 67. The expense of car repairs should be included, and in the absence of more definite data, this is assumed as 1.5c. per car-mile. The author's method, on page 67, of getting at the expression for cost of power per car-mile hardly seems correct, but it will not be far from the truth to assume the cost of power to be 1c. per kilowatt-hour delivered at the car, and take the amount of power for the several cars from Figs.

3–6. Adding the terms together gives an expression for operating expense per car-mile which indicates that car No. 169 is the most economical in operation. Going one step further and dividing the expression by the seating capacity of each car, gives the operating expense per seat-mile, which indicates that car No. 480 is the most economical.

Car No.	169	183	101	480
Platform labor	0.0475	0.0475	0.0475	0.0475
Interest and depreciation	0.0043	0.0056	0.0070	0.0087
Car repairs	0.0150	0.0150	0.0150	0.0150
Power	0.0069	0.0140	0.0180	0.0175
Operating expenses per car-mile	0.0737	0.0821	0.0875	0.0887
Operating expenses per seat mile	0.00368	0.00241	0.00257	0.00211
Seat factor	$\frac{0.23 \times 5.25}{1.30}$ $= 93\%$	$\frac{0.23 \times 5.25}{1.70}$ $= 71\%$	$\frac{0.22 \times 5.25}{1.70}$ $= 68\%$	$\frac{0.23 \times 5.25}{2.10}$ $= 57.5\%$

This method of discussing the question shows that if the seating capacity of car 169 is sufficient to accommodate the travel, this car is the one to use; but that if it has not sufficient capacity, then car 480 is the one most advisable to use because of its low operating expense per seat-mile.

Now if in addition to this information it is desired to introduce an expression indicating the amount of idle seating room in each type of car, this may be expressed by a separate ratio, which I have called "seat factor," and which is obtained by dividing the earnings per trip by the "value of the seated load." This expression I have also given in the table.

I have assumed 1.5c. per car-mile for repairs, but very little information on car repairs is available for determining the respective cost of repairs of large and small equipments. It appears from the table above that an increase in car repairs of 1.5c. per car-mile, on car 169 over car 480 for example, would make a four-motor equipment more economical from the standpoint of operation per car-mile, as well as from the standpoint for operation per motor-mile.

A claim that is often made for the superiority of the four-motor equipment over the two-motor equipment of the same aggregate capacity is that the four-motor equipment having a greater radiating service will run at a cooler temperature than the two-motor equipment when working under the same load. But comparative tests which I have made upon stationary motors indicate that the average four-motor equipment should operate at the same temperature as a two-motor equipment of the same aggregate capacity.

Turning to the appendix to the paper, it will be seen that the differences of temperature do not correspond to the difference between two-motor and four-motor equipments, but that cars 138 and 101 are running at temperatures in the neighborhood of 70°, while cars 480 and 169 are running at temperatures in the neighborhood of 30°. The cause of this difference in temperature is indicated in Figs. 2–6, inclusive, which show the large amount of power per car-mile used by the cars 138 and 101; while Fig. 2 in particular shows that the maximum peaks of power taken by car 138 (a 12-ton car with two-motor equipment) are equal to the maximum peaks taken by car 480 (a 20-ton car with four-motor equipment). Apparently the difference there indicated is due to the difference in gearing between the two equipments; and the differences in temperature shown in the appendix indicate very clearly that the two cars in question were geared for a speed too high for economical operation upon the schedule and for number of stops required.

Calvert Townley: Frequent comparisons between two-motor equipments and four-motor equipments have been made, and these comparisons are nearly always clouded by the introduction of other factors; for example, the question of the size of car to use, a question to be determined by the density of traffic and other local conditions. After the size of the car best suited for local conditions is selected, the number of motors to be used should be taken up as an entirely separate question. Similarly, within ordinary limits, any reasonable gear ratio can be applied to either form of equipment so that gearing should be eliminated from the comparison.

Mr. Crawford's comparison of the watt-hours per ton-mile shows the most economical motors to be those having the greatest gear reduction, as will always be the case for city service with low schedule speed and frequent stops. The comparison of a two-motor equipment with a four-motor equipment of a greater aggregate horse power capacity is unsatisfactory; to get an absolutely fair comparison, the same horse power per ton of weight carried should apply to both styles of equipment. A four-motor equipment would be somewhat heavier than a two-motor equipment having the same capacity and, therefore, if the horse power per ton were kept equal, the total weight of a car equipped with four motors will be greater than of one of equal capacity equipped with two motors. Additional energy to propel this car would be required at least in proportion to the additional weight. In a similar manner, the first cost of the four-motor equipment will be somewhat greater. Further, there is an increased maintenance to be charged against the four-motor equipment because, as is well known, repair-shop facilities must be provided for a given number of units, and a larger shop, with a greater number of men, is required to take care of twice the number of motors, with twice as many wearing parts, etc., to be maintained.

Summarizing, therefore, there should be charged against the four-motor equipment an increased first cost, an increased consumption of energy due to increased weight, increased number of bearings, pinions, gears, etc., and an increased cost of maintenance. Admitting this, what is the reason for the tendency toward the substitution of four-motor equipments that is noticeable in the practice of to-day? The answer always is: because four-motor equipments afford increased traction.

The speaker excludes from the comparison, cars of such great weight or high speed that sufficient motor capacity in a two-motor equipment can not be provided, and limits the comparison to cases where either arrangement will be available. With the two-motor equipment, there will be from 55% to 60% of the total weight of the cars on the drivers. Under the best conditions of rail, straight track, etc., 20% adhesion is easily obtainable. With 60% on the drivers, there are 1200 pounds on the drivers for every ton weight of the car, and 20% of this is 240 pounds. Therefore, there is available with a two-motor equipment, under good conditions of track, 240 pounds tractive effort per ton. On a very heavy grade, say 8%, 160 pounds per ton will be required to lift the car up this grade, and if 20 pounds be allowed to overcome friction (an allowance rather higher than usual), there will still remain 60 pounds per ton for acceleration, which will give a very satisfactory performance. This brief consideration of the problem shows that even for very heavy grades, with fairly good track conditions, there is ample adhesion with two-motor equipments to get the necessary acceleration.

On the other hand, with snow and slush on the rail, there may be at times practically no adhesion from one truck, so that the 1200 pounds per ton is reduced to 600 pounds, and with an icy rail, instead of 20% of adhesion, only 10%, or even less, may be available. Ten per cent. of 600 pounds is 60 pounds, and with a slight grade and heavy snow in front of the wheels this amount is at times insufficient to start the car. These conditions, therefore, demand a four-motor equipment.

Engineers should not be carried away by fashion and adopt a four-motor equipment because others do so, or simply because such equipment afforded better traction, unless a careful study of the local conditions shows that such traction is necessary for the service.

A paper presented at the 194th Meeting of the American Institute of Electrical Engineers, New York, February 24, 1905.

ON TRACK BONDING.

BY C. W. RICKER.

In the earliest days of electric-railway work with crude apparatus and light loads, track resistance was neglected. As the need became evident, auxiliary return wires were run and connected to the rails at frequent intervals, but of a size which now seems absurdly small. Joint bonds were first of small iron wire like railroad signal-system bonds, then pieces of copper wire with the ends riveted in holes in the rail-web, then pieces of trolley wire with channel-pins and so on, until specially-designed terminals were developed.

About eight or ten years ago, the real usefulness of high track conductance began to be understood. The work of Mr. F. H. Farnham regarding the electrolysis of buried metals called attention strongly to the return-circuit losses in what was then a well-equipped electric railway system. Since then the progress has been along the general direction of utilizing the track metal to best advantage for the return circuit; and except in the case of rather complex city networks and single lines fed from a power-plant unfavorably situated, this course has proved more economical than the installation of copper return cables. In the special case of elevated railways using steel structures, the metal of the latter has been used to excellent advantage, though this presents some peculiar problems in bonding, and a serious risk of electrolysis of anchor bolts.

With the prospective use of alternating currents and the six- to sevenfold increase of apparent track resistance, an increased use of copper may become necessary; but with all direct-current operation the engineering problem is to use the rails to best advantage, and this is largely a matter of the selection and installation of track bonds.

The first condition to determine the character of the bonding is the rail joint, which in turn is determined by the roadbed. Track joints are of two general types, rigid and flexible. The first is applicable only to track laid on continuous rock cr concrete foundation, with the rails buried in hard pavement, and includes electrically-welded, cast-welded, and riveted joints. Electrically-welded joints require no secondary electrical connection, but their availability is limited and they have not attained great use. Cast-welded joints are widely used in large cities, and unless the current density is high need no additional bonding. Riveted joints, used somewhat abroad, are similar to cast-welded. The majority of all track, including all not buried in pavement, must have flexible joints of either bolted or wedge types, and the electrical conductivity must depend upon bonds installed for that sole purpose, that of the rail joint itself being slight.

Classification of Rail Bonds. While rail bonds are made of a wide variety of forms and materials, all in general use have some flexibility, for ease of application and for durability afterward, varying with the amount of flexure expected in the track structure. This has led to the general adoption of a form consisting of two terminals with a connecting shank of considerable length, to which all bonds conform, except some special kinds of very limited use, so it is convenient to classify bonds by the kind and form of contact with the rail. Contact with the rail is made in the following ways:

1. *Compressed Terminals.* A hole is drilled or punched in the rail and a cylindrical terminal of the bond is upset in the same way by great pressure applied slowly till the bond metal fills the hole very tightly, with the two metal surfaces in intimate contact and held there by elasticity. This is commonly called a compressed terminal and is the kind most generally used in this country.

2. *Expanded Terminals.* A terminal of the same form is expanded in the hole in the rail by means of a drift driven through a hole in the terminal. This may be called an expanded terminal.

3. *Soldered Terminals.* A flat terminal is soldered to the surface of the rail with either soft or brazier's solder.

4. *Amalgamated Terminals.* The terminal of a copper bond

and the surface or a hole in the rail are amalgamated and held in contact with slight pressure, depending upon a layer of tin amalgam to maintain the metallic contact. In one form a mass of tin amalgam is placed between amalgamated surfaces of the rail and joint plate and held in place by a cork washer squeezed between the same.

5. *Bolted Terminals.* Copper strips or sheets are pressed against the surface of the rail by bolts designed for that purpose, or are pinched under the joint-plates.

6. *Makeshift Terminals.* There are many sorts of makeshift bonds, used mainly where there is no money with which to get those of better designs—channel pins, and cylindrical washers for round wires, and hammer rivetting are the most common. They depend mostly upon the ingenuity of the man on the work and are seldom worth consideration save when no better can be got.

Conditions Governing Material, Form, and Structure of Bonds. To get the necessary conductivity, bonds are nearly always of copper, about the only exception being those of tin amalgam. To reduce cost and resistance, they must be as short as practicable, and the manufacturing cost must be kept low, to preserve the scrap value as near the first cost as possible. For durability they must be flexible enough so as not to break or lose contact by the allowable relative motion of the rails. They must be formed so they may be applied to the types of rails in ordinary use, in such position as to be protected from accidental damage and from theft. They should be readily accessible for inspection and repair. The cost of application must be kept low, and to this end it is very important that the process shall be so simple and easy that no highly-skilled labor or extraordinary care is required to install them with certain and uniform results. The bond that satisfies all these conditions has not yet been devised.

The ordinary process of selection has developed a form of bond made of annealed copper and consisting of a flexible stranded or laminated shank about eight to twelve inches long, welded to solid terminals of considerable mass, which are attached to the rail-web under the joint plates or less frequently under the base of the rail. Accessibility for inspection and repair, however, is almost wholly sacrificed and the importance of good work in manufacture and application is thereby greatly increased.

Pure copper is a very plastic material of low strength and elastic limit, and under moderate pressures behaves almost like a liquid. The surface oxidizes slowly at ordinary atmospheric temperatures, but very readily at high temperatures, and so it is very difficult to weld. The result is that the union between the shank and terminals of a composite bond is always subject to suspicion, and not the less so that the outside of the same and all the welds that show at or near the surface may be very nice and neat to look at and the resistance moderate as the unwelded interior contacts are still bright when the bond is new. Under the smooth exterior may be defective welds that will corrode, and weakened strands that will soon be broken by the motion of the rails, either of which will materially diminish the utility of the bond.

It is a common practice to saw partly through a terminal and split the copper with a wedge. In some cases this will open up defective welds, in other cases the soft metal will tear close to a bad joint without showing the same. The writer has seen some bonds of excellent appearance that when compressed much harder than in ordinary practice developed open cracks in the upper parts of the terminals. Perhaps the most satisfactory inspection of the workmanship is made by sectioning the terminals in various planes, polishing the cut surfaces with a smooth file, emery, and crocus to remove all burrs, and then etching with a mixture of strong sulphuric and nitric acids, when the defective welds will show as fine black lines, and the actual welds and the form of the various component parts of the bond at that surface can be traced by the different colors of the metal after etching.

With a good process carefully followed out bonds of good and uniform quality can be produced, but the material is delicate and a little carelessness may spoil many bonds. Considering the cost of copper bonds and the importance of their function, it would seem worth while to have their material and manufacture inspected in the shop, in much the same manner as is done with structural steel and machinery, by the engineering inspection bureaus. The writer has not heard of any great amount of inspection of electrical apparatus by these bureaus, but the quality of their work in other directions would suggest their probable usefulness in this one.

Area of Contact. Discussion of the ratio of contact area to cross-section of bond, has not lead to the adoption of any standard.

Practice seems to be to get as large contact area as convenient and make the best of that. The ratio increased as the size of bonds increased, till with No. 0000 short bonds with 0.875-in. cylindrical terminals it became about 9.33, while with 500 000 cir. mils bonds of later design, it is only 4.5. The smaller ratio seems ample to secure a negligible contact resistance, if the contact is only close enough. Unfortunately the full possible contact area is seldom realized, because of rough or dirty surfaces and insufficient compression or soldering.

Failure of Bonds in Service. The failure of a bond is that condition in which the resistance of the joint made by the same is seriously increased, which may occur without interruption of the continuity of the bond itself. The general cases are

1. Breakage of bonds;
2. Disintegration of the bonds;
3. Impairment of contacts

Breakage of Bonds. Breakage may occur because of defects in manufacture, as in copper bonds with welded terminals the strands may be weakened by overheating where they enter the terminal; and a slight but continuous motion of the joint will cause them to break, one by one, at this place. Long-continued jar and repeated flexures will produce fatigue in the metal (what has been called the Bauschinger effect in steel). Such breakage in the case of either welded or solid bonds is of course most frequent where the flexure of the bond due to rail movements is too great for its flexibility, which means ill-selected bonds or badly-kept track.

A less common manner of breakage occurs in laminated under-plate bonds which are too large for the space between the joint-plate and the rail, the bond shank is pinched and the working of the joint under passing wheels tears off the outer strands by a kind of ratchet effect, working them into the narrowing space at top or bottom of the rail-web and sometimes squeezing them out of the joint in thin ribbons. Bonds secured under the base of the rail may be frozen in the ballast and torn off by the movement of the rail.

Disintegration. The surfaces at the imperfect welds in composite bonds corrode, increasing the resistance greatly and loosening and weakening the bonds so that they may be pulled apart.

Tin amalgam used at contacts or in masses, hardens and shrinks, losing flexibility and contact with the bonded surfaces.

In the case of amalgam plugs enclosed in cork boxes, the cork sometimes breaks allowing the soft amalgam to run out.

Impairment of Contact. By far the most important cause of impaired contact is oxidation. This is greatly facilitated by the presence of moisture, so that the slightest crevice into which moisture may penetrate and lodge is dangerous.

Soft-soldered contacts underground are not to be trusted, especially on track laid in streets, which is sure to be wet with dirty water, though there is no apparent reason why soldered contact entirely above ground should not be durable, if all traces of corrosive flux are removed. Brazed joints seem to give no trouble.

Amalgamated steel surfaces are not durable and soon rust in track exposed to dampness.

Expanded or compressed terminal bonds, which have not been properly applied, may be loosened by the movement of the rail, and well-soldered bonds may be loosened or torn off by the same means if they are too rigid.

No mention has been made of accidental breakage of bonds. Of course bonds which are improperly located may be knocked off by rolling stock; and various local external conditions may operate to destroy any kind of bonds.

Importance of Good Contacts. The rapid deterioration and general unreliability of track bonding has been a favorite subject of complaint. Impairment of contacts and breakage are the most common grievances, and while the latter is easily traced to improper selection or ill-kept track the former is no less due to poor work in applying the bonds, which too often is left to cheap workmen; with poor supervision and as the work is usually covered up as soon as done and is seldom tested at all, it gets no more attention till trouble develops. The writer knows of one case in which the superintendent of a rather notable electric railway made public a letter praising the performance of a certain kind of bond used on his road and in less than three months careful tests showed the condition of the bonding to be so poor that it had to be completely renewed.

The importance of clean and tight contact between bond and rail can not be insisted upon too strongly, both for immediate effect upon track conductivity and for its still greater effect upon deterioration, yet the importance of this is not generally enough understood. The apparatus most commonly used for applying bonds throws light upon this. In two recent jobs using compressed terminal bonds, the screw presses for applying which were got from large and highly reputable makers and were selected for the bonds used, the writer was able to get reasonably good contact only by overworking the presses to such an extent that two presses were always being repaired for each one on the work. A press would seldom do 200 terminals without breaking down. The makers of the presses said merely that the presses were used too hard.

The resistance at the terminal of a bond depends upon the area and intimacy of the actual contact; with good bonds of ordinary design this may be made negligible if proper care is taken. If contact by pressure is to be used, both copper and steel surfaces must be smooth, clean and dry; if soldered they must be clean, well tinned and free from corrosive flux when the operation is finished. As large a proportion as possible of the surfaces must be brought into contact and kept there.

The writer has inspected many compressed terminals, some applied with ordinary care, some with greater care, and usually a considerable part of the copper surface, sometimes more than one half, shows plainly that it has never touched the steel. In a short time that part of the contact surface becomes oxidized and is of little further use. A film of oil, such as is left in holes in which oil is used to lubricate the drills, decreases the conductivity seriously and increases the deterioration. Such holes show in time a black deposit from the decomposed oil, and ultimately rust. Rough surfaces require greater pressure to get good contact and allow more crevices into which moisture may penetrate with resulting corrosion. In the case of soldered bonds complete contact between the terminal surface and the rail is seldom obtained, no matter how carefully the work is done. The heat capacity of the rail is so great that it is difficult to get any considerable part of it to soldering temperature by exernal heat application, without excessive expense and possibly damage to the rail, so the edges of the terminal surface are usually well soldered and the middle portion but imperfectly.

Large flat surfaces held in contact by bolts have been tried, though they have never attained great vogue. The cost and bulk of any arrangement of bolts and plates which could maintain intimacy of contact similar to that of an ordinary compressed terminal, together with the cost of finishing and fitting the flat surfaces, would be prohibitive. In some cases such bonds have been used in joints where there is supposed to be enough motion to keep the surfaces rubbed bright, but here there would seem to be little advantage in using copper, as the joint-plates fill the same office.

The following data illustrating the foregoing may be of interest. A track laid with 87-lb., 60-ft girder-rails on concrete base, in unusually substantial manner, with joints driven tight and made as rigid as possible, was bonded with two 0000 bonds with 0.875-in. terminals expanded with a steel drift left in the hole. On account of the rigidity of the joints the bonds were very short, of horseshoe type 4 in. and 2.5 in. between terminals. Bond holes were punched at the mill and reamed bright with taper reamers just before applying the bonds, which were set with the shank at the small ends of the taper holes. Measurements of 15 joints by comparison of fall of pressure through the joint with that in ten feet of rail, made with a millivoltmeter, showed the mean joint resistance equal to that of one foot of rail. The same joints measured in the same manner with the same instruments one year later showed no perceptible increase in resistance.

A double track railway laid with 60-lb. T rails, rock ballasted and maintained unusually well for an electric railway, was bonded with masses of tin amalgam enclosed in washers of treated cork, pinched between the rail-web and joint-plates. After the road had been in operation about four and a half years and parts of it one and two years less, measurements were made upon joints in the various sections by the same method as the preceding test.

Number of joints.	Years in service.	Mean resistance of joints		Res. too high to read (over 500 ft. of rail)
		No. measured	Equiv. ft. of rail	
13	4.5	8	15.7	5
6	3.5	5	12.4	1
18	2.5	17	8.4	1

About 40 joints of various ages were opened for inspection and in none of them were the amalgamated surfaces unimpaired, while the older joints were nearly or completely rusted over. The amalgam masses were (with one exception) either dry and crumbly or hard and brittle. The cork washers were generally intact, though a few were broken.

In a single track interurban electric railway laid with 70-lb.

T rails on private right of way, the joints were each bonded with one 0000 copper bond 10 in. long with 0.875-in. welded terminals. In the earlier part of the work, the bond holes were drilled with oil lubrication and the bond terminals were upset with a screw compressor by one man using a wrench about 36 in. long. To estimate the improvement possible, the resistance of 633 ft. of one rail containing 20 joints was determined in the condition described, then the bond terminals were thoroughly compressed with a similar compressor using a wrench about 66 in. long with a heavy man on the end applying the pressure slowly and steadily. Then a similar section of one rail 425 ft. long containing 14 joints was drilled with soda-water lubrication, the holes carefully wiped and the bonds compressed thoroughly as above. The sections of rail when measured were disconnected at both ends and the ballast scraped clear. The readings were taken at night in dry weather and very nearly uniform temperature. Pressure readings were taken with a low reading voltmeter. Only switchboard ammeters were available for current measurements, but they were new and three were connected in series and the mean readings used. They checked very closely and were reliable enough for comparative measurements.

	Ohms per ft. rail.	% increase res.
Drilling with water, bonds well compressed,	1.29×10^{-5}	0
" " oil, " " "	1.47×10^{-5}	14
" " " " poorly "	1.96×10^{-5}	33

Cost of Applying Bonds. Two cases are presented in detail as it is proposed to try to derive from them some conclusions regarding the most economical expenditure for bonding in two typical roads.

On a single-track interurban railway quoted herein, it was neccssary to organize a bonding gang of entirely green men, none of whom had ever seen a bond before. It contained 12 men at $1.75 per day and a foreman at $3.00, total of $25.00 per day. The work consisted in unplating the joints which were half bolted up, drilling two 0.875-in. holes in the rail-web, compressing one bond per joint, and replating and bolting up the joints in permanent shape with four bolts each. The equipment consisted of three portable rotary track-drills, three screw-compressors, about sixty 0.875-in. twist-drills and the necessary track tools, costing altogether about $350, on which the salvage was about $150. The capacity was 100 bonds per day, making a labor cost of 25c. per bond. Grinding drills cost about $1 per day and repairs to compressors, about $1.50, making total cost 27.5c. per bond, of which 5c. was chargeable to plating and 22.5c. to bonding. The work was continually interrupted by construction trains, and the temperature was so high that several men were overcome by heat. With clear track and decent temperature the daily output could be increased 20% at the same total cost

On a larger installation in somewhat more favorable conditions, the bonding gang consisted of ten or eleven men and a foreman, with a total pay roll of $23 to $25 per day. The drilling apparatus consisted of a gang-drill driven by an electric motor which made two 0.875-in. holes at once, piercing the rail web in one minute and drilling an average of 30 joints per hour when smartly handled. The position of the drills was determined by a jig so that no time was lost in adjustment. The machine used an average of 2000 watts when drilling, derived from the trolley wire used by the construction trains. It weighed about 1500 pounds and had to be removed from the track by the bonding gang about four times per day to allow construction trains to pass. The capacity of this gang was 200 bonds daily, making the labor cost about 12c. each, of which 3c. was chargeable to plating and 9c. to bonding. The machine contained a drill grinder so there was no additional expense for sharpening drills. The equipment included six screw compressors of the best type obtainable, but they were too light and three or four were always crippled, adding 1 to 2 cents for repairs to the cost per bond. The drilling machine was built especially for this job and required considerable changes after work was begun, so the cost of tools was rather large, about $2000, on which the salvage was probably $1000.

Economical Bonding. It is at once evident that the proportion of the resistance of the rail circuit due to the bonds is small; in the first case cited using 60-ft. rails, it is a little less than 2%, in the third case it is about 13%, and as the resistance of the rail circuit is usually not over 25% of the whole resistance, the saving by a considerable increase in bonding is relatively small.

In order to reach some general conclusions regarding the economical expenditure for bonding in cases similar to the two described, by means of Kelvin's law, it is necessary in order to make the law apply to make certain assumptions, which are not strictly true, but which if carefully adjusted to the case taken up may be near enough for the purpose.

The following data of equipment may be taken as typical of the interurban electric railways of moderate size and capacity built extensively in the middle Western states. The 0000 copper bond 12 in. long with solid 0.875-in. terminals, is is selected as a unit, because it is a convenient market size and well adapted for use with the rails assumed.

Single track......................two 75-lb. T rails
Cost of power in line..............0.02c. per kw-hr.
Mean current in track.............200 amperes
1 joint bond......................0.19c. per 1000 cir. mils
(based on No. 0000 × 12-in. bond @ 40c.)
Applying same....................0.094c. per 1000 cir. mils
(based on 20c. per bond)
Scrap value of bond...............0.056c. " " "
Net cost of bond..................0.23c. " " "
Useful life of bond................10 years
Annual cost of bond @ 15%.......0.034c. per 1000 cir. mils
Resistance of bond, ohms..........0.0116 " " "
(12-in. 0000 copper + 8% for contacts)
Annual (7300 hours) loss in one bond 847 kw-hr. per 1000 cir. mils
Cost of same @ 2c................$16.94 per 1000 cir. mils

$$\frac{0.00034 \text{ cir. mils}}{1000} = \frac{16.94 \times 1000}{\text{cir. mils}}$$

$$\text{cir. mils} = 223\,000$$

The equipment described would correspond to that of a road operated by synchronous converter sub-stations having an average traffic of two 40-ft. cars per section. Such a road would usually have one 0000 bond per track joint, which would seem to be a little too small.

For a road of somewhat heavier construction and traffic and operated at high speed the following data may be assumed; items which are the same as in preceding case are not repeated.

Double track.................four 80-lb. T rails
Mean current in track.........800 amperes
1 joint bond..................0.19 per 1000 cir. mils
Applying same................0.057c. " " "
(based on 12c. per bond)

Scrap value of bond............0.056c. " " "
Net cost of bond...............0.203c. " " "
Annual cost of bond @ 15%....0.0304c. " " "
Annual (7300 hours) loss in bond 3.387 kw-hr. per 1000 cir. mils
Cost of same @ 2c.............$67.76

$$\frac{.000304}{1000} = \frac{67.76 \times 1000}{\text{cir. mils}}$$

$$\text{cir. mils} = 472\,000$$

This case is fairly comparable with the Aurora, Elgin, and Chicago Railway which is bonded with two 250 000 cir. mils bonds per joint.

If this method indicates a cross-section of bonding varying greatly from a multiple of the typical bond selected, a second approximation will be necessary, as the cost of bonding will not vary with the cross-section unless the unit size is practically adhered to. In a more precise solution the square root of the mean square of the current should be used instead of the mean current. It would be interesting to compare the results obtained by this method carefully carried out, with those obtained by the summation of annual cost and annual loss curves covering all the elements of the conducting circuit in the above typical cases. The brief time at the writer's command does not permit of his doing this at present.

DISCUSSION ON "SOME NOTES ON TRACK BONDING."

C. W. RICKER: The cost of applying bonds, which I have given, may be criticized as unduly low; it is intentionally very close, but it is attainable with compressed or expanded terminal bonds. The use of reliable hydraulic compressors might reduce the figures a little, but the amount would not be great, as the copper must be compressed rather slowly and the hydraulic machines are heavy and difficult to handle, so that the net saving of labor cost would be probably small, though the quality of work might be improved by their use.

The expression for the economical cross-section of bonding may be stated conveniently.

$$\text{Sq. cm.} = 1000\sqrt{\frac{\text{annual loss}}{\text{annual cost}}}$$

or the economical cross-section varies inversely as the square root of the annual cost. In the first case considered the net cost per 1000 sq. cm. of bond was 23 cents of which 9 cents was for application, about 0.4 of the whole (based on cost of application of 20 cents per bond). It is evident that any considerable increase in the cost per 1000 sq. cm. of applying bonds will radically decrease the economic section of the same. In this case increasing the cost of application 50 per cent. will decrease the economical cross section 10.4 per cent., and doubling the cost of application will decrease the economical cross section 19 per cent. This is worthy of attention in view of the increased cost of application of various soldered bonds, for which lower contact resistance is claimed. Unless a considerably greater saving is made than the 8 per cent. herein allowed for contact resistance of compressed terminal bonds, which seems also to accord with the results of tests by Mr. W. C. Burton, the greater cost of soldering to the rails would seem a rather doubtful investment.

H. A. LARDNER: The trouble in securing a suitable bond is largely due to the difficulty of obtaining a permanently good contact between the bond terminal and the rail, and the speaker believes that this is primarily due to the difficulties under which bonds are usually installed. Therefore, some radically new methods of bonding should be devised. The question of a proper weld between the bond strip and the terminal has been worked out, and the market contains plenty of good bonds, so far as this feature goes.

The attainment of a low contact resistance between the terminal and the rail depends so largely on the individual applying the bond that even with the best supervision we cannot be certain that a low resistance contact will be permanently secured. Undoubtedly all rails should be drilled, or at least reamed on the work, and it is a question whether or not the bond terminals themselves should not actually be machined so as to present an accurate fit. If this is done, less expanding will be necessary. If the fit is not very close, the bond must be expanded to such an extent that the copper becomes hard and does not actually fill the hole. Such bonds when removed after a period show a very small percentage of the surface actually in contact with the rail itself.

Owing to the many difficulties experienced in placing expanded terminal bonds, it is likely that in the end they must be supplanted by some form which will obviate this difficulty. This is especially true in the case of heavy traction, where the bonds must be installed under the plates of an existing track. The placing of bonds under these conditions becomes very serious, owing to the lack of proper time for drilling the holes in the rails and for installing the bonds with all the care and attention that is demanded. It is also a matter of great expense, especially where lock-nuts or some of the special forms of bolts are used for keeping the joints tight; in such cases it usually means throwing away the old bolts and providing new ones. The difficulty in maintaining bonds located under the splice-bars is also very serious for the same reasons, especially on steam railroad tracks where the train service is frequent.

The speaker feels, therefore, that eventually we must look for relief to some form of bond which can be more readily inspected than the expanded terminal bond commonly placed underneath the splice-bars. The usual form of long bond extending around the splice-bar is expensive, its resistance is great, and the bond is easily stolen. It is to be hoped that some form of bond can be devised to utilize splice-bars with short flexible connections between them and the rails.

A. A. Knudson: In Brooklyn last fall I saw the application of a method of bonding which has not been referred to in the paper. I believe this method has features equal in importance to any of those mentioned by the author.

Briefly, it consists of two steel bars electrically welded to the web of the rail, one upon each side. Heat is applied by electricity at three points, one near each end of the bars and one at the center. When the metal is brought to a welding heat, hydraulic pressure is then applied.[1]

In reference to electrolysis the author says:

"In the special case of elevated railways using steel structures, the metal of the latter has been used to excellent advantage though this presents some peculiar problems in bonding, and a serious risk of electrolysis of anchor bolts."

In my opinion, there should not, except in special cases, be much concern on this point, as the large masses of metal composing the structure would, as a conductor, very largely

1. This method originated with Professor Elihu Thomson and has passed through several stages of improvements. Details may be found in an illustrated article in the *Street Railway Journal*, Sept. 12, 1903.

exceed that of underground mains, and therefore but little if any current would be diverted to them. There may be some cases where such damage will prevail, but probably there will not be any general corrosion of anchor bolts as seems to be inferred in the paper.

The author has considered the various points bearing on the subject in a very fair way, the defects as well as advantages of the many styles of rail bonds mentioned being explained.

WM. PESTELL: I have had occasion during the last few years, in construction and reconstruction of electric railways, to observe several kinds of bonds applied under different conditions. I have noted the extent of corrosion at terminals under various conditions. The compressed or expanded terminal bond in a track exposed to moisture and street conditions, as in street railway service where T-and girder-rails are laid in a roadway surrounded by paving or macadam, deteriorates more rapidly than where the track is on private right of way, the bonds in the latter case not being exposed to the action of moisture to so great an extent as when buried in the ground. Bonds that have been recently tested and shown to be of good conductivity indicate a great deterioration, sometimes as much as 50% of the original conductivity after the falling of trolley wire and consequent passage of an excessive amount of current through them. I have also noted in taking out some of the earlier types of the bonds, particularly in New England, where the steel terminal riveted bond was used, that after being in service for 12 or 14 years the terminals seemed to be as clean and bright as when first applied, the only corrosion being between the copper wire and the terminal. This was also the case with the so-called West-End or Brown bond used in and about Boston, Mass. This bond consists of a tapered steel sleeve, through which is soldered the copper wire, the steel being expanded in a hole in the rail. These bonds are usually in good condition, and show practically no corrosion between the steel terminals and the rail.

CALVERT TOWNLEY: A mathematical expression for the most economical bond should take into account the effect of increased bonding in reducing electrolysis. The greater the capacity of the bond, and the consequent greater conductivity of track, the smaller would be the tendency for current to seek a channel through water pipes. This factor makes a general mathematical expression difficult, because in a locality having numerous water pipes the value of minimizing the chances of electrolysis will be much greater than in cross-country running where there are no water pipes.

RALPH D. MERSHON: I would like to ask Mr. Ricker whether he has any data regarding the contact resistance itself in relation to the resistance of the bond. On page 91, eight per cent. is allowed for terminals, which presumably applies to the contact resistance. The question of contact resistance would seem to be a very important factor in any economical calculations such as have been made. Instead of basing his calculations on the centimeter cross-section of the bond perhaps he ought to take account of the resistance of contact as well; in other words, with the same sq. cm. of bond, better results might be obtained with two, three, or four bonds than with a lesser number.

H. A. LARDNER: I have had some experience in trying to measure the contact resistance of new bonds, with the result that if the joint resistance shows the bond to be properly applied, the actual contact resistance will be so small that it is impossible to measure it. The usual method of measuring the contact resistance of the bond is to determine the fall of pressure from some point on the rail to some point on the bond terminal. Of necessity, this measurement includes not only the contact but a small portion of the rail and a small portion of the bond, so that even if a reading on the milli-voltmeter is obtained it is not possible to say definitely that it represents the resistance of the contact. In a large number of tests with from 200 to 300 amperes passing through the rail and bond it is generally possible to get the contact points so near together that the difference in pressure can not be read on a sensitive milli-voltmeter. The above results apply to new bonds. If the contact resistance is measurable, it generally indicates that the contact is bad and would probably grow worse if left in place.

C. W. RICKER: In several cases where I have tried to learn the probable contact resistance of compressed or expanded terminal bonds by measuring the resistance of a definite length of rail in the track and subtracting therefrom the resistance of the rail and that of a length of copper equal to the aggregate length of the bonds, measured between centres of terminals, the average resistance per contact of 0000 bonds with 0.875-inch terminals, in good condition, was that of about 0.5 inch of the bond. In Foster's Pocket Book, Mr. W. C. Burton is quoted as saying that tests show an average resistance of 0.375-inch of the bond per contact. My measurements were all made in the course of work on track that was in service, and often they could not be made as complete as might be wished.

A paper presented at the 195th Meeting of the American Institute of Electrical Engineers, New York, March 24, 1905.

LINE CONSTRUCTION FOR HIGH-PRESSURE ELECTRIC RAILROADS.

BY GEORGE A. DAMON.

The single-phase high-pressure trolley has arrived and evidently has come to stay. The advantages gained by delivering energy directly to a car without the necessity of an investment in synchronous converters and heavy feeders has long been recognized. That it is entirely practicable to take current from a high-pressure conductor by means of a moving contact has been fully demonstrated. It has required some time to show that there is a field for a single-phase traction motor sufficiently promising to justify its commercial development, but a number of motors of this type are now upon the market and within the last few weeks have been put in actual every-day operation.

To get the full benefit of the new system, it is desirable to carry as high a pressure as practicable on the trolley wire. It is apparent at once that the methods of installation which have become standard with the 500-volt system are inadequate for the new conditions. Several methods of supporting the high-pressure trolley wire have already been developed, and now the time has come to standardize the pressure and the location of the current conductor, as well as the method of current collection in order to provide for an interchange of equipment.

It is the object of this paper to present a brief record of what has already been accomplished in line construction, and to examine the requirements and difficulties of installation in order to obtain permanent insulation at reasonable cost, safety to the public, and reliability in service. It is important that a discussion be developed at this time which will at least indicate the tendency of the developments which are taking place. In order to allow an opportunity for the presentation of the details and advantages of certain systems which are being perfected by others, this paper is purposely left incomplete in certain parts.

THREE CLASSES OF CONSTRUCTION.

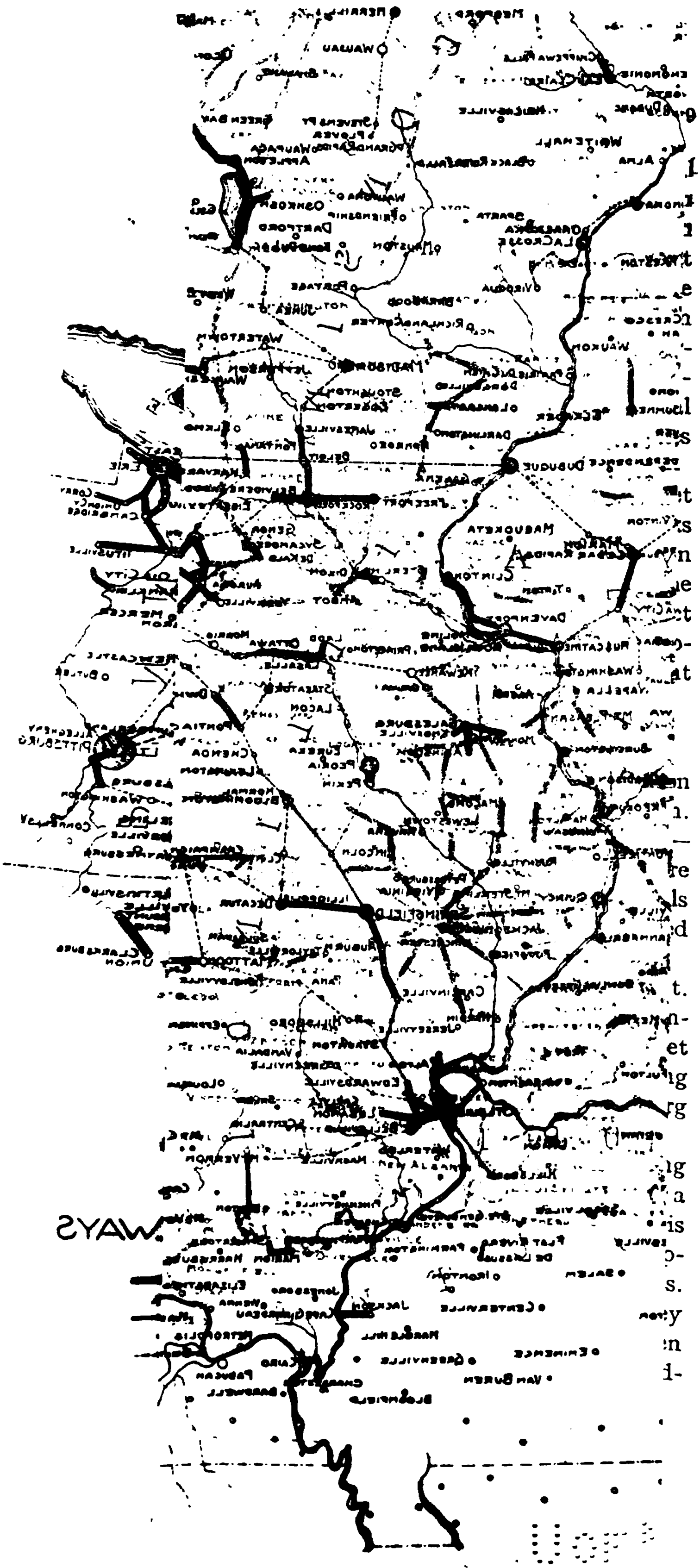
The successful use of a single high-pressure trolley wire will have a marked stimulus upon three distinct branches of the electric railroad art:

1. Moderate speed and inexpensively equipped electric lines for country districts.
2. High-speed interurban roads for service between large centers of population.
3. Electrification of steam railroads.

This will leave the city systems with their suburban extensions to be served, for the present, by the direct-current motor. In studying the methods of line construction, it will be desirable, to keep in mind that each of the three classes of roads indicated will have its own individual problems and requirements.

For moderate speed lines in the country districts, the full benefit of the high-pressure system will be obtained only when the first cost of such a road has been reduced to a minimum, consistent with good work. A study of the map, Fig. 1, which shows the electric railway situation in the middle Western States, will emphasize this point. It will be seen that nearly all the territory which promises even a fair return on the investment has been preempted and that some roads are even now being built where there may be some doubt as to their being able to stand the fixed charges resulting from the cost of the illogical synchronous converter sub-station system. There are still left whole sections of rich productive agricultural districts which will remain unserved by a trolley road until a system has been developed which is so simple in its requirements that it can be built and equipped complete for less than $15 000 per mile, and operated on a basis equally economical. This class of installation means a trolley pressure as high as possible, as well as transformer sub-stations operating without attendance and working in parallel from one transmission line.

For high-speed interurban roads the high-pressure trolley



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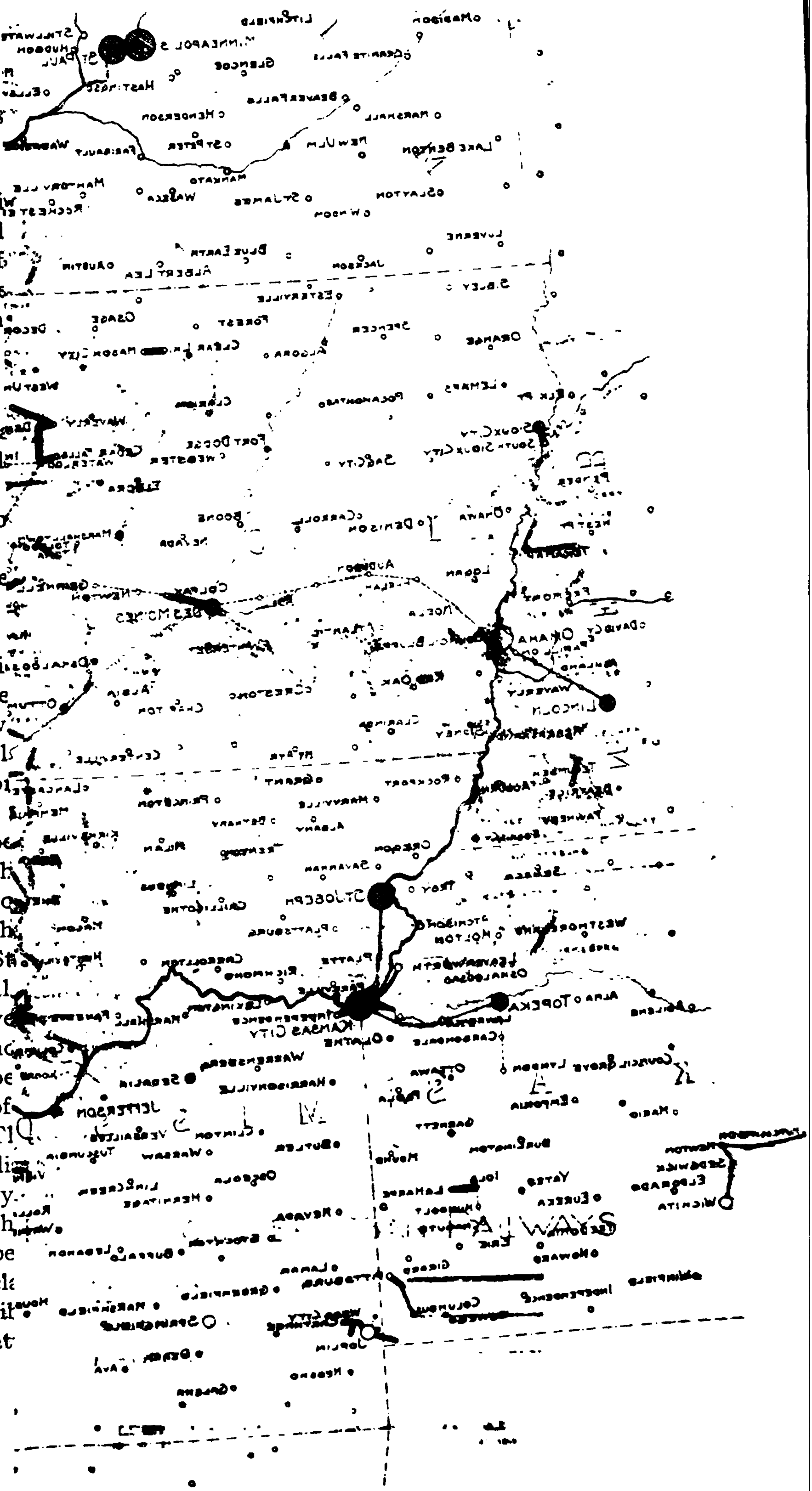


opens up new possibilities. Heavier cars with more powerful motor equipments can now be operated at high speeds between cities without prohibitive first cost. "Limited" electric train service with speed schedules of 60 miles an hour from the heart of one city to another will soon be in vogue, and without the necessity of changing from third rail to trolley in passing from private right of way at corporate limits. Roads of this character, with their better earning capacity, can afford such refinements in line construction as a sectionalized trolley, individual transmission lines to each sub-station, and separate pole lines for the trolley and the transmission systems.

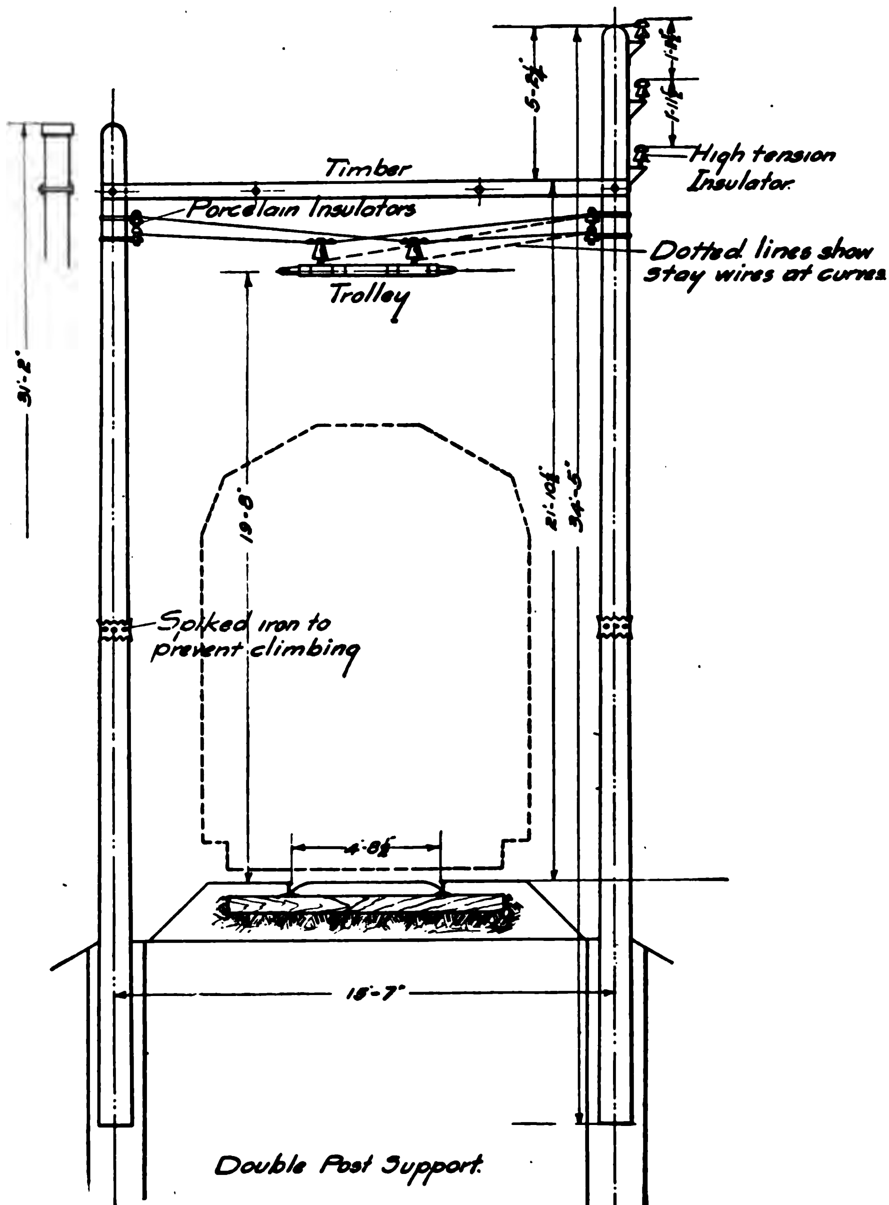
The electrification of steam roads will present a different set of conditions. Here the steam locomotive will share the tracks with its electric successor for some time, and will do all it can with its acid-charged gases to destroy the handiwork of the electrical engineer. This will make the installation of a contact wire anywhere except at the side of the track a doubtful proposition, and thus calls attention more strongly to the statement that line-construction problems must be divided into classes.

Lines Already Built.

It will be instructive to examine the details of construction of several high-pressure trolley lines already in operation. There are details available of three installations in Europe — Valtellina, Spindersfeld, and the Huber system. There are several other lines building in Europe, but either the details of the line work have not been disclosed or the systems adopted are similar to the ones described.

In this country the overhead equipment of the Lansing, St. Johns & St. Louis Electric Railway, the Indianapolis and Cincinnati Traction Co., and the Bloomington, Pontiac & Joliet Electric Railroad will present types, leaving the interesting work which has been done near Schenectady and at Pittsburg to be described and discussed by others.

Valtellina, Figs. 2 to 7. This is really a three-phase road having two trolleys, but the line construction could easily be adapted for a single trolley. The line is 66 miles long, with three branches; is located near Milan, Italy, and has been in operation since September, 1902. The trolley pressure is 3000 volts at 15 cycles. The transmission line, at 20 000 volts, is carried on the trolley poles. The contact wires are fixed at a height of 20 feet in open stretches and at 16 feet in tunnels. The trolley wires are hard-



Timber
Porcelain Insulators
High tension Insulator
Dotted lines show stay wires at curves
Trolley
Spiked iron to prevent climbing
5-8¼"
1-11½"
1-11½"
31-2"
19-8"
21-10½"
34-5"
4-8½"
15-7"
Double Post Support

FIG. 2.

drawn copper wires of 8-mm. diameter, and the span wires consist of galvanized steel wires of 5-mm. diameter. The span wires which hold the trolley wires, after the usual suspension method, are attached to the poles by means of porcelain insulators of a

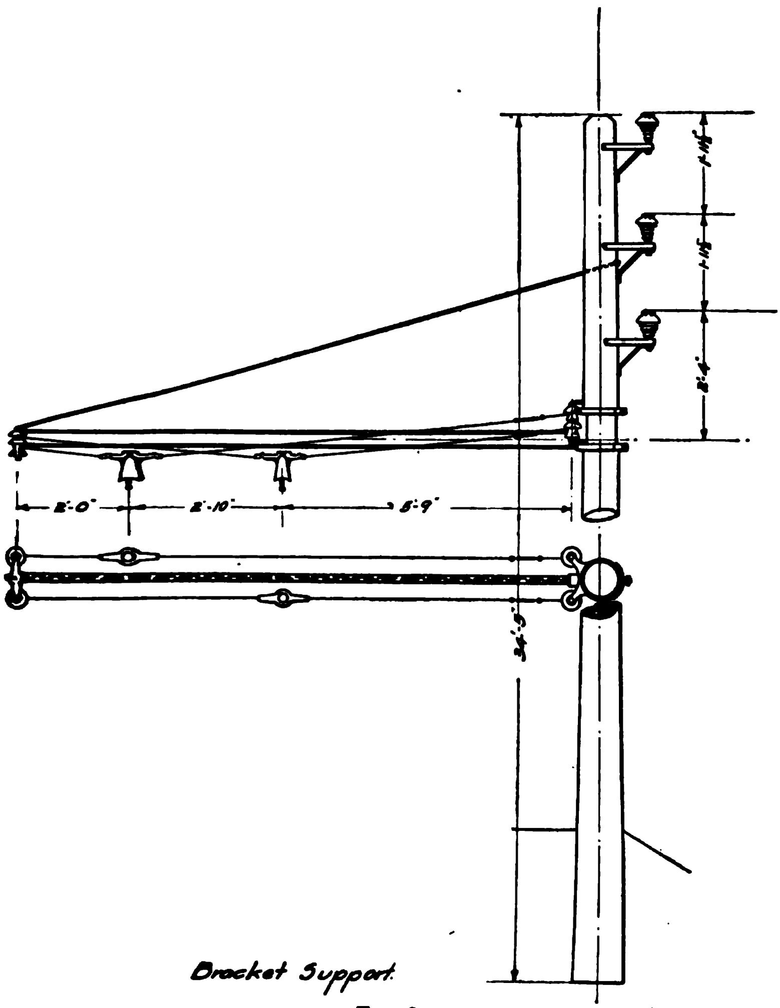
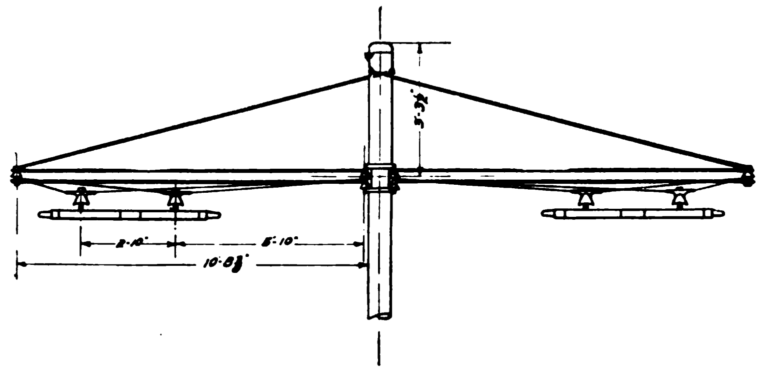


FIG. 3.

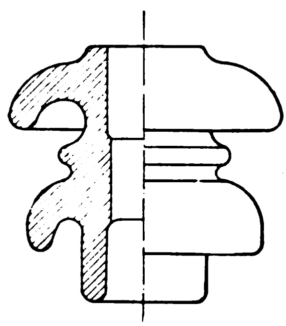
special type. The contact wire is suspended by ambroin insulators consisting of a cast-iron bell holding a steel bolt imbedded in ambroin and having a mechanical clip at its lower end. The insulators are tested to 10 000 volts.

On tangents and on curves with a radius greater than 3000 feet, single-bracket poles are used; on curves the contact wires are suspended on double poles with span construction. At



Two Arm Support
FIG. 4.

stations double-bracket poles are used. A peculiar detail is a circlet of iron with protruding spikes to prevent people from climbing the poles.



Porcelain Insulator
FIG. 5.

High Tension Insulator
FIG. 6.

The current collector consists of a roller of electrolytic copper of 3.125 in. diameter and 2 ft. 1.625 in. long. The current is taken from the roller by contacts rubbing on both ends of the roller. One break of the contact wire on this line is reported, the wire falling on the roof of the car, which was thoroughly grounded and thus no harm was done.

Spindersfeld, Fig. 8. This is a single-phase experimental electric line installed on the State Railroad near Berlin. The line is three miles long; it was put in operation in June, 1903. The trolley pressure is 6000 volts at 25 cycles. The trolley wire is hung from two steel catenary wires with suspensions every

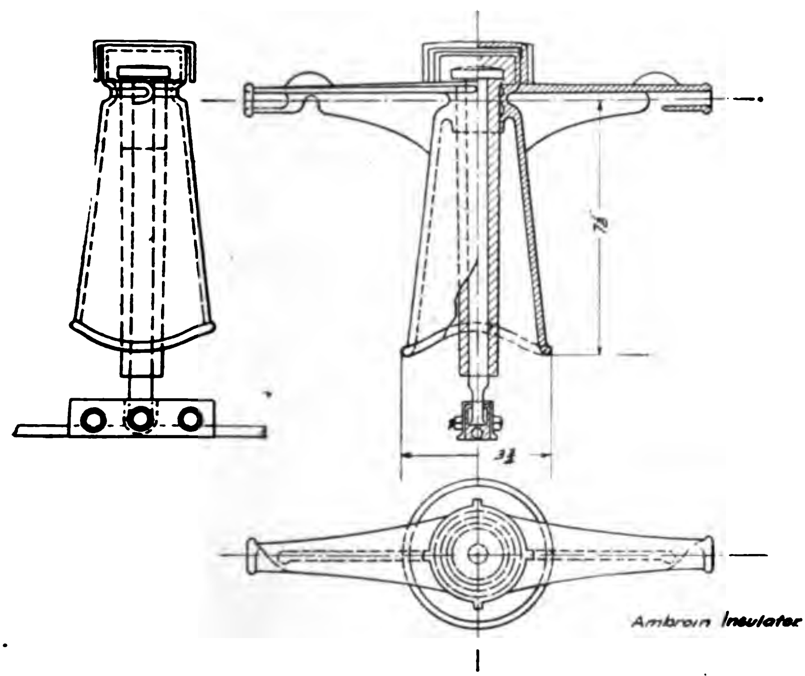


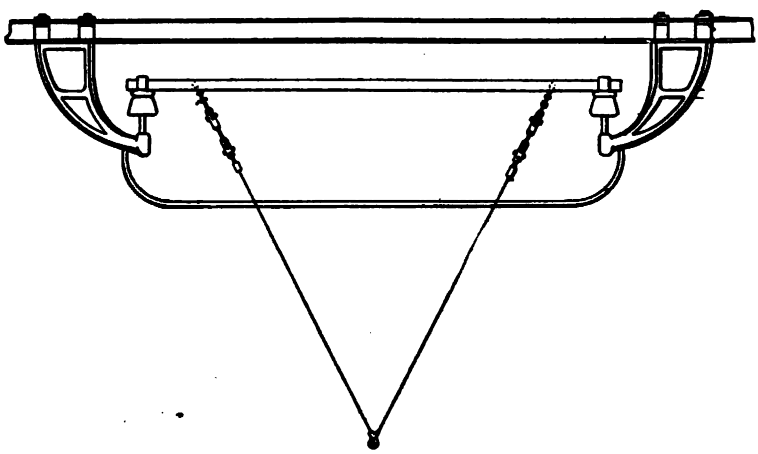
FIG. 7.

10 ft. The steel wires also act as current conductors.

The copper wire is of 8-mm. diameter; this seems to be the standard size on foreign roads. This wire is slightly smaller than No. 0 B. & S. gauge. The contact device is a sliding bow. On parts of the line a single catenary suspension is used, the double catenary being a later development, having been adopted to insure greater safety and to increase the lateral rigidity of the conductor. The catenary wires are attached by short rubber chains to a bar mounted on two insulators and fastened to the bracket arms by means of special clamps.

Underneath the bridle wire there is an earthed bar, so arranged that a break in the line or in the catenaries will cause a contact to be made with the live conductor, grounding the system and throwing a circuit-breaker and thus protecting the line.

All telegraph, telephone, and other wires passing over the trolley, are protected by a wire cage which completely surrounds them in order to prevent any possibility of their coming in contact with the high-pressure railroad conductors.



Detail of Catenary Construction.
Spendersfelds Line.

Fig. 8.

Huber System, Figs. 9 *to* 17. An experimental line has been built by the Oerlikon Machine Works after the plans of E. Huber, technical director of the Company. The line uses a single-phase current at 14 000 volts directly on the conductor wire. The current-collecting device is of novel design; it consists of a curved metallic stem with its convex surface bearing lightly on the top of the current-carrying conductor. Normally the wire is located at the side of the car, but in passing through a tunnel or under an over-head crossing, the wire can be brought over the center of the track. The collecting stem has a rotary motion in a plane perpendicular to the track; the position of the stem at any time is regulated automatically by the location of the overhead conductor wire. Figs. 9 to 17 indicate diagrammatically the various relative positions of the collecting device and the wire.

In making contact with the wire when over the car the collector arm rubs beneath the wire, but this is only done in tunnels and in other contracted spaces. The current collector is mount-

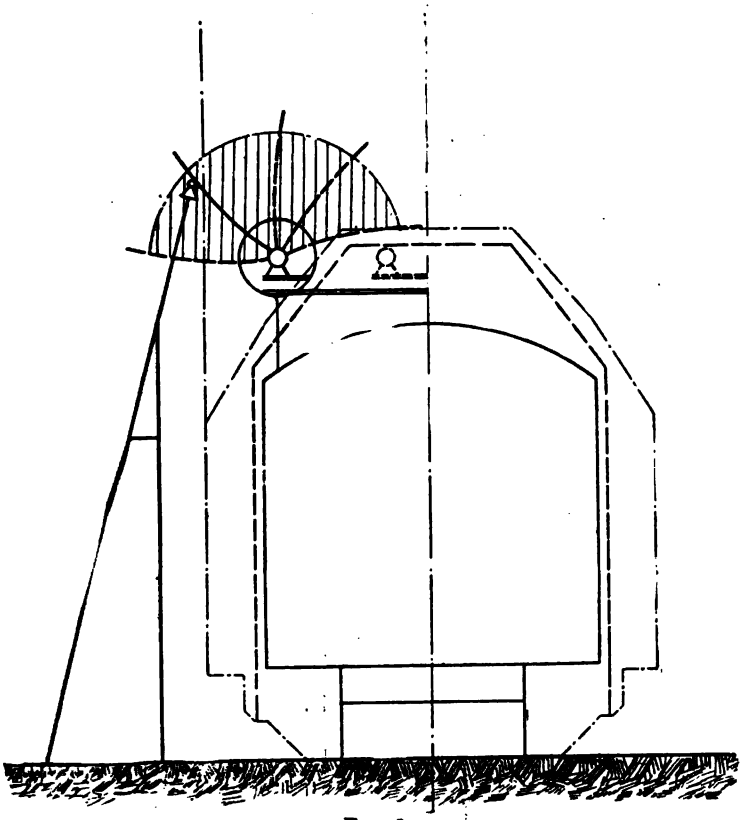


FIG. 9.

ed on porcelain insulators and the light arm is held in place in such a way that it can readily be removed and renewed. The entire device is further mounted on a parallel link motion, which is controlled automatically so as to shift the center of rotation of the contact stem when required.

The side wire is carried in mechanical clips held in place on the top of the poles by special porcelain insulators made large enough to stand a test of 30 000 volts. The entire line has withstood a test of 16 000 volts. The average height of the contact wire alongside of the track is 15 ft., and inside tunnels

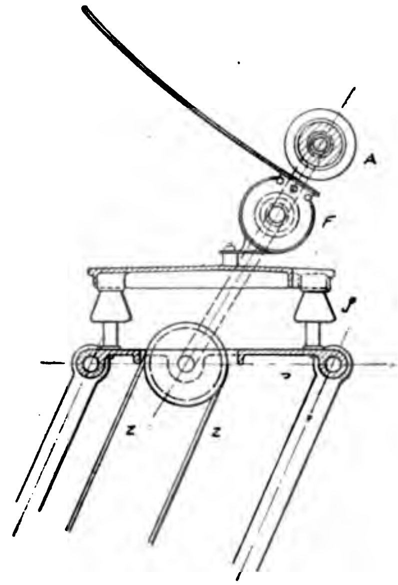


FIG. 10.

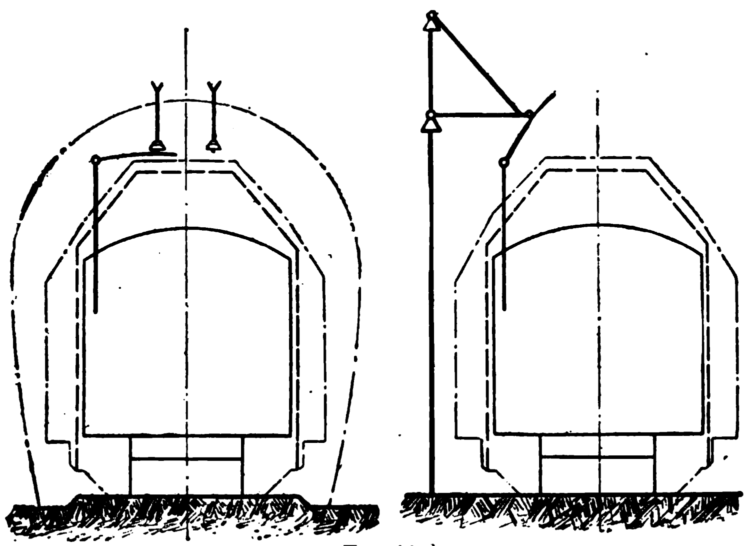


FIG. 11.

16.5 ft. The distance between supports is about 100 ft.

The Huber system is being installed upon the Seebach-

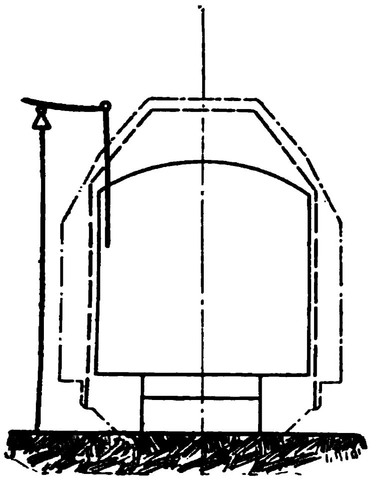


FIG. 12.

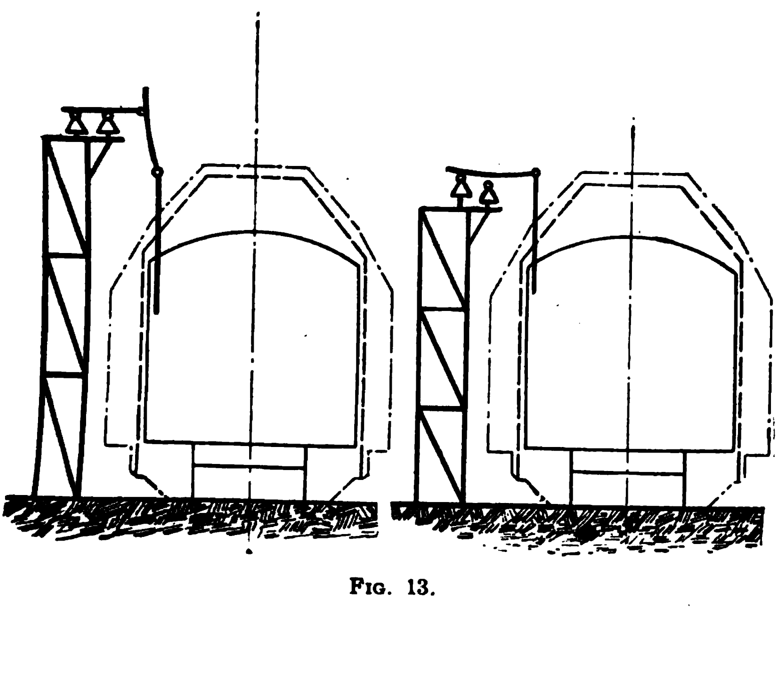


FIG. 13.

Wettigen line, where its operation will be watched with more than ordinary interest.

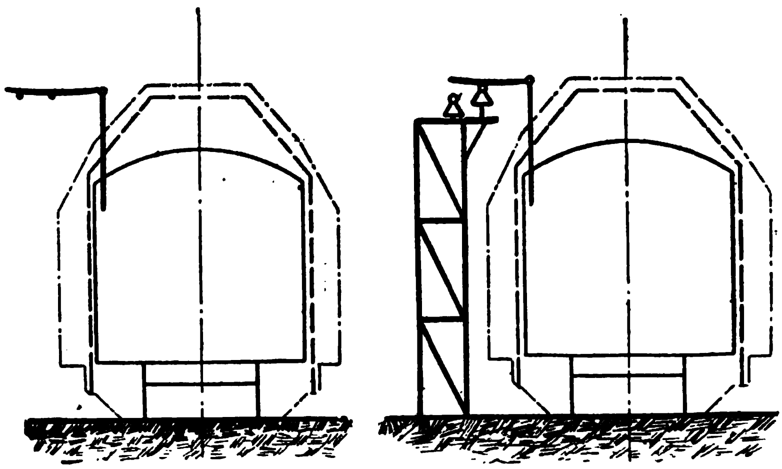


FIG. 14.

Swedish State Railroad. It is instructive to note that upon the experimental line authorized by the government of Sweden,

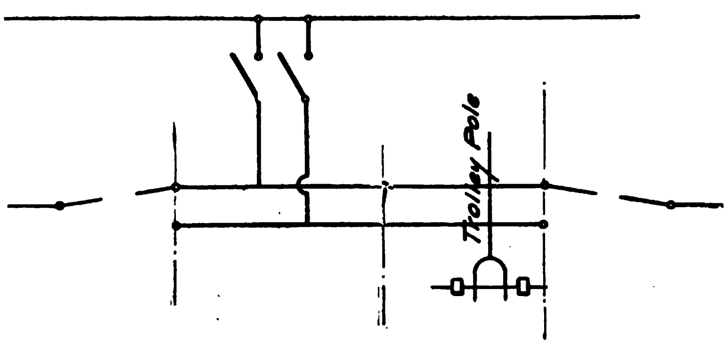


FIG. 15.

and now building, a pressure on the contact wire of 6000 volts at 25 cycles will be used.

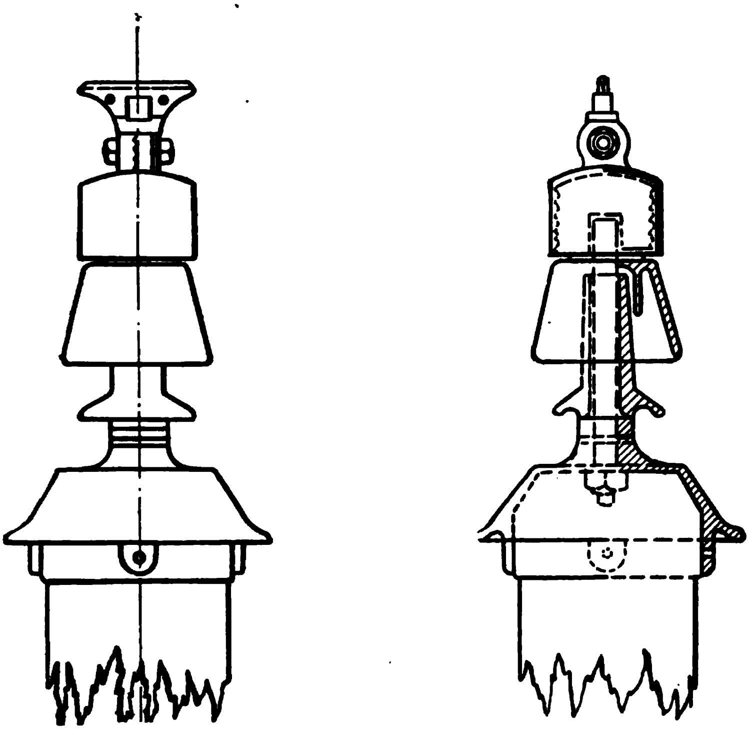


FIG. 16.

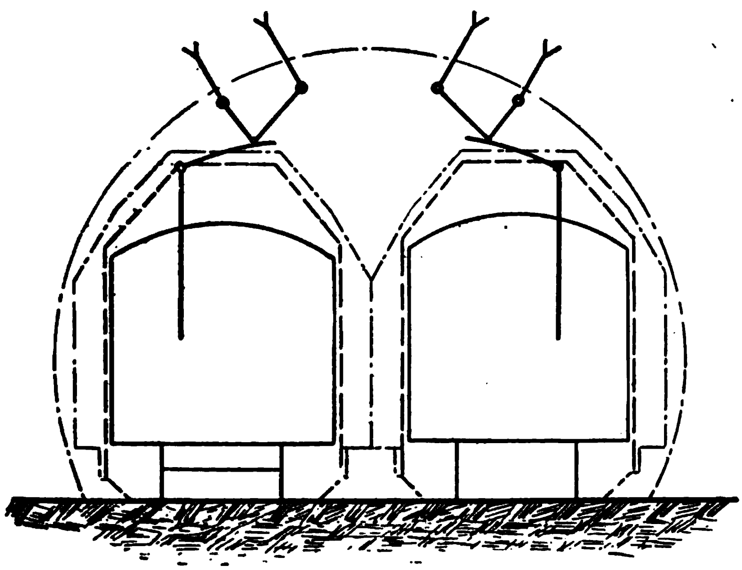


FIG. 17.

Lansing, St. John's & St. Louis El. Ry., Figs. 18 & 19. This was the first single-phase electric road to be built. It runs 20 miles north from Lansing, Michigan. The line was the scene of the pioneer single-phase work done by Bion J. Arnold in 1900-1904. The line has been operated with a pressure of 6000 volts on the trolley wire. The general method of suspending the trolley wire followed in direct-current work was adopted for this line, but the usual hanger was replaced with a large special insulator of annealed glass, tested to 30 000

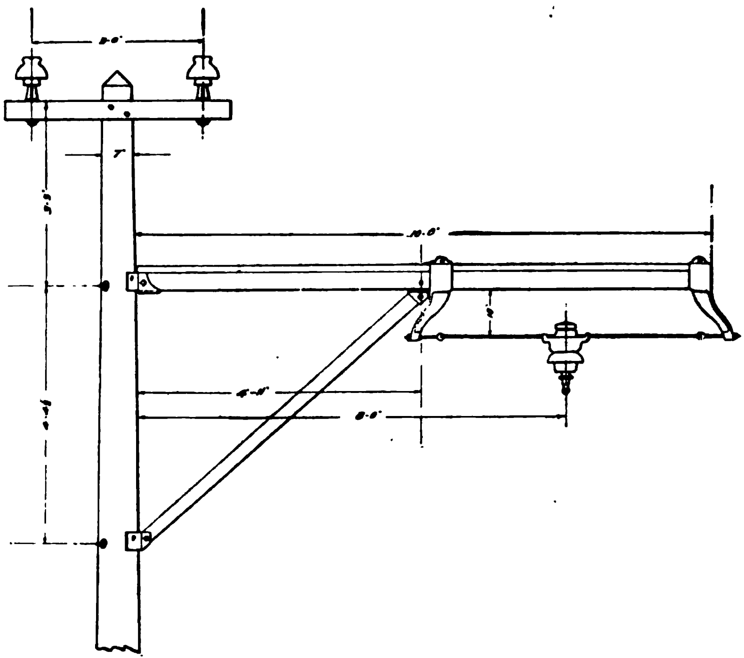


FIG. 18.

volts. This special hanger was held in place on a flexible cross wire suspended between malleable-iron brackets attached to a wooden cross-arm. It was originally intended to stagger the wire supports and use a bow collector, but the experiments were finally conducted with the use of an ordinary trolley wheel. This wheel would at times slip off the wire, and the breaking of the glass hanger insulators from this cause soon demonstrated that this form of suspension was not adapted for places when there was any probability of an ordinary trolley wheel being used.

This line proved, however, that the use of trolley pressures as high as 6000 volts were entirely practicable; and the attention which was attracted to single-phase possibilities by the early

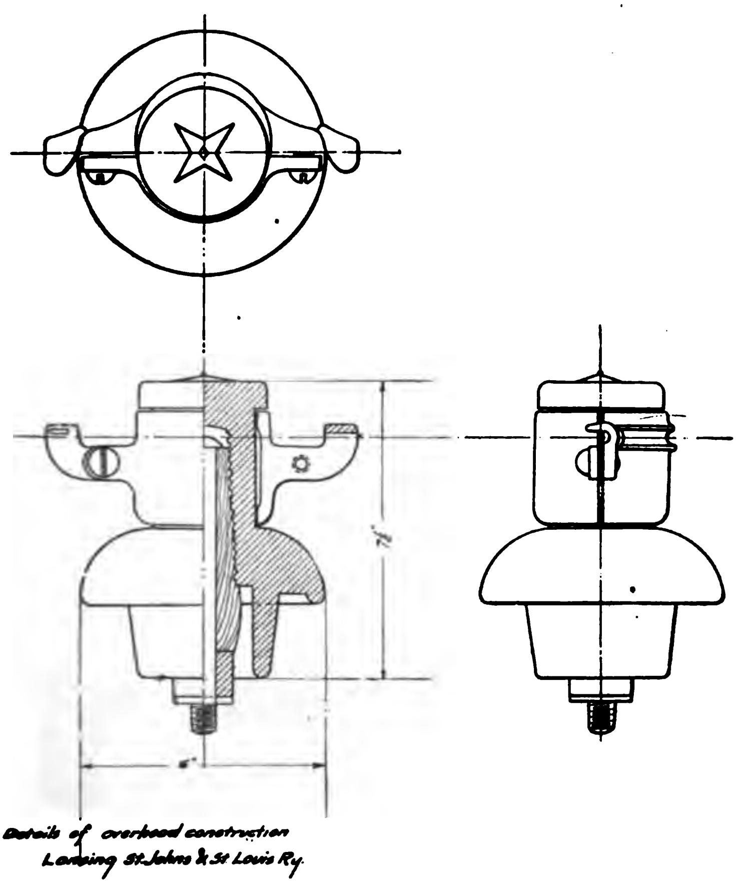
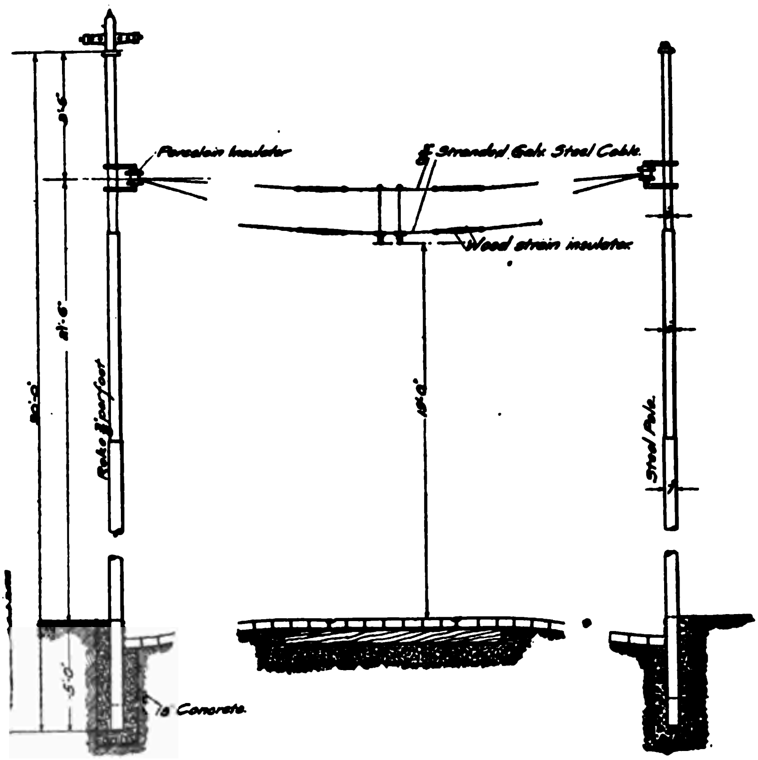


FIG. 19.

work done at Lansing had a marked influence in creating the demand for the general development of high-pressure railroad systems.

Bloomington, Pontiac & Joliet Electric Railway. Figs. 20 to 24. This line will be 90 miles long, connecting Bloomington and Joliet, Illinois. A section of the line was put in operation February, 1905. The trolley pressure is 3300 volts, and the wires are held in place by catenary construction. Owing to local conditions, such as turnouts, there are two No. 00 grooved trolleys over each track, each hung from a 0.375-in. galvanized steel cable. The poles are so placed that eventually they will be in the center between a double track. The brackets holding the catenary



Cross suspension for high tension trolley. City Streets.

Fig. 20.

insulators are made of Washington fir, with a wooden brace underneath. The insulators are cemented on iron pins.

The trolley wires are suspended from the steel catenaries by means of special mechanical clips attached to the wires every 11 feet. In Pontiac iron poles are used and a special insulator has been designed for the support of the cross-suspension wire.

Above the trolley in city streets a lighter catenary construction is placed for protection in case the trolley wire should break; but most of the strain is carried by the regular cross-suspension wires.

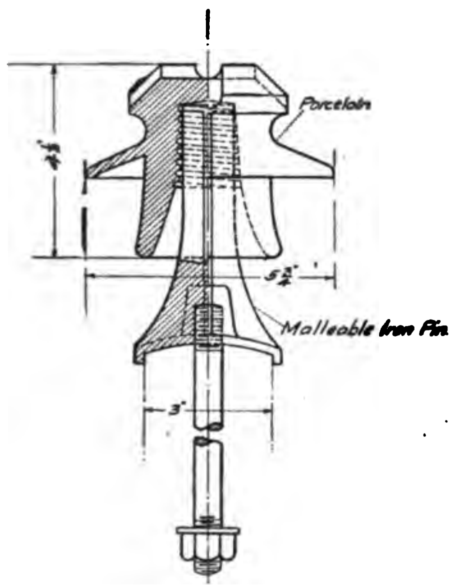


FIG. 21.

Indianapolis and Cincinnati Traction Co. This is a high-speed interurban line, 41 miles of which are practically finished. Sixteen miles were put into service January, 1905. The trolley

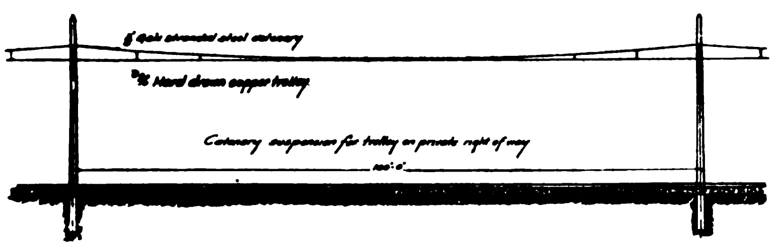
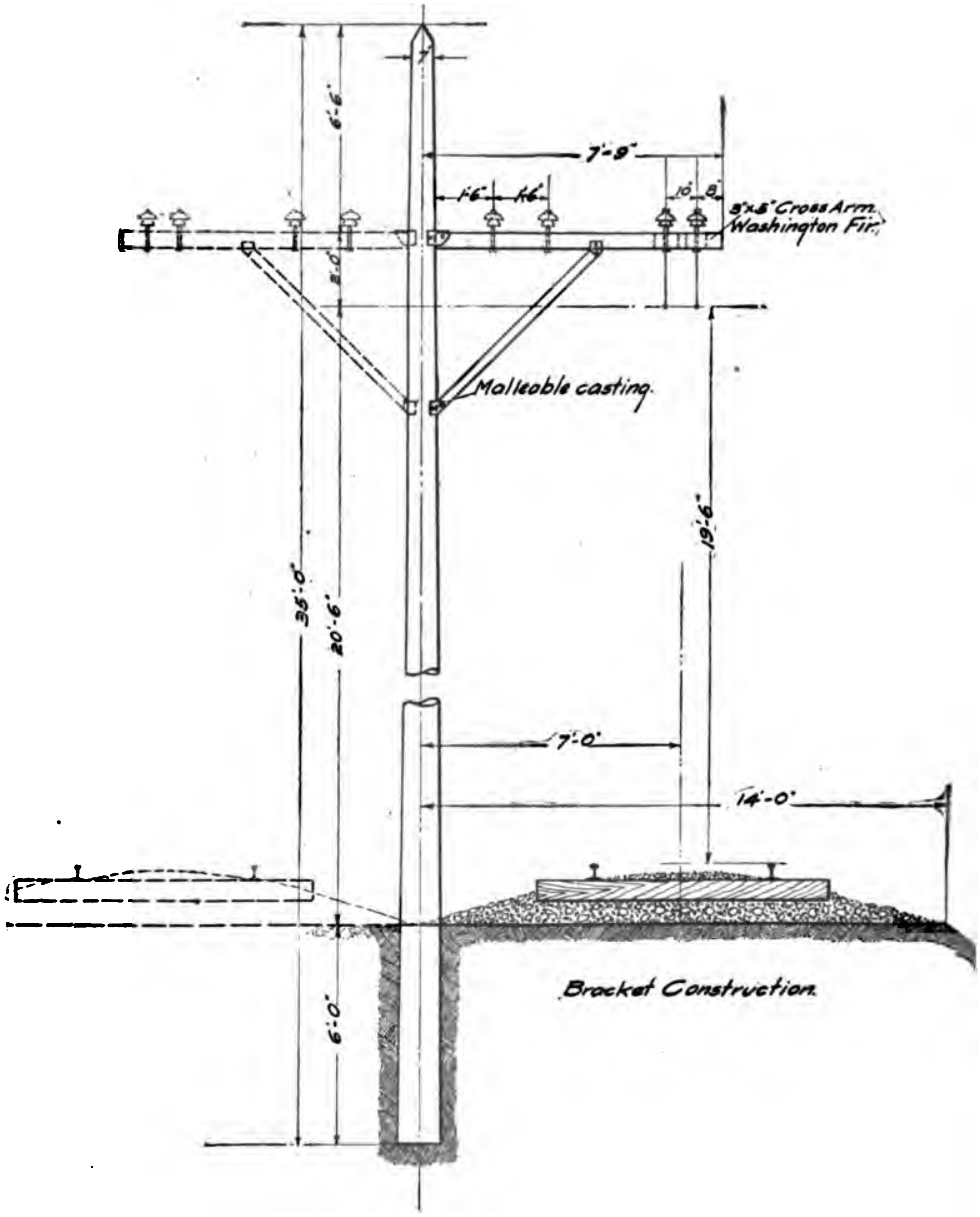


FIG. 22.

pressure is 3300 volts. The catenary form of suspension is used with one 0.4375-in. steel messenger wire supported every 100 ft. by large flat insulators held on an iron bracket. The



6'-6"
7'-9"
1'-6"
1'-6"
10"
8"
3"x5" Cross Arm.
Washington Fir.
2'-0"
Malleable casting.
19'-6"
35'-0"
20'-6"
7'-0"
14'-0"
6'-0"
Bracket Construction.

FIG. 23.

copper trolley wire is No. 000 B. & S. gauge and is carried eight inches under the messenger cable. The trolley is supported every 10 ft. by means of special steel clamps in such a manner that the wire is held very nearly at a perfect level. Over the center of the track and 18 ft. above the rail.

The transmission line pressure is 33 000 volts; a separate pair of wires connects the power-house with each sub-station. The trolley pole-line and the transmission pole-line are separate, the former being at one side of the right of way. The

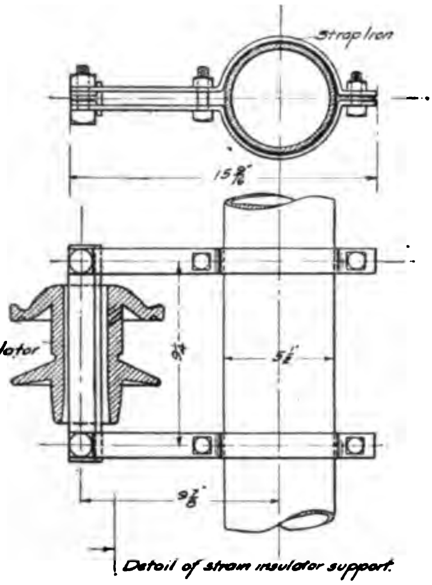


FIG. 24.

iron brackets holding the catenary insulators are made of angle-iron with a loop at the outside; this will allow for considerable adjustment in the position of the insulator. It is the intention to stagger the position of the catenary supports and thus produce a horizontal wave in the trolley line, which will distribute the wear on the bow collector, eventually to be used on this line.

Requirements of Installation.

Bearing in mind the distinct requirements of the three classes of roads already referred to, the problem of line construction may be discussed under the following heads:

1. Pressure and Insulation;
2. Location of Conductor;
3. Requirements for Safety and Stability.

As an entire paper might be devoted to any one of these subjects, there is offered an opportunity for considerable discussion.

Pressure and Insulation.—The single-phase lines now in operation in this country have 3300-volt trolleys, and several lines under construction have also decided to use this pressure. From present appearances, therefore, 3300 volts is to be the standard for interurban lines. It would be well, however, to consider just at this time whether it would not be advisable to use a trolley pressure of 6000 volts. From an operating standpoint there seems to be no reason why this higher pressure is not just as practicable as a lower one; and to get the full benefit of all the advantages inherent with the high-tension system the higher pressure should be adopted.

Even if a few of the first roads are built with a 3300-volt trolley, there is no reason why, with the catenary suspension, the insulation provided should not be capable of standing a working test of 6000 volts, so that when the time comes to double the pressure, the expense of the change will be a minimum.

For steam-railroad conditions, the larger amount of energy required indicates that a pressure of at least 15 000 volts will probably be desirable. Just where to strike a balance between the cost of copper and the cost of insulation for steam-road work is a problem which should be carefully worked out; but there seems to be no reason at this time why pressures of over 10 000 volts for steam-road electrification should not be considered.

The so-called catenary form of suspension affords so convenient a method of insulation that it should become standard practice for interurban electric lines. When selecting an insulator for this construction, mechanical strength should be the first consideration, and a few cents more spent on the insulator will insure an abundance of insulating qualities. As far as insulation is concerned, there is no reason why the catenary construction could not be operated at more than 30 000 volts, if desired. For pull-offs and cross suspensions to iron poles special porcelain insulators are being designed and used with success.

It has long been admitted that dry wood is one of the best insulators. The convenience with which a wooden rod fitted with suitable terminals can be worked into an overhead construction will commend this form of insulation. Impregnated with an insulating compound, and of sufficient length to withstand high pressure tests, the long wooden insulator is applicable to the insulation of guy wires, anchors, and cross suspension wires. Its use in actual practice will be watched with interest.

The use of a wooden bracket to hold the insulator for supporting the catenary will probably appeal to some as a step backward. As far as looks are concerned, however, it may be said that a wooden bracket of a section 3.5 by 5 in. presents an appearance fully as attractive as the ordinary cedar pole to which it is attached; and that a double-track road with a line of center poles equipped with wooden brackets will be much less offensive from an æsthetic point of view than a double row of side suspension poles raked outward in the usual fashion.

The wooden bracket has an element of safety not possessed by an iron support, as the insulating properties of the wooden arm would be useful in the case of the failure of an insulator. Unless the wooden bracket were wet it would safely hold up a 6000-volt catenary until the line could be repaired.

Location of Conductor and Collector Systems.

For moderate-speed roads the natural tendency will be to have the trolley wire where it has proved to be so thoroughly satisfactory; that is, over the center of the track, and to continue to use the present trolley-harp and wheel. For speeds not exceeding 40 to 50 miles an hour at trolley pressures up to 3300 volts this arrangement will work satisfactorily.

For high-speed electric lines there will be little objection to the conductor wire remaining over the track, provided it is properly suspended; but the danger of the ordinary trolley wheel jumping off the wire at high speeds will, no doubt, suggest the use of some form of collector other than the wheel. The bow, the roller, and the shoe will each find advocates until more experience has been obtained and the results are reported and discussed.

Special cases will arise such as the installation of a high-pressure conductor wire over a road already equipped with a direct-current trolley, as was the case with the Ballston, N. Y., road. In such an event the catenary construction can be very nicely adapted to suspending the wire at the side of the track. This location could be advocated for an entirely new installation on the grounds of cheaper first cost and some additional safety in case the wire should break and fall, but both these arguments lack sufficient weight to establish the wire in the side position as standard practice.

For steam-road conditions considerable objection may be found to locating the conductor wire over the center of the track: the danger to trainmen standing on top of the cars; the fouling of the conductor; the deterioration of the insulation, and the destruction of the wire and supporting cables by the gases of locomotives which may jointly occupy the tracks; the blocking of traffic when it is necessary to repair a broken wire — all these are serious drawbacks to this location of the conductor for heavy railroad practice. To avoid the deleterious effect of the locomotive gases it would seem to be imperative to place the contact wire at one side and as low as possible consistent with general safety. The advisability of installing an independent and duplicate system of conductors is also to be considered for lines of importance; this can be done only by putting the wires on opposite sides of the track.

The Huber system appears to have been carefully worked out, and at the present time is the best suggestion for a solution of the line problems in connection with the electrification of steam roads. There is one serious objection to the arrangement, but this can be overcome. The contact wire carried from pole-top to pole-top is liable to break, and some form of support should be devised to prevent the broken ends falling to the ground. A double-catenary suspension system with one wire carried on an insulator at each end of a cross-arm attached to the pole, say a foot from the top, could be provided, and the contact wire could be supported from the apex of triangular supports attached to the two catenary wires. This method would offer advantages over any system of guard-wires or cradles which might be devised to catch the broken wire, as it would require three wires to be broken before any part of the system could fall to the ground.

Requirements for Safety.

Frequent Supports. Whatever method of construction is followed, every precaution should be adopted to prevent accidents to the public or employees from the loose ends of a broken live wire. Suspensions or supports properly installed every 10 to 15 ft. will lessen this danger.

With bracket construction having poles about 100 ft. apart, there will be no need of a double-catenary suspension for the wire which is to be used with an under-running collector. In such a case, the double suspension would mean twice as many insulators as would be required with the single catenary, thus decreasing the insulation resistance and increasing the chances for trouble. With what is known as the "tower" method of construction—using long spans—the double catenary, spreading at the points of insulated supports and converging at the center of the span, will be found desirable. The necessity of keeping the wire from swaying will justify the double catenary in this case, and the fact that the number of points of support is reduced by using long spans will more than balance the use of two insulators at each support.

The frequent clips holding the contact wire are not only advantageous from the standpoint of additional safety, but they contribute to the permanency of the construction by keeping the wire almost perfectly horizontal at all temperatures, and thus avoiding the bending of the wire up and down at the support points every time the collector passes. The only disadvantage to clips holding the wire every few feet is the tendency for the trolley wheel to spark at these points. This is not a serious objection if a collector similar to the bow device is used, in which case there will be no interference between the collector surface and the mechanical clips.

Protection from Sleet. In a hard sleet-storm every attachment connected to the wire will naturally be the cause of additional trouble. The arcs due to a coating of ice between the wire and the collector will be much more vicious at 6000 to 15 000 volts than at 500 volts, but there is no occasion to become alarmed at the possible danger from this source. In this country one of the high-pressure lines using a trolley wheel on a 3300-volt wire has already passed through a hard siege of sleet; and though the sparking was spectacular, very little damage was done. The frequent trolley supports, however, added considerably to the sparking.

Greased trolley wires are sometimes used to prevent the trouble caused by sleet; it would be interesting to learn the experience of members of the INSTITUTE with this device. It is well known that the grease finish of an aluminum wire prevents the collection of sleet upon the wire, and it may be possible that a coating of grease on the high-pressure conductor wire would entirely obviate this trouble. It is evident that with a collector taking the current by means of a contact made on the top of the wire, as in the Huber system, the trouble from sleet would be a minimum. In sleet storms in which icicles are formed and hang from the wire, a top-bearing collector would have every advantage, but when the sleet freezes equally all round the wire the lighter pressure of the top-bearing contact might put the Huber collector at a disadvantage.

Transmission Lines. The transmission lines from the power-plant to the sub-stations will be at a higher pressure than the trolley pressure, and will therefore require careful treatment. For a road which is to be built economically, a single set of transmission wires serving all of the static transformer stations in parallel will be sufficient. These transmission wires will ordinarily be carried on the tops of the same poles which support the trolley bracket.

The next refinement would be to have a separate set of transmission lines from the power-house to each sub-station, making it possible to put the overload protective devices on the central-station switchboard and thus eliminate the sub-station attendance. With this multiplicity of wires and consequent higher first cost adopted, it is but one step farther to separate entirely the two systems and to install two pole lines on the same right of way; where the electric road is of the high-speed class this should be done.

To be consistent, however, in insuring safety to the public, it would be well to advocate as standard practice the plan of carrying the high-pressure transmission lines entirely around small towns and cities instead of through them. If the transmission lines are too dangerous to be carried on the railroad company's trolley poles, then there is more danger in carrying them along the streets and over the network of telephone wires inside the corporate limits. The problem of the proper regulation for this situation is one that will shortly have to be faced.

The first investment in the transmission line, the cost of maintenance, and the loss by leakage—all these can be cut in half by thoroughly grounding one side of the single-phase transmission line so as to use the earth as one leg of the circuit. An actual trial of this suggestion to further simplify the distribution system is under contemplation, and no doubt will furnish valuable information as to its effect on telephone and telegraph lines as well as data in connection with the resistance of the earth with alternating currents.

Grounded Guard Wires. Where the transmission lines pass over other wires, there should be a cradle of grounded wires to prevent a broken transmission line from coming in contact with a foreign wire. This cradle will be of little use unless it is of ample dimensions. Some effort has been made on European roads so to install grounded wires that the breaking of a conductor would at once cause the live end of the wire to make a contact with the grounded guard-wire, but in two cases which have come to notice the grounded guard-wire caused more trouble than it eliminated; for this reason it was soon abandoned.

In order to encourage the discussion of the unsettled features of line construction for high-pressure electric railroads, the following are offered as

General Conclusions.

1. There are no reasons why the standard pressures of the conductor wire for interurban electric lines should not be at least 6000 volts; this is suggested as a standard in order to provide for interchange of equipment.

2. For the electrification of steam roads a pressure of about 15 000 volts on the conductor wire is desirable.

3. For electric interurban lines, the present tendency is toward the catenary form of suspension, with the trolley over the center of the track. A connection should be made about every 10 ft., between the steel catenary wire and the trolley wire.

4. For steam-railroad conditions a contact wire at the side of the track appears to offer the greatest advantages. Some form of construction should be adopted, however, to prevent the falling of the conductor in case it should break.

5. A successful bow collector for interurban work and a contact arm for steam-road installations similar to that in use by the Huber system would allow the location of the contact wire to be standardized.

6. A trolley wire 20 ft. above the center of the track is suggested for interurban roads. For steam-road electrification the height of the contact wire at the side of the track could be made standard at 16 ft.

A paper presented at the 195th Meeting of the American Institute of Electrical Engineers, New York, March 24th, 1905.

HIGH-PRESSURE LINE CONSTRUCTION FOR ALTERNATING-CURRENT RAILWAYS.

BY THEODORE VARNEY.

The chief advantage to be derived from the direct application of the alternating current to railway service is in the use of high trolley-pressures. Having a successful alternating-current motor, the remaining problem of greatest importance is the method of supplying current to the car. The third rail, which is largely used in heavy railway work, is obviously unsuited for carrying 3000, 6000, or 10 000 volts on the score of insulation and of safety. Moreover, the third-rail construction, whatever be the pressure, is not suitable for terminal yards in which there are many tracks and in which derailments are not unusual. A smash-up would be almost certain to result in tying up the system.

Of the various methods of current supply heretofore employed the overhead conductor is believed to be the only one capable of development into safe or permanent operation with trolley pressures running up into thousands of volts. The present paper will describe some preliminary work which has been carried out on a practical scale with overhead conductors. In laying out a suitable overhead high-pressure alternating-current system, it was decided to make a radical departure from the present methods of construction wherein the insulation is made only good enough and the supporting structure only strong enough to keep the cars running by the aid of an efficient repair department. It was rather the aim to obtain a system which would be serviceable and reliable for several thousand volts and which when once in place would at least equal in durability and cost of maintenance the bridges, track, and other portions of a standard railroad. While the exacting conditions and heavy traffic of the present steam roads will require for successful operation by electricity a carefully planned and substantial construction, the lighter interurban roads may frequently be equipped with a less expensive system.

Several classes of construction have been designed; of these the least expensive type employing bracket arms will be described first.

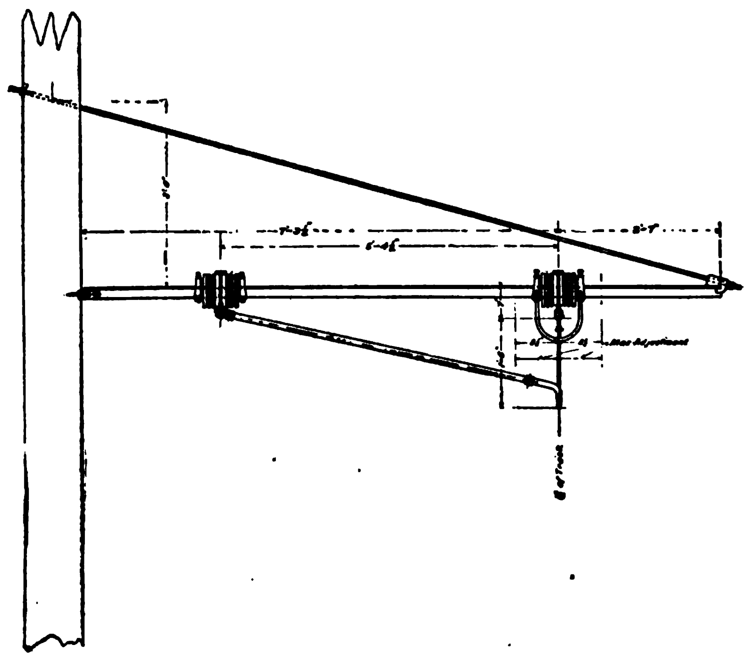


FIG. 1.—T-Iron Bracket with Main Insulator and Steady Strain.

BRACKET-ARM CONSTRUCTION.

This system consists of a single line of wooden poles spaced well apart and fitted with bracket arms and steel catenary suspension cable for supporting the trolley wire. The bracket arm is a T-iron supported by a tension rod at its outer end and fitted at the inner end with lugs which partly embrace the pole and to which they are bolted with lag screws. Fig. 1 indicates the construction.

The insulator is of corrugated porcelain, cemented to a malleable-iron sleeve which in turn is slipped over the bracket arm and held by clamps and set screws. The porcelain insulator has a groove at its center surrounded by a malleable-iron collar similar to a pipe clamp. This collar has an eye on the lower side into which the hooks of a clamp which carries the steel supporting cable or messenger are inserted. Wheel trolleys will probably be used to a considerable extent with the lower pressures. Guard loops are provided to prevent breakage of the porcelain, in case the trolley should leave the wire under a bracket. The insulator with its fittings is shown in detail in Fig. 2.

The guard loops are also of service in temporarily supporting the cable while it is being run out and pulled up. The trolley and messenger are run out together, and the former is supported from the messenger at occasional points by temporary tie-wires. The tension in the messenger cable is adjusted to give the proper sag, and the trolley wire is pulled up tight enough to take out all kinks and bends. Both trolley and messenger are then anchored. The messenger is next clamped to the insulators and the trolley is permanently supported from the messenger by means of hangers or clips which are adjusted in length in such a manner as to hold the trolley horizontally. By this means, the tension in the trolley is slightly relieved and allowance is made for expansion and contraction. The hangers are stiff and, being placed only 10 feet apart, correct any tendency of the grooved trolley wire to twist. This insures that the smooth lower surface will always be downward, a feature especially necessary when bow or sliding trolleys are used. The short distance between hangers also prevents the end of a broken trolley wire from coming dangerously near the ground.

The method of supporting the messenger below the bracket arm enables a tension rod to be attached to the outer end of the bracket without the necessity of fishing the messenger cable over the arm and under the brace. The cable and trolley may be run out along the track and pulled up in place under the brackets with a minimum amount of labor. Another advantage in this arrangement is the slightly flexible character of the point of support of the messenger; this is not sufficient to permit any considerable vibration of the span as a whole but will allow any small vibration set up by the trolley to pass on. It has been noticed in rigidly-supported spans of considerable length that a tendency exists for waves to be reflected from these fixed

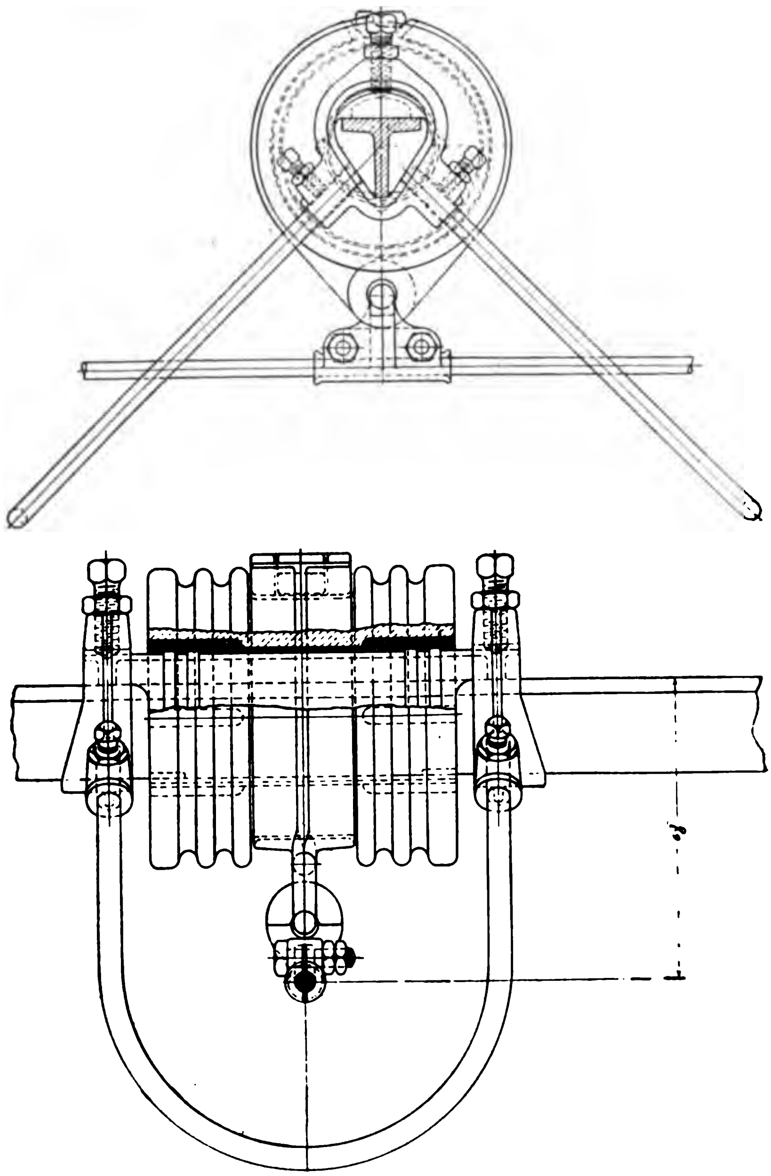


Fig. 2.—Single Catenary, Main Insulator Details.

points which, when they reach the trolley, lift the wire from it, thereby causing flashing.

The hanger is illustrated in Fig. 3 and consists of a galvanized malleable-iron casting made in 10 lengths. It is fitted with a bolted clamp to take the messenger cable and is secured to the trolley with screws. At intervals of about 1000 ft. and upon curves of large radius, a steadying device shown in Fig. 1 is used. The pull-off used on sharp curves the method of anchoring, and the section-break insulator are shown in Figs. 4, 5, 6, 7, and 8.

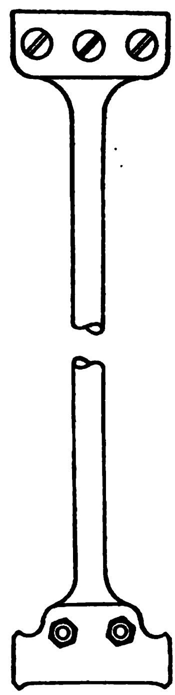


FIG. 3.—Hanger made in Ten Lengths.

Fig. 11 illustrates a 120-ft. span and anchor. Fig. 12 represents an 80-ft. span with steady strains on a slight curve. Fig. 13 is a view taken from an overhead bridge, showing the use of steady strains on a moderately sharp curve.

MEASUREMENTS ON SPANS IN SERVICE.

A road five miles in length has been in operation for about five months, and upon this road several forms of construction have been installed. One portion has been equipped with

120-ft. spans with sags of 24 in. in the messenger cable. Another section has spans of about 96 ft. and sags of about 4 inches. In the latter case both messenger and trolley wire are tighter than the former. The effects of temperature upon these two forms of construction are indicated by the following observations during a period of two months:

Date.	Temperature fahr.	Height of Trolley Wire above Rails	
		Span No. 1	Span No. 2
		120-ft. Span.	
12-22-04	33.8°	21 ft. 3.4 in.	21 ft. 5.1 in.
12-23-04	52.3°	21 " 2.0 "	21 " 3.6 "
1- 4-05	16.0°	21 " 4.1 "	21 " 5.5 "
		96 ft. Span.	
12-22-04	34.7°	20 ft. 7.0 in.	20 ft. 7.5 in.
12-23-04	52.3°	20 " 6.8 "	20 " 7.4 "
1- 4-05	14.7°	20 " 7.4 "	20 " 7.9 "

The greatest temperature variation noted on the 120-ft. spans was 36.3° fahr., and the corresponding changes in height at the centers of the spans were 2.1 in. and 1.9 in. respectively. For the 96-ft. spans the temperature variation was 37.6° and the corresponding changes in height were 0.6 inch and 0.5 in. respectively.

The combined weight of messenger, 000 trolley wire, and hangers averages one pound per foot which gives a tension in the messenger cable with 120-ft. span and 24-in. sag of about 900 pounds. The tension with 96-ft. span and 4-in. sag is about 3500 pounds.

Best Arrangement.

For best results with this form of construction both as regards cost and operation, the following arrangement is considered satisfactory: the spans should be 120 ft. long on straight track, reducing the length as may be necessary on curves. The messenger to consist of a 0.4375-in. galvanized Bessemer steel cable composed of seven strands and having an ultimate strength of about 6000 pounds. The trolley wire to be 000 grooved section supported in horizontal position by hangers placed 10 ft. apart. The messenger cable is to be pulled up to a minimum cold-weather sag of about 11 in., corresponding to a tension of about 2000 pounds.

Cross-Span Construction.

For conditions where bracket arms cannot be used, cross-span work may sometimes be employed. For this purpose the arrangement indicated in Figs. 9 and 10 has been designed. The difference between this arrangement and the bracket-arm construction is the substitution of a 0.4375-in. steel span cable for the bracket. Other details are practically the same.

Bridge Construction.

For the heavy service requirements of steam roads having from two to four tracks, the construction described above is

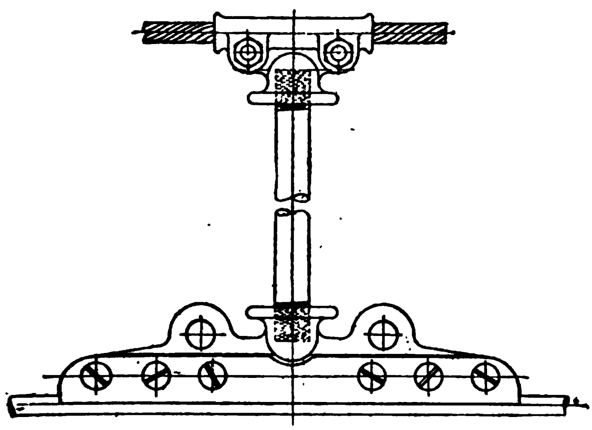


Fig. 4.—Single Catenary, Curve Pull-off.

not adequate; a more substantial equipment and one which will not encroach upon the present standard clearances is necessary. Obviously, the best form of support to accomplish this result is a bridge long enough to span all tracks with ample clearance on the sides and overhead, and stiff enough to carry all of the overhead conductors without undue vibration. Bridges of this character are at present in use on many roads to support semaphores and other signal apparatus.

Fig. 14 illustrates a section 2500 ft. long of a three-track road, one track of which has been equipped with the bridge construction. The double catenary system is used, each messenger being a 0.4375-in. steel stranded cable. The trolley wire

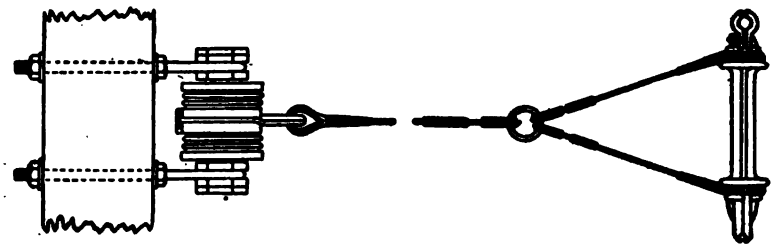


FIG. 5.—Curve Pull-off.

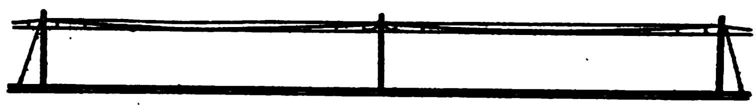


FIG. 6.—Anchor Scheme.

FIG. 7.—Anchor Scheme.

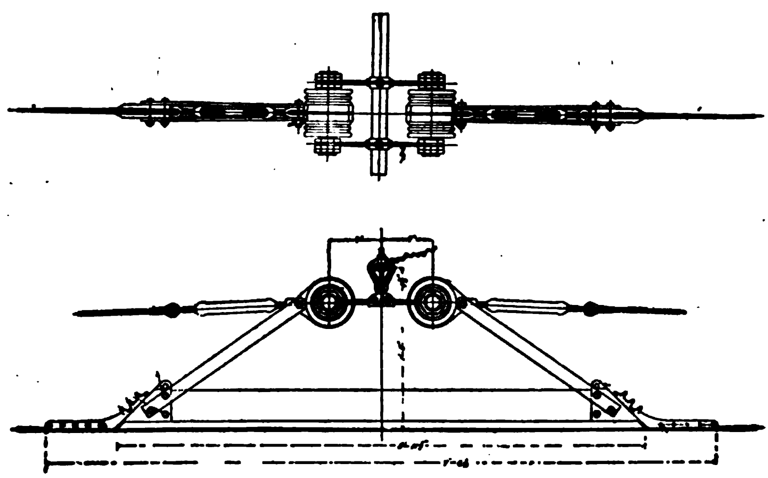


FIG. 8.—Single Catenary, Section-break Insulator.

is 000 grooved, and the supporting hangers are placed 10 feet apart. The average total weight per foot supported by each cable, including its own weight, is 0.91 pounds. The vertical sag in the first span, which is 230 ft. long, is 2.6 ft., and in

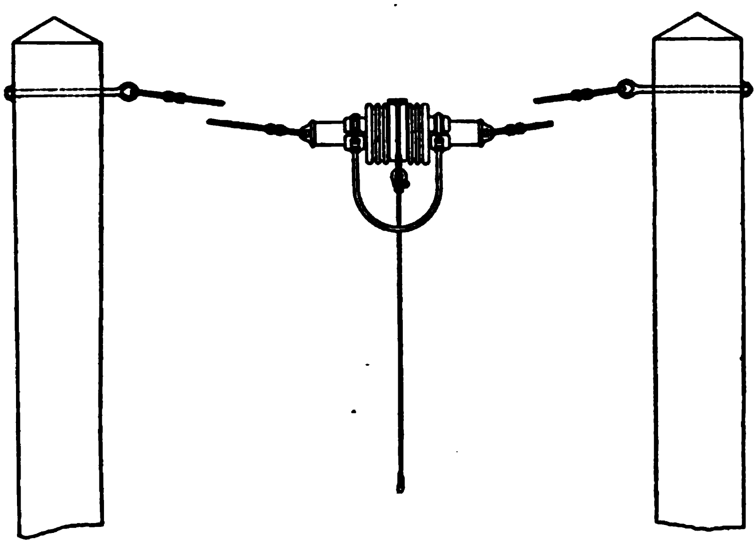


FIG. 9.—Cross-Span Main Line Suspension.

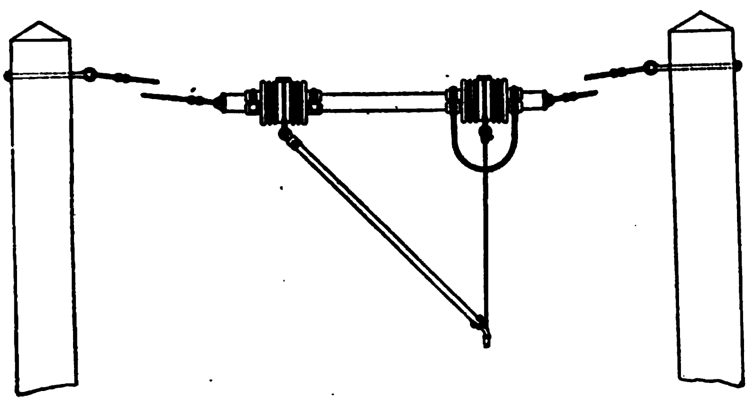


FIG. 10.—Cross-Span Suspension and Steady Strain.

the second span, which is 270 ft. long, 3.6 ft., both at 26.6° fahr. The corresponding tension in the messenger cables is 2300 pounds.

The observed variation in height of trolley wire due to temperature change was as follows:

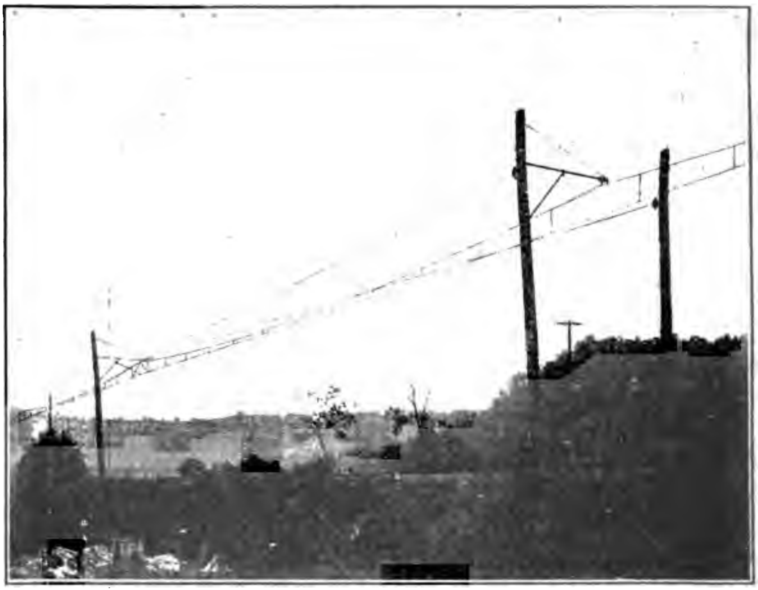


FIG. 11.—Single Catenary, 120-ft. Span and Anchor.

FIG. 12.—Single Catenary, 80-ft. Span with Steady Strain on Curve.

Date.	Temperature fahr.	Height of Trolley Wire above Rails	
		Span No. 1	Span No. 2
1–16–05	26.6°	23 ft. 9.1 in.	23 ft. 7.1 in.
1–26–05	6.8°	23 " 10.1 "	23 " 9.9 "
2– 9–05	39.2°	23 " 7.3 "	23 " 4.3 "

FIG. 13.—Single Catenary Curve Showing Use of Steady Strains.

The maximum temperature variation is 32.4° and the corresponding change in height of trolley wire is 2.8 in. for the 230-ft. span and 5.6 in. for the 270-ft. span.

Fig. 14.—Double Catenary Bridge Construction.

Fig. 15 shows an extension of the double catenary construction supported upon latticed poles, while Fig. 16 represents a curve of 425-ft. radius. In the latter view the use of double catenary curve pull-offs is illustrated.

Proposed General Plan.

It was first thought advisable to run the messenger cable over the bridges. Fig. 14 shows this construction. It is necessary, however, to provide an unobstructed view of the signal

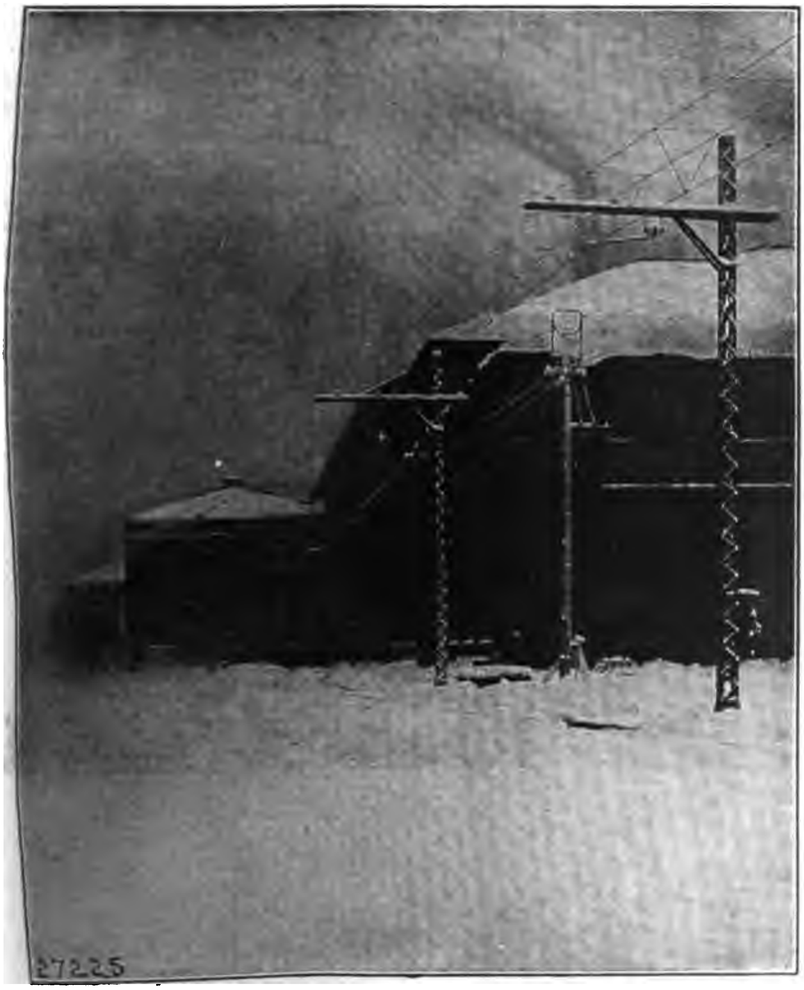


Fig. 15.—Double Catenary, Latticed-pole Construction.

apparatus and it is accordingly considered preferable to make the bridge high enough to permit the semaphores to be suspended below the truss.

Fig. 17 indicates a signal bridge which has been devised for a four-track road carrying beside the semaphores, the four sets of cables and trolley wires suspended below the truss. This construction is a decided advantage in erecting, as the cable and trolley wire can be run out along the track and lifted into place. Massive porcelain insulators will be used mounted on heavy pipe and fitted with collars having soft lead strips under them. From these the cables will be hung by means of bolted clamps. By anchoring all cables to the bridges after being drawn up to a uniform tension, the effect will be to steady

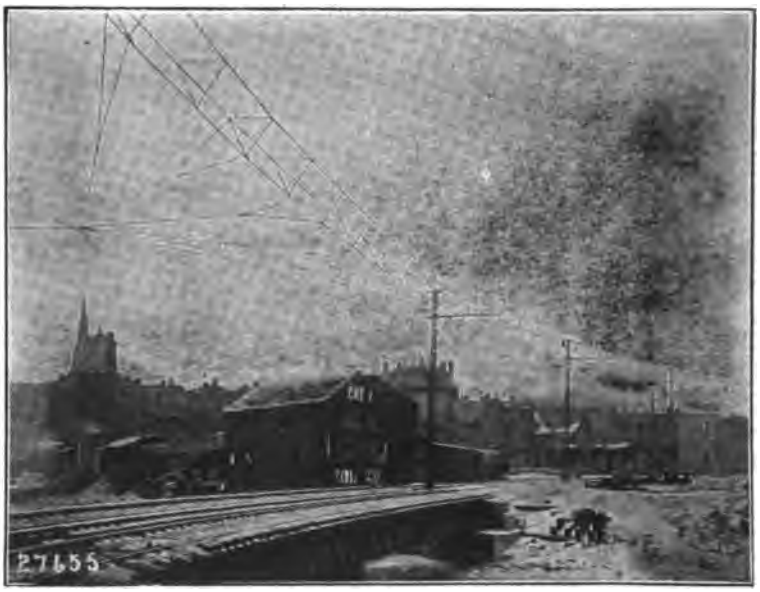
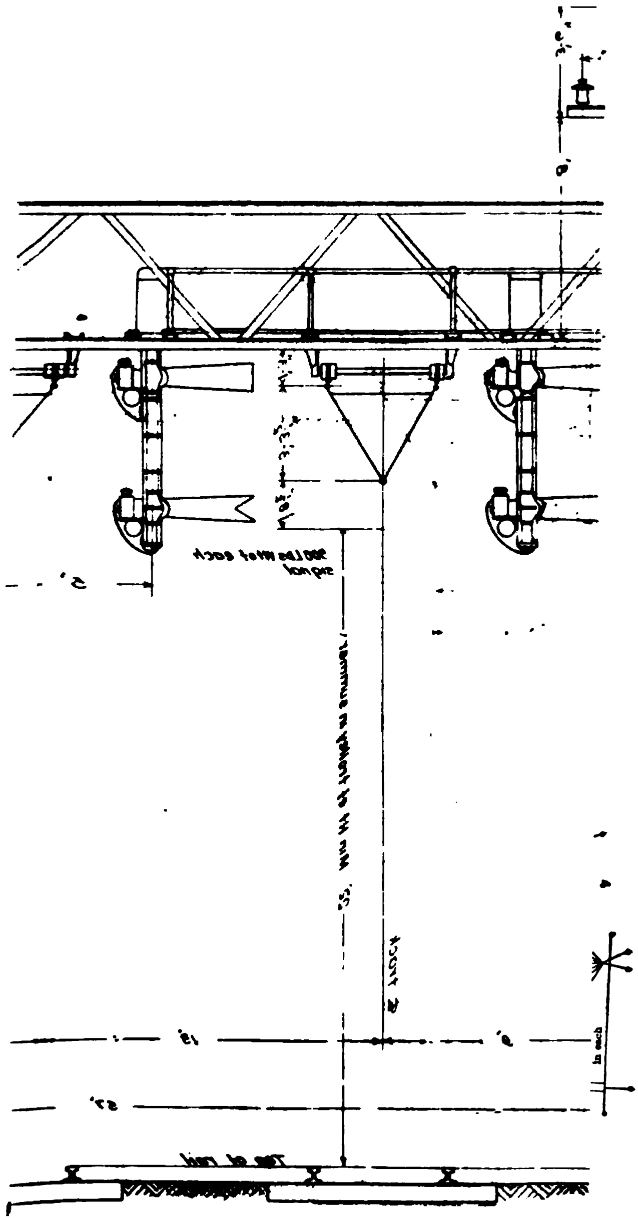


FIG. 16.—Double Catenary, Curve with Pull-off.

the bridges. For roads having wide rights of way comparatively light bridges steadied with guy cables may be used, but for most cases a substantial structure similar to those now used for signal towers will probably be preferable. It will be noted, however, that owing to the comparatively long intervals between signals only a few of the bridges carry semaphores; the others may be made lighter than the one indicated in Fig. 17.

Spans of 300 ft. for straight tracks appear to be satisfactory, not being so long as to permit undue vibration in the cables, and not so short as to require a large number of bridges per mile.



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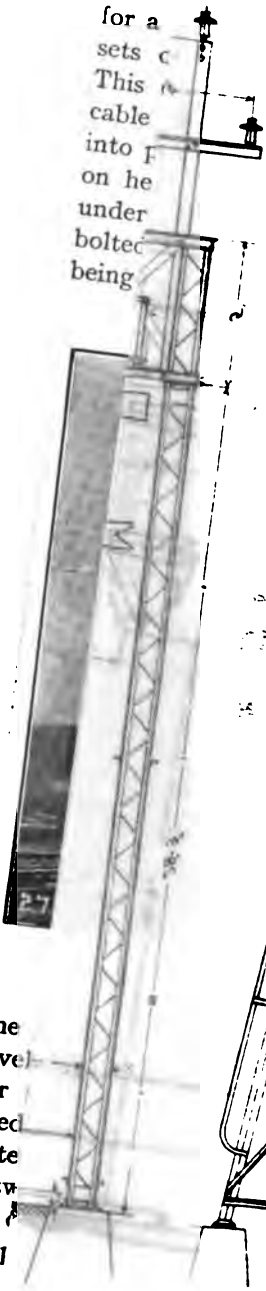

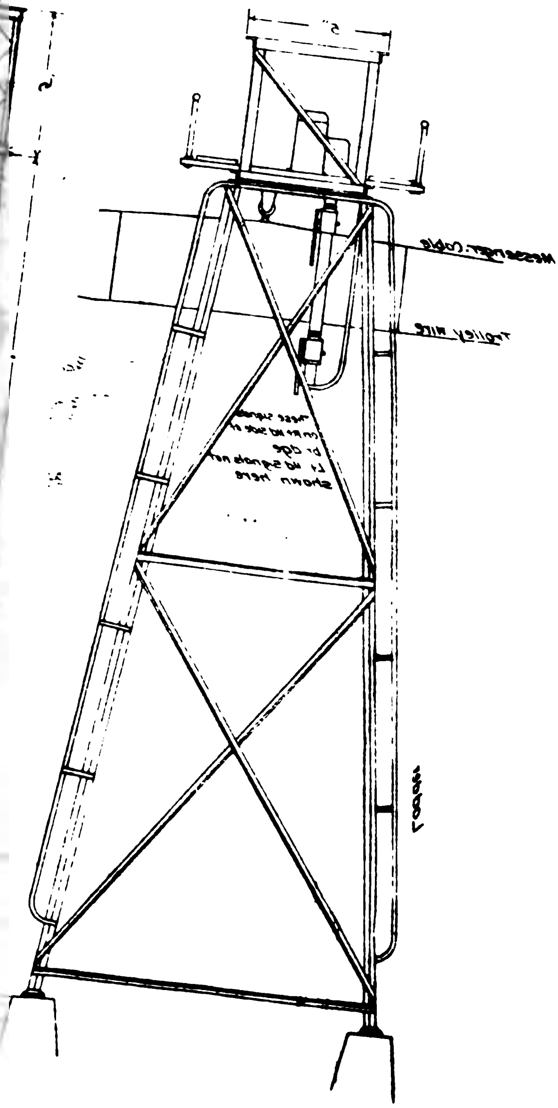

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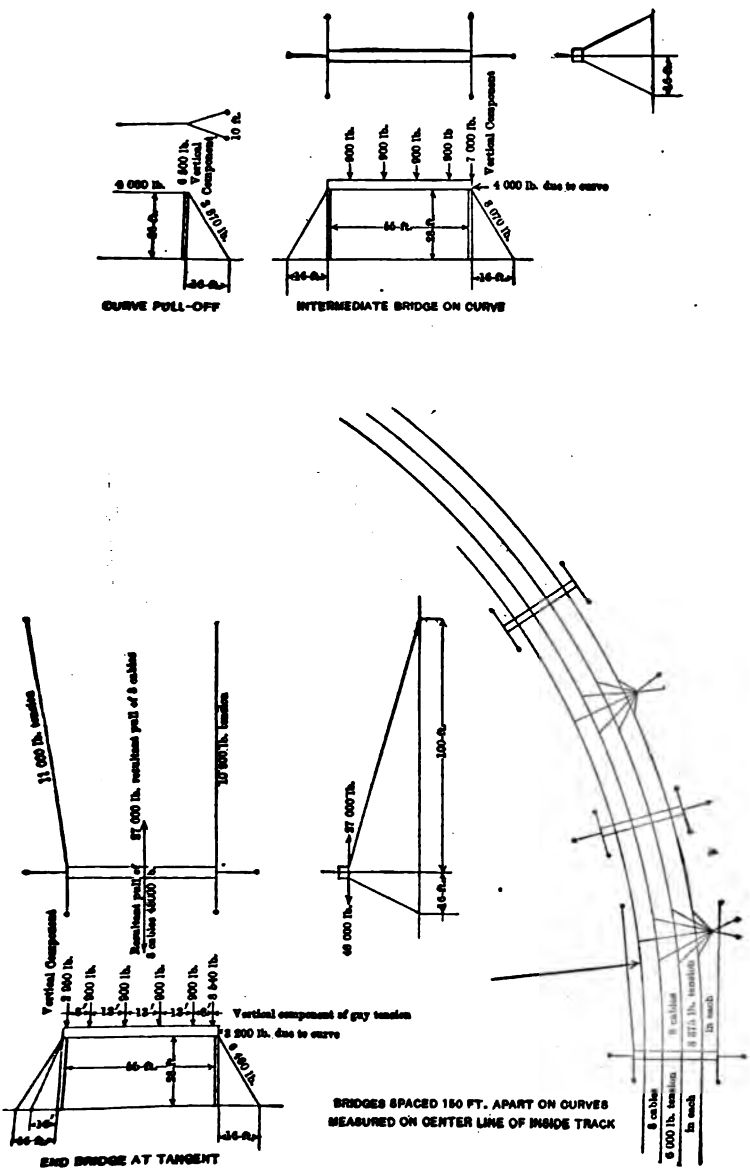


FIG. 18.—Curve, 500-ft Radius.

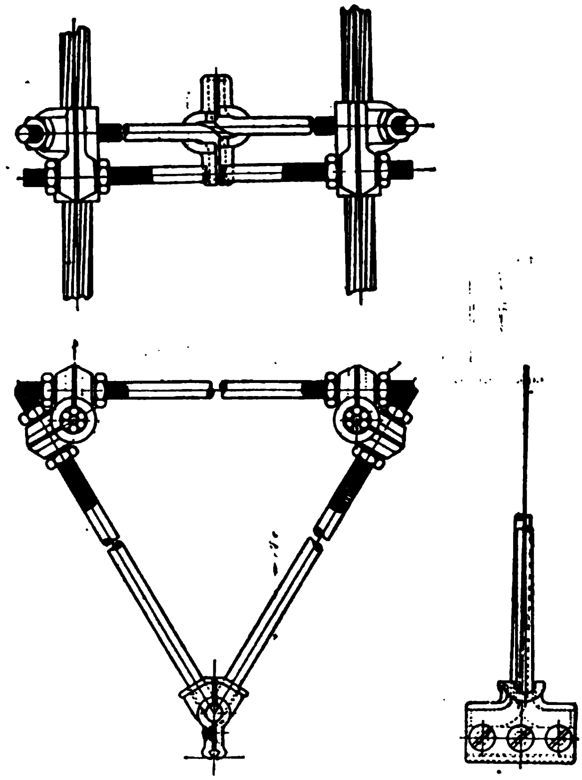


Fig. 19.—Double Catenary, Adjustable Trolley Hanger.

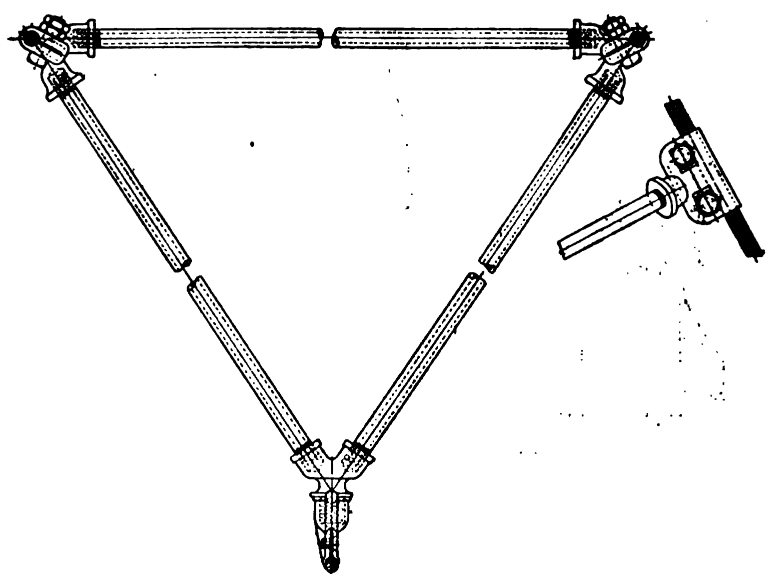


Fig. 20.—Double Catenary, Curve Pull-off.

For the messenger cables 0.625-in. extra-high strength steel strands are suitable. With a 0000 grooved trolley wire and hangers spaced 10 ft., the average load per foot on each cable is 1.43 pounds, and with a vertical sag of 2.7 ft. the tension is 6000 pounds. In a rough climate, wind and sleet will at times increase this tension; assuming that the tension may be doubled, a factor of safety of about 3.5 will still remain, as the breaking strength of the cable is about 40 000 pounds.

For use in localities where milder weather conditions may be assumed, lower grades of steel may be used having breaking

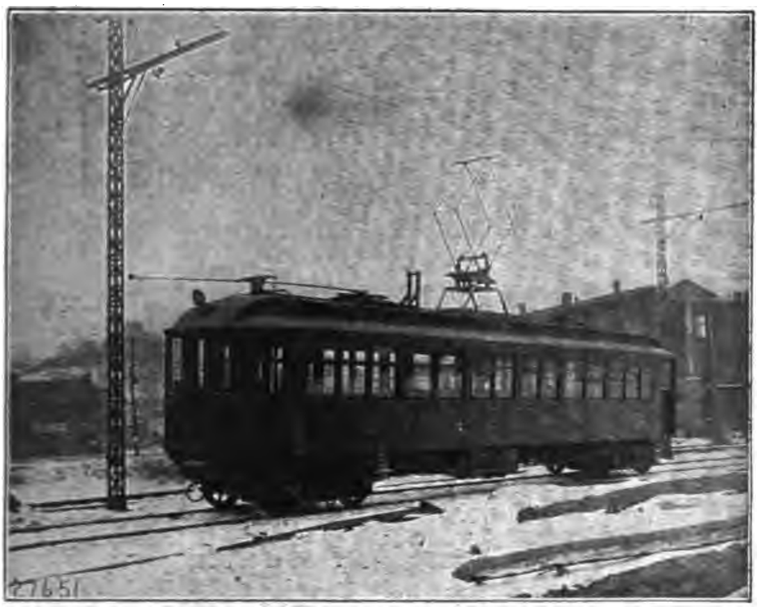


Fig. 21.—High-pressure Pantagraph Trolley.

strengths for the same weight per foot of 25 000 pounds and 19 000 pounds. These latter cables are somewhat easier to handle and would be sufficiently strong for most conditions.

The sag given above is taken to be the cold-weather condition and for 100° fahr. rise the sag would be about 4.4 ft., or a variation of 1.7 ft. In Fig. 17, this allowance is made in the height of the bridge so that the lowest point of the trolley wire will be 22 ft. above the track. It is not believed that the variation will be this much on account of the giving of the supports and other causes.

For curves, the length of span will be decreased; and when necessary to hold the wire in the center of the track radial pull-offs will be used, secured to strain insulators. These will be mounted on latticed poles which in turn will be braced by guy anchors.

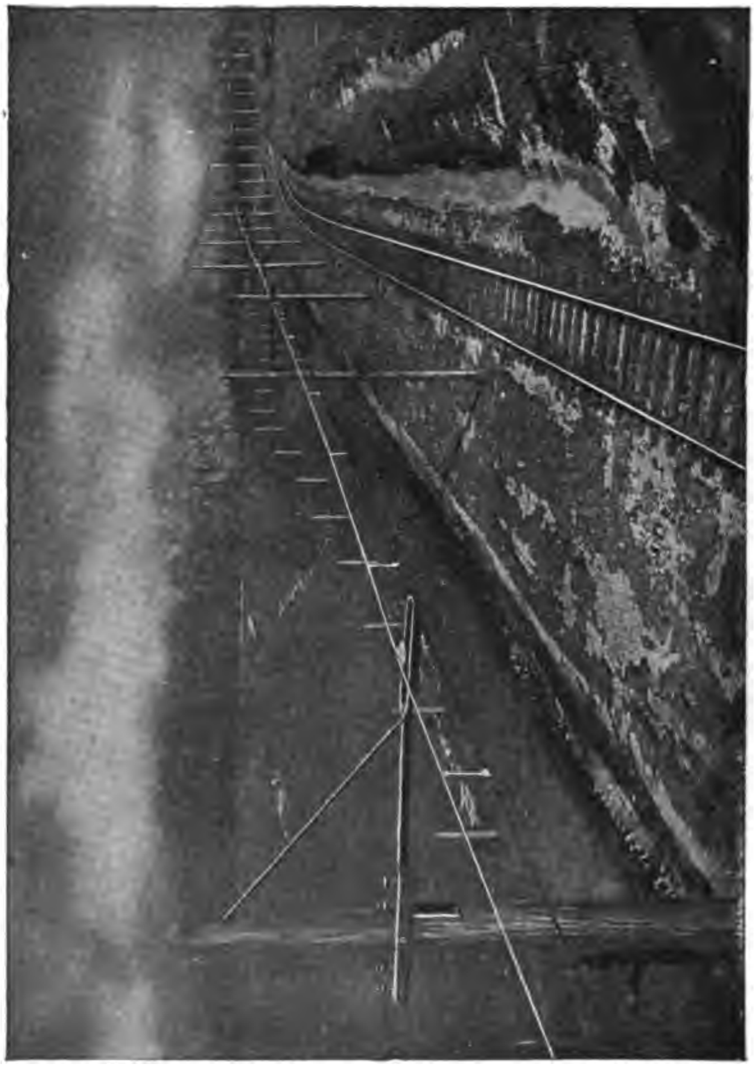


FIG. 22.

For sharp curves, the radial pull of all the messenger cables would be severe, and it is intended to provide at the tangent points anchor bridges which will have trusses stiff enough in the horizontal plane to stand the strain of slacking off the cables about one half. These anchor bridges will then be held by long guys running out a considerable distance from the bases of the bridges and anchored to cross-ties or channel-irons buried in the ground and concreted. Fig. 18 represents in outline a 500-ft. radius curve.

Several details for the double-catenary construction are shown in Figs. 19 and 20. All of the metal parts other than

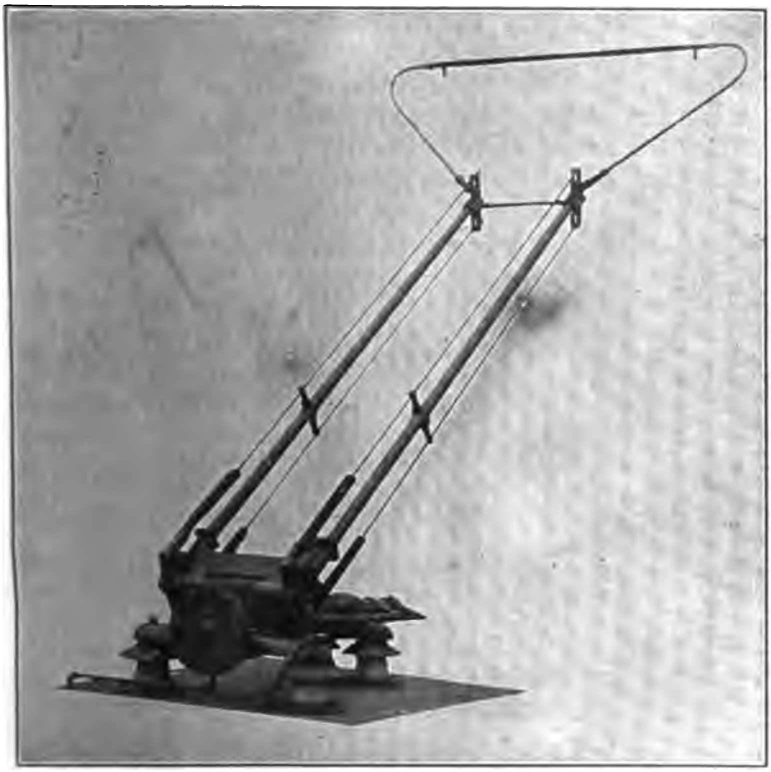


FIG. 23.

the bridges and trolley wire are galvanized, but as a further protection against depreciation from locomotive fumes periodical painting is advisable.

Regarding the efficiency of the insulation employed, it may be stated that under the snow-clad conditions indicated in Fig. 15, the 2500 ft. of iron bridge work and five miles of single-catenary construction showed under test a leakage of one ampere at 6000 volts.

Conclusion.

The foregoing describes the actual work which has been carried out with the view of developing a system of overhead conductors for moderate and heavy traction service which will approach in a far greater degree than heretofore the reliability and permanency of present steam-railroad equipments.

Aside from the work described above, 40 miles of road using the single catenary wood-pole construction have been put in operation in Indiana. This has been in successful running order since the first of this year. Fig. 22 is a view of a portion of the road showing the track and overhead construction. The remaining 60 miles of this road will probably be completed in the near future. The pressure is 3300.

Fig. 23 is of interest in showing the type of air-operated sliding-bow trolley in use on this road. Another form of trolley with which satisfactory results have been obtained is shown in Fig. 21. It is also air operated and is insulated for 6000 volts.

DISCUSSION ON "LINE CONSTRUCTION FOR HIGH-PRESSURE ELECTRIC RAILROADS," AND "HIGH-PRESSURE LINE CONSTRUCTION FOR ALTERNATING-CURRENT RAILWAYS."

PRESIDENT LIEB: I am sure it is gratifying to all interested in this class of work to learn from Mr. Varney's paper the character of the electrical engineering construction that is being done in connection with heavy traction on steam railroads, and that it is comparable with the civil and mechanical engineering construction of railroads, as represented in track and bridge construction. It would be most unfortunate for the development of electric traction on our great steam railroad systems if the character of construction followed in the pioneer days of electric traction at comparatively low voltages were continued in pioneer high-pressure traction work. It is apparent from the details laid before us that in attempting to solve the problems of important trunk-line traction, electrical engineers are alive to the necessity of avoiding anything that savors of flimsy or cheap construction, and are seeking to devise equipments based upon such sound engineering principles as will ensure safety in operation and permanence under the strain incident to heavy work.

The papers of Mr. Varney and Mr. Damon are now open for discussion, and I think they can be profitably discussed together. The suggestion in connection with protection by guard-wires, referred to in Mr. Damon's paper, is a reminder of the danger that sometimes follows an attempt to add a safeguard to a system, whereby an element of danger may be introduced even greater than the trouble which it is desired to guard against. In one of the earlier installations of the synchronous converter system, it was important to prevent the high-pressure current from getting over to the low-pressure system through contact between the primary and secondary windings of transformers. To that end, some of the earlier transformers were equipped with ground-shields between primary and secondary windings. In the first two years all the troubles encountered with the system as a whole were due to the presence of the ground-shields; they were an element of danger rather than of protection, as in the case cited by Mr. Damon.

F. N. WATERMAN: The papers of the evening have very fully covered the limited field of actual experience in this kind of engineering work. But some observations in the way of further details and as to the results of use may be worth adding even if somewhat incomplete.

The longest experience with the problem of conveying energy at high pressure to a moving vehicle has been that of the Ganz Co., which has now extended over about five years. This has all been with three-phase currents at 3000 volts and low frequency, and, therefore, two trolley wires were employed. The preliminary trials on the experimental line at Budapest lasted for something over a year, and the system has been operated in Italy altogether nearly four years, of which two and one-half years represent actual practical service. The original line erected at Budapest was practically reproduced at Valtellina, except for a few minor details.

During the experimental work at Budapest both single- and double-catenary suspension were tried, the construction being essentially similar to that used on the Spindersfeld line. The cross-suspension type, however, was adopted, the system of double insulators and double supports, shown in Mr. Damon's paper, being used. A considerable sag was allowed in span-wires, and every effort was made to give an elastic and uniform suspension. The insulators, as installed, are extremely heavy, and certainly do not aid in securing this result. Dry wood, impregnated, as suggested by Mr. Damon, forms an important feature both of the old and new construction.

For long spans and at switches an arrangement similar to that of Fig. 20 of Mr. Damon's paper is employed, and a very interesting special type of span-wire construction is also used, particularly where the trolley wires are lowered to pass under bridges, and for this reason undue rise and fall with the passage of the trolley would be objectionable. This consists of a catenary type of cross-suspension connected at intervals by suspension wires with an upwardly arched span-wire, which carries the insulators, thus making a construction that does not sacrifice the substantial elasticity of the line, but holds it accurately in place, permitting a limited rise and fall with the passage of the trolley.

During the experimental period some difficulty was experienced with the overhead construction, and in one or two cases the wire broke. But the chief difficulty was encountered in the tunnels; it was both mechanical and electrical in its nature; the accumulation of deposits from the steam locomotives continually running through the tunnels during the experimental period, and the leakage of tunnel roofs, caused insulation troubles; while owing to the very small clearance of the tunnels, difficulty was experienced in keeping the wire from grounding between supports. This was overcome by shortening the distance between supports, and weighting the conductors by clamping small iron rails upon them, which were put on in sections several feet in length in the same manner as a mechanical clip.

Although the construction is not by any means heavy, and the workmanship shows the effect of inexperience on the part of the linemen, it has successfully withstood the wear and tear of use, and so far as I have been able to learn is still in place. In one or two instances at the beginning of the experimental operation the trolley caught in the suspension-wire, owing to the improper location of curves and turnouts, the result was to break some portion of the trolley mechanism, but to leave the rest of the line unharmed.

For the latest construction the double-catenary type is used; no span-wire supports whatever being employed, and two messenger wires serve to carry both contact conductors. The spacing of the conductors is maintained by wooden insulator-bars upon which the insulators proper are carried, and to which supports from the messenger wires are attached. The insulators have been very much lightened by the substitution of pressed steel for malleable-iron castings. The messenger wires are carried on iron girders, spanning the track, and placed 130 ft. apart; the distance between points of attachment to the wire is 65 ft., there being two supports between girders and none immediately under them.

The block-signal system is interconnected directly with the contact conductors, and the entrance of a train into a section in face of a danger signal disconnects the section. I was unable to learn the details of this system. In addition, the conductors within the limits of the stations, and for a definite distance on each side, are dead at all times, save when a train is actually approaching or starting from a station. These sections can only be thrown in by the signal operator. It is customary for express trains to coast over the dead parts of the conductors with trolleys down, and it is the usual practice for trains moving at full speed to lower the trolleys at all switches, excepting such trains as are off schedule and are making up time.

The feature of double insulation, which is used throughout, has proved particularly useful in rendering possible the breakage of a single insulator without causing interference with traffic until repairs can be effected. This feature, while, of course, not a novelty, seems particularly worthy of perpetuation in high-tension lines where special liability to mechanical breakdown exists. The idea of cutting out sections at stations, and the extension of the same idea carried out on the Spinderfeld line, of cutting out sections under bridges where the right of way passes under highways, seems also worthy of consideration, at least for special cases.

The Valtellina system seems to have been free from trouble with the overhead construction to a remarkable extent, notwithstanding the fact that two overhead wires are required; and this fact emphasizes the importance of using a trolley contact-device that cannot get off from the wire and thus either break insulators or pull down the construction.

The trolley itself is a single apparatus and not two independent devices. It requires, however, two separate bases and poles, the same as if there were two single trolleys. The outer ends of the two poles are connected by a continuous bar of impregnated wood, the centre portion of which for a distance of about eight inches is the full diameter of the rolling contacts. On either side the diameter is reduced to receive two contact-cylinders, which are slipped over and supported on insulated ball-bearings, the current being taken off by carbon contact-rings at the ends and carried by flexible jumpers to the trolley poles.

The cross-bar, with its contact-rollers, is flexibly connected to the ends of the arms by horizontal spiral springs, permitting simultaneous contact with the two wires even where they are at widely different heights. The rollers originally used were of copper, which gave trouble by elongation under the hammering incident to service, and a resulting binding of the bearings. Ganz & Co. now send out copper-plated steel rollers, and claim for them a service of 10 000 km. per roller, or 20 000 km. per vehicle before replating becomes necessary. The copper rollers gave a life of 30 000 to 40 000 km. per vehicle, but then had to be entirely renewed. The operating company prefers bronze, and finds no trouble from elongation.

The trolley poles are supported by spiral springs in tension, the tension being put on from within the vehicle by compressed air. With this device the slow-moving trains take 300 amperes without sparking or burning the wire. The normal speed of passenger trains is 40 miles per hour, and the maximum current that has been taken off at that speed is about 240 amperes, under which conditions the collectors worked satisfactorily. The highest speed at which the device has been tested is 62 miles an hour, taking off a current of about 100 amperes. This test was made without alteration of springs or line construction and gave entirely satisfactory results. The plan of construction employed has therefore demonstrated its effectiveness at moderate speeds in spite of the handicap of the extreme weight of the insulators.

After two years of use the trolley wires show practically neither wear nor evidence of burning. Very little sparking is perceptible at night when running at full speed; but, as would naturally be expected, such flashing as does occur takes place at the points of suspension. The type of trolley used seems therefore to combine the advantages of the wheel- and bow-forms. It cannot leave the wire, and, as at present constructed, cannot catch. The rolling contact practically eliminates the wear on the wire and contact conductors. The only serious objection to the overhead construction raised by the local engineer was to the location of the wires over the track, necessitating much of the work being done at night, or else conducted under serious disadvantages. During the entire period of operation no one has been injured or killed by contact with the overhead construction, but an engineer of the Ganz Co. was killed in one of the sub-stations.

The organization for the maintenance of overhead construction is very interesting. The line is 66 miles long, and for the purpose of controlling is divided into five sections for each of which five men are required. Their duties include patrolling the line and visiting the sub-stations at regular intervals. When not otherwise engaged one man is always on duty at the sub-stations. In general charge of all sections is a superintendent who reports to the electrical engineer.

The total cost of maintenance of primary and secondary lines, care, attendance and maintenance of sub-stations, and patrolling of the line on this plant is about $102.00 per mile, per annum. This force is not kept fully occupied, but it is held that no smaller force would be allowable. The engineers of the operating company, and of the Rete Adriatica, seem to agree that the exigencies of trunk-line railway service demand that a sufficient force should be maintained to insure the prompt resumption of service in case of accident, and that the cost of maintenance and repairs, and of the supervision of sub-stations is not determined by the actual labor involved, but by the necessity for prompt action in emergencies. The difference in cost of maintenance between a three-phase and a single-phase line on trunk-line railways is, therefore, according to this view, simply the difference in the cost of material and hence a negligibly small quantity. This point of view is interesting, and, so far as I know, has not been mentioned in just the same form in this country; but in view of the higher cost of labor here it is questionable how far the plant could be adopted.

Regarding the Huber system, the practical difficulties are not fully brought out in the papers of the evening. The contact device itself is carried on a rectangular framework hinged to the car-roof, and leaning outwardly for contact with the conductors when at the side of the line, but requiring to be moved inward when the line passes the centre of the track in entering tunnels and bridges. This movement is not automatic, and does not follow from mere change of position, but must be caused by special actuating devices, which must be operated from within the train, or by means of a contact-rail laid along the side of the track and operated by a contact-shoe. Any failure of this auxiliary contact would mean the tearing of the structure from the roof of the locomotive. The actual contact-maker is a light brass tube which, as seen on the experimental line, showed deep cuts, indicating rapid wear from use; and wherever it showed the effects of wear the damage was considerable. As used on the experimental line last spring, the device gave the impression of being still in the early experimental stages.

CALVERT TOWNLEY: The only changes in the overhead construction for trolley service have been those of improvements in detail, whereas the proposed departure in the direction of using high-pressure current is an extremely radical one. The advantages of high-pressure trolleys are not to be disregarded, but a considerable amount of caution should be observed in the immediate adoption of very high pressures.

I disagree with Mr. Damon's recommendation that it is now time to standardize trolley pressure and the location of the trolley wire, on the ground that although it will be essential to standardize with reference to these points ultimately. Enough is not yet known about the matter from practical experience to enable standards to be selected without the danger of making very serious mistakes.

Regarding Mr. Damon's suggestion that 15 000 volts should be adopted for steam railroads, it is doubtful if so high a pressure would be warranted by any railroad problem now in sight, either on the ground of first cost or of operating advantage. I am inclined to think that a system for such a high-pressure would be more expensive to install and maintain than one for a lower pressure.

A. H. ARMSTRONG: It would seem advisable that the trolley line pressure shall be kept as low as possible under the operating conditions involved. A trolley wire suspended from a steel catenary can be insulated for 15 000 volts or more, as Mr. Damon says, but because a construction has been found capable of withstanding higher pressure, and because a motor system has been found that can use high pressure, that is no justification in using higher trolley pressure than the operating needs of the road requires. The apparatus is increased in cost; the liability to breakdown is increased, and the 3000 volts ordinarily in use upon our suburban lines seems to be high enough to secure all the economic advantages of higher trolley pressure.

There is another way of looking at the matter. With 3300 volts at the sub-station, it is possible to operate heavy suburban cars at speeds approaching 50 miles an hour on from one-half-hour to one-hour headway, with sub-stations placed fully 20 miles apart, assuming, of course, that the sub-stations are tied together. It is a question in the operation of the road how much trolley line is liable to be disabled in case of accident. Twenty-mile blocks seem too long for satisfactory operation; and a higher trolley pressure, permitting of greater distance between sub-stations, is an undue refinement, unnecessary expense for the apparatus, and presents a refinement that entails disadvantages which outweigh any possible saving in feeder copper.

In considering the operation of heavy freight trains of 2000 or 3000 tons, where the output of the locomotive must reach 1500 h.p. or more, it is proper to consider trolley potentials higher than 3000 volts suitable for single-car suburban work.

Long blocks upon steam railroads are much more objectionable than upon suburban roads, and consideration of the operating conditions involved will show that 5000 or 6000 volts upon the trolley is amply able to provide an electric system having a cost as low as the conditions will warrant, while a higher trolley pressure in many cases offers no reduction in first cost, and carries with it the additional chance of breakdown.

The position of the trolley wire has been alluded to; there are arguments in favor of both the center trolley and the offset trolley. Of the three alternating-current lines now in operation in this country, two have center trolleys, and the third is equipped with a trolley wire placed over the edge of the car; in all three roads the trolley wire is suspended from a steel catenary. The advantage of using a center trolley is that it permits the use of the same trolley-pole for both city and suburban tracks. Suburban service, however, may be carried on by means of sliding-bows, or rollers, for which the city overhead construction is not adapted, thus in some measure destroying any argument in favor of the center trolley for suburban service. It is possible that our suburban lines will adopt a trolley-bow, or roller, best adapted for high-pressure trolley operation, in which case it will be necessary to provide an extra trolley-pole, with wheel, for city operation. With four trolley-poles upon the car, there is no objection to considering a trolley suspended at the side of the track, while the adoption of this construction offers certain advantages not enjoyed by the center suspended trolley. In changing from alternating current to direct current, and vice versa, the side-suspended trolley permits contact being made with both alternating-current and direct-current lines at the same time, thus facilitating changing over. We are hardly in a position as yet to standardize in any way the location of the trolley-wire, and the operation of the different lines now constructed and in process of construction will be watched with considerable interest as affording operating data in this connection.

The frequency of hangers between the supporting cable and the trolley itself is also an open question. The Pontiac and Ballston lines are both operating with a single connection between trolley and catenary, placed midway between poles, while the Indianapolis & Cincinnati line provides for supports every 10 ft. The latter line is not yet running at full speed, and we cannot say how much inconvenience is caused by the frequent supports, but it would seem hardly necessary to provide supports more frequently than once or twice between poles.

Mr. Damon has suggested the use of a separate transmission line to each sub-station, as an improvement upon a trunk transmission line feeding all sub-stations in multiple. From experience in transmission systems I am led to believe that any trouble experienced with them is proportional to the number of miles of wire in operation, and separate transmission lines to each sub-station is open to criticism on this score. Separate transmission lines offer the possibility of operating the sub-stations without labor, but while such a system of operation is possible it would seem advisable to have an attendant within call of a sub-station, although the proportion of his time taken up in sub-station duties is negligible.

A road operating from a high-pressure trolley is new to this country, and as yet we are hardly in a position to attempt any standardizing either in type of apparatus, or in the construction of overhead lines.

President Lieb: I will now call upon Mr. Babcock, the consulting engineer of the Southern Pacific Railroad, and Secretary of the San Francisco Branch of the Institute.

A. H. Babcock: On the Pacific coast the conditions are such that the first and third classes of construction mentioned in Mr. Damon's paper will probably be the ones that will be encountered first, namely, comparatively inexpensive lines over a country not very well settled between points where there is a large movement of freight and over which the freight traffic must form the large proportion of the earnings. Then there will come the steam roads, of which we have hopes. But the natural prejudices of railroad men to radical innovations must first be overcome.

The question of line pressure and installation is one that is very vital along the ocean front. It has been demonstrated that transmission lines of very high frequency can be operated in the interior and in the southern portion of California with comparatively little insulation, but on the coast the fogs make the conditions entirely different.

As to operating above 3000 or 6000 volts, it becomes at once a question not only as to whether it is worth while from the standpoint pointed out by Mr. Armstrong, but whether it is worth while in view of the leakage. The construction, as detailed in Mr. Varney's paper, certainly has the appearance of fine workmanship; but the leakage that he gives, if that is to be carried throughout the length of the line in bad weather, I think it is a question how far we may go even with the best developed form of construction. For example, on page 139, he states that five miles of single catenary construction showed under test a leakage of one ampere at 6000 volts. Now, on a 40-mile line of double track this would be equal to 96 kw. constant loss. In 500-volt direct-current work the loss-constant is not great. The greatest loss is while the cars are moving. It appears that this constant loss would pay for a whole lot of line loss while the cars are moving.

C. O. Mailloux: The subjects discussed and suggested for discussion in the papers presented this evening are, undoubtedly, of great importance at the present time. If the statement be true that the question of the hour, in electric railroad engineering, is the extension of electric traction into the field that has been hitherto occupied exclusively by steam, then the first question to answer is of necessity that of conveying electrical energy in large amounts safely and conveniently from a stationary conductor to an electric locomotive or motor-car. I have had the conviction for some time that material progress in the direction of a general supplanting of the steam locomotive by the electric locomotive must wait for progress in methods adequate for the purpose just stated.

Before making, last year, a personal inspection and study of experimental and commercial alternating-current traction systems in Europe, I was somewhat skeptical in regard to the feasibility of raising above 3000 volts the difference of pressure applied direct to the motors, in spite of the fact that 3000 volts had been used successfully in this manner for a year or more on the Valtellina line in Northern Italy. Doubts on this point were dissipated by what I saw, especially on the Spindersfeld line near Berlin, and the experimental line built in Switzerland by the Oerlikon Company near Zürich, which has since become a working line. I am now a firm believer in, and a strong partisan of, high-pressure contact lines, whether overhead trolley or third-rail conductors.

Mr. Damon's view, expressed on page 116, in favor of higher contact-line pressures for alternating-current railway motor cars is in the right direction; and as between 3300 volts and 6000 volts, I am inclined to favor 6000 volts as the standard which should be adopted for interurban lines. As Mr. Damon says, for steam railroad conditions a line contact pressure of at least 15 000 volts is desirable. Its feasibility is borne out by tests and experiments that I made abroad.

The contact line with catenary suspension has been recently introduced here, and, judging from the data contained in Mr. Damon's paper, has already reached a high stage of development. The catenary contact line on the Spindersfeld line, with 6000 volts pressure difference, appeared to work satisfactorily in every respect. Nevertheless, it would seem that either on account of municipal restrictions or for other reasons not readily apparent, the catenary contact lines for other projected alternating-current single-phase roads, that came to my notice, were limited to 2400 volts. I surmise that notwithstanding the fact that so few breakdowns of the contact line have occurred at Spindersfeld, and that none of these breakdowns caused any accident, there is still some feeling of unrest associated with the thought of a contact line of 6000 volts placed directly over the car or locomotive; and even though the *probability* of accident is very remote, yet, so long as the *possibility* thereof still remains, the objection will doubtless persist.

The double catenary, as Mr. Damon states, has the advantage of keeping the contact wire from swaying, but its increased cost does not appear always to justify its use. With the tower method of construction, using long spans, probably the double catenary would be indispensable. With the ordinary trolley-line form of suspension, where the distance between poles is not excessive, the single catenary would seem adequate and satisfactory for all purposes. At Spindersfeld, the poles are placed about 39 metres apart. Both the single- and the double-catenary suspension have been tried, and both have proved satisfactory.

The reference made by Mr. Damon to spectacular sparking, when the contact line was coated with ice or sleet, emphasizes a very serious and, in my opinion, radically inherent, defect in any contact line arranged to deliver current from its lower side. The fact that the sparking increases with the frequency of the trolley supports, in the cases observed by Mr. Damon, proves conclusively that ordinary trolley-line construction, using a trolley-wheel, is wholly unsuitable for high-pressure contact lines. With the catenary suspension, even with a trolley-wheel, the sparking should be independent of the number or frequency of the line supports.

The necessity of employing higher pressures for the transmission lines will obviously depend on the pressure of the contact line. When this pressure difference is as low as 3000 volts, undoubtedly it would still be necessary to employ higher transmission pressure in most cases for interurban lines; but if the pressure difference at the contact line is raised to 6000 volts, there are many cases where this pressure would be sufficiently high for both transmitting and distributing purposes. When the contact line pressure is raised to still higher values, say, for instance, to 15 000 volts, the same pressure difference will suffice in a large number of cases for both transmitting and distributing purposes. Indeed, if it were not for the convenience of subdividing the total line into blocks or sections the contact line itself could serve as the feeder.

Mr. Huber, of the Oerlikon Company, mentioned a project for the equipment of a steam line in Switzerland, where it was proposed to supply 50 miles of track, in both directions from a central station, without feeders, simply by using duplicate contact lines, one on each side of the track. This method has the advantage of providing a duplicate line equipment, which can still answer the purpose at lower efficiency and without materially crippling the service in case of defect or derangement in either of the two contact lines.

Mr. Huber has kindly furnished me with a set of slides and photographs showing interesting details of his system, which I will now show.

(Completion of Discussion after Adjournment.)

The slides and photographs referred to illustrate the characteristic features of the high-pressure, single-phase, alternating current electric railroad equipment of the Seebach-Wettingen line, in Switzerland. This line, which is a branch of the Swiss National Railroad system, is about 20 kilometers long, with single track of standard gauge. It has been operated by steam since it was first built, and will continue to be partly operated by steam for some time to come. When visited by me last summer, a portion of the line situated a short distance from the works of the Oerlikon Co., was equipped electrically, and was used by the Oerlikon Co. for making experiments with electric locomotives and various forms of contact lines and line supports.

It was then expected that the entire branch-line would be equipped and operated electrically by November or December, 1904; but it seems that sufficient allowance had not been made for official procrastination and obstruction. The plans for the equipment of the Seebach station, for instance, were only approved some time last January.

The portion of the road equipped and the electric locomotive intended to be used were both inspected by the Federal authorities, on November 18, 1904. As Mr. Huber states, it would have been difficult to select worse weather, there being a thick, wet fog, which lasted all day. The results were entirely satisfactory, however; not the slightest defect being observed as the result of a great diversity of very severe tests of the line and of the electric locomotive.

This case is interesting as being the first in which the Huber contact-line system, referred to by Mr. Damon and illustrated in Figs. 9 to 17 of his paper, has been adopted. It is particularly interesting and important as a pioneer movement toward the electrification of steam railway lines in Switzerland; for apparently both the Swiss government and the Oerlikon Co. are as much interested in the ulterior possibilities as in the immediate results; and in endeavoring to produce a satisfactory "sample" of electric traction as a substitute for steam traction for the specific conditions, both parties are evidently desirous, the former of testing, the latter of demonstrating, the general fitness of the system for all kinds of steam roads. This may account, in a large measure, for the careful and time-consuming scrutiny which has been given by the authorities to every detail of the proposed equipment. The further development of the line is to proceed apparently in the same conservative and cautious manner. It has been decided that the regular daily trips for which the official time-table has been issued shall be made, for a certain time at least, on the short portion of the line already equipped, before proceeding further with the electrification of the rest of the line.

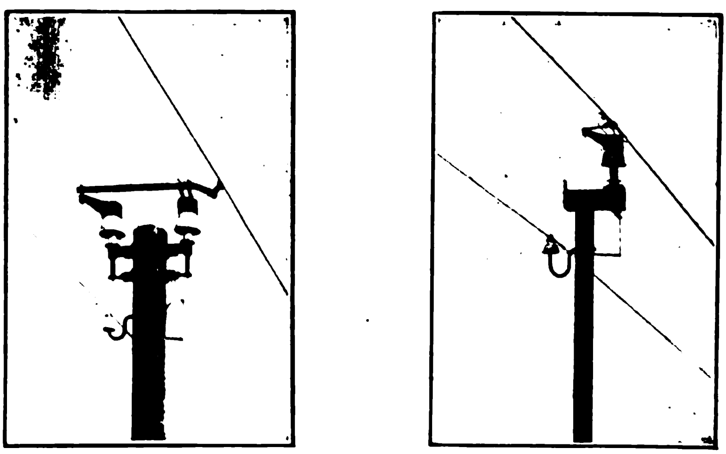
The following is a quotation from remarks by me before the New York Electrical Society, last November, as published in the *Street Railway Journal*, Nov. 26, 1904:

"The electric train service proposed for this line will require eight trains, or four trains in each direction, per day. It is expected that this service can be done with one single electric locomotive. Each train will carry both freight and passengers, mostly freight. The estimated average train loads, not including the weight of the locomotive, are: 180 to 200 tons for trains running west, in which case the up-grades average about 0.8%, and 150 to 170 tons for trains running east, in which case the up-grades average about 1.0%. The average speed will be about 40 km. per hour. There are seven stations in the line including the two terminal stations. One of the present steam locomotives will be retained in service, at first, to run at least two more trains per day, one each way. This will be done partly to avoid the necessity of a second locomotive, but principally to enable the comparison between steam and electricity to be made under substantially the same operating conditions."

The members interested will find in this article a brief reference to the electric locomotive which is passed by here as extraneous to the subject under discussion. The following para-

FIG. 1.—Single Wire Held by Wire-Holders Rigidly Supported.

graph, which is a quotation from a reference made by Mr. Huber to the slides and photographs, contains interesting details regarding various forms of contact-line supports experimented with by him:



FIGS. 2 AND 2A.—Single Wire Held with Clamps with Lever to Secure the Wire Horizontally.

" From the photographs you will see that we are experimenting with different methods of carrying the trolley or contact-wire over the poles. You will find (Fig. 1) the single wire held by wire-holders rigidly sup-

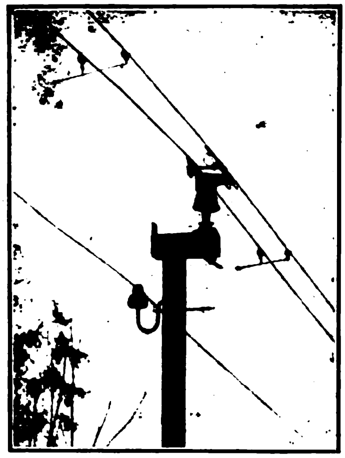


FIG. 3.—Pair of Wires Interconnected by Loose Links.

FIG. 4.—A Specimen of "Inverted" Catenary.

ported in the way which you know from our short experimental line inspected by you when here. Next, you find (Figs. 2, 2A) a single wire held with clamps to which a kind of lever is attached for securing the wire horizontally, while a spring made of steel wire, having some play vertically, supports the weight of the wire and takes up the hypothetical 'blows,' or the downward pressure, of the current collector. You will also find (Fig. 3) a pair of wires carried over the poles with the two wires interconnected by loose links. The inside wire is intended as the contact-wire for the current-collector, the outside wire as a reinforcement of the cross-section or conductivity of the line. The outside wire, having a somewhat greater sag, is less likely to break and will therefore constitute a safety-suspension for the inside wire in case the latter should

FIG. 5.—Another View of the "Inverted" Catenary Suspension.

break near a support, it being then held above the ground by the interconnecting links just mentioned. The same principle of mutual safety-suspension has been adopted for road crossings of small importance (Fig. 6). You will also find two different forms of 'inverted' catenary suspension, which have so far given excellent results (Figs. 4 and 5). This suspension has been used on about 5/4 kilometers of length. During these last days, when the weather was very cold, the trolley or contact-wire, supported on these catenaries, was so straight that the current-collector showed no appreciable up-and-down motion. We have, however, come to the conclusion that this suspension, although it costs only about 200 francs per kilometer more for erection, and hardly as much for material, will not be desirable for ordinary purposes. With two current-collectors on the car there has never been any appreciable sparking in passing over the supports of the contact-wire at the poles, with line construction of the types shown in Figs. 1 to 3."

Fig. 6 shows the arrangement of the contact-line at an ordinary crossing. The arrangement is based on the form of contact-line construction illustrated in Fig. 3; there being a pair of wires, which are interconnected by loose links. The object is, obviously, to make provision for supporting the ends of one of

Fig. 6.—Arrangement of the Contact Line at an Ordinary Crossing.

the wires in case it breaks, and to prevent the ends from reaching the ground.

Fig. 7 shows a more elaborate form of road crossing. In this case a bridging structure made of angle-iron is placed over the road and under the wire, and serves both to catch and to ground the ends of the broken line wire. In order to make the protection more adequate, a short section, or "block," of the contact-line itself, varying in length from 40 to 70 meters;

according to the width of the crossing, has its connection with the source of electricity controlled by the gates in such manner that this short section is connected with the line-wire only when the gates are closed and a train is passing; it is entirely disconnected and "dead" when the gates are open, at which time the current passes through a short auxiliary line which is specially installed over the street crossing. The cost of an

FIG. 7.—Angle-Iron Bridging Structures at Important Crossing, to Catch Broken Wires.

ordinary street crossing, such as shown in Fig. 6, is estimated at 600 francs. The cost of a street crossing such as shown in Fig. 7 is estimated at 1300 francs.

Fig. 8 shows the line-contact construction at a station, and over switches and side-tracks. In this case, the line construction is such that the current-collector makes contact partly above, partly at the side, and partly under the contact wire. It is proper to emphasize, at this point, the fact that while the Huber system is designed to permit the collector to take current from the contact-wire by touching it either below, on the side, or above, the top contact is preferable and is the normal method.

The collection of current from the side or from below the contact-wire is to be regarded as, in reality, only an expedient called for by certain conditions, especially by the limited space usually available for trolley supports, in railroad tunnels, under bridges, and at switches and side-tracks. On steam railroad lines only a comparatively small percentage of the contact-lines would require other than top-contact current collection.

Where a sufficient width is available, under bridges and ' ·gh-ways, the shifting of the pivot of the current-collector can be readily eliminated. This has been done in the case illustrated

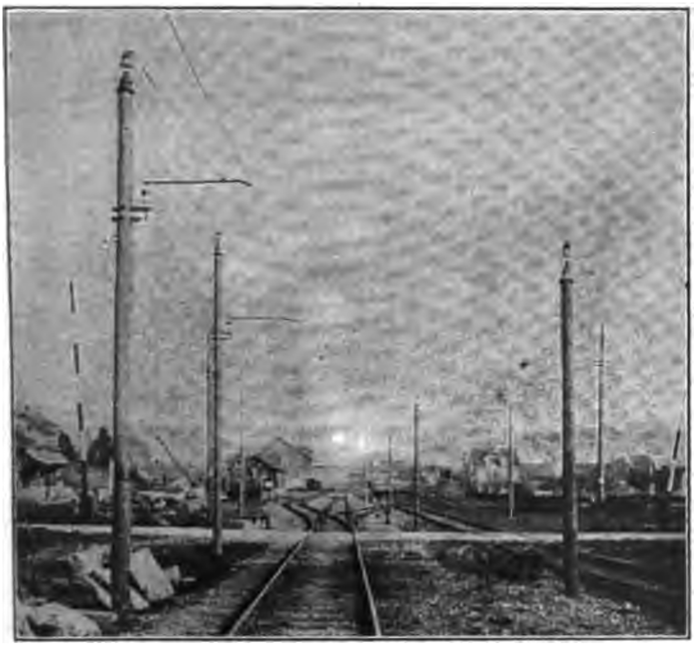


Fig. 8.—Line Contact Construction at a Station, over Switches and Side Tracks.

in Fig. 9. It does not follow, therefore, that the shifting of the current-collector, which has been criticised as one of the objectionable features of the Huber system, would be required in every case. Moreover, this device has now been brought to such a degree of perfection that its use is no longer a serious objection.

Referring to the large photographs, attention is called to the thin wire carried on ordinary insulators on the side of the pole away from the track. This wire forms part of a "block" system devised by the Oerlikon Co. The entire length of the

Seebach-Wettingen line is to be divided into 13 sections. The contact-wire at or near each station will form a section or block, and the portion extending from one station to another will also constitute a section; hence, there being seven stations, including the terminal stations, there will be 13 electrical sections or blocks in the entire distance of 20 km. The small wire shown in the photographs, which is called the "cut-out" wire, or the "feeling" wire, is connected with a weatherproof fuse to each *insulator pin*. If the insulator begins to leak excessively, or if it actually breaks down, current flows through its pin, and through the fuse, and is conveyed by the cutout

FIG. 9.—Illustrating an Instance where a good Bridge Clearance makes Unnecessary the Shifting of the Current-Collector Pivot.

wire to the operating solenoids of certain line switches located at the ends of the sections. Thus, any section or block on which there is a leaky or faulty insulator is automatically cut out. When the fuse is blown there is an explosive sound like that of a gun-shot, serving to attract the attention of the guardmen or station-men, even at a considerable distance. After the fuse has blown, the fuse-holder hangs from its support in such a position as to make it visible even from a considerable distance. Some of the switches controlling the blocks or sections are placed on poles. Figs. 10 and 11 show one of the switches open and closed, respectively.

Another form of section switch is shown in Fig. 12. The

FIGS. 10 AND 11.—Block Controlling Switches Closed and Open.

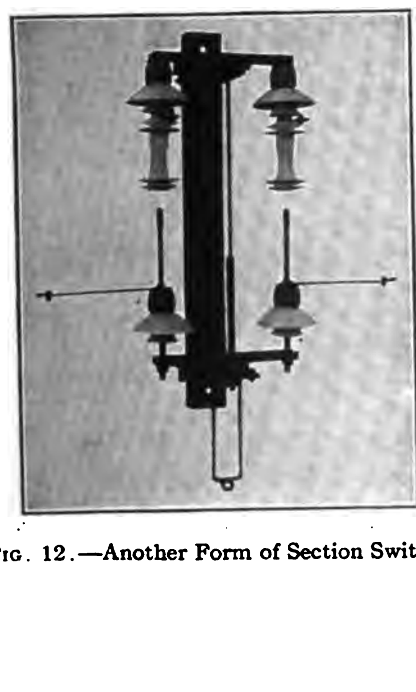


FIG. 12.—Another Form of Section Switch.

faulty insulator is located, first, by the audible signal produced by detonation of the fuse; secondly, by the visual signal given by the displacement of the fuse holder, and thirdly, by the absence of the fuse from the fuse holder.

As Mr. Huber stated to me, perhaps some of these operating features will be found superfluous, and sufficient reliability in line equipment can be realized without some of them. It was deemed prudent, however, to develop and apply such devices in this case, if only to meet the objection urged by steam railroad men that electrical troubles on a trolley line will be hard to detect, and that their removal would cause trouble and delay. At my request the experiment was tried of making an artificial ground at one of the line-contact insulators, to simulate the case where the insulator breaks down and grounds the contact-line. On making the artificial ground the audible and visual signals were unquestionably such as would attract attention, even though the location of the pole were not definitely known. It took less than three minutes for a lineman to replace the damaged insulator with a new one, and to have the current again turned on to the affected section.

Mr. Huber has paid close attention to the requirements of the contact-rod of the current-collector. After trying different metals, he has found that brass or composition metal tubes answer the purpose very well. He has also succeeded in lubricating the rod, and furthermore, has resorted to the expedient, of zigzagging the contact-line for the purpose of minimizing wear on the contact-rod, and to equalize it along the length of the rod, thereby preventing the rod from being sawed through by the contact-wire.

The top-contact method of current collection is unquestionably superior to all others in sleety and frosty weather. On this point Mr. Huber furnishes interesting evidence in the following comment on the results obtained since the portion of the line electrically equipped was put in regular operation:

"The aggregate number of kilometers run, up to the present time (Jan. 25, 1905), is 450 km. The speed varies between 45 and 50 km. per hour. We have thus far always had to contend with a very large amount of frost on the wire during the first trip, in the morning. The frost, owing to its nature, envelops the wire from all sides, while the sleet, which very often is produced from the frost, clings only to the under side of the wire. For this reason, on one day when the frost was exceptionally heavy, there was a continuous light sparking on the current-collector, which, however, was without any influence upon the volt- and ampere-meters; and, on the next trip, the line was perfectly free from sparking, simply because the frost, as formed on the upper side of the wire, will always be inevitably wiped away by the current-collector, while a cover of sleet will never be destroyed in the same way. It has also been observed that the sparking is very much heavier on those portions where the current-collector touches the wire from the side or from below. It is therefore proved that with regard to frost and sleet on the wires the contact from the top of the trolley wire is a marked advantage."

In conclusion, I may state, that after careful study of the Huber system, I have become a convert to, and a partisan of, the top-contact theory for contact-lines intended for long-distance traction. It possesses constructive and operative features which recommend it as preferable to the under-contact system. Not the least important of its recommendation is that of cost. I am convinced that if a comparison is made on the basis of equal mechanical and electrical results, also including cost of maintenance, the top-contact method is so much lower in cost as to outclass the others. This is the more true, the higher the line-pressure, and consequently the more perfect the insulation demanded.

The impedance of the iron rails of the track on this line has been carefully studied by the Oerlikon Company. The members who are interested in this matter will find an article on this subject in the *Electrotechnische Zeitschrift* for April 1, 1904, by Dr. H. Behn-Eschenburg, of the technical staff of the Oerlikon Company. It has been found that the pressure loss due to impedance of the track rails assumes such importance in some cases as to necessitate a special system of current-return line, with special booster transformers for the track, an interesting form of which is described in the article just mentioned.

THEODORE VARNEY: Referring to Mr. Babcock's remarks concerning leakage, it is important to keep in mind the fact that the entire line was covered with wet snow. Upon another day when the line was clear of snow, although the insulators were black with locomotive and other kinds of smoke which exists in the Pittsburg district, the leakage could scarcely be read with shop instruments. This appears to be the only point requiring especial remark.

GEO. F. SEVER: The remarks of Mr. Armstrong are particularly pertinent as to the continuity of service by having fewer transmission lines, having one trunk line connecting all sub-stations, and having the sub-stations nearer together than is contemplated by the higher trolley pressure suggested in Mr. Damon's paper.

PRESIDENT LIEB: I think it should be said that undoubtedly a great deal of credit is due to the pioneer builders of this high-pressure trolley line, Messrs. Ganz & Company of Budapest; but I think it also might be stated that the road in question could hardly be considered a heavy trunk-line. While it is a branch of the Adriatic Railway system it is rather a spur from the main line. I do not remember the exact conditions as to amount of traffic, but the impression that I got in reading the description of the road, led me to believe that it was not a very heavy line, not at all approaching our trunk-line conditions.

A paper presented at the 196th Meeting of the American Institute of Electrical Engineers, New York, April 28, 1905.

SOME NOTES ON POLYPHASE METERING.

BY J. D. NIES.

During the summer of 1904 a series of tests was carried on for an operating company for the purpose of determining the most satisfactory method of metering the power delivered to certain consumers whose demands ranged from 200 to 1000 kilowatts. The aim was to determine, as far as possible, the nature and probable extent of the errors that occur in the established available methods of polyphase metering, and to find which of these methods would be on the whole the best to use for the given work—regarding as best that system in which errors are not only least liable to occur, but also in which, if they do occur, their presence can be most quickly and readily detected.

The established practice of this company had been to install polyphase meters on such circuits, and in cases where especial accuracy was desired to put two of them in series. It was found in such cases that the two meters would never give identical readings; they were seemingly affected differently by changes in frequency, pressure, and power-factor. The difference between their readings was not constant; one meter would sometimes register alternately faster and slower than its mate; but always in the long run, the divergence between the two readings would become so great as to make it a matter of some risk to accept either of them, or the average of both, as the true value of power registered. The behavior of the instruments seemed somewhat capricious, indicating clearly enough that errors existed other than those of calibration, errors which would make it unwise to place implicit confidence in the readings of such meters unless some means were provided whereby their readings could be continuously checked.

The field of application of the polyphase meter is necessarily rather limited. It will probably always remain true that the bulk of the alternating-current output will be delivered through single-phase meters. On the one hand, it is true that when power is consumed in large blocks—from 25 to 1000 kilowatts or more—the delivery is nearly always made in the polyphase form; for example, the power measured at the input end of a transmission line or at the input side of a synchronous converter has to be measured nearly always by a polyphase meter. Therefore, though there are fewer examples of polyphase meter installations the individual cases are of greater importance. The requirements for high accuracy are far more strict, inasmuch as the load carried by such a polyphase meter may be several thousand times as great as that on the average single-phase meter, and an error of a small fraction of one per cent. in its registration means a considerable error when figured in dollars. It is not correct to say that a percentage error bears the same significance whether it applies to a large or to a small amount. Besides, many of the errors occurring in individual meters will be averaged out when a large number of them is considered; it would be possible to have an error of one per cent. in each one of 100 meters, and yet have a combined error of almost vanishing dimensions. But a polyphase meter of large capacity must operate as an individual, and will impress its own peculiarities upon the power bill that is based on its readings. In this fact may be found the justification for what might appear to be an unreasonable amount of hair-splitting, apparently more fit for the laboratory than for commercial work, which, however, is necessary in the effort to analyze the errors involved in measuring polyphase power. In what follows, the reference is principally to the high-tension, three-wire, three-phase system with balanced load, employing instrument transformers as intermediary between the line and the meter, the latter being of the induction type.

Inasmuch as the errors introduced by instrument transformers have the same effect upon the accuracy of all meter systems, whether single phase or any form of polyphase, the consideration of them will naturally precede consideration of the different systems. For many well known reasons it is necessary, in all high-pressure meter work, to use instrument transformers instead of connecting the meters directly into the line. In this way the meter instead of receiving upon its shunt coil the full line pressure, receives a known fraction of that pressure, through the agency of the pressure transformer; and, instead of carrying through its current coils the full line current, it carries a known fraction of that current, through the agency of the current transformer. The result is, that the meter receives at its terminals only a small fraction of the actual power undergoing measurement, and its reading must, therefore, be multiplied by the product of pressure transformation-ratio into current transformation-ratio, in order to get the registration. The instrument transformers then really constitute parts of the meter system, and should be considered in connection with it. The question may then be asked, do the instrument transformers correctly perform their function of delivering to the meter those fractions of line pressure and of line current called for by their ratios?

A pressure transformer differs in no radical way from an ordinary transformer, its operation is similar and is governed by the same rules, and therefore the pressure delivered from the secondary coils (supposing constant primary pressure) will vary with the amount of load that is put upon the transformer, by reason of the impedance drop in its coils.

Take for example a 200-watt transformer built for 10 000 volts in the primary and 100 volts in the secondary; the impedance of such a transformer would be about 10 000 ohms, and with the full-load current the impedance drop would be 200 volts, reduced to the primary; this would represent a drop of 2%, but as it is a vector subtraction, the error is less than this; it is about 1.6%. This will vary with the frequency, and with the power-factor of the load. All instruments supplied by such a transformer at full load would read 1.6% low. The error could be reduced by putting more turns on the secondary coil; but in that case the secondary pressure would be too high at all lower loads. Perhaps the best that could be done would be to make the ratio correct at half load. The point is, that the ratio can not be correct throughout the whole range of the transformer; and that the results of even the most careful calibration can be vitiated by using a meter in connection with a recklessly loaded pressure transformer.

For a transformer supplying voltmeters only this will be the only error to expect; but when wattmeters are supplied there is another effect to be considered, namely, phase displacement between primary and secondary electromotive forces. In a perfect transformer without reactance this phase displacement should be exactly 180 degrees, so that when the secondary electromotive force is reversed it will be returned into perfect phase with its original, the line electromotive force. If the displacement is not exactly 180 degrees, the result will be that the meter receives an electromotive force the phase of which, with respect to the line current, is not the same as it actually is in the line; the meter, therefore, works on and registers a false power-factor. The phase error introduced by a loaded shunt-transformer represents an apparent decrease in the angle of lag of the system of perhaps one-half degree—this depending upon the frequency and upon the power-factor of the secondary load.

The error in the case of the current transformer arises not directly on account of the impedance of the coils, but on account of the fact that not all the primary current is transformed, as part is diverted for the purpose of magnetizing the core. After the exciting-current component is subtracted vectorially, the residue is transformed at the true ratio. Consequently two errors are introduced: the quantity of secondary current is too small, unless the ratio of the transformer is corrected by removing the proper number of turns from the secondary coil; and the phase of the secondary current is different from the phase of its primary. The curves in Fig. 1, which were calculated from measurements of exciting current and coil impedance over a wide range, give the variation in ratio on a percentage basis, taking the full-load ratio as 100%, and the variation in phase from 180°, for a current transformer with 60-ampere primary and 5-ampere secondary, and with a load rating of 40 watts. The curves in full line are for a secondary load resistance that will take up full load at full current; those in broken line are for a load consisting of an ordinary wattmeter series coil and 200 feet of No. 12 B. & S. wire for leads, making about $\frac{1}{3}$ full load. The curves indicate a falling off of ratio and an increase of phase displacement on low loads, which would introduce errors quite comparable with the usual low load calibration error.

The curves in Fig. 2 show the per cent. of error introduced by a current transformer into the readings of a 5-ampere, 90-volt wattmeter supposed accurate in other respects, as a function of the lag of the load current. The current transformer is supposed to be correct in ratio at full load, and to be supplying a wattmeter together with 200 feet of No. 12 B. & S. wire as leads (in all about one-third full load). Curve A is for full volt-amperes, curve B for 0.5 full volt-amperes, and curve C for 0.2 full volt-amperes. The curves in Fig. 3 give the corresponding errors translated into watts; the lettering is the same. It is clear that the effect is negligible in circuits that are operated normally at or near unity power-factor, except on low loads.

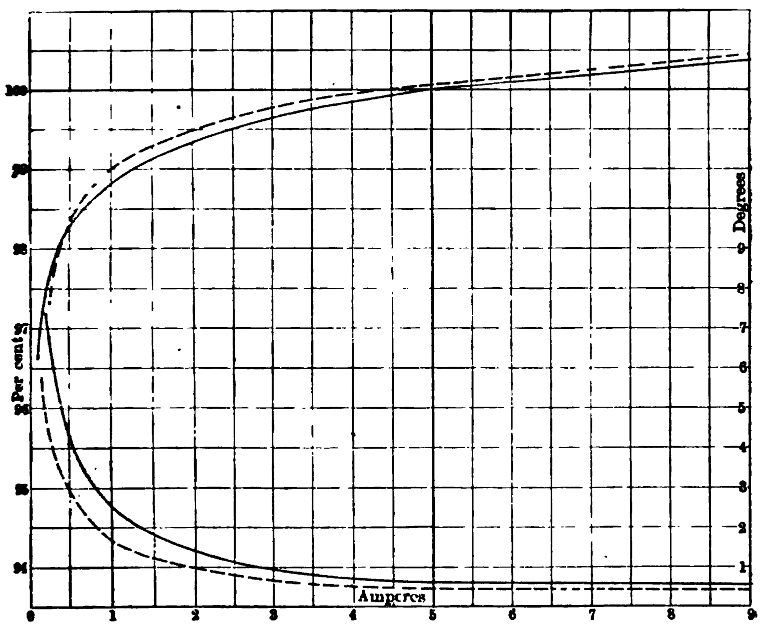


FIG. 1.

Fig. 4 illustrates the combined error produced by shunt and current transformers. E_p represents the primary pressure, and E_s the secondary pressure, the latter more than 180° behind its primary. I_p is the primary current, and I_s the secondary current, less than 180° behind its primary. These statements apply only to the usual condition of nearly non-inductive load on the transformers. The angle between E_s and I_s is less than that between E_p and I_p. That is, the effect of both transformers is to produce an alteration in the apparent phase of the current in the direction of lead, which may be called the phase error; combined with a reduction, both of pressure and of current, which may be called the percentage error. Thus a lagging current registers in the meter with a reduced angle of lag, hence higher power-factor and increased registration; therefore the percentage error and the phase error are to some extent compensative. A leading current registers in the meter with an increased angle of lead, hence lower power-factor and decreased registration, and the phase error and the percentage error are additive. The curves in Fig. 5 may serve to indicate the

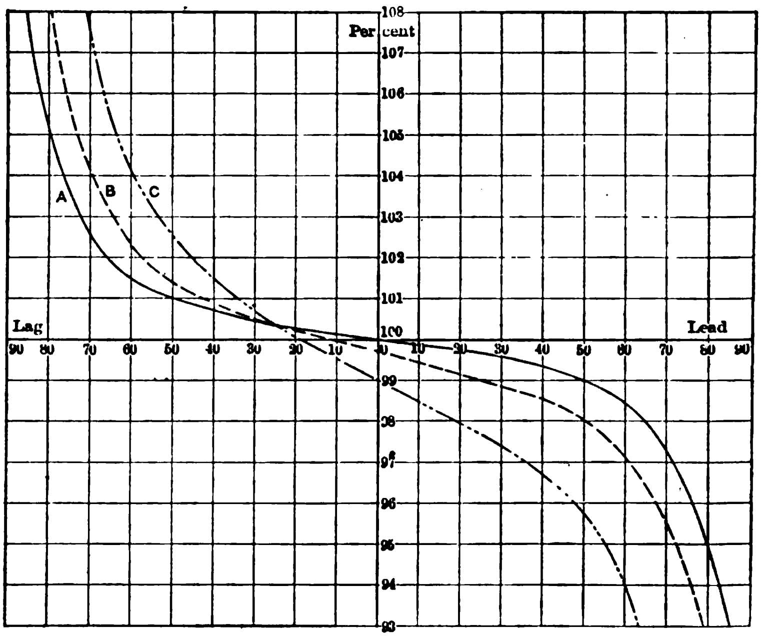


FIG. 2.

probable magnitude of this error. Curve A is for the condition of full load on both pressure and current transformers, the impedance of the secondary circuit of the latter being such as to take up rated full load at full-load current, in a single-phase circuit of 90 volts and 5 amperes; the per cent. of total registration is plotted as a function of the circuit lag. Curve B is also for the condition of full volt-amperes in the circuit but with half-loaded instrument transformers. Curve C gives the percentages of curve A reduced to watts on a basis of 450 watts at unity power-factor. This curve gives the probable limit of the error; to avoid this extreme it is evident that it is necessary to use instrument transformers with judgment; and wherever the highest possible accuracy is desired it is best to install special transformers for the meter and use them for that purpose only, or else run the risk of introducing errors which may completely overshadow the ordinary errors of calibration.

Current transformers are subject to another error which may occur if they are installed too closely together Ordinarily the primary winding consists of but few turns, and on that account the magnetizing effect of strong currents in neighboring conductors cannot be neglected in comparison with the magnetizing effect of the current in the transformer's own primary circuit. This result is the same sort of inaccuracy in the registration of the meter that would occur if the meter itself were installed in the presence of an external field. The error simply arises in the transformer instead of in the meter. Ordinarily in high-pressure circuits the necessary mechanical separation between conductors is sufficient to prevent this effect.

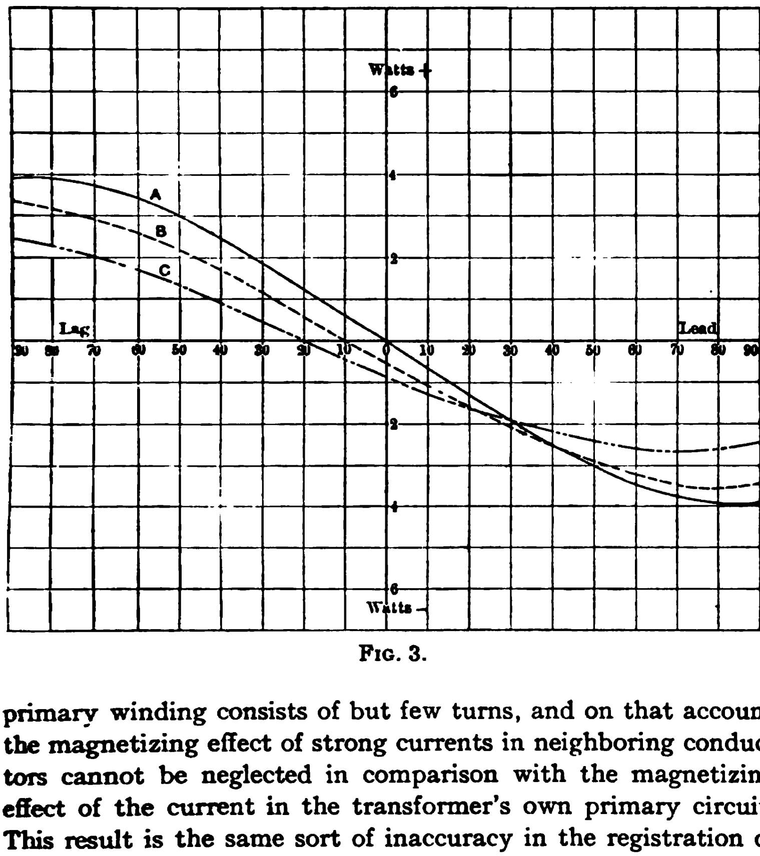


FIG. 3.

At this point may be considered an inaccuracy which is due to the wiring loss between transformers and meter. It is the usual practice to provide the two sets of transformers, for pressure and for current, with the same common return. The

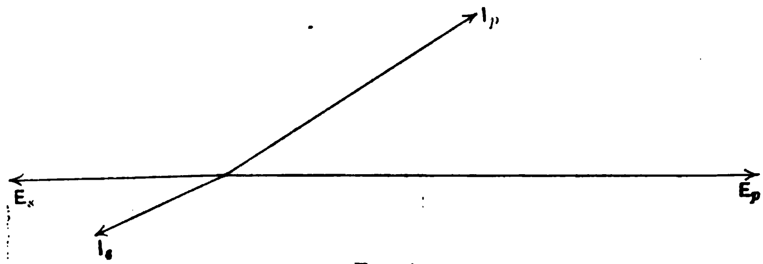


FIG. 4.

result is, that the drop of pressure in this common return, though it does not affect the operation of the current transformers materially, is subtracted from the pressure delivered

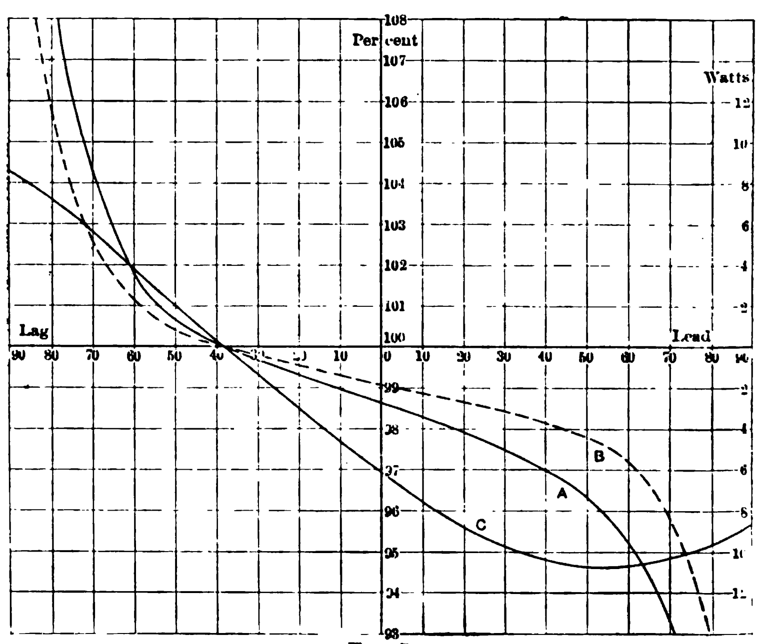


FIG. 5.

from the pressure transformers as shown in diagram in Fig. 6. The triangle $A\ B\ C$ represents the electromotive forces as delivered from the terminals of the pressure transformer secondaries.

Then if the two-meter method is used, $C\ A$ and $C\ B$ are the electromotive forces that should be received upon the terminals of the meters. C is the common return, in which the current, assuming non-inductive load, is I. This current in passing through the conductor C will cause a resistance drop r and a reactance drop x. Then the one meter will receive the pressure $C'A$ and the other the pressure $C'B$. It is easy to prove that the registration of the meters will be too low by just the amount of the $I^2\,R$ loss in the common return, and is therefore the same for the same current no matter what the load power-factor may be. If the common return is 100 feet of No. 12 B. & S. wire, the error will be about 5 watts when the current

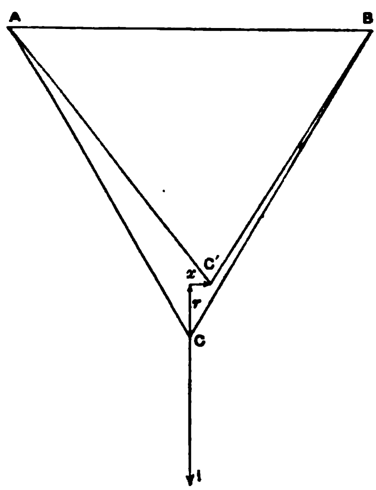


FIG. 6.

in the common return is 5 amperes. This is far too great an error to neglect, and it would be a good deal greater if the return wire were longer or of smaller size. This one item may mean a difference of hundreds of dollars annually in the bills based on the readings of a high-capacity meter. The effect could be prevented by running a separate return wire for the pressure transformers, connected at but one point to the return wire for the current transformers. It is interesting to note that reactance in the common return is entirely without effect upon the total registration of the meters, unless by way of interfering with the normal operation of the current transformers; this means that the point C' can be displaced in either direction to any distance along the line x without altering the total registration, provided the meters can withstand the abnormal pressure conditions that this would impose. All meter wires should be run close together, preferably in conduits, to prevent inductive effects from outside fields.

As is well known, meters of all types have a tendency to run "slow" on full load and also on low load. This difficulty can best be met by calibrating a meter for its probable average load. By careful calibration and checking, a very close average registration can be obtained, the more so because in his class of service a meter is rarely called upon to operate without a fairly large load, and the light-load errors would ordinarily have little significance.

Occasionally a considerable error is introduced by displacement of the phase of the shunt field from the proper position, 90 degrees behind the impressed electromotive force. This displacement may arise in several ways. It may be due to improper adjustment at the factory, the method of adjustment being such as to permit a possible variation of the shunt phase-angle of from 0.5 to 0.75 of a degree on either side of the true position. The usual plan is to supply a meter with a pressure and a current in quadrature, and to adjust the phasing resistance for no motion of the disk. The adjustment should be made for *no torque*; *no motion* and *no torque* mean the same thing only when the frictional resistance of the moving parts is zero. No torque exists when the shunt and series fields are exactly in phase. But there will be no motion until the deviation from quadrature phase produces sufficient torque to start the meter in either direction. If W is the watts—non-inductive—necessary to produce perceptible motion of the disk, V the volts, and A the amperes used in making the adjustment, then the range of variation of the shunt phase when thus adjusted will be:

$$2 \sin^{-1} \frac{W}{V A}$$

The effect of the friction compensating torque will not be to alter this range, but merely to shift its location with reference to the 90° point. Perfect friction compensation would place one end of this range at the 90° point, which simply moves the middle point of it away from 90°, and increases the chances for an incorrect adjustment. The effect is not eliminated by tapping the meter to remove friction. The displacement may arise after the meter is put into service on account of the aging of the iron composing the cores of the reactance coils, or on account of the variations in the resistance. It may be caused by mechanical alterations of the positions of various parts; for instance, a change in the length of an air-gap. Usually it is affected more or less by the operation of adjusting the light-load calibration. Variations of circuit pressure, wave form, and frequency, always alter the phase of the shunt field. That the effect is not always negligible may be shown by the full-line curve in Fig. 7, worked out for a single-phase meter with a shunt phase-displacement of 2° (to 92°), with full pressure and full current, and with various angles of lag of the load current. The meter is supposed to be in perfectly correct calibration for non-inductive load. The curve shows the error to be a maximum for a lag or a lead of 90° in the load current; therefore, any system of polyphase metering that compels a meter to operate at or near a phase difference of 90°, is liable to be subject to this error. Evidently when high accuracy is desired, and the power-factor of the load is variable, the phase of the shunt field should be checked with just as much care as is devoted to the regular calibration on non-inductive loads, as it determines to a great extent the performance of the meter on inductive loads.

Mention must be made of the error caused by variations of temperature; it makes a very complex problem in the induction meter, and analysis of it is out of place in this paper. The effect of any one of the factors is not large, and to a certain extent they are compensative, making the probable total effect small, though the whole matter is somewhat problematical. A meter should be calibrated under the same temperature conditions that it will be subjected to in service; in this way the error can be made practically negligible.

We may now take up for consideration the different methods of applying induction meters to the measurement of polyphase power. One method employs a single-phase meter with star box, the meter pressure-coil acting as one arm of the star-box. The meter reading is then to be multiplied by three. This method is open to the objection that it is difficult to get the impedances to balance perfectly, and to restore them if the balance becomes disturbed. The method is not accurate unless the load is in perfect balance; the entire responsibility rests on a single meter, and any error that occurs in it is multiplied by three in making the final estimate; and there is no check on its reading.

A preferable method of applying a single meter to a balanced circuit would be to insert the current coil into one of the conductors, and connect the pressure coil between that conductor and the middle point of the transformer secondary connected across the two other conductors; the true power is found by multiplying the reading by 2. This method eliminates the troublesome star-box.

Another method in common use employs two separate single-phase meters so connected that the two meters receive in their current coils the currents in two of the wires, and receive in their pressure coils, respectively, the pressures between these wires and the third wire. This method gives results which are theoretically correct on any three-wire circuit whatever, with balanced or unbalanced load; but it has practical disadvantages, particularly on circuits where the average power-factor is low, when by reason of the unequal division of the load, one meter—the one on the lagging side—is made to run habitually on the low-load end of its calibration curve, and the other meter carries nearly the whole load. This introduces the low-load error of the lagging meter into the final result, even though the actual load of the circuit may be fairly heavy.

To give correct readings on circuits in which the power-factor goes below 50%, the meters used must be able to register as accurately when running backwards as when running forwards. Any meter which is provided with a friction compensating device is debarred from consideration for this particular service. This statement should be qualified to suit those cases where the power-factor of the circuit may only occasionally go below 50%. The commutator type is entirely unfit. Another objection is that the meters are compelled to work under false phase-angles, which is especially the case with the meter on the lagging side. This increases the probability of error due to improper adjustment of the phase of the shunt, which error has been shown to be a maximum at 90° of lag or lead.

Besides, the meters do not furnish a check on each other, and in many cases practically the whole responsibility rests upon one meter only. Another and much better method is to use two single-phase meters as just described, but with the difference that the meters are combined and both moving elements are attached to the same shaft, thus making the so-called polyphase meter. This removes most of the objections that may be urged against the preceding methods, except that the error due to the displacement of the phase of the shunt is just as great in the polyphase meter as it is in the two separate single-phase meters. The speed of the combined meter is the average for the separate meters, and in this way the operation of each of the latter is brought to a better point on the calibration curve.

The fact that both meters are combined into a single unit increases materially the difficulty of calibration. If the calibration is done by the process of "bucking" the meters, and adjusting for no motion, then the difference between them will fall somewhere within a range of no motion the extent of which is determined by the starting friction of the meter.

It is suggested that a better plan than any one of the preceding would be to employ three separate single-phase meters, one for each phase of the circuit, having three pressure coils connected in star, the junction point of which is connected to the neutral formed by a star connection of the secondary of the pressure transformers. The summation of the three readings gives the true power on either balanced or unbalanced circuits. This is true, even though the neutral is displaced from the true central position—which might happen if the junction point of the three meter shunts is not connected to the transformer neutral, in which case the three branches must establish their own neutral—provided the deviation from the correct position is not great enough to bring an abnormal pressure to bear upon any one of the meters. It is better, however, to make use of the fixed neutral than the derived one. Such an arrangement of three meters would possess many marked advantages over the polyphase meter. In the first place, there would be no difficulty in calibration, more than exists in the case of the ordinary single-phase meter, and very much less than exists in the case of the polyphase meter. By arranging the meters in series, all three could be calibrated in but little more time than would be required for one alone. This is surely a strong point in favor of this method. Other things being equal, that meter which is most easily calibrated is most likely to be correctly calibrated.

The checking of the meters in place, which is practically impossible with polyphase meters, becomes comparatively easy and simple when three single-phase meters are used, as each meter can be checked individually, either by using a standard indicating wattmeter, or by temporarily connecting two of the meters in series on the same phase and thus checking them against each other. This should conduce to high accuracy. After a meter becomes inaccurate it can be taken down for recalibration, and the registration will be maintained by the two remaining meters. Another advantage is that the responsibility is distributed over three meters instead of one, and it may be expected that the average of the three will be more nearly correct than any one of them singly. Again, an installation of three single-phase meters is less liable to be affected by errors due to displacement of the shunt phase. It is true, that if all meters in any installation are subjected to the same error, then the total error is the same for any system of metering whatever method is used; but it is altogether unlikely that all the meters should be affected in the same way, and if they are not, then the total error, if the three meters are used, will be less than if the two-meter method or polyphase meter is used. This is because in the three-meter installation the meters are not compelled to operate on false phase-differences, thus reducing the error which has been shown to be a maximum when the phase-difference is 90°.

The curves of Fig. 7, all worked out for the same displacement to 92°, illustrate this point. Curve *A* shows the per cent. of error caused by a displacement occurring in both sides of a polyphase meter and in each of three Y-connected single-phase meters with full volt-amperes in the line, as a function of the (three-phase) angle of lag. Curve *B* shows the result of a displacement in the leading side only of a polyphase meter, and curve *C* in the lagging side only. Curve *D* shows the result of such a displacement in two of three Y-connected single-phase meters, and curve *E* in one of three. These curves indicate that in this respect the three star-connected single-phase meters would have a noticeable advantage.

But the prime advantage that this method presents is that, on balanced circuits, the three meters give a continuous and automatic check on one another. On such circuits all three readings should always agree, or at least should differ by a fairly constant ratio. Any departure from these usual conditions, any failure on the part of one of the meters to agree with its companions, would result in throwing suspicion on that particular meter; thus no inaccuracy can arise in any one of the three meters without immediate notice being given of the fact. It is true that errors affecting all three meters in the same way could not be detected thus, but the chances are, of course, that the three meters would not develop the same error simultaneously. They might become subject to it one after another; but the first one to go wrong would give warning immediately of its error; whereas in the polyphase meter the same error might be present for a long time with no means whatever of detecting it, except by comparison of readings from time to

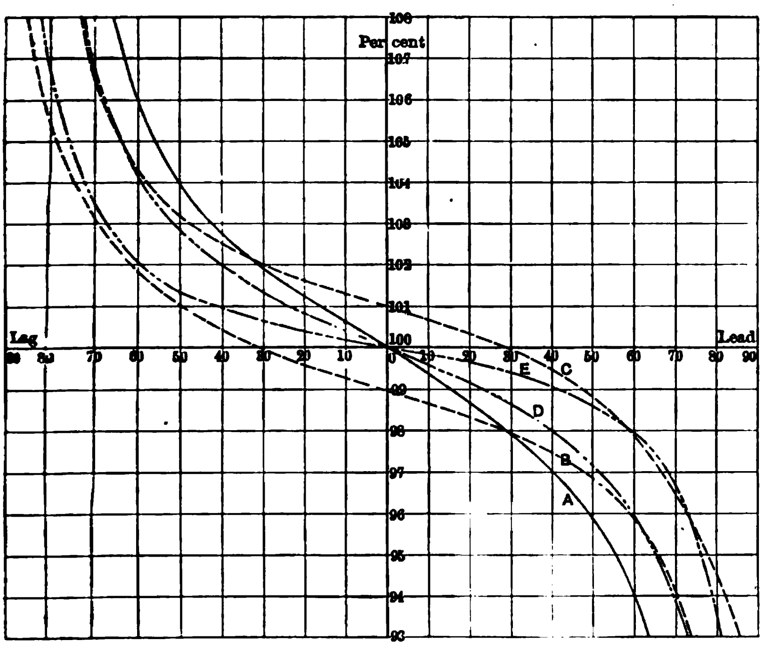


FIG. 7.

time—a very unsatisfactory and untrustworthy method. Each meter would act in the capacity of a critic of its companions; if the three readings agree, then the same credence can be given them that is accorded to three agreeing witnesses in law. Such occurrences as the blowing of a pressure-transformer fuse, the short circuiting of a current transformer, or bad contacts anywhere in the meter wiring—which with a polyphase meter installation might be present for a considerable time without detection, perhaps until someone "guessed" that something must be wrong—would be immediately discovered if the three meters were used. The latter would act like a "trouble indicator," and no variation of any sort from normal circuit conditions could occur without being brought to light at once.

To use a homely illustration: suppose that on a certain farm there were three woodchucks and that the farmer's boy owned three dogs, one for each. If he wanted to make sure of capturing the woodchucks, he would not begin operations by tying the three dogs together, but would leave each dog free to do the best that might be in him. The chances of getting the woodchucks would not only be improved, but after the hunt was over he would also be able to tell which dog was eager, and which dog was slow. This is a fair though crude statement of the advantage of using three separate single-phase meters on a three-phase system.

The only disadvantage of the method is that it requires the presence of a neutral conductor, and therefore is not available for ordinary three-wire three-phase service. This disadvantage does not exist in systems using pressure transformers, since the secondaries of the latter can as easily be connected in star as in ring, thus furnishing the required neutral. The cost of the three meters is higher; but this item sinks into significance in comparison with the value of the output that would be passed through the meters when used on a circuit of large capacity.

In conclusion, the statement can be made that in metering three-phase systems the method of using two separate meters is not entirely satisfactory; the modification of this method, the polyphase meter, is much better, but is still very far short of perfection; that three separate single-phase meters make the best arrangement, and should be employed when the highest degree of accuracy is demanded. For low-pressure three-wire circuits of small capacity the polyphase meter would undoubtedly be preferred. The conclusions reached in this paper are intended to apply mainly to high-capacity circuits using instrument transformers and involving a large multiplier. On such circuits it would seem almost essential to employ the three Y-connected meters.

A paper presented at the 196th Meeting of the American Institute of Electrical Engineers, New York, April 28, 1905.

NOTES ON THE USE OF INSTRUMENTS ON SWITCHBOARDS.

BY F. P. COX.

The object of this paper is to invite discussion on what seems to be the more important features of instrument engineering, and its value to the INSTITUTE should be found in the discussicn rather than in the paper itself.

In selecting instruments for any particular class of service the conditions under which they are to be used must be given careful consideration. It is evident that the conditions on a central-station switchboard will not permit of the same accuracy as could readily be obtained in a laboratory, and the information to be derived from the instrument readings does not require so exact a determination of values. For example, consider a shunt ammeter: an instrument best adapted for laboratory conditions would have a shunt loss too great for switchboard service, and one designed for switchboards would have temperature errors so great that its use in the laboratory could not be contemplated. It is the author's intention to confine these notes to the conditions which are found on switchboards in central stations.

One of the most important considerations is in connection with the capacity of instruments to be used, and present needs cannot be altogether overshadowed by possibility of future growth. An ammeter whose needle constantly hovers around zero position is of comparatively little use, and an integrating wattmeter, which normally operates at ten per cent., and frequently at less than one per cent. of its rated capacity, may give a false impression of the operating efficiency of the station.

Under such conditions agreement is difficult to obtain where totality meters are used and an effort is made to check them up with the sum of the individual feeders. Better results would be obtained by metering each generator, for under these conditions the meters would not be required to operate upon as low loads as they would if placed upon the feeders.

The friction of a jewel-bearing is generally considered so small that it may be neglected; but it must not be forgotten that a torque of 25 millimetre grammes is a little less than one five-thousandth of a foot-pound, and friction must be very small indeed if it is negligible as compared with this torque. Under normal working conditions, integrating instruments frequently operate at much lower torque, and even at full scale indicating instruments never approach this value.

It must also be remembered that the vibration of the board tends to impair the perfect polish of both jewel and pivot, and thus affect the accuracy of the readings. Other things being equal, it is apparent that these errors will be minimized by high torque, but they must not be altogether overlooked even under the most favorable conditions.

In deciding upon the capacity of an instrument it is necessary to take into consideration the relations between the smallest load, which it is desired to read, and the peak. It is generally considered advisable on railway circuits to have considerable overload capacity, and but little attention is paid to the light-load period. On lighting circuits, however, the overload is not considered to be as important as on railway circuits, and the light load is given more attention. It is usually good practice to select instruments of such capacity that under normal working conditions the needle of an indicating instrument will rest between half- and two-thirds scale. This allows a reasonable capacity for growth and for overloads, and at the same time permits of sufficient accuracy during the light-load period.

Integrating instruments should be fully loaded under normal conditions, for they have an inherent overload capacity not possessed by indicating instruments; such practice insures not only low-load accuracy but also a reasonable dial registration over comparatively short periods of time. Where hourly or even daily readings of the dial are recorded, it is not necessary that the registering train should have a capacity sufficient to care for several months' output. A rapidly-moving dial-train permits full advantage to be taken of the meter's accuracy, and a change of one or two figures should be recorded for each observation period.

Accurate records necessitate occasional calibration and adjustment of switchboard instruments, and suitable arrangements should be made for conveniently doing this work. Too little attention has been given to this feature in the past. It is frequently very difficult and sometimes impossible to introduce standards in circuits for calibration purposes. Perhaps this is a matter which should come under switchboard design rather than under instruments, but it is one of great importance and should be very thoroughly discussed.

Stray fields are always present in central stations and are frequently so strong that they cause marked instrument errors. In locating instruments on the board it is not sufficient to allow for position of bus-bars in relation to the instruments themselves, but the location of the iron framework of the board must also be taken into consideration. Magnetic fields have been carried by such iron frames and have introduced errors in instruments located many feet from the bus-bar itself. Such errors may be almost entirely eliminated by properly shielding the instrument, and no error need be introduced on account of residual magnetism or hysteresis of the iron shield. Properly designed instruments of this class show no appreciable difference between ascending and descending scales, or between alternating and direct currents, and they are entirely unaffected by fields which would influence the readings of unshielded instruments as much as 10 or 15 per cent.

The use of series transformers, even on circuits of comparatively low pressure, seems to be increasing; the added convenience in removing or in cutting out instruments for recalibration, and the added security for the operators, more than compensate for the slight errors introduced by their use. This practice is particularly to be recommended in those cases where both sides of the line are brought into the same instrument; such for example as the polyphase, integrating, or indicating instruments. It is also a good practice to interconnect the stationary and moving circuits and case of indicating instruments, and very often this would hardly be practicable unless series and pressure transformers are used.

Commutator meters are the only ones available for measurement of direct current; properly equipped with cupped diamond jewels, and occasionally corrected for commutator friction, they give excellent results. But induction meters with light moving element and no commutator are to be preferred wherever their use is possible.

Balanced three-phase circuits may be accurately measured by a single-phase wattmeter with a Y box. An instrument of this character records three times the energy of the phase in which the current coils are connected; therefore, it should be used only in those cases where there is no possible question as to the circuits being exactly balanced.

Polyphase instruments, both integrating and indicating, are to be preferred even for balanced circuits, and for unbalanced circuits they become a necessity. Professor Nies advocates the use of three independent single-phase meters. Of course the resulting records of the different phases are interesting, and on a balanced circuit any material difference in the readings of the three instruments would indicate an error in one of them, and serve as a warning that recalibration is necessary, or that the circuit has become accidentally unbalanced. In any case, it indicates a necessity for investigation. Still it is very doubtful if these advantages are sufficient to offset the added expense of three instruments and the space required on the switchboard for their installation.

In the measurement of polyphase circuits, the greatest care should be taken to see that the instruments are installed exactly in accordance with instructions received from the manufacturer. Sometimes a slight deviation from the connection shown on the diagram to connections which seem to be equivalent introduces considerable error, due to the instrument coils being in wrong phases; instruments are not infrequently charged with errors which should properly be attributed to incorrect connections.

A paper presented at the 190th Meeting of the American Institute of Electrical Engineers, New York April 28, 1905.

THE OSCILLOGRAPH AND ITS USES.

BY LEWIS T. ROBINSON.

The usefulness of a satisfactory method of observing or recording the wave forms of rapidly varying electric currents and pressures has been appreciated almost from the time that investigators and designers commenced working with electrical apparatus. The various methods which have been used for obtaining these records or indications have had, and are having, an important influence on the design of apparatus and a clearer understanding of the phenomena accompanying their use. It is the purpose of this paper to outline briefly the steps which have led up to the methods in use at the present time, and to describe more fully the devices which are now most employed and the uses to which they may be put.

Instruments for obtaining wave forms divide themselves naturally into two classes; those using point-by-point methods, most generally useful in connection with the investigation of recurring waves, and continuous methods which show recurring waves or record the individual waves. The first class can be traced to a common origin in the point-by-point method of Joubert,* and the second to the vibrating-coil device of Elihu Thomson, 1881 (not previously described), and to his later apparatus, and that of Frölich for observing the excursions of a telephone diaphragm acted upon by the current, the wave form of which is to be investigated. A description of these early methods will be given:

Comptes Rendus, vol. 91, 1880, p. 161; *Journal de Physic*, 1881.

Joubert's Method. One of the collector rings of the alternator is connected through its brush to one terminal of a condenser. The other terminal of the condenser is connected to a brush which touches, during a small part of a revolution, a moving contact attached to and rotating with the alternator shaft. At the instant this contact is broken the condenser is left with a charge which is proportional to the instantaneous pressure in the armature. The charge may be measured by discharging through a suitable galvanometer or continuously indicated by an electrometer. By setting the contact to correspond with

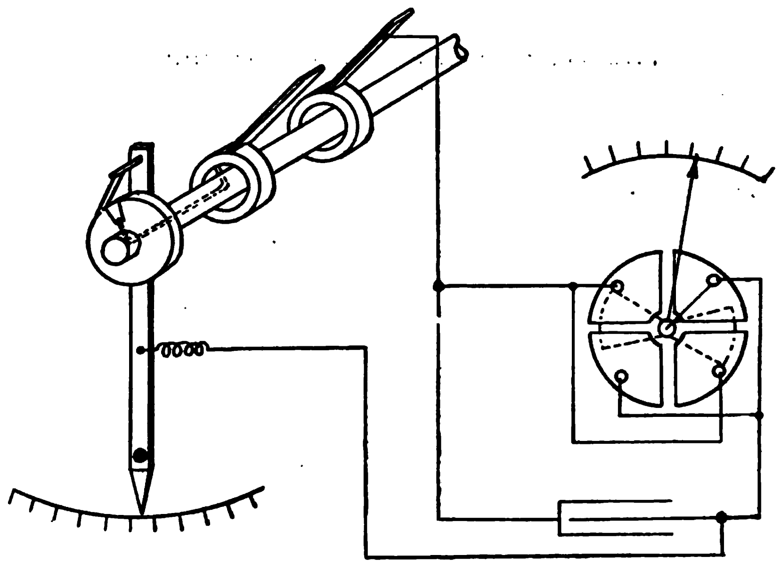


Fig. 1.

various points in the revolution of the armature, the curve of pressure may be plotted, Fig. 1.

The device of Elihu Thomson, constructed in 1881, while it would not satisfy the modern requirements as to frequency and absence of appreciable inertia in the moving parts, is a true continuous method. Dr. Thomson has furnished the following description of his early instruments, which will be given in his own words:

"I first started to study the wave forms given by the coils in our three-coil arc light dynamo in New Britain in 1881. To this end I made a powerful electromagnet, the poles of which were brought near each other with a small space between. One pole was a ring and the other a cylinder as shown in Fig. 2. In the polar space was mounted a small light coil through which the waves to be investigated were sent. This caused oscillation of the coil which was mounted upon an arm of a lever, the other end of which carried a fine aniline pencil point resting lightly on a surface of paper carried on a cylinder, which, when revolved, was screwed along as in a chronograph; Fig. 3. The lever was held in a central position by springs and was, also, damped. With this apparatus I was enabled to map curves of current and e.m.f., some of which records I still have, I believe. The instrument was a sort of crude oscillograph."

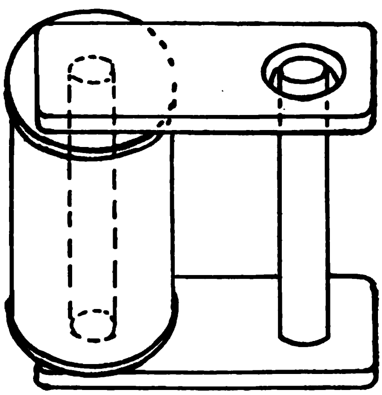


FIG. 2.

Following this device we find, in 1887–1889, the diaphragm instruments of Dr. Thomson and Frölich.* That of Dr. Thomson will be described, as information concerning this was more readily obtained by the writer. Again quoting Dr. Thomson:

"When we began alternating-current work, or about 1887, I made two instruments as follows:

One of these consisted of a dark box in which was mounted a polarized (adjustable) magnet on whose pole was a coil through which the waves or impulses to be mapped were passed. In front of the magnet pole was a telephone diaphragm to which

* O. Frölich, May, 1887, *Elektrotechnische Zeitschrift*, vol. 8, p. 210; Thomson, reported in United States notes by Wetzler, *La Lumière Electrique*, February, 1888, vol. XXVII., p. 33; Frölich, July, 1889, E. T. Z., vol. 10, pp. 65 and 345.

was fastened a very light lever, which in turn was attached to a small pivoted mirror. See Fig. 4.

A spot of light from the mirror was thrown upon a screen and showed as a vertical streak when the wave was on. By

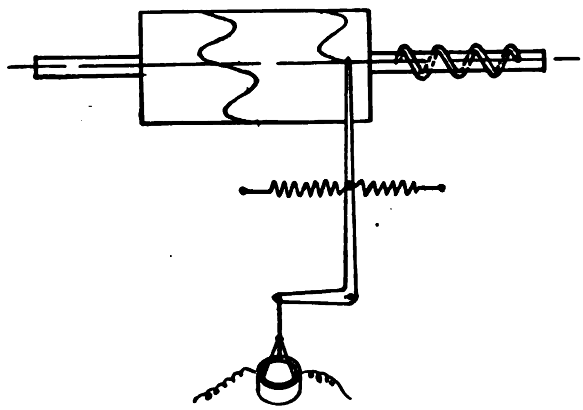


FIG. 3.

traversing the magnet so as to cause the spot of light to traverse the screen horizontally the wave form was disclosed. In this case a sensitive plate was used to record the wave form. A considerable number of these photographic records were made.

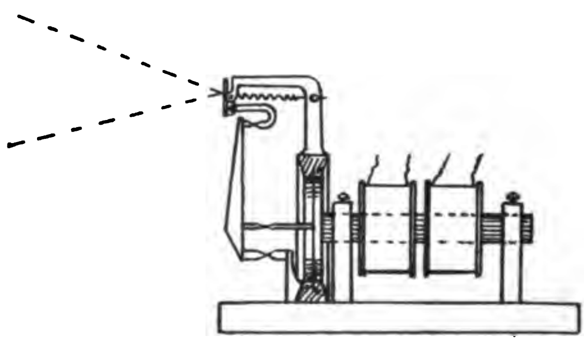


FIG. 4.

The other apparatus was a duplication of this, except that there were two magnets which acted on a single mirror to swing it on axes at right angles with each other. See Fig. 5.

It is thus possible to compare the phase relations of two waves and obtain figures on the screen or plate depending on the phase relations.

Adjustments were made to give the same amplitude of swing to the mirror from each of these magnet systems.

With waves at exactly 90° phase difference the figure was a circle, a luminous ring (with sine waves). When the waves were in the same phase the figure was a vertical line, and when in opposite phases, also, a line at right angles to that when

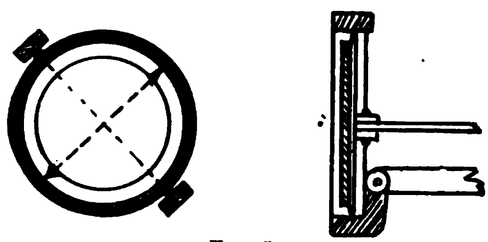


FIG. 5.

in phase. Intermediate phase relations gave approximate ellipses (with sine waves) leaning to right or left. The single waves alone gave slanting lines at right angles to each other. The diaphragms were damped. See Fig. 6.

The apparatus which you remember was the one with sensitive flames observed by revolving mirrors, Fig. 7. This was the first made and in this case the gas pressure was modified by

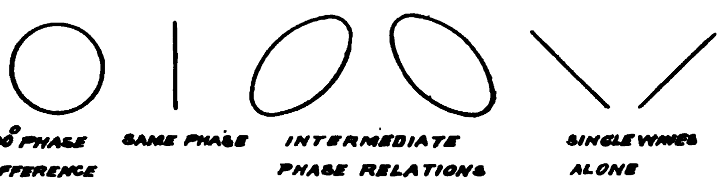


FIG. 6.

diaphragm under action of wave forces with polarized magnet (adjustable in power).

The flame seen in the revolving mirror showed the wave forms thus, Fig. 8.

The original apparatus of 1881 came nearest to being like the oscillograph, although it was, of course, very much less refined in all respects. It embodied an idea only."

Referring to the point-by-point methods which has been traced to that of Joubert we find, after various modifications, the resulting modern instruments: Hospitalier's Ondograph Rosa's Curve Tracer, and the General Electric Wave Meter. While there may be other methods in practical use at the present time, it is believed that these are the only ones which have been used commercially to any extent, at least in this country.

These instruments are not suited to commercial work on

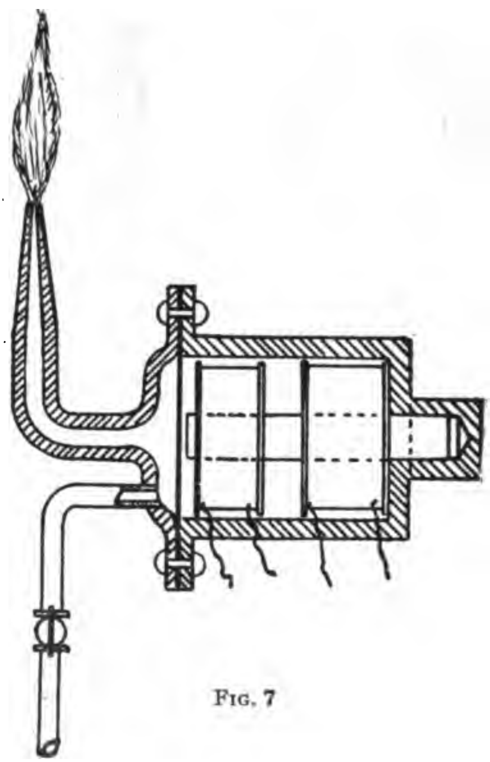


FIG. 7

instantaneous phenomena, as they require many repetitions of the wave to be viewed or recorded before its complete form is shown. They can, however, be made to operate with very little energy from the circuit to which they are attached and can be constructed to give records of any desired size and of considerable accuracy. These records are, therefore, well suited for analysis and furnish a positive means by which records or observations by the oscillograph may be checked and the absence of errors, due to lack of critical damping and sufficiently high frequency of vibration, determined.

No doubt they will for this reason continue to be used although the oscillographs, to which we will turn our attention later, are more universal in their application and may be used to study many events which, by reason of the time required to record a complete wave and the impossibility of reproducing many conditions a sufficient number of times to produce a record by means of succession of points, cannot well be handled by any point-by-point method. The three instruments referred to, while they accomplish broadly the same purpose, show that their designers in each case thought it desirable to emphasize strongly some features at the expense of others.

In the Rosa Curve Tracer the record is obtained on a drum by printing automatically from a potentiometer contact which

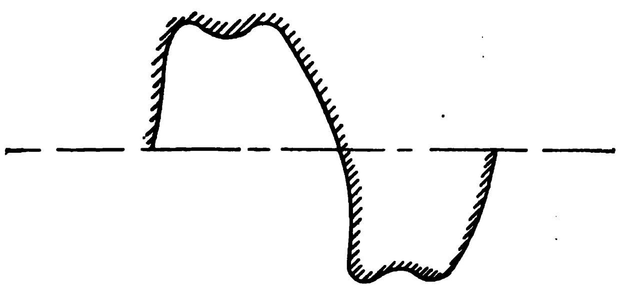


FIG. 8.

is set by hand to a point indicated by a zero reading on a galvanometer. We have then an instrument producing highly accurate records but which requires the close attention of the operator for a comparatively long time and which, as usually made, requires, also, direct attachment to the dynamo. Fig. 9 shows the instrument complete and Fig. 10 a diagram of the connections when taking an ordinary curve of current or potential.

LL_1 are the terminals of the circuit whose wave is required. CM is the contact maker. G is the galvanometer above referred to. D is the drum on which the record is made. P is the potentiometer contact which is moved along the potentiometer wire $M\ N$ until balance is secured when record is made on the drum by the printing finger F. $V\ M$ is the voltmeter by means of which the current flowing through the potentiometer wire $M N$ is kept constant, using the variable resistance R to vary the current if necessary.

In the General Electric Wave Meter the record is obtained on a photographic plate from a galvanometer receiving the discharge from a condenser which is charged and discharged continuously, by means of a commutator and contact brush attached to a synchronous motor, which is, in turn, electrically connected to the circuit under test. The contact brush or commutator is carried around, with reference to the poles of a synchronous motor, automatically at any desired speed, and

FIG. 9. Rosa Curve Tracer.

in this way the record of the wave is made. We have here an instrument producing records accurate enough for all practical purposes, entirely automatic in its operation, and with a speed limited only by the limitations of the recording galvanometer. Fig. 11 shows the complete device and Fig. 12 a diagram of the connections.

LL_1 are the terminals of the circuit whose wave is required. B is the brush passing over the segments of the 8-part commutator (8-pole motor is used) by means of which the condenser C is charged and discharged. B_1 and B_2 are brushes connecting to the four long and four short segments respectively of the commutator. *S* is sector by means of which the contact *B* is carried around with reference to the poles of the synchronous motor by means of the weight W. *D P* is a dash-pot which controls the speed with which the contact *B* is moved. *P* is the photographic plate which receives the record from the galvanometer. *R* is a resistance in series with the galvanometer, which may be adjusted to obtain deflection of suitable size if the condenser *C* is not sufficiently subdivided.

In this instrument the inconvenience of obtaining photographic records was thought to be outweighed by the fact that a photographic recording instrument can be operated with a minimum

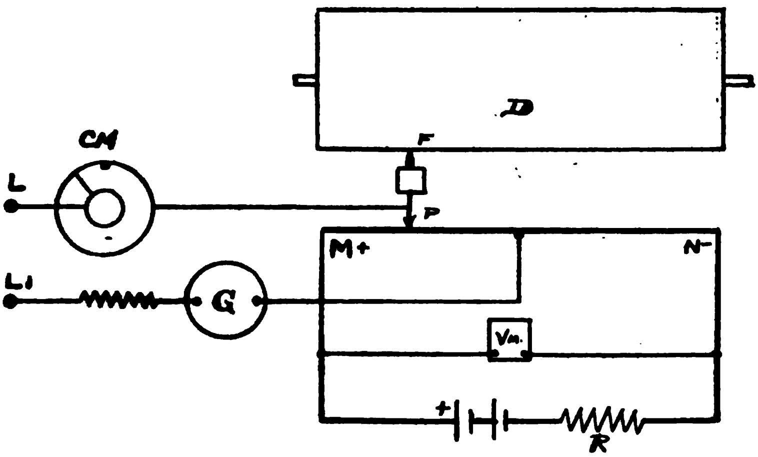


Fig. 10.

of energy, and its record can be produced almost absolutely correct with reference to rectilinear coördinates.

In the Ondograph the record is obtained by an inking pen on a revolving drum. The actuating part of the recording instrument is traversed by the discharges from a condenser. The condenser is charged from a revolving contact which, by an ingenious method of gearing, is automatically changed with reference to the poles of the synchronous motor, thus producing on the recording surface the desired record of the wave. We have here an instrument entirely automatic in operation, but in which the time of taking the record is fixed by the frequency of the circuit to which the synchronous motor is attached.

The Ondograph is, also, not particularly well suited to producing waves for analysis by reason of the fact that the record is not made with the abscissas referred to a straight line, therefore, the record is bent over (see Fig. 13), which is a little confusing to one who is not used to the records made with the instrument. This distortion is due to the fact that the pen arm, although of long radius, still travels across the recording

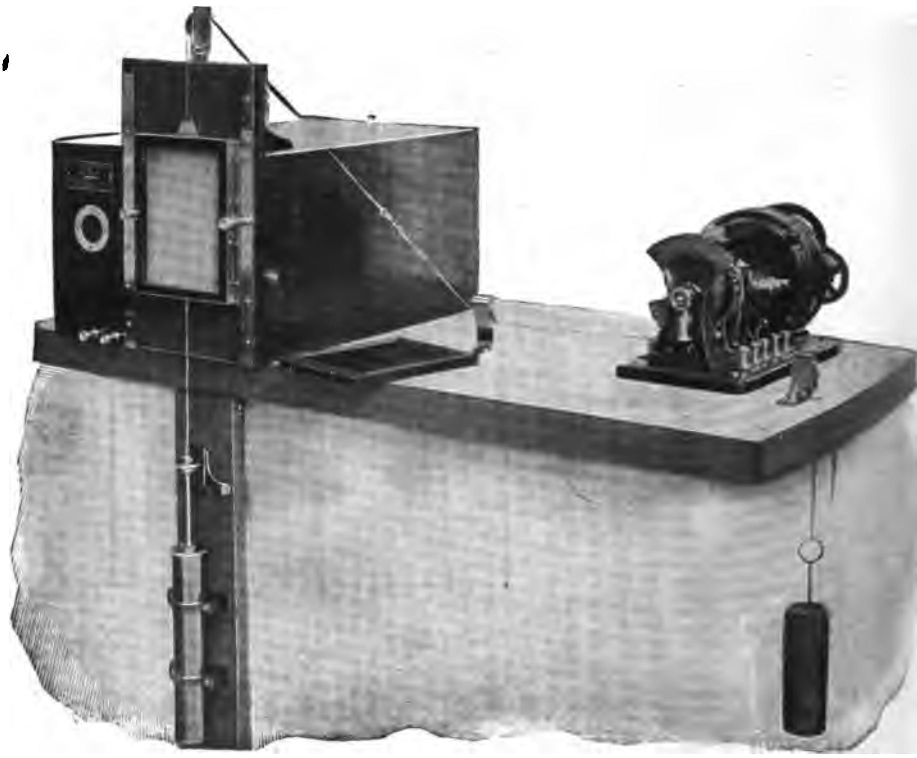


FIG. 11.
Wave Meter and Wave Meter Photographic Attachment.

surface in a curved line and all abscissas must be referred to this curved line instead of to a straight line as in the other two instruments referred to. Fig. 14 shows the complete device and Fig. 15 a diagram of connections.

LL_1 are the terminals of the circuit whose wave is required. C_1 and R are the condenser and resistance as before. D is the drum on which the record is made by means of the curve-drawing galvanometer. B, B_1, B_2 are the contacts bearing on the revolving commutator by means of which the condenser is charged and in turn discharged through the galvanometer. The commutator is geared to the drum and to the synchronous motor in such a way that the commutator makes 999 revolutions when the synchronous motor makes 1000, and hence the commutator is revolved around with reference to the motor poles and the wave drawn. The drum D is also driven by gearing from the synchronous motor.

The true oscillograph, that is, the instrument with high period, critical damping, and comparatively good sensibility is to-day existent in two forms, both due primarily to Blondel, C. R., April, 1893, who has developed, to a high degree of per-

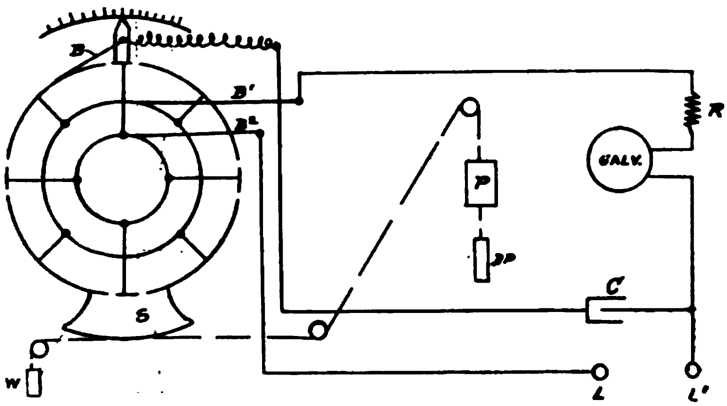


FIG. 12.

fection, the moving iron or vibrating strip type.

This consists of a thin ribbon of iron tightly stretched between the pole tips of a powerful magnet, thus forming a polarized needle, held in position by the directive force of the magnetic field, and, also, by the resistance to torsion of the strip itself. Two small coils, to which the circuit under investigation is connected, are arranged on either side of this strip in such a way that the strip is acted on by the current flowing in them and at any instant the strip, having the necessary high period of vibration and critical damping, takes up a position which is a measure of the current flowing in the coils at that instant. A minute mirror is attached to the middle portion of this vibrating strip and a beam of light reflected from its surface can be made, by suitable means, to render the wave of current in the coils visible, or to record it on a suitable photo-

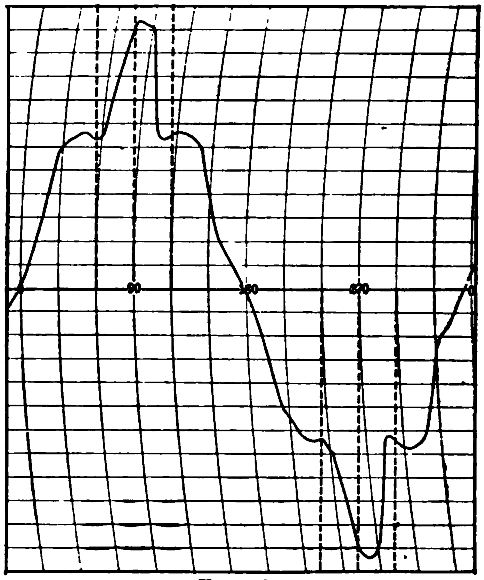


FIG. 13A.

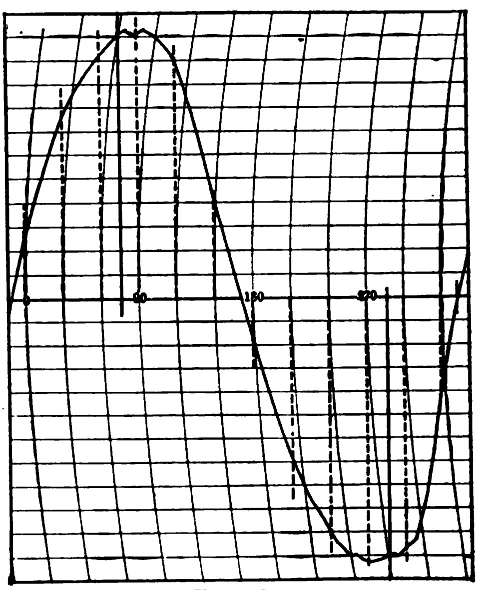


FIG. 13B.

graphic surface. Fig. 16 shows the general arrangement of the parts.

In the plan view " C," N and S are the poles of the magnet. $P\,P$ and $P\,P_1$ are the pole pieces. C and C_1 are the coils. And in the enlarged sectional plan " D," M is the small mirror

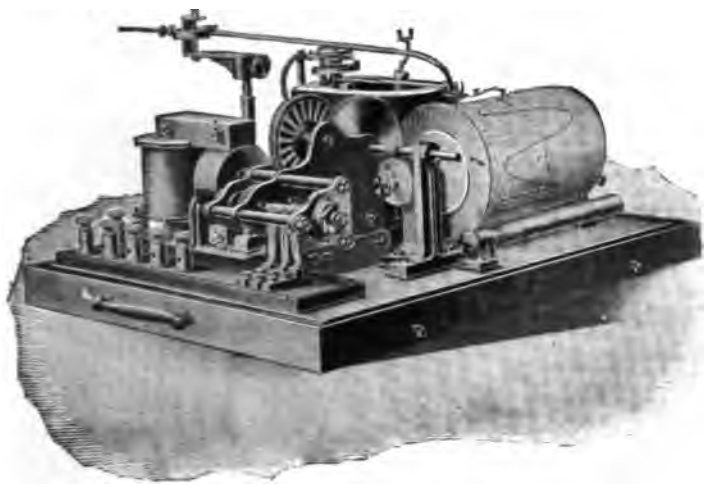


FIG. 14. Hospitalier Ondograph.

attached to the vibrating strip. $G\,C$ is the insulating tube and $P\,T$ are the pole tips which concentrate the field on the vibrat-

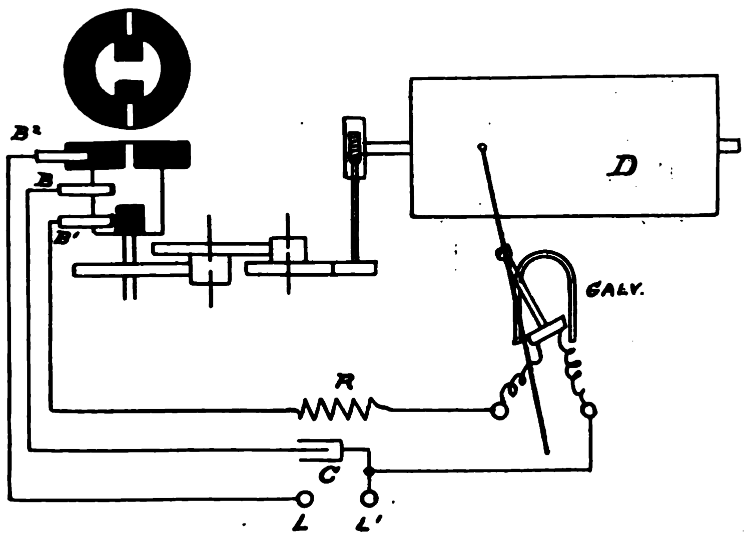


FIG. 15.

ing strip $I\,S$. M is the mirror attached to the strip $I\,S$.

The alternate type, or the vibrating-loop construction, is in reality a D'Arsonval galvanometer in which two small metallic bands constitute the moving coil, as well as the suspensions. These are located in a strong magnetic field and the varying current to be investigated is led through the strips in opposite directions. The current flowing through the strips will then,

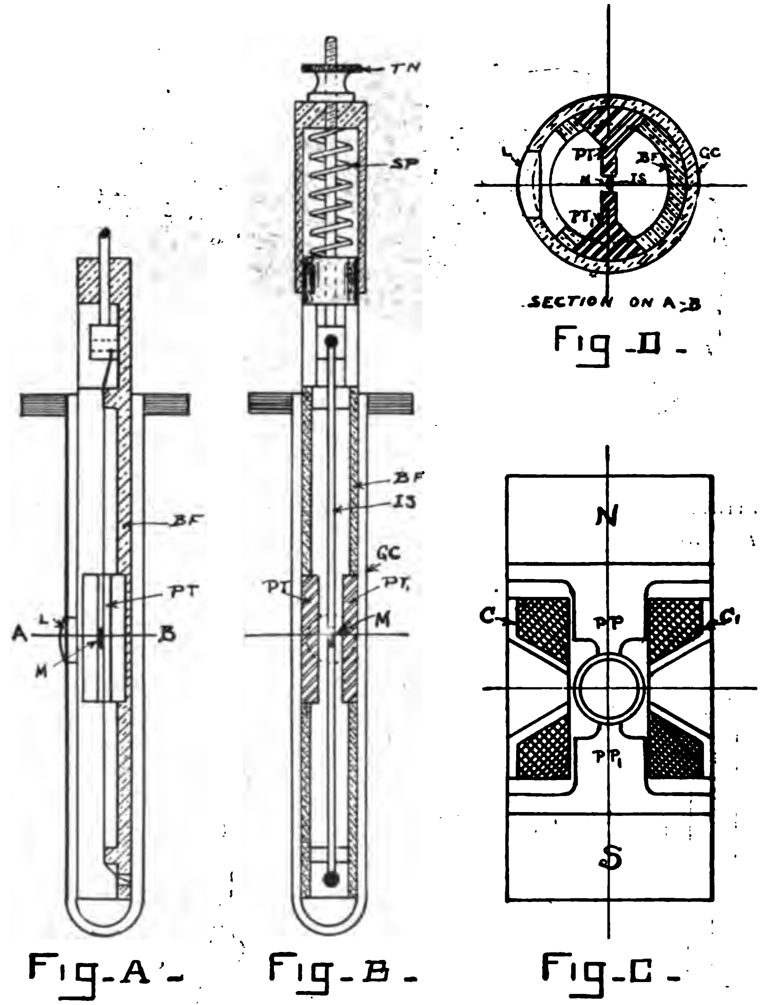


Fig. 16.

at any instant, bend them in opposite directions, with reference to the field in which they are situated, and a small mirror, attached by its edges to the middle portion of the strips, will be deflected. The deflection of this mirror can be used, as in the first mentioned type, to indicate or record the wave form of the current passing through the strips. Figs. 17, 18, 19 show diagramatically the strips in the magnetic field, traversed by a

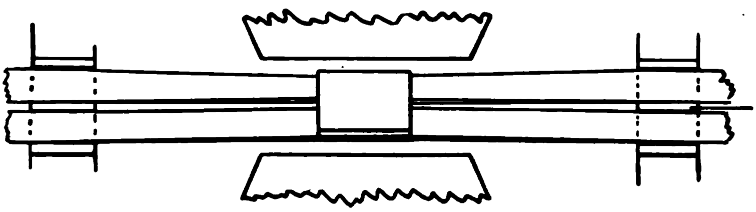


FIG. 17.

current, with the mirror deflected. At this point we may consider briefly the advantages and disadvantages of the two types.

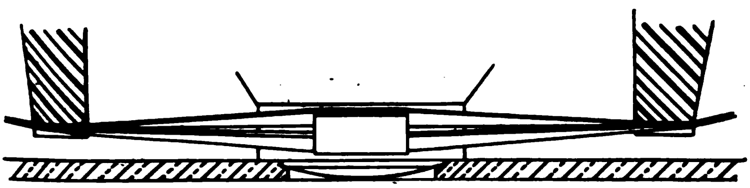


FIG. 18.

An oscillograph, to give satisfactory results, should have:

1. A short free periodic time compared to the period of the wave forms being recorded.

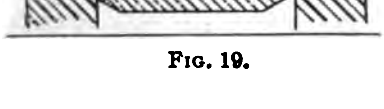


FIG. 19.

2. Critical damping, that is, the motion just ceases to be oscillatory.

3. Negligible self induction.

4. Sufficient sensibility (Duddell, *Inst. of Elec. Engineers' Journal*, vol. 28, No. 138, p. 7).

And we might add the fifth consideration: The instrument should be so constructed that the working parts are readily accessible and of sufficient size so that they may be renewed or repaired by persons ordinarily skilled in the handling of testing instruments.

Referring to these various conditions in the order given, it is undoubtedlv true that the iron strip type can be made to

FIG. 20.

have a shorter free periodic time than the moving strip type, unless the dimensions of the parts in the latter are reduced to an impossible degree.

Both types can be given critical damping.

The vibrating-loop type is superior as far as negilgible self induction is concerned, and it is believed that it can also be operated with less expenditure of energy than the iron-band type.

The fifth condition is believed to be more fully realized in the instrument which you have before you than in any instrument which has heretofore been made, and which will, at the same time, satisfy, to a reasonable extent, the other conditions given. For practical work it is, in most cases, not necessary to use a periodic time shorter than that which can be conveniently obtained with the moving strip type, and it is, also believed, that the negligible self induction and small resistance of this type is of the greatest advantage when large currents, especially undirectional ones, are to be dealt with. Cases have frequently arisen in practice where such currents of several thousand amperes have been measured by passing them through shunts, similar to those used in connection with direct current moving coil ammeters, which is believed could

FIG. 21.

not have been successfully handled with the iron-strip type.)

Referring to accessory parts of the oscillograph, the arrangements which have been adopted for photographing and viewing the waves, these exist in great variety and have been developed to meet the special requirements of various investigators. It is not possible at this time even briefly to refer to these arrangements, except such as have been found necessary in connection with the instrument to be described. We shall, therefore, describe those which have been adopted for the instrument with which the writer is most familiar, and refer those who may be further interested to the list of references at the end of this paper.

The instrument consists of a light tight box, Figs. 20 and 21, in which is placed a three-element galvanometer, and to which are attached devices by means of which the waves may be viewed, or photographic records of them taken.

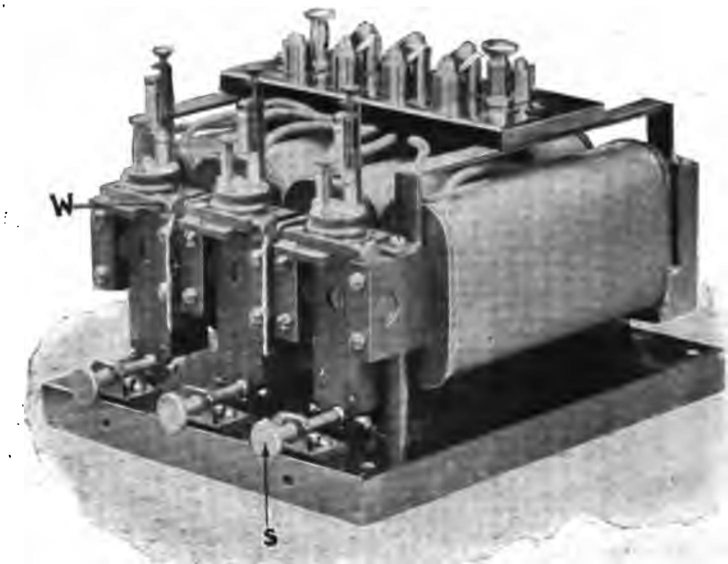


FIG. 22.

The three-element galvanometer is shown complete in Fig. 22, and the moving element removed from it in Fig. 23. The details of the containing cell which is inserted and held between the pole pieces of the magnets, and in which the vibrator

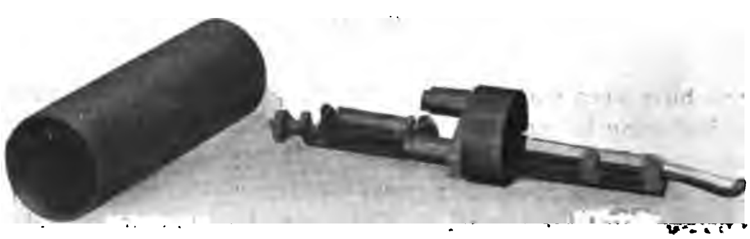


FIG. 23.—Vibrator for Oscillograph.

is inserted, are shown in Fig. 24.

The principle on which the instrument operates has already been referred to in speaking of the vibrating-loop type in general. The three elements of the galvanometer are entirely complete within themselves, with the exception of the magnetizing coils, and can, therefore, be insulated from one another to stand almost any required pressure. It is then not necessary to insulate the vibrating loop from the frame which holds it, or to rely for insulation on the somewhat uncertain condition that the vibrating loop can always be kept a safe distance away from the pole pieces, between which it moves. In fact, it has been found desirable in most cases actually to

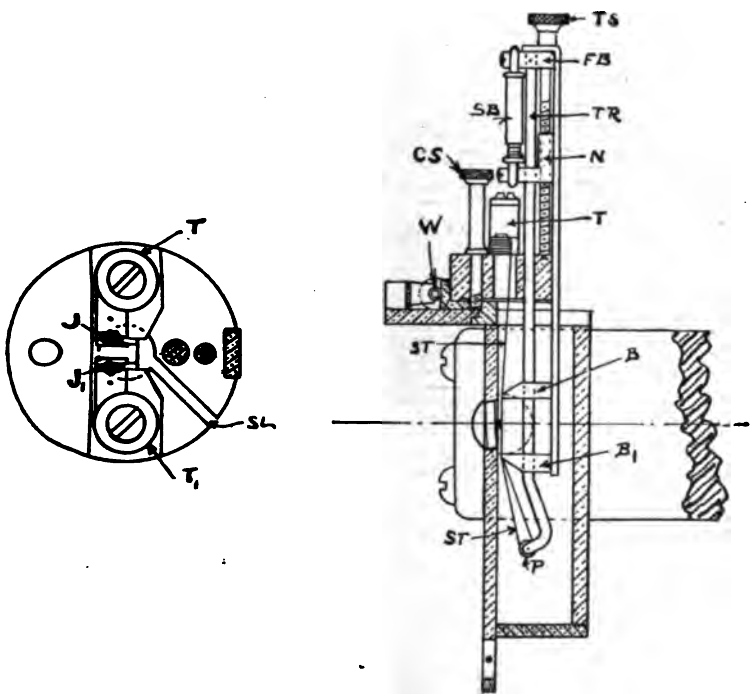


FIG. 24.

connect the strips electrically to the magnet, between the poles of which they are located. In the instrument shown, a pressure of 5000 volts has been applied between the separate galvanometer elements and between all of these and the frame, to which they are attached.

Referring to Fig. 23, it will be seen that the vibrating strips, when the vibrator is removed from the containing cell, are exposed on all sides; this is of the greatest advantage in restringing the vibrator and making any required adjustments to the moving parts. The vibrating strips, and consequently the mirror to which they are attached, can be moved around a vertical axis passing through the center of the mirror by means of the knurled head on the worm *W*, Fig. 22. The containing cell as a whole is movable around a horizontal axis passing through the same point by means of the screw *S*, Fig. 22.

These two adjustments make it possible to bring the image of the mirror into the desired place on the photographic film

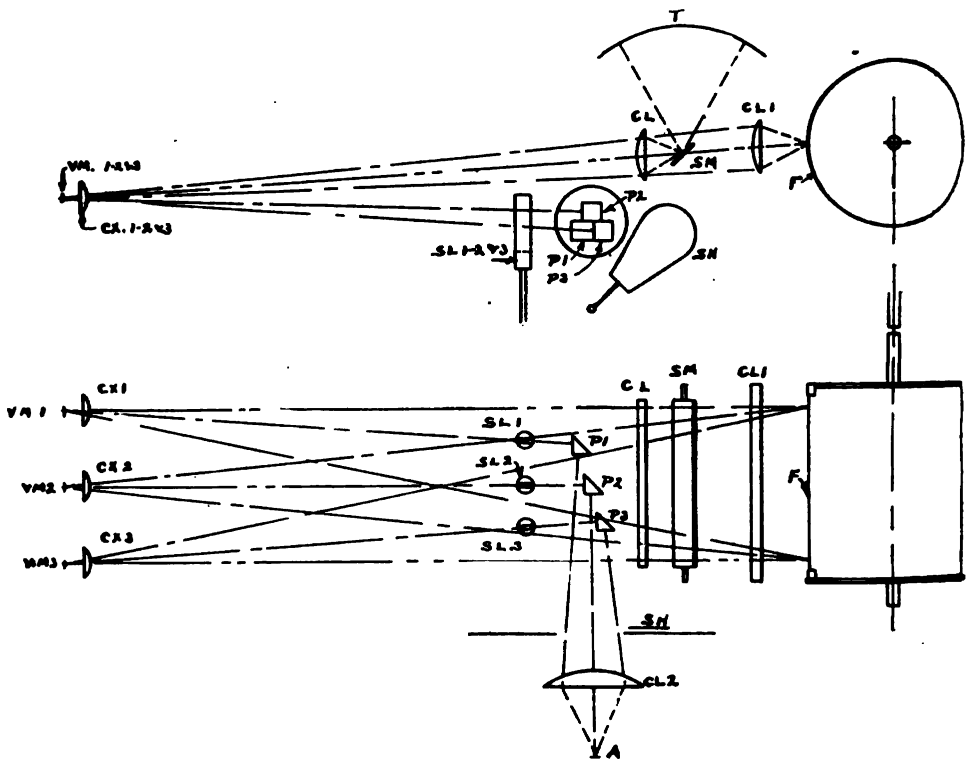


Fig. 25.

or vibrating mirror, even though it has been attached to the vibrating strips in a somewhat imperfect manner. The containing cell is filled with a damping liquid above the level of the bridge *B*, Fig. 24. The vibrating loop, or strips, is usually made of pure silver hard drawn, and the mirror of silvered glass.

Referring again to Fig. 24, $T\ T_1$ are the terminals conveying the current to the strip $S\ T$ through the soldered joints $J\ J_1$. By means of the slit $S\ L$ the strip is placed in position without being passed through any holes. *C S* is the clamping screw by means of which the removable vibrator is held in the containing cells. *T R* is the tension rod attached to the block *F B* through which the pull of the spring balance *S B* is transmitted to the pulley *P*. *T S* is the tension screw by means of which the tension is regulated by moving the tension nut *N*.

In a standard pattern the period is one five-thousandth second, the sensibility about 0.007 amperes per millimetre deflection, and the resistance about one ohm.

The dimensions of the mirror which is employed are 80x20x10 mils, which is large enough to be easily handled and admits of a better photographic record than a smaller mirror. It is, of course, possible, by employing smaller mirrors, to obtain higher period, up to, perhaps, 10 000; but unless such a high period

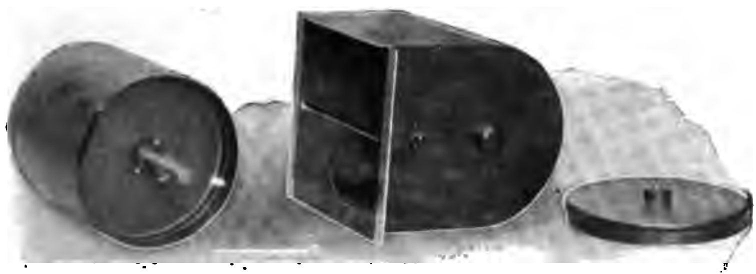


FIG. 26.
Oscillograph.—Film Holder for Photographic Attachment.

is absolutely necessary, the advantages are more than outweighed by the difficulty in handling the very small mirror required and of reflecting sufficient light from its surface.

The advantage of silver over phosphor bronze which has usually been employed for the vibrating strips, is considerable. The resistance, and consequently the energy required to operate the vibrator, is, by this means, much reduced, which permits current waves to be taken with shunts having comparatively small fall of pressure, and the danger of creeping of the reflected image, due to expansion of the strips on account of the current passing through them, is entirely overcome. With high resistance alloys this is one of the limiting features.

The optical system employed is shown in Fig. 25. We have here the source of light at *A*, usually an arc lamp; the condensing lense $C L_2$, by means of which very nearly parallel beam strikes the three small prisms P_1, P_2, and P_3, and is, by this means, split up into three portions, which are directed on to the vibrating mirrors $v m$, 1, 2, and 3, and from this are reflected to the photographic drum F or to the synchronous mirror $S M$, from which they are reflected on to the surface T where they may be viewed or traced.

In front of the photographic film is a cylindrical lens $C L_1$,

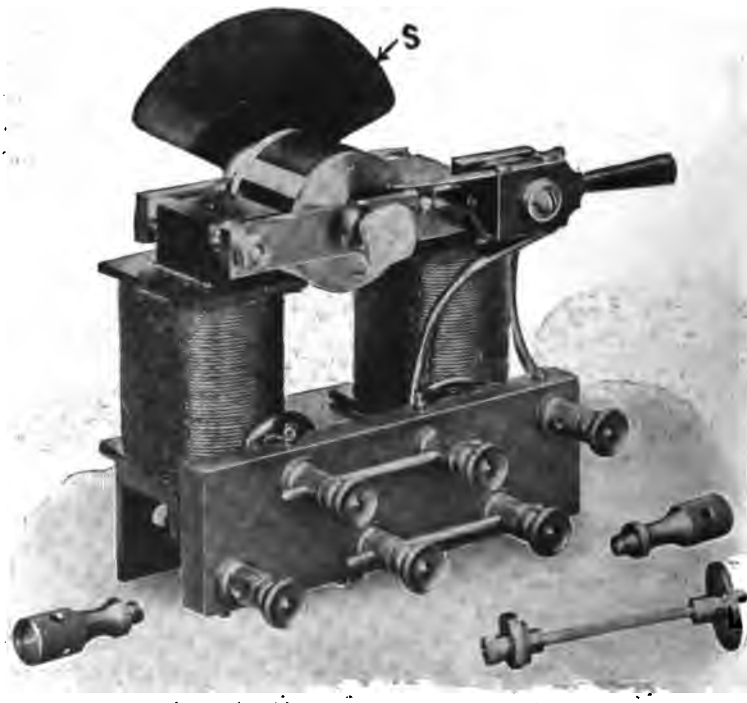


FIG. 27.—Oscillograph. —Synchronous Motor.

and in front of the synchronous mirror a cylindrical lens $C L$. The synchronous mirror and its cylindrical lense are removed from the path of light when photographic record is to be made, in a manner which will be described in connection with the general arrangements for viewing the waves.

The light from the arc lamp is intercepted by the shutter $S H$, which is operated by electrical contacts by the arrangement shown at the left of Fig. 2[illegible]. The shaft which operates the shutter contacts is also arranged to drive the photographic drum and usually receives its motion from a small electric motor. the motion of which is transmitted from a cone pulley through a counter-shaft. By this means speeds of from 6 to 600 revolutions per minute of the drum may be obtained, with a wide range of intermediate values. The photographic drum is shown in Fig. 26.

The shutter operating mechanism is so arranged that the shutter *S H*, Fig. 29, is open during one revolution of the drum,

FIG. 28.

and for this purpose two devices are employed. In the first the shutter is opened just after passing the joint in the film and is closed when the joint is again reached. The cylinder which carries the contacts by means of which the shutter is opened and closed may be advanced by means of spring pin and holes in the ends of the cylinder, so that time required by the shutter to open may be allowed for. The adjustment required varies with the speed at which the photographic drum is rotated. For obtaining records where it is not possible to wait for the joint in the film before the exposure is made, the second device has been provided; this opens the shutter at any required instant and allows it to remain open for one revolution.

For viewing recurring waves the arrangement shown in Fig. 27 and Fig. 28 is used. By means of the lever *L*, shown in Figs. 21 and 28, the lens and vibrating mirror are lowered into the path of light and the shutters, which cannot well be shown, but which close the opening to the tracing surface *T*, are opened. The synchronous motor and mirror driven by it then being in operation and the shutter *S H* open, to allow the light to pass along the path indicated, the wave is visible on the surface *T*.

The vibrations of the mirrors having been adjusted to have

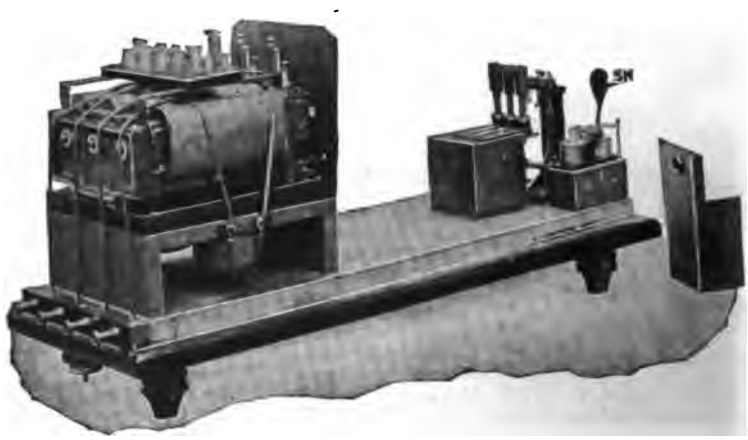


Fig. 29.

a suitable amplitude, and the synchronous mirror being moved through a suitable angle during one complete cycle, the point of light on the surface *T* will move through a path equivalent to the figure obtained when the wave is plotted to rectilinear co-ordinates. As the mirror returns to its original position the shutter *S*, Fig. 27, cuts off the light and again allows it to pass when the mirror again moves in the direction first indicated. This prevents the admission of light to the surface when the mirror is not moving in the proper direction. Fig. 29 shows the internal arrangement with cover removed.

Given an apparatus similar to that just described we can see and record waves of current and electromotive force in any circuit which can furnish sufficient energy to operate the device, and the frequency of which is not too high to be correctly recorded by it. In general it may be said that a period in the neighborhood of 5000 is sufficient for handling most phenomena which occur on circuits up to and including those having a fundamental frequency of 125 cycles.

The tests in which such a device has been found useful are of such great variety that it is possible to allude to them only briefly and in a general way. The following records which have been taken will, in connection with the description given with each one, show the field of usefulness of the instrument better than it can be described in words.

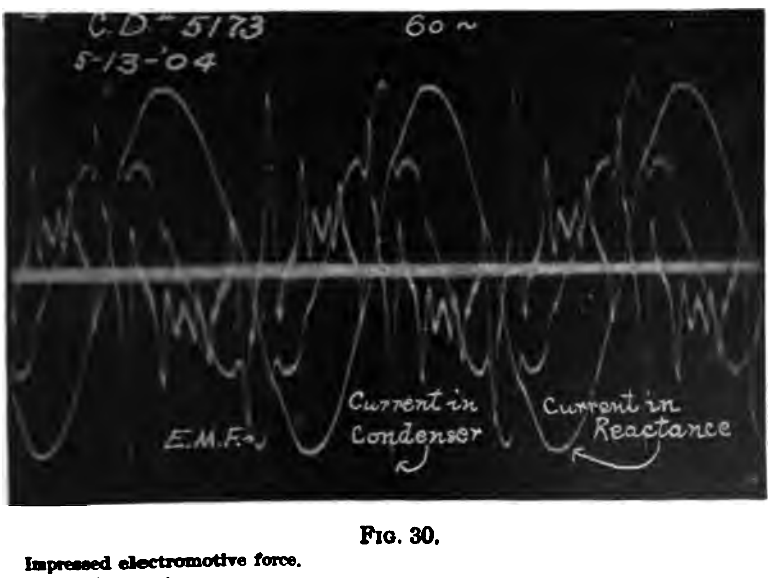


FIG. 30.

Impressed electromotive force.
Current in reactance
Current in condenser. Reactance and condenser connected to same electromotive force. Reactance without iron core. All three waves recorded simultaneously and having common zero. In Fig. 34 the records were made simultaneously but with separate zero lines.

Fig. 81.—Inductive rise of pressure in direct-current motor. Shunt field opened by quick-break switch.

Fig. 82.—Shows condition of critical damping. The vibrator was connected to a direct-current source, which was opened and closed several times. Excessive damping would be shown by a creeping of the record after each closing or opening of the circuit and insufficient damping by overshooting.

Fig. 33.—Current rush in primary of 1875-kw. transformer, secondary circuit open. The film was turned through several revolutions and the circuit was closed three times or more. Instantaneous rise of the current is obtained, depending on the point in the alternating-current wave at which the circuit is closed and the previous condition of magnetizing in the transformer core; 25 cycles, 2300 volts.

Fig. 34.—Short circuit applied to large alternating-current generator and opened by automatic oil-switch. The film shows the current and pressure of the short-circuited phase and the reaction of the armature current on the direct current in the generator field; 25 cycles, 2300 volts.

Fig. 35.—17 800 Amperes and 600 volts broken by automatic circuit-breaker.
The record shows the gradual rise of the current up to the breaking point and more rapid return to zero. Vibrator attached to shunt in circuit with main current.

Fig. 36.—Spoken word "Oscillograph".
Vibrator was connected in secondary of small transformer, primary of which was connected to battery and telephone transmitter.

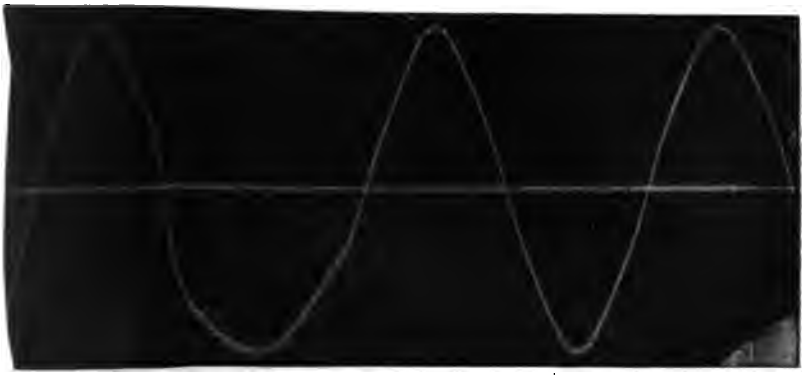


Fig. 87.—No load pressure wave, 3750-kw., 2800-volt, 25-cycle alternator.

The following is a list of references relating to the subject; these may be of interest.

Some of the devices described in the articles have not been referred to as it was not the intention to touch on anything which was not distinctly related to practical work. Given conditions to be met which are different from those which prevail at the present time, some of these devices might be of the greatest practical use as they have already been in special investigations. The Abraham Rheograph and the Braun Tube are deserving of special mention.

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MAINTENANCE OF METERS.

BY W. J. MOWBRAY.

To the company supplying electric energy which is measured by meters and charged for accordingly, the maintenance of meter accuracy is of supreme importance. Losses in other apparatus become insignificant when compared with the loss of revenue from meters that are allowed to follow their natural tendency to run slow. For example, in a steam boiler a drop of 10% from normal efficiency would be detrimental to approximately the same percentage in the single item of the cost of coal, whereas in the metering system it would be 10% of the entire gross revenue to which the supplying company is legitimately entitled. Furthermore, if a metering system did actually deteriorate so as to record 10% less than the true energy, this loss would by no means remain constant; it would continue to increase.

Periodic overhauling is the obvious and generally adopted means of maintaining meter accuracy. Overhauling—a strict examination for correction and repairs—is efficient in proportion to the cheapness and accuracy with which it is done and to the permanence of the result. Means of making the result as permanent as possible will be considered later. Attention will first be called to a portable test-meter used by the writer for the accurate and almost instantaneous determination of the percentage by which a meter is running fast or slow.

This meter is similar to a customer's ordinary watt-hour motor-meter in that it has a rotating armature, each revolution of which represents the passage through the meter of a certain number of watt-hours. A rotating armature in a test-meter is advantageous in that its revolutions and those of the meter under test are directly comparable, making it immediately apparent whether the latter runs faster or slower than it should. Another advantage is that the comparison of revolutions is quite unaffected by fluctuations in pressure or current which would tend to render an indicating instrument unreadable because of the swinging of the needle.

The ampere capacity of this test-meter can be varied at will by means of a plurality of windings. To understand the utility of an adjustable carrying capacity it should be noted that a meter generally operates most accurately at full load and that as the load is decreased the meter is likely to become inaccurate. This is because it is impossible entirely to eliminate friction from the bearings and contacts of a meter armature, or to keep this unavoidable friction at a constant value. Suppose this friction to vary sufficiently to cause an inaccuracy of one per cent. at full load and full torque, then at one-half load and one-half torque the proportion of this same friction variation to the torque would be doubled, and the inaccuracy would also be doubled. Similarly at one-quarter load the inaccuracy would be increased four times, and at one-tenth load ten times. Suppose it be required to test a meter of 15-ampere capacity. On full load a corresponding 15-ampere winding of a test-meter could be used with a high degree of accuracy. On a light load, however, say 1.5 amperes, both meters would be subject to the serious light-load inaccuracy above noted. In the latter case an adjustable ampere capacity in a test-meter can be utilized by changing say from a 15-ampere to a 1.5-ampere winding, thus restoring the test-meter to full-load conditions of torque and accuracy. Meters of widely varying capacity have to be tested in practice, and a test-meter should accordingly be equipped with at least three different current windings and two different pressure windings.

A test-meter in use by the writer can be started or stopped at will by means of a switch, the meter under test meanwhile rotating continuously; in practice this test-meter is allowed to rotate only during the interval that the meter under test takes to make 1 or 10 revolutions. A comparison of the watt-hours corresponding to the latter revolutions with the true watt-hours as recorded by the test-meter shows instantly whether the rate is fast, slow, or correct. Explanatory of the relation between armature revolutions and watt-hours, it may be noted that integrating watt-hour meters have what is called an armature or disk constant. Generally speaking, this armature constant in any particular meter is the number of watt-hours corresponding to one armature revolution. Hence, the number of revolutions multiplied by the constant gives the watt-hours. If either of these factors—revolutions or constant—be made equal to 1, 10, or 100, the multiplication necessary to obtain the watt-hours resolves itself into a mere shifting of the decimal point. Accordingly, in the case of the meter under test, 1 or 10 revolutions are taken, and therefore the constant of that meter with proper location of the decimal point, becomes equal to the recorded watt-hours. The true watt-hours can be similarly obtained from the revolutions of the test-meter, since in the latter the *constants* are arranged decimally; and it can at once be seen whether the consumer's meter records more or less than the true energy.

Accurate and cheap calibration is, however, of comparatively little value if a meter soon returns to its former condition of inaccuracy, therefore in old meters appliances should be provided for increasing the permanence of calibration. Owing to the advance of the art, modern meters are fairly reliable, but their improvements are not generally applicable to the older forms. Suitable appliances, have, however, been developed, chiefly by the large operating companies, with the result that meters manufactured some ten years ago can now be made at least equal in efficiency of operation to the most modern ones. Among the most prominent of these appliances are the adjustable friction compensating coil, the cupped, or concaved, diamond bearing, and a means for correcting the disposition of the drag-magnets relative to the field coils.

The friction compensating-coil in operation carries a current of constant value, and can be moved into such proximity to the rotating armature that its accelerating effect exactly neutralizes the retardation due to friction. Commutator friction increases very rapidly when a meter is first put in service, but after a time it assumes practically a permanent maximum value. If at this time the compensating device be adjusted, a great part of the inaccuracy due to commutator friction will be permanently removed.

The cupped diamond bearing is partly the result of what has been termed by Lockwood the " cross fertilization of the sciences." Diamond being the hardest known substance, was long recognized as the most desirable bearing material, but it seemed impossible to get any one to grind out a nicely curved and highly polished cavity in a diamond to receive the lower end of the vertical steel shaft. In the search for a new optical effect, however the lapidary art has so developed that no serious difficulty is now experienced in satisfactorily cupping the surfaces of a diamond. As a meter-bearing it seems to embody the ultimate degree of perfection, the initial friction being a minimum and the wearing qualities a maximum. It is especially necessary in the old types of commutator meters with their very heavy rotating elements, because in these meters the material next in hardness to the diamond and which is generally used sapphire, quickly breaks down in service.

The object of changing the disposition of drag-magnets is to prevent meters from running fast after being subjected to the tremendous currents resulting from short circuits. In old meters the stray flux thus produced found a convenient path along the drag- or braking-magnets; this tended to demagnetize them, thus causing the meter to record more than the true energy. It has been found that by changing the disposition of the magnets so that the stray flux traveled *across* instead of *along* them, this effect was minimized, and manufacturers changed their designs accordingly. Old meters can now be modernized in this respect by removing the magnets and attaching additional small bases thereto, the drilling of these new bases permitting the magnets to be remounted in the meter at right angles to their former positions.

In conclusion, it may be stated that this general system of overhauling has been productive of excellent results, and is coming into extended use as the importance of maintaining meter accuracy becomes more fully realized.

Discussion on Measuring Instruments.

President Lieb: The papers presented this evening represent an interesting series relating to indicating and recording instruments. This is a subject in which we are interested, either as buyers or sellers of current, or engaged in making tests, or conducting investigations in which this class of apparatus is used.

One of the most interesting questions in connection with supplying electricity is the proper metering of the product. There is not the proper public confidence in the systems of metering ordinarily in use, to which the results obtained would seem to entitle them; and there is also, unfortunately, no adequate legislative provision as to what really constitutes an accurate meter.

It is obvious that when a meter is tested under laboratory conditions, with ideal surroundings, it is possible to eliminate vibration, stray fields, variations in current strength, and other factors that affect the accuracy of the test. It is also possible to eliminate the personal equation and the errors of the test itself, and greater accuracy is to be expected and can be attained than when one undertakes to test a meter in a dark cellar, probably by candle light, located high on the side walls, or in other places difficult of access, and with a testing current that is influenced by a neighboring elevator motor and subject to variations of current and pressure—in general where the conditions for conducting the test are wholly unfavorable.

Hence, there is considerable variation as to the requirements that can be imposed or the results that can be expected in a meter test made on a customer's premises, as compared with a test in the laboratory. It is somewhat difficult, on the other hand, to persuade a customer that a test on a meter that has been removed from his premises and the influence of local conditions is a satisfactory one. He feels that the meter should be tested under the conditions and in the location in which it is to be used.

Unfortunately, as I have said, there is no legislative provision or municipal regulation, or even accepted custom, which clearly defines what shall be the conditions of test to obtain commercial accuracy, and this is the more remarkable when one considers what large amounts of money depend on the indications and registrations of such instruments. We hear from time to time about erratic meter performances, not only in regard to the accuracy of the electric meter, but also as to the indications of its elder brother, the gas meter. It is often difficult to reconcile the opinion a customer holds in perfect good faith, as to the amount of current he believes he has consumed, with the actual indications of his meter; and I know of no more difficult task than that of satisfying a customer who believes that in a certain month he has used only half as much current as in the preceding month, and yet receives a bill of substantially the same amount, as shown by the meter. On the one hand one is face to face with a question of fact, as registered by the best instrument that is available, and on the other hand with a matter of belief, which may be the result of personal observation, or, what is more likely, a general impression as to what the conditions of use may have been.

We all know, as has been pointed out in the papers, that the tendency of most recording apparatus in use is to run slow. As to the extent to which apparatus of this character runs slow under commercial conditions, it is difficult to state; but the ordinary types of commutator meters must, of necessity, considerably under-record. To begin with, it is difficult, owing to the extension of installations and the maximum demand which each installation is likely to make upon the street service, to obtain a total meter capacity that is much less than the total installation capacity connected with the street mains. It is not difficult to obtain a satisfactory ratio in the case of residences, but it becomes difficult in installations that have variable demands and in which sudden changes in current strength and unusual demands must be taken care of. For this reason it is considered good practice so to proportion the ratio of meter capacity to installation, that some meters may be burned out from time to time; and it is safe to infer that a supply system in which no meters are ever burned out, is "over-metered"; the rate at which meters burn out gives a rough indication as to whether an economical policy is being pursued in selecting the appropriate sizes of meters.

Assuming a ratio of meter capacity to connected installation capacity of 1 to 1, we find that under the conditions of heaviest load on the system, the meters, on the average, will then operate at only 30 to 50 per cent. of their capacity; and since the heaviest load on a large system lasts for little more than one hour a day, for only a few months in the year, and during the months of light load, and for considerable periods of the day and night the load carried is insignificant, the meters will practically work under conditions where the load is considerably under 10 per cent., and probably not over five per cent. of their capacity. Now, we know what the results are of operating meters on loads well under 10 per cent. of their average capacity.

To get an approximate idea of the conditions that may be expected on a large system, I will give a few facts as to commercial accuracy of meters in every-day service. The figures refer only to commutator meters. In a large meter system that is kept in good condition, the records show that of one thousand meters tested at random on the customers' premises, after they had been in operation for about one year, 75 per cent. were between plus five and minus five per cent. of absolute accuracy; and of the remainder approximately twice as many were slow as fast; the average accuracy of all the meters was 98.12%; and only 2.7% of the whole number were more than 10 per cent. fast. The tests were made under what may be considered full-load conditions; that is, at 50 to 100 per cent. of the meter capacity. Under light load conditions of 10 to 25 per cent. of the meter capacity, 50 per cent. of the meters were between plus five and minus five per cent., and of those outside of this range, four times as many meters were slow as fast.

Those who have to do with apparatus of this kind should carefully consider the conditions under which results are obtained, and in case of doubt should thoroughly investigate these conditions before questioning the accuracy and reliability of the metering instruments.

Caryl D. Haskins: I wish to call the attention of the Institute to some valuable official statistics which are now available, covering the real facts as to the accuracy of the electric meter, and also of the gas meter. For several years the State of Massachusetts has been conducting on the consumers' premises official tests upon electric and gas meters against which a complaint of inaccuracy had been made. The average error of all the electric meters tested, in 1904, in the State, was 1.08 per cent. at full load, and less than one per cent. at one-fifth load, which was 50 per cent. better than shown by the tests made on gas meters. These figures are more flattering to the meter than those that the President has cited. The reason for that is, the layman does not appeal to the State unless he thinks his meter is fast.

It is my impression that Mr. Nies has assumed conditions more adverse to accuracy than those that usually prevail. I suspect also that some of his statements in regard to transformer accuracy might not accord with general observations that have been made on devices of that kind. The same statement applies also to the meters—the aging of the iron in the meters.

Mr. Cox has mentioned the importance of studying the relation of stray fields about the switchboards to the instrument accuracy. This has not been studied enough. There are innumerable switchboards in the United States where the effect of stray fields almost destroys instrument accuracy. He has also referred to the inaccuracy of indicating instruments at the very low reading of the scale. A safe rule to adopt is that an indicating instrument should not be installed of such a capacity as to call for the acceptance of readings below the one-fifth scale. That area might almost as well be left blank.

There is scarcely any electrical phenomenon the study of which will not be made twice as easy by the use of the oscillograph or of the kindred devices of which it is a type.

I think Mr. Mowbray errs in attributing at least some, perhaps many, of the latest improvements in integrating instruments to the operating companies. The manufacturing companies have been more largely concerned in making such improvements than have the operating companies. They naturally should be.

EDWARD B. ROSA: I have not yet made use of the oscillograph, but am familiar with the point-by-point process and have used one of the instrments that Mr. Robinson describes for that work. Some experiments with the curve tracer were made at the Bureau of Standards last summer to illustrate the possibility of attaining great accuracy in the determination of the wave-forms of alternating currents. The dynamo used was built to have, as nearly as possible, a sine wave; it was constructed by the General Electric Company. The wave when drawn looks so nearly like a sine wave that one would not be able to identify any harmonics by inspection. The current was used in the absolute determination of inductance; that is, the value of our standard inductances, and it was necessary to determine the wave-form with the greatest possible accuracy. In order to do this three circuits in parallel were used, all supplied with the electromotive force of the machine; one circuit was inductive, another had non-inductive resistance, and the third contained a condenser. The condenser, of course, would amplify the harmonics. It is obvious that if the forms of the three waves of current in the three circuits, respectively, are plotted, one can be derived from the other; that is to say, from the form of the condenser current, after analyzing it and determining the harmonics, the exact value of the harmonics of the electromotive force to produce that current can be calculated. Having the electromotive force, the form of current which would flow into and through a certain inductive circuit can be calculated; that is, the harmonics in the current curve can be derived directly from the electromotive force curve and also from the condenser current curve.

These curves were analyzed and computed in this way: the current first from the electromotive force, and second from the condenser current to see how closely they checked, with the following result: the fundamental was 46 738, the average of six separate determinations. The third harmonic had a value of a little less than two per cent. of that—0.866 is the average—and the average variation from the mean was about two per cent.; that is, about two per cent. of the component of the wave. The fifth harmonic had an average value of 0.056 as compared to 46 720—a little more than one-tenth of one per cent.—and the variation from the mean was very small. The seventh harmonic was 0.040, the ninth 0.008, the eleventh 0.004, and the thirteenth 0.004, out of a total of 46 738; that is, the ninth, eleventh, and thirteenth had values of only about one in 10 000 of the fundamental, as determined from the analysis of the electromotive force waves.

The analysis of condenser-current waves gives still more accurate results, for the reason that when the harmonics are determined and divided down to obtain the harmonics of the current, the errors in drawing the curves and making the analyses are themselves divided down in a similar ratio. The results agreed closely with those which precede, but the independent determinations agreed more closely among themselves, and gave, for example, in the case of the third harmonics, an average on the basis of the three observations, of 0.874 instead of 0.866, which is a difference of one in 100 in the value of the harmonic, which latter is only two per cent. of the total. If that were drawn out on a curve five inches high, for example, the error in the determination would amount to about one-thousandth of an inch. In order to get that degree of accuracy it was necessary to eliminate the errors of the paper on which the curves were drawn, and those due to the slight inequalities of the potentiometer wire. Then these independent analyses were made, which agreed with surprising accuracy, the ninth, eleventh, and thirteenth harmonics being practically absent; that is, all the six separate analyses agreed in showing that the magnitude of these highest harmonics were not more than one or two parts in 46 000.

I would like to emphasize one point in Mr. Cox's paper in regard to the inadvisability of using switchboard instruments as precision instruments for testing. It is hardly necessary to say they should not be so used, but nevertheless they are frequently employed for that purpose. We have recently tested at the Bureau of Standards a series of four current shunts which had been used in the test of an important electric railway station, the capacities of which were from 1 000 to 3 000 amperes, and we were requested to get their correct values. Their temperature coefficient was considerable, the thermoelectric effect was pronounced, and the design was such that on certain contacts the variations in the resistances at the contacts of the leads would change the distribution of current in the terminals of the shunts and so change the potentials at the ends of the shunts. In one particular case, which was investigated, several values were found by connecting up and disconnecting that varied eight per cent. from the minimum to the maximum value, and yet the shunt had been used on a test of some importance. Other shunts were better, and yet showed a difference of two or three per cent. between their capacity values at full load, and values at light load the current being continued for some time.

The suggestion to correct the instruments by inserting a known resistance in the bus-bars, is valuable and should be followed up. It is perfectly practicable, if arranged in advance; to connect in a standard resistance in order to calibrate the instruments of a switchboard. The standard resistance may be sent away to be tested, and thus be used at intervals to test instruments, no matter how high the range of current might be.

Standard current shunts should be submerged in oil or otherwise kept cool, or they should have large radiating surfaces. They should be made of materials having a very small thermo-electric coefficient. One of the most important precautions is to have the design such that a variation in the contacts where the current enters and leaves the shunt shall not so alter the distribution of current in the terminals of the shunt as to alter the difference of potential between the potential terminals. That can be done, but is not generally done.

As to potential transformers, my experience is that they are more accurate and more reliable than is popularly supposed, provided the load on the secondary is constant, or provided the transformer has been calibrated and its ratio of transformation with a given load is known. The chief cause of variation of the ratio of the transformer is the varying load upon it; whether it is supplying current to one instrument or to two instruments, and whether the instrument is taking more or less current.

CLAYTON H. SHARP: The danger of the influence of stray fields on the accuracy of indicating instruments placed on a switchboard is a real one. The errors so introduced may be quite large. The influence of stray fields is likely to be much greater upon alternating-current instruments without iron than upon direct-current instruments of the permanent-magnet, moving-coil type. The remedy proposed by Mr. Cox is a radical one, but it is hardly applicable to instruments at present installed and in use. The important thing, as far as such instruments are concerned, is to check their accuracy in position and under working conditions.

The difficulty with the ordinary methods of checking by comparison with standard instruments is that the standard instruments themselves may be so affected as to yield erroneous results. This difficulty may be surmounted in two ways: the first way is to use an instrument that is unaffected by stray fields in the work of making checks. The potentiometer is such an instrument, which, in a simplified form, has been introduced into central-station practice for this purpose with good results. The second method is to use an alternating-current instrument as standard. The moving coil of the instrument is first connected in circuit, and the position of the instrument determined in which the moving coil is unaffected, and readings are taken with the instrument in this position. This method of eliminating the influence of outside fields has been pointed out by Mr. Thos. Varley.

Mr. Cox mentions the increasing use of current transformers. It is a good plan to get a determination of their ratio of transformation before installing them permanently. Inasmuch as the ratio changes with the degree of saturation of the iron, it should be measured with different values of current. By having the results of such measurements on record, it is necessary only to check the indicating instrument when it is desired to determine the accuracy of the measuring devices at any future time. This error, combined with the transformer error, gives the total error in measurement. The measurement of the ratio of transformation may be made with the aid of two ammeters or with a Kelvin balance and an ammeter, and can be carried out on a low-tension line—a consideration of importance. When used with integrating meters the errors of series transformers can largely be compensated for by adjusting the meter.

The paper by Mr. Robinson relates to a subject that has not previously been discussed by the INSTITUTE. I am able to speak from personal experience with the wavemeter and oscillograph, instruments of the sort described by Mr. Robinson.

The wavemeter is an exceedingly practical instrument, and is to be preferred to the oscillograph for recording and studying periodically recurring phenomena, such as alternating-current waves, because the instrument is easy to manipulate and gives a result on a larger scale and hence more easily studied. In cases where it is desired to analyze alternating-current wave-forms to determine the harmonics present, it is advantageous to dispense with the photographic attachment and to substitute a voltmeter or millivoltmeter for the galvanometer. The contact brushes are moved forward one notch or five electrical degrees at a time, and the indications of the voltmeter are read for each notch. There are 72 notches, so that a series of observations of this sort covers an entire wave. The values so obtained are at once available for making the computations for the analysis of the wave-form. They may also be plotted in rectangular coördinates, and the wave-form thus be reproduced to any desired scale. A set of observations of this sort can be made in a few minutes.

In my own work I have attached a strip of millimeter paper to the ground glass of the photographic attachment, so that the measurements can be made by using the galvanometer and spot of light already provided, and the point-by-point record or the photographic record can be made without changing any electrical connections.

The ondograph of Hospitalier is an extremely convenient instrument for recording alternating-current waves, being small, self-contained, always ready for use, and easy of manipulation. It does not, however, have the range and the flexibility of the wave-meter described by Mr. Robinson. Professor Rosa's curve tracer, while capable of yielding very accurate results when its contact maker is directly connected to the shaft of the alternator that is being studied, would, it seems to me, practically be no more reliable than the wave-meter used with a voltmeter, as indicated, provided the contact of the curve tracer is driven by a synchronous motor, as in the case with the wave-meter.

As to the oscillograph, as nearly as I can find out it is difficult to use and certain to get out of order sooner or later by the rupture of the vibrating strips or by the mirror becoming injured or detached therefrom. This being the case, it is of great importance that the oscillograph should be so constructed that the user of it may be able to repair it when it meets with an accident.

I have studied the construction of two very well known foreign makes of oscillographs and I believe that no man of ordinary skill could replace in them a broken strip without the expenditure of a great deal of time and patience, and perhaps not at all.

The oscillograph that Mr. Robinson has designed can, on the contrary, be readily repaired; as I have found out by experience, a broken strip can be replaced by a new one and a mirror attached in a very few minutes. The rupture of a strip due either to overheating or to undue tension is no longer a serious matter. The manipulation of this oscillograph is in other respects quite simple, and the results obtained with it seem to be all that are required for ordinary testing. I have obtained satisfactory records of capacity currents of a frequency as high as 3 500 cycles per second, and an instrument that will do this has as high a frequency as is required in commercial work. For the purposes of the physical investigator it might sometimes be desirable to have an instrument of greater refinement and of higher natural period, but for the ordinary purposes of the electrical engineer it would be a disadvantage to attempt too much in the way of high period, as this would involve reduction in size and increase in delicacy of the moving parts of the instrument.

The means whereby the oscillograph record is made visible is of great utility, because by its aid changes can be watched as they occur. Engineers have felt the need of a more intimate knowledge of the phenomena which takes place in lines, in generators, and in motors; the oscillograph is the only instrument by means of which these phenomena can be studied to the best advantage. The production of a practical oscillograph, which can be used without making an extended special study of this form of instrument, is therefore a valuable achievement.

Referring to Mr. Mowbray's paper, it has found its way very extensively into the meter-testing practice of a number of large electric lighting companies. The principle on which it works is an excellent one, not only for the attainment of accuracy in testing customers' meters but also for saving time and expense in doing so.

A. R. EVEREST: The subject of transformers used in connection with instruments has been referred to several times this evening. Dr. Sharp suggests the desirability of calibrating the current transformer before it is put into service, in order that complete data may be on hand regarding it for future reference. This is undoubtedly desirable in connection with the apparatus of a standardizing laboratory, but I hardly think Dr. Sharp intended to suggest its necessity in the case of a transformer employed for switchboard use; at least when such transformer is of a design known to introduce errors of less than one per cent. throughout the useful range of the instrument with which it is employed.

As to the potential transformer, Professor Nies says: "A potential transformer differs in no radical way from an ordinary transformer; its operation is similar and is governed by the same rules." He refers to the fact that the accuracy of the transformer depends on the regulation drop, which he suggests varies with the load on the secondary. This gives an erroneous impression. A potential transformer, especially one designed for high voltage and low frequency, takes a very large exciting current in proportion to its output, and since the impressed voltage is practically constant that part of the regulation drop that is due to exciting current is also constant and may be taken care of by a permanent correction in the ratio of the winding. Professor Nies, for illustration, mentions a transformer having total regulation drop of 1.6%, and says: "All instruments supplied by such a transformer at full load will read 1.6% low." As a matter of fact, with proper ratio correction for the constant drop due to excitation, the ratio variations due to changes in load would be well below one per cent.

Another characteristic feature of the potential transformer Professor Nies has not mentioned, namely, its extremely low reactive drop due to the fact that the output of such a transformer is always very small for its size, as compared with a transformer designed for lighting service. The reactive drop in a potential transformer will usually be a small fraction of one per cent.

Referring to the question of phase displacement, Professor Nies suggests that the displacements produced by the current and potential transformers are in the opposite direction, and therefore cumulative. This disagrees with experience, both in calculations and tests on the designs employed for instrument transformers. In the potential transformer the exciting component being relatively large, and the reactive drop small, the impressed primary voltage lags behind the counter electromotive force; that is, the reversed secondary voltage leads with respect to the primary. In the current transformer, since the primary current contains a magnetizing component that is not present in the secondary, the latter reversed leads the primary. Thus both phase displacements are in the same direction and tend to cancel each other. Since the magnitude of either is usually not over one degree, the resultant error is very small. If the potential circuit were derived from a heavily loaded transformer having large reactive drop, or in other abnormal cases, the reverse conditions would be found; but with proper apparatus, employed under the conditions for which it is designed, the errors introduced by current and potential transformers will be much smaller than Professor Nies' paper would lead one to expect.

W. H. Pratt: In supporting a particular method of metering which is adapted to a few cases, Mr. Nies seems to place the general problem of polyphase metering in an incorrect light. The matter of the transformer has been already well discussed, but a word may be added as to the stray field of one transformer influencing another transformer. It would be an almost neligible effect.

The case cited of errors introduced by variation of the lag adjustment of the meter gives the impression that errors of large magnitude are likely to occur, whereas in fact they rarely occur in anything like the magnitude shown by the curves.

As to the use of two meters for metering a polyphase circuit, it is true that when two meters are used with a circuit that is lagging, one meter will take a much higher load than the other, and will, therefore, register at a higher percentage accuracy. However, when the fact that the meter giving the lower accuracy has the lighter load is taken into account, it will be found that the total error due to friction is uninfluenced by the distribution of the load. The friction error of a meter may better be considered as a constant than as a percentage error. For instance, a meter inaccurate on account of friction to the extent of two per cent. at five per cent. of load full, gives therefrom a constant error of 0.1 per cent. of its rated capacity irrespective of its load. This will hold good for the light-load error in any motor-meter, and hence in the use of two meters for a polyphase load the distribution may be ignored down to the point where one meter should stop.

The same general line of remarks applies also to the matter of phase displacement. In a pòlyphase meter with equally incorrect phase adjustment in both elements, the total effect on registration is the same as in a single-phase meter with the same error in adjustment. In the case of equal and opposite errors in phase adjustment of the two elements, there is only a very slight error, and a small correction factor proportional to the sine of the lag angle.

I cannot agree with Mr. Nies that a polyphase meter is more difficult to calibrate than two single-phase meters; in many cases, where it is only a matter of checking, it is certainly much easier to calibrate the former; and, further, there is only one running mechanism to examine and one set of readings to take; the two elements can be thrown in series as easily as two or three single-phase meters can be thrown in series for calibration.

The use of single-phase meters would, of course, entail the use of three currents and three potential-transformers on a circuit such as described. And it is an open question whether the same amount of effort that would have to be expended on the three meters could not be more judiciously employed in other directions.

G. C. Van Buren: I wish to mention a condition which was recently brought to my attention for correction of the two-single-phase-meter arrangement. The installation consisted of one three-phase, 220-volt motor and one single-phase, 220-volt motor. Both meters rotated in the proper direction when the three-phase motor alone was running; upon starting the single-phase motor one meter would decrease its rate of speed, and by varying the load upon the single-phase motor this meter could be made to come to rest and reverse its direction of rotation.

A. H. Ackermann: In a certain central station there are some 15 or 16 balanced three-phase high-tension generator meters. Considerable difficulty was encountered in keeping them accurate on account of the sapphire jewel bearings. From the meters the circuits were split into some 30 feeder meters, the registration of which was seldom within five or ten per cent. of the correct readings as observed by the system operator. After all these meters were equipped with cupped diamonds the errors were considerably diminished and the average error for the past eight months has not exceeded 1.5%.

There is a point in Mr. Cox's paper which needs emphasizing—that suitable arrangements should be provided on every switchboard for testing the meters. The maker of the switchboard puts it up, and is done with it; the man that sets the meter is through with it after he has put it in place, but the meter department begins its work from that time on, and periodically tests the meters, say, once a month, once in six months, or once a year.

The 45 meters before mentioned have been equipped by the operating company with short-circuiting switches for the series transformers and double-throw switches for the potential transformers to disconnect them from the high-tension system and for the purpose of testing them with rapidity as secondary meters. Formerly, two men tested one or two meters in a day under the old system of disconnecting from the back of the board; now the work is expedited through the employment of the switches, so that it is possible for two men to calibrate 10 or 15 meters in a day. It is practically the same in low-tension work. In New York about six to eight meters are tested per day; this is the average for all classes and of meters in use, including large capacity meters. The average would be considerably higher if all the meters were of small capacity.

The greater part of the time required for testing meters is consumed in getting the standard instruments in position, disconnecting the leads, and work of a similar description, all of which could be avoided by providing convenient devices for inserting the standards. There are 50 1 200-ampere meters in use in New York, besides two 3 000-ampere meters; tests of meters of such large capacity naturally reduce the average rate of making tests. I have investigated the method of testing by calibrating the bus-bar to obtain a definite drop at a suitable load, and connecting therewith a milli-voltmeter to read current; this method eliminates the laborious operation incident to insertion of a standard shunt; the test can be accomplished in about one-fifth of the time needed with the present method.

The figures quoted by President Lieb on the results of 1 000 periodic tests were made at the expiration of one year, and as he stated, included tests on meters as they came, irrespective of size, capacity, condition, or any other influence. I have in mind also another set of tests that were made on large-capacity meters, all of which were equipped with the so-called flat-diamond jewel bearings, which have been superseded by cupped-diamond jewels. The tests showed the extent to which the accuracy of a meter is affected by the character of the bearing and resulting friction. The figures were increased about 50 per cent. with the old flat-diamond jewel over those obtained with meters provided with sapphire jewels. Those within plus two and minus two were considerably more—some 25 per cent. more at full load—than the figures for the sapphire jewel. The old meters with their heavy moving elements must be provided with some suitable means for decreasing friction; the cupped-diamond jewel seems to be the solution of this vexatious problem.

Discussion on Measuring Instruments at Philadelphia, May 8, 1905.

President Lieb: I know that if there is a spirit pervading the administration of the Institute—it has also pervaded previous administrations—it is the feeling that the Institute is not merely a body of electrical engineers living and working in New York, but that it is a national body, that it represents and has at heart the interests of electrical engineers all over the United States. I feel that the central organization is certainly alive to its obligations and to its duties to the local organizations, as representing a very much larger constituency than merely the local membership of New York. Perhaps this feeling of greater interest which the members removed from New York should have will be aroused when our engineering building shall have been completed.

Work is about to begin on this building; the contracts are about ready to let. I think we shall shortly have a worthy monument to the engineering professions in which the electrical engineer—the youngest profession—has had a very fortunate and proud part in developing and bringing to a fruition.

As representing the parent organization of the Institute I bring to the Philadelphia Local Branch its warm salutations, and wish you continued success and continued activity along the lines which have already produced such good results in Philadelphia.

Ralph W. Pope (Secretary of the Institute) addressed the meeting upon the condition of the affairs of the Institute and its future prospects.

Chairman Pike: The papers that were read at the last meeting of the Institute in New York are before you for discussion to-night. I shall ask Mr. J. F. Stevens to give a short discussion of Mr. Cox's paper.

J. F. Stevens: Mr. Cox says that in the case of the shunt ammeter an instrument best adapted for laboratory conditions would have a shunt loss too great for switchboard service, and one designed for switchboards would have temperature errors too great for laboratory use. I do not agree with this statement. In the first place the laboratory ammeter, being an instrument of considerably greater delicacy, operates, as a rule, with a smaller potential drop in the shunt than is the case with a switchboard instrument. It is not unusual to find laboratory instruments operating on a drop of from 25 to 50 millivolts at full scale, while in switchboard work the customary drop is from 50 to 100 millivolts. Laboratory and switchboard shunts do not differ in materials of construction, and in both cases it is customary to wind the moving coil of the millivoltmeter with copper wire. Since a correctly made shunt is constructed of material having practically zero temperature coefficient, the increased heat in the switchboard shunt, made necessary by the increased drop, does not interfere with the accuracy of the ammeter's indications. Temperature errors may be larger in switchboard ammeters than in laboratory ammeters but this is simply because the temperature of the engine-room cannot be regulated as conveniently as the temperature of the laboratory.

It is true that ammeters should be selected of such a range that the normal indications will be at about two-thirds of the maximum reading. But Mr. Cox intimates that indicating instruments are unreliable when readings are taken in the lower part of the scale, and Mr. Haskins, in his discussion, states that indicating instruments are substantially worthless at low scale readings. I do not view the matter in the same light. The percentage accuracy is the same throughout the working range of any instrument. An instrument having an equally divided scale, such as the d'Arsonval type, may be read with equal facility and equal accuracy at any part of the scale.

Instruments having unequally divided scales, such as the hot-wire, the electrodynamometer, or the electromagnetic types, are, as a rule, safe and accurate within the calibrated range marked on the scale. Instruments of this type do not, as a rule, give readings at less than from one-tenth to one-fifth of the total range. One instrument maker has asserted that the reason instruments of this type are not calibrated below one-tenth the total range is because of the errors in this portion of the scale, forgetting the fact that the law of the instrument will not permit such readings to be obtained. The curve of calibration of these three classes of instruments shows that the largest divisions are near the middle of the scale, which may or may not be half the total range of the instrument. At and around this point, of course, it is most easy to obtain accurate readings.

Mr. Cox states a real trouble when he mentions the difficulty of obtaining an agreement in reading between the totalizing ammeter and the various generator or circuit ammeters. Circuit loads are constantly changing, and unless it is feasible to station an attendant at each ammeter and another attendant at the totalizing ammeter so that readings can be taken simultaneously, it will be found almost impossible to make the sum of the circuit readings agree with that of the totalizing ammeter. In my opinion it is far better to test each ammeter separately, for it is comparatively easy to control the load on one circuit at a time.

Friction in the jewel bearing is an element of inaccuracy, but would not be so if the instrument were properly handled from the time it leaves the factory until placed on the switchboard. The actual energy necessary to operate the instrument is exceedingly small. Undoubtedly jewels tend to wear the points or polish of pivots on account of switchboard vibration, and it is wise so to install the switchboard as to reduce this vibration to a minimum. But the greatest damage usually occurs between the time an instrument leaves the factory and the time it starts in service. Switchboard builders are apt to be careless in handling instruments. It is well known that if a switchboard instrument is laid on a board, and the board struck a sharp blow, that in nine cases out of ten the lower jewel of the instrument will be pierced.

In checking the calibration of switchboard instruments by means of portable instruments, it is, of course, important that the portable instrument should not be subjected to the same stray field which may be present at the switchboard. Portable instruments are not, as a rule, shielded. They may, however, be removed to a considerable distance from the switchboard and are almost invariably used at right angles to the switchboard instrument. The influence of stray fields on portable instruments can be counteracted by constructing these instruments on the principle of the electrodynamometer. This point is brought out by Mr. Sharp.

Mr. Rosa objects to the commercial type of instrument shunt now on the market. My experience is that this shunt is very satisfactory if it is properly installed. The instrument maker can not of course be responsible if bad contact is made. I know of errors caused by poor contact where the leads connect the instrument to the terminals of the shunt.

I do not quite see how thermoelectric effects are introduced in shunt ammeter readings, for all the shunts with which I am familiar are so constructed that thermoelectric effects are neutralized. There are, however, errors introduced by the Peltier effect. These are inevitable, but fortunately the errors introduced are usually negligible.

The influence of external fields on switchboard instruments affects the instrument readings. Practically all switchboard instruments are shielded by enclosing them in iron cases. I do not know of any difficulties caused by the proximity of the iron framework of the board, but errors have been introduced on account of a field produced by the busbars or feeders. In one case the generator cables were led to the top of the board, forming a loop, within which was mounted the generator voltmeter. As these risers carried 2000 amperes, the effect of this field was very marked, causing variations of as much as 15% in the readings of the voltmeter. This could be corrected by proper switchboard design.

For two- or three-phase alternating-current work at least two ammeters or two wattmeters should be used. The potential coil should be connected in circuit with a Y-box for three-phase systems. Aside from the advantage of knowing whether the system is balanced or unbalanced, it is not advisable to depend on the switchboard attendants remembering to multiply readings by two or three.

WM. MCCLELLAN: The great value of the oscillograph is its ability to give the wave form from one wave. The shortest time in which I have seen a record made with the Rosa tracer is about six minutes. With a 60-cycle current, this would mean uniform conditions through about 20 000 waves. But owing to the operator's inexperience and the complexities of the instrument, the time necessary is usually much longer. The time required to obtain a curve with the ordinary contact-maker and voltmeter is still longer, and usually requires two operators.

There is one feature that, so far as the writer knows, has received little attention. When curves are taken with the double oscillograph, it is frequently assumed that the plate shows the phase difference between the quantities recorded.

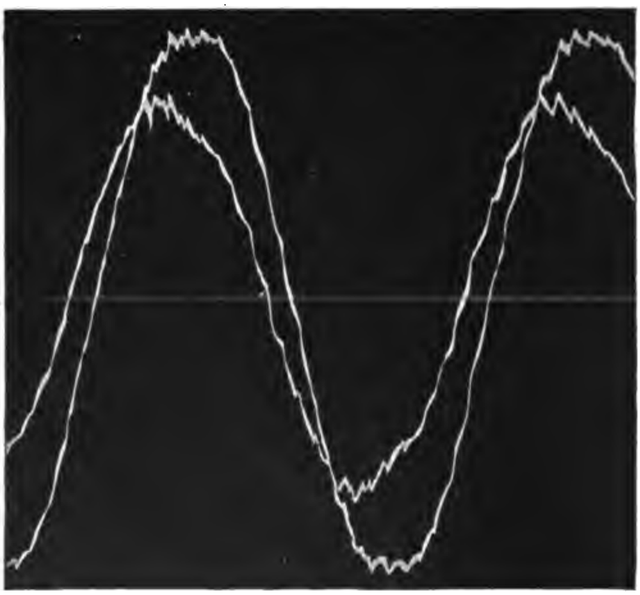


FIG. 1.

The accompanying illustration shows the current and electromotive force curves taken on a standard of self-induction. The frequency was 60 cycles, the resistance 9.89 ohms, and the inductance 40 millihenries. This would give an angle of lag of about 54°. Measurements on the plate will show that the angle is about 17° 20 min. The error is, of course, the same error that always accompanies wattmeter measurements. The instrument must always be put in circuit so that it includes either the electromotive force or the current of one of the coils. In the illustration given we have an extreme case, for the current in the coil under measurement was about equal to the current in the loop of the oscillograph.

The true phase angle can be obtained by measurements on several plates, the least number being three. One of these gives the ratio of the galvanometer actions of the two loops, the second eliminates the induction of the loops, and the third (Fig. 1) gives the apparent lag. There are many cases of course, where the angle on the last plate, that is, the apparent lag, will be very close to the true angle. When the oscillograph is shunted, it is difficult to obtain the true angle of lag.

The oscillograph proper, or what has been called the oscillograph galvanometer, is comparatively a simple piece of apparatus; but usually there is rather a large amount of accessory apparatus that makes the use of the instrument tedious. To make it thoroughly commercial there should be a finely adjustable non-inductive resistance, to bring the electromotive force within the limits of the instrument. A shunt, easily adjustable over wide limits, should also be provided. Otherwise there is considerable risk of injuring the very fine loops. Transformers may be used for high voltages and heavy currents, but one is always a little uncertain as to results, especially in the details of the waves.

PRESIDENT LIEB: In the presentation of the papers of the evening at the New York meeting, the accuracy of recording wattmeters was particularly considered. I made a statement as to the results that were obtained under average conditions by tests on Thomson commutator meters, made on customers' premises connected with a very large system—New York Edison system. The tests were usually conducted under very unfavorable conditions, on account of inaccessibility, varying voltage of pressure, stray fields, and vibration. The results, as I remember, were obtained from regular periodical tests upon 1000 meters that had been tested perhaps 12 or 18 months before. Therefore after perhaps a year had elapsed these same meters came under test again.

On full load, that is, on 75% to 100% of the meter capacity, 75% of the meters were between 5% fast and 5% slow, and of the remaining meters there were twice as many slow as fast. Under conditions of light load; that is, approximately 10% of the meter capacity, about 50% were between the limits of 5% fast and 5% slow, and there were four times as many of the remaining meters slow as fast. The average arithmetical accuracy of the 1000 meters was 98.1% at full load, and 89.34% at light load. The tendency of the meters is to run slow after installation on account of the well known Joule effects and the commutator effects, so that, as a general thing, they require correction by means of their adjustable shunts after they had been installed and running from two to three months.

The current delivered to the customer's premises is well-known to be much greater than the current paid for. Just what the difference is cannot be stated, but I think it is safe to say that even with very carefully maintained meter systems the current unaccounted for is very close to 10 per cent. of the current delivered.

The fact can be appreciated, however, when the difference between the efficiencies at full load and light load, as before given, is called to mind; and it is further realized that usually, even in the best adjusted systems, it is not practicable to install meters of a full-load capacity much less than the load that would be put upon them if the customers' installations were in full operation. It is practicable, of course, to install meters of much less capacity in residences; but as a general rule the average meter capacity cannot be less than 75% of the customer's installation; it is usually nearer 100%. Now, when it is considered that during times of maximum load in a large system probably not more than 30% of the installation in use at any one time contribute to the maximum load, that the maximum load lasts for only an hour or an hour and a half, and occurs for only a very few months in the year, and that during the remainder of the time we have merely a fraction of that fraction of the maximum load, it will readily appear that the meters on the average are operating considerably under 10% of full load, so that the conditions that are obtained of low reading of 10% short or 90% efficiency are quite extricable.

I have a series of readings of induction meters which were made for another purpose and which tell quite a different story. The meters had been running perhaps six to eight months; and their average accuracy at full load was 99%. The average accuracy at light load was 101; all the meters were accurate within +5 and −5%, and over 88.9% of them were accurate within +2 and −2; so we have quite a different story as to accuracy in the case of the induction meter as compared with the direct-current commutator meter.

CHARLES HEWITT: Has President Lieb any data as to the relative difference between the loss in the Edison chemical meter and the Thomson recording meter since it has been installed; whether that loss is as great as before the present type of recording meter came into use?

PRESIDENT LIEB: I can not give any exact figures in answer to the question; but I think that the current not accounted for in the case of the Edison chemical meter was greater. To venture a guess, I should say that it was at least 15%. When the change was made in large systems from the Edison chemical meter to the Thomson recording wattmeter, it was expected that a larger difference would be found; in other words, that the recording wattmeter would be the more accurate; but I know that in almost every case this expectation was not realized, and only a part of the expected improvement was actually obtained, and I think perhaps 15%—a ratio of 15 to 10—would represent about the degree of improvement.

Discussion on Measuring Instruments, at Pittsburg, Pa., May 8, 1905.

Wm. Bradshaw: One would infer from Mr. Nies' paper that the polyphase meter is an inherently inaccurate instrument. A polyphase meter so constructed that there are no mutual electrical or magnetic influences between the two meter elements, should and does operate just as accurately as the single element of a single-phase meter. This independence of the two meter elements is made permissible by connecting them together mechanically instead of electrically and magnetically. A polyphase meter mechanically connected between the two elements (that is, with two complete meter elements respectively acting upon two discs fixed to the same shaft) is polyphase only in that it may be so connected with polyphase circuits as to measure accurately the power whether the circuits are balanced or unbalanced.

A polyphase meter is not more difficult to calibrate than two single-phase meters. When the "bucking" process is used to bring the two meter elements into step, the error introduced by friction is negligible because the adjustment is made midway between the limits that give motion forward and backward. The total range being about 0.5% of full-load torque, the roughest approximation will give results of sufficient accuracy. If this method is used for setting the meter for zero power-factor, it will give very reliable results on loads of any power-factor.

Either a mechanically or an electrically constructed polyphase meter will be affected to the same degree as the single meter element is affected by varying voltage, frequency, wave form, etc., hence the use of a number of separate single-phase meters in place of a polyphase meter will not insure any greater reliability.

The possibility of using the separate readings of single-phase meters as a check on each other would be very remote, because a polyphase circuit that would be balanced within the limits of a modern service meter would be an ideal condition seldom attained; if it were attained it would be better to connect the two meters in series in one phase.

A polyphase meter with mechanically connected meter elements, and connected with transformers especially designed for use with instruments, will give, when the transformers are not overloaded, far more accurate results than those maintained in Mr. Nies' paper, under any condition of load, voltage, or frequency. It is strongly recommended, when a change is to be made from the readings of a meter, that each meter be installed with a separate series transformer.

Referring to Mr. Cox's remarks on switchboard indicating instruments, good switchboard instruments should have the following requisites: the readings should be accurate within plus or minus 2% under all conditions after being installed.

The instruments should have the maximum length of scale permissible for minimum switchboard space. The scale should be conveniently divided, with open divisions. The instruments should be deadbeat. The ratio of torque per unit weight should be maximum. The total weight of moving elements should be small. They should be but only slightly affected by external fields, changes of temperature, wave-form, frequency, unbalancing of the circuit, and should be accurate on inductive loads. Their mechanical design should be pleasing and substantial.

The testing meter described by Mr. Mowbray has a useful field, but it must be used with discriminating judgment. Such a standard meter should be used to test meters in service to indicate whether or not the service meters need to be removed for recalibration. And the central station using an integrating standard meter for this service should have an accurate and reliable indicating standard for frequently checking the calibration of the standard integrating meter. The best service is obtained from a standard meter when its use is practically continuous, because a meter while standing idle is more liable to get dust in the jewel and develop friction than is a meter that is in continuous operation. The standard meter should be of the same type as the service meter under test; or else the load, voltage, and frequency characteristics of both the standard meter and the service meter under test should be known and compared before the service meter is condemned as being inaccurate. Some types of meters will run fast on less than their normal voltage and frequency, while others will run slow; and consequently a meter might be condemned as being as much as four or five per cent. in error, when in reality it would be within two per cent. of being correct. When a standard integrating meter is used with the precautions given above, it furnishes a reliable, accurate, and rapid method of checking integrating wattmeters while in service.

STEPHEN Q. HAYES: Concerning Mr. Bradshaw's remark that there is no reason why the series and shunt leads, referred to on page 173 of Mr. Nies' paper, should be connected together, I understand that Mr. Nies' idea is to connect one side of all of the series transformers and one side of all of the shunt transformers to a common ground wire. One side of the current coils and one side of the voltage coils of the switchboard instruments would also be connected to a common ground, and the two grounds would be connected together by a single wire.

Referring to Mr. Cox's paper, page 182, relative to the size of indicating instruments to be used on generator and feeder circuits, some engineers advocate the use of instruments of such size that even on a sudden heavy overload there shall be no possibility of the needle swinging to the end of the scale and possibly being bent or broken. The rule of the Westinghouse Company is to supply instruments of such size that they will take care of 50% overload on the feeder or generator circuits with which they are connected; but for special cases, when required, larger instruments have been furnished to obviate the possibility of damage to the needle due to heavy overloads.

Referring to page 183 of Mr. Cox's paper, relative to the calibration of switchboard instruments, the Westinghouse Company recently made it a practice, whenever requested to do so, to place testing plugs on the switchboard panels, both for the current coils and for the voltage coils of the instruments, so that it is a comparatively simple matter to connect in a portable testing meter in order to calibrate the various instruments.

Too much importance cannot be placed on the last paragraph, on page 184 of Mr. Cox's paper; with polyphase instruments it is of the utmost importance that the connections should be made correctly; it is better to be guided by a diagram of connections than for one not thoroughly familiar with the switchboard instruments to connect up meters in a manner which he supposes will give the same results.

Discussion on Measuring Instruments, at San Franciso, May 9, 1905.

C. W. Hutton: The idea of frequently calibrating and adjusting instruments, particularly integrating wattmeters, and providing a means for readily inserting standardizing instruments is to be highly commended. The use of modern potential and current transformers greatly simplifies the operations of standardizing and adds to the safety of the installation. The cupped-diamond bearing is a recent innovation; its use is highly recommended by those who have tried them.

The Y-box and single wattmeter method has little to commend it, as slightly unbalanced conditions cause its records to be totally unreliable.*

In measuring polyphase power by the use of integrating wattmeters, there is little choice between the polyphase meter and the combination of two single-phase meters by the so-called two-wattmeter method. Two independent wattmeters are, it is true, easier to calibrate than is a polyphase meter, but not, I think, quite so easy as Professor Nies says. Very good results could be obtained by placing the current coils in series and putting the potential windings in parallel on the same transformer; in this case the speed of the meter would be twice the speed of the single-phase standard calibrating meter.

Another interesting method by which two single-phase wattmeters may be used on a three-phase circuit was brought out some time ago by one of the large manufacturing companies. It has been used in a few cases for indicating wattmeters, but not so far as I know for integrating wattmeters, although I see no reason why it could not thus be used. This method has one virtue in common with the three-wattmeter method—the two meters run at the same speed as long as the load is balanced, regardless of the power-factor of the load. The chief drawback to the use of this method is its complication and the fact that one meter operates on 86% of full voltage, and the other on 86% of full current as compared with each other. This, of course, introduces complications in calibrating.

J. W. Swaren: In the ordinary small plant of one or two generators and a proportional number of feeder panels, if proper regard is had for peak loads, the instruments and meters are working on the low end of their load curve the greater part of the time. Incidentally, all the costs of operating are comparatively higher at this time, so that the showing made by the engineer in charge is really worse than the conditions justify.

In larger plants, unquestionably the best plan is to meter each generator separately, doing away with totality meters and instruments generally. This leads us to switchboard design, and we may as well look at it from this standpoint. The

*For results of experiments by the author and A. J. Bowie, Jr., with this method see the *Electrical World and Engineer*, Vol. 33, page 500.

instruments are the most important part of a switchboard, the brains of it, to use a common simile. Switchboards may be classified into two parts—direct-current switchboards and alternating-current switchboards. Take the direct-current switchboards first and beginning with the generator end, one usually finds a swinging bracket with one or two voltmeters. If the swinging bracket has two voltmeters, there is a plug-switch to give the generator voltage in paralleling. If it has one voltmeter, there is a shelf to hold a portable voltmeter for use in paralleling. This practice cannot be too strongly condemned; it is placing a delicate instrument in the presence of stray fields and subjecting it to rough handling. Nor is it in a convenient place to be read. With two voltmeters on a swinging bracket, they are in plain view of the operator, and can both be read at a single glance. This is less likely to result in an error in throwing a new machine into service. On the generator panels proper, we find an ammeter, selected according to the size of the generator. All these instruments should be of the illuminated-dial type.

The recording meter is usually placed on a sub-base; this is relatively a good place for it, as the vibration is less. If placed high enough from the floor, the meter is easily accessible for repairs. Here we are confined to the commutator type of meter, as the author of the paper under discussion states. But there are two vital points which he has not brought out; the demagnetization of the magnets, and errors due to stray fields. The last virtually covers both points.

As pointed out by Mr. Mowbray, the demagnetization caused by short circuits may be overcome by the relative positions of the field coils and magnets. This applies to the fields of force set up by the field coils only. To guard against other demagnetization forces, the magnets must be carefully shielded. The speaker has in mind an interurban road operating a third-rail system, with meters on the feeder panels of the sub-stations. The road had not been operating long before the feeder meters showed a greater output than the generator meters. Tests showed the feeder meters to be very fast. The trouble was overcome by installing meters with properly shielded magnets.

The error in running due to stray fields must be a min.mum. A meter that is not practically insensible to stray field effects has no place on a switchboard.

An ammeter should be sufficient on the feeder panels. On the battery panels there should be an ammeter with the zero in the middle of the scale, and a low-reading voltmeter for the cell voltage. The second voltmeter on the bracket should be sufficient for the battery voltage by using suitable switches. Here also should be placed a meter to register on separate dials the charge and discharge of the battery. In selecting instruments, the same points in reference to stray fields apply as well as to meters. Other points to be considered carefully are:

retention of calibration; liability to injury due to short circuits; ability to obtain repair parts, and the ease with which repairs can be made.

As for accessibility for calibrating, this can be taken care of by using a standard switch throughout the switchboard. A standard shunt can be fitted with lugs and inserted in place of the switch-blade. Current measurements can then be made with a millivoltmeter.

Alternating-current switchboard practice may be criticized in two respects: first, there are too many meters and instruments on a board of this type; secondly, bus-bars and high-tension wires are brought unnecessarily close to the instrument, and frequently into the instrument itself. A switchboard attendant usually concentrates his attention on a definite operation involving only a small proportion of the apparatus at present found there; the fewer instruments he has to distract his attention, the less likely he is to make a mistake. For this reason a great deal of the apparatus now put on the face of the switchboard should be put elsewhere. With this in view, it will be well to divide the switchboard into two divisions, the operating division and the recording division.

Taking the operating division first, and beginning with the generator end, we find a swinging bracket and on this bracket is placed a synchronizer and two voltmeters. One of these voltmeters is connected permanently to the middle phase of the bus-bars; the other voltmeter is connected by a system of plug-switches to any phase of any generator.

On the generator panels there is found an ammeter in each phase, and possibly a power-factor indicator, also the necessary plug-switches for the voltmeter on the bracket. The exciter panel holds the customary ammeter and voltmeter, and the feeder panel a single ammeter, and a voltmeter if a feeder regulator is installed. On the end of the feeder section there is another bracket with a single static ground-detector on it. On the feeder panels will also be found plugging devices to connect this ground-detector to any line. It is doubtful if this instrument is worth the complications necessary to connect it to the generator panel. On switchboards supplying current to step-up transformers it would obviously be omitted.

The point of the second criticism can be overcome by supplying all the meters and instruments through current and potential transformers.

At the generating end of the recording division there is a polyphase meter on each generator Notwithstanding Professor Nies' advocacy of three single-phase meters, the speaker thinks that a polyphase meter should be placed here. This meter should never operate on a light load, and the power-factor should never go low enough to introduce the errors he points out. The polyphase meter requires less space, and shows the entire record on one dial. It thus requires less of the operator's time to obtain the readings and, being under constant observation, any variation in its registration would be noticed at once. As to Professor Nies' contention that it cannot be calibrated while in service, the speaker does not agree. This applies especially in the case under consideration, where the load is large. The single-phase meter with Y-box should never be used, as balanced loads are mostly mathematical fictions. Here we should also find any curve-drawing instruments that are wanted.

It does not seem advisable to place recording meters on the feeder panels unless it is desired to go into the segregating of the load very carefully. The panel supplying the station auxiliaries should however, be carefully metered. Where the feeder panels are metered, the three wattmeter method might be advisable.

As to curve-drawing instruments, it is simply a matter of refinement. Voltmeters on the feeder panels would be the most important in lighting stations. Their use is also important on circuits supplying municipalities. When used to a sufficient extent, the superintendent has a check on every man's work. Curve-drawing instruments should be especially free from vibratory effects, yet sensitive to load fluctuations. They should draw a fine clear-cut line. In the curve-drawing wattmeters, the speaker thinks the polyphase instrument should not be recommended, as the ones he has examined are especially liable to the faults Professor Nies has pointed out.

Throughout this discussion, the speaker has taken the view that the following points are of most importance: first, accuracy; secondly, obtaining the results desired; thirdly, maintenance; fourthly, first cost. Too often, first cost is made the most important point. Where accuracy should be the most important consideration, the slight per cent. increase of the cost of the whole station in getting the apparatus necessary instead of something just good enough, should not be allowed to influence their selection.

R. F. Monges: The determining feature for the capacity of instrument will generally be the overload capacity of the piece of apparatus with which it is to be used. Machines built for general power and lighting purposes have usually an overload capacity of 50% for one or two hours. The indicating instruments, such as ammeters and wattmeters will, therefore, have to be sufficiently large to take care of this overload. In railway plants, momentary overloads as great as 100% are frequent and will require instruments capable of indicating them.

As pointed out by Mr. Cox, the integrating instruments need not be so large in capacity; ordinarily they can be of the same normal capacity as the machine to which they are connected.

Regarding the instruments that are to be mounted on a panel. These will vary slightly with the needs of the plant. For direct-current generators, a voltmeter, an ammeter, and a recording integrating wattmeter are all that are required. For alternating-current generators, an ammeter will generally be required in each phase, one voltmeter with two potential transformers to take the voltage on each leg, and a field ammeter. To this equipment, an indicating wattmeter could well be added in plants containing two or more generators to indicate the division of load between the prime movers; also, an integrating wattmeter. One integrating wattmeter for each machine is better than one total-output meter, as it operates at more nearly full load all the time.

In plants where most of the load is three-phase apparatus, such as synchronous converters and synchronous motors, two of the ammeters could be omitted and a power-factor indicator substituted.

Regarding the use of series and potential transformers, I think these should be used with all instruments on circuits of 2000 volts and more, so as to remove all high-tension wire from the face of the board.

The only place where balanced three-phase meters can be used is on plants having a purely three-phase load, such as railway plants operating synchronous converters; even then the polyphase meter is to be recommended.

Regarding the question of making provision on the board for the introduction of standardizing instruments. If this were done, switchboard instruments would be more closely checked. As it is now, a machine has to be shut down and time taken to introduce a standard into the circuit. Some simple and inexpensive means could probably be provided, particularly where series and potential transformers are used.

C. L. Cory: Where switchboard instruments are supposed to indicate the output of the plant without careful checking, serious errors are sometimes discovered. I happen to know of one case where the error was carried into the bookkeeping and financial side of the plant. It was said that the plant was generating a certain number of kilowatts with a certain number of barrels of oil, that the cost at the switchboard was a certain number of cents per kilowatt-hour. Now, as a matter of fact when the test was made the results were in error over 25%. That sort of test, particularly when applied to the financial side of a power plant, is not a proper way for engineers to make up such data. It is not difficult to place in connection with the switchboard some arrangement whereby these instruments could be kept straight.

F. E. Smith: Periodic testing is without doubt the only means of maintaining meter accuracy, such testing to be done on the customer's premises and under as near working conditions as possible. If the test should prove that the meter requires a general overhauling or repairs, it should be removed to the company's meter department for the purpose, and a new meter installed in its place.

My experience in checking recording wattmeters with a portable standardized recording wattmeter has not been very successful, mainly for the reason that I found the portable meter unreliable, its failings being due principally to disarrangement in carrying it about.

It is a well-known fact that hardly two recording wattmeters are installed under like conditions; the adjustment for eliminating initial friction varies in each installation, and an error due to this cause would apply to some extent in the case of the portable meter. The greatest liability for error would lie in the commutator and brush adjustment, which many times requires hours of running before a normal and lasting contact is established. For this reason it is not always wise to attempt to clean and dress the brushes and commutator of a meter on the customer's premises; on the contrary, if they must be cleaned, it is much safer to remove the meter and put a well-seasoned one in its place.

In practice I find the most reliable tests are those made with indicating instruments having two or more ranges in order to meet conditions of greatest accuracy, the testing load being an artificial one. In my practice this load consists of a bank of special resistance lamps giving loads from the minimum to the maximum. Under such conditions, the only variations to be contended with are the ordinarily small fluctuations in voltage, which as a rule should not affect the results to a greater extent than perhaps one per cent.

One of the greatest sources of loss to companies supplying electric energy by meter is that caused by slow meters due to cracked or scratched jewels; this fault, as indicated in Mr. Mowbray's paper, can be lessened to a very great extent by the use of the diamond-cupped bearing.

This question of providing a pivot and bearing that will withstand the very heavy duty imposed upon it seems to be the all-absorbing topic in meter construction, the tendency being to increase the torque to such an extent that the friction would form only a small percentage of the power to be overcome by the motor.

With a perfect jewel and pivot, this theory may hold good; but in practice and under the severe conditions imposed, namely, a hardened-steel pivot rotating on a jewel under a pressure of approximately 500 000 lb. per square inch, it would seem that a very great reduction in the weight of the moving element would tend more toward removing jewel troubles than any attempt to compensate for the ever increasing friction by means of a greater torque.

A paper presented at the 197th Meeting of the American Institute of Electrical Engineers, New York, May 16, 1905.

TIME-LIMIT RELAYS.

BY GEORGE F. CHELLIS.

In power stations and sub-stations feeding large alternating- and direct-current distribution systems, relays form a necessary part of the station equipment for the protection of apparatus and feeders, and for the purpose of rendering the operation of a system automatic. In connection with the operation of oil-switches on high-pressure alternating-current systems the function of the relay is to close the control-circuit to the switch, thereby opening the main circuit when the current exceeds the value at which the relay is adjusted to operate. Not taking into consideration the time-element of the switch, its operation would be practically instantaneous if controlled by a simple relay. Therefore, since heavy currents due to swings of the load may often flow for such short periods that it would not be desirable to open the circuit, relays are provided with some form of time-limiting device by means of which the length of time a given current may flow without operating the switch can be adjusted to meet existing conditions.

Relays may be divided into three classes:

1. Differential relays, operating at a lower current value when the direction of the flow of energy is reversed than when flowing in its initial direction.

2. Straight overload relays, operating when the current reaches a certain predetermined limit, irrespective of the direction of flow of energy.

3. Reverse-current relays, operating when the current reaches a certain predetermined limit, upon reversal of the direction of flow of energy.

Alternator Relays.

The type and design of the ideal relay for the protection of alternators will depend upon the conditions under which it is to operate. A relay should operate on overload at normal pressure; on short circuit at zero pressure, or reduced pressure, or when the direction of the flow of energy is reversed. It can be designed to operate in the event of any of these conditions prevailing, and each at a different value, in which case a differential relay would be required. The principal advantages of the differential relay are that it can be so designed as to permit the alternator to be loaded to its maximum current capacity at normal pressure without danger of being cut out, and also operate on short circuit, when the pressure is zero, at a point sufficiently under the short-circuit current of the alternator to allow a suitable factor of safety. Compared with the straight overload relay, set to operate on short circuit with an equal factor of safety, at power-factor values usually attained (50% and higher), it will permit a greater load being carried at any operative pressure.

Assuming that the relay is to operate on short circuit and reversal, but not on overload at normal pressure, the ideal relay should have the following characteristics:

1. It should permit the alternator to be loaded to its maximum current capacity at normal pressure.
2. It should limit the current on short circuit to not more than 75% of the short-circuit current of the alternator.
3. It should limit the current on reversal to the lowest value at which no difficulty is experienced when synchronizing.
4. It should be provided with a positive time-limiting device, the time adjustment of which is independent of the current value at which the relay is operated.

In existing forms of alternating-current relays of the differential type the energizing coils consist of two windings with a common magnetic circuit. These windings, which for convenience will be called *a* and *b*, receive current from a shunt transformer, and a series transformer, respectively connected with the alternator. Therefore, the current in *a* is dependent upon the pressure, and that in *b* upon the current.

Since with constant pressure the magnetomotive force due to coil *a* is fixed in direction and magnitude, it serves to polarize the relay. The action of coil *b* in conjunction with coil *a*, at 100% power-factor, depends therefore on the direction of the magnetomotive force due to coil b, and the ratio of ampere-turns of coil a to those of coil b. Under normal conditions coils a and b act differentially; but if the direction of the magnetomotive force of b is reversed their action is cumulative.

In Fig. 1, let $O\,A$ represent the magnetomotive force of coil a; $O\,B'$ the magnetomotive force of coil b for normal conditions, and the angle (supplement of ϕ, as given in diagram) their phase relation; the coils act differentially, the resultant magnetomotive force being $O\,C'$. On reversal of the direction of flow of energy in coil b the magnetomotive force thereof will be represented by $O\,B$; as will be seen, the action of the coils

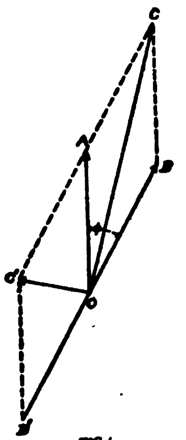


FIG. 1.

is now cumulative, the resultant magnetomotive force being $O\,C$.

Assuming the constants for an alternator in terms of the secondary current to be: rated current, 2.2 amperes; short-circuit current, 6.6 amperes, and minimum current permissible on reversal (on account of sensitiveness when synchronizing), 1.1 amperes, a differential relay to comply with the previous specifications should operate on short circuit (pressure assumed to be zero) at 75% of the short-circuit current of the alternator $= 0.75 \times 6.6 = 4.95$ amperes for coil b. The current for coil a, expressed in terms of the operating current for coil b, must be $4.95 - 1.1 = 3.85$ amperes.

A relay having these characteristics would operate as follows: short circuit $= 4.95$ amperes; overload current at normal pressure = 4.95+3.85 = 8.8 amperes; reversal = 4.95 − 3.85 = 1.1 amperes.

Since at unity power-factor the value for coil a, in terms of the operating current of coil b, is 4.95 − 1.1 = 3.85 amperes, coil a bears to coil b the ratio of 0.775 to 1. This ratio is called herein the "differential factor" of the relay. While this would give the desired operative characteristics, it is doubtful if a relay having so high a differential factor could be successfully constructed, and for the following reasons:

In general, relays of this type involve such principles of operation as to include a partly closed magnetic circuit, which is closed by the operation of the relay. The reluctance of the magnetic circuit therefore varies, being maximum at the starting point, and minimum when the relay has operated. If started in operation by a heavy current of short duration, due to an exchange of current between the alternator and the bus-bars at the moment of closing the circuit when synchronizing, the magnetic conditions in the relay would so change that it would operate at a much lower current than the normal if the current did not drop sufficiently low to permit the core of the relay to recover its normal position. The liability to this condition is greatest when the time-limit is comparatively short. By a series of experiments it was found that the highest permissible differential factor was about 70%. With a differential factor higher than 70% for the core-type relay, especially at low frequencies, a rise in pressure with no current in coil b would set up a series of vibrations of the armature in synchronism with the alternations of the current, which in some cases would not cease if the pressure were reduced to normal, the relay also being so sensitive as to make synchronizing very difficult.

While the solenoid-type relay was free from this disadvantage, it was found that after the relay had operated the flux due to coil a was sufficiently great to prevent the relay core from recovering its normal position.

In Fig. 2, is shown the characteristic curves for a bellows-type differential relay, having a differential factor of 61.8%; and in Fig. 3 the curves for a similar relay having a differential factor of 25 per cent.

Differential relays are commonly so connected that the current in coils a and b is in phase, when the alternator is operating at 100% power-factor. In a three-phase system this is accomplished by bringing out a tap from the centre of the secondary coils of the pressure transformers, which are Δ connected. This gives, by Fig. 4, the pressures $a\,b$, $c\,d$, and $e\,f$, in phase with the currents 1, 2, and 3 respectively, and at an angle of 30 degrees to the pressures $a\,c$, $c\,e$, and $e\,a$, which gives for the relay pressure $x \cos 30°$, where $x = \Delta$ pressure at secondary of transformer.

The actual connections for a two-coil relay are shown in Fig.

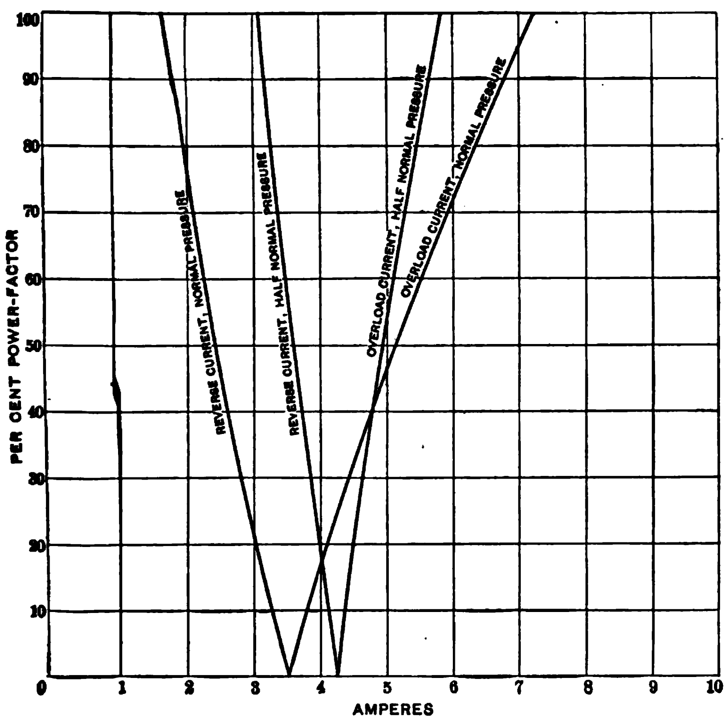


FIG. 2.

Characteristic curve of differential relay. Differential factor 61.8 per cent. Current in A and B coils in phase at unity power-factor for the alternator.

5, the b coils of which are connected to the secondaries of the current transformers in phases 1 and 2, and the a coils receive respectively, the pressures $a\ b$ and $c\ d$ of Fig. 4. By this method of connection the power-factor of the relay is approximately that of the alternator.

When the load condition is such that a low power-factor of the alternator is always caused by a lagging current, the average power-factor of the relay may be improved by the method of connection shown for a two-coil relay, in Fig. 6. The *b* coils are connected to the secondaries of the current transformers in phases 1 and 2, and the *a* coils are connected, respectively, across *a c* and *a b*, of Fig. 6a. This causes the current in the *b* coils to lead that in the *a* coils 30 degrees at 100% power-factor for the alternator, and to lag 30 degrees at 50% power-factor.

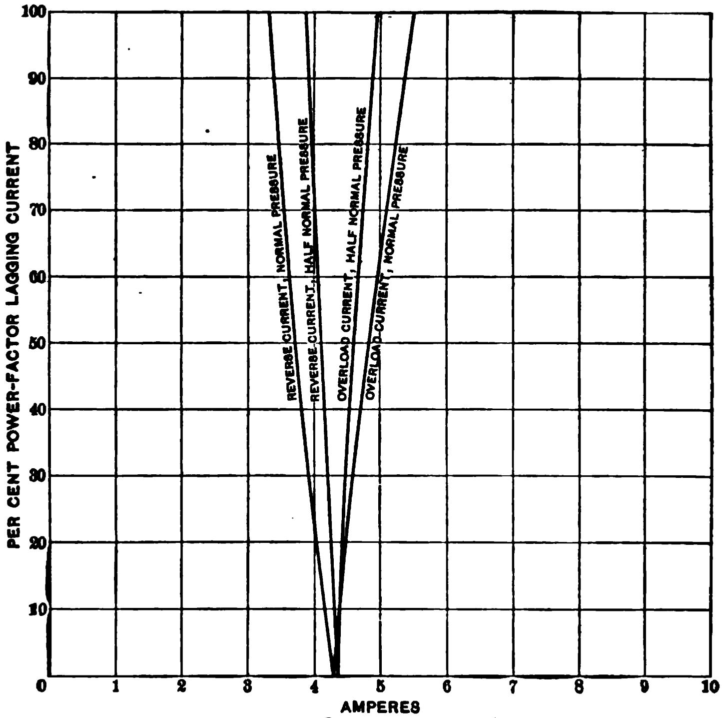


FIG. 3.

Characteristic curve of differential relay. Differential factor 25 per cent. Current in *A* and *B* coils in phase at unity power-factor for the alternator.

Therefore, at a sacrifice of 14% at unity power-factor, the average power-factor of the relay is kept high over a range of from 100% to 50%. At 50% power-factor for the alternator, that of the relay would be 86.6%, as against 50% with the previously described method of connection.

Fig. 7 shows the characteristic curves of a relay with the current in the *b* coils 30 degrees ahead of that in the *a* coils. A comparison of Fig. 7 with Fig. 2 will show the advantages of the method of connection shown in Fig. 6.

A two-coil relay as shown in Figs. 5 and 6, would protect a three-phase alternator, as follows: reversal at normal pressure,

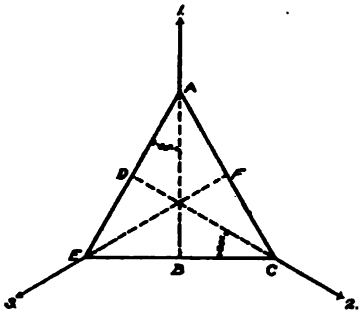


FIG. 4.

poles 1 and 2 operate; short circuit between phases 1 and 2, poles 1 and 2 operate; short circuit between phases 2 and 3, pole 2 operates; short circuit between phases 1 and 3, pole 1 operates.

To the knowledge of the writer, no relay having a positive

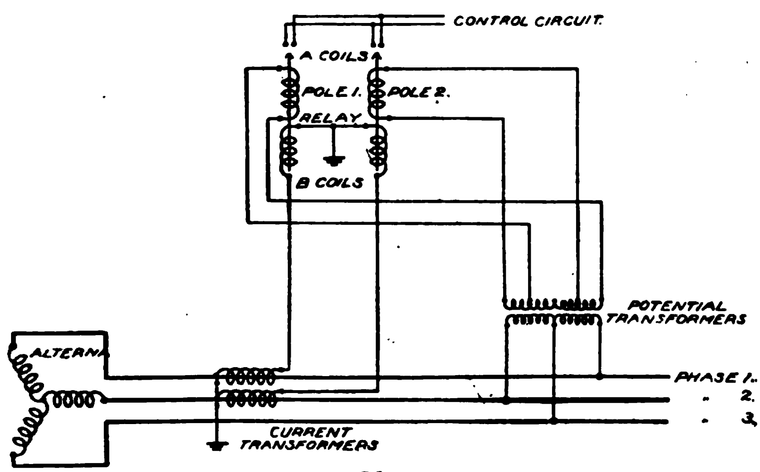


FIG 5.

time-limiting device has been placed upon the market. In relays brought out recently, a form of pneumatic time-limiting device has been adopted, such as a bellows, or dash-pot, which is acted upon directly, or through a system of levers connected with the core of the solenoid, and provided with suitable means for adjusting the air discharge. While ideal from the standpoint of simplicity, these devices are not positive, the time adjustment being inversely proportional to the current at which the relay is operated.

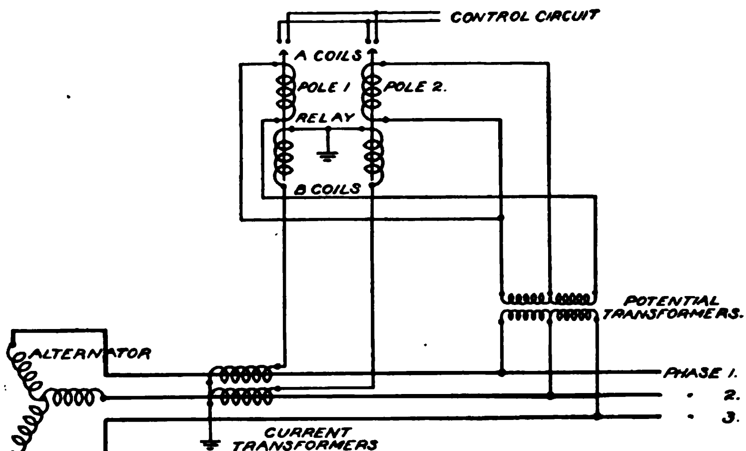


FIG 6

In Fig. 8 is shown an ampere-time-curve for a bellows-type overload relay. This curve was obtained by adjusting the relay to operate with five amperes in 10 seconds, the current

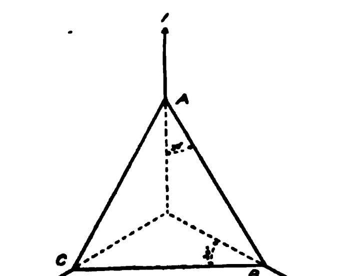


FIG.6.A.

was then increased step by step and the times for the relay to operate were noted. The " inverse " feature of this relay as described later, may be used to advantage in connection with the protection of feeders.

Feeder Relays.

The method of protecting feeders depends upon the operating conditions. This subject may be most consistently discussed by considering the conditions from the power-house alternating-current bus-bar to the sub-station direct-current bus-bar.

To guard against overload, and to open the circuit in the event of a short circuit, a relay is required at the power-house end of

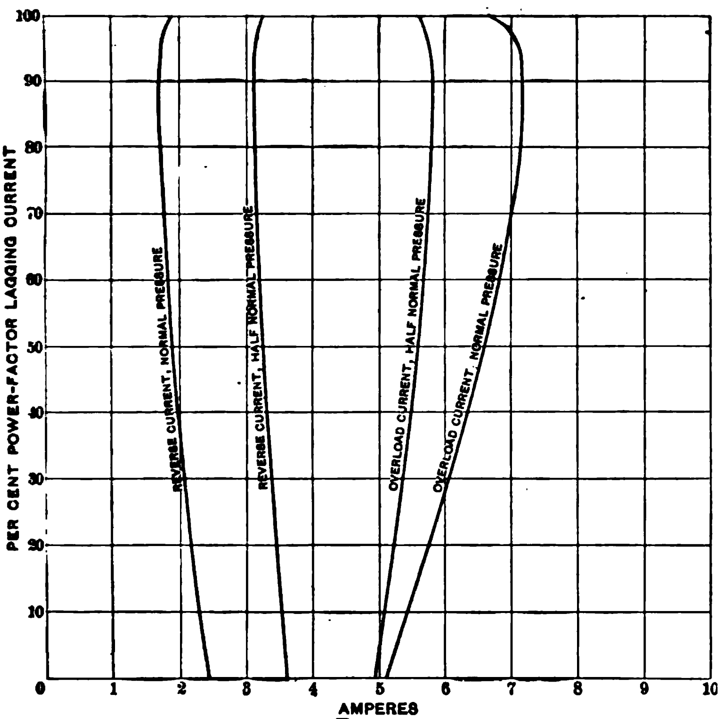


Fig. 7.

Characteristic curve of differential relay. Differential factor 61.8 per cent. Current in coil B 30° ahead of coil A at unity power-factor for the alternator.

each feeder. A relay is also required at the sub-station end, where the feeders are operated in parallel, being connected to a common sub-station bus-bar, or where the sub-station bus-bar is divided, leaving groups of two or more feeders in parallel. This can be seen by considering the diagram, Fig. 9, in which four feeders, *a*, *b*, *c*, *d*, are shown in parallel, and four converters connected to the sub-station alternating-current bus-bar and feeding the direct-current bus-bar. Should a short circuit occur at the point *x* on *b* feeder there would be a rush of current from the power-house bus-bar, and also from the sub-station bus-bar to the point *x*. In *a*, *c*, and *d* the current would be increased, due to the short circuit being fed by these feeders through the sub-station bus-bar.

Since a synchronous converter generates an alternating-current electromotive force corresponding to rated pressure at synchronous speed, in case the point *x* is near the power-house it is possible that the direction of the flow of energy in feeders

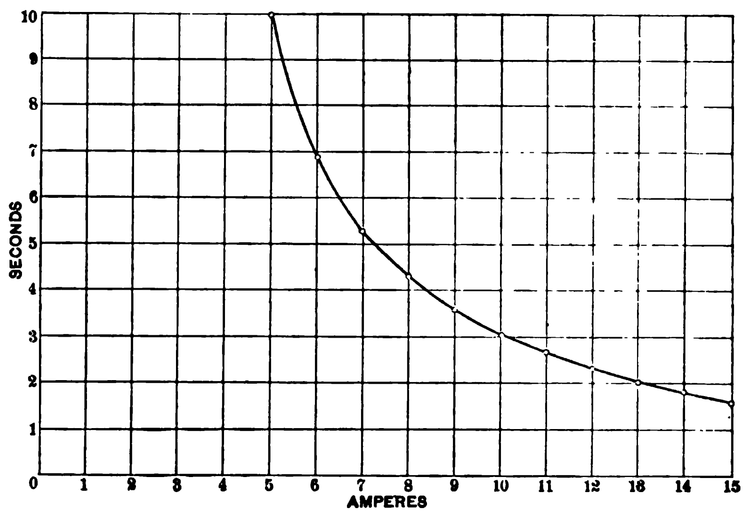
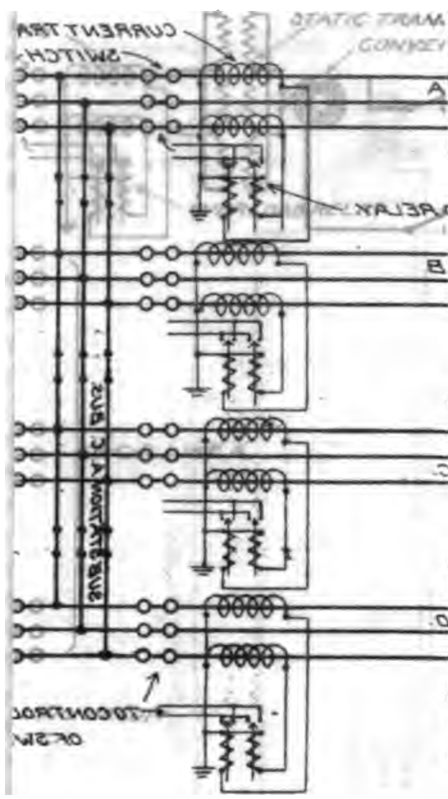


Fig. 8.

Ampere-time curve for bellows-type overload relay.

a, *c*, and *d* would be reversed, due to the synchronous converters feeding the short circuit back through the power-house bus-bar, as well as directly over the short-circuited feeder.

Because of the great amount of energy stored in the synchronous converters, it is also possible for all the sub-stations to feed back into a short circuit in this manner. To fulfil requirements properly an ideal combination would be an overload time-limit relay at the power-house end and an instantaneous reverse-current relay at the sub-station end of each feeder. The writer does not know of an alternating-current reverse-current relay, the operation of which does not depend upon the pressure of the system, nor a relay that depends upon the pres-



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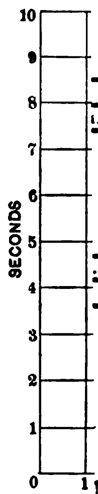

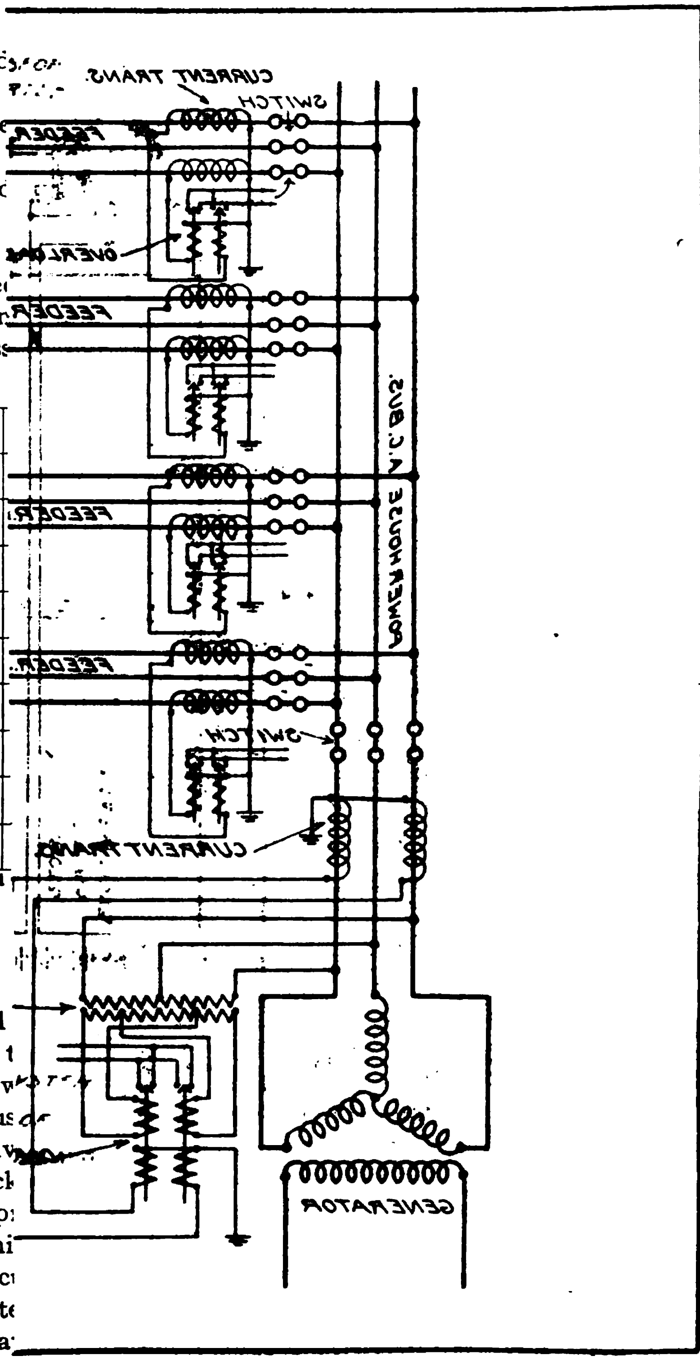

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sure operating on a reversal only, that would not become completely inoperative at zero pressures or at comparatively low pressures. If differential relays were used, with a " differential factor " sufficiently high to render the relays of any appreciable value at low pressures, it is probable that they would be so sensitive that any disturbance causing a momentary reversal, without a serious decrease in pressure, would cut the station out unnecessarily.

This theory is borne out by the experience of the Interborough Rapid Transit Company in the sub-stations of the Manhattan division, where instantaneous differential relays were installed at the sub-station end of the feeders. When feeders were operated in parallel, it was found in most all cases where a feeder became short circuited that all the differential relays at the sub-station end would operate, and also those of one or more of the other sub-stations; this caused the remaining relays in the other stations to operate because of overload, thus resulting in a total shutdown. After straight overload time-limit relays were substituted for the differential relays, on the occasion of several very severe short circuits the affected sub-station cleared itself in a perfectly satisfactory manner and without disturbing the rest of the system. It would appear, then, that the straight overload time-limit relay is the most satisfactory device obtainable for the protection of feeders at the sub-station end.

With synchronous converters a straight overload time-limit relay in the high-pressure side of the transformers will give satisfactory protection for the alternating-current side; while for the direct-current side a reverse-current relay, operating the direct-current breaker, will be required to open the circuit and thereby prevent the synchronous converter from attaining destructive speeds, in the event of the field circuit being opened.

Satisfactory direct-current reverse-current relays are obtainable; they are commonly of the motor type, having an armature separately excited from a source of constant pressure, such as a storage-battery. They are provided with a stop to prevent continuous rotation, the field depending for its intensity and direction upon the line current. This type of relay, as installed on the 1500-kw. synchronous converters of the Interborough Rapid Transit Co., will operate at about 15% rated current on reversal.

The relative value of the time adjustments for the various relays depends on the order in which it is desired to open the switches. If feeders are operated in parallel, when a short circuit takes place on any given feeder there will be a rush of current to the point of short circuit from the power-house and also from the sub-station bus-bars; the comparative value of these currents depending upon the location of the point of short circuit, the number of feeders in parallel, and the ratio of the kilowatt capacity of generators to the synchronous converters in service at the time. While the overload current limit may be exceeded in all feeders, both at the power-house and sub-station ends, the current in the short-circuited feeder at the sub-station end with n feeders in parallel will be $n-1$ times as great as that in the other feeders, plus the current supplied by the synchronous converters; or the current may be supplied entirely by the synchronous converters, and the direction of the flow of energy in the unaffected feeders reversed; in any case the current in the latter will be the same at both ends. The current at both ends of the affected feeder will, therefore, reach a higher value than in the other feeders, and to clear it necessitates opening the switches at both ends.

To break the circuit at the lowest possible current value it is necessary first to open the switch at that end of the feeder which has the highest current value. Since the circuit will still be closed from the other side, there will not be a high pressure across the terminals of the switch at the point of breaking. This permits making the final break with the resistance of the other feeders, plus the resistance of the affected feeder in series therewith to the point of short circuit, in which case the current at the time of the final breaking of the circuit will be much lower than in the event of the operation being made in reverse order.

Since the current in the affected feeder will always be heavier than in the others, a relay having an inverse time-limiting device may be used to advantage. A series of tests carried out with the bellows-type time-limit overload relay, showed that with equal current adjustment, by adjusting the time of two relays in the ratio of 0.5 to 1, when operated in series, they would discriminate properly at all loads—the one with the shorter time adjustment operating a sufficient time in advance to leave ample contact clearance on the one with the longer time adjustment.

Therefore, with equal time adjustments at a given current value, the rélay having the heavier current will operate in a correspondingly shorter time, and thereby disconnect only the affected feeder. The time-limit for these relays should be adjusted at the current value at which they are intended to operate, and so as to make the final break at the lower current value; the time and current adjustment at both ends should be the same, the time being that at which it is desired to limit the overload on the feeders. In all cases the time-limit of the alternator relays should be greater than that of the feeders to permit the operation of the latter without operating the former.

Assuming the safe time-limit of the alternators to be twice that of the feeders, and that of the synchronous converters equal to that of the feeders, but at a lower current value, the numerical value of the time ajdustments may be three seconds for the alternators, and 1.5 seconds for the feeders and synchronous converters, which values are within the range of most relays.

Special operative conditions may demand adjustments varying greatly from these values, but in all cases they should be so made as to give the desired protection for emergency conditions, as far as these can be predetermined.

A paper presented at the 197th Meeting of the American Institute of Electrical Engineers, New York, May 16, 1905.

DUPLICATION OF ELECTRICAL APPARATUS TO SECURE RELIABILITY OF SERVICE.

BY H. W. BUCK.

The question of the proper reserve in an electrical installation is a problem, like many in engineering, which must be settled largely upon a basis of cost. It is nearly always a question involving a balance between a power company's obligation to its customers and the obligation to its stockholders. From the standpoint of the consumer the more reserve the surer will be his supply of power. On the other hand, to the power company's stockholders the less the investment in reserve the larger the dividends, unless the reserve has been cut down to a point where the power company's reputation is endangered by interruptions to service. The question is purely a practical one and no definite laws can be enunciated, nor can any curves be plotted which will indicate the proper amount of reserve to be installed under various conditions. The decision in each case must be based on intimate knowledge of the local conditions and requirements of the particular installation in question. All that will be attempted in this paper will be a discussion of the general principles involved.

Before a decision can be made upon the degree of duplication advisable for any given piece of apparatus, an analysis must be made of the defects which may develop therein, the length of time required for repairs in case of a breakdown, and the number and importance of the power customers dependent upon that particular appliance.

For purposes of discussion electrical reserves may be divided into several classes of apparatus, each governed by different conditions. These classes are:

1. Generating units.
2. Generating plant switchboard.
3. Generating plant transformers.
4. Underground distribution system.
5. Overhead lines.
6. Sub-station apparatus.
7. Apparatus on premises of individual customers.

Reserve apparatus applicable to the above can again be divided into two classes:

a. Actual apparatus installed complete ready for service.
b. Reserve parts held in storeroom.

Generating Units.

There is no place in a power system where reserve apparatus is so important as in the generating station. In the writer's opinion the following conditions should be observed in every large generating plant where continuous service is demanded: the maximum overload capacity of the generators normally operating on the bus-bars should be such that at any time and under any conditions of load any one of the generators can be instantly disconnected from the bus-bars without necessitating a reduction of station load or causing a serious momentary drop of pressure. If any trouble, either incipient or actual, should then develop in one of the generating units, the unit can be immediately put out of service without waiting to start up another machine to take its place. Furthermore there should, if possible, be one unit held as absolute reserve which need not be operated except as a substitute. This enables any one generator to be out of service for repairs, even during load-peaks. The size of generating unit selected for an installation has an important bearing on the question of reserve. The larger the unit the lower the cost of the plant per kilowatt, but, by necessity, the larger will be the investment in the idle reserve machinery. The proper relation can only be determined by a study of the local conditions under which the plant is to operate.

A station operated by steam-turbines or by water power has certain advantages in reserve conditions. With steam turbo-generators, on account of the comparatively high part-load efficiency of the steam-turbine, all the units installed in the plant, including the reserves, can be kept in operation on the bus-bars at all times without serious sacrifice in steam economy due to the partial load on each unit. This enables a generator to be quickly disconnected from the bus-bars at any time without overloading the remainder or causing a serious drop in pressure. This condition also obtains in a water-power plant since the additional use of water caused by the continuous operation of the reserve units has only little effect on the cost of producing the power. With a reciprocating engine, however, each unit must be operated as far as possible at exactly the full-load point on account of the economy required in steam consumption. This prevents obtaining the full utility of the reserve machines.

The exciters in an alternating current generating station are of course the heart of the entire system, and the most careful provision should be made to insure continuity of service therefrom. Since the cost of the exciters is in every case only a small proportion of the cost of the plant there is little excuse for not installing ample reserves in connection with the exciter equipment.

Of equal importance with the complete reserve machinery installed is the stock of reserve parts held in the storeroom. There should be kept on hand at all times ready for immediate use a complete outfit of the parts of the prime-movers and generators which are most likely to wear out or break down. In the selection of such spare parts the most careful judgment should be exercised. In many instances a carefully selected reserve stock will enable breakdowns to be repaired in a few hours, that might require weeks, if the new parts, many of which might be special, had to be obtained from the manufacturer. From the standpoint of reserve, then, there is no part of the power-plant of more importance than the storeroom.

Generating Plant Switchboard.

Under this heading might be included all of the electrical equipment of the station from the terminals of the generators to the point where the outgoing feeders leave the power-house. This will necessarily involve a large amount of cable as well as all of the switch equipment and controlling appliances. Here the question of reserve is almost wholly a storeroom proposition. In the writer's opinion, the actual installation of duplicate cables in the station wiring and duplicate switches, controlling devices, etc., should be avoided as far as possible, as tending to occupy too much valuable space and to complicate the organization of this vital part of the plant. There should, however, be kept on hand, preferably in the power-house itself, the fullest inventory of switch-parts which are liable to injury, and full lengths of all sizes of cables used in the installation. The duplication of bus-bars is of course quite necessary in a generating plant, but more for reasons of flexibility of operation than for reserve. Bus-bar installations as now constructed are less liable to breakdown than almost any part of an electrical system. A great deal can be accomplished toward reserve in the case of switchboard equipment by keeping on hand a suitable outfit of jumpers with proper terminals soldered on to use for emergency connections to temporarily transfer feeder or generator leads from one switch to another.

Generating Plant Transformers.

Many of the considerations involved in the generating units enter into the question of duplication for reserve in a transformer equipment. Here also a proper balance must be established between the saving in cost per kilowatt by the adoption of large units and the saving in investment in reserve transformers by the installation of smaller ones. Another important question has recently been brought up in connection with transformer plants by the introduction of one polyphase transformer as a substitute for two or three single-phase transformers for a bank. A polyphase transformer occupies less space and costs less than a bank of single-phase transformers, but when reserve is considered it is not so good. If a bank of separate single-phase transformers breaks down the trouble is not likely to involve more than one of the component transformers and this can be replaced by a small kilowatt reserve. If, however, a polyphase transformer breaks down, capacity equal to its full polyphase rating is put out of service.

In the writer's opinion all important transformer stations should have a complete spare bank which can be shut down at any time without overloading the remaining transformers, and in addition one single-phase transformer should be held in stock to make good any bank in case one of the component transformers should break down.

A transformer station usually involves more or less of an equipment of high-pressure cables, switches, lightning-arresters, etc.; and in the present state of the high-pressure art there is nothing more liable to frequent destruction than the devices involved in this part of an electrical system. Consequently, here the storeroom reserves should be most carefully provided for.

Overhead Distribution.

If there is a single element in an electrical system where trouble is sure to develop sooner or later it is on the overhead lines, and the higher the pressure the more likely is the trouble to occur. This is so because the overhead lines are subjected to influences over which the power company has no control. These influences are principally lightning, general abnormal weather conditions, malicious interference, and accidental interference caused by the contact of other companies' wires during construction work. For these reasons it is practically out of the question to attempt to maintain a continuous power service over a single-circuit overhead line. There should always be enough circuits installed so that at least one can always be shut down without necessitating a reduction in load. This is especially true in the case of high-pressure lines. In low-pressure systems of 2300 volts or less it is nearly always possible to replace insulators and do other work on the line while it is "alive," but at higher pressures this should not be allowed if there is any regard for human life. In many plants where important interests are dependent upon the power transmitted the matter of duplication should be carried beyond the circuits and reserve pole-lines installed. Carried to its limit without regard to cost, the ideal condition would be a number of single circuits each installed on a single pole line and each line following a different route. With this arrangement lightning would not be likely to disturb more than one line at a given time, and a complete shut-down from malicious interference involving all the lines would be very improbable. The cost, however, in such a separation of lines would in most cases be prohibitive on account of purchase of right of way, patrolling, etc.

Underground Distribution.

When trouble develops on an overhead line the location of the breakdown can usually be quickly found by patrol, and repairs made without delay. In an underground feeder, however, the conditions are radically different. Breakdowns are difficult to locate and when found repairs frequently occupy many hours on account of the necessity for pulling out the defective cable from the ducts, putting in new cable and re-splicing. Duplicate or triplicate cables should always be installed where important service is involved. This obligation is conceded by most engineers, and spare underground cables are usually installed. The installation, however, is apt to be carried out in such a way that the security of the reserve cables is impaired. Underground conduits as now generally constructed consist of a congested mass of ducts so grouped that in the manholes the cables are crowded closely together and all in constant danger of destruction in case of a violent short circuit in the manhole. There is little value in installing spare cables when they are liable to be damaged at just the time when they are most urgently required. Such risk can only be obviated by constructing electrical conduits in such a way that the cables can be separated in the manholes by short-circuit proof barriers. Preferably, whenever possible, duplicate conduits should be constructed on opposite sides of the street or, still better, laid through different streets. Only by such precautions can the full benefit of the reserve cables be insured.

Investment in duplication of generating units and transformers for reserve purposes does not result in any saving in operating expenses. On the contrary, if the reserves are kept in continuous service, in general the losses will be increased and consequently the efficiency of the plant lowered by just so much. Investment, on the other hand, in reserve cables and overhead circuits can be made to pay directly; for if such reserve circuits are kept in operation the efficiency of the transmission is raised and the cost of producing the power lowered by that amount.

Sub-Station Apparatus.

The general considerations which apply to generating-plant reserves also apply to outlying sub-stations but in a less degree, for the complete shutdown of a sub-station involves only a portion of the power system. Farther out on the power network to the plants of individual customers, where the transformer or other apparatus is supplied by the power company, no reserve seems necessary under the ordinary obligations of such cases. If a breakdown occurs only the individual is inconvenienced, and therefore the risk is usually justified.

General.

The above stated conditions of reserve apply particularly where certain public utilities are involved. Among which may be mentioned:

1. Electrified steam railroads.
2. Traction system in large cities.
3. Street lighting and the lighting of large public buildings.

Where such interests are at stake storage-battery reserves are probably justified aside from all considerations of economy resulting from improvement in load-factor.

When the present steam railroads adopt electricity as a motive power for all traffic, both passenger and freight, more rigid requirements in reserve are likely to be found than have ever been considered necessary as yet in central-station practice. Under present steam road conditions if a locomotive breaks down, as frequently happens, probably only one train is stopped. The simultaneous breakdown of every locomotive on the road is of course improbable, consequently there is no likelihood of a complete tie-up of the system. Under a complete electrification, however, one whole division of the railroad might be operated from a single power-house and a breakdown in that plant would involve every train on the division. No important railroad system would venture to operate with such a risk hanging over it. This condition, in the writer's opinion, will lead beyond the mere duplication of apparatus in a power-house to the installation of duplicate or possibly triplicate generating plants, having such capacities that any one of the plants can be shut down in cases of catastrophe and the whole load of the system carried by the others. Such an arrangement with suitable reserves in transmission conductors would practically insure continuous train service at all times.

Where water-power is used for the operation of important power systems, duplication of generating stations is especially important. In steam-plants as now constructed with multiple stacks there is no single element of the plant which is common to and necessary for the operation of all the power units. Consequently any part of the equipment can be inspected and repaired without a total station shutdown. In an hydraulic plant, however, there are a number of elements in the development which are essential to the operation of the whole plant, among which may be mentioned the dam, flume, fore-bay, tail-race, tunnel, etc. In cases of emergency it may become necessary to shut off the main water supply in order to get access to these parts. Furthermore hydraulic plants are subject to ice troubles and floods in winter and low water in summer. It therefore seems essential if steam roads or other public utilities are to be operated electrically by hydraulic power that the system should be operated by more than one generating station.

Such are some of the considerations entering into this problem of duplication for reserve. The matter of reserve grows more important each year with the development of electrical applications. Ten years ago or more shutdowns on electrical power systems were taken as a matter of course, and no one used electrical power unless interruptions to service could be taken without serious inconvenience. At the present time, though the obligations of the power-generating companies are much more serious, and absolutely continuous supply of electric power is demanded by all users. To avoid loss of revenue and possibility of damage suits from shutdowns every power company is justified now in making a large investment in reserve to assure continuity of service.

Discussion on, "Time-Limit Relays", and "Duplication of Electrical Apparatus to Secure Reliability of Service", at New York, May 16, 1905.

H. G. Stott: The ordinary overload relay as described in Mr. Chellis' paper is employed to do the opposite of what the telegraph relay does : that is to say, the telegraph relay is used to apply a strong current to operate the receiving apparatus, while the purpose of the overload relay is to apply a comparatively weak current to operate a switch apparatus, because the main current has reached such pressures and strengths that it has become exceedingly expensive if not impossible, to design relays to work on main-line current. Different requirements have called for the design of different types of relays. The principal types mentioned in the paper—the overload, the differential, and the reversed-current, all have an application which is very concisely described in the paper.

I think that in this paper the principal points having to do with the control of a large amount of energy, are given on page 264; there the author recommends first opening the switch at that end of the feeder having the highest current and by that means making use of the resistance of the transmission lines to reduce the current on the short circuit when the second and final relays open on that current. This, of course, is an extremely important point in reducing the possible limit of current to be broken on short circuit.

Passing to Mr. Buck's paper, it contains a general and timely treatment of several important subjects. I do not quite agree with the recommendations in regard to the treatment of some of the apparatus. There seems to be a tendency nowadays to believe that the limit in size of stations has been reached. What the reason for that belief is it is rather difficult to tell. A capacity of at least 50 000 kw. has been attained, and there is no reason why power-houses should not be constructed with a capacity of 100 000 kw. or even more.

The principle of design in modern power-stations is to make each unit virtually a separate power-station in itself. The isolation of the generators, the main cables, the individual cables connected with them, the oil-switches, bus-bars, etc., permits all operating devices in almost all modern stations to operate as one unit, back to the boilers. Economy does not, however, dictate this separate operation. The question of how large to make the station is simply a question of how safe each unit can be made. I do not think the impression should be conveyed that the limit in size in large power-plants has been reached, unless there is some special point, where there is unreliable apparatus, such as the dam, flume, forebay, tailrace, etc., that regulates the entire amount of energy. In the steam-plant there is no one operating element of the plant that controls the whole amount of energy; the nearest approach to this condition is found in the water supply. In practically all stations the water supply is in duplicate and is also further assured by the use of large storage-tanks.

In regard to the safety of underground cables, one point has been rather neglected in the paper, which is that the higher the voltage the less the damage that is likely to be done to surrounding cables. It is a fact, which has been proved by experience, that the safety of a cable, in regard to its neighbors, varies inversely with the voltage; in other words, the larger the current carried, the greater the danger to surrounding cables, and the damage done is proportional to the square of the current. For instance, the damage done to itself by a short-circuit in a three-conductor, 11 000-volt cable, is very small, and practically no outside harm results. The limit now is not the amount of energy that can be transmitted, but the amount of voltage which can be carried safely, or for which the cables can be constructed. I think that shortly cables will be built to withstand pressures of 25 000 volts, as danger to the surrounding apparatus is much lessened by using high voltage.

On page 267, Mr. Buck emphasizes the importance of having several power-stations, at least more than one energizing electric railroads, in order to avoid the failure of the energy supply to the trains. I think too much stress has been put upon this point: I do not think the liability of failure of energy in this way is so important. I have examined the statistics of the percentage of time of interruption of train service in three years due to various causes, and find that of the total interruptions those due to the failure of electric energy are less than one per cent. If by the duplication of a station one per cent. of the interruptions could be avoided the other 99 per cent. due to such causes as derailments at switches, cross-overs and collisions, etc., would not in any way be affected by the use of two, three, or more power-houses. I think that is a rather important thing to emphasize, as it increases our respect very materially—at least it has mine in the investigations I have made—in regard to the reliability of service which can be given by one power-house.

Philip Torchio: The problem of protecting high-tension systems against shutdowns is of great importance, and it has necessarily received the careful attention of the engineers who have been concerned with the operation of central-stations. It is probably true that our largest central-stations are now equipped with protective devices to meet almost all of the exigencies of the service for each particular condition. It is also true that these conditions vary greatly in different stations, and it is doubtful if the same devices would be applicable to all cases.

The speaker has been connected with the development of the system of protective devices used by a prominent New York company; it may be interesting to describe the general features of the system that has, for the particular conditions of that company, given most satisfactory results. Seven years ago the company adopted for use on all of its high-tension switchboards two types of relays; one type a fixed time-limit overload relay installed at the generating end and one at the receiving end of each high-tension feeder, and the other an instantaneous reverse-current relay placed at the receiving end of the feeders. At the beginning the company did not feel confident of the reliability of these safety devices, so the relays were connected only to signal lamps. The relays were not entirely satisfactory and for considerable time a lot of experimental work had to be done before it was felt safe to connect a few of these relays to the trip mechanisms in a few stations. Then followed a period of investigations to find out whether the relays did more good than harm. About 3 years ago the experience was quite discouraging. Investigation of relays used on other systems proved equally unsatisfactory. A careful study of the problem clearly demonstrated two facts; one, that the existing type of relay was inadequate to fulfil all requirements of the service; the other, that to accomplish satisfactory results it was necessary to develop a well coördinated scheme of relays in which each element should have its proper relation to the other elements of the protective system. It was thought that the solution of this problem lay in the development of a time-limit relay which would operate in an interval of time in inverse proportion to the amount of current. The only relay of this nature available at that time was the dash-pot device attached to the ordinary overload relays; this was found to be unsatisfactory in service, and was dismissed from consideration. The manufacturers had been urged to develop a better relay to meet certain specifications which were given in detail. Developments along such a line of apparatus were, however, slow to materialize and in the meantime the New York Edison Company was not making great headway in protecting its increasing high-tension system.

A form of overload bellows-type relay which gave a characteristic curve somewhat similar to that of Fig. 8 of Mr. Chellis' paper, was brought to the speaker's attention and upon this type of relay a scheme of safety appliances was designed for the system. Aside from the system of protection of auxiliaries at stations and sub-stations, the continuity of the service of the system is safeguarded by the following relays:

Generators.—It has not been found desirable to install automatic circuit-breakers on the generators, as reliance is put upon the attendant to disconnect the generators by hand operation of the oil-switches whenever he finds it necessary so to do. To guide him an overload relay, operating signal-lamps, is mounted on each generator, This relay is without time-limit.

High-Tension Feeders, Waterside Station.—On each feeder is mounted an overload relay with a variable time-limit in inverse proportion to the amount of current. Curve I, Fig. 1 shows the characteristic curve of this type of relay, the points at which it is adjusted, and its relation in time and load to other similar relays at the sub-station end of the feeder.

High-Tension Feeders, Sub-stations.—The feeder-switch is automatic and is controlled by a relay similar to the one at the Waterside end of the feeder. The relay itself is identical and by suitable current transformer ratio a curve is obtained as shown in curve ?

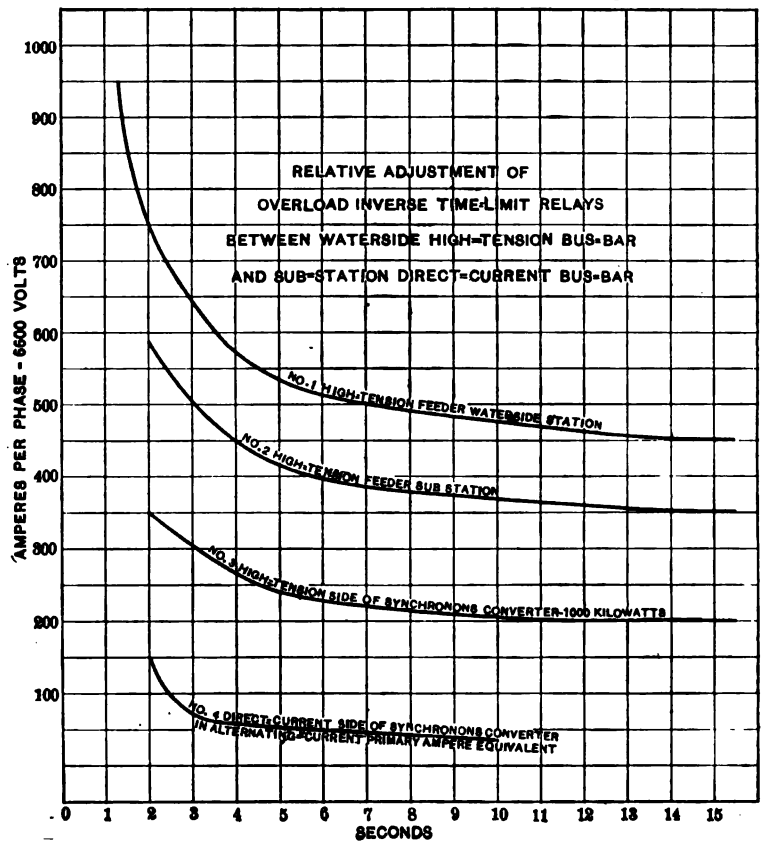


FIG. I

High-Tension Side of Synchronous Converters.—Each synchronous, or rotary converter, is equipped with a relay of the same kind as previously discussed, its load being proportioned by the current transformer ratio. Curve 3 shows the calibration of this relay.

Direct-Current Side of Synchronous Converters.—To be consistent with the general scheme above outlined the direct-current side of each converter should be equipped with a reverse-current inverse time element direct-current relay. A relay with an instantaneous opening could not be used at this point unless set to operate at a very heavy reverse current, which would in itself largely defeat its purpose. A fixed time-limit irrespective of current would render the relay of very little value, as the short circuit on the direct-current side might reach disastrous proportions before the fixed time of the relay had expired. The selection of the reverse-current direct-current relay in this instance is made feasible by the fact that each sub-station is equipped with large storage batteries which can always energize the pressure coils of the reverse-current relays. Curve 4 shows the characteristic curve of this relay, figured on a basis of primary amperes for the purpose of comparison with the curves above it. It will be noted that Curve 4 has only approximately the same characteristics as the other curves, but as the relay is not called upon to operate in a fixed relation with other relays this difference in the characteristics of the curves is not material.

These relays are now being installed to operate only signal lamps, until such time as they may demonstrate their ability to meet the emergencies for which they are eventually intended.

Two years ago in a paper before the INSTITUTE the speaker outlined the respective features of the relays just described and he then summarized the subject saying:

"All relays at the different points of the system and their time elements must be properly adjusted to operate the different circuit-breakers in the proper order, so that if the trouble is once cleared by the opening of certain circuit-breakers, the other relays reset themselves in the normal position, leaving the rest of the system in operation".

It is gratifying to report that expectations have been fully realized by subsequent experience. The success of such a system of protection is dependent upon the care that is given to the maintenance of the several relays, but it is also a fact that apparatus is now available which is not freaky and unreliable and certainly sturdier than most of the other switchboard instruments.

It is probable that as further experience is obtained it will be found that a number of these intricate and delicate pieces of auxiliary apparatus may be advantageously omitted, but as matters now stand inconvenience of this kind must be put up with. Experience proves that a system based on the use of the inverse time-element relays gives a solution free from serious drawbacks.

There are cases in water-power installations where a short circuit on one line reduces the speed and voltage of the generators. and when the short circuit is cleared the speed and pressure increases, while the synchronous motors operating on the other lines fall out of step, overload the lines, and cause their circuit-breakers to open. Troubles of this kind have created a feeling of uncertainty as to the desirability of installing automatic relays in such cases.

The speaker does not wish to advocate a complex system of protective devices, if such can be omitted with advantage; but if it is found necessary to install these relays, he would emphasize the necessity of not confining the installation of the relays to only a portion of the systems, but to extend them to the whole installation so as to coördinate the different factors into a protective scheme in which every element bears the proper relation to the other elements.

C. O. MAILLOUX: The relay question is a very interesting one. As Mr. Torchio has pointed out, there have not been any satisfactorily working relays until recently. Having had occasion to study the question closely both in this country and abroad, I was surprised to notice the impatience, so to speak, with which the relay question is discussed by most operating engineers. This is especially so in the far West, where it is found that if the designing engineer does put in relays the operating engineer insists on making no use of them. He prefers to take his chances with machinery without the relays rather than with the relays in the state of their development up to two or three years ago.

In a case where there are synchronous converters, it is indispensable to have some device that will prevent the synchronous converters from running away. In cases where the distribution is by alternating currents, as well as the transmission, and therefore converters are not required, for example, where the load is principally or wholly lighting, it may be said that there is scarcely any necessity for relays. In New York city and many other large cities, the transmission is by alternating current at high pressure, and the distribution is by direct current at low pressure. In such cases synchronous converters must be introduced to convert the alternating current into direct current, and it is necessary to have some system of relays.

Referring to Mr. Buck's paper, the preamble, so to speak, contains an interesting statement of what might be called the equation of obligation, where he equates the obligation of the company to its stockholders with the obligation of the company to the public. That is an important question, and one that every engineer has to consider, whether he is designing a station or operating it. Unfortunately, it is difficult to define and formulate the quantities that enter on each side of the equation. On the one hand too much disregard of the quality of the service may be shown, with the object of reducing the initial cost and fixed charges; and on the other hand many engineers are inclined to err in the other direction by taking too many precautions for the security and continuity of the service, the result being that there is a large investment and an expensive one. The evolution of central-station design is greatly increasing the obligation of control and of safety. The switchboard and all the appliances that go with it and are part of it, which originally were but a small part of the central station,—have now become not only a large part, but an important part and in many cases a very expensive part of the equipment. It may be said that in some cases there has been too much elaboration, just as there has been too little in others. The reference to what is called the " store-room " reserve, is a sensible and timely one. There are many instances where the reserve can be provided in just that way, and where it is possible to avoid incumbrances of extra parts at the switchboard and elsewhere. The reference, made by the last speaker, to the station where everything is accessible is also important; every one who has visited modern stations and studied the question of the requirements of their design realizes that they should be made that way; otherwise they could scarcely be managed or operated at all. The reference to the cost of replacement, as affected by the size of the unit, is indeed a very important question, but as the last speaker pointed out it is a question which the engineer should really discuss and consider at the time the system is designed. One sees, especially in electrical traction stations, the wonderful growth which they have had; they have had suburban extensions which have called for increased power and compelled the company to resort to all manner of expedients in order to get current at all to operate its lines. The difficulties are sometimes great, but where it is at all possible to anticipate such growth, the question of the number and size of the units should be carefully considered. That has a great bearing, not only upon the initial cost of the plant, but also upon the cost of the reserve apparatus, as Mr. Buck points out. There are cases where large units would be desirable, but of course the reserve must be larger, and here the character of the load-curve comes in. It is important to consider that. If the load-curve is comparatively flat, the reserve capacity required might be quite different from what it would be if there was a heavy peak; and the size of the units for reserve would be different.

It is almost always the rule in Europe that polyphase transformers are used for polyphase transmission and distribution, while here the general rule is to use single-phase transformers. So far as I have been able to ascertain, this difference in practice is due to the fact that it costs less in America to make single-phase transformers, and in Europe to make the polyphase transformers; the reason for the difference in cost being, perhaps, that more handwork is required to make polyphase transformers than to make single-phase transformers. I am not familiar enough with the methods of manufacture to understand the reasons for the difference, but it is a fact that the cost of the reserve capacity is greater when polyphase transformers are used than when single-phase transformers are used. I have been compelled to use single-phase transformers, not only because polyphase transformers could not be obtained, but because in the case of the three-phase plant, for instance, the reserve transformer only added one-third, making four single-phase transformers, instead of adding another polyphase transformer.

S. D. SPRONG: The proper selection and adjustment of the various relays in a system of this nature is one of the determining elements in the continuity of service.

Referring to the last paragraph on page 249, it is said that some of the characteristics of the relay referred to for generators would be as follows: Short circuit current, 4.95 amperes; overload current at normal pressure, 8.8 amperes.

Is it not probable during periods of light load when only one or two units are running that a short circuit on one of the feeders, if occurring close to the power-station, would so depress the generator voltage as to cause the relays to operate under the characteristics of "short-circuit" rather than under those of "overload" at normal pressure? if so, this would reduce the opening point to nearly one half of what it should be for any kind of feeder trouble, which is in its relation to the generators an overload. If it is essential to maintain the differential factor, it would seem for these reasons that the differential feature is not desirable in a generator relay at all points of the 24-hour load.

The question arises, however, whether a generator that gives 6.6 amperes on short circuit will give the necessary overload current to trip at 8.8 amperes at or near normal pressure. In other words would the generator under any conditions ever trip its relay by overload?

In the last sentence before Fig. 6 on page 254, it is said that a time limiting device such as a bellows or dash-pot, while ideal from the standpoint of simplicity, is not positive. One of the large operating companies in New York has had a varying number—more than 150—relays of this type in operation for a period of about 18 months and has not experienced failure in operation in a single instance, nor has the regular periodic inspection and test made on all the relay devices disclosed any of them in an inoperative condition due to the air type of time-limiting device.

Referring to the broad question of relays in the generator circuit, does Mr. Chellis consider it essential for good operation to have automatic opening of switches in the generator circuit under any conditions. It is not the practice among some of the larger companies that have been in operation for some years to have automatic operation of the generator switches. Their practice of having a relay that will signal the operator only at times of extreme load has proved entirely satisfactory.

In the last paragraph on page 256, it is said that in an ideal combination the sub-station end of the feeder should have an instantaneous reverse-current relay. This seems open to question, unless the relay is set at a high figure in consequence of which it would lose much of its value for the purpose intended. If set at a relatively low point, practice shows that the momentary reversals due to synchronizing a synchronous converter, or short depressions of voltage due to short circuit, will cause the converters to reverse for an instant due to the energy stored in them, and trip the relay, thus cutting out one or more good feeders. This will occur whether there are storage-batteries in multiple with the system or not.

In the second paragraph on page 257, it is said that a direct-current reverse relay operating a circuit-breaker on the direct-current side may be used to open the circuit of an inverted converter thereby preventing the converter from attaining destructive speed in case of open field circuit. It would seem that relays of the type described, and without time-limit either fixed or inverse, would be very liable to disconnect the converter during momentary depression in the system voltage resulting from short circuit on a feeder, or other causes. This applies to sub-stations where storage-batteries are employed, or where a system is divided into two or more sections operated independently, each section supplying a portion of each sub-station's load. The next paragraph says that the relays referred to are adjusted to operate at about 15 per cent. rated current in the reverse direction, and that such relays have a value for limiting the speed of the converters. It seems to be the opinion of most engineers that when a speed-limiting device is found necessary, it should be a device designed for that purpose only, and its operation should depend solely on the speed of the converter.

In the first sentence of the paragraph on page 258, beginning with the bottom line of the preceding page, it is said that the order of operation of relays may be determined by the value of the time adjustments. This, of course, is true up to a certain point, but does not hold over the whole range of current flow in cases of severe short circuit. It has been found in practice that even with a considerable difference in time adjustment a number of relays that may be in series would all operate and open their respective switches. This is possibly due to the fact that two relays which are adjusted for series working, and have a considerable difference of time in operation at certain overloads, will both come within a certain minimum time if the overload is carried to the extreme point which is sometimes reached in operation. This minimum time is that which is required for an oil-switch to operate. It is therefore easily seen that while the relay with the lesser time will start the operation of the oil-switch, if it does not actually open and free the circuit of the load before the second relay has reached the operating point, both switches will open. The practical result of this is that no discrimination is possible between relays in series if the load goes above a certain point.

This is referred to again in the last paragraph on page 258 where it is said that they will discriminate at all loads; they no doubt will at all ordinary loads or overloads, but when current flow reaches an extreme figure, as sometimes occurs in a large system, all the relays connected in series are very liable to open their switches.

W. F. WELLS: In the opening paragraph Mr. Buck says, "The question of the proper amount of reserve capacity in an electrical installation is purely a practical one, for which no definite laws can be enunciated". Experience is reputed to be a good teacher and the general practice of a large lighting company, deduced from the experience of a number of years, may be of interest. This company generates alternating current at 6 600 volts, which is transmitted underground to sub-stations, where it is transformed to direct current at 120–240 volts.

In general sufficient equipment is installed and operated to render it possible at all times to disconnect instantly any individual or group unit, wthout interfering with the service. As the number of units increases, the proportion of investment in emergency or spare equipment diminishes and soon becomes of relatively minor importance. The interest and depreciation charges on account of this spare equipment are partly offset by the greater flexibility in operating, and decreased transmission losses. The proportion of reserve required in each of the seven classes of apparatus mentioned by Mr. Buck, depends to a large extent on the reserve in the following class. It is simpler to discuss them in reverse order.

Commencing with the distribution net-work supplying customers; sufficient feeders connect this with the sub-stations to maintain the pressure in case any of them should burn out. In growing districts this simply means the installation of feeders a year or so in advance, and the fixed charges incident thereto.

In the sub-stations, the reserve is proportionately of as great importance as in the generating stations, as it must provide not only for accident in the sub-station but also for part interruption of supply caused by accident to the transmission system, or in the generating station. In general, the practice has been to design the sub-station to contain from 4 to 8 transforming units and to install one more unit than is necessary to carry the maximum load. A storage-battery has been found absolutely necessary, the capacity of which at the one-hour discharge rate, is equivalent to one of the transforming units. Where more than 5 units are installed the battery capacity exceeds 25 per cent. of the maximum load. An important part of the reserve of each sub-station is the assistance that can be rendered by the adjacent sub-stations.

All the transmission cables are underground and in order to avoid interruptions from "congested mass of ducts and cables crowded in manholes" as referred to by Mr. Buck, 4 separate and distinct lines of subway have been constructed, starting from 4 separate manholes in front of the generating station. Each sub-station has at least one more cable than is required for its maximum load, and these cables are divided among the different subway routes. In this way the greatest possible harm to the transmission system by a violent short circuit in a manhole would be to put out of service, and perhaps destroy less than 25 per cent. of the transmission system. Should this amount of damage occur at the time of the maximum load, the overload capacity of the cables following the other routes would be sufficient to maintain the service.

To guard further against a violent short circuit the cables in all manholes are protected by a fire-proof covering over the lead. In 5 years' experience on a system containing many miles of high-tension underground cable, there has been no case where a cable burn-out has injured an adjacent one.

In the generating plant the high-tension and exciter bus-bars are the only parts of the plant which are common to and necessary for the operation of all power units, and these have been designed and constructed with the greatest possible care. Every known precaution has been taken with each generating unit, consisting of engine with individual condenser, and generator with its armature, field, and control cables, switches, rheostats and instruments to protect them from possible injury from adjoining apparatus or external source. The installation of two oil-switches, of the compartment type, in series in generator leads has not only insured the opening of the circuit between the generator and bus-bar in case of trouble, but has provided an additional means for synchronizing, etc. in case a switch or instrument transformer fails to operate properly. The reliability of the supply of current for the generator fields and control circuits is secured by a storage-battery, connected at all times to the excitation bus-bars. The station lighting and all auxiliaries can be connected by these bus-bars.

It has not been found necessary, as stated in the paper, to operate reciprocating engines at exactly full load on account of steam consumption. The engines and generators are so proportioned that the variation in steam consumption per kilowatt hour as shown by tests, between the limits of 25 per cent. underload and 25 per cent. overload is less than 5 per cent. from the maximum economy. The practice is to operate engine-driven units at slightly under normal load and to depend on their overload capacity in case one is instantly disconnected. Should it be necessary to disconnect two simultaneously, the batteries would supply the necessary energy until an additional unit could be started.

During the maximum, all units carry approximately normal load, and if it is necessary to take one out of service the overload capacity of the remaining units and the batteries can be depended on as a substitute. It has not been deemed commercial, nor has it been found necessary, to hold one unit out of service as reserve during the peak.

In the boiler-plant duplication is avoided by arranging the steam-piping so that all boilers and engines are connected to a ring-main, divided by suitable valves. This renders it possible for any group or groups of boilers to be used with any combination of engines. Boiler feed lines are similarly laid out and at least one more feed-pump operated than is required by load conditions. With such an arrangement it is necessary to run only a very small percentage of boilers for emergency use.

In general each group of transmitting and transforming equipment has sufficient capacity to permit the withdrawal from service of any individual unit without making it necessary to operate the balance beyond the normal capacity. The generating station is capable of carrying the entire load when operating at normal capacity. In case of accidents the substation storage-batteries and overload capacities of the remaining equipment are capable of maintaining service until repairs are made.

G. F. Chellis: With regard to the various remarks in connection with relays, I think a great deal of relay trouble is caused by improper connections and adjustments. That is my experience.

H. W. Buck: Mr. Stott has spoken of the relative damage in underground cables between those operating at high voltage and those operating at low voltage in cases of manhole short circuits. In general I fully agree with this contention, but I have noted a number of instances where 11 000-volt, 3-conductor cable short circuits have caused considerable damage to neighboring cables, due to the fact that the circuit-breakers on that feeder have not opened promptly at the power-house, thereby allowing the short circuit to hang on for some time. That is a condition which may occur on any system.

In spite of what Mr. Stott has said in the matter of one powerhouse vs. two or more. I still favor two independent plants as the sources of power. In the case of steam-plants, for the reasons stated in my paper, this duplication of generating stations may not be so necessary, but accidents may happen even to steam-plants: boilers and steam-pipes may burst, and fly-wheels or armatures may also burst, due to engine runways, all of which might temporarily wreck the powerstation. I, therefore, believe that with either steam or waterpower two generating stations are more reliable than one. Whether one plant is reliable enough or not under a given set of conditions is another matter.

The variety of apparatus in the generating station is very important. This applies especially in the case of some of the older plants, where good judgment was not exercised by the engineers who laid them out. There is a tendency sometimes in designing plants to provide generating units for immediate load conditions only, without taking into consideration the possibility of greater demands upon the station in the future. The result is, after a few years, that the station is called upon to meet a load demand of an entirely different character, which necessitates the installation of units not only of different size, but of entirely different type. At the end of 5 or 10 years, then, a miscellaneous, assortment of generators will be found, which makes the problem of reserve a difficult one, since the generators installed cannot be used interchangeably on the various circuits.

DISCUSSION ON "TIME-LIMIT RELAYS," AND "DUPLICATION OF ELECTRICAL APPARATUS TO SECURE RELIABILITY OF SERVICE," AT PITTSBURG, JUNE 5, 1905.

H. R. STUART: Mr. Chellis is mistaken about one or two things. There are two time-limit devices that are independent of the load; that is, they are not inverse time limits and will operate in the time they are set for, no matter whether the overload is 100% or 500%. One device operates as follows: on one end an arm works a dash-pot, and the weight of the core holds that arm down; and on the other end imagine a weight which will not quite balance the armature core, but will slowly move the dash-pot and arm when the core is removed. A short circuit raises the armature core, allowing the arm to move slowly. When it has made its full travel, it will make contact, closing a tripping circuit. The other design has a clockwork mechanism that has the same time no matter what the overload is.

No two installations of relays are alike, for different conditions require different applications of the same relays. The relay described by Mr. Chellis is in some respects similar to a wattmeter in that it has series and shunt coils. One might infer that it is not so good as a straight overload relay, which is simply a kind of solenoid movement that closes a contact, and is kept from closing that contact by means of an opposing or retarding force, such as a dash-pot or bellows. I do not know how many different applications have been made of these relays. Various types of these relays are on the market, each one good for its particular purpose.

P. M. LINCOLN: The first law of the operating man is to keep the power on his circuit. It is only when he is convinced that the addition of a relay is going to prevent more trouble than it is likely to cause that he decides to insert it. The tendency is to abandon the finer developments of relays, the feeling being that they cause more interruptions to the circuits than they prevent. The relay acting wrong on one occasion and throwing off the load, will do more toward prejudicing the operating man against it than a good many years' experience when it goes all right.

H. R. STUART: I think the time-limit relay is all right in its place. Even if it did not work satisfactorily 90% of the time, it would still be satisfactory. In motor work above 100 h.p. at high voltage, a fuse is a bit dangerous; it simply keeps the circuit breakers from opening when the motor starts; when the current drops to normal the time limit goes back and everything is all right. If something goes wrong for more than the time limit, the breakers come out and protect the apparatus. A good deal of damage might be done in 10 seconds, but this is better than not having any protection at all. The tendency in generating stations is to fasten in the generator breakers, making them non-automatic; then the automatic breakers on the far end of the feeder circuits will open to protect them and the time limit on the station end of the feeder circuits will protect the station. But it is a question whether it is best to put them in on the generators or not.

Chas. F. Scott: Perhaps Mr. Buck's paper will lend itself to a mathematical solution—a solution involving a coefficiency of reliability for the different parts of the plant. For example, take all the generators in the country; they will have accidents, say once a year; the switchboard cables and power-house cables may have an accident once in five years; transformers once a month or once in 20 years, as you choose. Then take the cost of duplicating these different elements and make calculations for definite limits. Say a generator is liable to have an accident once a year, and some other element, a transformer or time-limit relay, once a year; it is evident that one could be duplicated at very small cost, the other at considerable cost. Therefore, although both have the same liability to accident, you could increase the reliability of the system at much less cost by duplication at one place rather than at another.

A case came to my attention two years ago: the transmission voltage proposed was 30 000, with two circuits run on one line of poles. The distance was only 15 or 20 miles. I suggested that possibly the voltage was rather high, that it would be better to have two pole lines. I asked what the total cost of transmission was, including poles and wires, in percentage of the whole plant. I have forgotten the figure; it was something like 2 or 2.5%. I suggested that this most vital part of the system would be much safer by reducing the voltage and putting in duplicate pole lines at an increase of only 1 or 2% of the total cost of the plant; and that was done.

A plant about 25 miles long, at 20 000 volts, running through a rocky, mountainous country, had a single-pole line and gave remarkable service. I think it is running still with simply one line of poles; I know some time ago it had the record of running several years with practically no interruption due to the line.

While visiting some Western transmission lines I found that the operating engineers were not very solicitous about generators or switchboards or line. They were more concerned with the choking effect of leaves in the flume. The flume line was constantly patrolled, and there were automatic means of readily opening the flume at different points to let the water out. In short, the reverse-current relays were applied to the hydraulic transmission rather than to the electric.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

THE ORGANIZATION AND ADMINISTRATION OF NATIONAL ENGINEERING SOCIETIES.

PRESIDENTIAL ADDRESS.

BY JOHN W. LIEB, JR.

The most important factors in promoting the advance of the engineering profession, and in disseminating and rendering available to the world the valuable experience and data accumulated by engineers, are the professional associations or national engineering societies. The importance of interchange of data, and results of observation and experience, was realized long before the practice of engineering had been exalted to the dignity of a profession.

While military engineering was recognized as a special calling from the earliest times, and great military engineers, such as Vauban, and bridge and highway engineers, such as Perronet, had achieved eminence, it was manifestly impracticable for military men to associate for the purpose of interchanging information, on the secrecy of which the military establishments of nations were dependent for their offensive and defensive efficiency. The first important step for associating engineers into a professional body was taken, in 1828, by Thomas Telford, who applied for Royal Charter for the Institution of Civil Engineers, of Great Britain, in the name of 156 of his colleagues, some of whom had already formed a society as early as 1818. The original charter recites that the body is formed:

* * * * "for the general advancement of mechanical science, and more particularly for promoting the acquisition of that species of knowl-

edge which constitutes the profession of a civil engineer, being the art of directing the great sources of power in nature for the use and convenience of man, as the means of production and of traffic in states both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation, and docks, for internal intercourse and exchange, and in the construction of ports, harbors, moles, breakwaters, and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and adaptation of machinery, and in the drainage of cities and towns."

It will be seen that this comprehensive, and now historic, definition of the field covered by the profession of the civil engineer, as formulated by Tredgold, includes broadly all branches of modern engineering science, except military engineering, and, directly or by implication, includes within its scope, mechanical, mining, electrical, and sanitary engineering, and naval architecture. It was not long before important discoveries in the realm of physical science, and epoch-making inventions and improvements in the mechanical arts, opened new fields of industrial activity, which broadened the field covered by the engineer, and were reflected in a differentiation of the profession, resulting, in Great Britain, in the organization of the Institution of Mechanical Engineers, in 1847, the Iron and Steel Institute in 1869, and the Society of Telegraph Engineers and Electricians in 1871, which, in 1889, became the Institution of Electrical Engineers.

Coming now to our own country, the American Society of Civil Engineers was organized in 1852, the American Institute of Mining Engineers in 1871, the American Society of Mechanical Engineers in 1880, and the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS in 1884. While these are the distinctively national engineering societies, there are other technical associations like the Society of Naval Architects and Marine Engineers; the American Society of Heating and Ventilating Engineers, the American Street Railway Association, etc., which, although of national importance, do not come within the scope of this address.

There are many other professional bodies in the United States also identified with the engineering profession, some of them of a national character, which, in addition to professional activities, are organized for commercial relations, and whose members consist largely of business corporations. To this class belong the National Electric Light Association and the Association of Edison Illuminating Companies.

There are also others that are largely local in character, such as the Pacific Coast Transmission Association, the Engineers' Society of Western Pennsylvania, and the league known as the Association of Engineering Societies, which represents a total membership of 1766, in 11 local Engineers' Clubs or Societies.

In this review we shall confine our attention to the four national engineering societies first referred to, with some reference to the corresponding bodies in Great Britain and on the Continent.

The membership of these bodies, divided into classes according to the last official reports, is given in the following table; as a matter of general interest there is also added a corresponding tabulation of the more important European engineering societies.

NATIONAL ENGINEERING SOCIETIES (U. S.).

Name and Date of Organization	Date of Report	Hon. Members	Full Members	Asso. Members	Associates	Junior Members	Total
American Society of Civil Engineers, 1852	Jan. 1, 1905	9	1795	903	127	*367	3203
American Institute of Mining Engineers, 1871	Jan. 1, 1905	7	3483	—	190	—	3680
American Society of Mechanical Engineers, 1880	Jan. 1, 1905	19	1915		237	609	2780
American Institute of Electrical Engineers, 1884	Jan. 1, 1905	2	481	2851	—	—	3334

* Including 27 Fellows.

FOREIGN ENGINEERING SOCIETIES.

Name and Date of Organization	Date of Report	Hon. Members	Full Members	Asso. Members	Associates	Total
Institution of Civil Engineers (of Great Britain) 1818	Jan. 1. 1905	19	2191	4116	271	*6597
Institution of Mechanical Engineers 1847	Mar. 1, 1905	9	2351	1545	72	†3977
Iron and Steel Inst., 1869	Jan. 1, 1905	11	1898	—	—	1909
‡Institution of Electrical Engineers 1889	Aug. 31, 1904	6	§1101	1435	1761	‖4303
Verein Deutscher Ingenieure, 1891	Apr. 24, 1903	6	17543	—	—	17549
Societé des Ingénieurs Civil de France, 1848	1901	—	—	—	—	3691

* Includes 136 Foreign Members.
† Not including 450 Students or Graduates.
‡ Originally organized as the Society of Telegraph Engineers and Electricians in 1871.
§ Not including 1144 Students or Graduates.
‖ Not including 1107 Students or Graduates.

A study of the annual reports of these bodies and of their constitutions and by-laws is of considerable interest, as showing their progressive expansion, growing influence, and higher professional standing from year to year, and the lines along which these developments take place. We shall not undertake a retrospective analysis, however, but rather confine ourselves to a comparative study of the methods of organization and business administration of the four national engineering societies, as revealed in their last annual reports.

It should be stated at the outset that this study is not undertaken with the view of criticizing the methods followed, or results accomplished by, our sister societies, but for the purpose of profiting by their experience, and, if possible, avoiding in our own rapidly growing body any abnormal development which may detract from its efficiency as a whole, or result in purely local development at the sacrifice of general usefulness and national standing.

One of the first questions we encounter is the grades of membership, then the requirements of admission to them, and the method of election. These questions are of fundamental importance and are worthy of the closest attention, because upon them more than upon any other feature of the organization must depend the professional standing of the society and its healthful growth in membership and influence. There is no honor within the gift of the society that requires the exercise of so much judgment, such fidelity to its interests, such conscientiousness, impartiality, and impersonality, as membership on the Board of Examiners, or committee on admissions, and it is deserving of the highest recognition. The requirements for Honorary Membership demand no lengthy discussion, as the practice of all the societies is essentially identical in this respect. The requirements for full membership vary greatly in the four societies, as will be seen in extracts from their Constitutions.

AMERICAN SOCIETY OF CIVIL ENGINEERS.

Constitution—Article II—Membership.

2. A Member shall be a Civil, Military, Naval, Mining, Mechanical, Electrical, or other professional Engineer, an Architect or a Marine Architect. He shall be at the time of admission to membership not less than thirty years of age, and shall have been in the active practice of his profession for ten years; he shall have had responsible charge of work

for at least five years, and shall be qualified to design as well as to direct engineering works. Graduation from a school of engineering of recognized reputation shall be considered as equivalent to two years' active practice. The performance of the duties of a Professor of Engineering in a technical school of high grade shall be taken as an equivalent to an equal number of years of actual practice.

AMERICAN INSTITUTE OF MINING ENGINEERS.

CONSTITUTION—ARTICLE II—MEMBERS.

Sec. 3. The following classes of persons shall be eligible for membership in the Institute, namely: As Members, all professional mining engineers, geologists, metallurgists or chemists, and all persons practically engaged in mining, metallurgy or metallurgical engineering.

AMERICAN SOCIETY OF MECHANICAL ENGINEERS.

CONSTITUTION—MEMBERSHIP.

C 9. A Member shall be thirty years of age or over. He must have been so connected with Engineering as to be competent, as a designer or as a constructor, to take responsible charge of work in his branch of Engineering, or he must have served as a teacher of Engineering for more than five years.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

CONSTITUTION—ARTICLE II—MEMBERSHIP.

2. A Member shall have been an Associate, and at the time of his transfer to membership he shall be not less than twenty-seven years of age, and shall be:

a. A Professional Electrical Engineer; or

b. A Professor of Electrical Engineering; or

c. A person who has done important original work, of recognized value to electrical science.

3. To be eligible to membership, as a professional Electrical Engineer, the applicant shall have been in the active practice of his profession for at least five years; he shall have had responsible charge of work for at least two years, and shall be qualified to design as well as direct electrical engineering works. Graduation from a School of Engineering of recognized standing shall be considered the equivalent of one year's active practice.

4. To be eligible to membership as Professor of Electrical Engineering, the applicant shall have been in responsible charge of a course of Electrical Engineering at a college or technical school of recognized standing for a period of at least two years.

It will be seen that two of the societies fix an age limit of 30 years, one of 27 years, and one fixes no limit; one society requires professional practice for 10 years, one for 5 years, and two set no limit; three of the societies require professional competency in designing as well as constructing or directing engineering works, and one requires the applicant to be professionally or practically engaged in the branch of engineering with which the organization is identified.

In the case of the Mechanical Engineers and the Civil Engineers the election is by ballot of the membership at large after approval by the Executive Board or Council; in the case of the Mining Engineers and Electrical Engineers, election is by direct vote of the Board of Directors, in the latter after submitting the names to the membership at large, in the former without so doing. In the Mining Engineers, Mechanical Engineers, and Electrical Engineers the application is first passed upon by a Board of Examiners and then by the Executive Board or Council; in the case of the Civil Engineers it is passed upon by the Board of Directors without action by an Examining Board. The Electrical Engineers' Constitution requires that all Members shall first be elected as Associates, and then transferred by the Board.

It will be seen from the above how different are the requirements for full membership in the several societies, and how varied is the procedure for election. It would seem at first thought that the more explicit the Constitution in its exact definition of the conditions for membership the easier it would be for the Membership Committee to act, but this is by no means always the case, as it often prevents taking a broad view of the candidate's eligibility and is liable to exclude desirable material on technical grounds, although on the other hand it is a protection against too liberal an interpretation of the requirements by examiners. It would seem that a better division of responsibility and a more direct control of the class of men admitted to membership ought to result by giving wide publicity to their candidacy and election by ballot of the membership at large, after the candidates have passed the scrutiny of the Board or an examining committee. A young society covering a branch of engineering that has but recently become specialized cannot in the beginning impose rigorous requirements as to age limit or time of professional service; furthermore the branch of engineering may be such as to make it difficult to impose severe technical requirements.

In the case of the Civil Engineers the accepted definition is sufficiently broad to cover applicants who are professionally engaged in any of the other branches of engineering; the Mechanical Engineers' definition is somewhat less comprehensive; that of the Mining Engineers is still less so, while that of the

Electrical Engineers is really restrictive to professional electrical engineers. Under our INSTITUTE's constitution, however eminent a man may be as a civil, mechanical, or mining engineer, he may not fulfil the qualifications of an electrical engineer. It will thus be seen that anything like standardization in the matter of requirements is wholly out of the question, although a greater uniformity in requirements and procedure for election would be advisable. It is difficult for an applicant in every respect qualified for full membership in our INSTITUTE to understand why it should be necessary for him to pass through the preliminary, or, as it were, probationary grade of Associate, and then be transferred to full membership, but the Constitution is clear on that point. Applicants whose superior qualifications would entitle them to immediate election to full membership, after their election to the preliminary grade of Associate—which would take some time, several months at least—are liable not to make application for transfer, with the result that many remain in the Associate grade who should certainly be transferred, and when they find the cause of the delay are likely to criticize the administration.

We now come to the consideration of the other grades of membership—associate membership, associates, juniors, etc. It would lead us too far afield to treat each grade in full and we shall confine ourselves to some general observations. It is necessary to provide one or more grades for young men just entering professional life through which they can rise, as they acquire experience, to the dignity of full membership; but it is necessary also to provide for another class of men who, though not professional engineers, nevertheless coöperate with them, and conduct engineering works, while at the same time acting as executives or as business managers. To such men, eminent in their particular branches of activity, it is humiliating to be placed permanently in an inferior grade of membership with the beginners in professional service; the situation could be satisfactorily met by establishing the grade of Associate, Junior, and Associate Membership, to represent successive steps in the advancement to full membership, the Associates forming a class by themselves.

We now come to the question of dues, and at the same time we may with advantage consider the general question of income and expenses, or the cost of conducting the business of the societies.

The expense of membership in the several societies is as follows:

	Entrance Fees.			Annual Dues.			Foreign.	
	Juniors.	Associates.	Members.	Juniors.	Associates.	Members.	Associates.	Members.
Amer. Society Civil Engineers	$10	$20–25	$30	$10–15	$10–15	$15–25		
Amer. Institute Mining Engineers....	—	10	10	—	10	10		
Amer. Society Mechanical Engineers.	15	25	25	10	15	15		
Amer. Institute Electrical Engineers..	—	5	15	—	10	15	5	10

In view of the new relations entered into between the three national engineering societies that are to occupy jointly the Union Engineering Building, and as they now have approximately the same number of members it would seem desirable to have membership dues as nearly uniform as practicable.

It is probable that the entrance fees of our INSTITUTE might be revised without disadvantage by increasing the entrance fee for Associate to at least $10, and requiring payment of an additional $15 on transfer, making a total of $25 for full membership. An increase in annual dues, also, is not at all improbable in the near future, and they might with advantage be increased to $15 for resident Associates (within 50 miles of New York) and to $25 for resident Members; this increase for resident membership would seem to be warranted by the greater advantages enjoyed by the members residing in or near New York, more especially after occupancy of the Union Engineering Building.

Let us now consider the annual receipts and disbursements per paying member per year in the four societies. These figures are presented purely as a matter of general interest and not at all for the purpose of invidious comparison; the table of receipts and disbursements per member is subdivided under appropriate heads as accurately as they can be compiled. These figures do not include extraordinary receipts and disbursements, but, as far as can be learned from the annual reports, they cover only the regular and ordinary items of income and expenditure.

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

RECEIPTS.	Civil	Mining	Mechanical	Electrical
Entrance Fees	$2.59	$0.28	$2.45	$0.83
Dues	16.99	10.64	14.04	9.30
Transactions, Sales and Adv.	1.86	2.09	1.64	1.70
Badges and Certificates	.65	—	—	.28
Interest	.36	.34	—	.21
	$22.45	$13.35	$18.13	$12.32
DISBURSEMENTS.				
Transactions	$4.63	$5.28	$7.50	$3.77
Salaries, etc	6.13	4.22	3.99	2.20
Meeting Expenses	.29	.30	.94	.82
Library, including Rent and Salaries	.30	.80	.39	.81
Rent	2.84	.74	2.79	.75
Stationery and Miscellaneous Printing	.62	.34	1.19	.70
Postage	1.10	1.02	.26	.66
General Expenses	.34	.47	.11	.54
Badges and Certificates	.50	—	.33	.25
Express	—	.83	—	.22
Totals	$16.75	$14.00	$17.50	$10.72
Credit Balance per Member	$5.70	—$0.65	$0.63	$1.60

It should be borne in mind that no deductions of value can be drawn from a comparison of these figures alone. Take the cost of the Transactions for instance: In order to make a comparison of the relative economy with which this item is handled in the several cases, it would be necessary in each instance to know the number of pages and cuts, and the number of advance copies distributed at meetings, or monthly advance publications sent to members in addition to the regular annual volumes. The figures therefore represent the amounts which are being spent on the several items, rather than a comparison of their economic handling; it would be fallacious to assume that the figures necessarily represent the comparative economy with which the societies conduct their affairs as indicated by the items in the table.

It may also be interesting to compare the receipts and disbursements per INSTITUTE member within the last five years, during which the membership has increased from 1 260 to 3 460.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the last five years.

Year	1901	1902	1903	1904	1905
Membership	1260	1549	2230	3027	3460
RECEIPTS PER MEMBER					
Entrance Fees	$0.61	$1.16	$1.59	$1.65	$0.83
Dues	8.61	10.06	9.01	9.33	9.30
Transactions, Sales and Advertising	1.03	1.54	1.79	2.11	1.70
Badges	.18	.26	.35	.39	.28
Interest	.12	.24	.21	.18	.21
	$10.55	$13.26	$12.95	$13.66	$12.32
DISBURSEMENTS PER MEMBER:					
Transactions	$2.83	$3.50	$4.67	$3.43	$3.77
Salaries	2.49	2.78	2.49	2.50	2.29
Meeting Expenses	1.05	1.13	.87	1.16	.82
Rent	.94	.94	.65	.79	.75
Library, including Rent and Salaries	.55	1.85	1.38	1.39	.81
Postage	.46	.51	.69	.66	.66
Stationery and Miscellaneous Printing	.39	.53	.96	1.01	.70
General Expense	.33	.59	.52	.45	.54
Badges	.16	.19	.27	.35	.25
Express	.15	.15	.15	.28	.22
Total	$9.35	$12.17	$12.95	$12.02	$10.72
Credit Balance per Member	$1.20	$1.09	$0.00	$1.64	$1.60

Our next concern is with the officers of the societies and the methods of nominating and electing them. A truly national society should draw its membership from all parts of the country, and should afford representation, through its officers and those on its administrative committees, to the membership at large; in other words, it should select its officers as far as possible with a view to their geographical distribution. It is admitted that this plan is difficult owing to the opportunities afforded to practising engineers by large enterprises, whose administrations, technical as well as financial, are generally located in the important commercial centres. For this reason the important groups of members are found in the large cities, and from them are drawn the majority of the officers, such selection being emphasized by the necessities of the central administration of the society. This procedure is liable, however, to operate to the disadvantage of candidates qualified for the important posts of honor within the gift of the societies, candidates that happen to be stationed some distance away from headquarters. To keep the INSTITUTE on the plane of national standing it should have a care to the broad geographical distribution of its officers. This end can best be accomplished by having a nominating committee the several members of which are respectively selected from the same number of geographical groups of members of the society, each group to consist of, say, 300 or 400 members. Upon this committee, in consultation with a number of past officers, should rest the selection of the official nominees. Provision should also be made for the filing of such nominations as may be made directly by the general membership. This procedure was introduced by the American Society of Civil Engineers several years ago; it has the advantage of providing geographical representation and at the same time discouraging unseemly electioneering and advertising by circular for the coveted posts of honor. It is thought by some members that our own INSTITUTE could with advantage modify its procedure in this direction.

Furthermore it would be to the advantage of the interests of the INSTITUTE if the officers-elect were to take office at the close of the Annual Meeting, or at latest as the last act of the Annual Convention. The retiring of the President and other officers and the installing of their successors should be an official function at a general INSTITUTE meeting, the lack of which in our present method of procedure allows four months to elapse after the election of officers before they assume their duties, and within three months, or at most four months, after taking office the active canvass for their successors is already under way.

It will be admitted by all who have had experience in the administration of professional societies that it is desirable to eliminate every tendency toward political agitation in connection with the election to honors within the gift of the membership, and to concentrate every effort upon advancing the professional standing of the society and the interests of its members. It would also seem of advantage to have the fiscal year coincide with the calendar year; this would lengthen the time between the Annual Meeting and the Annual Convention, and by spreading the time taken by the former over several days a larger number of the out-of-town members would be secured for the transaction of business at the Annual Meeting and to attend the annual banquet, or for other functions which could be held in the time available. The Annual Meeting as held at present is not markedly distinguished from the regular monthly meetings, and there is usually only a month between it and the Annual Convention. With the growing importance of the financial interests confided to the care of successive administrations the business matters of the Annual Meeting should receive more attention, and the membership at large should participate in them to a greater degree than is the case at present.

The administration of the societies should be conducted by their Board of Directors or Councils, and similarly the important standing committees, with whom rests the conduct of affairs in the several branches of administration, should be committees of the Board or Council. Such being the case it is desirable that their appointment should, in the beginning, rest with the Board itself, and that one member of each standing committee should retire each year, and the new President fill the vacancies; this would be a much more satisfactory arrangement than the plan followed by our INSTITUTE at present, under which the responsibility of appointing all committees, whether standing, special, or temporary, rests alone with the President. The suggested plan of appointing the administration committees primarily by the Board or Council, the President filling the vacancies that occur each year, is not the one usually followed by our national societies; but even where all the appointments devolve upon the President alone, membership on the standing committees is limited as a rule to Members of the Board. The advantage of selecting the standing committees from the members of the Board is evident; the committees are then not likely to follow a policy at variance with the wishes of the executive body, which would disturb harmonious relations between the society officials and continually raise questions of jurisdiction.

It is also desirable to avoid constant changes in the personnel of such important committees as the committee on Finance, the Library Committee, and the Board of Examiners; provision should be made for standing committees of three or five members, with one member retiring each year, the vacancies to be filled by the incoming President. This plan secures continuity of policy, gives the committees the benefit of accumulated experience, and relieves the President of the responsibility of making a large number of appointments on entering his term of office Such standing committees as the committees on finance, membership, library, publication, and meetings, or the last two consolidated into one, are necessary for all societies, together with such other committees as the particular field covered by the work of the society may require. Outside of the standing committee required by the regular routine, it is desirable to avoid as far as practicable the appointment of special or temporary committees, and when the special work assigned to them has been performed, such committees should be discharged. Nothing is more subversive of energetic and effective administration than Board meetings at which an interminable series of committees make "no report" or the chronic "report of progress."

In case it is considered inadvisable to appoint a separate committee on meetings, or on papers and meetings, and a committee on publications, or editing committee—a division of work which becomes necessary when monthly meetings are held with reading of papers and discussions, in addition to one or more general business meetings of the INSTITUTE—it becomes necessary to define their respective responsibilities very clearly, placing upon the committee on meetings, or papers, the responsibility of accepting papers or communications for presentation at the meeting, and upon the publication, or editing committee alone, the responsibility for the publication of papers and discussions, in whole or in part, in the official Transactions of the society.

It might be observed here that great care should be exercised so to conduct a society identified with a specific branch of engineering, that, as far as practicable, all of its divisions receive due consideration. In an Institute of Electrical Engineering, the telegraph and telephone, electric traction and electric lighting, the central station and the isolated plant, transmission and distribution, design and construction, theory and practice,—in fact all branches of electrical engineering, should receive consideration; and in soliciting papers for the series of meetings held during the year a wide range of subjects should be covered so as to interest and attract the largest circle of members.

Reference has already been made to the importance of conducting a national society on broad lines so that the members at large shall have a share in the benefits as well as the obligations of membership, whether they are located near the headquarters of the society or at a distance therefrom. It is manifest that when the monthly meetings, as well as the more important annual functions, are held at the headquarters of the society, the distant members feel that they are at a disadvantage, from which arises a tendency to form local clubs, or organizations, and to secede from the parent society, or at least to lose interest in it. Our INSTITUTE has met this situation courageously, and through the initiative of Past-president Scott a series of local organizations was established, the number of which has been increased under succeeding administrations. These organizations have done much to keep up the interest of distant members in the INSTITUTE, and have undoubtedly induced desirable accessions to our membership and are an important stimulant to professional activity.

Our sister societies are facing the same problem and are watching the result of our undertaking—it can no longer be called an experiment—with great interest. But this scheme of local organizations, while undoubtedly successful, is developing new problems and new conditions, and requires the constant care and supervision of the central administration.

As the close of another administrative year draws near I have felt it incumbent upon me, in the fulfilment of a duty, to direct your attention to some of the questions that are before us, and to give expression to a few thoughts that have occurred to me as a result of several years of experience in connection with the administrative work of our own society, and a study of the methods followed by our sister engineering societies.

The comparisons which have been presented and the suggestions which have been offered are not made in a spirit of criticism, nor am I unmindful of the splendid work accomplished by the framers of our present Constitution, to whom the highest credit is due for that altogether excellent instrument. But our INSTITUTE is growing rapidly and with its expansion new problems are arising; its field of activity is constantly broadening, and it should be expected, therefore, that modifications in its organic law may from time to time become necessary.

It is in the meeting and solving of new problems of society administration, such as I have referred to, that the youth and enthusiasm of our members is of the utmost advantage; we are less handicapped by precedent and tradition than some of our older sister societies, and we may therefore expect for the INSTITUTE OF ELECTRICAL ENGINEERS a glorious future, full of activity, initiative, and prosperity, and successful in the attainment of the highest professional standing, dignity, and usefulness.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

HIGH-POWER SURGES IN ELECTRIC DISTRIBUTION SYSTEMS OF GREAT MAGNITUDE.

BY CHARLES PROTEUS STEINMETZ.

In the following, I intend to give a review, investigation, and discussion of a high-power surge, which occurred in the high-potential distribution system of the Manhattan Railway, in New York, during the early days of its electric operation. The very complete data on the phenomena occurring during the surge and the effects caused by it have been furnished by Mr. H. G. Stott, at that time Superintendent of Motive Power of the Manhattan system. The surge resulted in a complete shutdown of the power station at 5.50 p.m., July 23, 1903, and again during the following night at 12.45 a.m.

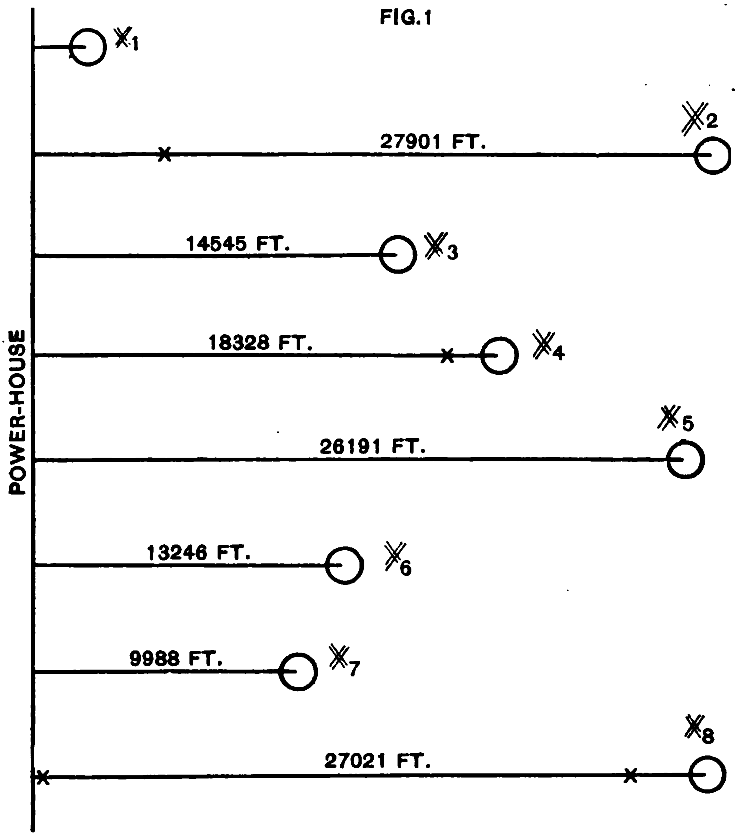
At 5.50 p.m., July 23, the load on the generating station was 37 000 kw. and was being carried by six 5000-kw., 11 000-volt, three-phase, 25-cycle generators, No. 1, 2, 4, 5, 6, and 7. This power was being transmitted to a sub-station, No. 1, located in the generating station, and also to seven other sub-stations by three-conductor, lead-covered underground cables, as follows:

To sub-station No. 2—6 cables each 27 901 ft. long.
To sub-station No. 3—5 cables each 14 545 ft. long.
To sub-station No. 4—5 cables each 18 328 ft. long.
To sub-station No. 5—4 cables each 26 191 ft. long.
To sub-station No. 6—5 cables each 13 246 ft. long.
To sub-station No. 7—5 cables each 9 988 ft. long.
To sub-station No. 8—4 cables each 27 021 ft. long.

The sub-station high-tension bus-bars were divided into as many sections as there were synchronous converters installed, and at the time of the trouble they were being operated with these section-switches open.

All feeders to sub-stations, except 4-C and 7-C, were protected with static dischargers at the power-station end of cable but not at the sub-station end. The dischargers consisted of nine air-gaps in series with three carbon resistances each of 0.003 megohms

FIG. 1



resistance. Feeders to sub-stations are designated by a number and a letter; the number denoting the number of sub-station and the letter the number of the feeder. For example, feeder 8-F is feeder F of sub-station No. 8. A diagrammatic sketch of the high-pressure, three-phase distribution system is given in Fig. 1.

At about 5.45 p.m., sub-station No. 7 notified the powrestation that there was quite a lot of static discharge on cables at that station, but that it could not be located on any particular cable. Immediately after, sub-station No. 8 made a similar report and then the power-station operator went to the cable gallery to examine static dischargers and try to locate the trouble. He had examined the dischargers on two cables when a loud explosion was heard; whereupon he ran up to the switchboard gallery, and as soon as he arrived there No. 4 generator short circuited. Two or three seconds before the generator short circuited, a synchronous converter in the power station arced over, and its positive direct-current circuit-breaker opened. This circuit-breaker was arranged to operate on reverse current only. The explosion heard before the generator short circuited came from a manhole just outside the power-station, and was caused by a cable short circuiting. When the generator short circuited, the time-limit relays on generators Nos. 1, 2, 4, and 5 opened their respective oil-switches, and the oil-switches of generators 6 and 7 were opened by the switchboard attendant. As these relays were set to operate after three seconds, it is possible that the switchboard attendant opened switches 6 and 7 before the relays had time to act.

On the feeder system the following occurred: feeder 8-F short circuited at a joint 243 ft. from the power-station, the three conductors being blown out for about 12 in., and one leg of the feeder punctured a porcelain insulating tube and grounded in the power-station between the oil-switch and cable-bell. Feeder 8-B broke down in a section, and at point 23 980 feet from power-station. The breakdown showed two legs completely open and the other grounded. Feeder 2-E broke down at a joint 4 800 feet from the power-station, the break showing one leg open and grounded.

At the power-station the time-limit overload relays on feeders 4-E, 4-F, 8-B, and 8-F opened their switches; the connections from the main leads to the static dischargers on feeder 4-A, 4-B, and 2-F burned off; the walls of the static discharger compartments of 4-B were cracked and sprung, and two small holes were burned in the end-bell on the power-station end of 2-F.

At the sub-stations no damage was done, but most of the reverse-current relays and some overload relays operated, showing that the converters in the sub-station were feeding back into the cable system.

Careful investigation shows that the following damage was caused by the cables and generator short circuiting: On generator No. 4, 28 armature bars and 11 connectors at the terminals of machine were broken, bent, or badly burned. On generator No. 1, the insulation at the end of a bar in phase "A" and one in phase "C" was punctured, showing that the pressure had jumped across the intervening air-gap of four inches; the pressure also jumped from an end-connector of phase "A" to the frame, a distance of six inches, and a number of overhanging ends of armature bars of phase "C" were slightly bent. On generators 2, 5, 6, and 7 some of the armature bars of phase "C" were also slightly bent, showing excessive current.

In addition to the damage mentioned above, some harm was done to the transformers supplying power for lights in the passenger stations.

Step-down transformers—11 000 to 2300 volts—for the lighting system are located at the sub-stations. The current is transmitted to the passenger stations at 2300 volts and is there transformed to 110 volts.

When the cables broke down and the generator short circuited at the power-station, the fuses blew on nine of the 2300/110-volt lighting transformers, and on four of them several coils of the high-pressure winding short circuited.

The damaged parts of the system were cut out, and the power-station and sub-stations again started.

On the following night, July 24, at 12.45 a.m., a complete shutdown of the system again resulted from a surge.

The load on station at the time was about 3500 kw., being carried by generators 1 and 5. A short time previous (about midnight) the ground-detectors on the 11 000-volt bus-bar indicated a 10 000-volt ground on one phase. Preparations were at once made to locate the ground by a process of elimination, by cutting out the feeders of each sub-station in turn. Some delay was caused by waiting for the adjacent sub-stations to cut in enough synchronous converters to carry the load of the station cut out. Just as everything was ready to cut out sub-station No. 8, a synchronous converter in the power-station blew its direct-current positive circuit-breaker. Immediately thereafter the following occurred:

Feeder 4-F short circuited in a section 16 000 feet from the power-station, burning one conductor completely open and grounding another conductor. The current transformer in one phase of feeder 3-D, and the relay on the transformer, burned out.

One main lead from the bell at the power-station end of feeder 3-B burned off for about two inches at a point seven inches from the copper sleeve of the joint. The static-discharger lead was connected at this point of main lead. The copper sleeve was found to be loose when the cable was repaired. The static-discharger leads from this cable were burned off, the discharger-compartment division walls were badly cracked and sprung, and a hole one inch in diameter and another four inches by two inches was burned in the bell at the power-station end. On feeder 3-A the static discharger leads were burned off, and the discharger-compartment walls were slightly cracked. No damage was done elsewhere to the system.

Regarding this occurrence, Mr. H. G. Stott makes the following comments:

" A summary of the happenings of that night in their proper sequence is:

" *First*: A static discharge over the high-tension insulators and cables was observed in sub-stations, Nos. 7 and 8.

" *Second*: Within a few minutes a feeder short circuited in the manhole nearest to the power-station, blowing out about 12 inches of three-conductor cable, and raising the manhole and pavement all around it with a loud report.

" *Third*: One of the six generators operating in multiple short circuited near the terminals, conductors on two turns of the winding being driven out until they struck the iron of the frame of the generator; *i.e.*, to say, the armature bars, which are 2 in. by ⅜ in., three in each slot, were bent edgewise for over six inches, showing that the force bending them probably amounted to at least 3000 or 4000 lb.

" *Fourth*: Practically simultaneously several of the three-conductor feeders from sub-stations 8, 4, 3, and 2 short circuited, some of them in the manholes at a greater or less distance from the power-station, and some of them on the static dischargers in the power-station, and one across an end-bell in the power-station. No damage took place in the sub-station.

" Upon examination, one of the generators, which was apparently otherwise uninjured, showed that the current had jumped across between the end connectors near the end of one phase, a distance of four inches, through the air. At another point on another phase of the same machine marks showed that the current had jumped from one of the end bars to the iron through the air, a distance of six inches. Other arcing distances showed conclusively that the potential must have risen to not less than 70 000 volts.

" The above is a brief resumé of what happened.

" My own opinion is that the source of all the trouble was in the feeder in the manhole next to the power-station breaking down the insulation to ground; this caused the static to show up at the sub-stations; the large capacity current of the system burned the insulation of the neighboring conductors in the three-conductor cable, and formed a short-circuit which blew out the arc, due to the sudden expansion of air in the manhole from the heat generated by approximately 70 000 kw. (each machine being capable of giving out 12 000 kw.). The arc was probably re-established several times, thus setting up an oscillating current, and giving rise to the potential above mentioned."

The most characteristic feature was the enormous volume, and relatively very low frequency, of the oscillating surge occurring in the system. This explains the severity of the destruction and its widespread extent. Any oscillation of very high frequency could be local only and could not extend over any considerable part of such a system, since the high capacity of the cables necessarily would act as a short circuit to any very high-frequency oscillation.

The trouble was undoubtedly started in the manhole next to the power-house by a spark discharge between one of the conductors of feeder 8-F and the cable armor, possibly due to the gradual breaking down of a weak spot in a cable-joint.

This spark discharge between conductor and cable armor, or ground, was oscillating in character, local in extent, and of moderate power and pressure, but of rather high frequency. It was the discharge of a condenser of a pressure equal to the pressure between conductor and ground; that is, the Y pressure of the system, or about 6400 volts, and the capacity and inductance between the cable conductor and ground. The capacity and inductance however in this case were distributed.

The length of cable, from the sub-station where the electrostatic displays were observed to the point of discharge in the manhole, was 26 780 ft. The estimated capacity between conductor and ground was approximately 0.115 microfarad, and the inductance between conductor and ground 0.106 millihenry per 1000 ft. of cable, or a total of 3.07 microfarad and 2.83 millihenry respectively.

In general, in a circuit containing distributed capacity, inductance, resistance, and (shunted) conductance, let:

$Z = r - j x$ = impedance per unit length of circuit, and

$Y = g - j b$ = shunt-admittance per unit length of circuit,[1]

where:

$$x = 2 \pi N L,$$

$$b = 2 \pi N C.$$

1. Alternating Current Phenomena, Steinmetz, 3d edition, p. 163, *seq.*

Let N = frequency, L = inductance, and C = capacity per unit length of circuit, and denoting the distance on the circuit, from a starting point 0, by u:[2], the equations for electromotive force and current are, respectively:

$$\left.\begin{aligned} E &= \frac{1}{Y}\left\{(A\,\varepsilon^{\alpha u} - B\,\varepsilon^{-\alpha u})\cos\beta u - j\,(A\,\varepsilon^{\alpha u} + B\,\varepsilon^{-\alpha u})\sin\beta u\right\} \\ I &= \frac{1}{V}\left\{(A\,\varepsilon^{\alpha u} + B\,\varepsilon^{-\alpha u})\cos\beta u - j\,(A\,\varepsilon^{\alpha u} - B\,\varepsilon^{-\alpha u})\sin\beta u\right\} \end{aligned}\right\} \quad (1)$$

where: $z = \sqrt{r^2 + x^2}, \quad y = \sqrt{g^2 + b^2}$

$$\left.\begin{aligned} V &= \alpha - j\,\beta, \\ \alpha &= \sqrt{\tfrac{1}{2}\,\{y\,z + (g\,r - b\,x)\}}, \\ \beta &= \sqrt{\tfrac{1}{2}\,\{y\,z - (g\,r - b\,x)\}}, \end{aligned}\right\} \quad (2)$$

and A and B are (complex) integration constants.

Neglecting, as a first approximation, resistance r and conductance g, which is permissible in such a cable of very low energy loss, and means that we assume the oscillations as not noticeably weakened by the energy absorption when traversing the length of the cable,[3]

$$r = 0; \qquad g = 0 \quad \text{gives:}$$

$$\alpha = 0,$$

$$\beta = \sqrt{b\,x} = 2\,\pi\,N\sqrt{L\,C}; \quad (3)$$

and, substituting:

$$\left.\begin{aligned} A - B &= C = c_1 + j\,c_2, \\ A + B &= D = d_1 + j\,d_2, \end{aligned}\right\} \quad (4)$$

gives:

$$\left.\begin{aligned} E &= j/b\,[C\cos\beta u - j\,D\sin\beta u] \\ &= 1/b\,[(-c_2\cos\beta u + d_1\sin\beta u) + j(c_1\cos\beta u + d_2\sin\beta u)], \\ I &= j/\beta\,[D\cos\beta u - j\,C\sin\beta u] \\ &= 1/\beta[(-d_2\cos\beta u + c_1\sin\beta u) + j\,(d_1\cos\beta u + c_2\sin\beta u)] \end{aligned}\right\} \quad (5)$$

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2. Alternating Current Phenomena, Steinmetz, 3d edition, p. 169 (14).

3. Alternating Current Phenomena, Steinmetz, 3d edition, p. 181, sec. 122.

Equations (5) apply to a circuit supplied by an impressed frequency as well as to an internal surge or oscillation of the circuit. In the latter case, however, the frequency is such as to make the circuit a quarter-wave, or an odd multiple thereof.

That is, the frequency N of the circuit is given by the condition:

$$\cos \beta l = 0, \tag{6}$$

where l = length of circuit.[4]

This gives:

$$\beta l = (2 \kappa - 1) \pi/2,$$

hence, equation (3):

$$N = \frac{2 \kappa - 1}{4 l \sqrt{L C}} = \frac{2 \kappa - 1}{4 \sqrt{L_0 C_0}}, \tag{7}$$

where L_0 and C_0 are the inductance and the capacity, respectively, of the total circuit.

The oscillation therefore has the fundamental frequency:

$$N_1 = \frac{1}{4 \sqrt{L_0 C_0}}, \tag{8}$$

and the higher harmonics:

$$N = (2 \kappa - 1) N_1. \tag{9}$$

From the available data on the breakdown in the Manhattan system, in the cable 8-F, which discharged to ground in the manhole near the power-house, it is estimated that

$$L_0 = 2.83 \text{ millihenry},$$

$$C_0 = 3.07 \text{ microfarad},$$

hence:

$$N_1 = 2670 \text{ cycles}.$$

Denoting then by u the distance from the fault in the manhole towards sub-station 8, with l = 26 780 ft. the total length of this cable, and representing the total distance l by angle $\omega = 90° = \pi/2$, or a quarter-cycle, that is:

$$\omega = \frac{u}{l} \frac{\pi}{2}; \tag{10}$$

4. Alternating Current Phenomena, Steinmetz, 3d edition, p. 184.

hence:

$$\beta u = (2\kappa - 1)\,\omega, \tag{11}$$

the equation of the oscillation is:

$$\left.\begin{aligned}
E &= \frac{1}{2\pi N_1 C}\sum_1^{\infty}\kappa\Big\{[-c_2^{\kappa}\cos(2\kappa-1)\omega + d_1^{\kappa}\sin(2\kappa-1)\omega] \\
&\qquad + j_{\kappa}\,[c_1^{\kappa}\cos(2\kappa-1)\,\omega + d_2^{\kappa}\sin(2\kappa-1)\omega]\Big\} \\
I &= \frac{1}{2\pi N_1\sqrt{LC}}\sum_1^{\infty}\kappa\Big\{[-d_2^{\kappa}\cos(2\kappa-1)\omega + c_1^{\kappa}\sin(2\kappa-1)\omega] \\
&\qquad + j_{\kappa}\,[d_1^{\kappa}\cos(2\kappa-1)\,\omega + c_2^{\kappa}\sin(2\kappa-1)\,\omega]\Big\}
\end{aligned}\right\} \tag{12}$$

where: N_1 = fundamental frequency of oscillation,

c_1^{κ}, d_1^{κ}, c_2^{κ}, d_2^{κ} = integration constants.

The spark passing in the manhole, at $\omega = 0$, from the conductor to the cable armor, that is, to the ground, connects the conductor to the ground by an arc. The potential difference E between conductor and ground, therefore, falls to zero, or practically zero, while a current I flows towards the break $\omega = 0$, which is the charging current of the system against ground, or about 200 to 300 amperes. With the potential difference E disappearing, the current in the short arc shunted by capacity blows out the arc explosively, and so disconnects the conductor from ground. At the moment when the grounding arc opens, it is therefore: $E = 0$, $I = i_0$ = constant, in the conductor, at least near $\omega = 0$. The current i_0, still flowing towards $\omega = 0$. produces a potential difference in the conductor, so that as a result of this period, we get zero current: $I = 0$, but a potential difference $E = e_0$, in the conductor, at least at and near $\omega = 0$. This potential difference e_0 again causes a spark to jump at $\omega = 0$, and again grounds the conductor. In the moment when the spark jumps, it is: $I = 0$, $E = e_0$.

We have the two periods succeeding each other, the starting condition of each being the final condition of the preceding:

a. From the moment where the arc at $\omega = 0$ ruptures, until a spark restarts it. During this period the conductor is not connected to ground at $\omega = 0$.

b. From the moment where the arc starts at $\omega = 0$, until it ruptures itself again, or while the conductor is grounded at $\omega = 0$.

This results in two oscillations or wave trains, originating at $\omega = 0$, and alternating with each other.

a. Conductor not connected to ground at $\omega = 0$. The duration of this period is the time required for voltage e_0 to jump a spark and ground the conductor. The starting condition, at time $t = 0$, or $\phi = 2\pi N_1 t = 0$, is: $E = 0$; $I = i_0$. (13)

b. Conductor grounded at $\omega = 0$. The duration of this period is the time required by the arc to produce sufficient heat to blow itself out explosively. The starting condition, at $\phi = 2\pi N_1 t = 0$ is:

$$I = 0; \quad E = e_0 \tag{14}$$

Both wave trains follow equations (12).

These equations, by eliminating complex quantities, and substituting:

$$\phi = 2\pi N_1 t$$

assume the form:

$$\left.\begin{aligned}
E &= \frac{1}{2\pi N_1 C}\sum_1^\infty \kappa \Big\{ [-c_2^\kappa \cos(2\kappa-1)\omega + d_1^\kappa \sin(2\kappa-1)\omega] \\
&\quad \cos(2\kappa-1)\phi + [c_1^\kappa \cos(2\kappa-1)\omega + d_2^\kappa \sin(2\kappa-1)\omega] \\
&\qquad \sin(2\kappa-1)\phi \Big\} \\
I &= \frac{1}{2\pi N_1 \sqrt{LC}}\sum_1^\infty \kappa \Big\{ [-d_2^\kappa \cos(2\kappa-1)\omega + c_1^\kappa \sin \\
&\quad (2\kappa-1)\omega] \cos(2\kappa-1)\phi + [d_1^\kappa \cos(2\kappa-1)\omega \\
&\qquad + c_2^\kappa \sin(2\kappa-1)\omega] \sin(2\kappa-1)\phi \Big\}
\end{aligned}\right\} \tag{15}$$

And the terminal conditions are:

a. Open circuit:

for: $\phi = 0$:

$E = 0$,

hence: $c_2^\kappa = 0$; $d_1^\kappa = 0$;

$I = i_0$

hence:

$$\sum_1^\infty {}^\kappa [-d_2^\kappa \cos(2\kappa-1) + c_1^\kappa \sin(2\kappa-1)\,\omega] = 2\pi N_1 \sqrt{LC}\, i_0;$$

$$\sum_1^\infty {}^\kappa [-d_2^\kappa \cos(2\kappa-1) - c_1^\kappa \sin(2\kappa-1)\,\omega] = -2\pi N_1 \sqrt{LC}\, i_0;$$

hence: $$d_2^\kappa = 0,$$

and:

$$\sum_1^\infty {}^\kappa c_1^\kappa \sin(2\kappa-1)\,\omega = 2\pi N_1 \sqrt{LC}\, i_0 \tag{16}$$

gives the terminal conditions of the equations of oscillation:

$$\left.\begin{aligned} E &= \frac{1}{2\pi N_1 C} \sum_1^\infty {}^\kappa c_1^\kappa \cos(2\kappa-1)\,\omega \sin(2\kappa-1)\,\phi\ ; \\ I &= \frac{1}{2\pi N \sqrt{LC}} \sum_1^\infty {}^\kappa c_1^\kappa \sin(2\kappa-1)\,\omega \cos(2\kappa-1)\phi. \end{aligned}\right\} \tag{17}$$

From equation (16) are found the coefficient c_1^κ in the usual manner

$$\int_0^{\pi} \sin(2\kappa-1)\,\omega \sum_1^\infty {}^\kappa\ c_1^\kappa \sin(2\kappa-1)\,\omega\, d\omega$$

$$= 2\pi N_1 \sqrt{LC}\, i_0 \int_0^{\pi} \sin(2\kappa-1)\,\omega\, d\omega;$$

hence:

$$c_1^\kappa = 2\pi N_1 \sqrt{LC}\, i_0\ \frac{4}{(2\kappa-1)\pi} \tag{18}$$

and:

$$\left.\begin{aligned} E &= \frac{4 i_0}{\pi} \sqrt{\frac{L}{C}} \sum_1^\infty {}^\kappa \frac{1}{2\kappa-1} \cos(2\kappa-1)\,\omega \sin(2\kappa-1)\phi, \\ I &= \frac{4 i_0}{\pi} \sum_1^\infty {}^\kappa \frac{1}{2\kappa-1} \sin(2\kappa-1)\,\omega \cos(2\kappa-1)\,\phi; \end{aligned}\right\} \tag{19}$$

and by similar considerations, for the period:

(*b*) short circuit:

$$\left.\begin{aligned} E &= \frac{4\,e_0}{\pi} \sum_1^{\infty}{}^{\kappa} \frac{1}{2\,\kappa-1} \sin\,(2\,\kappa-1)\,\omega \cos\,(2\,\kappa-1)\,\phi, \\ I &= \frac{4\,e_0}{\pi} \sqrt{\frac{C}{L}} \sum_1^{\infty}{}^{\kappa} \frac{1}{2\,\kappa-1} \cos\,(2\,\kappa-1)\,\omega \sin\,(2\,\kappa-1)\,\phi; \end{aligned}\right\} \quad (20)$$

or, substituting the approximate numerical values:

$$e_0 = 6400, \quad \sqrt{\frac{L}{C}} = \sqrt{\frac{.115}{.106} \times 10^3} = 33$$

$$i_0 = 300, \qquad (21)$$

Hence, the equations of the two wave-trains are:

(*a*) open circuit:

$$\left.\begin{aligned} E &= 9900\,\frac{4}{\pi} \sum_1^{\infty}{}^{\kappa} \frac{1}{2\,\kappa-1} \cos\,(2\,\kappa-1)\,\omega \sin\,(2\,\kappa-1)\,\phi, \\ &= 300\,\frac{4}{\pi} \sum_1^{\infty}{}^{\kappa} \frac{1}{2\,\kappa-1} \sin\,(2\,\kappa-1)\,\omega \cos\,(2\,\kappa-1)\,\phi; \end{aligned}\right\} \quad (22)$$

(*b*) short circuit:

$$\left.\begin{aligned} E &= 6400\,\frac{4}{\pi} \sum_1^{\infty}{}^{\kappa} \frac{1}{2\,\kappa-1} \sin\,(2\,\kappa-1)\,\omega \cos\,(2\,\kappa-1)\,\phi, \\ I &= 194\,\frac{4}{\pi} \sum_1^{\infty}{}^{\kappa} \frac{1}{2\,\kappa-1} \cos\,(2\,\kappa-1)\,\omega \sin\,(2\,\kappa-1)\,\phi. \end{aligned}\right\} \quad (23)$$

where: $\omega = \pi/2$ corresponds to the length of the line,
$\phi = 2\,\pi$ corresponds to one cycle of the fundamental frequency of oscillation of $N_1 = 2\,670$.

$$\frac{4}{\pi} \sum^{\infty}{}^{\kappa} \frac{1}{2\,\kappa-1} \cos\,(2\,\kappa-1)\,\omega \sin\,(2\,\kappa-1)\,\phi = 1 \text{ for: } \phi > \omega,$$

$$= \tfrac{1}{2} \text{ for: } \phi = \omega,$$

$$= 0 \text{ for: } \phi < \omega.$$

$$\frac{4}{\pi} \sum_{1}^{\infty} \kappa \frac{1}{2\kappa - 1} \sin (2\kappa - 1) \omega \cos (2\kappa - 1) \phi) = 1 \text{ for: } \phi < \omega,$$

$$= \tfrac{1}{2} \text{ for: } \phi = \omega,$$

$$= 0 \text{ for: } \phi > \omega.$$

The two wave-train equation (22) and (23) alternate with each other and so cause a successive series of impulses of high electromotive force but zero current, and of high current but zero electromotive force, to run along the circuit, starting from the fault at $\omega = 0$ and traveling toward the sub-station 8 with such a velocity that the distance from $\omega = 0$ to $\omega = \pi/2$, or 26 780 ft. is traversed during $\frac{1}{4}$ cycle of the fundamental frequency of oscillation $N_1 = 2\,670$. 26 870 ft. in $1/4 \times 2670$ sec. gives a velocity of wave propagation of $4 \times 2\,670 \times 26\,780 = 285 \times 10^6$ ft. per sec. = 54 000 miles per second, or about 30% of the velocity of light.

The duration of the successive periods of current and of electromotive force depends on the conditions existing at the starting point of the wave; that is, at the fault in the manhole, but not directly on the constants of the rest of the circuit, and as a rule the duration of the period of high electromotive force and the period of high current are not equal.

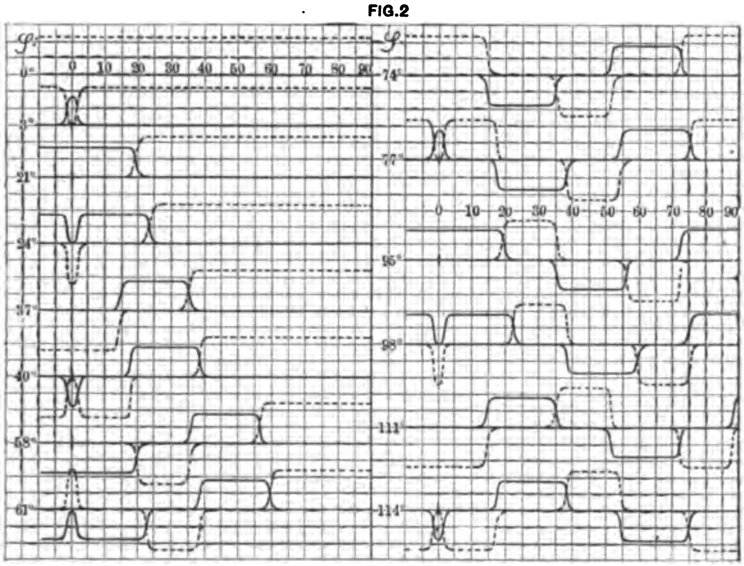
As illustrations, the distribution of electromotive force between cable conductor and cable armor are shown in Fig. 2 by dotted line, and of the current flowing in the conductor towards the ground by full line, with the distance along the cable as abscissas, denoted by the angle ω, and for successive moments of time represented by the angle ϕ, which is chosen so that $\phi = 2\pi$ corresponds to one complete period of the fundamental frequency of oscillation $N_1 = 2\,670$. The period of high current, or the time from the start of the spark towards ground until the rupture of the arc, is assumed as 21°, and the period of high electromotive force, or the time-lag of the jumping of the spark after the application of the electromotive force, as 16°.

These two successive wave-trains also constitute a cyclic phenomenon with a period $\phi = 74°$; that is, at $\phi = 74°$ from $\omega = 0$ a second wave issues identical with the wave issuing at $\phi = 0$.

A complete period of $\phi = 74°$ of this traveling wave gives a frequency $N_0 = 360/74\, N_1 = 13\,000$ cycles.

These waves of current and electromotive force which travel along the circuit from the source of disturbance, with high frequency, are in their simplest form flat-topped with steep wave front and back. The steepness of wave front and back depends upon the rapidity with which the arc at $\omega = 0$ establishes itself and ruptures, and also upon the distance ω from the starting point. The latter feature is not shown in Fig. 2, since the resistance and conductance of the line r and g are neglected. Taking them into consideration shows a gradual rounding off

FIG. 2



of the wave with the increase of distance from the starting point.

Where these waves meet obstructions, as localized inductance, the steepness of the wave front results in the induction of high electromotive forces of very limited extension, and gives the pyrotechnic displays observed at the switchboards of high-pressure stations when there is a disturbance on the line, which sometimes are called "static." Due to their very limited power, these phenomena are relatively harmless of themselves; their danger rather lies in producing or establishing a path for short circuits or surges of high power, as happened in the case under discussion.

Localized inductance offers some protection to the system against these waves even if the inductance is very small. For instance, assuming 11 000 volts and 300 amperes as full-load condition of the feeder cable and an inductance of 0.05 millihenry inserted. This inductance at the impressed frequency of 25 cycles would give a reactance $x_0 = 0.008$ ohms; hence 300 amperes consume 2.4 volts or about 1/50 of one per cent.

Assuming in Fig. 2 the maximum current of the traveling wave as 300 amperes and at the steepest part of the wave to change in strength 250 amperes during $\phi = 1°$; that is, $t = 1/360 \times 2\,670 = 1.04 \times 10^{6}$ sec. This gives $d\,i/d\,t = 240 \times 10^{-6}$, and the counter electromotive force which this wave front would meet in such a reactive coil would be:

$$L\,di/dt = 12\,000 \text{ volts.}$$

I have dwelt somewhat fully on this system of wave-trains and the frequency of propagation along the circuit, since I believe this phenomenon of a third frequency, besides the impressed frequency and the frequency of circuit oscillation, has not before been fully recognized. It seems, therefore, that in an electric circuit containing distributed capacity and inductance, as in an underground cable, a long-distance transmission line, or in the high-pressure winding of a transformer or high-pressure generator, three distinct frequencies must be recognized that are essentially independent of one another.

1. The impresed frequency supplied by the generating system, of 25, 40, or 60 cycles as fundamental, and their odd multiples as higher harmonics or wave-shape distortion, which higher harmonics are usually of small or even negligible magnitude.

2. The frequency of oscillation of the system, or natural period of the circuit, depending on the constants of the circuit, mainly the capacity and the inductance, and consisting of a fundamental frequency $N_1 = \dfrac{1}{4\sqrt{L_0 C_0}}$, and all the odd multiples thereof as higher harmonics. The relative magnitude of fundamental and higher harmonics depends on the distribution of pressure and current in the circuit at the moment where the oscillation starts. As a rule the higher harmonics are not negligible, but usually rather predominate.

3. The frequency of circuit disturbance, which has no direct relation to impressed frequency or to the natural period, but depends upon the character of the disturbance. It appears as a system of waves traveling along the line, and results in the

static displays at the end of the line; that is, at the station switchboards. In its simplest form, as a single wave or impulse traveling along the circuit (frequently visible to the eye as a luminous streak), it probably appears when a moderate lightning flash or side discharge strikes a transmission line, and from there to the ground, giving at the point of impact a sudden rise of pressure against ground, immediately relieved by the discharge to ground.

This phenomenon, so far as I know, has never been investigated from the theoretical point of view. While of itself rather harmless, its danger consists in the self-destructive forces that it may set into play. In the circuit under discussion here the impressed frequency is 25 cycles, the natural period 2 670 cycles. The frequency of the static display 13 000 cycles, but of such steep wave front as to correspond to a far higher frequency, possibly of the magnitude of 200 000 cycles per second.

In the breakdown in the Manhattan system, starting with a spark discharge between conductor and cable armor in a faulty joint in the manhole near the power-station, attention was called to the disturbance by the arrival of the wave trains and the resultant static displays on the cables and switchboards of the next sub-stations. No direct harm was done by this "static," but before the fault could be located and cut out, the spark discharge had reached the next conductor of the cable and started a short circuit between two conductors. With six generators of 5000-kw. rating and a momentary maximum of 12 000-kw. each, and the synchronous converters feeding back into the short circuit as evidenced by the opening of the reverse-current relays in the sub-stations—it probably is a conservative estimate to assume that for a short period a power of 100 000 kw. was concentrated in the short-circuiting arc in the manhole. The energy of 100 000 kw. applied during only one-tenth second equals the explosion of about half a pound of dynamite.

The explosion tore off the insulation and protection of the conductor, and a flaring arc started in the manhole, and being oscillating or self-rupturing in character, created a surge of low frequency and enormous power in the whole system, beyond the disruptive strength of any part of the system or any protective device. This short-circuit oscillation was a surge of the whole system throughout, and almost instantaneously caused all the breakdowns in feeders, cables, cable-bells, transformers, generators, etc. The static protectors apparently discharged and somewhat lowered the pressure, but could not be expected to take care of the enormous volume of the surge. Some burned up explosively due to the excessive pressure imposed upon them.

From the data available I estimate the capacity of the system between two conductors as $C = 76$ microfarads. In series with this capacity is the self-inductance of the generating system. Extensive tests which I made some years ago on a long-distance system at high pressures with aid of the oscillograph, proved that electric oscillations due to changes of circuit conditions, when occurring in a high pressure line, are not limited to the line but extend back into the generating system even if the generators are separated by transformers from the oscillating line, as was the case in my experiments. That is, the whole system, including generators, oscillates electrically. This has since been corroborated by observing that a breakdown in one feeder causes breakdowns in other feeders issuing from the same generator bus-bars, and therefore that the oscillation passes into and over the main generator bus-bars.

Assuming that the short circuit current or synchronous impedance current of these generators at full pressure and no-load excitation is about three times full-load current or approximately 800 amperes, gives a synchronous impedance of 8 ohms Y. We may probably assume that somewhat less than one-half of this is self-inductive reactance participating in the oscillation, and that the rest is armature reaction.

With the understanding that there is some reactance in the station wiring, current transformers, etc., we may assume the self-inductive reactance per generator as about $x = 4$ ohms, corresponding to an inductance of 25.5 millihenrys. The self-inductance of the six generators in circuit during the accident then is: 4.25 millihenrys. Allowing 0.25 millihenrys for effective resultant inductance of the cable system gives a total inductance: $L = 4.5$ millihenrys.

The fundamental frequency of the surge of the whole system would be: $N_0 = \dfrac{1}{2\pi\sqrt{LC}} = 270$ cycles, or quite low.

With $C = 76$ microfarads, $L = 4.5$ millihenrys, and $e = \dfrac{11\,000}{3} = 6\,340$ volts per phase, the instantaneous short-circuit current or the volume of the surge would be:

$$i_0 = e/2\pi N L = 9\,000 \text{ amperes.}$$

where N = impressed frequency, and the pressure of oscillation:

$$e_0 = 2\pi N_0 L i_0 = 68\,800 \text{ volts per phase}$$

or 119 000 volts between lines, where N_0 = frequency of oscillation.

With such a volume of surge all breakdowns that occurred would also be oscillating and therefore would not relieve the system by discharging the oscillation, but set up secondary oscillations. I observed this same feature in the experimental tests referred to above, where in one instance I had three oscillating circuits simultaneously in existence, and still enormous electrostatic displays.

Thirty-two static protectors of 0.003 megohms each, hence of a total delta resistance of 282 ohms, and a "Y" resistance of 94 ohms, would, at 100 000 volts delta or 58 000 volts Y, carry off about 630 amperes or 7%, and therefore lower the pressure of oscillation by 7%, that is, to about 110 000 volts between lines, but they would be loaded far beyond their capacity, as evidenced.

As seen, the most prominent features of the surge seem to have been its enormous volume and relatively low frequency, which account for its very wide extent and destructiveness.

From another phenomenon we can also estimate the approximate frequency of the surge. The burning out of the fuses of some 2300-volt transformers without destruction of these transformers is explained by assuming that the high-pressure oscillation penetrated to these transformers and that their primary pressure rose so as to bring the iron of the transformers beyond magnetic saturation and blow the fuses by the excessive exciting current, due to magnetic saturation. This did not occur in the 11 000-volt transformers, which were operating at lower magnetic density; while the 2300-volt transformers, built originally for higher frequency, were operating normally at fairly high density on the 25-cycle circuit.

From this we may estimate the frequency of the surge. 25-cycle transformers are necessarily operated at fairly high magnetic density, so that increasing the normal magnetic density two- or threefold results in such high saturation as to blow the fuses by the exciting current. The magnetic cycle of the surge is superimposed upon the normal magnetic cycle of the transformer. It then depends at what point of the normal cycle the abnormal cycle started. If at the maximum point, an abnormal cycle of one-half the amplitude of the normal cycle would double the density and so saturate. If at the negative maximum point, an abnormal cycle would have two times the amplitude of the normal to treble the density. The most probable is that the abnormal cycle or the surge started near the zero point of the normal cycle or near the maximum point of the circuit pressure and then at 1.25 times the amplitude of the normal cycle, the abnormal cycle would increase the density 2.5 times.

Assuming from the striking distance a pressure of 80 000 for the oscillation, or 7.2 times normal pressure, to give an abnormal cycle of 1.25 times the amplitude of the normal cycle would require a frequency of 9.0 times the normal frequency or 225 cycles respectively. The frequency of oscillation therefore would probably be in the neighborhood of 225 cycles.

The shutdown of the generating station ultimately stopped the surge. I should believe it quite possible, however, that besides the breakdowns which have been observed by their destructive effect, some more breakdowns have occurred lasting so short a time before the taking off of the generating system as not to cause any noticeable destruction, and merely weakening and partly breaking down the insulation. The breakdown occurring again towards midnight I attribute to such a partial breakdown, which was completed by some small oscillation as the opening of a converter circuit-breaker.

Two years have passed now, and I believe no further surge of this magnitude has occurred, and a protection of the system has been devised.

A paper presented at the Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

AN EXPERIMENTAL STUDY OF THE RISE OF POTENTIAL ON COMMERCIAL TRANSMISSION LINES DUE TO STATIC DISTURBANCES CAUSED BY SWITCHING, GROUNDING, ETC.

BY PERCY H. THOMAS.

The purpose for which the tests hereinafter described were undertaken was the experimental study of "static effects," on full-sized commercial systems, the method used being the isolation of the various sorts of phenomena and the elimination of disturbing influences. It was hoped that by a study of the effects of simple fundamental causes on commercial plants the understanding and control of the more complex static disturbances met with in actual experience would be much facilitated.

In papers before this INSTITUTE, in February 1902, and before the Franklin Institute, in May 1902, the writer discussed the nature of static disturbances, as met with in commercial circuits, and applied to them some fundamental laws of wave-motion of general application, to establish certain principles governing the location and maximum magnitude of the potential strains resulting from the more simple types of static discharges. One object of the experiments described in this paper was the empirical verification of these principles in a full-size plant.

The tests on the lines of the Missouri River Power Company and on those of the Utah Light and Power Company were conducted under the direction of Mr. M. H. Gerry and Mr. R. F. Hayward, respectively, and carried out jointly by them, and by the writer representing the Westinghouse Electric and Manufacturing Company. The tests were eminently satisfactory.

The tests on the lines of the Telluride Power Company, which constitute the major portion of the static tests here described, were planned and carried out jointly by the writer and by Mr. F. D. Olmsted, to whose personal supervision the work is indebted for many of its most valuable results and for the signal opportunity of securing so large a number of simultaneous readings, covering several weeks' time, at points over 100 miles apart upon a line otherwise in commercial service at high voltage. Mr. Olmsted's illness, followed by his death, in 1903, prevented his conduct of further work along this line, and his contribution of other material for this paper.

Before describing the actual tests, the point of view from which they were planned, and from which they are to be studied, should be outlined. Broadly speaking, the functions of ohmic resistance, inductance, electromagnetic induction, etc., in electrical circuits are well understood, and can be expressedby mathematical formulas. The effect produced in a given circuit and under a given set of conditions by any one or all of these causes, can be pretty well predicted. Such, however, has not always been the case, and this highly desirable result has only been secured by the most painstaking study of the effect upon a circuit of each of such causes by itself. The same may also be said as to the phenomena of hysteresis and electromagnets. In each case the simple and fundamental laws governing the phenomenon had to be carefully determined experimentally by the elimination of other influences. Once the fundamental laws are understood, it is comparatively easy to combine their various effects and predict more or less complex cases.

Our knowledge of the phenomena of static disturbances in commercial circuits is in a much confused and comparatively undigested form. We know of a great many things that have happened, but very little as to why and how they happened. Reports are frequently recounted of discharges at tremendously high voltage (some perhaps well founded) and in explanation the name of some well-known principle is generally mentioned Rarely, however, is the application of this principle so made, or the conditions under which it was supposed to have operated so stated as to enable an accurate knowledge to be obtained of what actually took place. Consequently such explanations are of little help in foretelling or forestalling similar disturbances.

The principles indicated by the words "resonance," "surge," "oscillation," etc., are of comparatively little value, as an explanation of any phenomenon, without a statement of how these principles apply. For example, in the case of resonance, the location and source of the exciting periodic force, the designation of the apparatus or portion of the circuit that constitutes the capacity or the inductance of the resonating circuit, etc., should be stated, otherwise the attributing of the phenomenon to " resonance " has little significance.

Elementary static phenomena have been studied mathematically and in the laboratory, and their fundamental principles and laws fully determined. They are common knowledge to those who have given the subject particular attention. All these fundamental laws apply, of course, to static disturbances in commercial circuits, but in such circuits new conditions are introduced and new limitations imposed on account of their size, and a new determination of the relatively practical importance of the old laws becomes necessary.

In the same manner as our knowledge of the laws of inductance has been built up step by step, and the limitations that apply in commercial circuits, such, for instance, as hysteresis in iron cores, have become gradually recognized and finally experimentally investigated quantitatively, so must our exact knowledge of static phenomena on commerical circuits be built up step by step, largely by experiment and experience, and their practical bearing on the design and operation of such circuits be finally determined. Furthermore, in view of the complex nature of static phenomena, and the difficulty of making measurements of the extremely rapidly varying currents and voltages involved, and determining the exact facts in any case of serious accidental disturbance, or even in a case where careful preparation has been made beforehand, the complete knowledge and control of static phenomena in full-sized commercial circuits will be slow in coming.

It is not to be assumed that the writer means to ignore the comparative success of the present apparatus for the protection of circuits from static disturbances; the point intended to be emphasized is the empirical cut-and-try methods which are now necessary in attempting to eliminate trouble from these causes.

To emphasize this matter a little more strongly, it will be well to summarize the fundamental principles, static or otherwise, that may cause or have a direct bearing, under favorable circumstances, upon a rise of potential in commercial electric circuits This summary is necessarily incomplete, as some possible causes are sure to be omitted from oversight, and some from lack of knowledge, but it will serve as a beginning, which may be extended hereafter.

I. The fundamental laws applying to all electric circuits, as Ohm's law, laws of magnetic and electric induction, Joule's law, the magnetizing power of a current, laws of branch circuits, laws of impedance, condenser charging, oscillating circuits; that is charging or discharging condensers through coils skin effect, abrupt opening of inductive circuit, resonance, etc.

II. Practically all commercial circuits involve capacity and inductance, as well as resistance, (usually the capacity and inductance are "distributed,") so that there will be a tendency to oscillating charges and discharges.

Owing to the presence of capacity, inductance, and resistance, commercial circuits may resonate, and will do so if an electromotive force of the right frequency be applied to the circuit; a voltage will then be built up, and a corresponding increase of current will result in the condenser and inductance, which continually increases, alternation by alternation, until the rate at which energy is lost in the system becomes equal to the rate at which energy is supplied under the exciting electromotive force. If the periodicity of the exciting electromotive force is not exactly right for perfect resonance the building-up of voltage and current will still occur but to a less maximum, and, furthermore, will be of a pulsating character. It should be remembered that resonance can occur locally, either in a small or in a large portion of a transmission circuit.

Where the inductance and capacity in an electric circuit are "distributed," as in a transmission line, any change of voltage or disturbance at any point causes an electrical wave or charge to pass through the line in the same manner as a disturbance will cause a wave to pass along a trough of water. Such electrical waves cause changes of potential at various points, as follows:

(a) A wave passing along a uniform wire will be unchanged, except for a diminution in amplitude, and alteration of form due to energy losses, and will always travel at a definite rate; and if the ènd of the wire be open, the wave will be reflected back toward its source, and will cause a rise of potential at the reflecting point of double the potential of the wave as it reaches the reflecting point.

If however, the end of the wire, be short-circuited or connected to a large condenser, so that this point is maintained at zero potential, the wave will be reflected back toward the source with the opposite sign; that is, the positive wave will then be reflected as a negative wave.

(b) Two or more waves passing one another add their numerical values at the passing point, and each passes on without affecting the form or intensity of the other.

(c) Where a wave on a line of large capacity passes into a line of smaller capacity, a rise of potential occurs at the end of the former, since this is virtually a part reflection; but this rise is always less than the rise of potential that would be caused by reflection from an open wire, the relative capacities and inductances determining the exact numerical value of the rise at the reflecting point. In this case a portion of the energy is reflected into the original line, and a portion passes into the smaller line, going forward at a new rate, appropriate to the new line, and having a maximum intensity equal to that at the point of junction of the two lines. If the second wave reaches an open end in the smaller wire, there results a rise of potential double the value of the wave, as it reaches this reflecting point. Consequently, this rise theoretically may be four times that of the original wave in the first line; and, similarly, if the wave pass into a third line of still smaller capacity than the second, there may be a still further rise.

(d) When a wave meets a division of the line into two or more branches or a change to larger capacity, waves pass into all the lines, but each is of less magnitude than the original wave. The wave reflected back into the original line is reversed in direction.

(e) When a wave meets a choke-coil inserted in a line, or at the end of the line, but with capacity beyond it (as is almost always the case), the wave suffers reflection and a change in value, and a rise of potential beyond the coil may even occur, due to the oscillating circuit formed by the coil and the capacity.

(f) If the cause of static waves be periodic, so that a succession of waves passes into the line, and the constants of the line be such that the waves reflected back arrive again at the periodic source in the right phase, resonance may occur as in properly-timed circuits of "undistributed" capacity and inductance.

(g) When a wave traversing a line comes to a coil, such as a high-tension transformer winding, its progress electrically around the turns is slow in comparison with its speed along the line wire, on account of the greater inductance and capacity of the coil, so that when the crest of the wave has reached the beginning of the coil the front of the wave may have penetrated only a short way into the coil, and thus the full potential of the wave is impressed only on the outer portion of the coil. This phenomena is the well-known concentration of potential on windings of apparatus caused by static discharges and needs no further description.

(h) Theoretically, a portion of the energy of a wave transmitted along a line wire is radiated, which causes a certain loss of intensity; furthermore, with very high potentials a discharge of energy directly into the atmosphere takes place, which has the same effect.

(i) An arc of considerable length inserted in a circuit causes a great deformation of the wave-form of the current; this is the equivalent of a superposition of one or more harmonics of current of higher frequency on the fundamental, which in certain cases may cause a rise of potential as a direct or indirect result of some of the principles above mentioned. In case such a rise does occur, however, it should be possible to point out in what manner it is produced.

III. The possible sources of static disturbances include the following:

(a) Lightning, either by direct stroke, or electromagnetic or electrostatic induction, or by a combination of these causes.

(b) Induction, or actual contact with higher voltage lines when such contact results in an abrupt discharge.

(c) Any of the static changes of potential that result from accidental causes, such as grounds, short-circuits, etc., or from the normal operations of switching and similar causes.

(d) Miscellaneous disturbances in the electric circuit itself that may possibly result in an abrupt discharge somewhere in the system, as for example, the short-circuiting of a part of the primary of a transformer, thereby causing a rise of potential on the secondary, or the short-circuiting of the one secondary of a double Y-connected group of transformers where the middle point of the generator is not connected to the middle of the primary star. Under this heading are also included such causes as running-away of the generator, paralleling out of phase, great deformation of the electromotive force from any cause, momentary building-up of generator field from heavy momentary charging current, resonance from generator frequency, etc.

The headings I to III roughly summarized the definite knowledge we have of the laws governing static disturbances in commercial circuits. Other particular elements can undoubtedly be added, and with such additions the list should be complete. If we were able to get at the facts of any particular static manifestations, it should be possible to point out in the above list the exact cause or causes, and to state definitely the actual law or laws governing the observed results. Of course, this condition is not likely to be fully realized, but the nearer we approach to it the more certain and satisfactory will be our control of the danger from static disturbances.

A much fuller discussion of the matter summarized under headings I to III, inclusive, will be found in the two papers by the writer referred to in the opening sentences of this paper.

It is often convenient to think of a charged commercial electric circuit as a long stretched spiral spring that is being pulled in all directions, but in a state of equilibrium except for a certain motion representing the normal flow of current. If any of the supports of this spring, which are analagous to the insulation of the electric circuit, give way, there will be a sudden release and motion of a portion of the spring, usually resulting in little disturbances or waves throughout its full extent, which, in turn, will produce mechanical strains at various points. Similarly, the electric circuit, charged at the instant of the highest electromotive force with quantities of energy in the form of electric charges at all points where capacity exists, and in the form of magnetism at all points where inductance and current exist, will suffer a shock and an electrical surging throughout different parts whenever any breakdown of insulation occurs, or other disturbance takes place that tends to change the distribution of the stored energy. The surging and oscillations resulting from a disturbance of equilibrium will continue until a new condition of equilibrium is established, and in doing so will cause a rise of potential above normal in some point or points of the system if the discharges are of such a nature that, in accordance with any of the principles already laid down, a rise of potential should properly occur.

Undoubtedly all the laws hereinbefore enumerated apply to every commercial circuit, but their relative numerical importance will vary enormously. If the conditions are such that any one principle produces a numerical effect of only one per cent. for any discharge, it would be considered as practically negligible under these conditions. For instance, if a long line be suddenly charged so that a wave is sent into the line and reflected at the far end, this will be of no importance, provided the resistance or other losses in the line cut down the maximum intensity of the wave to a small part of its original value by the time the reflecting point is reached; for in this case the doubling of potential at the end by reflection will be much less than the normal potential impressed when the line has had time to become fully charged. Again, it is theoretically possible where a small transformer is being fed through fuses in an underground cable system, by the blowing of one fuse and grounding of this leg on the transformer side, to cause the whole system to be charged through the impedance of the transformer. In this case if the generator frequency happens to be right, resonance will occur tending to break down the cable insulation. If, however, the iron losses in the core of the transformer (which is supplying the inductance for the resonance) becomes sufficient, as the voltage rises, to equal the inflow of energy from the supply circuit, say at double voltage, and if the insulation of the system is able to stand three times normal voltage, probably no harmful result will follow; whereas if the iron loss did not exist a very high potential might result.

Examples may thus be multiplied to show that although, theoretically, a principle applies to a commercial circuit, the numerical constants may be such that its effects are a negligible quantity. It is thus of great importance to determine, usually by actual experiments on full-size lines, under what conditions each principle may become of serious importance. With such knowledge it will usually be feasible to change conditions so that the effect of this principle, numerically, will be of little or no importance.

The tests described in this paper were carried out in accordance with the plan outlined above, that is, to determine by actual tests on full-size commercial circuits the bearing of a few of the above principles. The tests, broadly considered, are necessarily limited in their range of conditions. But they were carefully made, and, within the degree of accuracy obtainable by the methods used, are believed to be reliable and trustworthy.

Description of Tests.

In studying static discharges, the most important information to be sought is the resulting maximum potentials at various points in the system, the average or effective value being of little importance. The exact determination of the maximum values of extremely rapid discharges is by no means an easy matter. The motion is, of course, too rapid for any mechanical instrument to respond, and no magnetic or optical means is readily available.

The most convenient measure is the spark-gap, which is widely used for this purpose, and though it is not possible to get very accurate measurements from a spark-gap, an approximate indication of the maximum voltage may be obtained by this means. In the tests hereinafter described such gaps were used to measure the maximum potential.

In order to prevent the discharge from one gap interfering with the circuit as a whole and thus influencing discharges at other gaps, condensers were placed in series with all the gaps. The condensers, though small in static capacity had a very considerable capacity as compared with that at the air-gaps, so that the gaps received the major portion of the potential impressed on the measuring device as a whole. Calibrations were made with the gaps in position and in series with the condensers, as will be noticed in the accompanying calibration plot. It was found convenient to use two different sizes of condensers, as mentioned in the tests.

Furthermore, since the result of any operation that is independent of the generator electromotive force, such as switching, short-circuiting, etc., depends upon the exact instant in the cycle at which it may happen to occur (whether near the maximum, or the zero point of the electromotive force wave) the test must be repeated a considerable number of times to insure the maximum condition having been reached. In these tests about 10 trials were made at each setting of the gap. To explore the static results in the various tests, gaps were placed to measure the potential between line-wire and ground, between line-wires, and also across switches at various places, as seemed desirable, and from these, simultaneous readings were taken by as many observers with different settings of the gaps, until a condition was reached where each gap was just ready to spark, but none actually sparked. This ideal condition was not reached in all of the tests. The tests were made on commercial lines, as they stood, with lightning-arresters, transformers, and the switches used in actual service, and usually with the addition to the circuits merely of the measuring gaps. In the tests summarized below, under heading "Analysis of Data," the probable sequence of events in each case has been arrived at only by inspection of the observed maximum potentials taken in connection with the known operations.

I-A. Tests on the Provo-Logan Plant of the Telluride Power Company.

Tabulation of Readings, Diagrams, Analysis of Data, etc.

Test (*a*). *Object of Test.* Effect of charging a single unexcited open-circuited line wire together with a bank of raising transformers. No other line wires connected. Low-pressure switch closed last.

Connections according to Diagram *a*.

Switch A closed, others open. K used for test.

For calibration of spark gap see Diagram *b*.

(See Table No. 1.)

Analysis of Data. As line No. 3 is charged up it does not seem to rise appreciably above normal pressure at generator end but does experience a rise of some 30% at the reflecting end. This indicates that the apparatus charges quickly enough to cause an appreciable time lag between the exciting of the generator end and of the reflecting end. That is, a small portion of a wave is formed; if the line were several times as long, it may be assumed that a full charging wave would have resulted. Strangely the pressure between the live and dead line is greater than the pressure to ground at the generating end and less at the reflecting end. This may be due to the fact that the dead line is a disconnected line conductor and has no stable potential.

The pressure rises a little higher on the I and II transformers not connected to the line than on III. This is natural as no energy is drawn off from these.

No noticeable rise of potential occurs on opening the low-pressure switch, as would be expected.

The unconnected line wires received a potential something like half of that of the excited wire though entirely disconnected from the circuit.

A slight rise (25 or 30%) due to reflection at open end of wire may occur even in charging a very long line from the low-pressure bus-bars, though it would be expected that with low-pressure switch closed last that the pressure would rise too slowly to allow a lag between charging of the two ends of the line.

Test (*b*). *Object of Test.* Effect of charging one line wire

TABLE I.—TEST A.

Gap No.	Location of G p.	No. of Sparks Observed at the Settings Noted. All gap readings in 32ds, except a few marked 24ths. On Closing Switch.	On Opening Switch.	Voltage corresponding to sparking distances corrected for normal voltage of 21 000. Closing.	Opening.	Normal.
	Logan.			25 000		21 000
2	Transf. II to ground	Continuous at 8		21 000	0 at 21 000	21 000
3	Transf. III to ground	(2 in 10 trials at 7)	+(0 in 7 trials)	8 000		
11	Line I to ground	Continuous at 1½		8 000		
*12-L	Line II to ground	Continuous at 1½		24 300	22 700	
10-L	Line II to Line III	1 in 10 at 20	1 in 10 at 15			
	Provo.					
14	Line I to ground	0 at 2/24		0 at 11 000		
15	Line II to ground	1 in 10 at 3	0 in 10 at 3	12 000	0 at 12 000	
16	Line III to ground	1 in 10 at 19	7 in 10 at 10	28 000	24 500	21 000
18-L	Line II to Line III	4 in 10 at 7	0 in 10 at 7	18 000	0 at 18 000	

* L indicates that large condensers were used with this gap.
+ 0 indicates that no sparks were observed at this setting.
Note.—On gap 19 around two arrester choke-coils on transformer 1, 2 sparks in 20 trials at 1/24 in. (3800 volts). On gap 20 around 2 arrester choke-coils on transformer III, 0 in 10 at ½/24 (2300 volts). On gap around choke-coil in ground connection, 0 in 20 at ½/24 the normal voltage on all these gaps is too small to measure.

TABLE II.—TEST B.

Gap No.	Location of G p.	On Closing Switch.	On Opening Switch.	Closing.	Opening.	Normal.
	Logan.					
3	Transf. III to ground	(2 sparks in 10 trials at 30)	2 in 10 at 20	35 000	29 000	21 700
5	Transf. III to Trans. II	1 in 10 at 217	1 in 10 at 137	70 000	54 500	37 500
8-L	Transf. III to Line III	0 in 10 at 30	6 in 10 at 70	0 at 25 000	39 000	
10-L	Line III to Line II	5 in 10 at 45	1 in 10 at 60	33 000	36 000	
13	Line III to ground	2 in 10 at 45	1 in 10 at 45	31 000	30 500	21 700
	Provo.					
14	Line I to ground	(10 in 10 at 2/24) 0 at 3	(10 in 100 at 2/24) 0 at 3	13 000	13 000	
15	Line II to ground	1 in 30 at 3/24	ditto	14 000	13 000	
16	Line III to ground	1 in 10 at 51	10 in 10 at 30	43 000	Over 28 000	21 700
18-L	Line III to Line II	2 in 10 at 21	3 in 10 at 20	23 000	22 000	

On gap No. 19 on choke-coil of arr. 1, 7 in 10 on both make and break at 1/24 (3800 volts).
On gap No. 20 on choke coil of arr. III, rarely on both make and break at 3/24 (9500 volts).
On gap No. 21 on choke-coil in ground connection 0 in 20 at ½/24.

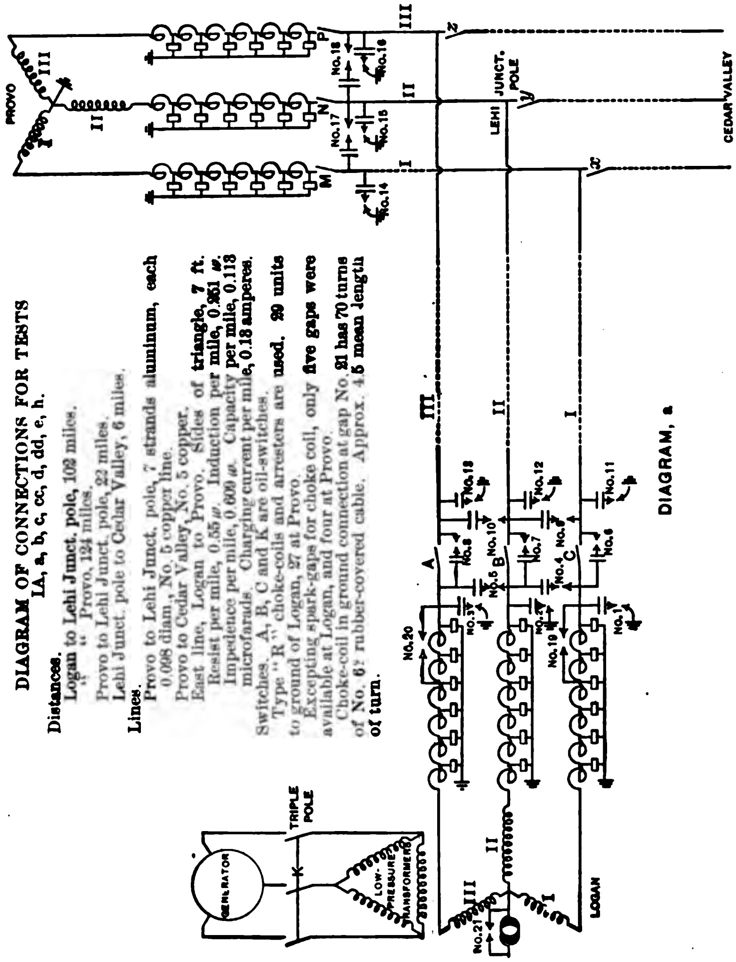
from a bank of previously excited transformers. No other line wires connected. High-pressure switch closed last.

Connections according to Diagram *a*.

Switches all open except K. Switch A used for test.

(See Table No. II.)

Analysis of Data. Evidently the sudden charging current causes a building up of normal electromotive force shown by the 35 000 volts at closing on transformer III (also the 31 000

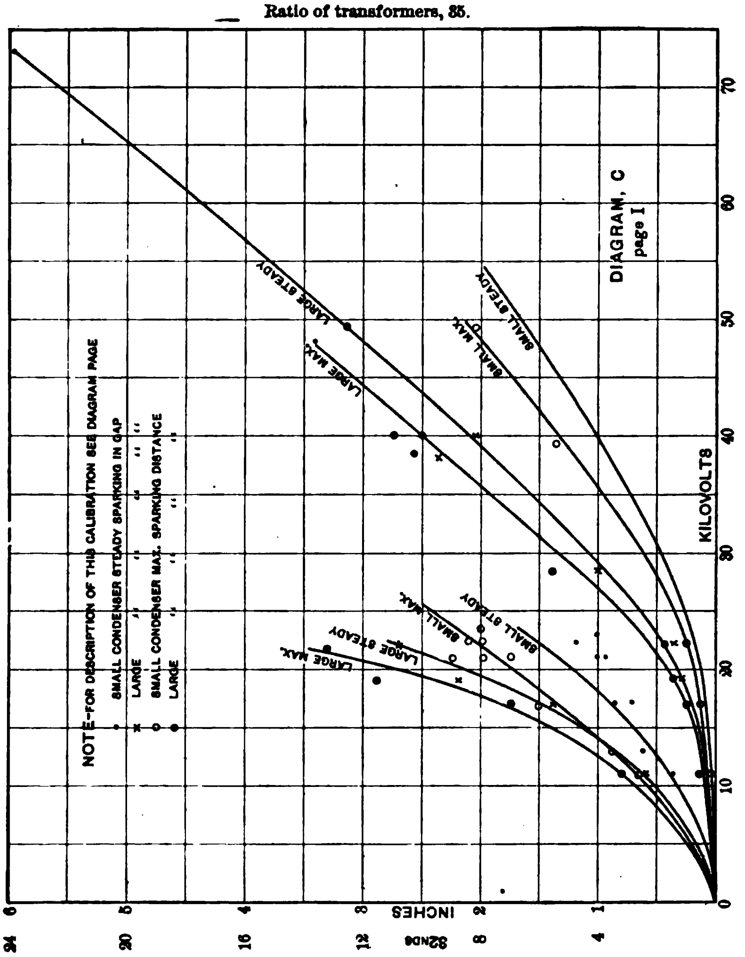


on line III) and probably by the high pressure between transformer III and II.

The charging is evidently in the form of a wave as a rise of potential is found at the end of line III—a rise of nearly double normal electromotive force. Probably partly due to the momentary heavy charging current and partly to the reflection at end of the line.

As in test (*a*) the dead lines receive something like half potential by induction.

CALIBRATION OF SPARK-GAPS.
Ratio of transformers, 85.



The excessive pressure between transformer III and transformer II is probably partly momentary increase of electromotive force due to instantaneous charging current and partly due to the dropping and probable reversal of potential of the lead of transformer III when switch is closed.

The action of opening the circuit is a repetition with small variations of that of closing—probably because the line being left charged at the zero point of the current in opening the switch is charged again in opposite direction at the end of one alternation by the pressure jumping the small gap in the opening switch; this explanation is indicated by the pressure across the switch on opening (39 000 volts) which is some 80% above normal; showing that the line is left charged in one direction while the generator assumes the opposite potential. This explanation receives strong confirmation from the fact that switching may leave an open line charged to nearly full pressure as shown experimentally by tinfoil electroscopes.

Lightning-arrester choke-coils in line III show some signs of abrupt discharges due to high-pressure switching.

Test (*c*). *Object of Test*. Effect of charging one line wire from a previously excited bank of transformers, two other line wires being already connected to same transformers. High-pressure switch closed last.

Connections according to Diagram *a* except that lines I and II are connected to transformer III on transformer side of switch A.

All switches open except K. Switch A used for test.

(See Table III.)

Analysis of Data. In this test no marked rise of potential occurs at the generator end, though a small rise is shown by the potential of 27 000 volts to ground on transformer II; also the 27 000 and 24 000 volts between lines II and III at Provo on opening and closing.

Only a small rise is indicated at the end of line III. This is partly because lines I and II have only twice the capacity of III. They do not act as a rigid bus-bar but allow a certain drop of potential momentarily. This means that a considerable increase of potential must occur at the reflecting point from the first wave before the ultimate normal potential is exceeded. No considerable evidence of sudden change of potential of bus-bars is found on the lightning-arrester choke-coils—a slight wave, however, on transformer III.

This test has the conditions under which a maximum rise of potential may be expected from reflection since a charging wave should be sent into a line by connecting it to a reservoir of electricity already stored, so to speak. But on account of the limited number of lines available for the "reservoir" the effect is much masked.

TABLE III.—TEST C.

Gap No.	Location of Gap.	No. of Sparks Observed at the Sittings Noted. All gap readings in 32ds, except a few marked 24ths. On Closing Switch.	On Opening Switch.	Voltage corresponding to sparking distances corrected for normal voltage of 21 000. Closing.	Opening.	Normal
	Logan.					
2	Transf. II to ground	Continuous at 12	1 in 70 at 12	27 000	25 000	23 100
3	Transf. III to ground	0 in 10 at 6	1 in 20 at 10	0 at 17 000	22 500	23 100
8-L	Transf. III to Line III	1 in 20 at 18	1 in 10 at 27	20 000	22 500	
10-L	Line III to Line II	1 in 20 at 20	1 in 10 at 27	21 000	22 500	
13	Line III to ground	1 in 10 at 15	Continuous at 12	25 000	27 000	23 100
	Provo.					
14	Line I to ground	2 in 30 at 15/24	9 in 20 at 10/24	30 000	26 000	23 100
15	Line II to ground	1 in 10 at 19	9 in 10 at 12	25 500	27 000	23 100
16	Line III to ground	1 in 10 at 25	1 in 10 at 25	30 000	30 000	23 100
18-L	Line III to Line II	2 in 10 at 43	1 in 10 at 32	27 000	24 000	

Note.—On gap No. 19 around two coils in arr. 1, 1 in 90 at 2/24 on opening (7200 volts).
0 in 20 at 1/24 on closing.
On gap No. 20 around two coils in arr. III, 0 in 10 at ½/24 on either opening or closing.
On gap No. 21 around two coils in ground 0 in 20 at 1/24 on either opening or closing.

TABLE IV.—TEST CC.

Gap No.	Location of Gap.	On Closing Switch.	On Opening Switch.	Closing.	Opening.	Normal
	Logan.					
2	Transf. II to ground	1 in 40 at 8	2 in 40 at 12	22 000	25 000	21 000
3	Transf. III to ground	About continuous at 6	1 in 20 at 7	22 000	20 000	21 000
8-L	Transf. III to Line III	0 at 20	2 in 60 at 50	0 at 23 000	26 000	
5-L	Transf. III to Trans. II	About continous at 64	1 in 70 at 72	39 000	38 000	36 000
13	Line III to ground	Continuous at 12	Almost continuous at 15	28 000	29 000	21 000
	Provo.					
14	Line I to ground	1 in 80 at 11/24	?	26 000	?	21 000
15	Line II to ground	2 in 10 at 14	1 in 10 at 13	27 000	25 000	21 000
16	Line III to ground	1 in 10 at 18	1 in 10 at 20	28 000	29 000	21 000
18-L	Line III to Line II	1 in 10 at 42	1 in 10 at 47	29 000	31 000	

Note.—On gap No. 19 around two coils in arr. I apparently on sparks at 1/24.
On gap No. 20 around two coils in arr. III apparently on sparks at ½/24.
On gap No. 21 around coil ground connection 0 sparks at ½/24.

Test c c. Object of Test. Effect of connecting line six miles long at Lehi Junction pole, with other connections of test same as test (*c*).

Connections according to Diagram *a* except that lines I and II are connected to transformers III on transformer side of switch A. Switches K, X, Y, Z closed, others open. Switch A used for test.

(See Table No. IV.)

Analysis of Data. Very much the same result as test (*c*). The rise at end of line III being cut down if anything as would be expected by the division of the wave at the junction point. The results are not marked enough to be conclusive.

No sign of abrupt wave on lightning-arrester choke-coils.

The usual slight rise due to effect of momentary charging current on generating system is seen. This is apparently emphasized at the receiving end which might result from a reflection of a small wave and might not have any significance.

Test (d). Object of Test. Effect of charging one line wire from a previously excited bank of transformers, two other line wires being already connected to the two other transformers. High-pressure switch closed last.

Connections according to Diagram *a*.

Switches B, C, and K closed, others open. Switch A used for test.

(See Table No. V.)

Analysis of Data. Closing the high-pressure switch causes a " killing " of terminal III, of transformer III, and the subsequent rush of charging current causes a rise of potential on all three transformers, the greatest of course on transformer III as shown by test. The results at reflecting point show a slight rise on all three lines, the greatest on III. That is, a wave is partly formed and causes a slight rise at the reflecting end and as usual the supply pressure is slightly raised. The sum of the two causes is perhaps a 50% rise.

On opening the circuit the same result is found slightly accentuated. The cause of this is already explained.

Across the switch is found practically double normal potential to ground, which is in accordance with the theory in the paragraph above.

A very decided concentration of strain is produced on the choke-coil in the transformer lead III showing a very abrupt change of the terminal potential, probably from the instantaneous

TABLE V.—TEST D.

Gap No.	Location of Gap.	No. of Sparks Observed at the Settings Noted. All gap readings in 32ds, except a few marked 24ths. On Closing Switch.	On Opening Switch.	Voltage corresponding to sparking distances corrected for normal voltage of 21 000. Closing.	Opening.	Normal.
	Logan.					
2	Transf. II to ground	3 in 50 at 12	2 in 50 at 15	25 000	27 000	21 000
3	Transf. III to ground	1 in 60 at 15	3 in 60 at 15	26 000	27 000	21 000
8-L	Transf. III to Line III	0 in 10 at 45	5 in 50 at 128	0 at 30 000	53 000	?
13	Line III to ground	1 in 20 at 25	1 in 10 at 30	32 000	34 000	21 000
10-L	Line III to Line II	4 in 20 at 144	3 in 50 at 172	57 000	63 000	36 000
	Provo.					
14	Line I to ground	1 in 10 at 14/24	?	29 000	?	21 000
15	Line II to ground	1 in 20 at 23	7 in 10 at 15	31 000	29 000	21 000
16	Line III to ground	2 in 10 at 30	1 in 10 at 33	35 000	35 500	21 000
18-L	Line III to Line II	1 in 10 at 190	2 in 10 at 130	66 000	55 000	36 000

Note.—On gap No. 19 around two coils in arr. I 0 (make or break) at ½/24.
On gap No. 20 around two coils in arr. III 2 in 50 approx. on both make and break at 4/24 (12 000 volts).
On gap No. 21 around coil in ground connection 0 in 50 at ½/24.

TABLE VI.—TEST DD.

Gap No.	Location of Gap.	On Closing Switch.	On Opening Switch.	Closing.	Opening.	Normal.
	Logan.					
2	Transf. II to ground	2 in 50 at 10	4 in 30 at 12	24 500	25 000	21 000
3	Transf. III to ground	1 in 60 at 30	9 in 40 at 20	34 000	30 000	21 000
8-L	Transf. III to Line III	0 at 112	2 in 70 at 128	0 at 48 000	54 000	?
13	Line III to ground	9 in 20 at 10	1 in 50 at 30	25 000	35 000	21 000
10-L	Line III to Line II	0 in 20 at 128	3 in 40 at 160	0 at 54 000	60 000	36 000
	Provo.					
14	Line I to ground	?	1 in 30 at 11/24	?	26 000	21 000
15	Line II to ground	10 in 20 at 10	1 in 30 at 17	25 000	28 000	21 000
16	Line III to ground	?	1 in 10 at 31	?	35 000	21 000
18-L	Line III to Line II	?	1 in 10 at 200	?	68 000	36 000

Note.—On gap No. 19 around 2 coils in arr. I approx. no sparks at 2/24.
On gap No. 20 around two coils in arr. III, 1 in 20 at 2/24 in closing (7000 volts), 2 in 40 at 4/24 on opening (12 000 volts).
On gap No. 21 around coil in ground connection 0 sparks at ½/24.

"killing" of the terminal by the connecting of the "dead" line. The other transformer terminals showed no concentration nor did the ground wire from the neutral point of the high-pressure star.

The concentration shown on the few turns of the choke-coil III probably occurred in much greater magnitude on the transformer winding.

Test d d. Object of Test. Effect of connecting line six miles long at Lehi Junction Pole. Other conditions same as test (*d*). *Connections* according to Diagram *a*. Switches B, C. K, X, Y, Z closed, others open. A, used for test.

(See Table No. VI.)

Analysis of Data. There is very little difference between this test and test (*d*) though some of the individual readings vary. The addition of the line to Cedar Valley does not seem to cause much effect. This cannot be assumed to be always true, however, as the length of this branch line was hardly great enough to cause an effect on such long waves, and further in this test and in test (*c*) and (*c c*) no distinct static wave was formed (as was to be expected).

Test (*e*). *Object of Test.* Effect of having transformer connected on the farther end of long line when connecting line wire. Same as test (*d*) except for transformer at end of line.

Connections according to Diagram *a*. Switches B, C. K, M, N, P closed, others open. Switch A used for test.

(See Table No. VII.)

Analysis of Data. The effect of adding the transformers at receiving end is to reduce the rise of potential all around but especially at the reflecting point on line III and across the switch A which now gets the normal potential between lines on account of connection through the lowering transformers.

Severity of concentration of potential on choke-coil III is somewhat reduced.

Test (*f*). *Object of Test.* Effect of throwing potential into two high tension line wires with the third disconnected, potential being thrown in by low-pressure switch and high-pressure arrester so adjusted as to discharge.

Connections according to Diagrams *c* and *a*.

Switches A and B only being closed. Three-pole switch K used for test.

Arrester II discharges often.

(See Table No. VIII.)

TABLE VII.—TEST E.

Gap No.	Location of Gap.	No. of Sparks Observed at the Settings Noted. All gap readings in 32ds, except a few marked 24ths. On Closing Switch.	On Opening Switch.	Voltage corresponding to sparking distances corrected for normal voltage of 21 000. Closing.	Opening.	Normal.
	Logan.					
2	Transf. II to ground	2 in 70 at 8	3 in 70 at 8	25 500	26 000	17 900
3	Transf. III to ground	1 in 10 at 7	1 in 30 at 8	23 500	25 500	17 900
8-L	Transf. III to Line III	0 at 24	3 in 10 at 56	0 at 28 000	40 000	?
13	Line III to ground	2 in 70 at 6	1 in 20 at 8	22 000	24 500	17 900
10-L	Line III to Line II	2 in 20 at 40	4 in 20 at 72	34 000	44 000	31 000
	Provo.					
14	Line I to ground	2 in 60 at 10	2 in 10 at 9	29 000	28 000	17 900
15	Line II to ground	5 in 30 at 13	1 in 30 at 13	31 000	29 000	17 900
16	Line III to ground	1 in 10 at 12	1 in 10 at 12	28 500	28 500	17 900
18-L	Line III to Line II	1 in 10 at 99	1 in 10 at 97	53 000	52 000	31 000

On gap No. 19 around two coils in arr. I, 0 on make or break at 1/24.

On gap No. 20 around two coils in arr. III, 1 in 10 at 2 on charging (2000 volts), 7 in 10 at 1 on opening (3000 volts).

On gap No. 21 around coil in ground connection, 0 in make or break at 1/24.

TABLE VIII.—TEST F.

Gap No.	Location of Gap.	On Closing Switch.	On Opening Switch.	Closing.	Opening.	Normal.
	Logan.					
2	Transf. II to ground	1 in 10 at 30	4 in 30 at 8	34 000	22 000	13 200
3	Transf. III to ground	1 in 40 at 60	1 in 40 at 45	46 000	40 000	13 000
7	Transf. II to Line II (?)	1 in 20 at 60	0 in 30 at 30	46 000	0 at 34 000	—
10-L	Line II to Line III	2 in 20 at 120	5 in 40 at 80	51 000	40 000	24 000
12-L	Line II to ground	1 in 20 at 10	1 in 10 at 5	19 000	14 300	13 000
	Provo.					
14	Line I to ground	?	?	?	?	—
15	Line II to ground	?	1 in 5 at 32	?	30 000	13 000
16	Line III to ground	0 in 10 at 59	1 in 5 at 65	0 at 46 000	49 000	13 000
18-L	Line II to Line III	0 in 13 at 112	1 in 5 at 130 (possibly higher)	0 at 48 000	54 000	24 000

Note.—Part of the time arr. II has 11 units to ground and part of the time 10.

On gap 19 (arr. I) some sparks at 1/24—3800 volts.

On gap 20 (arr. III) one spark at 4/24—11 500 volts.

On gap 21 ground connection rarely at 1/24—3800 volts.

Analysis of Data. The exciting cause is the discharge of arrester, and this being often continuous little distinction can be made between opening and closing. The same concentration of potential on lightning-arrester choke-coils is found.

The low-pressure switch makes very little difference as the cause here is the discharge of arrester with *double star* raising transformers.

Apparently there is the same rise of potential at the end of line III due to reflection as in I-A test (*g*).

Test (*g*). *Object of Test.* Effect of connecting two high-pressure line wires with arresters so adjusted as to discharge to ground. Third line disconnected. Two-pole high-pressure oil-switch closed last.

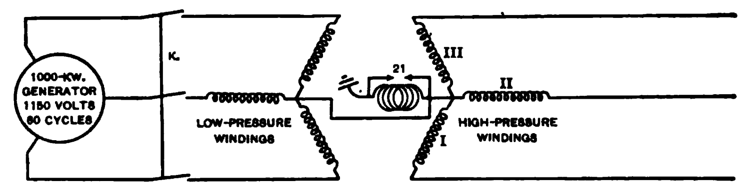
Connections according to Diagrams *c* and *a*.

Switches A and B operated together for test.

(See Table No. X.)

DIAGRAM OF CONNECTIONS FOR TESTS IA, f, ff, g, gg, ii.
Same as Diagram A, except that low-pressure windings of transformers are in star with neutral grounded.

DIAGRAM C.



Analysis of Data. This is a very complicated test and must be judged more by the maximum results than by analysis of exact occurrences, for there are several actions taking place in rapid succession, each depending on another and only the maximum effect can be recorded. Evidently one pole of the high-pressure switch must close last, probably III by the high potential developed for a very low normal electromotive force. When one pole closes (say II) and raises its potential a little the arrester jumps to ground and throws approximately double potential upon the other transformer which causes a rush of charging current and further rise and meantime the potential of line II drops to a low value. This effect is clearly seen on the values of potential to ground on transformer III at both ends. The charging wave only gets partly formed and gives a slight rise at the reflecting point.

TABLE X.—TEST G.

Gap No.	Location of Gap.	No. of Sparks Observed at the Settings Noted. All gap readings in 32ds, except a few marked 24ths. On Closing Switch.	On Opening Switch.	Voltage corresponding to sparking distances corrected for normal voltage of 13 000. Closing.	Opening.	Normal.
	Logan.					
2	Transf. II to ground	3 in 80 at 10	0 in 10 at 8	23 700	0 at 23 000	13 600
3	Transf. III to ground	1 in 20 at 40	3 in 50 at 60	36 500	44 700	13 600
7	Transf. II to Line II	1 in 20 at 60	1 in 20 at 60	44 000	44 000	?
10-L	Line II to Line III	0 in 80 at 120	7 in 80 at 120	0 at 49 400	50 000	23 800
12-L	Line II to ground	1 cont. in 10 at 40	2 in 20 at 60	30 000	33 000	13 600
	Provo.					
14	Line I to ground	?	?	?	?	?
15	Line II to ground	?	4 in 10 at 12	?	24 700	13 600
16	Line III to ground	4 in 10 at 45	1 in 10 at 50	40 000	40 000	13 600
18-L	Line II to Line III	15 in 80 at 75/24		42 700		23 800

On gap No. 19 (arr. I) some sparks at 1/24 (3800 volts).
On gap No. 20 (arr. III) some sparks at 2/24 (7000 volts).
On gap No. 21 slight evidences at ½/24 (2000 volts).

On opening, probably III is left charged to a high potential and when II is charged again in the opposite direction by the next alternation it will inductively raise the potential of III which is practically connected to the transformer III. And a discharge of arrester II will accentuate this effect.

Little reliance, however, can be placed on the detailed analysis of the exact sequence of actions. The extremely severe effect of having the double-star connection with high potential neutral grounded on the raising transformer is evident.

There is serious concentration of potential on the choke-coils I and III in this test.

It must be noticed that the normal pressure is only 60% approximately of that of previous tests.

I-B. Tests on the Missouri River Power Company's Lines to Butte from Canyon Ferry.

Tabulation of Readings, Diagrams, Analysis of Data, etc.

Test (*a*).

Object of Test. Effect of suddenly charging single line wire from a previously excited bank of transformers. High-pressure switch closed last. Two other line wires dead. *Connections* according to Diagram *e*. Transformer leg C grounded. All switches open. Switch B used for test.

(See Table No. XIV.)

Analysis of Data. Evidently the momentary charging current here causes a momentary rise of supply pressure which is increased on B by the rise due to sudden charging of the line; that is, the true condenser action. The results at Butte are not very clear but it seems that a higher pressure was reached on B than in A and C but none of them was excessive.

The fact that more severe disturbances are found on opening the switch is explained as before; viz., that the line is left charged by pulling off the switch and that the next alternation recharges the line see I-A test (*b*). This result is confirmed by the fact that on pulling off a live open line, a minute more or less is required for the line to discharge as is shown by the electroscope. The pressure across the line switch B indicates the same conclusion.

The ground in leg C though a most excellent one could not prevent a slight rise of potential during the discharges. The amount of this rise was small, however.

Test (*b*).

TABLE XIV.—TEST A.

Gap No.	Location.	Maximum Sparks. Closing.	Volts on Gen.	Opening.	Vots on Gen.	Voltage Corresponds corrected for normal voltage of 30000 Closing.	Opening.	Normal
	Canyon Ferry.							
1	Transf. leg A to ground	1 in 1 at 48	38 200	4 in 6 at 48	27 200	25 000	36 000	17 300
2	Transf. leg B to ground	2 in 2 at 60	35 300	2 in 2 at 60	24 700	31 000	43 600	17 300
3	Transf. leg C to ground	0 in 3 at ½	27 200	2 in 3 at ½	27 200	<3 000*	4 500	17 300
4	Transf. leg B to leg A	Intermittent at 48	28 600	1 in 2 at 60	23 400	34 600	46 000	30 000
5	Trans. leg B to Line B	0 in 2 at 60	23 400	1 in 1 at 60	24 700	<34 000	42 400	?
6	Line B to ground	1 in 1 at 60	38 200	3 in 4 at 60	24 700	28 800	42 400	7 300
	Butte.							
7	Line A to ground	0 in several at 5	31 000	0 in several at 5	31 000	Record confused but more sparking occurred on B than on A or C which showed approx. normal voltage.		17 300
8	Line B to ground	1 in 3 at 24	27 200	2 in 3 at 36	24 700			17 300
9	Line C to ground	0 in several at 5	31 000	0 in several at 5	31 000			17 300

All gap readings in 32ds, except a few marked 24ths.

Note.—These points with appropriate generator voltages are chosen from the records omitting readings that are not definite.

Note.—By volts on gen. are meant volts measured on high tension side of transformer excited from generator bus.

* < signifies "less than."

TABLE XV.—TEST B.

Gap No.	Location.	Closing.	Volts on Gen.	Opening.	Vots on Gen.	Closing.	Opening.	Normal
	Canyon Ferry.							
1	Transf. leg A to ground	Steady at 48	35 500	0 in 6 at 60	35 500	<33 000*	34 000	20 300
2	Transf. leg B to ground	Steady at 60	35 500	0 in 6 at 60	35 500	33 000	<34 000	20 300
3	Transf. leg C to ground	2 in 3 at 1	33 400	0 in 3 at ½	35 500	5 000	<3 000	
4	Transf. leg B to leg A	Steady at 60	35 500	0 in 6 at 60	35 500	38 000	<34 000	35 000
5	Transf. leg B to Line B	0 in 6 at 48	33 400	1 in 6 at 48	33 400	<31 500	32 000	?
6	Line B to ground	0 in 3 at 36	35 500	2 in 3 at 36	33 400	<27 000	31 000	20 300
	Butte.							
7	Line A to ground	Continuous for a short time on B and C but stopped before pulled off V = 33 400 high, 26 000 low at 18. A line was continuous until pulled off.						
8	Line B to ground							
9	Line C to ground							

Object of Test. Effect of charging a single line wire from a previously excited bank of transformers with two line wires already connected to the same poles. High-pressure line closed last.

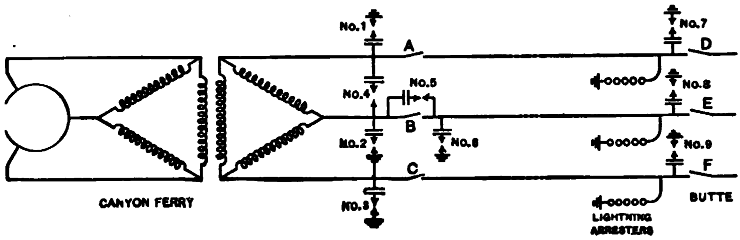
Connections according to Diagram *e*. Transformer leg C grounded. All switches open. Lines A and C connected to transformer side of switch B. Switch B used for test.

(See Table No. XV.)

Analysis of Data. This test showed no rise of potential at any point except the general rise due to momentary charging current. This test is not very satisfactory. Little rise was to be expected except perhaps on line B at Butte. Nothing was observed there, however. (See I-A, test (*c*), page 7).

One condenser with each gap at Canyon Ferry. Two condensers with each gap at Butte. Switches A, B and C are fused circuit breakers with explosion tubes for fuses. All tests taken at 7900 alts., and switches operated were fused breakers in all cases.

DIAGRAM e DIAGRAM OF CIRCUITS FOR TEST I B a-b-c



Test (*c*).

Object of Test. Effect of grounding one side of a symmetrically charged three-phase line.

Connections according to Diagram *e*. Switches A, B, and C closed. Switch A (fused breaker type) used to ground line B.

(See Table No. XVI.)

Analysis of Data. The test shows a slight rise of potential above normal (perhaps 15 or 20%) probably rather due to momentary charging current building up the pressure.

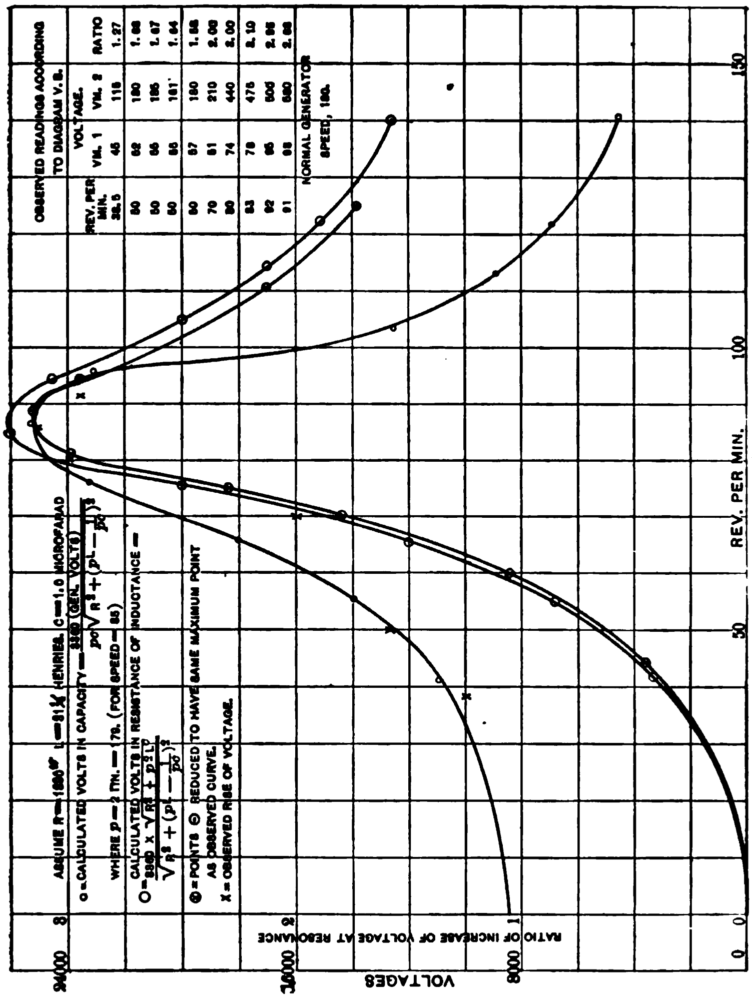
No rise of potential was indicated at Butte.

Apparently the break to ground of phase B occurs at a point of the wave where A has a high electromotive force, and C a comparatively low one, and is shown by the larger pressure to ground on leg A.

TABLE XVI.—TEST C.

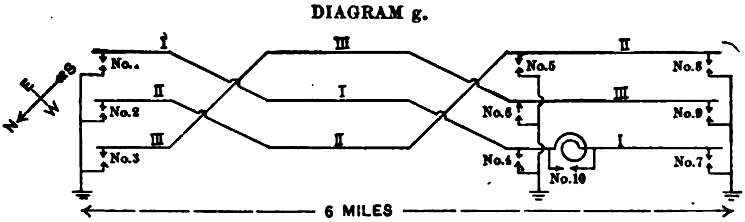
Gap No.	Location of Gap.	No. of Sparks Observed in Several Trials at Settings Noted. Closing.	Volts. on Gen.	Opening.	Volts. on Gen.	Voltage Corresponds corrected for normal voltage of 31000 Closing.	Opening.	Normal.
	Canyon Ferry.							
1	Line A to ground	Steady at 48	31 500	1 in 6 at 48	31 500	34 000	32 000	31 500
2	Line B to ground	0 in 6 at 24	31 500	0 in 6 at 24	31 500	<24 000	<24 000	18 300
–	Line B to ground	0 in 3 at 24	31 500	0 in 3 at 24	31 500	<24 000	<24 000	18 300
3	Line C to ground	0 in 3 at 42	31 500	0 in 3 at 42	31 500	* <29 000	<29 000	31 500
4	Line B to Line A	2 in 3 at 48	31 500	3 in 4 at 48	31 500	38 000	33 000	31 500
	Butte.							
7	Line A to ground	Usually continuous at 18. Sometimes no sparks, V. on gen. 31 500.						
8	Line B to ground	No sparks at closing or opening at 18.						
9	Line C to ground							

* < signifies "less than."



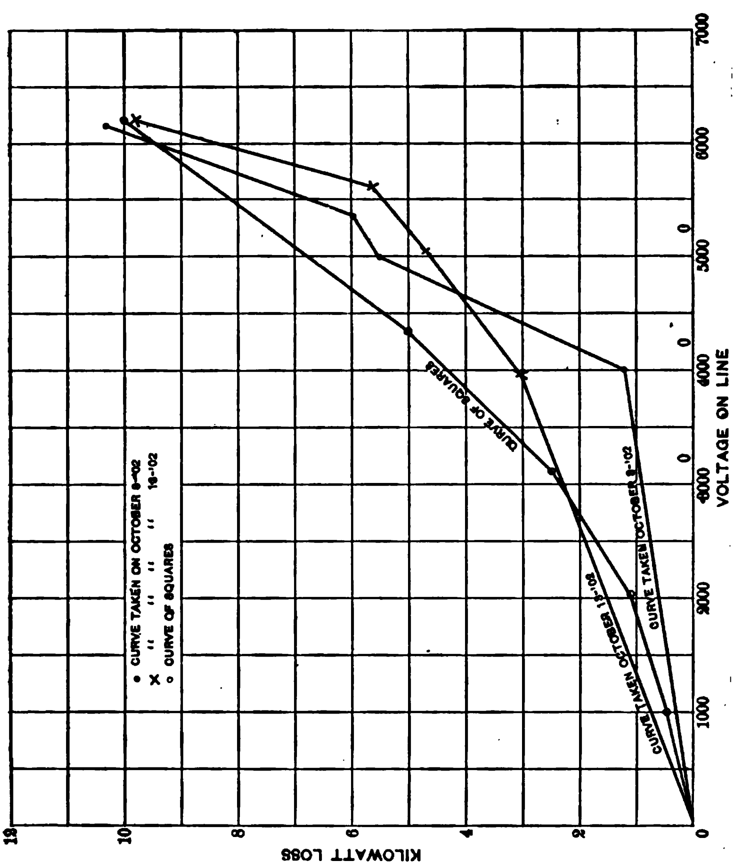
REV. PER MIN.
DIAGRAM f. Fig. 2.

DIAGRAM g.



General Conclusions for Static Tests. The discussion under this heading must be considered in connection with the paper read before the Franklin Institute in May, 1903. The theory that, strictly as a result of switching operations and arrester discharges where no secondary effects occur, no rise of potential can occur over double that of the

DIAGRAM p.

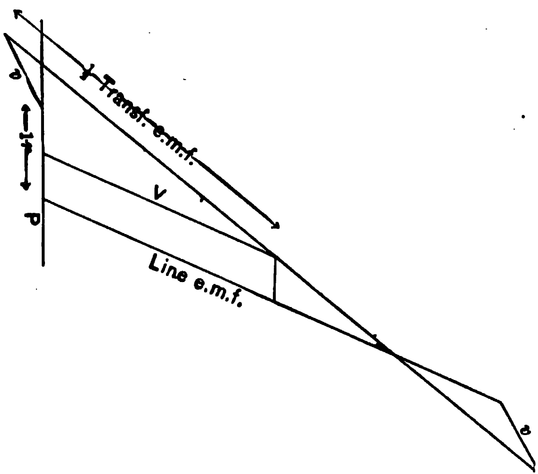


exciting potential change, is borne out by the experiments. In fact, this rise of potential still excluding secondary effects is usually less than 50% of its maximum theoretical value. However, secondary effects resulting from the static disturbances and modifying the maximum rise must be allowed for. The most common of these is the effect of the sudden excessive momentary current flow, and its results in practically building up the " generator " pressure for the time being. This effect may increase the rise of potential resulting from reflection of charging waves, to double potential in actual experiments.

The effect of static disturbances of any kind to cause in a full-sized plant concentration of potential on the outer portions of windings connected to the circuit is proven clearly. Note that the existence of the *strain* is proved clearly. Severe damage may or may not result. The use of choke-coils in series with the line may or may not protect a transformer coil from

DIAGRAM q.

V. Electromotive force in static interrupter units, v is parallel to and equal to 0.5 line electromotive force between neutral point p and line.



the strains according to its power. In the case of an insufficient powerful choke-coil the full value of the pressure change occurring at the line lead may be impressed on a small portion of the transformer winding, the exact proportion affected depending upon the suddenness of the static change. As a matter of experience it is found that serious damage results from local concentration of potential much less frequently than would be expected.

Three-phase transformers connected star in primary and secondary with high tension neutral grounded with two legs will cause approximately 1.7 times full voltage to ground when a short circuit occurs in such a manner as to affect one leg only of high pressure. This causes 1.7 normal strain on lightning-arresters and on all insulation to ground on the legs not short circuited. This extra potential on lightning-arresters is a very troublesome condition to meet if allowed to exist; it can be avoided by grounding the neutral point of the generating system. The excessive rise does not occur when two legs are simultaneously grounded.

III. Observations on the Effect of Lightning on a Dead Line.

During the making of these tests a number of miscellaneous observations and experiments were made in allied subjects

TABLE NO. XXI.

	Gap No.	Max. Set.	Volts Cor.	Remarks.
32ds	1	21	30 000	1 puncture 1/16 in. diam. — prob. result of several single p. 1/64 in. (8/12).
"	2	24	31 000	4 punctures, probably more. up to 1/32 in.
"	3	15	25 000	Large number charring hole ½ in. diam.. some very small.
"	4	21	30 000	One .025 in. diam. others at 9/32 on 8/2. Also great numbers (8/30) at 12. Some others at 12.
"	5	15	25 000	6 or 7 punctures, 2 occasions. Many at 12/32. 1 at 8/32.
24th	6	12	26 000	2 — also 2 at 9 and 2 at 6, none over .02.
"	7	18	31 000	Two .01 in. diam.. no others.
"	8	9	22 000	Two .01 in. diam. and .005 diam., no others.
"	9	20	32 000	Many, mostly fine.
"	10	3	9 600	2 very fine (.005 diam.) but perfectly clear, also 2 larger ones (perhaps composite) at 1½ (8/29) also large number fine gaps at 1½ (8/30).

Inspection makes it seem probable that there are no large single punctures but that the charring of the paper in record papers is due to a large number of superimposed and quickly recurring discharges.

some of which are of general interest and are here given. They are self explanatory.

(a) Six miles of line extended from the Utah Power Company's station at the mouth of Big Cottonwood Canyon to the town of Sandy. This is quite a severe lightning district. Ten gaps and one choke-coil were placed in this line as shown in diagram *g* and test papers kept in them being inspected and changed after every storm.

Examinations made after five or six storms showed sparks as follows:

(See Table No. XXI.)

Analysis of Data. Apparently all wires are raised to about equally the same potential above ground and each wire the same at all points.

Discharges are apparently very numerous. This is good reason to believe that this line was not struck directly during this time.

The reading on gap 10 shows that there are very sharp concentrated waves on the line which may be due to the direct lightning or to the discharge of gaps in the same wire, as no condensers were used.

See also article by N. J. Neall, *Elec. Club Journal*, March, 1905.

IV. Miscellaneous Static Notes and Tests.

(*a*). *Effect of Static in High-Pressure on Ground Connection to Low-Pressure Coils.* Apparently the ground connection (see diagram *a*) used in these static tests was entirely adequate to prevent a momentary deviation from zero potential in the low-tension coils even when severe static disturbances were taking place in the high-pressure windings. This is very important and the evidence is very good. The wiring to the ground connections was heavy but not particularly short. There was one common ground and connecting wire for all circuits.

(*b*) *Effect of Static in High-Tension on Type R Choke-Coils in High-Pressure.* The severe static disturbances of the switching tests caused very severe short circuiting strains on the choke-coils of the lightning-arresters (see diagram *a*), (some 50 turns about three feet in circumference average, quite well separated) receiving between the start and finish strains as high as 18 000 volts. Further, it is entirely probable that the transformers received strains very much greater on account of the enormously greater choking power of their high-pressure coils. These particular choke-coils, though offering a certain amount of protection, are probably unable to remove entirely the strains on the transformer windings tending to cause short circuits on account of their small power. There is little doubt that the actual transformers did receive very high instantaneous potential strains as a result of static changes. No damage appeared to result.

(*d*) *Length of Time Required to Discharge Line by Leakage.* The phenomenon that disconnecting an idle line sometimes leaves it fully charged has been referred to. This fact was shown conclusively by a tin-foil electroscope hung on the end of the line. The two legs of the electroscope would of course diverge widely when the line was charged and sometimes when the line was disconnected by a high-pressure switch the electroscope would stay spread. In some such cases more than a minute by watch was required for the spread of the electroscope to drop to 1/10th of its original spread. This shows how slowly the charge leaked off the line. This phenomena was noticed both at Logan with an oil-switch and at Canyon Ferry with an air-break switch.

These electroscopes may be made very helpful in high-pressure work as ready indicators of high pressure. They must, however, be shielded against the action of outside pressures or they may indicate even on a dead line.

(*h*) *Mutual Induction of Parallel Lines.* From the Logan power-house of the Telluride Power Company, two high-pressure lines of three wires each run on separate pole lines parallel for a distance of approximately 80 miles. The lines are spaced about 100 ft. on the average. The east line in addition to the 80 miles parallel to the west line extends 44 miles further to Provo. It had been found by experiment that when the east line was uncharged, and even grounded at the farther end that a severe shock could be obtained from this line. An investigation was made to determine the cause and amount of this pressure. It was first determined to be alternating current by a telephone and its pitch determined as either the same as that of the generators or in harmony with it. Measurement showed a maximum of probably 200 volts between line and ground, which occurred at Logan when the three wires were grounded and short circuited at Provo. The measurement of this pressure under a number of different conditions with different points grounded and paralleled and with lines grounded through one or more lamps, indicated that this pressure was due to the effect of the slight charging current induced by the west line which built up pressure on account of the inductance of the east line. This rather surprising result seems pretty well justified by a considerable number of experimental combinations. Except at the time of atmospheric disturbances there seemed to be no other cause of pressure on the transmission line.

(*k*) *Tests at Utah Light and Power Company.* No very difinite tests were made in the plant of the Utah Light & Power Company, due to the conditions at this plant, although all lightning-arresters in the system were supplied with test papers and a number of spark gaps and condensers installed at various places and left on the lines.

Static disturbances cause waves to pass along the high-pressure lines of great suddenness as shown by the short circuiting of two secondaries of 50-kw. transformers in series with the line and boosting the voltage of the Cottonwood line to that of the Ogden line. These were thus placed in the middle of a long high-pressure line and were burned out in coils carrying the line current at a time of static disturbance. The same thing is shown by the choke coil in the idle line described above (p. 731).

Papers were put in a great many gaps of lightning-arresters between lines and ground with condensers at a number of points,

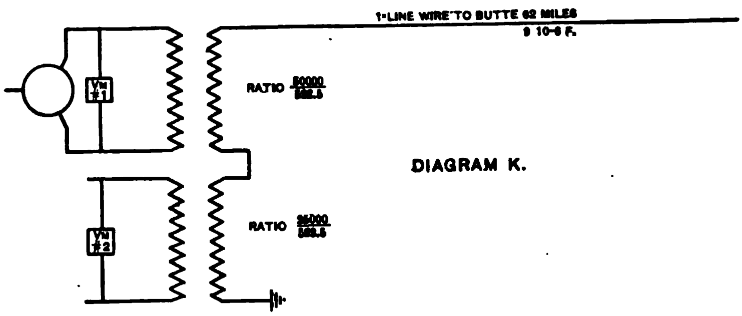


DIAGRAM K.

but little definite data was obtained for the system was not wholly mapped and no serious disturbances occurred during the time of observation. Lightning made frequent punctures in the papers, however, showing on the type *R* arresters a very free discharge to ground and on the resistance type a very slight spark.

V. Tests for Resonance.

At Canyon Ferry, Missouri River Power Company.

Object of Test. To obtain a rise of potential due to resonance from line charging current passing through an idle transformer.

Connections according to Diagram *k*.

With the above arrangement the speed on the generator was varied between wide limits. The ratio of the readings of $V m_2$ (idle transformer) to $V m_1$ (generator pressure) are plotted with the speeds in Diagram F.

With slower speeds than that of resonance the pressure on the idle transformer should fall toward zero since the charging current and the inductive ohms are both steadily getting less. Above this speed the pressure on the idle transformer approximates that of the generator since the charging current is so great relative to the increased inductive ohms through which it passes as to cause the latter to absorb all the generator pressure. Compare the actual curve for resonance. (See Diagram F.)

In this case we have the maximum pressure on line shown by diagram n = 2.93 times generator volts.

DISCUSSION OF FORMULA.

The complete formula giving the current at any instant in a circuit containing electromotive force (V), resist (R), inductance (L), and capacity (C) is as follows:

$$i = \frac{E}{\sqrt{R^2 + \left(pL - \frac{1}{pc}\right)^2}} \sin\left(pt - tan^{-1}\frac{pL - \frac{1}{pc}}{R}\right)$$

for a sine electromotive force.

The formula shows that with perfect resonance the current and the resistance volts are in exact accord with the generator pressure and that the L and C pressure are exactly equal and opposite.

The formula gives the current for any condition; the pressure over any one or more portions of the circuit can be obtained by deriving the pressure on each R, L, or C as the case may be from the simple formulas,

$$i = \frac{E}{R} \sin pt. \; i = \frac{E}{pL} \sin\left(pt - \frac{\pi}{2}\right) i = Epc \sin\left(pt + \frac{\pi}{2}\right),$$

combining these if necessary by the usual geometrical or trigonometrical process. The numerical values of the pressure may be obtained by multiplying the various factors R, L, C,

$$R, L, C, \sqrt{R^2 + p^2 L^2}, \sqrt{R^2 + \frac{1}{p^2 C^2}},$$

etc., by the current strength.

The curve for any condition of partial resonance may be found from the above formula or for any of the simple cases where $R = 0$, $L = 0$, or $C = 0$ or combinations of these.

Analysis of Data. This test is good and important.

In Diagram F, the pressure across the condenser, that is, between line and ground, and also across the inductance and resistance in series both included principally in the transformer (2) are shown. The observed values should follow the latter curve and do quite closely when such values of R, L, and C are taken as to give the same maximum for calculated and observed values. The value of R (1880 ohms), L (31.25 henrys), and C (1 microfarad), are taken to give the maximum observed pressure rise as if on condenser, using the known capacity of the line and the frequency and hence are only roughly approximate. The resistance R is assumed to represent all the energy losses in the circuit.

It will be noted that the observed points below resonance speed are considerably higher than the calculated resistance and inductance $\sqrt{R^2+p^2 L^2}$ curve. This probably results from the variable inductance in the iron. The resonance was obtained by a gradually increasing speed. When a point is reached where the inductance of an idle transformer is such as to give a resonance the pressure and current and induction in the iron increase which reduced the value of the permeability of the iron and the inductance so that a higher speed is necessary to produce resonance. That is, the maximum value is postponed so to speak by the increase of induction and decrease of permeability in the iron.

Furthermore, it must be noticed that the maximum rise of potential, even with perfect speed adjustment, is limited by the loss in the iron included in the R factor. To make this more definite, assume the idle transformer excited to full induction by a generator without electrostatic capacity. It is evident that then by adding just the right amount of capacity to produce resonance the generator pressure may be considerably lowered and the pressure in the transformer and the induction in the iron remain unchanged. The reduction can be made only in that ratio which the true watts of the current through the transformer bear to the apparent watts. In the case where this ratio is three as in the above test the power-factor of the leakage watts is approximately one-third and the magnetizing volt-amperes are $\sqrt{8} = 2.8$ times the true watts. In this test the induction in the iron was probably about normal, being half pressure and half frequency. The observed results thus seem very reasonable.

Under conditions in which the pressures and inductions would run far above normal some higher ratio of resonance increase of pressure might be obtained as the power-factor of the magnetizing current in such cases would be much smaller. In this case, however, the change of permeability will vary over a very wide range requiring a constant adjustment of speed.

In conditions where there is a choke-coil with an *open magnetic* circuit or in transformers built for high inductive drops there is no such moderate limit for resonance pressures as in these cases the losses in the choke-coil are comparatively small. Fortunately in these cases too the inductances are too small to give often the conditions of resonance. They are not so small, however, especially in the case of transformers for large leakage that precaution can be omitted. In large plants cases do exist where resonance with installed apparatus is a possibility. For certain accidents, as blowing of single-pole breakers or fuses or wires burned off by grounds may cause such electrical connections as to render resonance certain if the constant of L and C happen to be right. The resonating circuits in such cases are quite obvious and the necessary conditions have already been discussed.

Resonance at the frequency of static discharges except of a comparatively mild and transient type is unlikely, as persistent generating sources hardly exist so that the repetition of impulses necessary to build up resonance is lacking.

VI. Measurement of Loss into the Atmosphere and over Insulations of Two-Wire Line of the Missouri River Power Company between Canyon Ferry and Butte—62.5 Miles.

Two 950-kw. transformers having the primary and secondary windings each in series were used to charge the two line wires and the middle point was grounded in the high-pressure as shown in diagram *o*. Pressure was measured by a voltmeter in the low-pressure and the high-pressure calculated from the transformer ratio $\frac{50\ 000}{522.5}$ making allowance for the building up of pressure by leading current through the inductance of the transformer. The cycles were nearly constant at 60.

Connections according to Diagram *o*.

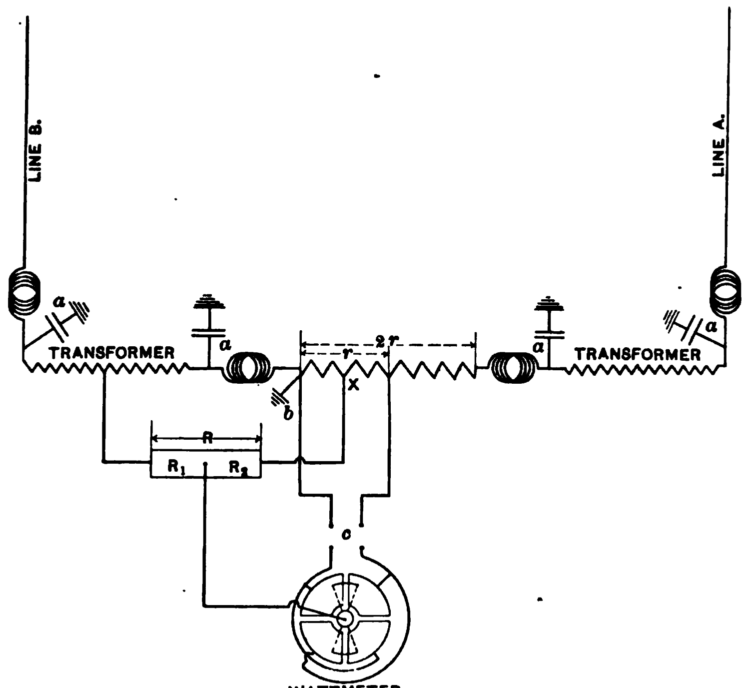
(See Table No. XXII.)

For plot of results see Diagram P.

Analysis of Data. A wattmeter constructed on the principle of the quadrant electrometer was used for these measurements. This type of instrument has the great advantage of being free from error of lowering voltmeter transformers or multiplying resistances. For a description of this instrument see paper by Miles Walker, TRANSACTIONS, A. I. E. E., vol. XIX., p. 1035.

DIAGRAM O.

a. Coil and condenser of static interrupter. b. Ground connection on high tension system. c. Commutator to reverse direction of swing of needle.



Corrections of Wattmeter. These are; temperature of suspension fibre, the presence of charged bodies in the neighborhood, adjustment for mechanical return of needle to zero and for the dissymmetry of needle and quadrants causing a deflection due to the presence of pressure on quadrants when no energy is being measured. All but the first of these errors are corrected by taking the average of readings in opposite directions and a commutator was provided with the wattmeter for this purpose. This correction is eliminated by keeping the wattmeter approximately at the temperature of calibration.

The two curves of observed losses (see Diagram P) are very much alike except for the point 5 on the second curve; this loss seems larger than would be expected from the other curve. This is very likely accounted for by the fact that in the first curve the line had been kept charged for hours before the test, while in the second the line was not so treated and the insulators may not have been wholly dry when this reading was taken. As considerable time elapsed between readings, this leakage loss had very likely reached a normal steady value by the next or the next but one reading.

TABLE NO. XXII.

Voltage between lines.	Total loss.	Loss in line resistance.	Loss over insulators and into air.
Weather wet but line alive at 40 000 volts for some hours before test.			
40 000	2 864	1644	1 220
50 200	8 120	2595	5 525
53 500	8 892	2940	5 950
61 400	14 160	3830	10 330
Line not alive more than a few minutes before test; weather fairly clear.			
39 600	4 544	1600	2 840
50 600	7 216	2550	4 666
56 000	8 824	3210	5 610
62 000	13 710	3950	9 760

Both curves would be very well represented by a straight line starting at about 40 000 volts and having a tangent about $\frac{10}{60\ 000}$ or they may be better represented by a rapidly rising curved line. This represents a loss on two wires of about 140 watts per mile at 62 000 volts.

On a 150-mile three-phase line of similar dimensions the loss might be estimated for 75 000 volts as $600 \times 150 = 90\ 000 = 90$ kw., though such estimation may be very misleading and is of little value. However, it seems probable that before the true loss reaches a value that will menace the efficiency of the plant at least 80 000 volts will be reached.

The loss seems slightly larger on a wet day but the difference is small.

These two curves can be relied upon to give a trustworthy measure of the approximate line wire loss at 50 000 to 60 000 volts on a full-sized plant under normal operating conditions, but only indicate roughly the form of the curve.

It appears to the writer highly desirable that further tests of the same general character to those recorded in the paper should be made under as many different commercial conditions as possible.

Discussion on, "High Power Surges in Electric Distribution Systems of Great Magnitude", and "An Experimental Study of the Rise of Potential on Commercial Transmission Lines, Due to Static Disturbances such as Switching, Grounding, Etc."

H. G. Stott: In opening the discussion on the two important papers presented this morning, I think very little can be added to either of them, except to outline what has been done in the endeavor to prevent a repetition of this very disastrous rise of potential which, besides putting one generator out of commission for a week or two, destroyed the insulation on, I think, 13 cables. Each of these cables was punctured in one, two, or three places, apparently without relation to their distance from the power-house. Singularly enough no damage whatever was done in the sub-stations. After that occurrence the Interborough Company took up the matter with both Mr. Steinmetz and Mr. Thomas, who aided us in proposing different methods for preventing such a rise, and in the general investigation of the whole subject.

In the first place it has been invariably noticed that the static ground detectors indicate the presence of a ground on one phase before a short circuit occurs in the feeder. The indication might come from 5 to 25 min. before the short circuit occurs. In this case the indication was given several minutes before the short circuit took place, as shown by the fact that the sub-stations telephoned to the main power-house that they had static display on insulators, oil-switches, etc. From this it seems that if the cable which had the ground in it could be isolated and cut out of service before the current had burned the insulation on the neighboring phases no damage would be done. With something like 35 feeders it is a very tedious process to isolate a feeder having a ground, as it would not be possible to test all feeders in less than 45 min., because an oil-switch would have to be opened at each end of each feeder; meantime the sub-station would have to be communicated with and arrangements made to carry the load on other feeders. If the feeder in question happens to be the last one to be tested it might be 45 min. before it would be reached; chance might determine that it be the first one tested, but this kind of good luck is rare.

If the feeder in trouble were isolated what would happen to the lead sheaths on the surrounding cables in the manhole? If the short circuit occurred in a feeder would the feeder not be carrying more current through the lead sheaths than they would safely stand? and would the short circuit burn places through these lead sheaths, especially in the manholes where there is more or less ground on the cable hangers? In order to get around that we have put in a resistance of large carrying capacity, one with a resistance of 6 ohms, and a rated capacity of 1 000 amperes for 2 minutes. The reason for this is, of course, the Y voltage is approximately 6 300 and sufficient current must pass through that ground resistance, and through the ground which might occur at any future time, to make certain of opening the oil-switch on an overload. That in itself will evidently discriminate and pick out the bad feeder immediately, and ought to do so at both ends simply by the use of plain overload relays on each end of each feeder. This system is now installed. Putting the system into service has been delayed by the fact that two power-houses are operating in multiple, and grounding one set of generators without the other has been purposely avoided. In future it is expected that any cable which grounds will be cut out of service automatically long before it can do any damage.

Another point which was brought out very strongly by Mr. Steinmetz was that we ought to guard in every way possible against the open arc. This is well taken care of in an oil-switch, as more than three and one-half years experience under all conditions of operating have failed to shake confidence in the ability of the oil-switch to perform its functions satisfactorily under the most severe operating conditions.

In the ducts the cables are enclosed so that a flaring arc is impossible. We have never seen any indication of a rise of potential from a fault which happened in the duct. The only case where we have had a rise of potential — there have been several—has been where the arc was free to play in the air, so that the cables in the manholes were the weak point.

After a great deal of thought, it was decided to surround these cables with an iron sheet which would probably be heavy enough to withstand the short circuit incurred until the oil-switch opened, and so prevent a flaring arc. These cables were already covered with two layers of asbestos tape wrapped spirally in opposite directions, and then wrapped with steel tape. Covered as they now are with an iron sheath, every cable is completely enclosed. Since covering these cables—they have been covered now for some time—short circuits have occurred, but there have been no indications of a rise of potential in the manholes where they are covered.

There is another advantage to be gained by the grounding of the neutral, which is this: the Y points of the generators probably have zero potential relatively to the earth, in fact tests show that there is no perceptible difference of potential whatsoever. That of course is due to the effect of the balanced system, free from disturbances at the time. What the result might be during short circuits is of course difficult to foretell, but by grounding the neutral the sudden change of potential from zero at the neutral to zero on one of the phases is prevented. It seems to me the effect of sweeping a charging current, of something like 160 amperes, across the generator windings (that is to have a capacity current traveling through inductance), must result in a large rise of potential in the generator windings. On making the ground connection, the charge will sweep backwards and forwards across the generator windings from the zero point to the phase which is being grounded. That in itself will, I believe, cause a very serious rise of potential on the generator.

P. N. Nunn: The papers by Mr. Steinmetz and by Mr. Thomas apply to the weakest spot in the weakest branch of electrical work. The question is frequently asked by investors and business men, how far is it really practicable to transmit power electrically? They are usually referred to what is being done in Canada, in Washington, in California, and in Mexico. But when it is asked whether more or less trouble is not being experienced in the operation of the plants the electrical engineer has no clear and conclusive answer.

The time was when it required a machine shop to operate a few motors, and an expert winder to operate generators. To-day the mechanical apparatus involved in the application of electrical power has been perfected to a greater degree of continuity of service and to a lesser cost of maintenance than that of steam or water-power. The transmission has reached no such perfectness. A few years ago the limiting factor was the transformer; nowadays just as reliable transformers are built for 60 000 and 80 000 as for 5 000 or 10 000 volts. Later the question became how to construct the insulator, and 75 cents each seemed a large price. To-day we cheerfully pay $3.00 or $4.00 for an insulator which is reliable for 60 000 volts, perhaps for 80 000 or 100 000 volts, yet the history of daily transmission operation impresses one with a feeling of uncertainty.

The simple pole line carrying three or six wires, has given place to the more complex transmission system with trunk lines in parallel or in triangle and with branches from many points in all directions. A generating system of equal complexity is equipped with apparatus whereby each generator, when in trouble, may be automatically cut off without serious disturbance to the remainder of the system. As yet, however, there is no means whereby a section of a long high-pressure transmission may be cut out without danger of interrupting the whole system.

It is not a question of lightning. If lightning puts a plant out of service, there is some dignity about that; it is an "Act of God". But when an operator in the usual course of operating attempts to cut out a defective section of line, and a moment later finds the entire system shut down, he feels that there must be a glaring defect both in his science and in his application of it to the problems of transmission.

To quote a sentence from Mr. Thomas' paper, " Our knowledge of the phenomena of static disturbances in commercial circuits is in a much confused and comparatively undigested form". Although it seems that we know much of the theory involved, yet this statement appears true. One reason for this may lie in the extreme difficulty of testing the theory and working out the values of its factors upon practical transmissions. 100-mile, high-pressure lines cannot be taken into the laboratory and treated with the exactness and refinement of laboratory methods, nor can research work bear the expense of building long lines for experimental purposes. No sooner is a commercial line completed than it is put into service, frequently without allowing even a few days for test. Therefore opportunities to conduct experiments so prolonged and unbroken and under such constant conditions as those reported by Mr. Thomas are extremely rare.

The expression " without interruption " in Mr. Thomas' paper may be misleading. It is true that the purpose at first was to attempt only such experiments as could be conducted without interrupting or crippling the system, with the result that Mr. Olmsted became so engrossed in the theme that his demands upon both customers and operators became broader and broader, to the serious embarrassment of operating the plant.

To make this discussion the more complete some further tribute should be paid to the memory of Mr. F. D. Olmsted, a Member of the INSTITUTE, who died in September, 1903. As stated in the paper, the greater part of the experiments were conducted on the lines of the Telluride Power Company. Mr. Olmsted had immediate charge of these experiments; and to his personal efforts and coöperation throughout were chiefly due the rare opportunities for making the tests and the completeness and accuracy of the results secured.

S. M. KINTNER: Mr. Steinmetz has given an exceedingly plausible theory, if nothing else, and such experience as I have had with lines of this character seems to bear out that theory. I have made certain laboratory tests, which, as Mr. Nunn aptly states, are exceedingly limited in regard to any conclusions of value that can be drawn therefrom, but which also seemed to verify this same conclusion. I have succeeded to a limited degree in producing an open-air oscillating arc, and in getting excessive voltages therefrom. In only one case have I noticed this in practice on an actual transmission line, and there the data were not sufficiently accurate to warrant accurate conclusions. I was present on only one occasion when these phenomena occurred, although I was told by the operators in the station at the time that they had occurred in exactly the same manner on other occasions. The phenomena occurred in somewhat this order: a ground was indicated first of all on the ground-detectors; the telephone lines paralleling the circuit became noisy; and it was a question of only a few moments when the other disturbance came on, and a voltage much greater than normal, probably several times greater occurred, flashing over the terminal of the circuit as it entered the power-house. The arc that jumped across the open air-space must have had a voltage of two or three times normal value. The question of the steepness of the incoming wave, as Mr. Steinmetz has pointed out—his reduction of this to a certain wave-front steepness, if we may call it such, of a higher frequency circuit—is particularly interesting, and I have found it convenient to employ this same idea of looking at these phenomena though I had not formerly reduced it to a mathematical expression.

I have made some tests along this line in connection with choke-coils for determining their reflective power, etc., in which an attempt was made to produce the same wave-front steepness in each test. This has been a very interesting work, and a very difficult one on which to get any accurate data. The measuring implements for such work are as yet exceedingly crude, and it requires the averages of a great many tests to get any thing like consistent data.

F. A C. PERRINE: When hearing these two papers the first thought was that Mr. Thomas had given data which could be used directly in designing plants, while Mr. Steinmetz had given the explanation of circumstances that may arise, but which can not be guarded against. In this thought the obvious remedy which Mr. Stott has described to us was missed; namely, that Mr. Steinmetz's paper points out that anything that can be done to suppress the third frequency of the train-wave will tend to prevent the occurrence, and anything that can be done to prevent an open-air arc on the system will reduce the train-wave to such frequency and amount that its effect cannot be destructive.

Though, of course, the method that Mr. Stott has proposed of making cables always enclosed so that no open arcs of high enough frequency can occur to produce destructive effects, may be applied to certain systems, it may not be applied to others. One of the first and most serious occurrences of this nature to which my attention has been called happened in California, where a destructive arc occurred at the time when an oil-switch under short circuit was opened and blown to pieces by the arc, the oil scattering over the station. At that time the surge is said to have produced inductive currents in the iron structure of the power-house, so that one could see flashes all over the roof. There has been another occurrence in Hartford, experiments I think, performed under Mr. Steinmetz's instructions with lightning-arresters, where they attempted to perform a series of experiments on lightning-arresters attached to an idle line paralleling another carrying a current for lighting a theatre, without interfering with the service, but when the lightning-arresters acted the lights in the theatre went out and people in Hartford were left without light. That is to say the surge was so intense, that it opened the circuit-breakers on the parallel line, without destroying the insulation of the parallel line.

Mr. Steinmetz has intimated that lightning-arresters may stop the generating current very quickly. This difficulty is liable to be encountered, because stopping the generating current which would follow a lightning discharge, with great rapidity, might cause an exceedingly steep wave which might cause this result.

In Mr. Steinmetz's paper there is an observation that I think leads to a possible misunderstanding. He writes of the third frequency of the train wave as being independent of the line constants. He obviously does not mean this. The train wave must have a frequency that is largely dependent upon the constants of the circuits, but which is principally dependent upon the rate of interruption of the short-circuit current. In consequence it is not susceptible of calculation simply from the constants of the circuit, but also one must assume some rate of interruption of the short-circuit current in order to assume the steepness of the interrupted wave, in order to obtain the frequency of the train wave. The effect is exactly similar to the method of producing high rate of alternation by interrupting a circuit of known capacity and self-induction by means of a magnetic blow-out.

We are at this time greatly indebted to the conditions prevailing on the Manhattan Railway circuit which were so simple as to admit of calculation, but more especially to the care with which all the conditions were observed by Mr. Stott's assistants. The calculations given by Mr. Steinmetz are not open to objection if one allows his assumptions as to frequencies. The two ends of the calculations are tied together, and I do not think it can be said that this is in consequence of theoretical reasoning only. There are definite results here.

Finally, Mr. Steinmetz has pointed out the importance of the effect of the static discharge. There is no such thing as harmless static discharge. For a number of years engineers have been observing static effects. People say, "That is nothing but static discharge". But there never has been a static discharge that did not represent defective insulation and a leak. The result of the particular instance considered by Mr. Steinmetz shows how serious may be the consequences following static discharges; which invariably can be prevented by making insulation perfect. Such discharges invariably indicate defective insulation.

Mr. Thomas's paper shows the result of switching, and what may be considered as the worst conditions under switching. In consequence in the paper there is a very clear plan on the basis of which a remedy which can be definitely provided for the matters that are to occur every day. They do not represent, however, the worst conditions that may occur on identically the same lines; for example, the circuits that were made and broken under the conditions described in Mr. Steinmetz's paper.

H. W. Fisher: About 12 or 15 years ago I discovered the dangerous effects produced by breaking the capacity current going to cables. For several years I thought that large disruptive rises in voltage were only produced in power-houses where considerable cable was employed; but recently a rise of voltage of 6 to 8 times the normal was produced in a piece of cable about 20 ft. long. In this case the insulation was broken down but the lead was not punctured, showing that it is possible to get a very abnormal rise of voltage without a direct arc in air.

PRESIDENT LIEB: In connection with these papers I should like to say a further word on a matter that has been referred to by one of the speakers, and that is the extent to which the human element enters into the disturbances that are likely to take place on large transmitting and distributing systems. In the transmitting and distributing system of the New York Edison Company, I believe ten times as many disturbances take place due to mistakes and failures on the part of the operators as to any other cause. One of the serious problems that have to be contended with is to reduce the number of possible mistakes from this cause. In many of the plants of this company it is possible to reduce the number of probable mistakes by interlocking switching gear, and such a method of throwing switches in and out as would make it necessary to follow a preconceived method of procedure, thereby eliminating mistakes in the sequence of operation. But this is not always practicable.

Another important element that should be referred to is the difficulty of starting up large systems when once shut down. That difficulty is, of course, less with a railway system but it is great with a large lighting system; and the proper precautions and method of procedure which should be followed in case of a general shutdown of an extensive system with 20 or 30 sub-stations, with synchronous converter equipments and storage-batteries is a matter of very serious importance. These are systems which, unlike that of the Telluride Company, it is not possible to play with.

The Edison Company has desired to make tests on a large scale of the starting of such a system from a complete shutdown; not temporarily to deprive the whole city of New York of electric light and power but to undertake to start up a generator with converters connected with it, and also with their load. This was done satisfactorily on a small scale recently, by putting New York in connection with Brooklyn and starting up " Dreamland ", at Coney Island, from one of the New York stations; but unfortunately it was on a limited scale. We should like to establish the possibility of doing this on a larger scale, but the requirement of absolute continuity of service does not permit an opportunity of making such a test.

SAMUEL SHELDON: I should like some information from Mr. Steinmetz or Mr. Thomas. As I understand Mr. Steinmetz, the excessive rise of potential upon opening the circuit is due to the high *natural* frequency of the circuit. This high frequency makes the inductance and resistance different from what they would be at ordinary frequencies, and also brings into effect the distributed character of the capacity. The obtaining of this high frequency is dependent upon all of these quantities—the inductance, the capacity, and the resistance. Is it not a fact that upon opening a circuit the resistance becomes the determining factor, and that the resistance of the arc, varying as it must because of air current fluctuations and of its temperature, is the determining factor that gives rise to these high frequencies?

CHAS. P. STEINMETZ: My conclusion is that the origin of the disturbance and of the breakdown was due to the high-frequency oscillation of the traveling wave. But the high voltage was due to the oscillating short-circuit of the cable caused by the traveling wave, and was not an effect of distributed capacity, but due to an oscillation of massed capacity (that of the cable system, which has very little inductance) and massed inductance of the generating system. In this latter oscillation, the frequency was low and the destructiveness great, but it would never have started if there had not been a very high-frequency traveling wave preceding it.

P. H. THOMAS: In spite of the unusually full detail available in this case, it is impossible to establish any particular theory of the phenomena as the correct theory. As is almost universal in such cases, it is necessary to consider all possible theories and to accept provisionally that which seems most reasonable and most nearly fits the observed facts.

One cannot consider that the theory put forward in this paper, involving a self-interrupting arc, to be *demonstrated* to be a correct theory of what took place. This explanation may or may not be the true one. Personally, it has always been very difficult for me to conceive of a series of rapid self-interruptions of a very severe arc associated with an extreme rise of potential at the point of interruption, such as assumed in the paper. On the other hand, it is a fact that very often things that are not easily understood may, nevertheless, be true.

The extremely rapid heating and cooling of the gas which is taken to have a more or less steady condition of interruption, together with the fact that such a large majority of severe arcs occur without noticeable rise of potential, make it seem probable that in those cases, such as the present instance, in which a rise of potential is actually observed there is some other condition in addition to the presence of the arc, which is really the essential condition causing the extraordinary voltage.

In a considerable number of cases within my knowledge, prearranged for the opening of a short-circuit, apparatus for measuring instantaneous voltages has shown no sensible rise of potential. The opening of the charging circuit to an open-circuited line is another matter.

A careful examination of the details of the breakdown at the Manhattan Railway Co.'s power-house has suggested to me the possibility of another explanation of the phenomena, which differs from that proposed in the paper and does not involve a self-interrupting arc.

Consider the outline of circuits shown in Fig. 1 in which a number of generators in parallel feed three-phase bus-bars. which in turn, feed three-phase feeders, each feeder supplying a group of step-down transformers connected with synchronous converter. Assume a ground to occur on one leg of one feeder, as indicated at the point a; the full charging current of the system then flows from wire to earth at this point. This current is between 100 and 200 amperes. This will produce a certain amount of unbalancing of potential together with a low static noise at the cable heads, which is probably not sufficient,

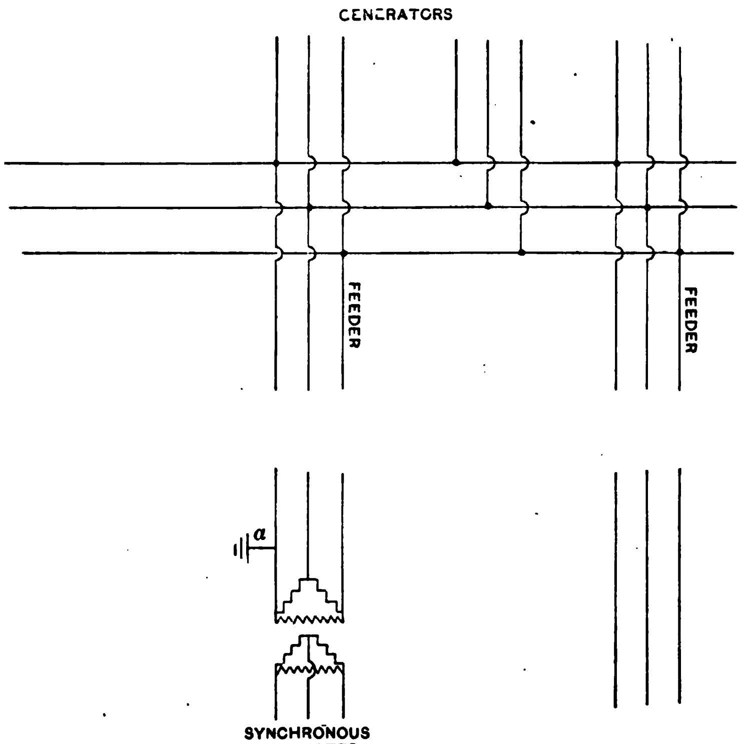


Fig. 1.

however, to account for the hissing observed in the sub-stations immediately before the breakdown. Suppose, again, that this charging current ultimately burns off the feeder at the point a, as shown, and that the charging current to earth continues on the end of the cable toward the converter, but drops out at the other side of the open circuit. The charging current is now passing from ground to the short end of the cable through the step-down transformers to the capacity of the rest of the system, and the leading current passing through the inductance of the transformers, which are built with a large magnetic leakage for the purpose of automatic regulation in the synchronous converters, with the result, provided the frequency be right, that resonance must occur tending to build up a high voltage between line and ground and across the transformers. A calculation of the capacity of the high-tension system and the inductance of the transformers indicates that the frequency of the system is not far from that required for perfect resonance. The calculations do not show, however, that the normal frequency is "the exact frequency for resonance". The electromotive force supporting the resonance must come in this case from the rotary transformer.

If the frequency be assumed to be somewhere near but not quite that of perfect resonance, there must be a complete building up of voltage to a certain maximum, and then there will be a decrease of the electromotive force as it gets out of step with the resonating circuit, down to normal again; then later a repetition of the rise of potential, and so on indefinitely. If the rise of potential is assumed to be insufficient to break down the insulation at any point, the hissing noise observed in the sub-stations can easily be accounted for; and then if some slight change in conditions of load or speed is assumed to cause a higher resonance rise so that a breakdown occurs, then there occurs a short circuit across the generator, probably on one of the other feeders, or possibly on one of the static dischargers, which may open the circuit-breakers on some feeder other than the one originally causing the trouble. In this case the short-circuit is eliminated and resonance will again start, causing another breakdown, and the opening of another circuit-breaker, and so on until the entire plant is shut down. According to this view of the phenomena that may occur the large number of breakdowns are accounted for by the permanent condition of resonance, which causes breakdowns and short circuits, the short circuits being immediately cut out by circuit-breakers. Naturally, the damage is finally stopped by the shutting down of the plant.

It should be noted here that it would be likely for the cable that was originally grounded to remain in circuit, since it was grounded and not short-circuited. On the subsequent starting up of the plant this cable would operate properly for a time until some circumstance causes the ground to be re-established, in which case a second resonance condition would be established, as in the first case, causing other breakdowns. A second breakdown actually followed a night after the original breakdown, and, subsequently, a cable was found with one wire open-circuited, but without short-circuit between conductors as has been assumed above.

Mr. Stott has stated that in many cases cables that have been grounded and seriously burned have subsequently failed to break down on test until as high as 20 000 volts between conductor and ground has been reached. This statement should be taken in connection with the assumption above that it was feasible to operate with one leg open-circuited and a puncture to ground. In this connection, it is important to notice that the synchronous converter at the end of the first injured cable will presumably keep in step in view of the fact that one phase remains intact, even after the opening of one leg at the point *a*. As a natural result, the open end of the conductor on the injured cable on the side toward the generator will not receive the potential to ground that is impressed upon the rest of the system, by an amount equal to the generator voltage.

A careful detailed study of the different arcs and punctures indicated that the results could all be readily explained by the presence in the circuit of abrupt changes of potential of not over 40 000 to 60 000 volts. In a number of cases considerable air-spaces apparently were jumped, but it seemed always possible that the original exciting spark causing the arcs started by a discharge over the surface of the insulation, and that the same subsequent arc so transferred itself to some other point as to give the appearance of having jumped a considerable distance. According to the above theory the breakdown in the cable at the street was the last rather than the first of a long series, as assumed in Mr. Steinmetz' theory. This subject is of sufficient interest and importance to warrant a much fuller discussion of the phenomena, but the above outline of an alternative theory is all for which space will be taken here.

A similar occurrence of less magnitude, in Berlin, has been described in an electrical magazine. Investigation and discussion of the accident showed conclusively that a cable system was made to resonate through the inductance of a small step-down transformer on account of the opening of one leg of its feeder. In general wherever it is possible for one leg of a circuit, supplying apparatus containing inductance, to become opened without the complete cutting off of the apparatus, there is a possibility of resonance, if the system has a considerable capacity, as will usually be the case with underground systems. This is a real danger, though it will not often be met with because only occasionally will the constants of the circuit be such as to cause resonance with the normal frequency of the generator.

Every engineer operating a plant should make calculations to determine whether any of the circuits contain the proper amount of inductance and capacity to resonate at normal generator frequency in case an accident should occur that might produce the necessary electrical connections. Usually it is easy to avoid the danger.

CHAS. P. STEINMETZ: To refer to the last question first: I have also been of the opinion that fuses are not permissible in a very high-voltage transmission system. However, in the last years we have made a number of tests with fuses in cutting off branch-lines of moderate power in large, high-capacity and high-voltage systems, and found that with certain types of fuses the oscillograph showed practically no voltage rise; that is, these fuses apparently did not cause instantaneous rupture, so that for branches of systems, (not the main line), that carry only a moderate amount of power, and for which, therefore, this elaborate and expensive system of control by automatic oil-switches, etc., is rather undesirable, the question of fuses may be reconsidered. I cannot yet say that I should recommend it broadly, but it may be taken into consideration in special cases.

In regard to Mr. Thomas's paper, I believe the statements made by Mr. Thomas on page 320 are important general discussion of the phenomena resulting from what I call wave-trains, or traveling waves, and of which in my paper, I endeavored to give the general outline of the theoretical equations; that is, oscillations resulting from a disturbance in a system of distributed capacity and inductance. I have not had time carefully to digest Mr. Thomas's paper, but it seems to me from the data of tests given therein that the phenomena observed by him were not so much the phenomena of a traveling wave as the phenomena of a surge of the system of fundamental frequency. The observed distribution of potential along the circuit, rising from the end where the switching takes place, towards the end where the circuit is open and the wave reflects, is the distribution of potential on a circuit resulting from a sudden change of circuit condition. This consists essentially of the fundamental wave but it is not the same as the traveling wave to which I have referred above. This would also account for the observations on branch lines, that the triple and quadruple voltage that a traveling wave should give on a branch line was not observed by Mr. Thomas, but that the branch line is merely a localized capacity oscillating together with the rest of the system. I had occasion to carry out investigations of this character a few years ago on a transmission system at Kalamazoo; but there I was able to double back a number of lines so as to get a considerable capacity, and also to choose the load, and to experiment with a non-inductive load, and with a load of very high self inductance; that is, a load of very low power-factor, and with a combination of both. I got rises of potential, with an impressed electromotive force of 30 000 volts, showing peaks of 100 000 to 118 000 volts. In these experiments I got a surge of the fundamental frequency of the system. I believe that the observations recorded in Mr. Thomas's paper are mostly of the same character.

A number of causes of such disturbances are mentioned on page 322, but what I consider the most important cause; that is, the oscillating or self-rupturing arc, is not given, possibly because Mr. Thomas is not quite satisfied with the existence of such phenomenon.

There is, however, no doubt that an alternating arc may be self-rupturing; that is, blow itself out with extreme suddenness. Such a self-rupturing arc becomes an oscillating arc if the supply voltage of the circuit is greater than the striking voltage of the gap between the arc terminals; that is, after the rupture of the arc, the supply voltage, by striking across the gap, restarts the arc; it again ruptures itself, to be restarted, and so on. As seen, the oscillating arc is a natural consequence of the self-rupturing arc.

This phenomenon of the self-rupturing arc was first brought to the attention of engineers a number of years ago by Mr. A. J. Wurts, in his paper on non-arcing metals. The discovery of the self-rupturing alternating arc announced in this paper has not made the impression it deserves, possibly because it was coupled with the announcement of a new form of lightning-arrester, and also because the conditions under which the phenomenon occurred were not completely known. As a result thereof, when repeating the experiments myself it frequently did not succeed. For instance, in starting an alternating arc between non-arcing metals, with a non-inductive resistance in series to limit the current, the arc is not self-rupturing, but is maintained.

This feature of self-rupturing arc is, however, now extensively used in lightning-arresters, and is practically the only known method of producing oscillating currents of very high frequencies. It occurs not only with the non-arcing metals, but more or less with all metals, and even with electrolytic conductors, and is, I believe, the explanation of the action of the electrolytic, or Wehmelt, interrupter.

The conditions most favorable for the production of an oscillating arc are that the flow of current the instant after the arc strikes is practically unlimited, and that after the striking of the arc the voltage drops practically to zero and remains low for a finite, even if extremely short, time after the rupture of the arc. The first condition is fulfilled by a condenser or equivalent device in shunt to the arc; the latter by an inductance in series with the arc and the condenser. When the arc strikes, a larger rush of current, (the discharge current of the condenser) passes, and since, due to the series inductance, the supply current cannot instantly rise, the voltage drops. At the moment of rupture of the arc, the supply current still continues to flow into the condenser, and the voltage across the arc-gap therefore remains low, rising gradually while the condenser is being charged. If the supply voltage of the system is greater than the striking voltage of the gap, as soon as the latter voltage is reached, by the jumping of an electrostatic spark, the arc is restarted, and ruptures itself by the explosive effect of the sudden heating due to the condenser discharge, etc., and so the arc becomes oscillating. As seen, then, by reducing the arc-gap, the striking voltage, and thereby the time required for the condenser to be raised to the striking voltage, is reduced; that is, the period of open circuit of the arc-gap is decreased; and because of the decrease of the condenser discharge resulting from the lower voltage, the duration of the arc flow is also reduced; that is, the frequency of oscillation is increased. I especially desire to call attention to this very interesting feature of an electric circuit, in which the frequency of oscillation not only depends upon the circuit constants, inductance, capacity, etc., but also very largely upon the length of spark-gap and supply voltage; the frequency of oscillation increases with decrease of the gap-length, with increase of supply voltage, with decrease of capacity and of inductance. The frequency can be varied by varying the length of the spark-gap. As is well known, this is the usual method of varying the frequency in apparatus for producing very high-frequency oscillating currents.

It is obvious now, how an alternating arc, with resistance in series with the arc, cannot well be oscillating, since coincident with the breaking of the arc the voltage would reappear at the arc-gap and so keep the arc from breaking. It also shows how the discharge between a conductor of a cable system and ground is specially liable to be oscillating, since with the passage of current between conductor and ground the potential difference that produced the discharge, disappears by the grounding of the conductor. The meaning and the effect of the inductance in the electrolytic rectifier, etc., is now easily explained by considering its action as due to an oscillating arc.

Under conditions like or similar to those described above an arc is oscillating, not only in an alternating-current circuit, but also when the supply voltage of the curcuit is constant or unidirectional.

The phenomenon becomes somewhat more complex when instead of the localized capacity and inductance, as described above, a circuit of distributed capacity and inductance is considered as in my paper. In its general character, however, the phenomenon is essentially the same, and an attempt at a mathematical investigation has been given in my paper.

Speaking in favor of this explanation of the oscillating arc, a rather strange coincidence is patent in Mr. Stott's statement that short circuits were almost always preceded by ground and static displays.

In regard to the numerical values given in my paper and in Mr. Thomas's paper, it is obvious that these values must be considered only as approximate, or restricted to the conditions under which the tests, or the assumptions, were made. Especially is this the case with the frequency of the traveling wave. This frequency is merely assumed by me, and it may be different.

The numerical values of the voltage rise given in Mr. Thomas's paper, I believe, do not mean that the voltage can never rise more than 30% or that it will always rise up to 30%. In all such cases where numerical values result from definite experiments they must be considered as merely showing the character of the phenomenon but not its magnitude. One may observe, for instance, that if the circuit of an electric conductor is closed the conductor rises in temperature by 30° cent. Now the conclusion would be, that the electric current heats the conductor, but not that it raises its temperature by 30°. The numerical value of the effect depends upon the conditions of the particular instance. So here the rise of voltage can not be determined generally, but frequently one can get at least the maximum possible values, and this may be sufficient. If the voltage of the surge were over 100 000, as it sometimes may be, and as I have observed by the oscillograph record, and the current during the surge as high as 9 000 amperes, then there is no chance to insulate and protect against these surges, and the only thing to do is what Mr. Stott has done, to avoid the cause of the surge, by eliminating the continued occurrence of a spark discharge between the conductor and ground, by disconnecting automatically that particular cable in which the spark discharge appears before the damage can spread further and cause the destructive short-circuit surge of the system, of high-power and low-frequency surge.

P. H. Thomas: Mr. Steinmetz in stating that the result of certain tests in my paper does not support the statement that a rise of potential at the end of a short line that is connected to the end of a long line, indicates that Mr. Steinmetz has misinterpreted my experiment. The rise of potential occurring at the end of the short line results only in the case where it acts as a continuation of a longer line, or, in other words, where the wave of the longer line is forced to enter the shorter line. The short line referred to in the test is a branch line and furthermore has the same capacity as the main line. Mr. Steinmetz's statement that the experiments given in my paper show nothing with regard to other line conditions on other plants is, I think, hardly justified. The object of the tests was to verify or disprove certain fundamental laws, derived theoretically. It appears to me that these laws have received a strong confirmation by the tests, which means that they are to that extent applicable to other cases. Because Ohm's law has never been tried for every possible case it is not assumed that it does not apply in any new problem that may arise.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

CONSTANT CURRENT MERCURY ARC RECTIFIER.

BY CHARLES PROTEUS STEINMETZ.

I. GENERAL.

The operation of the mercury arc rectifier is based on the phenomenon of the electric arc, that it is a good conductor in the direction of the arc blast, but a non-conductor in the opposite direction, and consequently permits only unidirectional currents to pass.*

In an electric arc the current is carried across the gap between the terminals by a bridge of conducting vapor, consisting of the material of the negative terminal or the cathode, which is produced and constantly replenished by the "cathode blast," a high velocity blast issuing from the cathode.

An electric arc, therefore, can not spontaneously establish itself. Before current can flow as an arc across the gap between two terminals, the arc flame or vapor bridge must exist; and to establish it energy must have been expended. This can be done either by bringing the terminals into contact and so starting the flow of current, and then by gradually withdrawing the terminals derive the energy of the arc flame from the current, as is done in practically all arc lamps; or by increasing the voltage across the gap between the terminals so much that the electrostatic stress in the gap represents sufficient energy to establish a path for the current, by causing an electrostatic spark to jump across the gap, which is followed by the arc flame. This occasionally happens against the wishes

*Regarding the apparent exception of the carbon arc, see my paper on "The Electric Arc," International Electrical Congress Transactions, 1904, Vol. II, page 710.

of the engineer, for instance in lightning-arresters. Or by supplying the arc flame from another arc, an arc can be established between two terminals, as occasionally happens when a switch opens or burns up and its arc flame envelops the blades of another switch.

The arc must therefore be continuous at the cathode, but may be shifted from anode to anode. Any interruption of the cathode blast puts out the arc by interrupting the supply of conducting vapor, and a reversal of the arc stream means stopping the cathode blast and producing a reverse cathode blast, which requires a voltage higher than the electrostatic striking voltage (at arc temperature) between the electrodes. With an alternating impressed electromotive force the arc, if established, will go out at the end of the half wave, or if a cathode blast is continuously maintained by a second arc (excited by direct current or overlapping sufficiently with the first arc) only alternate half waves can pass, which will be those for which that terminal is negative from which the continuous blast issues. The arc, with an alternating impressed voltage, therefore rectifies or permits only unidirectional currents to pass, and the voltage range of rectification is the range between the arc voltage and the electrostatic spark voltage, hence highest with the mercury arc, due to its low temperature, and zero with the carbon arc, hence the latter does not usually rectify.

II. Description of Rectifier System.

The constant current mercury arc rectifier system, as used for operating the direct-current series arc circuits of carbon magnetite, or mercury arc lamps from an alternating constant-potential supply of 60, 40, or 25 cycles, is sketched diagrammatically in Fig. 1.

It consists of: a constant-current transformer, with a tap C brought out from the middle of the secondary coil $A\ B$; a rectifier tube having two graphite anodes $a\ b$; a mercury cathode c, and usually two auxiliary mercury anodes near the cathode c (not shown in diagram Fig. 1), which are used for excitation, mainly in starting, by establishing between the cathode c and the two auxiliary mercury anodes, from a small low-voltage constant-potential transformer, a pair of low current rectifying arcs in the same manner as in the well known constant potential mercury arc rectifier. Two reactive coils are inserted between the outside terminals of the transformer and rectifier tube, respectively, for the purpose of producing an overlap between the two rectifying arcs, *c a* and *c b*, and thereby the required continuity of the arc stream at *c*. A reactive coil is inserted in the rectified or arc circuit, which connects between the transformer neutral *C* and rectifier neutral *c*, for the purpose of reducing the fluctuation of the rectified current to the desired amount.

The rectified or direct-current voltage is somewhat less than one-half of the alternating voltage supplied by the transformer secondary *A B;* the rectified or direct current is somewhat more than double the effective alternating current supplied by the transformer.

III. Mode of Operation.

In Figs. 2 and 3 let the impressed voltage between the secondary terminals *A B* of an alternating-current transformer be

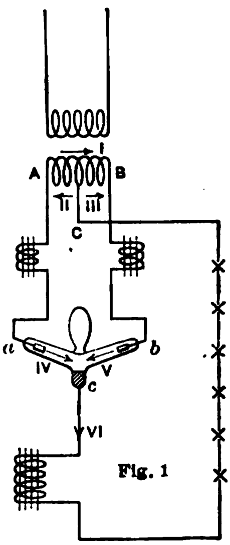


Fig. 1

shown by curve I. Let *C* be the middle or center of the transformer secondary *A B*. The voltages from *C* to *A* and from *C* to *B* then are given by curves II and III.

If now *A B C* are connected with the corresponding rectifier terminals *a b c*, and at *c* a cathode blast is maintained, those currents will pass for which *c* is negative or cathode; that is, the current flowing through the rectifier from *a* to *c* and from *b* to *c*, under the impressed electromotive forces II and III, are given by curves IV and V, and the current issuing from *c* will be the sum of IV and V, as shown in curve VI.

Such a rectifier as is shown diagrammatically in Fig. 2, would, however, not be self-exciting; it requires some outside means for maintaining the cathode blast at c, since the current in the half wave 1 in curve VI goes down to zero at the zero value of electromotive force III, before the current of the next half wave 2 starts, by the electromotive force II.

It is therefore necessary to maintain the current of the half wave 1 beyond the zero value of its propelling impressed electromotive force III, until the current of the next half wave 2 has started, in order to overlap the currents of the successive half waves. This is done by inserting inductances into the leads from the transformer to the rectifier; that is, between A and a, and B and b, respectively, as shown in Fig. 1. The effect of tnis inductance is to cause the current of half wave 1, V, to continue

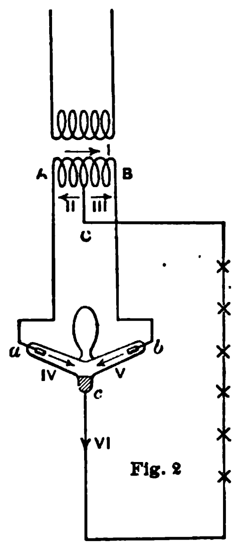
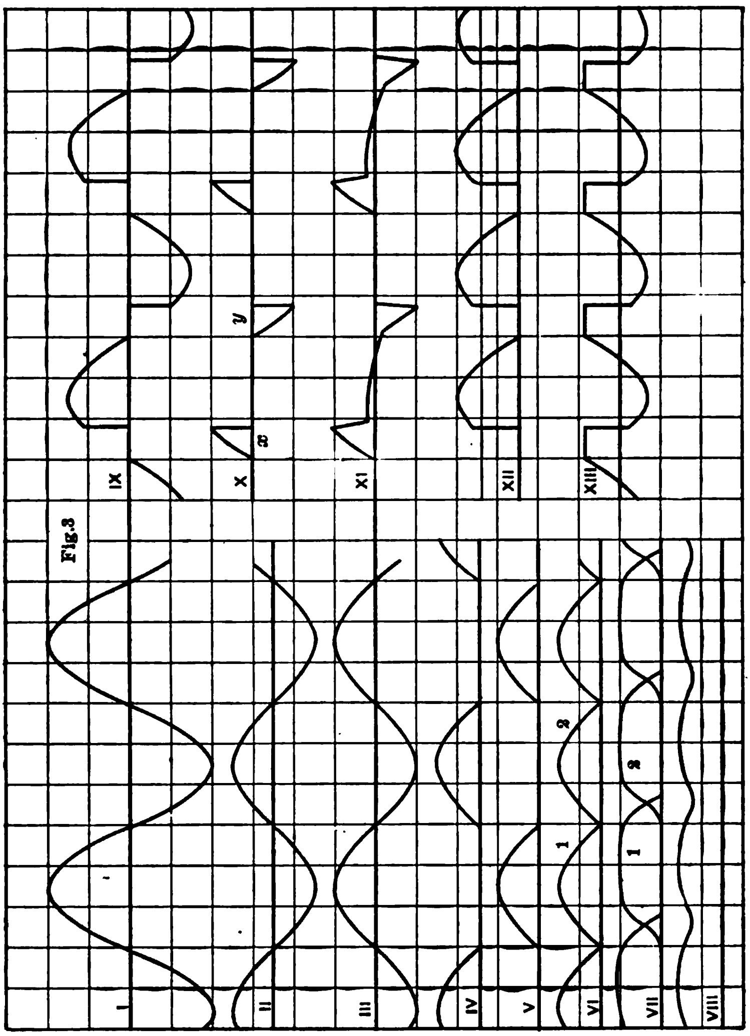


Fig. 2

to flow beyond the zero of its impressed electromotive force III, that is, until the electromotive force III has died out and reversed, and the current of the half wave 2, IV, has been started by electromotive force II. The two half waves of the current overlap, and each half wave lasts for more than half a period or 180 degrees.

The current waves are shown in curve VII; the current half wave 1 starts at the zero value of its electromotive force III, but rises slower than it would without inductance, following essentially the exponential curve of a starting current; and the energy, which is first consumed by the inductance as counter electromotive force, is later returned in maintaining the current half-wave 1 beyond the electromotive force wave, that is, ω degrees (44 degrees in the tests reported later on), beyond 180 degrees so that it overlaps the next half-wave 2 by ω degrees.



Hereby the rectifier becomes self-exciting; that is, each half-wave of current, by overlapping with the next, maintains the cathode blast until the next half-wave is started.

The successive current half-waves added together give the rectified or unidirectional-current curve VIII.

During a certain period of time in each half wave from the zero value of electromotive force, both arcs, $c\ a$ and $c\ b$, flow. During the existance of both arcs, there can be no potential difference between the rectifier terminals a and b, and the impressed electromotive force between the rectifier terminals $a\ b$ therefore has the form shown in curve IX, Fig. 3; it remains zero for ω degrees, and then, with the breaking of the arc of the preceding half wave, jumps to its normal value.

The induced electromotive force of the transformer secondary, however, must more or less completely follow the primary impressed electromotive force wave, that is, it must have the shape shown in curve I, and the difference between IX and I must be taken up by the inductance. In other words, during the time both arcs flow in the rectifier, the alternating-current reactive coils consume the induced electromotive force of the transformer secondary, and the voltage across these reactive coils, therefore, is as shown in curve X; the reactive coil consumes voltage at the start of the current of each half wave. at x in curve X, and produces voltage near the end of the current flow, at y. In the intermediary time, that is, while only one arc is flowing, the reactive coil has practically no effect, and its voltage is low, corresponding to the variation of the rectified alternating current, as shown in curve XI; that is, during this time the alternating-current reactive coils merely assist the direct-current reactive coil.

Since the voltage at the alternating-current terminals of the rectifier, $a\ b$, has two periods of zero value during each cycle, the rectified voltage, between c and C, must also have the same zero periods, and is indeed the same curve as IX, but reversed, as shown in curve XII.

Such an electromotive force wave can not satisfactorily operate arcs, because during the zero period of voltage, curve XII, the arcs go out. The voltage on the direct-current line must never fall below the counter-electromotive force of the arcs, and since the resistance of this circuit is low, frequently less than 10 per cent., it follows that the total variation of direct-current line voltage must be below 10 per cent.; that is, the voltage is practically constant, as shown by the straight line in curve XII. Hence a high reactance is inserted into the direct-current circuit, which consumes the excess voltage during that part of curve XII, where the rectified voltage is above line voltage, and supplies the line voltage during the period of zero rectified voltage. The voltage across this reactive coil is therefore as shown by curve XIII. Short-circuiting this reactance coil on an arc load therefore immediately puts out the rectifier, unless the external circuit contains sufficient reactance to prevent it.

Regarding calculation of the rectifier: The angle of overlap ω of the two arcs is determined by the desired stability of the system. From the angle ω and the impressed electromotive force is determined the sum total of electromotive forces which has to be consumed, and returned, by the alternating-current reactive coil; and upon this sum depends the size of the alternating-current reactive coil required.

From the angle ω also follows the wave shape of the rectified voltage; and therefrom the sum total of electromotive force which has to be given by the direct-current reactive coil. This electromotive force determines the size of the direct-current reactive coil required to maintain the direct-current fluctuation within certain given limits.

The given factors of the problem therefore are: the resistance of the circuit, the counter electromotive force of the direct-current circuit, the permissible fluctuation of the direct current, and the chosen angle of overlap of the rectifying arcs.

IV. Characteristics of System.

The efficiency, power-factor, regulation, etc., of the mercury arc rectifier system are essentially those of the constant-current transformer feeding the rectifier tube:

The losses in the system between constant alternating impressed voltage and constant direct current are: (1) The loss in the transformer, which changes from constant alternating potential toc onstant alternating current. This amounts from 5 to 10 per cent., according to the size of the transformer. (2) The $I^2 R$ and hysteresis losses in the reactive coils inserted into the alternating leads of the rectifier, the "alternating reactive coils," and in the reactive coil inserted in the rectified circuit, the "direct-current reactive coil." (3) The loss of power in the rectifier tube, which in a series arc circuit is negligible. There occurs a constant drop of voltage, which amounts to about 18 volts, irrespective of load or current in the tube; the mercury arc voltage. With a 75-light rectifier, at 6 000 volts full load, this loss in the tube is 0.3 per cent. The loss in the reactive coils obviously can be reduced to the extent that the customer is willing to pay for copper and iron.

Let N = frequency of the alternating-current supply, i_0 = mean value of the rectified direct current, and a = pulsation of the rectified current from the mean value, that is, $i_0(1+a)$ = the maximum, and $i_0(1-a)$ = the minimum value of direct current. Experience has shown that a pulsation from a mean of 20 to 25 per cent. is not only permissible in any type of arc, but advantageous in increasing the steadiness of the arc. The total variation of the rectified current then is $2ai_0$, and the alternating component of the direct current has the maximum value ai_0; hence the effective value is $\frac{a}{\sqrt{2}}i_0$(or, for $a=0.2$: $0.141 i_0$), and the frequency $2N$. Hysteresis and eddy losses in the direct-current reactive coil, therefore, correspond to an alternating current of frequency $2N$, and effective value $\frac{a}{\sqrt{2}}i_0$, or about $0.141 i_0$, which is insignificant even at relatively high densities.

In the alternating-current reactive coils, the current varies, unidirectionally, between 0 and $i_0(1+a)$, that is, its alternating component has the maximum value $\frac{1+a}{2}i_0$, and the effective value $\frac{1+a}{2\sqrt{2}}i_0$, (or, for $a = +0.2$: $0.425 i_0$), and the frequency N, The hysteresis loss therefore corresponds to an alternating current of frequency N, and effective value $\frac{1+a}{2\sqrt{2}}i_0$, or about $0.425 i_0$.

Regarding the power-factor of the mercury arc rectifier system, the non-inductive character of the direct-current load increases, but the use of reactive coils in the alternating-current leads slightly decreases the power-factor, so that the power-factor of the load on the secondary terminals of the constant-current transformer is about the same as that; that is, the power-factor of an alternating series arc circuit; and the power-factor of the whole system is therefore about the same as that of the same constant-current transformer operating series alternating-current arc lamps at the same percentage of load, that is, with the same position of transformer coils.

With decreasing load, at constant alternating current supply, the rectified direct current slightly increases, due to the increasing overlap of the rectifying arcs; and to give constant direct current, the transformer is therefore so adjusted as to regulate for a slight decrease of alternating current output with decrease of load. Obviously, just as in constant-current transformers for series alternating-current arc lighting, in larger units the regulation range for constant current is extended from full load down to ½ load only, and not down to short circuit.

The maximum voltage which can be rectified is unknown, because a sufficiently high voltage power supply to break down a rectifier of proper design and vacuum has not yet been obtained; and since a high-frequency oscillator, giving an 8-in. spark between 1-in. spheres, does not send a discharge through the vacuum of such a rectifier, it is not probable that a voltage limit of rectification will be reached in the range of voltages coming into commercial consideration. An electromotive force of 36 000 volts, impressed upon the rectifier terminals, has been rectified with small current. In the following some tests are given on the operation of a rectifier tube under an alternating impressed electromotive force upon its terminals of 25 200 volts, giving an output of 10 000 volts at 4.6 amperes direct current; and at 24 300 volts impressed, an output of 9 500 volts at 6.25 amperes, or 59.4 kilowatts, from a single rectifier tube.

V. Tests of System.

A constant-current mercury arc rectifier system has been in regular service for over a year, supplying 3.8 amperes constant current to 25 mercury arc lamps, for lighting streets and parks in a section of the city of Schenectady. The constant-current transformer is a so-called "6-light testing transformer," with the secondary coil wound for 2 amperes, and operating at somewhat higher magnetic density; therefore, the regulation range extends only down to 10 lamps. The records of test of efficiency, power-factor, regulation, etc., of this system is given in Fig. 4. As seen, in this small unit of only 3.9 kilowatts output, an efficiency of 80 per cent., and a power-factor of 70 per cent. is reached, between constant-potential alternating current received from the primary distributing mains, and constant direct current sent into the arc circuit.

Oscillograms of this constant current rectifier, at full load of 25 mercury arc lamps, are given in Figs. 5 to 14. These curves show: Fig. 5, primary supply voltage; Fig. 6, secondary terminal voltage of transformer; Fig. 7, potential difference of alternating-current reactive coils; Fig. 8, alternating voltage impressed upon rectifier tube; Fig. 9, unidirectional voltage produced between rectifier neutral and transformer neutral; Fig. 10, potential difference of direct current reactive coil; Fig. 11, rectified voltage supplied to arc circuit; Fig. 12, primary supply current; Fig. 13, current in rectifying arcs; Fig. 14, rectified current supply to arc circuit. As seen, the angle of overlap of the two rectifying arcs is 44°. It is interesting to compare these curves with the corresponding curves, Fig. 3.

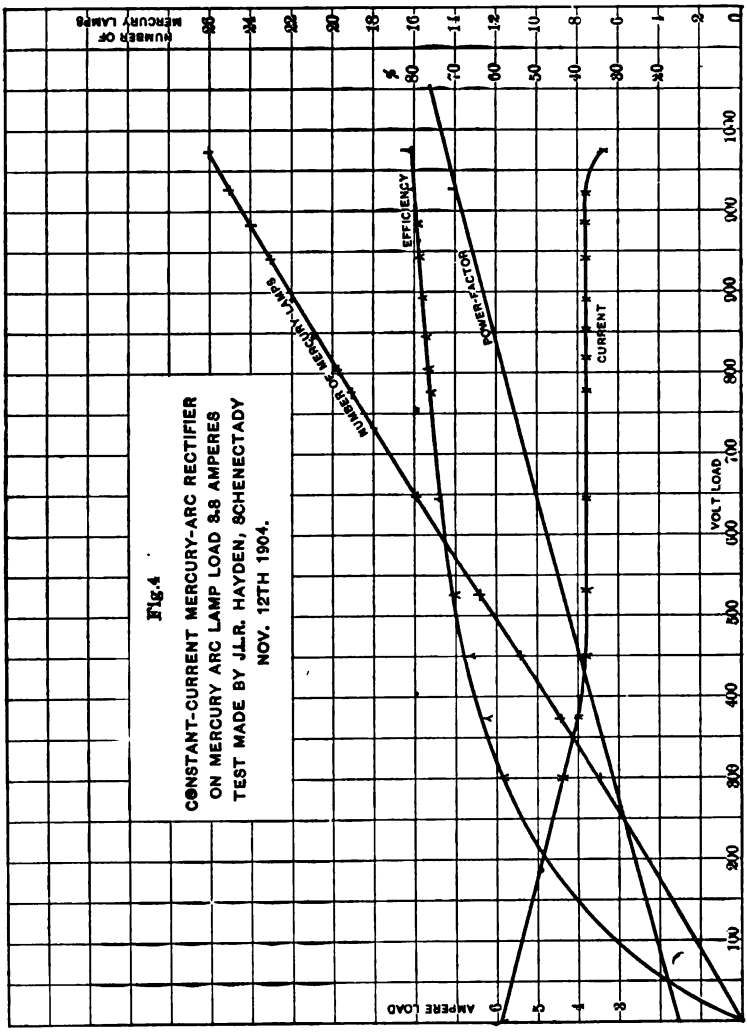


Fig. 15 gives secondary terminal voltage, efficiency, regulation, and load of a larger rectifier set, operating magnetite arc lamps. At the highest load, of 57 magnetite arc lamps, car-

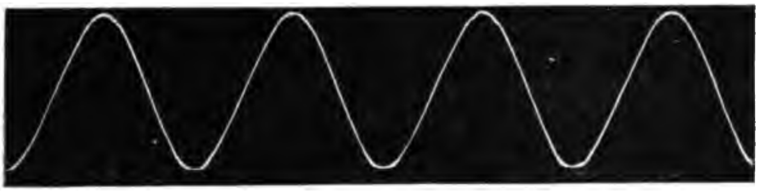


FIG. 5.

FIG. 6.

FIG. 7.

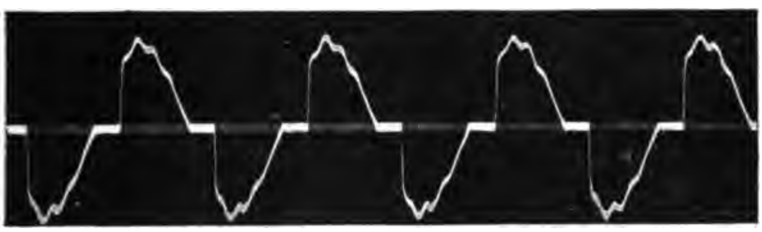


FIG. 8.

FIG. 9.

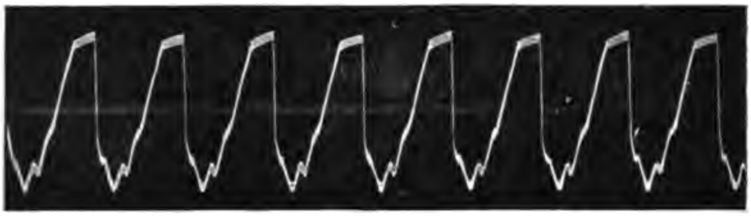


Fig. 10.

Fig. 11.

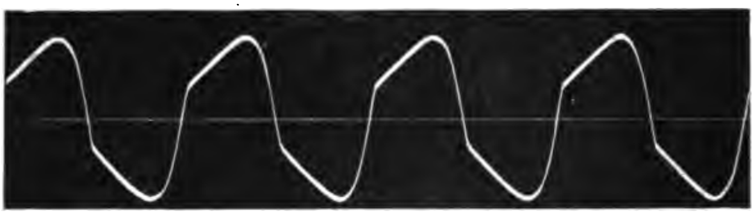


Fig. 12.

Fig. 13.

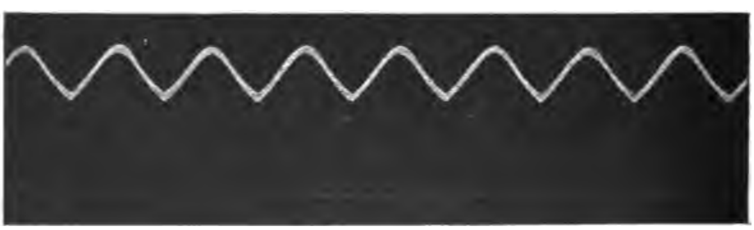


Fig. 14.

ried in test the rectified voltage supplied to the arc circuit at four amperes was 4 260, at a voltage of 11 800 impressed upon the rectifier tube by the transformer secondary; the efficiency was above 90%. This set is now in service in lighting some of the

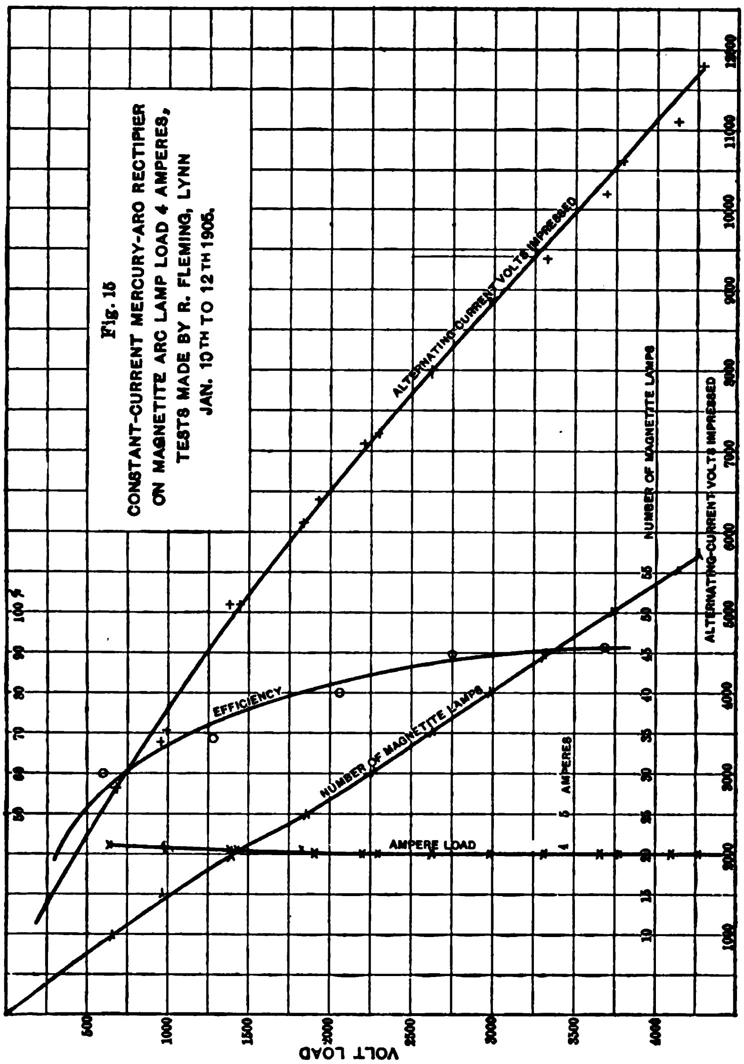
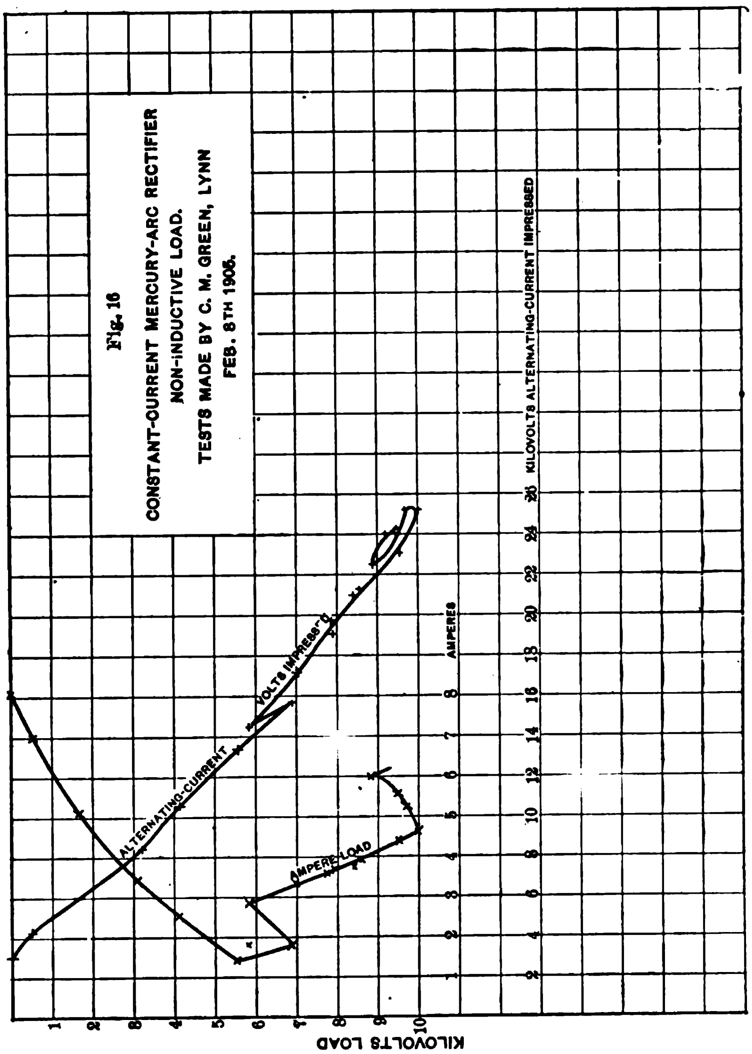


Fig. 15
CONSTANT-CURRENT MERCURY-ARC RECTIFIER
ON MAGNETITE ARC LAMP LOAD 4 AMPERES,
TESTS MADE BY R. FLEMING, LYNN
JAN. 10TH TO 12TH 1905.

streets of Schenectady, in the down-town district, with magnetite arc lamps.

Still higher voltages are shown in the test in Fig. 16. Here the power was supplied directly from an alternator, by a step-up transformer, to the rectifier tube, and a water resistance was used as load, because neither a constant-current transformer nor a sufficient number of lamps were available at that time to take care of the load. The maximum voltage was 10 kilovolts at 4.6



amperes, with an impressed alternating voltage of 25.2 kilovolts; and the maximum output was 9.5 kilovolts at 6.25 amperes, or about 60 kilowatts.

VI. Theory and Calculation.

In the constant-current mercury arc rectifier, shown diagrammatically in Fig. 17, let:

$e \sin \phi$ = sine wave of electromotive force impressed between neutral and outside of alternating-current supply to the rectifier, that is:

$2 e \sin \phi$ = total secondary induced electromotive force of constant-current transformer.

$Z_1 = r_1 - j x_1$ = impedance of reactive coil in each anode circuit of the rectifier ("alternating-current reactive coil"), in-

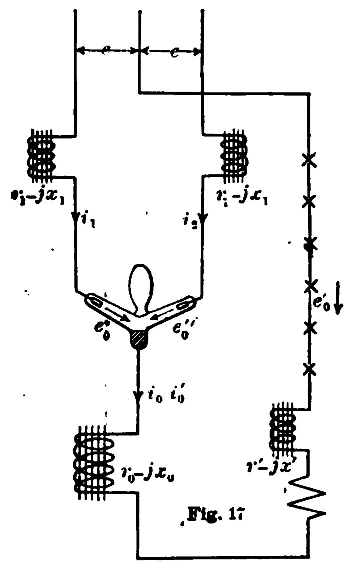


Fig. 17

clusive of the internal self-inductive impedance between the two halves of the transformer secondary coil.

i_1 and i_2 = anode currents, counted in the direction from anode to cathode.

e_0'' = counter-electromotive force of rectifying arc, which is constant.

$Z_0 = r_0 - j x_0$ = impedance of reactive coil in rectified circuit ("direct-current reactive coil").

$Z^1 = r^1 - j x^1$ = impedance of load on arc lamp circuit.

e^1 = counter-electromotive force in rectified circuit, which is constant (equal to the sum of the counter-electromotive forces of the arcs in the lamp circuit).

ω = angle of overlap of the two rectifying arcs, or overlap of the currents i_1 and i_2.

i_0 = rectified current during the period: $0 < \phi < \omega$, that is when both rectifying arcs exist.

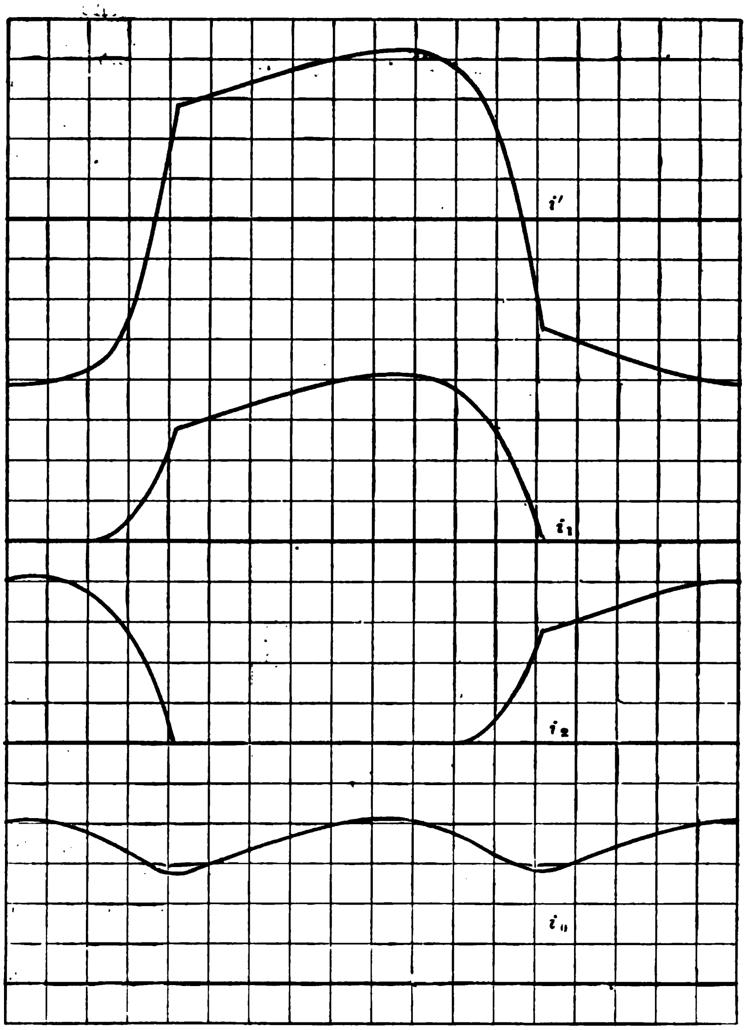


FIG. 18.

i_0' = rectified current during the period: $\omega < \phi < \pi$, that is, when only one arc, or one anode current i_1 exists.

Let:

$e_0 = e_0' + e_0''$ = total counter electromotive force in the rectified circuit.

$Z = r - j x = (r_1 + r_0 + r') - j (x_1 + x_0 + x')$ = total impedance per circuit.

We then have:

a. During the period when both rectifying arcs exist:

$$0 < \phi < \omega$$
$$i_0 = i_1 + i_2 \tag{1}$$

In the circuit including the electromotive force $2 e \sin \phi$, the rectifier tube, and the currents i_1 and i_2, we have, by Kirchhoff's law:

$$2 e \sin \phi - r i_1 - x \frac{d i_1}{d \phi} + r i_2 + x \frac{d i_2}{d \phi} = 0 \tag{2}$$

We have, in the circuit from transformer neutral over electromotive force $e \sin \phi$, current i_1, rectifier arc e_0'' and rectified circuit i_0, back to the transformer neutral, the electromotive conditions expressed by the equation:

$$e \sin \phi - r_1 i_1 - x_1 \frac{d i_1}{d \phi} - e_0'' - r_0 i_0 - x_0 \frac{d i_0}{d \phi} - r^1 i_0 - x^1 \frac{d i_0}{d \phi} - e_0^1 = 0$$

or:

$$e \sin \phi - r_1 i_1 - x_1 \frac{d i_1}{d \phi} - (r_0 + r^1) i_0 - (x_0 + x^1) \frac{d i_0}{d \phi} - e_0 = 0 \tag{3}$$

b. During the period when only one rectifying arc exists:

$$\omega < \phi < \pi$$
$$i_1 = i_0'$$

Hence, in this circuit:

$$e \sin \phi - r_1 i_0' - x_1 \frac{d i_0'}{d \phi} - (r_0 + r') i_0' - (x_0 + x^1) \frac{d i_0'}{d \phi} - e_0 = 0 \tag{4}$$

Substituting (1) in (2), and combining the result (5) of this substitution with (3), gives the

Differential Equations of the Rectifier:

$$2 e \sin \phi + r_1 (i_0 - 2 i_1) + x_1 \frac{d}{d \phi} (i_0 - 2 i_1) = 0 \tag{5}$$

$$2 e_0 + (2 r - r_1) i_0 + (2 x - x_1) \frac{d i_0}{d \phi} = 0 \tag{6}$$

$$e \sin \phi - e_0 - r i_0' - x \frac{d i_0'}{d \phi} = 0 \tag{7}$$

In these equations, i_0 and i_1 apply for the time: $0 < \phi < \omega$; and i_0' for the time: $\omega < \phi < \pi$.

These differential equations are integrated by the functions:

$$i_0 - 2\,i_1 = A\,\epsilon^{-a\phi} + A'\sin(\phi - \beta) \tag{8}$$

$$i_0 = B\,\epsilon^{-b\phi} + B' \tag{9}$$

$$i_0' = C\,\epsilon^{-c\phi} + C' + C''\sin(\phi - \gamma) \tag{10}$$

Substituting (8),(9), and (10) into (5), (6), and (7) gives three identities:

$$\left.\begin{array}{l} 2\,e\sin\phi + A'[r\sin(\phi-\beta) + x\cos(\phi-\beta)] + A\epsilon^{-a\phi}\,(r_1 - a x_1) = 0 \\ 2\,e_0 + B'\,(2\,r - r_1) + B\,\epsilon^{-b\phi}[(2\,r - r_1) - b\,(2\,x - x_1)] = 0 \\ e\sin\phi - e_0 - C''[r\sin(\phi-\gamma) + x\cos(\phi-\gamma)] - C'r - C\epsilon^{-c\phi}\,(r - c\,x) = 0 \end{array}\right\}$$

hence:

$$\left.\begin{array}{r} r_1 - a\,x_1 = 0 \\ (2\,r - r_1) - b\,(2\,x - x_1) = 0 \\ r - c\,x = 0 \end{array}\right\} \tag{11}$$

$$\left.\begin{array}{r} 2\,e_0 + B'\,(2\,r - r_1) = 0 \\ e_0 + C'\,r = 0 \\ 2\,e + A'\,(r\cos\beta + x\sin\beta) = 0 \\ A'\,(r\sin\beta - x\cos\beta) = 0 \\ e - C''\,(r\cos\gamma + x\sin\gamma) = 0 \\ C''\,(r\sin\gamma - x\cos\gamma) = 0 \end{array}\right\} \tag{11}$$

Denoting:

$$\left.\begin{array}{l} z_1 = \sqrt{r_1^2 + x_1^2} \\ \tan\alpha_1 = x_1/r_1 \end{array}\right\} \tag{12}$$

and:

$$\left.\begin{array}{l} z = \sqrt{r^2 + x^2} \\ \tan\alpha = x/r \end{array}\right\} \tag{13}$$

substituting (12) and (13), into (11), gives by resolving the 9 equations (11) the values of the coefficients a, b, c, A', B', C', C'', β, γ:

$$\left.\begin{aligned} a &= r_1/x_1 \\ b &= \frac{2r - r_1}{2x - x_1} \\ c &= r/x \end{aligned}\right\} \quad (14)$$

$$\left.\begin{aligned} \beta &= \alpha_1 \\ \gamma &= \alpha \end{aligned}\right\} \quad (15)$$

$$\left.\begin{aligned} A' &= -\frac{2e}{z_1} \\ B' &= -\frac{2e_0}{2r - r_1} \\ C' &= -e_0/r \end{aligned}\right\} \quad (16)$$

$$C'' = +e/z \quad (17)$$

from which follow the

Integral Equations of the Rectifier.

$$i_0 - 2i_1 = A\,\varepsilon^{-a\phi} - \frac{2e}{z_1}\sin(\phi - \alpha_1) \quad (18)$$

$$i_0 = B\,\varepsilon^{-b\phi} - \frac{2e_0}{2r - r_1} \quad (19)$$

$$i_0' = C\,\varepsilon^{-c\phi} - \frac{e_0}{r} + \frac{e}{z}\sin(\phi - \alpha) \quad (20)$$

where: a, b, c are given by equations (14);

α and α_1 by equations (12) and (13),

and A, B, C are integration constants given by the terminal conditions of the problem.

These terminal conditions are

$$\left.\begin{aligned} |i_1|_{\phi=0} &= 0 \\ |i_0|_{\phi=0} &= |i_0'|_{\phi=\pi} \\ |i_1|_{\phi=\omega} &= |i_0|_{\phi=\omega} = |i_0'|_{\phi=\omega} \end{aligned}\right\} \quad (21)$$

That is: At $\phi = 0$, the anode current $i_1 = 0$. After half a period, or $\pi = 180°$, the rectified current repeats the same value. At $\phi = \omega$, all three currents i_1, i_0, i_0' are identical.

The four equations (21) determine four constants: A, B, C, ω.

Substituting these constants in equations (18), (19), (20), gives the equations of the rectified current i_0, i_0', and of the anode currents i_1 and $i_2 = i_0 - i_1$, determined by the constants of the system: Z, Z_1, e_0, and by the impressed electromotive force e.

In the constant current mercury arc rectifier system of arc lighting, e, the secondary induced voltage of the constant-current transformer, varies with the load by the regulation of the transformer; and the rectified current, i_0, i_0', is required to remain constant, or, rather, at its average value.

Let then be given as a condition of the problem, the average value i of the rectified current: 4 amperes in a magnetite or in a mercury arc lamp circuit, and 5 or 6.6 or 9.6 amperes in a carbon arc lamp circuit.

Assume as a fair approximation, that the pulsating rectified current i_0, i_0', has its mean value i at the moment, $\phi = 0$. This then gives the additional equation:

$$|i_0|_{\phi=0} = i \tag{22}$$

and from the five equations (21) and (22), the five constants A, B, C, ω, e are determined.

Substituting (22), (18), (19), (20) in equations (21), gives:

$$\left.\begin{aligned} A &= i - \frac{2e}{z_1} \sin \alpha_1 \\ B &= i + \frac{2e_0}{2r - r_1} \\ C &= \varepsilon^{c\pi} \left\{ i + \frac{e_0}{r} - \frac{e}{z} \sin \alpha \right\} \end{aligned}\right\} \tag{23}$$

$$-A\varepsilon^{-a\omega} - \frac{2e}{r_1} \sin(\alpha_1 - \omega) = B\varepsilon^{-b\omega} - \frac{2e_0}{2r - r_1}$$
$$= C\varepsilon^{-c\omega} - \frac{e_0}{r} - \frac{e}{z} \sin(\alpha - \omega) \tag{24}$$

Substituting (23) in (24) gives:

$$\frac{2e}{z_1}\left\{ \varepsilon^{-a\omega} \sin \alpha_1 - \sin (\alpha_1 - \omega) \right\} = i \left\{ \varepsilon^{-a\omega} + \varepsilon^{-b\omega} \right\}$$

$$- \frac{2e_0}{2r - r_1}\left\{1 - \varepsilon^{-b\omega}\right\} \qquad (25$$

$$\frac{e}{z}\left\{ \varepsilon^{c(\pi-\omega)} \sin \alpha + \sin (\alpha - \omega)\right\} = i \left\{ \varepsilon^{c(\pi-\omega)} - \varepsilon^{-b\omega} \right\}$$

$$+ \frac{2e_0}{2r - r_1}\left\{1 - \varepsilon^{-b\omega}\right\} + \frac{e_0}{r}\left\{ \varepsilon^{c(\pi-\omega)} - 1 \right\} \qquad (26)$$

and, eliminating e from these two equations, gives:

$$\frac{\varepsilon^{c(\pi-\omega)} \sin \alpha + \sin (\alpha - \omega)}{\varepsilon^{-a\omega} \sin \alpha_1 - \sin (\alpha_1 - \omega)} =$$

$$\frac{2z}{z_1} \times \frac{\left\{ \varepsilon^{c(\pi-\omega)} - \varepsilon^{-b\omega}\right\} + \dfrac{2e_0}{i(2r - r_1)}\left\{1 - \varepsilon^{-b\omega}\right\} + \dfrac{e_0}{i\,r}\left\{ \varepsilon^{c(\pi-\omega)} - 1\right\}}{\left\{ \varepsilon^{-a\omega} + \varepsilon^{-b\omega} \right\} - \dfrac{2e_0}{i\,(2r - r_1)}\left\{1 - \varepsilon^{-b\omega}\right\}} \qquad (27)$$

This equation (27) determines angle ω, and by successive substitution in (26), (23), e, A, B, C are found.

Equation (27) is transcendental, and therefore has to be solved by approximation, which however is very rapid.

As a first approximation, $a = b = c = 0$; $\alpha_1 = \alpha_2 = 90°$ or $\pi/2$; and substituting these values in (27), gives:

$$\frac{\varepsilon^{c\pi} + \cos \omega_1}{1 - \cos \omega_1} = \frac{2z}{z_1} \frac{\left(\varepsilon^{c\pi} - 1\right)\left(1 + \dfrac{e_0}{i\,r}\right)}{2}$$

$$\cos \omega_1 = \frac{\dfrac{z}{z_1}\left(\varepsilon^{c\pi} - 1\right)\left(1 + \dfrac{e_0}{i\,r}\right) - \varepsilon^{c\pi}}{\dfrac{z}{z_1}\left(\varepsilon^{c\pi} + 1\right)\left(1 + \dfrac{e_0}{i\,r}\right) + 1} \qquad (28)$$

This value of ω_1 substituted in the exponential terms of equation (27), gives a simple trigonometric equation in ω, from which follows the second approximation ω_2, and, by interpolation, the final value:

$$\omega = \omega_2 + \frac{(\omega_2 - \omega_1)^2}{\omega_1} \qquad (29)$$

For instance, in the rectifier system of which tests are given in Fig. 4, oscillograms in Figs. 5 to 14, it is, at full load of 25 mercury arc lamps:

$$e_0 = 950$$
$$i = 3.8$$

The constants of the circuit are:

$$Z_1 = 10 - 185\,j$$
$$Z = 50 - 1000\,j$$

From which follow:

$$\left.\begin{aligned} a &= 0.054 \\ b &= 0.050 \\ c &= 0.050 \end{aligned}\right\} \qquad (14)$$

$$\left.\begin{aligned} \alpha_1 &= 86.9^\circ \\ \alpha &= 87.1^\circ \end{aligned}\right\} \qquad (15)$$

From equation (28), follows as a first approximation: $\omega_1 = 47.8^\circ$; and as a second approximation: $\omega_2 = 44.2^\circ$.

Hence, by (29):

$$\omega = 44.4^\circ$$

observed was 44∼45°.

Substituting a in (26) gives: $e = 2100$;
hence, the effective value of transformer secondary voltage:

$$\frac{2e}{\sqrt{2}} = 2980 \text{ volts}$$

and, from (23):

$$A = -18.94$$
$$B = 24.90$$
$$C = 24.20$$

Therefore, the equations of the currents:

$$i_0 = 24.90\,\varepsilon^{-.050\phi} - 21.10$$

$$i_0' = 24.20\,\varepsilon^{-.050\phi} - 19.00 + 2.11 \sin(\phi - 87.1°)$$

$$i_1 = 12.45\,\varepsilon^{-.050\phi} + 9.47\,\varepsilon^{-.054\phi} - 10.58 + 11.35 \sin(\phi - 86.9°)$$

$$i_2 = i_0 - i_1$$

The effective or equivalent alternating seconaary current of the transformer, which corresponds to the primary load current, that is, primary current minus exciting current, is:

$$i' = i_1 - i_2$$

From these equations are calculated the numerical values of rectified current i_0, i_0', of anode current i_1, and of alternating current i', which are plotted as curves in Fig. 18. As seen, they perfectly agree with the oscillograms.

DISCUSSION ON, "THE CONSTANT-CURRENT MERCURY-ARC RECTIFIER."

PRESIDENT LIEB: Mr. Steinmetz has outlined not only the practical instrument and its results, but he has given also a theoretical investigation of the phenomena involved. This apparatus is one which is very important in its applications, as it will often even determine the selection of the type of distributing system. With the extended application of series alternating-current arcs, it has become, I think, more and more evident that they are not of equivalent value to direct-current arcs; the result is that in many cases a strong pressure is brought to bear for direct current for series arc lighting. This apparatus is efficient, small, and inexpensive, and I hope it will enable this question to be solved from our ordinary alternating current distributing systems.

JOHN W. HOWELL: Mr. Steinmetz has said, that the constant-current mercury-arc rectifier enables one to operate constant direct-current apparatus from a constant-potential alternating source. That is a very desirable thing, as it enables one to substitute direct-current arc lamps for alternating-current arc lamps. It is well known that there are a number of recently developed direct-current arc lamps which are more efficient than arc lamps suitable for use on alternating systems, and substitution of these by means of small apparatus which is also highly efficient is desirable. This will simplify matters for those who operate alternating-current systems; they will need generate only one kind of current. It will also have useful application in the operation of series burning mercury-arc lamps with alternating current. A constant-potential series mercury-arc lamp is one the most efficient light-producing devises known, but is only applicable to direct-current supply, and this device will be very highly efficient in this connection.

P. H. THOMAS: We will all agree that the mercury-vapor converter has most remarkable properties and is capable of producing most astonishing results.

It is rather misleading to consider the converter as an arc in the same sense as the ordinary arc, as utilized for electric lighting. Although it is true that the passage of current through the converter and the operation of an arc have many features in common, it is still true that the particular characteristics of the mercury-vapor converter which enable it to be of commercial service and do the remarkable things of which we know a part, do not exist to any material extent in the commercial atmospheric arc. I refer principally to the "negative electrode resistance" residing substantially at the surface of the electrode, which in the converter will resist pressures of many thousand volts, but which in the open-air arc, if the distance between electrodes be made small enough, cannot resist over one hundred or two hundred volts. Furthermore, the form of the curve of voltage and sparking distance at these low voltages indicates the absence of any true negative electrode resistance in the arc. Again, the absence of impeding matter, such as the atmosphere, is necessary to secure a free transfer of current from one electrode to another. In its historical development the mercury-vapor converter came not from the commercial arc but from the Cooper-Hewitt mercury-vapor lamp, the origin of which was not connected with the arc.

Although theories of the operation of this apparatus are not the ultimate commercial object, yet they are important in directing development and in overcoming difficulties. On this account it is well to call attention to the fact that another theory than that given in the paper may be strongly supported for explaining the starting of current through the container. According to former theory, with a perfect vacuum current once started passes from electrode to electrode with almost absolute freedom, since the source of the ions is assumed to be the negative electrode. It seems probable that the only action of gas or vapor within the path of the current is to impede the flow of current. This action seems very natural if it is assumed that current consists of either electrons, or electrons associated with atoms. Consequently, according to this view no preliminary " bridge " or residual gas is necessary for the starting operation.

F. A. C. PERRINE: Mercury arc rectification was first described by Jamin, in 1875, who rectified with mercury arcs and with arcs between dissimilar substances. I took up this matter, about 1888, and reproduced the experiments published and the results in the London Electrician. At that time, I measured the electromotive force with a permanent magnet voltmeter. The idea that is entirely and absolutely new at the present time is the use of the arc in a closed, hermetically sealed tube. At the earlier time it was not advisable to go very far with the experiments because the work was dangerous; I was using a partly enclosed arc — a jar of mercury, with a vertical carbon passing through a cork in the top. Under these circumstances if anything had happened to smash the enclosing vessel it probably would have resulted in serious injury to the investigator.

E. F. NORTHRUP: There is one feature of these currents that, it strikes me, might lead to error. After the alternating current is rectified it becomes a pulsating direct current. Now most direct-current instruments give only indications of the *average* value of a pulsating current. As the form of the wave is unknown unless the wave be taken with the oscillograph, the square root of the mean square value, or energy value of the pulsating current could not be accurately judged by the indications of instruments constructed upon the plan of a Weston direct-current instrument. Therefore, if these rectified currents are to be measured, suitable alternating-current instruments must be used to obtain measurements that are at all accurate.

CHAS. P. STEINMETZ: The output may be measured by a wattmeter. By using an alternating-current meter and a direct-current meter in series with each other, I got a reading of 4 amperes in the direct-current, and 4.10 in the alternating-current meter.

In regard to the discussion by Mr. Thomas, on a negative resistance supposed to reside at the cathode surface: I have endeavored to explain the phenomena of the mercury-arc rectifier from the engineering point of view; that is based on strict empirical facts, and without introducing any hypothetical or mysterious phenomena, as negative resistances etc. I believe whatever success I may have had in electrical engineering, I owe mainly to my disinclination to leave the study and investigation of actual facts in favor of metaphysical speculations. I believe the reason why I have succeeded in developing this rectifier is that at a very early time I recognized that the phenomenon is an ordinary arc; it follows all the laws and characteristics of the typical arc, differing only by being enclosed in a glass tube.

All typical arcs show the phenomenon of rectification within a certain range of voltage. This range is between the arc voltage and the striking voltage at the arc temperature, and this range is therefore much greater with the mercury arc than with other arcs, and practically disappears with the carbon arc, but is still considerable in many other metal arcs. I had the pleasure last year to read a paper before the International Congress at St. Louis on this subject, giving a discussion of the character of the arc in general, and the mercury arc in particular from the engineering point of view without, as I stated, any metaphysical speculation. I refer you to that paper.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

DATA RELATING TO ELECTRIC CONDUCTORS AND CABLES.

BY H. W. FISHER.

In America, the underground electric cable manufacturing companies for the most part have refrained from publishing much experimental data relative to cables. The principal reasons for this are probably to prevent the disclosure of trade-secrets and manufacturing processes, and to refrain from giving electric data showing the highest excellence of cable construction because engineers would be apt to make specifications based on such data which might be difficult or impossible for the manufacturers to meet.

Such specifications are occasionally issued now, although not so frequently as was the case five or ten years ago. Within the last two months an engineer specified a test of 5 000 megohms per mile upon a rubber-covered electric-light cable of considerable size. If the test could have been met at all, it would have been only by the use of a very large amount of pure Para rubber, which would have entailed an excessive and unwarrantable cost. It is to be regretted that the manufacturers and operators of electric wires and cables in this country do not draw up a reasonable set of specifications comparable to what has been done in this line abroad, because it would very much simplify matters for consulting engineers, operating companies, and manufacturers.

The recommendations of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS even are not always followed by engineers, who occasionally disregard the meter-gramme standard, as published in the Supplement to the TRANSACTIONS, of October 1893, and specify some other Mathiessen standard.

In this paper, the copper conductor will first be considered and afterwards the insulation. It is a well-known fact that commercial copper of to-day has a resistance which is very close to Mathiessen's meter-gramme standard. It becomes possible, therefore, to make up stranded cables which shall have a conductivity of between 98 and 99 per cent. of Mathiessen's standard. The area of the stranded cable should be taken as the combined area of the wires composing it, based upon measurement of each wire at right-angles to its own axis.

In the case of twisted multiple-conductor cables, the actual length of each conductor must be used in estimating the conductivity.

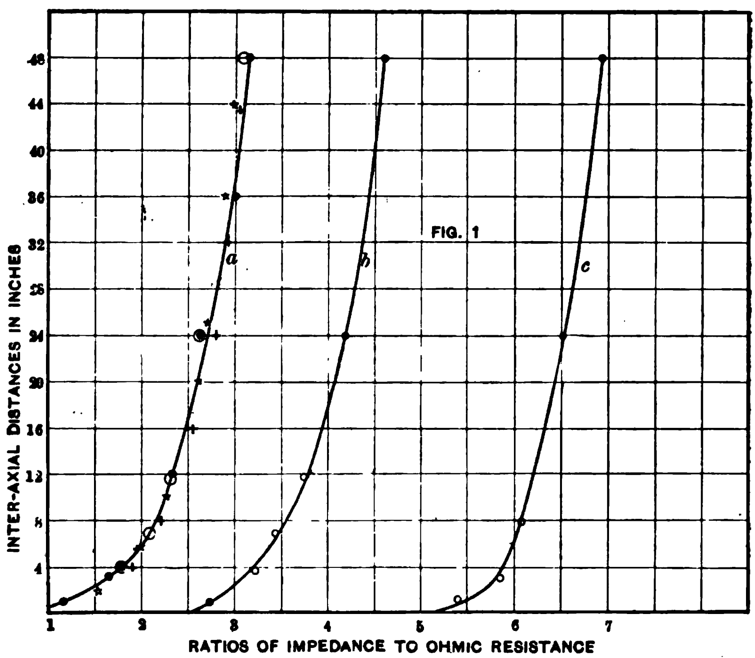
In a stranded-conductor cable the larger part of the current will flow along the individual wires, although, of course, there will always be a part short-circuiting action between individual wires of the strand. Hence, it cannot be expected that a stranded conductor will have a conductivity equal to that of a solid conductor of the same area. The tendency of the current to follow along the individual wires of a strand is forcibly illustrated by the curves shown in Fig. 1, which will now be explained.

A question arose whether it would not be advisable to use a steel wire with six copper wires around it for power-transmission circuits suspended in long spans from steel towers. It first became necessary to determine the impedance of such a strand; curve *b* shows the results of this investigation. If the wires were laid straight instead of spirally on the steel wire, one would expect to find the impedance only slightly greater than that of an all-copper strand, the impedance of which is illustrated in curve *a* by the circles.

The writer therefore concluded that the larger part of the current followed the copper strands spirally around the central steel wire, and by magnetizing it increased the impedance. It at once became evident that if two layers of copper wires of the same total cross-sectional area as the cable with a single layer of copper wire, were laid spirally in opposite directions over the same size steel wire, the increased impedance would be reduced, if not entirely counteracted. Although more current would flow in the outside layer of copper wires than in the inside layer, the distance from the steel wire to the former being greater than to the latter, the magnetizing actions of the oppositely flowing currents in the two layers would tend to neutralize each other.

A strand with two layers of copper wires was then constructed and subjected to impedance tests; the results are shown in curve *a* by solid circles. They practically coincide with the dotted circles, determined with an all-copper strand, and the writer's deductions were, therefore, confirmed.

The points on the curve marked by a + were calculated for a solid conductor 500 mils in diameter, and 250 000 cir. mils as cross-section. The points marked * were calculated for a stranded copper conductor of 250 000 cir. mils in cross-section, and 580 mils in diameter.



It will be noticed that at the shorter interaxial distances the calculations based on the diameter of a stranded conductor are closer to the experimentally determined curve *b*, while at the longer interaxial distances the calculations based on the diameter of a solid wire are closer to curve *b*.

From the fact that copper has a greater coefficient of expansion than steel it was thought that a strand made with a steel center might be subject to stresses that would finally cause it to break. For this reason a test was made upon a

7-wire cable of four copper and two steel wires around a central copper wire. The cable had a conductivity equal to that of 250 000 cir. mils of copper.

Curve c in Fig. 1 gives the results of tests on the last-mentioned cable. It will be noticed that the impedance is increased to an extent that would probably prohibit the use of such a conductor in practice. However, since the large electrostatic capacity of long aerial conductors tends to produce leading currents, it is thought that a conductor of higher impedance might be beneficial in tending to increase the power-factor of the circuit.

The following formulas relating to stranded conductors were derived by the writer many years ago, and may be of interest and value:

$$A = N d^2 = \frac{3 N D^2}{4 N - 1}.$$

$$D = (2 n + 1) d = d \sqrt{\frac{4 N - 1}{3}} = 1.1546 \sqrt{A \frac{4 N - 1}{4 N}}$$

$$N = 1 + 3 (n^2 + n)$$

$$n = \frac{1}{2} \sqrt{\frac{4 N - 1}{3}} - \frac{1}{2}$$

Where A = Area of stranded conductor in circular mils,
D = Diameter of stranded conductor
d = Diameter of single wires comprising stranded conductor.
N = Number of wires.
n = Number of layers.

The above data are for a perfect strand with one central wire.

Table 1 gives reactances throughout a considerable range, and includes an auxiliary table by means of which reactances can be calculated for any distance between centers of conductors. It is thought that this table may be of use to members of the INSTITUTE. The foot-notes fully describe the manner of using the table to obtain reactances for frequencies and distances between centers not given in the table. The diameters given in the table were used in calculating the corresponding reactances.

For 2-in. and 12-in. distances between centers of conductors the reactances are calculated to one more decimal place than for the other distances, so that by means of the auxiliary table it is possible to calculate any other reactance very accurately.

TABLE OF REACTANCES.

Size of Conductor in B. & S. Gauge.	Diameter in Inches	Resistance in ohms per 2000 ft. of Wire at 68° fahr.	Reactance in ohms per 2000 ft. of wire at a frequency of 60 cycles per second. Distances between centers of conductors in inches.													
			½	1	2	3	4	5	6	8	12	18	24	36	48	60
Solid 10	0.1018	1.994	0.116	0.148	0.1803	0.199	0.212	0.223	0.231	0.244	0.2626	0.281	0.294	0.313	0.326	0.337
8	0.1285	1 254	0.107	0.138	0.1695	0.189	0.202	0.212	0.220	0.233	0.2519	0.271	0.284	0.302	0.315	0.326
6	0.1620	0.7888	0.095	0.127	0.1589	0.178	0.191	0.201	0.209	0.222	0.2412	0.260	0.273	0.292	0.305	0.315
4	0.2043	0.4960	0.085	0.117	0.1482	0.167	0.180	0.190	0.198	0.211	0.2305	0.249	0.262	0.281	0.294	0.305
Strand 4	0.232	0.4960	0.078	0.111	0.1424	0.161	0.174	0.185	0.193	0.206	0.2247	0.244	0.257	0.275	0.288	0.299
3	0.260	0.3934	0.072	0.105	0.1372	0.155	0.168	0.178	0.186	0.199	0.2195	0.237	0.250	0.269	0.282	0.293
2	0.292	0.3120	0.067	0.099	0.1318	0.150	0.163	0.173	0.181	0.194	0.2142	0.232	0.245	0.264	0.277	0.288
1	0.328	0.2474	0.063	0.095	0.1264	0.145	0.158	0.169	0.177	0.190	0.2088	0.228	0.241	0.259	0.273	0.283
0	0.373	0.1962	0.056	0.089	0.1205	0.139	0.152	0.163	0.171	0.184	0.2029	0.222	0.235	0.253	0.267	0.277
00	0.418	0.1556	0.052	0.084	0.1153	0.134	0.147	0.158	0.166	0.179	0.1977	0.216	0.230	0.248	0.262	0.272
000	0.470	0.1234	0.046	0.078	0.1099	0.129	0.142	0.152	0.160	0.173	0.1923	0.211	0.224	0.242	0.255	0.265
0 000	0.528	0.09786		0.073	0.1046	0.123	0.136	0.147	0.155	0.168	0.1869	0.206	0.219	0.237	0.251	0.261
Cir. Mils. 300 000	0.630	0.06902		0.064	0.0964	0.115	0.128	0.138	0.146	0.160	0.1788	0.197	0.210	0.229	0.242	0.253
400 000	0.728	0.05178		0.058	0.0898	0.109	0.122	0.133	0.141	0.154	0.1722	0.192	0.205	0.224	0.237	0.247
500 000	0.815	0.04042		0.053	0.0846	0.104	0.117	0.127	0.135	0.148	0.1670	0.186	0.199	0.218	0.231	0.241
600 000	0.893	0.03452		0.048	0.0804	0.099	0.112	0.123	0.131	0.144	0.1628	0.181	0.195	0.213	0.226	0.236
700 000	0.964	0.02958		0.045	0.0769	0.096	0.109	0.120	0.128	0.141	0.1593	0.178	0.192	0.210	0.223	0.233
800 000	1.031	0.02598			0.0738	0.093	0.106	0.116	0.124	0.138	0.1562	0.175	0.188	0.207	0.220	0.230
900 000	1.093	0.02300			0.0711	0.090	0.103	0.113	0.121	0.135	0.1535	0.173	0.186	0.205	0.218	0.228
1 000 000	1.152	0.02070			0.0687	0.087	0.100	0.111	0.119	0.132	0.1511	0.170	0.183	0.201	0.215	0.225
1 250 000	1.289	0.01657			0.0635	0.083	0.096	0.106	0.114	0.127	0.1459	0.164	0.178	0.197	0.211	0.221
1 500 000	1.412	0.01381			0.0594	0.079	0.092	0.102	0.110	0.123	0.1417	0.160	0.174	0.193	0.206	0.216
1 750 000	1.526	0.01183			0.0558	0.075	0.088	0.098	0.106	0.120	0.1382	0.157	0.170	0.189	0.202	0.212
2 000 000	1.631	0.01035			0.0527	0.072	0.085	0.095	0.103	0.116	0.1351	0.154	0.167	0.185	0.199	0.209

A.	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50	1.60	1.70	1.80	1.90	2.00
B.	0.0022	0.0044	0.0064	0.0084	0.0103	0.0121	0.0138	0.0155	0.0171	0.0186	0.0216	0.0244	0.0270	0.0295	0.0319

For any other frequency f. the reactances given in the table must be multiplied by $\frac{f}{60}$

The reactances for diameters of conductors which lie between the sizes given can be found by direct interpolation.

The reactance for any distance D not given in the table can be found as follows· let d = the nearest smaller distance in the table. Divide D by d and taking a value of A nearest to the quotient find the corresponding value of B, which must be added to the reactance corresponding to the size of conductor and distance d.

For instance, suppose it is required to find the reactance corresponding to No. 4 solid wire with a distance between centers of nine ft. For one ft. the reactance is 0.2305, to which 0.0319 (corresponding to 2 in the auxiliary table) must be added

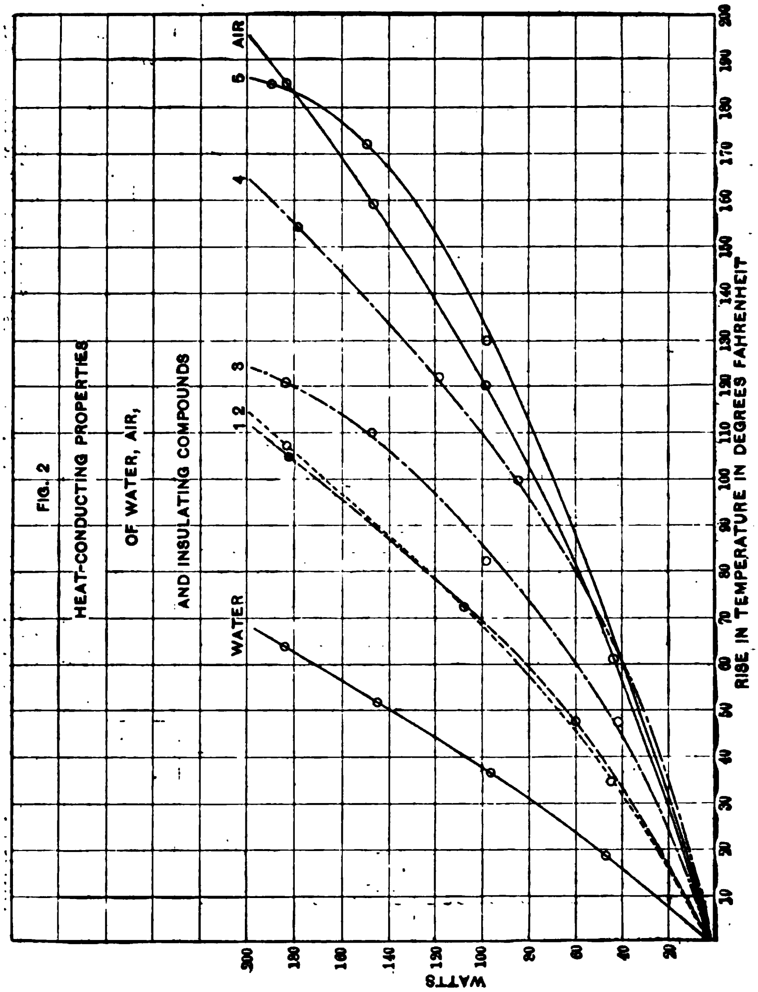


FIG. 2
HEAT-CONDUCTING PROPERTIES OF WATER, AIR, AND INSULATING COMPOUNDS

each time the distance is doubled. Therefore, for eight ft., there must be added $3 \times 0.0319 = 0.0957$, giving the total reactance for eight ft. $= 0.3262$. Now dividing nine by eight, gives $A = 1.125$, and by direct interpolation we obtain the corresponding value $B = 0.0054$, which added to 0.3262 gives 0.3316, the required reactance. Similarly, reactances for distances not given in the table can be calculated from those given in the column for distance between centres of two in. and reactances for distances less than two in. can be calculated by a reversal of the above process, that is, by subtracting instead of adding the values of B.

The curves of Fig. 2 show the heat-conducting properties of air and water, and of some insulating compounds. To make these determinations, three vessels were employed: an inner vessel containing oil in which four incandescent lamps and a rotating vane were submerged; a second vessel immediately surrounding it in which was placed the material to be tested, and an external third vessel in which water at the temperature of the room was circulated.

Energy was supplied to the lamps by direct current, which was kept constant until the difference of temperature between the water and oil remained constant. This difference in temperature is the abscissa of the curves, and is a measure of the heat-insulating properties of the material tested. During each test the pressure and current were carefully measured, from which the watts were calculated.

The equation of the water curve, the constants of which were found by the method of least squares is:

$$t = \frac{W}{2.41 + 0.00258\,W.}$$

and the equation of the air curve is:

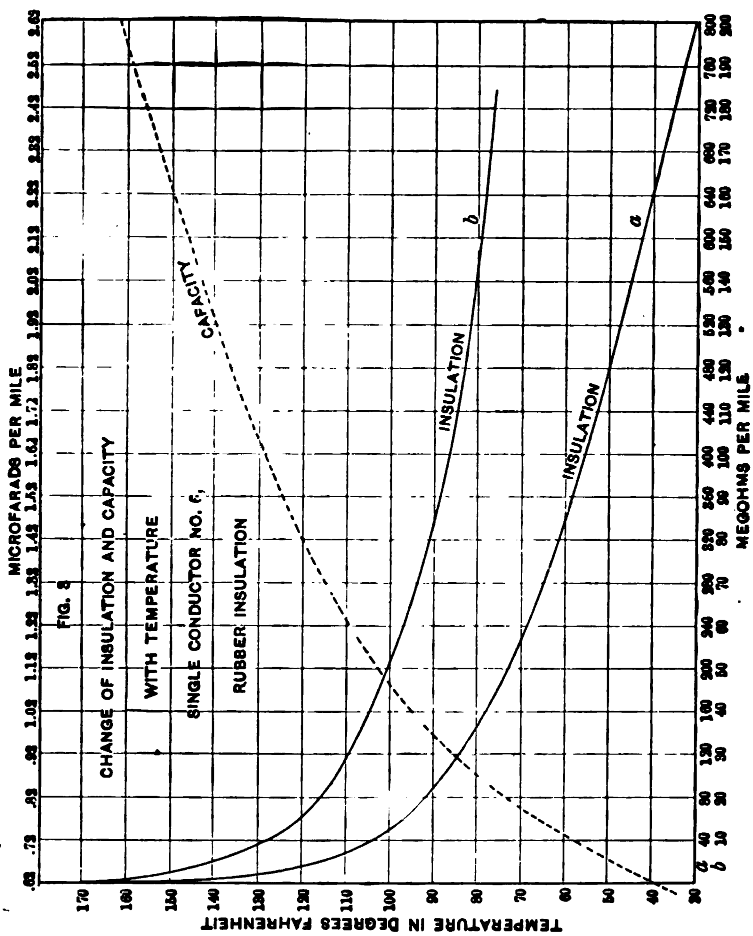
$$t = \frac{W}{0.6029 + 0.00211\,W}$$

Where W = watts
and t = rise in temperature, in degrees centigrade.

The other curves are for the following materials: 1, cotton seed oil; 2, linseed oil; 3, oil compound used in high-pressure cables; 4, hard ozite; 5, asphaltum compound. These data show that in order to most freely dissipate heat, cables saturated with an oily compound should be used.

I shall next consider the variation of insulation resistance and electrostatic capacity with change of temperature.

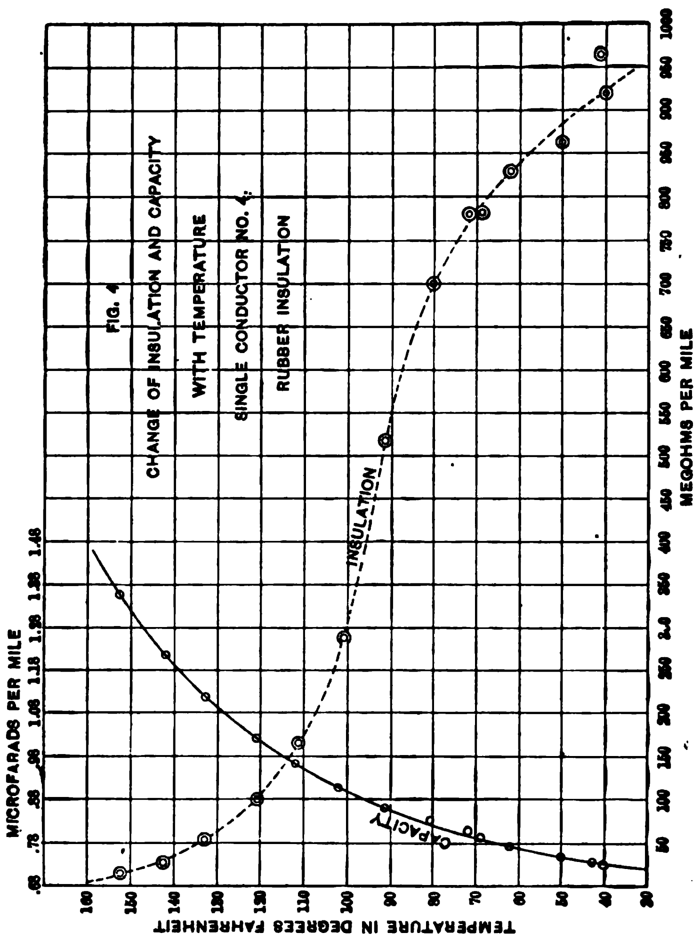
Figs. 3 and 4 show the results of tests on rubber-covered cables. The curves present a very interesting feature of dissimilarity in the presence of a double curvature in the curve of Fig. 4, and in its absence in Fig. 3. The writer has noticed this phenomenon several times; it is not necessarily dependent



upon the composition of the rubber compound. The variation in the insulation and capacity of rubber cables may be very much greater than is given by these curves.

The capacity tests were made with a galvanometer in the usual manner. The effective capacity for alternating currents (as determined from measurements of charging currents, frequency, and pressure) does not vary nearly so rapidly with change of temperature as is shown in the figures.

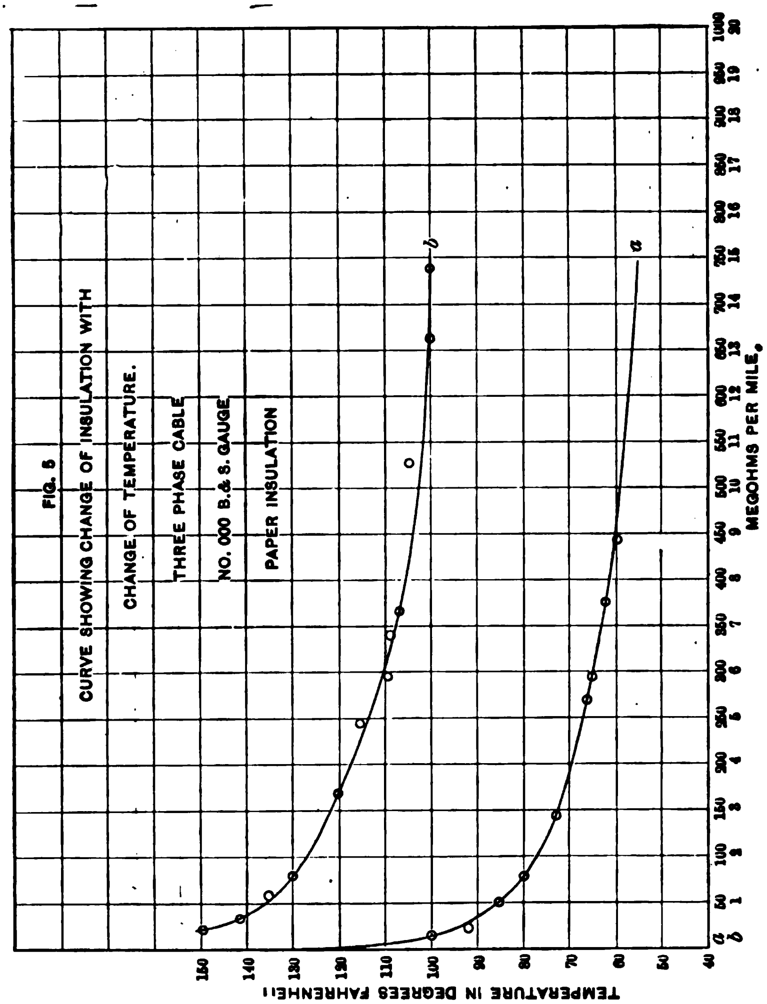
A study of the ratio between the effective capacity for alternating currents and the capacity, as measured by the discharge-deflection method, reveals many interesting and useful facts.



The smaller this ratio becomes the more apt is the dielectric of a cable to become heated under pressure stress.

Generally the ratio becomes greater with increased percentages of Para rubber, although this is not always the case. With rubber cables the ratio may be as high as 0.95 and as low as 0.75, at 60 cycles per second, and a temperature 60° fahr.; it decreases with increase of temperature. For good paper cables the ratio is in the neighborhood of 0.9. For varnished cambric it may vary between 0.75 and 0.50; hence, such cables are liable to become hot under high pressure stress.

Fig. 5 gives the variation of insulation resistance with change



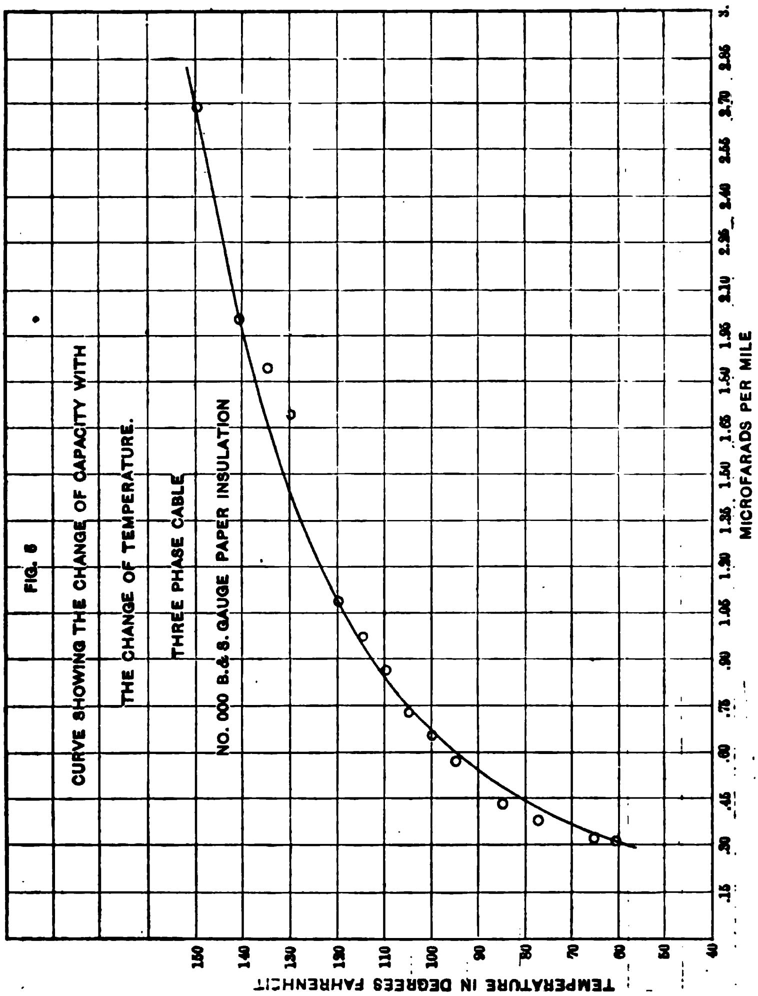
of temperature of a three-conductor 3/000 B. & S. gauge paper cable. The equation of this curve is:

$$\text{Log } I = 7.122 - 0.438\, T^{.5667.}$$

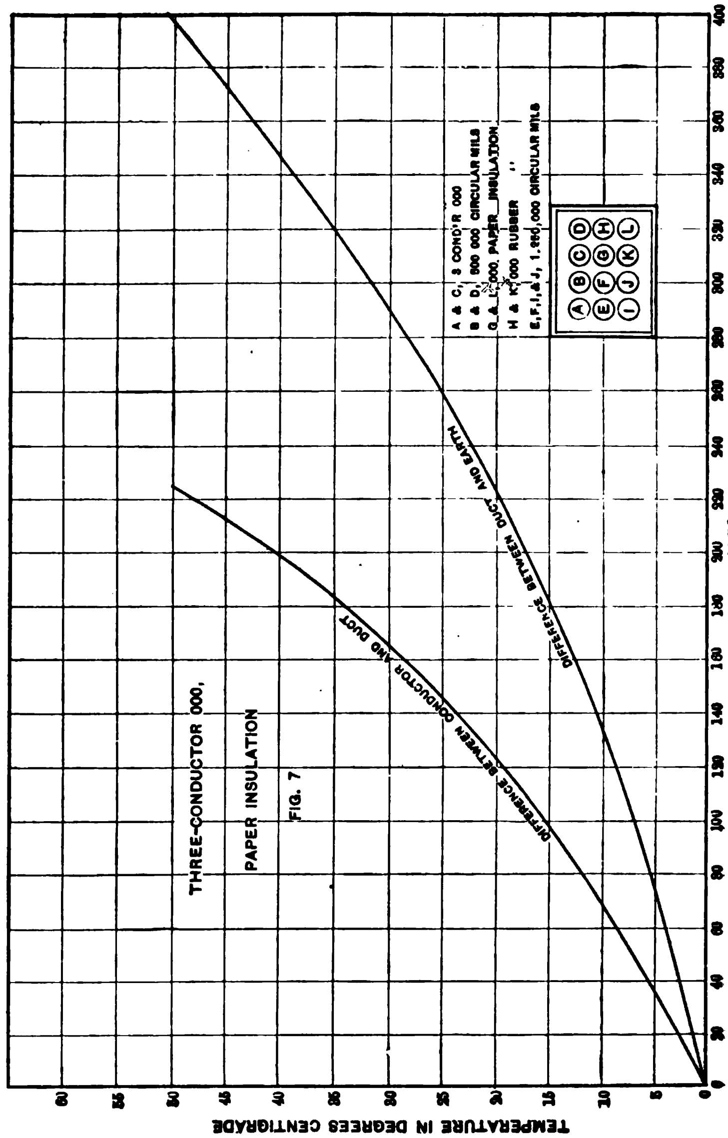
Where I = the insulation resistance per mile, and T = the temperature in degrees Fahrenheit.

Fig. 6 gives the variation in capacity with change in temperature of the same cable. The equation of the curve is
$\text{Log}\, C = T\, 0.38338 + (T - 32)^{1.50}.$

Where C = the capacity per mile,
T = the temperature.



With paper cables the variation is generally the greater the less viscous the compound. In the above case the insulating compound was quite oily, so that with other cables the variation may be either greater or less than the above.


THREE-CONDUCTOR 000,
PAPER INSULATION
FIG. 7
DIFFERENCE BETWEEN CONDUCTOR AND DUCT
DIFFERENCE BETWEEN DUCT AND EARTH
AMPERES
TEMPERATURE IN DEGREES CENTIGRADE

Oily compounds are the best because the cables can be readiest handled in cold weather; and offer the highest resistance strains.

Hence, the old idea of demanding high insulation resistance in megohms per mile, which was best obtained by the use of hard compounds, is incorrect, and the better-informed engineers of to-day either do not mention insulation resistance at all, or else specify 25 to 100 megohms per mile, depending upon the size of the conductor and thickness of insulation.

The subject which will next be considered is the carrying capacity of different cables. The results given were obtained from practical tests made at Niagara Falls.

Fig. 7 gives the rise in temperature due to currents of different strength in a three-phase 000 B. & S. gauge cable; the insulation on the conductor was of paper, $\frac{7}{32}$ in. thick; and over the three conductors, paper $\frac{7}{32}$ in. thick. The small diagram at the right of the figure shows the arrangement of ducts and the kinds of cables in the various ducts. The cables were connected in series so that the same current passed through them all.

The heating effect in the 500 000 cir. mils and 1 250 000 cir. mils cables was, of course, very small. The 000 single-conductor paper and rubber-insulated cable did not get nearly so warm as the three-conductor cable. It seems reasonably safe to assume that these curves are accurate enough for practical purposes for a duct system similar to the one used, in which three or four three-conductor cables similar to the two employed in the test are operating.

Fig. 8 gives the results of current-carrying capacity tests on single-conductor 000 cable with $\frac{7}{32}$ in. paper. The diagram to the right of the curve shows the arrangement of cables in the duct system. It is interesting to note that the difference of temperatures between the earth and the cable in duct *L* was not nearly so great as the difference in temperature between the cable in duct *G* and earth. During the various tests the corner ducts always radiated the best, and all of the outside ducts radiated heat much better than the inside ducts. For this reason, a conduit system, two ducts wide, is to be preferred because there is direct radiation from all the ducts to earth. The tests showed that a rubber-insulated cable dissipates heat more readily than a paper-insulated cable of the same dimensions. The rise in temperature in the paper cable was about one-third greater than that of the rubber cable.

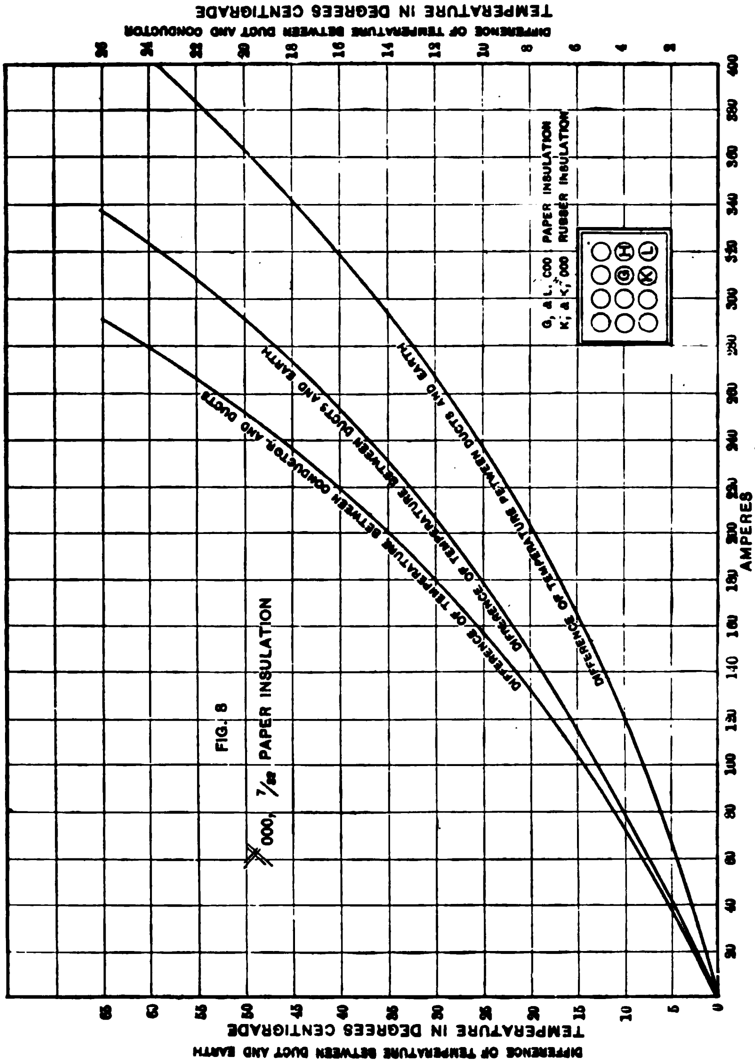
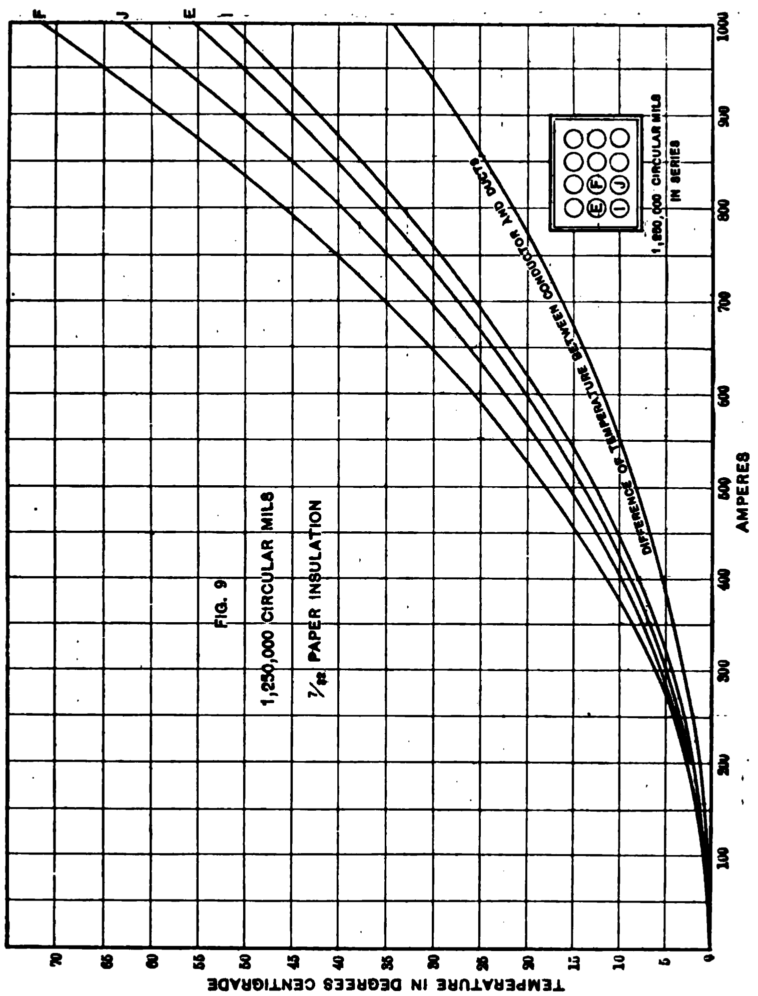


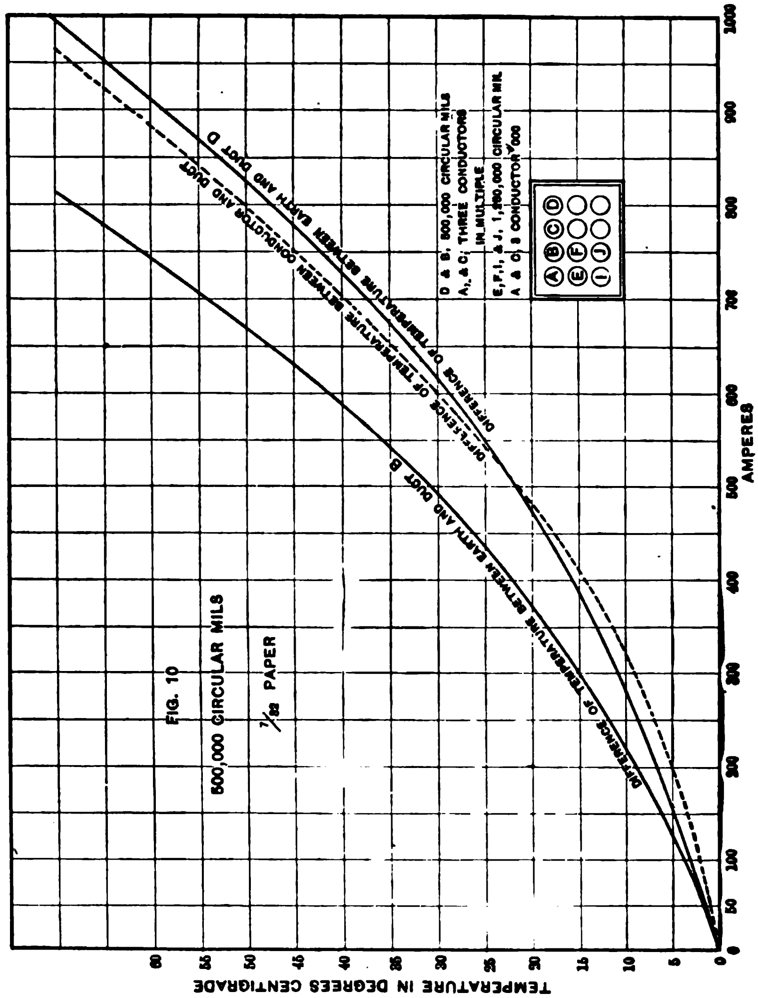
FIG. 8
000, 7/32 PAPER INSULATION

Fig. 9 gives the results of current-carrying capacity tests on a 1 250 000 cir. mils paper cable. Four such cables were connected in series and placed as shown in the diagram at the right of the curve. The lead covers of these cables were bonded



together at several points so as to give the condition for maximum temperature rise. It was a noticeable fact that with cables bonded the rise in temperature was slightly greater than when they were not bonded. In this case, also, the corner duct *I* was the coolest and the inside duct *F* the hottest.

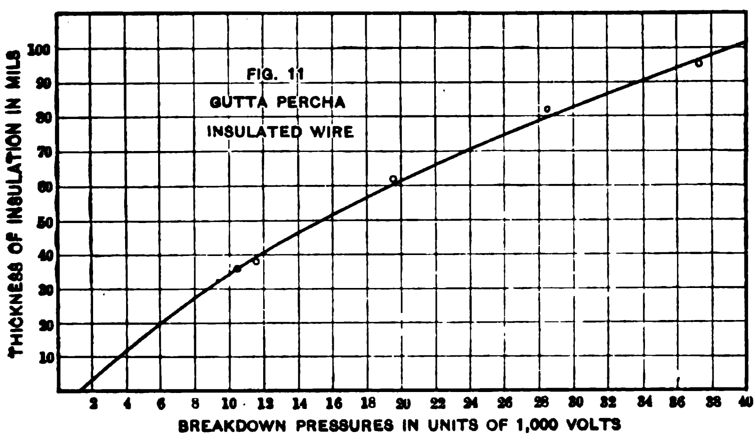
Fig. 10 gives the results of current-carrying capacity tests on a 500 000 cir. mils cable insulated with $\frac{7}{32}$ in. paper. The diagram shows the arrangement of cables and the same current flowed through all the cables in series. Before passing on to



the next subject, the writer wishes to say that it is impossible to lay down any definite rule for the current-carrying capacity of cables; the dampness of manholes and ducts, and the condition and kind of soil, and arrangement of cables—all are prominent factors in controlling the temperature rise. When the tests herein referred to were first started, the temperature rise was not so great as in later tests. For this reason current was applied to a lot of cables for about a week before the regular tests were made; and in this way the dampness in the duct system was largely removed so that the cables were tested under what might be considered "normal conditions."

The closing part of this paper will be devoted to a consideration of the pressures that should be applied to different sizes of cables.

Fig. 11 gives the breakdown pressures corresponding to different thicknesses of gutta-percha. This curve is more interesting than valuable because it is hardly safe to use gutta-percha for electric light or power cables owing to the fact that as soon



as the conductors get warm the gutta-percha will soften and the conductor become decentralized. Gutta-percha, however, has a wonderful dielectric strength; it will be noticed that 39 000 volts is required to break down an insulation of 0.1 in. The tests were made on short samples and hence, long lengths of the insulated wire could not be expected to give as good a showing as is presented.

Table 2 gives the thickness of paper recommended for different working pressures and different half-hour test pressures. In presenting this table, the writer wishes it to be clearly understood that there is a large margin of safety in the figures given. There is no doubt that cables with considerably thinner insulation than is recommended would work successfully under normal conditions, but the abnormal conditions which occur occasionally and have been the cause of much damage, not only to cables but accessory apparatus, must be provided for. The extra expense entailed by the addition of a little more insulation is small compared with the much larger factor of safety obtained thereby. For three-phase cables, the table gives the thickness of paper between conductors.

TABLE II.

Thicknesses of Paper Insulation.

Thickness of Insulation.	Working Pressure.	Factory Test 5 minutes.	Installed Test ½ hour.
4/32 in. to 5/32 in.	1 000 to 1 900	7 000	4 000
5/32 in. to 6/32 in.	1 900 to 2 250	10 000	6 000
6/32 in. to 7/32 in.	2 250 to 3 800	13 000	8 000
7/32 in. to 8/32 in.	3 800 to 5 000	16 000	10 000
8/32 in. to 10/32 in.	5 000 to 6 500	19 000	12 000
9/32 in. to 11/32 in.	6 500 to 8 000	22 000	14 000
10/32 in. to 12/32 in.	8 000 to 9 500	25 000	16 000
11/32 in. to 13/32 in.	9 500 to 11 000	28 000	18 500
12/32 in. to 14/32 in.	11 000 to 13 000	31 000	21 000
13/32 in. to 15/32 in.	13 000 to 15 000	34 000	23 500
14/32 in. to 16/32 in.	15 000 to 17 000	37 000	26 000
15/32 in. to 17/32 in.	17 000 to 19 000	40 000	28 500
16/32 in. to 18/32 in.	19 000 to 21 000	43 000	31 000
17/32 in. to 19/32 in.	21 000 to 23 000	46 000	33 500

It is difficult to predict at this time the maximum pressures that may be transmitted through cables in the near future. The experienced manufacturer can construct cables that will withstand very high pressure tests at the factory; but without subjecting such cables to pressures operating under working conditions for a long time, it is impossible to tell how they will withstand high pressures continually, and abnormally high ones occasionally.

All cables which are to be placed underground should be lead covered, because even if the insulated conductor can be submerged in water for an indefinite time without breaking down under pressure tests, yet if a non-leaded cable of the same material be placed in ducts, some ingredient that will injure it will, sooner or later, get into the ducts or manholes.

DISCUSSION ON, "DATA RELATING TO ELECTRICAL CONDUCTORS AND CABLES."

H. G. STOTT: There are one or two questions I would like to ask, probably Mr. Fisher can answer them. At the foot of page 404 it is stated:

"The capacity tests were made with a galvanometer in the usual manner. The effective capacity for alternating currents (as determined from measurements of charging currents, frequency, and pressure) does not vary nearly so rapidly with change of temperature as is shown in the figures."

I would inquire why the capacity as determined by alternating-current measurements and special measurements, does not vary so rapidly as it would if the capacity were measured by the ordinary discharge galvanometer method? On the next page 405 it is stated:

"A study of the ratio between the effective capacity for alternating currents and the capacity as measured by the discharge-deflection method, reveals many interesting and useful facts. The smaller this ratio becomes, the more apt is the dielectric of a cable to become heated under pressure stress."

Is it intended to indicate the presence of dielectric hysterisis? The presence of heat is undoubtedly due to that. The different tables of data and curves are I think of value to the art, particularly those showing the principle involved in the laying of conduits. Conduits are sometimes put in position under adverse conditions. In a limited space, already partly occupied by water-mains, gas-pipes, etc., a number of conduits must be installed. This paper indicates very clearly that the proper method is to have the minimum distance possible between each conduit and the earth in order to obtain maximum results from each conductor. Fortunately the heaviest load in cables is carried during the coldest weather. This fact is a boon to the engineer.

I think that Mr. Fisher has not made an exact statement of the limit of safety of a working current on underground cables. I note that he carried the working pressure up to 23 000 volts, and the test pressure up to 46 000 volts. That is encouraging because it indicates that manufacturers are prepared to build cables and guarantee them up to a pressure of 23 000 volts. I am looking forward to the day not being very far distant when cables will be furnished that will stand an operative pressure of 50 000 volts.

I would also like to ask Mr. Fisher if he has determined what relationship there is, if any, between the thickness of the lead jacket on a cable and the radiation of heat.

C. W. RICE: Referring to the first few sentences in the paper regarding the fear that giving out information will prove a hardship to the manufacture of cables. My experience in the purchase of cables has taught me that the greatest success is in not assuming to know more than the manufacturer, but rather to consult the manufacturer frankly and ask him what is the best specification?

Insulation resistance is often specified higher than is practicable. With the development of the paper-insulated cable, the manufacturer advises that requirements be reduced until now the insulation resistance is in the neighborhood of 300 or 400 megohms only for the three-conductor cable of 250 000 cir. mils such as are now used for three-phase transmission of power in cities with 6 600 volts or thereabouts. Formerly 1 000 megohms was specified. This is the result of accepting the advice of a manufacturer, and it has proved a complete success.

In New York, where probably there is more cable than in any other city in the United States, or in the world, interruptions of service due to the breaking down of a cable are almost unheard of. Most of the troubles are in the joints.

Another particular wherein consulting engineers may err is in asking for a breakdown test of several times the working pressure. I think that two and one-half times is the ultimate that should ever be required. More than that is a strain upon the insulation which gives it a permanent set, comparable to the set in mechanics.

C. O. Mailloux: This paper presents features that are worthy of special mention. They are first, the liberal use which has been made of diagrams to express graphically the relation between variable quantities; secondly, the thorough manner in which these diagrams have been made use of. Those who are accustomed to the use of graphical methods cannot help but notice in these curves the fact that they pass either through the plotted points, or very close to them.

The curves in Fig. 5, for instance, especially the one that is marked *a*, illustrate the manner in which it is possible to obtain an empirical formula that fits closely to data plotted graphically. The formula is given at the bottom of page 406. It will be observed that the exponent has been worked out to the fifth decimal and that the constants are given to the third and fourth decimal. In discussing this matter with Mr. Fisher, over two years ago, he showed me the necessity not only of determining carefully the constants in an empirical equation for expressing a mathematical relation of the kind represented in the formula just referred to, but also the importance of using a sufficiently large number of decimal places to suit the case. In this particular case it would not be possible to get an empirical curve that would even approximately fit the case, without working out the equation as carefully as has been done here. Of course this close approximation between the plotted points and the empirical curve depends greatly upon the accuracy of the measurements made.

In the last paragraph on page 398, it is noted that it is found in certain cases that the current apparently follows the copper strands helically around the central steel wire, making in consequence a different resistance for the cables—a higher resistance than would be obtained with the equivalent amount of copper wire laid straight for the same length as the cable. That is rather a small matter to figure out in a 7-wire cable, but in a 19-wire or 37-wire cable it is rather difficult to figure out, as the helical turns are unequal, and it is much more readily obtained with an ordinary apparatus for measuring the resistence, if one has the opportunity to apply it to cables, as Mr. Fisher has already done. The publication of the results of such measurements would be of great interest.

On the last page of the paper is given a table of thicknesses of insulation for paper cables; this marks a distinct step in advance that has recently been made by the manufacturers of such cables. A few years ago there was a limiting thickness in insulation beyond which an increase of thickness did not give a corresponding increase of permissible voltage. That was more particularly true of fibre-insulated cables than of paper insulation, but at the same time it was also true to some extent of paper-insulated cables, so that the table, which I believe is true to-day for one or more makes of paper-insulated cables, represents a distinct progress in cable manufacture. If cables up to 17-32nds of an inch, for pressures of 21 000 to 23 000 volts, can be relied upon to-day it is much better than could be done a few years ago. It is the result of efforts to learn how to make a paper cable that will continually withstand a higher voltage as the thickness of the insulation increases.

Chas. P. Steinmetz: Regarding power transmission of late years, electrical engineering has proceeded in overhead transmission to higher and higher voltages, voltages which were never thought of 10 years ago The increase of voltage in cable transmission has not kept step with it. Years ago cables were operated at 6 600 volts; and then, with fear and trembling, the pressure was lifted to 11 000 volts. This voltage, 11 000, seems to be the maximum just now. There are very few cables operating at a higher voltage. In operating voltages, in cable systems, the increase has not kept pace with that in overhead lines. Any information regarding underground cables that gives a clearer view of this matter, and thereby holds out a prospect of being able to follow in underground cable distribution, the advance of rising voltages in overhead transmission, is of value.

There is one minor point regarding which I desire to say a few words, since I do not quite agree with Mr. Fisher. It is on the effect of the greatly increased impedance in a cable with two iron strands. Such an increase of impedance may not be objectionable in many cases. It may even be beneficial, in those cases where inductance is desirable, as when controlling voltage by varying the phase relation in a transmission system connected with compound rotary conductors. I believe, however, that it is very undesirable in high-voltage, long-distance transmission lines of considerable capacity. I do not agree that this increased impedance compensates for the capacity of the long-distance line, since the impedance is a series impedance and the capacity is a shunted capacity. To compensate for the capactiy would require a shunted impedance. Series impedance increases vastly the liability to resonance, and this is an undesirable phenomenon.

Now one can look at it from another point of view. The frequency of oscillation of overhead long-distance lines can, with sufficient accuracy, be calculated by dividing 47 000 by the length of the line in miles. This applies whether they are single transmission lines or several transmission lines in multiple, but it applies only to a transmission line in air. If the material surrounding the conductor is not air, then the period of oscillation multiplies and the frequency divides by the square root of the permeability and the dielectric constant of the material; if the inductance is doubled, this means the velocity of propagation of the current in the transmission line and thereby the frequency of oscillation is reduced by $\sqrt{2}$. In other words, the transmission line has, in respect to the frequency of surges or oscillation and to their power $\sqrt{2}$ times the length; that is, it is 41 per cent. longer. Since the increased inductance is due to the iron such a surge or oscillation has a more rapid decrease due to the energy lost in the iron, than on an air line. Hence the matter is not quite as bad. Nevertheless, I do not consider the increase of inductance under such conditions as desirable wherever the capacity effects are considerable.

H. W. Fisher: In answer to Mr. Stott's question, the reason the capacity measured with a galvanometer increases more rapidly than capacity measured by the charging current method, is that when a cable is warm there is kind of polarizing action due to the return current, which in turn produces an augmented deflection. To a person experienced in cable testing, this kind of galvanometer deflection is familiar. Under such conditions, the galvanometer will show a permanent deflection for a long time after the cable has been charged. The capacity thus measured is, therefore, larger than the true capacity, as measured by the charging-current method.

Referring to the other question that Mr. Stott asked relative to the ratio between the capacities, as measured by the charging-current method and by the galvanometer method, it can be said broadly that when this ratio is small cables will get warmer under dielectric voltage stress than when the ratio is large. Whether the heating effect is inversely proportionate to that ratio, I cannot say. The heating effect is only produced when high voltages are applied, such as will nearly puncture the insulation.

Dr. Perrine asked for more data in reference to the resistance of stranded cables. The variables are so great that exact data on this subject are difficult to obtain. In the old days, cables were frequently not made in accordance with perfect construction;

namely, commencing with a one-wire center. Sometimes, the most peculiar strands are specified, such as cannot be made without having numerous open spaces between wires. The resistance of such a strand may be considerably higher than that of a perfect strand. I have known of cases where the conductivity ran as low as 96%; that is, two or three per cent. lower than that of a perfect strand. Of course, there is a variable function that cannot be eliminated; namely, the insulating compound getting in between the strands, tending to insulate one from the other.

H. G. STOTT: You suggested 23 000 volts. Are you prepared to make cables guaranteed to stand that voltage?

H. W. FISHER: Yes; there is no difficulty about doing that. The question is whether cables can be operated continuously at very much higher voltages, such as 40 000 to 50 000 volts?

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

METHODS OF MEASUREMENT OF HIGH ELECTRICAL PRESSURES.

BY S. M. KINTNER.

The need of some convenient and accurate method of measuring high electrical pressures has been felt for a number of years. The trend of modern development in electrical transmission of power toward higher pressures will doubtless make this need more and more urgent. The testing of dynamos, transformers, switches, cables, etc., at several times normal pressure, as a specified condition of their acceptance, is not infrequently the cause of considerable controversy as to whether the proper pressure test has actually been applied.

The purpose of this paper is to summarize briefly the various methods of high-pressure measurement at present employed, pointing out the respective advantages and faults of these methods, and then to describe a new type of static voltmeter.

RATIO METHOD. STEP-UP TRANSFORMER.

Probably the most convenient method of high-pressure measurement is the one employing the ratio of the step-up transformer supplying the power. The pressure on the low-pressure side of the transformer is measured by the customary low-pressure instruments; the high-pressure value is obtained by multiplying this measurement by the ratio of transformation. Unfortunately the pressure ratio is not accurately the ratio of the number of turns on the two sides, and the real ratio of pressure is not a constant but is dependent upon the load and its character. In well-designed transformers of large kilowatt capacity no serious error will be encountered in using this method when the transformer is supplying a very small current.

Owing to the large impedance of high-pressure transformers, due to the size of the spacings between windings required for insulation and the comparatively few interlacings of high- and low-pressure windings, currents of appreciable size will cause a considerable variation in the terminal pressure from that deducible from the ratio of transformation. If the current is used in charging a condenser the pressure may be higher than the ratio would imply, though for all other cases it would be less. The writer has noted instances of the first kind where the pressure was 20% high, due to the interaction between the inductance of the transformer and the electrostatic capacity of a machine under an insulation test.

The ratio method is used regularly for tests on insulating materials, such as treated cloth, fullerboard, paper, oils, line insulators, etc., and with all the accuracy necessary for these conditions. Owing to its convenience, cheapness, and safety to the operator, this method will doubtless always find a place in high-pressure measurement. It is fairly accurate except in such cases as require considerable current, when a serious error of either a positive or a negative value may be introduced, according to the character of the load.

Ratio Method. Step-down Transformer.

The use of an auxiliary transformer to reduce the high-pressure to a value suitable for ordinary low-pressure instruments has been used very successfully within a certain range of pressure. The limits of the usefulness of such a transformer are soon reached with increasing pressures, on account of the size of the transformer required. It is impracticable to build a 15- or 20-watt transformer for 50 000 volts—the minimum commercial transformer for that pressure would be more apt to have a rating of 15 or 20 kilowatts. The smallest size of wire that it is feasible to wind when properly insulated and placed on the most economical size of core, would give a transformer of approximately the size stated above, in kilowatts.

Results obtained by use of the voltmeter transformer are reasonably accurate over certain parts of the scale, but if accuracy over a greater range is desired it is necessary to change the ratio of the transformer for the lower pressure values. The changing of the ratio introduces at times a certain amount of uncertainty as to the proper connections. Voltmeter transformers for switchboard service, where the pressure range is limited and the high-pressure side of the transformer is from 12 000 to 14 000 volts, are quite satisfactory and are likely to be continued in that service for some time. This method for general testing is reasonably accurate over a limited part of the scale and is quite safe for the operator, but is defective on the score of cost and lack of portability.

Voltmeter Coil and Measurement Across Part of the High-Pressure Winding.

Special coils have been placed in the high-pressure circuit in an endeavor to have them linked with the same magnetic flux as the high-pressure winding and thus give an accurate and constant ratio. This method has met with only a limited degree of success; it is but slightly, if any, more accurate than the method of ratio from the low-pressure side. It is subject to certain errors due to the lack of uniformity of pressure induced per turn. This lack of uniformity is due to the leakage flux affecting some parts of the winding more than others.

The insulation between voltmeter coils and the high-pressure winding is essentially the same as that between the low-pressure and the high-pressure windings, consequently these coils are subject to practically the same flux leakage as the low-pressure windings. Practically, the insertion of the extra windings introduces insulation difficulties and necessitates the use of additional leads. This latter point assumes more and more importance with increasing pressure. For the safety of the observer the pressure coil should be connected to earth.

Measurement of the pressure over fractional parts of the high-pressure winding is quite similar to the method of voltmeter coils. If such measurements are made over symmetrical portions, like one-half or one-fourth of the winding, according to the individual case, very satisfactory results will be obtained. When employing instruments connected directly on the high-pressure circuits, or on circuits like voltmeter coils electrostatically inductive to them and not grounded, it is necessary to connect one side of the meter to a metallic screen surrounding it, as a protection against disturbance from external charges. The screen is insulated from earth for full line pressure, and is, of course, dangerous to touch.

It may be stated in general that the method of employing a voltmeter coil is but slightly better than the straight-ratio method previously described. It introduces insulation difficulties, and increases the cost of the transformer, which are not warranted by the slight advantages of the method. Measurements over certain symmetrical portions of the high-pressure winding give satisfactory results, when proper precautions are taken in the screening of the meters.

VOLTMETER RESISTANCE METHOD.

An extension of the well-known plan of using extra resistance as a multiplier for a voltmeter in order that it may be used on a circuit of higher pressure than that for which it was designed, has been employed on pressures up to 150 000. Such a resistance, while it can be made practically free from inductance, is subject to capacity action between parts and to ground and surrounding objects. The capacity currents may cause the voltmeter to read high or low, depending on the location of the voltmeter in the resistance circuit. It is practically impossible to correct for these variations, and such methods as have been proposed* for overcoming them are both complicated and costly.

The resistance required is bulky, difficult to mount, and delicate. It is also faulty in that considerable energy is consumed —about 6 kilowatts for 100 000 volts being an average value, which varies, however, according to the sensitiveness of the voltmeter employed. For a given sensitiveness of meter, the energy consumed in the resistance varies as the square of the pressure.

CAPACITY IN SERIES WITH A CURRENT-OPERATED VOLTMETER.

In all the preceding methods it is assumed that the voltmeters used depend upon current for their operation, and that the proper current-limiting devices are provided. A condenser of suitable size in series with a voltmeter will doubtless suggest itself as another possible combination. It is a possible method but not one to be recommended. A few of its many defects are the following: it requires a large and costly condenser; is subject to variation with frequency and wave-form; it is affected by static charges on surrounding objects.

SPARK-GAP METHOD.

The measurement of pressures by determining the sparking distance has been accepted as a standard method readily ap-

*Professor H. J. Ryan; International Electrical Congress, St. Louis, 1904. "Some Elements in the Design of High-Pressure Insulation."

plied, cheap, portable, and bearing the sanction of the American Institute of Electrical Engineers. While the method has the above advantages, there are certain undesirable characteristics to which spark-gaps are subject that need to be considered at greater length.

In the majority of high-pressure measurements it is desirable to measure the voltage step by step for increasing values, and frequently it is desired to hold a particular value for a certain length of time. The spark-gap is not at all suited to such conditions. It is simply a weak spot, of approximately known value, in shunt with the object under test, and the pressure is applied and its value increased until the weaker one of the two breaks. Such a test is analogous to a measurement of current strengths by placing fuses in series with some device whose current-carrying capacity is under test. Results obtained with each method in the hands of an ordinary observer would be of the same order of accuracy.

In order to give a certain device a pressure time-test, the amount of pressure being determined by the spark-gap, one of two methods must be employed.

First Method: A preliminary test with the spark-gap is made and the low-pressure reading noted, and then the regular test is applied according to the low-pressure reading. It is necessary for accuracy that all the apparatus be connected to the circuit at the time the preliminary test is made. The surges incident to the spark-discharge are liable to produce serious strains, both in the device under test and in the machine or transformer supplying the pressure. This method is to be condemned as unnecessary, and serious damage has resulted from this test on a number of different occasions. A part of this trouble can be eliminated by placing choke-coils on the terminals of the testing transformer; these choke-coils tend to make the action more sluggish and thus relieve the severe strains.

Second Method: The second method, which is preferable from the standpoint of abnormal insulation strains, consists of connecting current-limiting devices, such as condensers or resistances, in series with the spark-gap, to enable the pressure to be maintained without interruption after the spark-gap discharges. It is generally assumed that no appreciable drop of pressure through such devices is caused by the small charging current passing to and from the gap treated as a condenser, and that therefore it is possible to use the standard published spark-gap curves. This assumption seems to be unwarranted; the experience of the writer during the last two years has shown very conclusively that these devices do affect the sparking distance.

A number of tests made to ascertain the effect of various current-limiting devices arranged in different ways were recently made; the results of some of them are incorporated in the following sets of curves.

The peculiar phenomena noted were obtained on several different occasions and were produced under conditions likely to exist under the best testing arrangements for that particular apparatus. The curves in Fig. 1 illustrate the results obtained with sharp needle-point terminals. The variation of condition for each curve is stated on the drawing.

The observations from which data for the above curves were obtained were made on a 25-cycle circuit having approximately a sine wave-form. The practice of varying the gap opening for a particular pressure was followed, as more accurate results could be obtained in that way. The necessary pressure for most of the tests was supplied by a 25-kw., 100 000-volt transformer though a number of observations were made on other testing sets, which gave values in general agreement with the first mentioned.

Curve I was checked at several different values, as shown by the observation points. Sharp needles, properly supported, and with no current-limiting device in the gap circuit, were used in these determinations.

Curve II was obtained in the same manner as Curve I, save for the presence of a water resistance in the gap circuit. This resistance consisted of a 3-ft. glass tube, of 0.25-in. bore, filled with distilled water. The connections to the resistance were made by immersing about 1 in. of No. 22 B. & S. copper wire in the water at each end of the tube. A difference of 10 or 12 per cent. in the pressure required for a given gap is shown by Curve II in comparison with Curve I.

Curves III and IV show the effect of condensers in the gap circuit. They produce a noticeable change in the sparking distance, which is, in general, of the same order as that produced by the water resistance. An effort was made to eliminate the effect of the condenser by placing more capacity in the gap circuit, but for capacities 50 times greater than that employed in the test shown in Curve III a very perceptible discrepancy remained.

A modification in the spark-gap mounting produces a very decided change in the effect of the capacity or resistance, on the sparking distance. A certain amount of variation may also be produced by bringing objects near the spark-gap. This effect has been noted by Voege.*

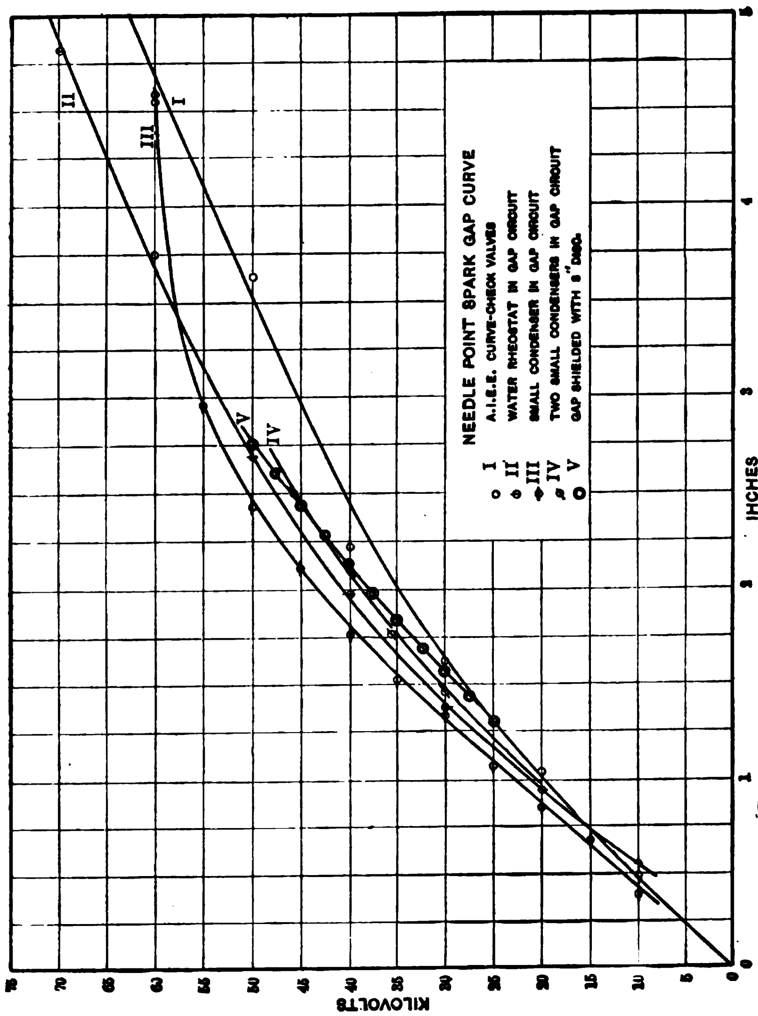


FIG. 1.

In general, anything that will tend to change the charging current of the gap, or of its mounting, will affect the sparking distance.

*Voege. *Electrotechnische Zeitschrift;* 1905; *pp.* 360.

The sudden bend in Curve III at about 50 000 volts is doubtless due to leakage of the condenser. It had a creep discharge over its surface at 65 000 volts.

Curve V was obtained by Mr. H. W. Fisher, and is reproduced here with his permission, from his paper, read before the International Electrical Congress at St. Louis.† The curve was obtained by using 8-in. shields in the form of slightly concave discs mounted 0.5 in. back of the needle points. Mr. Fisher has found the use of shields very advantageous, and he has been able to obtain remarkably uniform results over the range tested. Their use is to be recommended when not using current-limiting devices, but the increased charging current required renders their value doubtful when capacity or resistance is placed in the gap to limit the current after breakdown.

An interesting phenomenon was noticed with condensers used as current-limiting devices in the spark-gap circuit. As its action caused a very erratic behavior of the spark-gap, it will be briefly described here.

It was noticed that if there was a partial break or defect in the continuity of the spark-gap circuit, sufficient to cause a small spark at that point, the value of the measuring gap for a given pressure was very erratic. Variations of as much as 70 per cent. were obtained, which were always in the direction of an increase in the gap.

This phenomenon was investigated by placing a small spherical terminal gap in series with the condenser and needle-point gap. If, with the small spherical gap closed and the needle-point gap set at 10 or 15 per cent. beyond its breakdown value for a given pressure, the spherical gap was opened gradually a regular cycle of effects resulted. The needle-points showed a slight glow or coronal formation on starting; this changed to a brush discharge on further opening the spherical gap, and again to sparks on still greater opening, the sparks increasing in intensity, as judged by sound and color, as the spherical gap was opened still more. This action continued till a point was reached where all sparking ceased. An exact reversal of this action took place on closing the spherical gap gradually; *i.e.*, first heavy sparking which decreased in intensity; then the brush discharge, which was very pronounced, with beautiful long streamers; finally, when the spherical gap was completely

† "Spark-Gap Determinations of Voltages."

closed, the needle-points simply glowed without streamers or hissing sound.

The experiment was tried with the needles so arranged that the projecting streamers or brush discharges crossed each other at an angle; the streamers were projected out almost in line with the axes of the needles. The photograph shown in Fig. 2 gives a very good idea of the appearance of the discharges.

A repetition of the opening of the series spherical gap caused this arrangement to pass through the same cycle as noted in the previous arrangement in which the needle axes were in

FIG. 2.

line. Some idea of the appearance of the sparks that passed, with the needles set angularly to each other, can be obtained from Fig. 3.

The sparks follow the path of the brush discharge quite closely, and actually pass the point of crossing, choosing a point beyond from which to jump to the other terminal. This particular sparking arrangement is a rather critical one as regards the angular setting of the needles, but in all cases the sparks followed the discharges for quite a distance.

The phenomenon is intensely interesting, and more time should be given to its study than the writer had at his disposal. It was developed as a by-product, and, after a slight investigation, was dropped. Undoubtedly some form of a free oscillating circuit is established, which superimposes its values of pressure on the normal pressure and produces a marked increase.

The writer has observed on several occasions, when determining the capacity of high-pressure condensers by measuring the charging current and pressure of known frequency, that a small spark-gap in series or a loose contact would increase the ammeter reading 100 per cent. or more. This phenomenon indicates another cause for the erratic behavior of spark-gaps

FIG. 3.

when used with condensers; this is a very serious matter, and makes it imperative that good contacts be made in a spark-gap circuit. This has not heretofore been considered of any practical importance, it being not uncommon to join the ends of cotton covered wire without removing the covering at the splice.

Tests made in which spherical terminals were used in place of needle-points also gave some peculiar results. The tests were made with 0.5-in. hemispherical terminals of brass mounted on the same supporting device used in the needle-point tests, all other apparatus being the same as that previously employed. A ground on the high-pressure circuit, either direct through resistance or condenser, was found to have a very marked effect on the spark distance for a given pressure. This effect was not noticeable with the needle-point gap. The curve, Fig. 4, shows

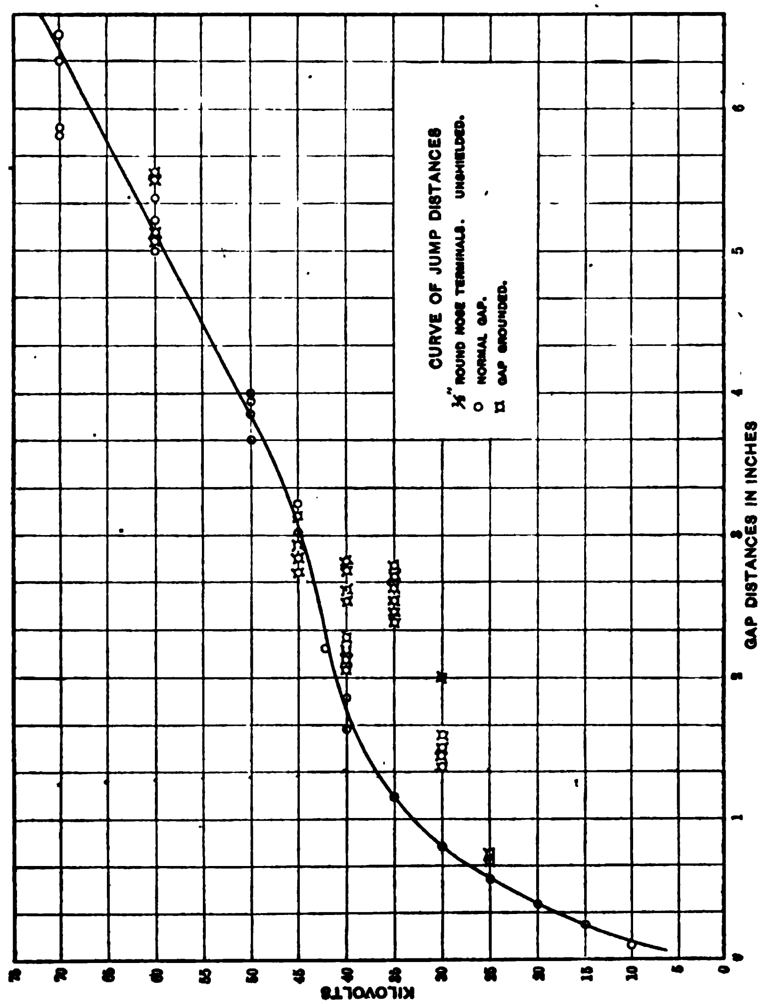


Fig. 4.

the variations noted for the same spark-gap, when grounded and when not grounded. A critical condition seems to exist at pressures between 25 000 and 45 000 volts. In the normal curve a very peculiar hump or change in the curve is noticed at about the same values. This range of pressure is particularly subject to variation.

In the *Elektrotechnische Zeit.*, 1904, several of the German

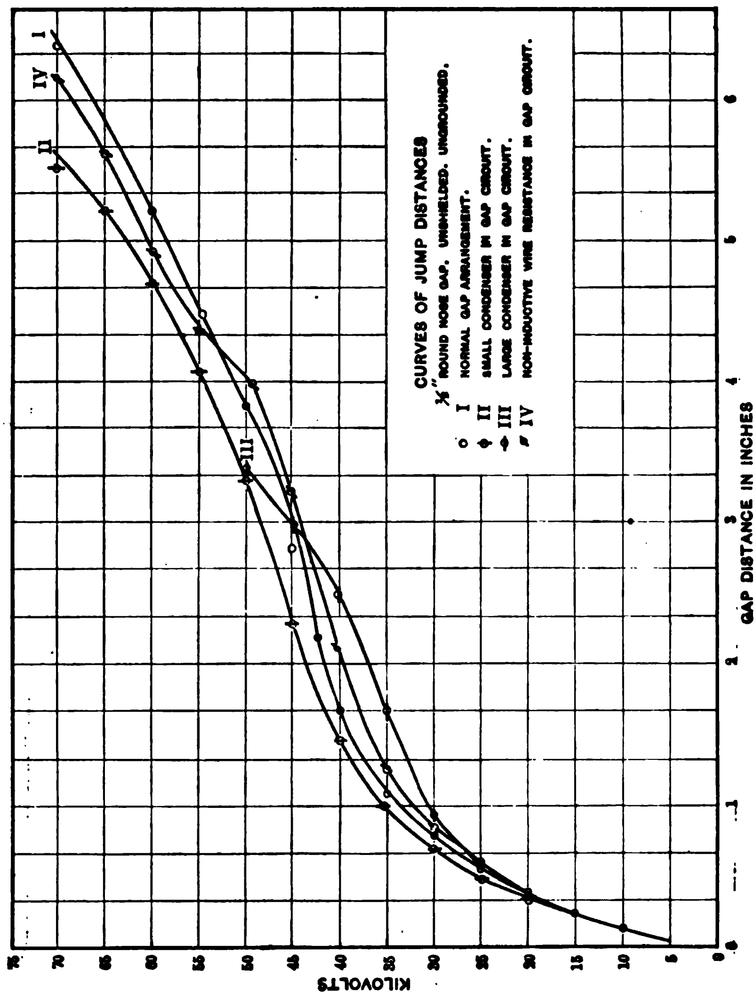


Fig. 5.

writers have called attention to this same critical part of the curve.

The effect of current-limiting devices when employing hemispherical terminals is shown in the curves of Fig. 5.

The effect of grounding when using the same current-limiting devices and terminals is shown in Fig. 6.

These curves show the same general effect of grounding noted

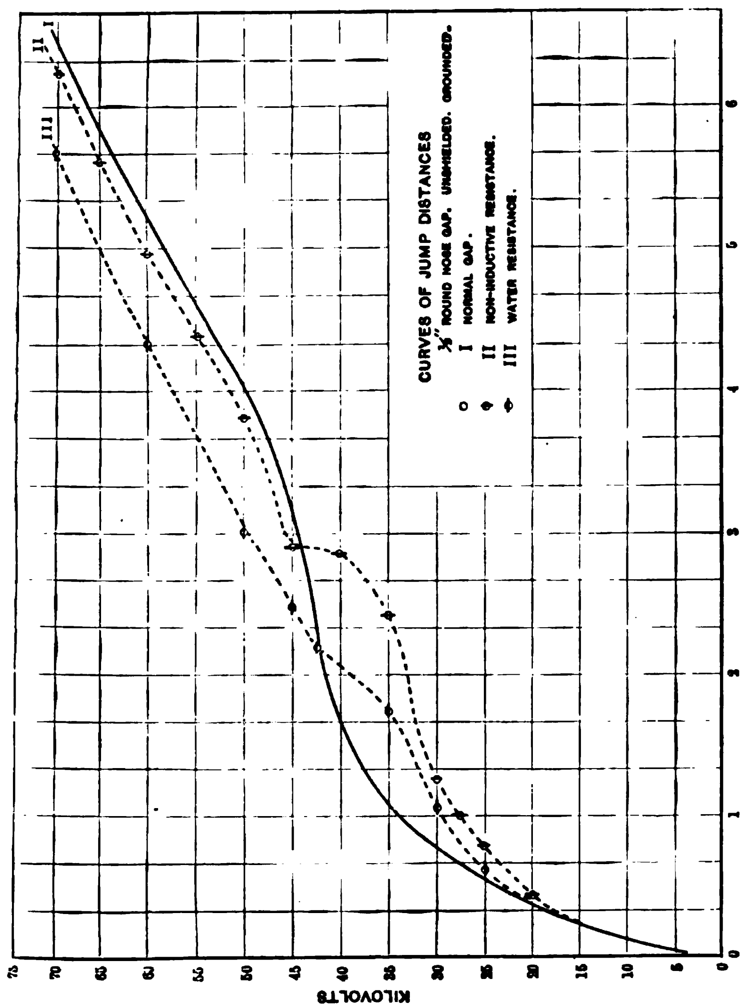


Fig. 6.

in the spark-gap curve in which no current-limiting device was employed, as illustrated in Fig. 4.

The application of shields to the 0.5-in. hemispherical terminals for the various current-limiting devices gave results shown in the curves of Fig. 7.

It will be noticed that the curves are very regular. Grounding one side of the line had no appreciable effect.

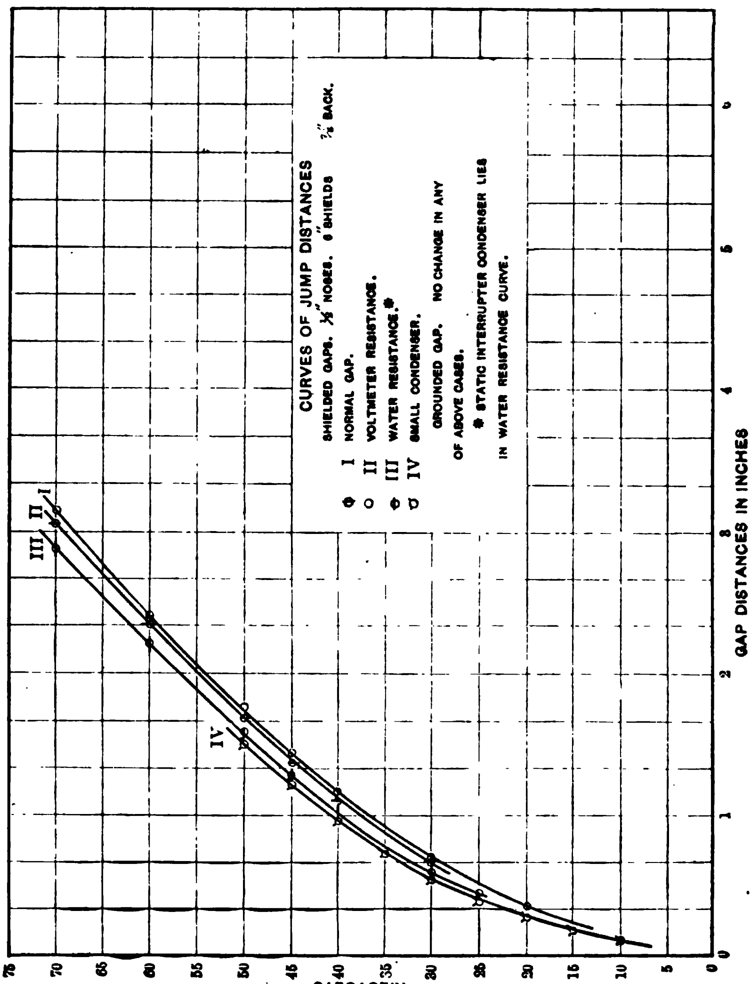


Fig. 7.

There are other objections to the general method of high-pressure measurement by the spark-gap than those previously mentioned. The erratic behavior of the apparatus renders the accuracy of the results uncertain, and it is the writer's opinion that this method should be used only when no other is available.

For the measurement of sudden pressure variations, such as those produced on transmission lines by lightning, switching, grounds, short circuits, etc., where the use of an oscillograph or similar device is not feasible, the spark-gap method is very useful. It is in fact the only method by which any satisfactory quantitative results can be obtained under such conditions.

When using a gap the writer prefers "round nose" (hemispherical) shielded terminals; the gap should be standardized over the range for which it is to be used just prior to taking measurements, and under as nearly the same surroundings, connections, etc., as possible. This preference is based on the convenience of operation and greater freedom from erratic behavior of this form of gap.

The spark-gap, although apparently a very simple device, requires an expert operator to get results that are at all satisfactory.

Coronal Formation Method.*

Professor H. J. Ryan has proposed to utilize the coronal formation on wires of various sizes, or at various distances apart, as a means of indicating the pressure impressed. Before any definite conclusion can be drawn as to its good or its bad features, this method needs a practical test to develop its reliability under service conditions.

Optical Methods.

It has been suggested† that high pressures might be measured by means of the effect produced by static stress on the refractive index of glass, quartz, or other transparent material. To the writer's knowledge, this method has never assumed a practicable form. It is of interest as a possible method, and might be applied to measuring the maximum effect of the almost instantaneous changes of pressures in a circuit due to lightning, short circuits, grounds, etc.

*Professor Ryan proposes in his paper read before the Institute in March, 1904, on "The Conductivity of the Atmosphere at High Voltages", the use of wires arranged in such relation to each other that the maximum voltage values impressed on them can be determined by the coronal formations noticed when viewing them in the dark.

†Pockels—Mechaniker; Vol. 7, p. 29.

Method Employing Condensers in Series, the Voltage Being Measured Across One or More.

The fact that condensers, when grouped in series, divide the total impressed pressure among themselves inversely as their respective capacities has been made use of as a means of high-pressure measurement. Puekert† proposed to use a series of condensers of equal, or proportional, capacities and an electrometer in shunt with one of the condensers, as an effective means for high-pressure measurement. Others have proposed to utilize an electrometer in shunt with one condenser, and keep its indication constant by varying a standardized condenser in series therewith as the pressure value changed. The use of static indicating instruments in series with condensers, standardized so as to be direct reading, is a modification of this same principle.‡

Attention has been called by Dr. Benischke to the fact that all condensers placed in series with electrometers or static voltmeters should have the same dielectric material, otherwise there would be a serious error upon change of wave-form or frequency, caused by the difference in electrostatic hysteresis or lag—of various materials. He proposes the use of air condensers for connection to electrometers in suitable relation. This method, if properly arranged, should give very good results. Care should be taken to see that little or no change in the apparent capacity of the condensers takes place, either by change in the proximity of adjacent objects, or leakage over the insulation. This method has not heretofore been used as much as its good features warrant.

Method Employing Electrostatic Meters.

Theoretically this is the ideal method of high-pressure measurement. Up to the present time it has not been as satisfactory a method in practical development and application as is desirable for commercial conditions. Of the meters developed along this line, those of Lord Kelvin are the best known. A

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†*Electrotechnische Zeitschrift*, September 29, 1898.

‡Benischke—*Elek. Zeit.* March 21, 1901.
Jona—*L'Eclairage Elect.*, June 3, 1901.
Barnett—*Electrical World and Engineer*, August 26, 1899.
Franke—*Wiedmann's Annalen*, —— 1893.
Merchant and Worrall, *Electrical Review*, November 13, 1903.

number of others, varying in detail, have been used with more or less success.

The fundamental difficulty encountered in developing this type of instrument for high-pressure work has been the failure to use an insulating medium of sufficient dielectric strength. This has necessitated a great separation of the operating elements, and a correspondingly great reduction in the actuating forces. The great separation of the elements makes the instrument particularly susceptible to external influences such as charges from adjacent objects, etc., and the weak actuating forces make necessary a sensitive, delicate mounting for the moving system. The form of the scale for most of the direct-reading meters has been very poor, there being but a slight movement of the pointer over an unproportional scale. Lack of proper damping of the moving element has rendered the reading of the instrument very difficult on circuits with even slight fluctuations. For very high pressures the size of this type of meter renders its construction costly and cumbersome. The fact that this principle of operation gives a meter that requires for its operation a negligible amount of power, that is free from the effects of variation of wave-form, frequency, etc., and is direct reading, makes it an attractive principle on which to attack the problem of developing a good high-pressure indicator.

A new type of static voltmeter, which will now be described, it is believed, will eliminate, at least in a large measure, the faults to which other high-pressure static instruments have been subject.

New Type Static Voltmeter.

The most important improvement embodied in this new static voltmeter consists in the method of its insulation, which is obtained by surrounding the active parts of the meter with a medium of greater dielectric strength than atmospheric air. Such a medium is supplied by various liquids, and by gases under pressure; in some instances it is advantageous to work the liquids under pressure. The advantages that result from this method of insulating static meters can be briefly summarized as follows:

Advantages common to both compressed gas and liquid insulation:

(a) A great reduction in the distance between the operating elements of the meter of different potential, and also between these elements and the case, thus permitting reduction in the size of the instrument.

(b) A great increase in the actuating forces due to the reduction of distance between active parts.

(c) A much better form of scale for reading the pressure values is made possible by the reduction of distance between the active parts of the meter. The nearer the moving element is placed to the stationary elements or plates, the better can the shaping of the plates be made to control the form of scale.

(d) The improved insulation and reduction in size permits the use of a metallic containing case which screens the instrument from external charges. It also makes it possible to operate the instrument on circuits that are grounded without any appreciable variation in its readings from those taken on ungrounded circuits of the same pressure.

The following additional advantages are gained by the use of the liquid insulation.

(e) It acts as a damper and renders the instrument nearly dead-beat, thus making it very easy to read.

(f) Having a higher specific inductive capacity than air, it gives a corresponding increase in the actuating forces.

(g) By properly shaping the moving system, making it hollow, etc., a buoyancy is obtained which relieves the bearings from the weight of the moving element. This greatly assists the restoring force in bringing the system to the proper position of equilibrium for each particular condition.

The improvements above mentioned have been found to exist in the meter which the writer has developed, one form of which will now be described.

The operating elements are immersed in a specially treated insulating oil. The general arrangement of the terminal plates, moving element, etc., is shown in the diagrammatic sketch, Fig. 8.

The terminal plates, T_1, T_2, are so arranged with regard to a moving element, M, that an angular deflection of M, in a positive direction, tends to shorten the gaps between it and the terminal plates. The induced charges on the two extremities of M are of such a nature that they exert forces of attraction on the charges of the terminal plates T_1, T_2, which bring about such a movement. The turning of M is restrained by a spring, while the amount of deflection is read on a scale, S, by the movement of the pointer P. The curve of the plates T_1, T_2, shown in the sketch is purely diagrammatic; it is found advantageous in practice to use another form of curve which gives a very uniform scale over a large part of its range.

Two or more moving elements can be used to advantage for different ranges of pressure; the ones for the higher pressures have a less spacing between the cylindrical extremes of the moving elements so as to give them greater gap openings to the plates. The form of the moving element, and its supports, pointer, etc., are shown in Fig. 9.

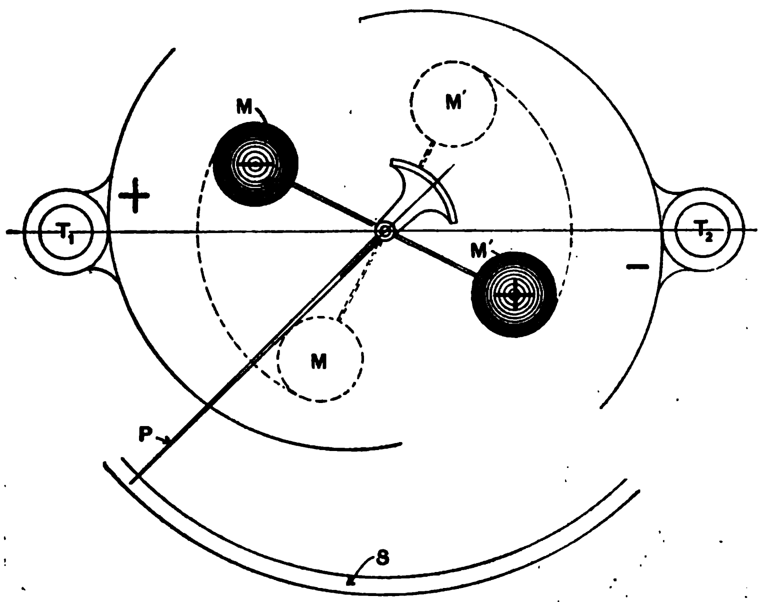


FIG. 8.

An additional moving element is shown in the right-hand side of the view. This one is used on higher pressures than the one mounted in the support on the left. The bearings, springs, adjustments, etc., are similar parts to those in use in electrodynamometers. The terminal plates are supported from the same insulating base that carries the moving element, and are supported in such a manner that they are always in constant relation to each other. The connections to the plates are made through separate insulating bushings.

The cylindrical parts of the moving element shown in Fig. 9 are provided with spherical ends which make them tight. They

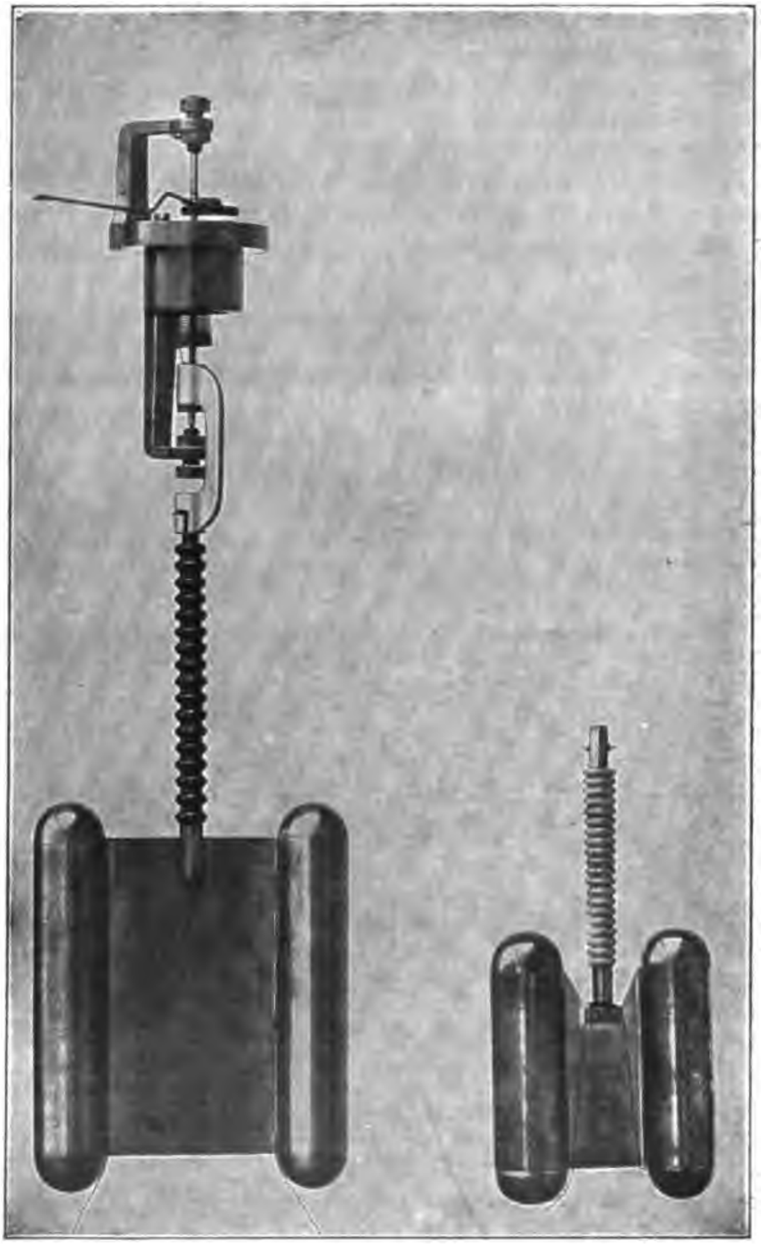


Fig. 9.

are so proportioned as to be almost buoyant in the particular oil employed.

The counter-balance adjustment is not shown in the photograph, but one has been found desirable so as to have the instrument balanced about its vertical axis. When thus balanced, no leveling of the meter is necessary. If not balanced, a small error, the amount of which depends on the imperfectness of the balance and the displacement from level of the meter, will be found in the readings.

A specially-selected torsion spring is used to supply the force against which the electrostatic forces operate and which serves as the standard of comparison. The amount of displacement of the moving system is read on a scale over which a pointer passes, the pointer being rigidly connected to the moving element.

The scale is placed on a cylindrical form similar to that of the horizontal edgewise type of instruments so well known. This arrangement permits the instrument to be read from a safe distance. In general two scales are placed on each instrument, one of proportional parts and the other to read directly in kilovolts. The proportional scale is found to be of great use in calibrating the instrument; it can also be used to advantage with other moving elements which may be used for various scale ranges in pressure.

In calibrating the meter the uniform practice has been followed of first determining the actual neutral position of the moving element. with regard to its plates. This is found by trial, pressure being applied and the direction of rotation noted. After determining the neutral position, from which the moving element will deflect in either direction according to which way it is slightly displaced, it is moved through a standard angle in the direction it is finally to deflect upon application of pressure. This practice makes it possible at any time to check the correctness of the angular position of the moving element with regard to the terminal plates, scale, and pointer. Troubles due to attractive forces between the needle and the scale support and cover are avoided by metallically connecting all of them and thus keeping them at the same potential.

The scale cover is all metal, except the glass window through which the scale is read; the cover acts as a screen to prevent external static fields from affecting the pointer. The containing case is of metal, and with it grounded or not the instrument operates equally well.

One of these meters, of which Fig. 9 is a photograph of the moving element, has been in successful operation for several months in one of the testing departments of the Westinghouse Electric & Manufacturing Company. Its case and insulation were designed for 35 000 volts service but no difficulty has been experienced in subjecting it to 50 000 volts. It has been tested to 79 000 volts, a suitable barrier being used to prevent a disruptive discharge from terminal to terminal, before a breakdown occurred. The form of scale can be seen in Fig. 10.

It will be noticed that the scale is very good from 5 000 to 25 000 volts, and no difficulty should be experienced in reading to the one-tenth part of the divisions over that range. The upper part of the scale from 30 000 volts up is very poor, but this could readily be remedied by a change in the form of the terminal plates.

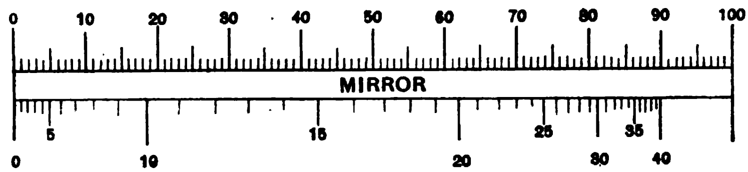


FIG. 10.

It is feasible to get an angular deflection of 90° with the pointer. The scale form given in Fig. 10 shows an angular deflection of 81° at 40 000 volts. This scale was started at 10° in the positive direction from the neutral point. The standardization curve is shown in Fig. 11.

This curve is the one from which the scale form, Fig. 10, was determined. It was obtained by reading the static meter on the proportional-part scale at various impressed pressures. The value of these pressures was determined by ratio, a Weston voltmeter being used on the low-pressure side of the step-up transformer. The transformer was of 100-kw. capacity at 100 000 volts and the curve is the result of a number of observations made at different times. These points when plotted were all very close to the curve shown, not varying more than the width of the line. Readings were taken at various frequencies with the same result.

The over-all dimensions of this meter are 12 in. by 12 in. by 10 in.; the terminals project to an additional height of 7 in.

above the top of the case. When filled with oil it weighs about 45 or 50 lb. and is readily moved by one person.

This form of meter is intended primarily for testing purposes, and it is believed it will be found to be very satisfactory

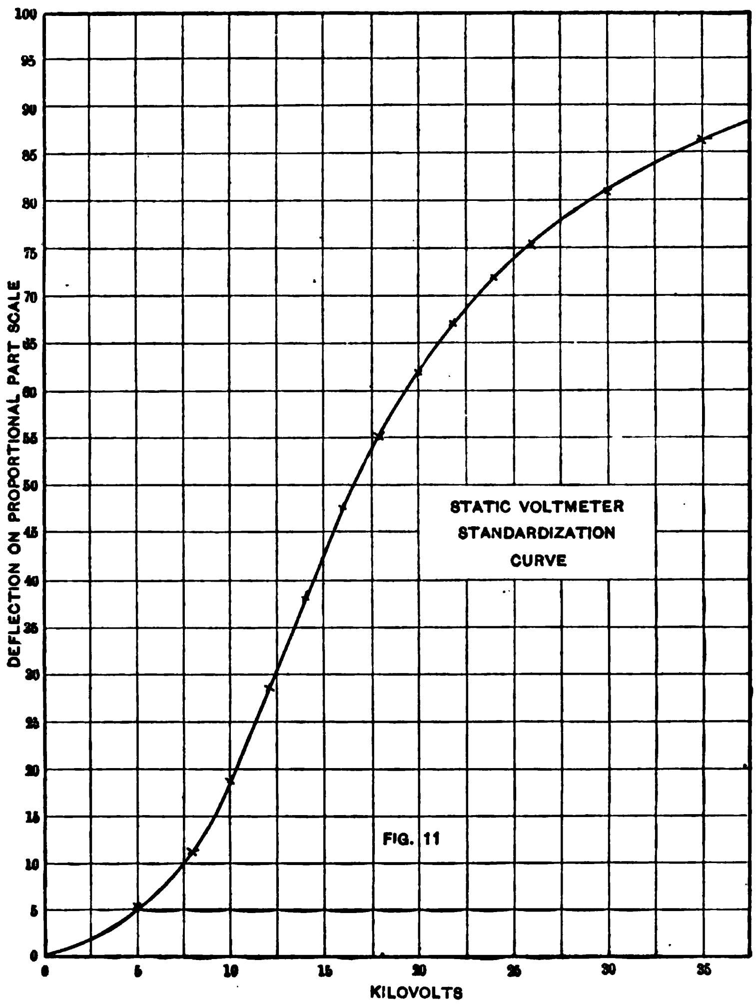


FIG. 11.

in such service. At the present time none of this type has been designed for pressures higher than 100 000 volts, but modifications are being made in the particular meter shown in Fig. 9 to enable it to be used in some 150 000-volt tests, this meter being considered to be the most reliable device for determining the test pressure on some very large transformers. There seems to be no good reason why meters of this type should not be used on pressures of 200 000 volts or even more.

Two publications have appeared, since the meter above described was constructed, in which descriptions of oil-insulated meters of the attracted-disc type were given. One of these in the *Electrical World and Engineer* by Mr. Semenza described a meter designed by Mr. Jona, and the other by Professor A. Grau in the *Elektrotechnische Zeitschrift*, March, 1905, was descriptive of a form devised by himself.

Like most high-pressure problems, the insulation is the chief factor, and it is believed that the limit of pressure for voltmeters of this type will be the same as that for the transformers.

DISCUSSION ON, "METHODS OF MEASUREMENT OF HIGH ELECTRICAL PRESSURES."

CHAS. P. STEINMETZ: I have been much interested in investigations of high potentials, and must confess I have always been prejudiced against electrostatic voltmeters, possibly because of some disastrous experiences with early forms of such voltmeters, that were liable to be 25 or 30 per cent. in error without giving indication thereof. Therefore I have always preferred the method of measurement by step-down transformer and the low potential voltmeter, or for very high voltages by ratio of transformation with step-up transformers, with a careful investigation of the high-potential circuit, to see whether there could be any deviation from the correct ratio by capacity effects and how much that might amount to.

The advantage of the step-down transformer is that it cannot well be wrong: the ratio is definite and unchangeable, or where several low-tension coils are used, connected in series or multiples, there may be a factor of 2 or 4, which, however, is not liable to cause an error since it can be noticed or easily checked by the spark-gap, and a low-potential voltmeter is an instrument very easily checked by comparison with other voltmeters. My objection to the electrostatic voltmeter has essentially been based on the undesirable characteristics of such an instrument in former times; these characteristics were, I believe, chiefly due to the fact that the step-down transformer method was quite sufficient for most purposes. The need and demand for an electrostatic voltmeter for engineering purposes and for scientific laboratory purposes was rather limited and therefore less energy was devoted to the development of such an instrument—less than was devoted to the development of the low-potential voltmeter. It is, therefore, gratifying to know that such an instrument has now been developed which promises to be reliable.

We must, however, consider, that at least for high-potential testing operations under the specifications of the Institute, not the voltmeter, nor the rate of transformation, but the spark-gap is the ultimate court of appeal. That is, if the apparatus is to be tested, say at twice the rated voltage, then, if the static voltmeter or the step-down voltmeter checks with the spark-gap at that voltage, the spark-gap is right; if the voltmeter and the spark-gap disagree, the spark-gap is correct, and not the voltmeter. The reason is that the purpose of the high-potential test is to expose the apparatus to a definite high-potential dielectric stress. If there is an absolute sine-wave of high-potential testing voltage, then the voltmeter and spark-gap will agree, but if the voltmeter and the spark-gap do not agree, and both are correct in their readings, then that shows that the wave differs from a sine-wave, and the electrostatic stress is different from that which corresponds to the sine-wave of the voltage; therefore a test of this voltage would expose the apparatus to a stress different from that specified. It is well known that the standard requires a test at a definite voltage, with a sine-wave of electromotive force, or at such voltage which gives the same striking-distance, as a sine-wave of the specified voltage. This feature has been considered because it is liable to be overlooked. The correct way is to use the sine-wave, but it is not always possible on the high-potential side of the transformer to get an exact sine-wave.

Where the wave differs from the sine form, then the voltmeter gives a quantity which is the true effective voltage, but not the measure of the electrostatic stress desired, according to specification, to expose the apparatus, and so the voltmeter is to be checked by the spark-gap. Now, the spark-gap, between needle points, is exact and reproducible within 2 to 5 per cent. according to the conditions and care of the observer. There are, however, some precautions to be observed. First, I believe in the insertion of non-inductive resistance in series with the spark-gap, so that the discharge does not produce a destructive oscillation. Such a resistance must, however, be relatively low, so that there is no appreciable drop of voltage in the resistance by the current that passes across the gap, a current that is quite appreciable. A moderate resistance will dampen out oscillations due to the discharge with sufficient rapidity to guard the apparatus against excessive stress by oscillating discharge. Secondly, I do not believe that shields are permissible. It may be possible, with the use of the shielded spark-gap, to draw out a curve which may be used as a measure, but the use of shields does not permit of the use of the sparking distances given in Appendix V of the Standardization Report, as can easily be seen when one considers the equipotential surfaces of the electrostatic system between the two points of the spark-gap and the surfaces of constant potential gradient which are most important. This I intended to show in the paper which I promised for this meeting, but unfortunately was not able to complete, since some tests which I desired could not be completed in time, due to the high-potential, 500 000-volt transformer burning out a coil, as occasionally happens with such transformers. If these potential-gradient surfaces are investigated, it will be seen that the shield modifies the electrostatic surfaces between the needle points, and so modifies the striking distances. It appears to be essential, therefore, that the needle points must be unshielded, and stretching back a distance greater than the actual striking distance—very much greater indeed. Furthermore, one feature I have had to guard against especially is to have in this spark-gap loose contacts which may produce an arc, and thereby an oscillation of extremely high frequency, the voltage of which will have no direct relation to the impressed voltage of the step-up transformer, and the spark-gap may breakdown at an impressed voltage lower than the voltage at which it is set, that is, a voltage will be produced at the gap higher than given by the transformer.

This can easily be found by having a spark-gap set for, say, 50 000 volts, and connecting it with a 40 000-volt circuit. The spark-gap at the moment of making connection, usually breaks down although set for 25 per cent. higher voltage. So the spark-gap must be guarded against becoming itself the seat of a high-frequency oscillation. With these very reasonable precautions, the spark-gap is the most reliable check for measurement. As Mr. Kintner very properly says, it is not a measuring instrument, but a check. If the electrostatic voltmeter as developed here, is of perfect reliability it is of the greatest value for testing, if checked by the spark-gap.

SAMUEL SHELDON: I have been engaged for a number of years in experiments upon large Holtz machines and have endeavored to make use of the condenser drop method which employs an ordinary electrostatic voltmeter. It is very unsatisfactory, for the reason that dielectric hysterisis causes a continuous variation in the capacity. With condenser conductors varying in size and shape from each other the various sheets of dielectric between them are subjected to different electrostatic flux densities. A little leakage into surrounding kerosene oil frequently, if not continuously, takes place and therefore the voltage drop over each sheet of dielectric of the condenser varies even though the voltage impressed upon the whole condenser remain constant. I have also found that the spark-gap voltage measurement is very much influenced by the presence in the vicinity of the gap of other parts of the conducting circuits or of conductors not directly connected in the circuit as may easily be expected.

C. O. MAILLOUX: I think that all who have had experience with high potential measurements, must agree with Mr. Steinmetz, that, after all, the court of appeal must be the spark-gap method. The author says, at the top of page 434, in reference to Fig. 7. "It will be noticed that the curves are very regular." The implication is that, as these curves differ from the curves shown in the previous figure, the other curves are irregular. Now, I must say that to me it seems that if there be any irregularity, it must be in Fig. 7. As Mr. Steinmetz has said, the effect of shields is simply to vary the striking distance. Fig. 7 illustrates a case where the striking distance has been changed, the effect being to change the scale or the size of the curve. I think that the curves shown in the early Figs. (4, 5, 6), are the regular ones. There is a physical reason why these curves should have that mathematical form, which, while it is not a form to be found in the standard works on analytic geometry, for instance, is, nevertheless, a regular form. It is not an irregular curve although it may seem to be one. It is a curve capable of being perfectly formulated. While we do not know all about all the different possible curves, nature knows more about them than we do, and there are reasons why nature "selected this" particular form of curve. I will endeavor to give a hint for such reason.

The curves with a hump in them, Figs. (4, 5, 6), express the well-known fact that for very short gap distances it takes a relatively large potential before the spark will occur. As the distance is increased, the *relative* increase of potential required diminishes; in other words, the differential coefficient of the curve diminishes, and for a certain · ·nge of the gap, it does not take as large an increase of potential to cause the current to strike across the gap, as it did at first; but eventually a point is again reached where the potential must increase faster than or at least as fast as the gap. It can readily be seen that this must be so. Assume a case like Fig. 7. The curves in this case have the form of what may be called a " standard parabola ". It is also a fact, that the other curves are parabolic curves. Fig. 7 contains a curve that is entirely, or almost entirely, concave with respect to the axis of x. In the other case there is simply a curve which is partly concave and partly convex. What is the reason? Mathematically, the reason is simple. This curve is simply the product of two curves of parabolic type, one of which has a very low exponent, or an exponent *less* than unity, and the other an exponent *greater* than unity. Algebraically, it would be put thus:

$$y = b\,x^n + c\,x^m$$

where $n < 1$ and $m > 1$, both having the positive sign. The first term represents a curve that is concave to the axis of x, and the other a curve that is convex to the axis of x. On selecting suitable values for the coefficients b and c, it would be found that the two curves make exactly a curve like this.

Instead of proceeding that way, the curve can be expressed in still simpler form by saying $y = b\,x^n$ with an exponent that is a function of x, the function of x ranging between zero and some function that is greater than unity, or $y = b\,x^{f(x)}$. I do not know which of these two curves it is, from a casual glance, but it is certain that here there is a *composite* parabola. These composite parabolas are constantly met with in nature. I have found numbers of instances where phenomena can be readily interpreted in terms of composite parabolas. It must be so in this case, for it will readily be seen that a curve like Fig. 7, which remains constantly concave to the axis of x, eventually reaches a point at which the potential would virtually cease to increase, the curve becoming asymptotic to a line parallel with the axis of x. There would be a point reached at which any given finite increase of potential will jump an indefinitely long gap between the two points. This is contrary to what is known to be the case. There must be a distance reached finally—and that distance is reached quite soon—at which no finite increase of potential capable of being produced is able to produce a spark between the two points.

H. G. Stott: In connection with the use of the static voltmeter, experience in the use of spark-gaps may be interesting. The Interborough Company started out some years ago to make high-potential tests on cables, generators, etc., using a spark-gap as the standard. A short experience proved that it was entirely unreliable under practicable conditions of tests. It was impossible to shield the spark-gap from currents of air, which varied the sparking distance with a constant potential. Where it was necessary to expend two or three hundred kilovolts in a test we were compelled to use an ordinary commercial generator to generate that pressure. As probably everyone knows, it is physically impossible to maintain constant voltage under fluctuating load. What was found was this, that when the spark-gap was set and the test started, almost immediately afterward a very slight change of voltage of two or three per cent. would cause the arc to jump across the needles, destroying them, and the test would have to be started over again with a new pair of needles. Under these conditions it became impossible to carry out a commercial test. The company abandoned that for another method, which involved the use of electrostatic voltmeters. These electrostatic voltmeters are calibrated before and after every test. That has proved very satisfactory and has been accepted by all companies with which we deal, both in cables and other high-potential apparatus.

CHAS. P. STEINMETZ: I can answer the question asked by Mr. Mailloux. A few of these curves have been carried up beyond 300 000 volts, and at these very high voltages the curve of the striking distance, whether between spheres or between needle-points, becomes a straight line. Furthermore, I may say that I have been able to produce by calculation from mere theoretical reasoning curves of the striking distance of a similar character to those given in Mr. Fisher's paper—theoretical reasons, based merely on the assumption that the air has a definite disruptive strength, that it breaks down and becomes conductive by a brush discharge as soon as the potential gradient exceeds a definite value, which value may obviously be a function more or less of temperature, air pressure, etc.; but it is as definite as the breaking strain of a piece of metal under constant conditions. That is one of the things that I intended to bring out in my paper, and which I hope to be able to report at a later meeting.

H. W. FISHER: In a paper, which I presented before the International Electric Congress at St. Louis, it was shown that the sparking distance is very much affected by the degree of sharpness of the needle-points. By measuring No. 12 needles, I found that the points varied from 0.0001 to 0.002. At 40 000 volts, the sharp points gave a spark distance of about 2.15 in. and the dull points about 3 in. Now the idea I want to bring out is this, that if these tests are correct—they were made repeatedly with the utmost care—it is unreliable to use ordinary needle-points where accurate results are desired. My tests showed that if one of the needle-points is dull, the sparking distance will be greater than when both points are sharp, with voltages ranging from 30 000 to 50 000.

C. O. MAILLOUX: I wish to add a word to what Mr. Steinmetz has said to the effect that of course it must be assumed that there are no discharges except from the point. If there are brush discharges, or any other shifting discharges, then, necessarily, what I have said is not wholly true. I am assuming the discharges to take place from the points, and that precautions are taken to prevent discharges elsewhere, otherwise it might start, or it might facilitate an action whereby the striking distance might be reduced, and in that case it would be impossible to get an ascending line. It would either remain straight or form a line which will be asymptotic to a line parallel with the axis of x.

E. F. NORTHRUP: I appreciate that the electrostatic voltmeter is a measuring instrument of precision, but I would like to ask Mr. Kintner how the scale of the instrument was calibrated to as high as 40 kilovolts. If the wave-form of the current used in the calibration were a sine-wave form, it seems to me he would have obtained a different scale than would be the case if the wave form were different from the sine form. I would be obliged if he would explain what standard he used to calibrate his scale.

CHAS. A. PERKINS; The chief interest in this apparatus is connected with its use for high pressures. I wish, however, to ask whether it can be used for ordinary pressures such as 2 000 volts?

The question suggests itself whether two needle-points resting in cups as close together as here described will accurately center the moving parts. In this form of bearing there is usually some play, and in the design here shown it would seem that this effect might be quite appreciable.

CHAS. P. STEINMETZ: In the tests referred to, there were no side discharges or brush discharges except the brush discharge that always precedes the discharge between the needle-points, and therefore is an essential part of the phenomenon.

S. M. KINTNER: Replying to the last question first, in regard to the possibility of using such a type of meter on low-voltage circuits: while it is certainly possible, there is, in general, not so much need for it there as in the higher voltage service.

Regarding the question of difficulty with the bearings, no special difficulty has been encountered with the form shown in Fig. 9. The fact that the moving element is buoyant, greatly reduces the wear on the bearings. If found desirable to do so there is no reason why the lower bearing could not be placed below the moving element. This would give very great distance between bearings and reduce the movement of the element due to the looseness of the pivots in their seats. No difficulty has been encountered from the amount of movement which the present arrangement allows. No doubt this is due to the arrangement of the respective parts which makes the displacement of the moving element to one side unimportant, as the increase in the force on one side is approximately equal to the reduction of the force on the other.

The meter was calibrated by placing it on the high-tension side of a large step-up transformer, on which a standard voltmeter was used to read the voltage on the low-tension side, and the low-voltage values multiplied by the ratio of transformation for comparison. Power was supplied from a generator giving a very close approximation to a sine-wave as determined by an oscillograph. The static meter reads effective values just the same as all alternating-current voltmeters.

I am much indebted to Mr. Mailloux for his discussion of the spark-gap curves shown in the paper. The work done in determining them was very interesting, but from the standpoint of one desirous of using the spark-gap as a measuring instrument it was not so pleasing. No effort was made on my part to determine an equation for them, as I found it necessary to run a curve every time I desired to use the gap and as nearly as possible under the exact conditions of the contemplated test. The great variation from day to day suggested to me that I did not have all the variables under my control. There is material for some very interesting research work in connection with the spark-gap and its eccentricities.

Regarding the use of low resistance in the spark-gap circuit: as suggested by Mr. Steinmetz, it has been my experience that when the resistance is low enough not to affect the gap it is too low to limit the current to a reasonable value. My experience with the spark-gap has been such that I invariably have a feeling of doubt after having made a measurement as to what the real voltage value was. It may have been anything within 50 per cent., high or low, from the value obtained.

The type of meter described in my paper is intended primarily for testing purposes, particularly for insulation testing of machines, transformers, cables, etc.

Regarding the use of step-down transformers, as preferred by Mr. Steinmetz, their use is allowable within limits, but as soon as higher voltages are reached the step-down transformer becomes a formidable piece of apparatus. A transformer for a voltmeter for 50 000-, 60 000- or 70 000-volt service will have a rating of 15, 20, or 25 kilowatts.

CHAS. P. STEINMETZ: It is practically duplicating the apparatus.

S. M. KINTNER: Practically; it becomes a very cumbersome piece of apparatus.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers. Asheville, N. C., June 19-23, 1905.

COMMENTS ON REMARKS MADE BY COL. R. E. B. CROMPTON BEFORE THE INTERNATIONAL ELECTRICAL CONGRESS AT ST. LOUIS.

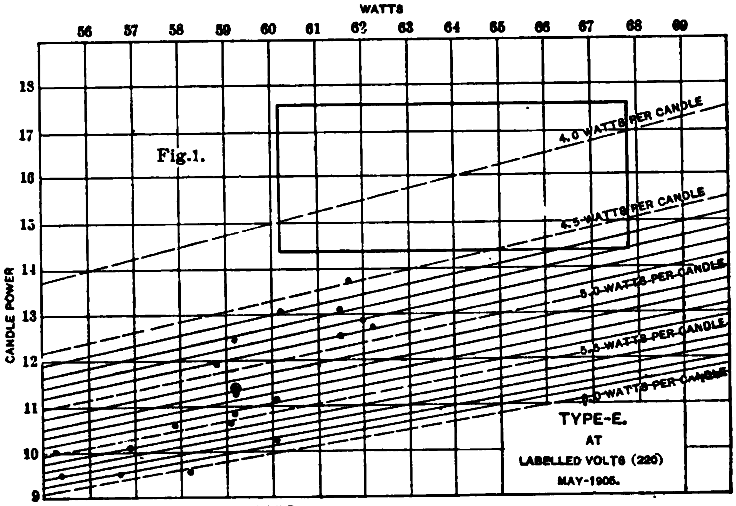
BY JOHN W. HOWELL.

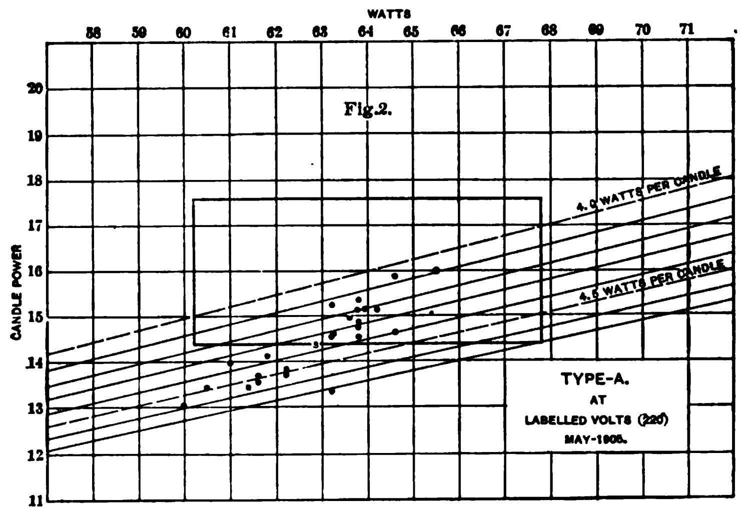
The following quotation is from the remarks made by Col. R. E. B. Crompton in his discussion of the papers read by Mr. Torchio and Mr. Dow, at the International Electrical Congress at St. Louis, last September.

" In England our variety of distribution systems is not so great as we find here. We started with three-wire 200- or 220-volt systems, distributing at 110 volts. We have everywhere practically doubled this voltage. All our largest cities in England, including London with its 6 000 000 inhabitants, after very careful consideration, practically adopted what you have called the double-voltage system. This doubling the voltage was not adopted without a struggle. For a long time the lamp manufacturers opposed it, and told the consumers, probably with some reason, that they would be at a disadvantage, as lamps of the double voltage could not be made so efficient as lamps at the single voltage; but we showed that this could be remedied by refinements in lamp manufacture, so that now it would be very difficult for the consumer to find that he was at any practical disadvantage on account of inferior efficiency of the double-voltage lamps."

" The result is that the majority of our consumers take their supply at pressures varying from 200 volts in London up to 250 volts in Glasgow. We therefore consider this question settled and therefore completely disagree with all the arguments on this point in both Mr. Torchio's and Mr. Dow's papers."

These remarks indicate that either the English makes of 220-volt lamps are very much better than those made or known in this country, or that English makes of 110-volt lamps are very much inferior to those made here, or that the considerations and conditions, other than the difference in quality of the two types of lamps, which effect the choice of one system or the other are different in the two countries.





As a lamp engineer seeking all available information on lamps, I recently secured samples of the best known makes of 220-volt lamps on the English market, thinking that the very extensive use of such lamps there had led to the development of a better lamp than that produced in this country. I here present data on tests which I have made on these lamps, and also

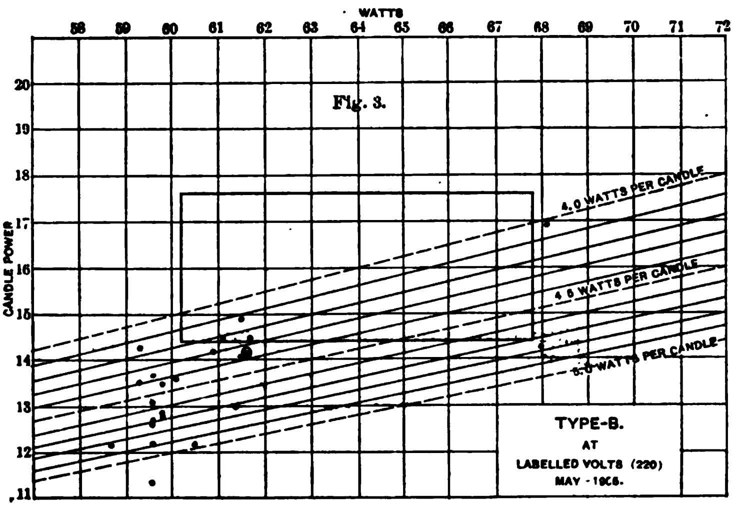


Fig. 3.

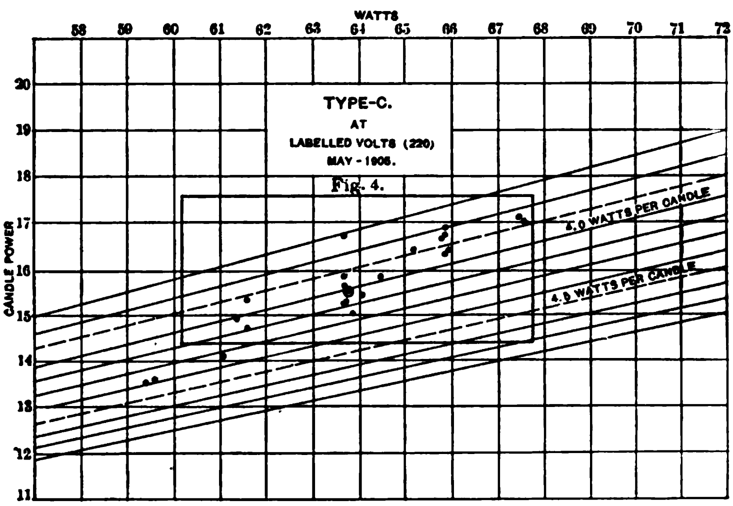
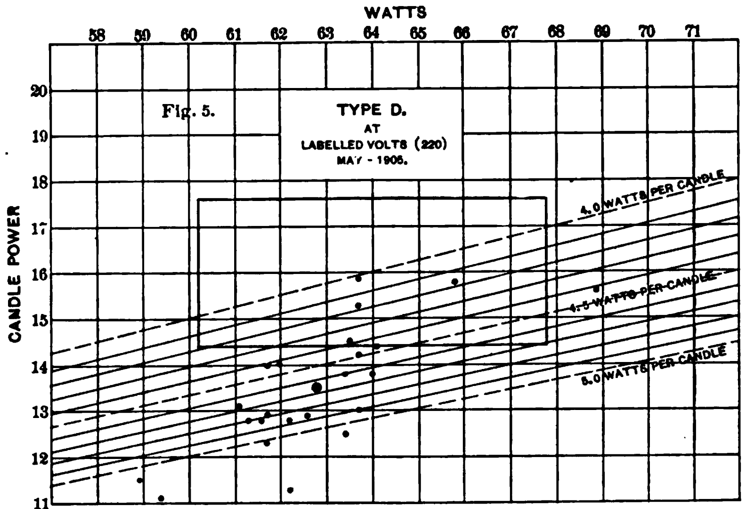
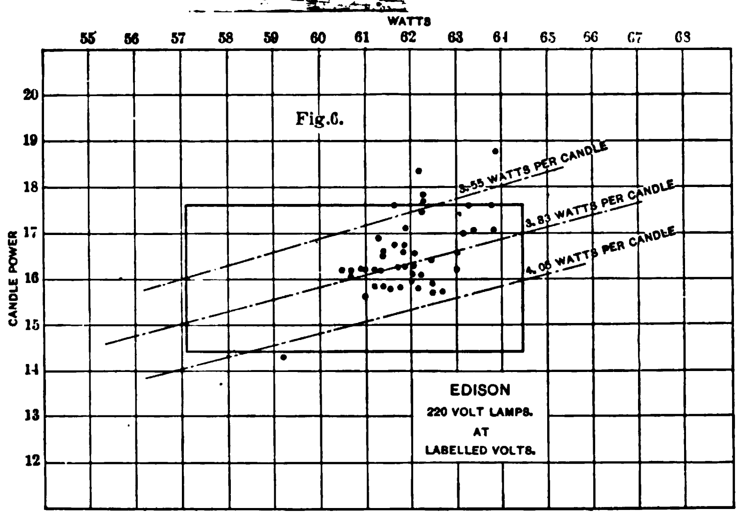


Fig. 4.

similar data on tests made on American-made lamps.

I obtained 25 of each of these five makes of lamps, Sunbeam, Stearn, Royal Ediswan, Robertson, and Cryselco, my letter to our English representative asking for samples of the best-known lamps on the English market. All these lamps were labeled 220-volts, 16 c-p. All of them were photometred at 220 volts; the results are shown in the target diagrams. These





diagrams show a very great lack of uniformity in the individual lamps of each make, and a tendency to low candle-power and high watts per candle. The average of each group is indicated on the diagram by a small circle.

These averages are as follows:

	Candles.	Watts per candle
Make C................	15.5	4.00
" D................	13.5	4.65
" B................	14.3	4.33
" A................	14.5	4.37
" E................	11.4	5.20

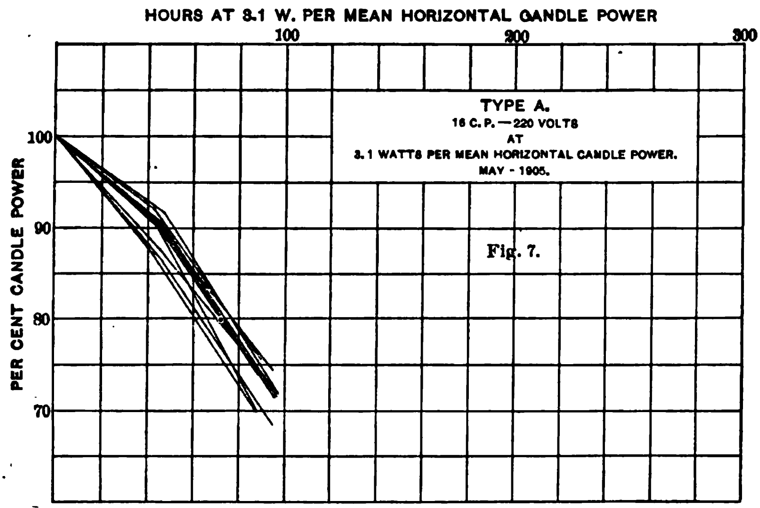


Fig. 7.

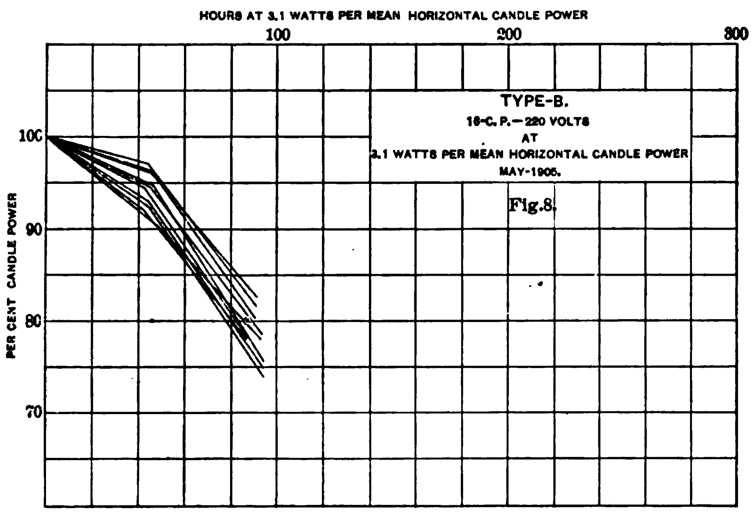


Fig. 8.

These are supposed to be 16 candles, 4 watts per candle.

For comparison with these I reproduce here a similar diagram made on Edison lamps—220 volts—4 watts per candle which I take from a paper read by Mr. F. W. C. Bailey before the National Electric Light Association, May 1902. Mr. Bailey obtained these lamps on the open market through a supply house. These lamps average 16.2 candles, 3.83 watts per candle, and

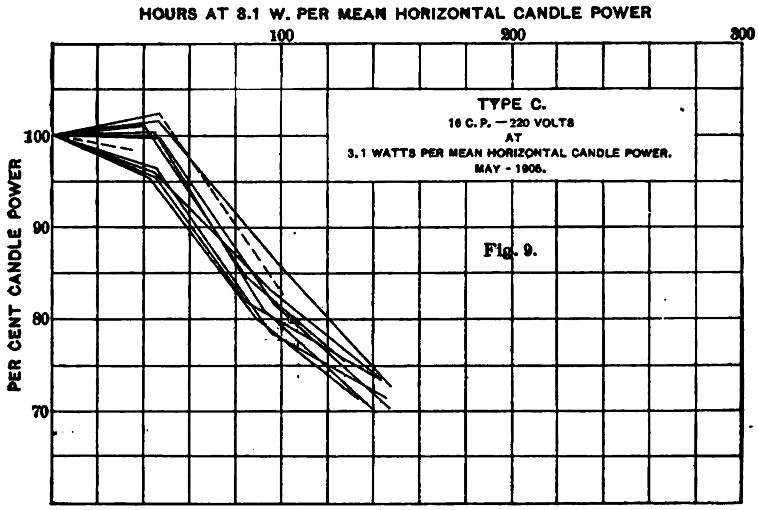


Fig. 9.

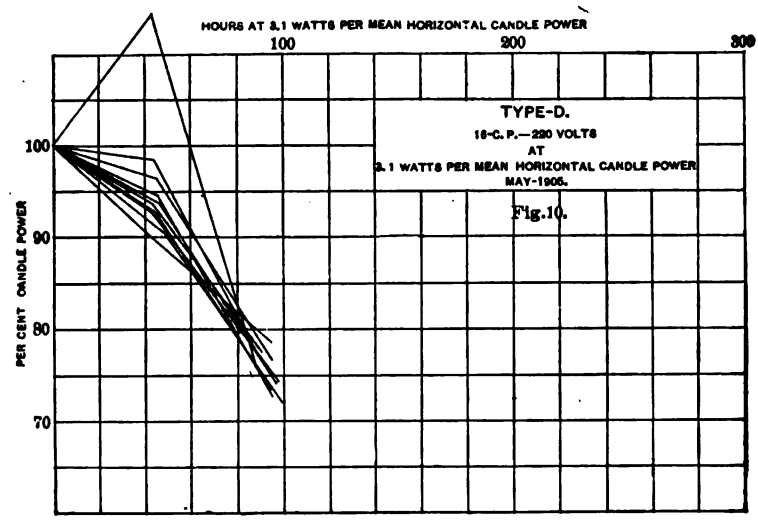
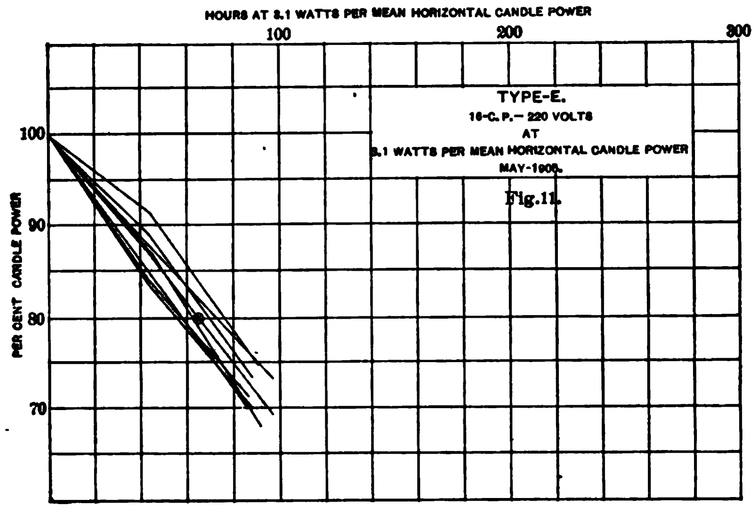


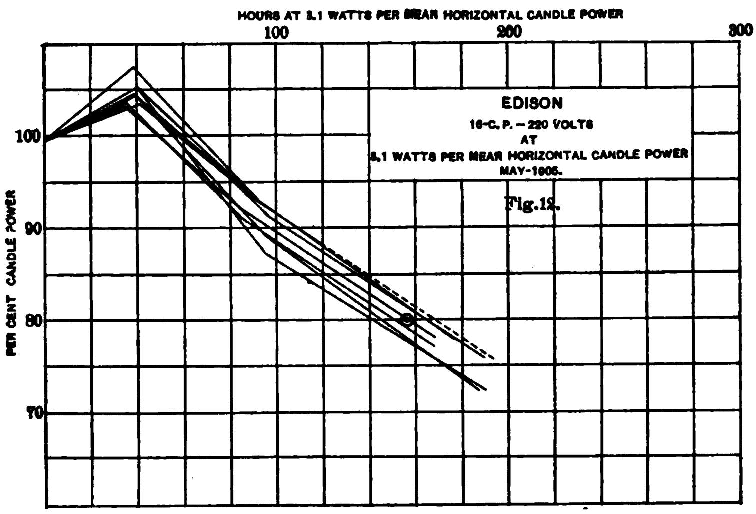
Fig. 10.

show very much greater uniformity of candle-power than the English lamps.

The rectangles shown in these diagrams indicate the limits within which these lamps must come to meet the requirements of the American market.

To determine the quality of these lamps, 15 of each lot were set up for life-test. In order to make this comparison fair all were set up at the same watts per candle, all were set up at 3.1 watts per candle as the lamps were received in May and it





was necessary to set them up above their rated efficiency in order to finish the test in time for this meeting.

For comparison with these I set up at the same time and under the same conditions lamps of our own make and rated the same as the English lamps. These lamps were taken at random from our own stock, no selection being made.

The results of these tests are shown in the diagrams showing loss of candle-power and time of burning. The lamps in each lot were quite uniform. The average results are as follows:

Make C	104	hours	to	80	per	cent.
" B	88	"	"	"	"	;
" E	65	"	"	"	"	
" D	82	"	"	"	"	
" A	72	"	"	"	"	
" Edison	156	"	"	"	"	

These results indicate that the Edison lamps made in this country are 50% better than the best make of English lamps of this type, and nearly twice as good as the average of the other makes tested.

These samples may not fairly represent the average quality of the different makes of lamps but the uniformity of the lamps in each lot indicates regularity in manufacture. The total result certainly indicates that the American-made 220-volt lamps are not inferior to those on the English market.

Regarding 110-volt lamps which are the standard for central-stations in this country. The Association of Edison Illuminating Companies purchases several millions of these lamps each year; all of these are inspected and samples are regularly tested for life.

These inspections and tests are made by the Electrical Testing Laboratories in New York. I have obtained from them the target diagram of Edison 3.1-watt, 110-volt lamps. They give it as a fair sample of these lamps at the present time.

The curve showing loss of candle-power with time for this class of lamps represents the average result obtained on 5 488 lamps tested for life during the year ending May 1, 1904. This shows 512 hours life to 80 per cent. The average efficiency of these lamps was 3.14 watts per candle, correcting this to 3.10 watts per candle gives the useful life to 80 per cent. to be 480 hours, which is over three times the useful life of the American 220-volt lamps and over five times the useful life of the average of the English 220-volt lamps tested.

At any efficiency other than 3.1 watts per candle, the relative values of these various lamps would be the same, so it may be said that at any efficiency 110-volt lamps are at least three times as long lived to 80 per cent. as 220-volt lamps.

It is our experience, based on many tests, that 110-volt lamps of 3.1 watts per candle and 220-volt lamps of 3.8 watts per candle have equally useful lives.

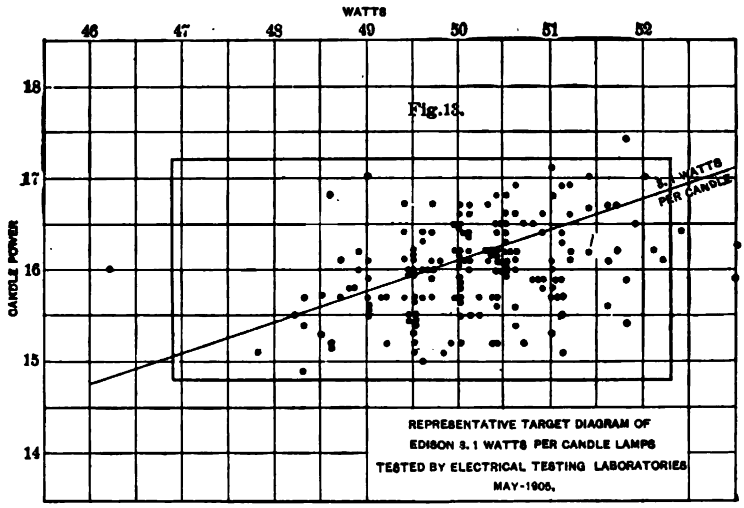


Fig. 13.

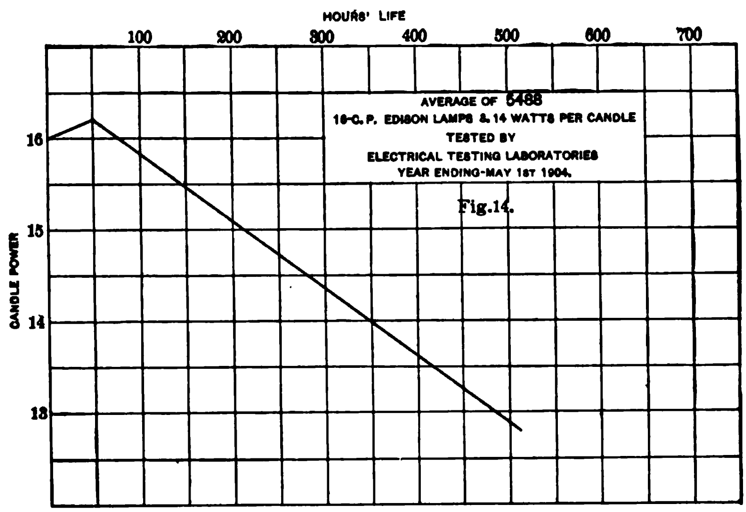


Fig. 14.

It is the custom in England for the consumer to purchase his lamps where he pleases, the electricity supply companies furnishing current only. Under these conditions using lamps of the same efficiency and considering them dead when they have fallen to 80% candle-power, the customer using 220-volt lamps would have to buy three times as many lamps as one using 110-volt lamps, and each lamp would cost more money.

Or if lamps of equal life were used each 220-volt, 16-candle lamp would consume 11 watts more than a 110-volt, 16-candle lamp. Assuming that both lamps last 500 hours, each 220-volt, 16-candle lamp would consume 5 500 watt-hours or 5.5 kw-hr. more than each 110-volt lamp; and with current costing 10 cents per kw-hr. each 220-volt lamp of 16 candle-power would during its life consume 55 cents' worth of current more than each 110-volt lamp.

Colonel Crompton says: "it would be very difficult for the consumer to find that he was at any practical disadvantage on account of inferior efficiency of the double-voltage lamps."

This may be true under English conditions, but in this country most large lamp consumers buy lamps on close specifications and make tests to see that the specifications are fulfilled. It is also a common custom in this country for consumers to buy samples of different lamps on the market and determine by test which makes are best. This forces lamp makers to mark their lamps very accurately for volts and candle-power, for any package may be tested in competition with lamps of other makers.

If these customs prevailed in England it would be impossible to sell such badly-rated lamps as those which are the subject of the tests given in this paper.

These tests indicate a general lack of information on the part of the English consumers on the subject of quality and performance of lamps. It is not surprising that people who will continue to use lamps so poorly rated for volts and candle-power as these are, would not appreciate the difference between 220-volt and 110-volt lamps but; English engineers should know the difference between good and bad lamps and between 220- and 110-volt lamps.

Discussion on "Some Comments on Remarks Made by Colonel R. E. Crompton Before the International Electrical Congress at St. Louis."

President Lieb: In the discussion which Mr. Howell refers to, and which took place in Section "E" of the International Electrical Congress, the question of the best form of distributing system to use hinged largely upon the question, whether the 220-volt lamp had arrived at a point where it was quite equal to the 110-volt lamp. Colonel R. E. Crompton and some of his confreres of the Institution of Electrical Engineers maintained very stoutly that this was the case in England, whereas general experience in the United States had been to the contrary, and therefore if their contention was right an explanation should be forthcoming why americans had not gone to the 220-volt × 2 system. If their contention could not be made good, evidently a part, at least, of the argument in support of their contention of the wisdom of changing to the higher voltage must needs fall. Hence the desirability of such information as Mr. Howell has laid before us in his paper.

C. P. Steinmetz: Before we leave that subject, though I do not care to discuss it, I believe it would be desirable for general information if Mr. Howell would tell us whether there is any probability or possibility that the 220-volt lamp can ever arrive at the standard of efficiency of the 110-volt lamp, or whether inherently there is not a difference in efficiency of some 20%. That is, even if the 220-volt lamp could be improved so as to have the efficiency of the 110-volt lamp, whether with the corresponding improvement the 110-volt lamp would not be more efficient. This would be of interest because the question still remains open: if these lamps are not so good as they are claimed to be, possibly they might eventually approach the efficiency of the 110-volt lamps. It would be important in deciding the question whether the 110- or the 220-volt lamp is the proper one to choose, or whether there is an inherent difference in efficiency between the two types.

J. W. Howell: In the present state of the art there is an inherent difference between the two lamps which cannot be overcome. I cannot prophesy what will happen in the future.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

THREE-PHASE TRACTION.

BY F. N. WATERMAN.

The development of the single-phase motor and the progress made toward the electrification of the terminals of the great railways entering New York City have given new interest to the discussion of the more general application of electricity to the operation of main line railways. The only line essentially of such a character which has thus far actually handled its entire traffic electrically is the so-called Valtellina line, in Italy, where high-pressure, low-frequency three-phase motors are employed. The final acceptance of this equipment and the planning of its extension to other parts of the system bring the subject of three-phase traction prominently to the front and make it especially worthy of study at this time.

Though much has been said and written upon the subject of three-phase traction, it has been for the most part speculative rather than practical, and based largely upon street-railway practice and experience. The excellent papers of Mr. de Muralt and Mr. Berg, read before the INSTITUTE, some years ago, dealt with the subject more concretely; and the adverse conclusions reached in the latter paper seem to have largely crystallized opinion in this country.

It is not the object of this paper to discuss three-phase traction in all its aspects, but to deal more particularly with specific features, and with some of the results attained and to be expected in practice.

Much of the objection that has been raised in this country to the use of three-phase motors for railway purposes finds its origin, directly or indirectly, in the question of air-gap, the assumption being made that the requirements in this respect as determined by direct-current practice are controlling and final, establishing a practical limitation not subject to review and correction by other considerations. European practice, however, does not support this conclusion; and since all engineering questions are in the last analysis matters of dollars and cents there is no obvious reason why this particular one should be an exception.

An examination of Mr. Berg's paper* shows that with a change in the assumption in this respect greatly altered results would be obtained. It seemed to the writer that no better method of bringing out directly the financial aspect of the air-gap question could be found than by a comparison on the basis of identical calculations made from the performance curves of motors having the same air-gap as is employed on the Valtellina line, and the subsequent discussion of actual results obtained in practice.

At first the writer hoped to make this comparison without introducing any other change, and then to repeat with the lower frequency employed in Italy, and thus separate these two factors; but unfortunately motor curves for this purpose were not available and therefore the figures given represent the effect of change of both air-gap and frequency. The data assumed by Mr. Berg are as follows:

A double-track road (loop) with 27 stations is supplied with power from a generating station located at a distance from the tracks. Eight trains are running in each direction; the entire distance is run in 52 minutes.

The weight of a loaded train, including locomotive = 180 tons (2000 lb.).

Weight on driving wheels = 50 tons.

Maximum drawbar pull, at 25% of weight, = 25 000 lb.

Which corresponds to a maximum acceleration of 2 ft. per second per second. (1.36 miles per hr. per second).

Distance between stops is 2560 feet.

Schedule speed is 15 miles per hour.

Maximum speed with direct current = 27 miles per hour; with alternating current = 26.5 miles per hour.

Total distance is covered in 95.5 seconds, 20 seconds is allowed for stops at each station.

* See TRANSACTIONS, AMERICAN INSTITUTE ELECTRICAL ENGINEERS, Vol. XVIII., p. 603.

Train friction assumed constant at 15.2 lb. per ton.

No appreciable grades exist and the effect of curves is negligible. Inertia of rotating parts is not considered.

Mr. Berg employed geared motors of four poles and 25 cycles, having open slots and air-gaps comparable with direct-current practice.

The calculations offered for comparison are based upon 8-pole

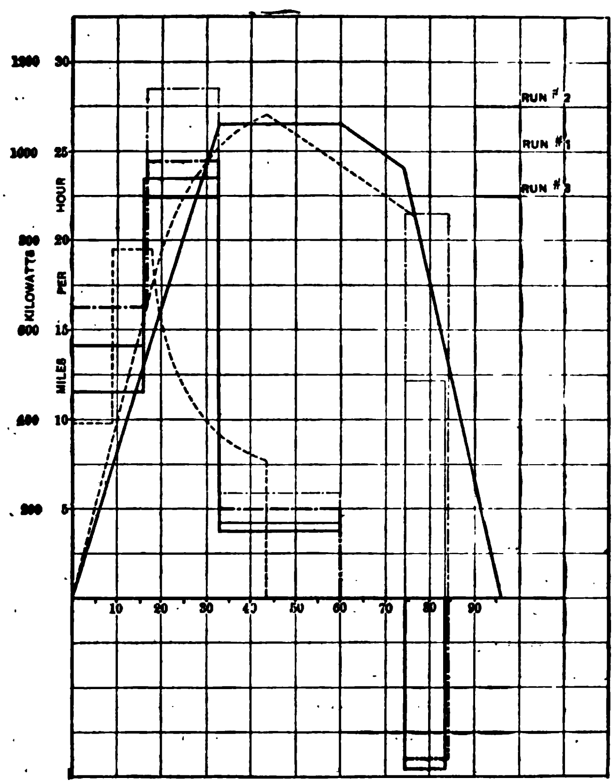


FIG. 1.

direct-connected motors and 14-cycle current. The motors have partly-closed slots and a total air-gap of 4 mm., equal to 0.079 in. clearance Only " concatenation " or cascade control, is employed, giving a speed reduction of one-half.

For the sake of direct comparison the run first taken for comparison is identical with Mr. Berg's standard run. This is indicated in Fig. 1. This figure also shows the true and apparent power inputs as given by Mr. Berg and as determined from the motor curves here used, Fig. 10. The alternating-current run is in solid lines; the true and apparent inputs, as given by Mr. Berg, are in broken lines; and those for the comparative run in solid lines. The direct-current run and input curves are given in dotted lines. Only one motor is used in running at full speed.

The ratios of power input in the two alternating-current cases are: for cascade connection 0.898; for single connection 0.917; while running 0.75, and in recuperation or cascade braking 1.069. Similarly, the ratios of apparent power are 0.613 for cascade connection; 0.829 for single connection; 0.704 for running, and 0.578 for cascade braking.

The average input as determined from the station load curve is 200 kw. and 251 kilovolt-amperes; as given by Mr. Berg it is 237 kw. and 416 kilovolt-amperes, neglecting transmission losses in both cases. Comparing these results with the results of Mr. Berg's direct-current run we find 200 kw. and 251 kilovolt-amperes for the alternating-current input, as against 190 kw. average input for the direct current.

Instead, therefore, of the alternating-current system taking "26% more power and 2.2 times as many volt-amperes as the direct-current system," as shown by Mr. Berg, we find that with the same run made in the same way but with motors having a smaller air-gap and at low frequency, the alternating-current system requires only 5% more energy and 32% more apparent energy. It should be remembered, also, that the run with alternating-current motors was made with an acceleration of 0.8 mile per hour per second, while the run with direct-current motors was made with an acceleration of about one mile per hour per second. When compared on the same basis, *i.e.*, with the direct-current run made at an acceleration of 0.8 mile per hour per sec. it is obvious that the ratio as to energy would be the other way, while that for apparent energy would be very much reduced.

Conditions of Distribution.

The motors are supplied with power at 2000 volts from four sub-stations distant, respectively, 16 600 feet, 17 400 feet, 33 800 feet, and 35 000 feet from the power-house. Each sub-station has four 500-kw., 11 000–2000 volt transformers (one in reserve). The high-pressure feeders are two three-conductor cables (of which one is reserve) of No. 0. B. & S.

gauge for each of the distant stations and two No. 3 B. & S. gauge cables for the two nearer stations. The losses and drops correspond to those given by Mr. Berg's distribution.

Station and Sub-station Load Curves. Kilowatt Run No. 3. (Losses not included).

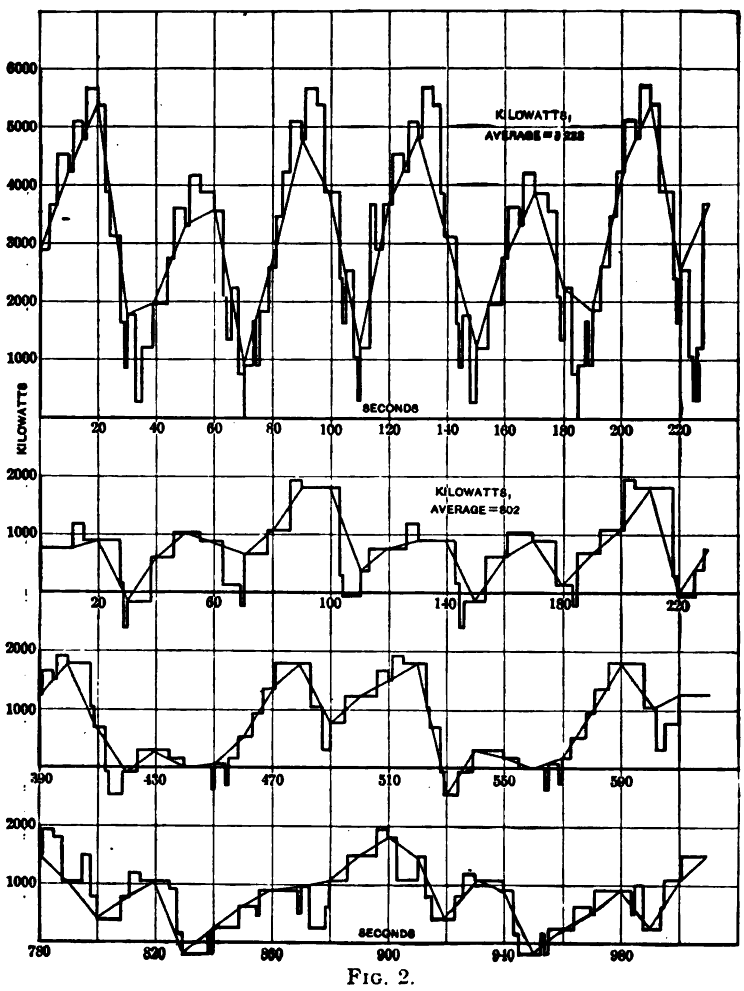


FIG. 2.

The trolley wires are No. 0000, three for each track, corresponding conductors being cross-connected. Only two wires are employed in European practice.

The generating station has five 1300-kw., three-phase, 11 500-volt generators, and five 1200-kw. engines, one set as spare.

The capacities of these units have been determined from the load curves, Figs. 2 and 3, as follows: the curves in heavy rectangular outline are the actual load curves (not including transmission losses) as determined from the time-table by point-to-point plotting, and from the maximum and

Station and Substation Load Curves. Kilovolt-amperes. Run No. 8. Losses not included).

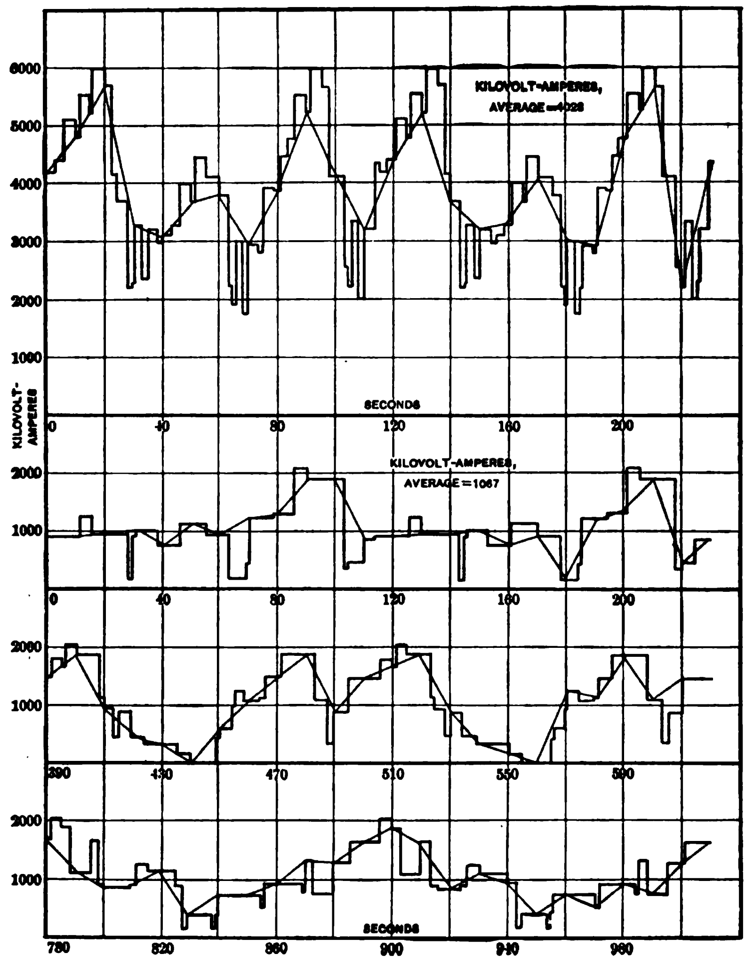


Fig. 3.

average loads indicated by the load curves the transmission lines have been calculated and capacities of electrical apparatus determined.

The curves in light lines represent approximately the load as determined by points taken at 10-second intervals, and are identical in form with those given by Mr. Berg. For the sake of corresponding ratings for central-station apparatus, the loads indicated by these approximate curves have been used, as otherwise no strictly comparable basis would exist. This is not only required as a matter of comparison but is allowable as to the steam plant as a matter of fact; for the reason that the highest peaks are of such duration that they are taken care of by the stored energy of the rotating masses, so that the steam-load peaks are lower. The generator ratings are also safe.

The true averages are:

Average power on sub-station, kilowatts	802
Average apparent power sub-station, kilovolt-amperes	1 067
Maximum power, sub-station, kilowatts	1 942
Maximum apparent power sub-station, kilovolt-amperes	2 100
Average power on generating station, kilowatts	3 222
Average apparent power on generating station, kilovolt-amperes	4 028
Maximum power on generating station, kilowatts	5 676
Maximum apparent power on generating station, kilovolt-amperes	5 990

This gives including losses:

Average kilowatt output of power station	3 510
Average kilovolt-amperes output of power station	4 320
Maximum kilowatt output of power station	6 520
Maximum kilovolt-amperes output of power station	6 822

The average load of the generators is 83% of rated full load.

The maximum load of the generators is 124.5% of rated full load.

The average load of the engines is 73% of the rated full load.

The maximum load of the engines is 128.7% of the rated full load.

These ratings are based on the approximate load curves.

Cost of Installation.

The selling prices given by Mr. Berg have been used except as to cost of transformers, which have been taken at $6.00 per kilowatt instead of at $4.50, on account of the decrease of frequency and change in size of units.

Complete steam equipment including installation, per kilowatt	$75.00
High-potential generators, switchboards and instruments, per kilowatt	26.00
Transformers (500-kw., air-blast), per kilowatt	6.00

Alternating-current electric locomotives, complete....	19 000.00
Passenger coaches (70 seats)........................	4 500.00
High-pressure cables (10 000 volts) No. 0, per 1 000 ft..	840.00
High-pressure cables (10 000 volts), No. 3, per 1 000 ft..	600.00
Copper, per lb....................................	0.186
Alternating current trolley construction, per mile....	1 200.00
85-lb. rails, per ton..............................	26.00
Track construction, per mile........................	500.00

For the sake of comparison, Mr. Berg's figures for direct-current motors and alternating-current motors with concatenated control are given.

1. Direct-current motors, acceleration 1 mile per hr. per sec.
2. Alternating-current motors, acceleration 0.8 miles per hr. per sec.
3. Alternating-current motors, with small air-gap and low frequency, acceleration 0.8 miles per hr. per sec.

	1	2	3
Power-house steam equipment......	$480 000	$525 000	$450 000
Power-house electrical equipment...	166 000	260 000	169 000
	646 000	785 000	619 000
Synchronous converter station......	312 000		
Transformer station...............		57 500	48 000
	312 000	57 500	48 000
17 locomotives complete...........	225 000	322 000	322 000
68 passenger coaches..............	306 000	306 000	306 000
	531 000	628 000	628 000
Cables, duplicate..................	157 000	†366 000	157 000
Trolley and feeder copper..........	49 000	31 000	49 200
	206 000	397 000	206 200
Track material and construction....	109 000	109 000	109 000
Trolley construction...............	23 400	31 200	31 200
	132 400	140 200	140 200
Total cost......................	$1 857 000	$2 008 000	$1 641 400

† There is apparently an error in this item, and cables have been accordingly calculated for same drops and losses as employed by Mr. Berg for his alternative plan with rheostatic control.

Therefore the alternating-current system employing motors with small air-gap and at low frequencies shows a cost equal to 81.5% of that of the system with large air-gap and high frequency, or $366 600 less; and a cost equal to 88.5% of that of the direct-current system, or $215 600 less.

POWER CONSUMPTION.

	1	2	3
Average power required	3 650	4 170	3 510
Kilowatt average loss	600	380	288
Per cent. loss	16.4	9.1	8.2
Per cent. of direct-current power	100	114	96.2
Per cent. of cost of direct-current installation	100	107	88

In other words, while the energy consumed at the train is somewhat greater with the alternating-current motors, the consumption at the central station is 3.8% less, owing to the difference in transmission and conversion losses.

So far as this case is a criterion, therefore, there is a reduction of 12% in first cost, 3.8% in power consumption, elimination of the attendance and repairs on synchronous converters, and on motor commutators, as compared with the direct current, while there is a saving of 15.8% in first cost and a reduction of 15.8% in power consumption as compared with the 25-cycle, large air-gap motors.

Compared with the direct-current system there are three overhead wires to be maintained instead of a third rail, and the expense of caring for motor-bearings to keep the rotors centered, while compared with the alternating-current motors with large air-gap there is the difference in maintenance of motor-bearings.

Mr. Berg assumed that 17 locomotives are required, 16 of which are always in service and one undergoing inspection or repairs. This allows about 21 days per year per locomotive for this purpose and makes no allowance for extra locomotives in use. If the same assumptions are made and one extra locomotive is added, on account of the smaller air-gaps, the time in the repair-shop will be is doubled, and as this is more than the ratio of the air-gaps it is more than a fair allowance to cover the difference in time out of service on account of bearings.

One locomotive, however, would represent but a small part of the total difference in first cost; it is evident then that the additional cost of maintenance would be far less than the interest on the difference in investment.

In this connection the experience on the Valtellina line is interesting. At the time of the writer's visit this line had been operating ten motor-cars and two locomotives, having four motors each, for about 18 months in regular service, and for more than a year in more or less regular, although experimental, service.

During the entire period three bearings had burned out, two by leakage of water into the oil-reservoirs and one by running dry. In neither case were the motors otherwise injured. No other repairs to bearings had been made. The maximum wear at the end of the first 25 000 miles of regular service as determined by the repair department, was 0.3 mm., or about one-third the available life of the bearings. The total distance that the car had run was estimated as at least 50 000 miles thus indicating a life for the bearings of 150 000 miles.

For the most part the road-bed is rock-ballasted. The regular running speed is about 40 miles per hour, and the number of revolutions per minute at this speed is 300, the motors being direct-connected.

The motor-bearings are very large and massive and are provided with ample oil reservoirs. The three-phase motor construction is particularly favorable to ample bearings on account of the large diameter and absence of commutators, the bearings being largely housed within the rotor.

On the schedule here dealt with the motors would make 90 000 to 100 000 miles per year, and assuming the same life as attained in Italy, the linings would require renewal every 18 months. Obviously the linings could require renewal at much shorter intervals without overcoming the advantages of lower cost of plant and reduced operating expense shown above.

Effect of Different Methods of Making the Run. From Fig. 1 it is seen that for the alternating-current run an acceleration of 0.8 miles per hr. per sec. was employed, while for the direct-current run the acceleration was about 1 mile per hr. per sec. In spite of this difference, however, the maximum kilowatt inputs are 977 and 896 for the alternating-current motors and 780 for the direct-current motors. If the run with alternating-current motors was made with an acceleration of 1 mile per hr. per sec., as shown by the solid curve (run No. 4) in Fig. 4, the maximum kilowatt input would be 1086, with proportionate increases for higher accelerations, as, for instance, 1404 kw. for the dotted curve (run No. 5) in Fig. 4. The effect on the load curve is indicated by Figs. 5 and 6, which correspond to curve 4 of Fig. 4. The ratio of mean to maximum in this case is 0.46 compared with 0.565 for the lower acceleration. Comparing the actual energy consumed, however, curve 4, Fig. 4, requires only 21 500 kw-sec.,

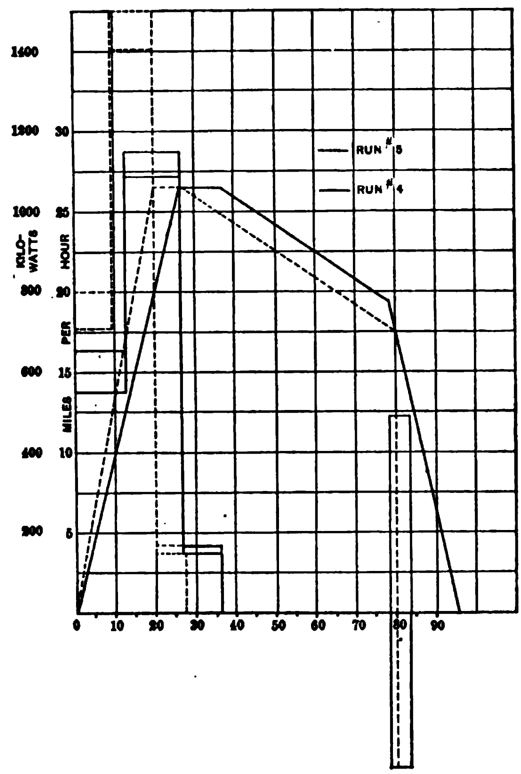


FIG. 4.

or 187 kw. average input, as against 23 028 kw-sec., or 200 kw. average input, for curve 3, and 21 800 kw-sec., or 190 kw. average for the direct-current run.

The high peaks thus shown are commonly taken to indicate the unfitness of the three-phase motor for traction purposes where runs of this kind are made. What they actually indicate, however, is that this is not the correct method of making the runs, and that the peculiarities of each type of motor must be considered throughout.

As illustrative of this statement curves 6 and 7, Fig. 7 are given. In curve 6, the acceleration to half-speed is 1.32 miles per hr. per sec., while full speed is reached in the same time as if made at 1 mile per hr. per sec. uniform acceleration (run No. 4). The total energy required is 21 565 kw-sec., and the average power is 187.5 kw., being therefore practically the same as for run No. 4, while the distance travelled during acceleration is greater and the maximum power less, being only 920 kw.

Station Load Curve. Run No. 4.

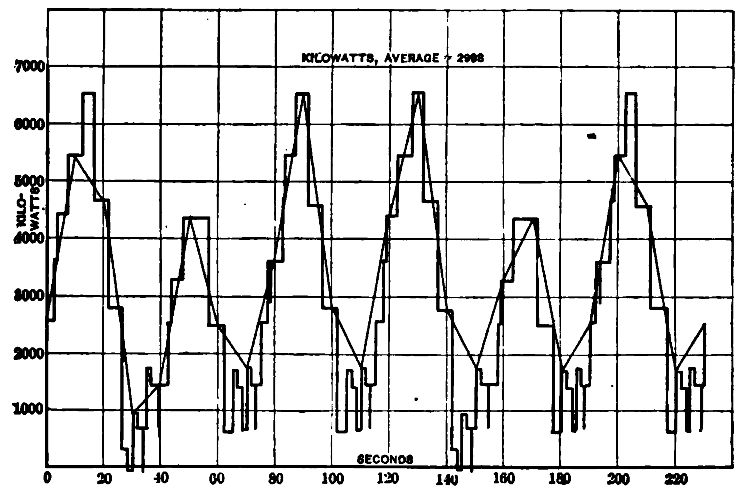


FIG. 5.

In curve 7, this method has been carried further to show how substantially the same results may be attained with three-phase motors as with direct-current motors. The acceleration to half-speed is made at 1.32 miles per hr. per sec., while from half to full speed it is 0.680. The maximum power required is 780 kw., or the same as for Mr. Berg's direct-current run; the total energy is 21 764 kw., a trifle less than for the direct-current run; the motors take power for only 35.75 seconds compared with 43.5 seconds, and therefore coast 42.75 seconds instead of 33 seconds. Referring to the corresponding load-curves, Figs. 8 and 9, the average kilowatt output, not including losses, is of course practically the same as for the direct current, while the maximum is 4680 kw., compared with 4 400 kw., the maximum kilovolt-amperes being 4 940. The ratio of mean to maximum kilowatts (without losses) is 0.652; for the kilovolt-amperes it is 0.71. The actual station kilovolt-ampere outputs, however, are practically identical, as shown by the following comparison.

	Direct-current.	Three-phase
Maximum kilowatt at motors	780	780
Watt-hours per ton-mile at the trolley	70	69
Watt-hours per ton-mile at power-house	85	76.4
Volt-ampere-hours per ton-mile at power-house	85	87
Maximum kilovolt-amperes output	5 650	5 600
Per cent. loss	16.4	8

Station Load Curve. Run No. 4.

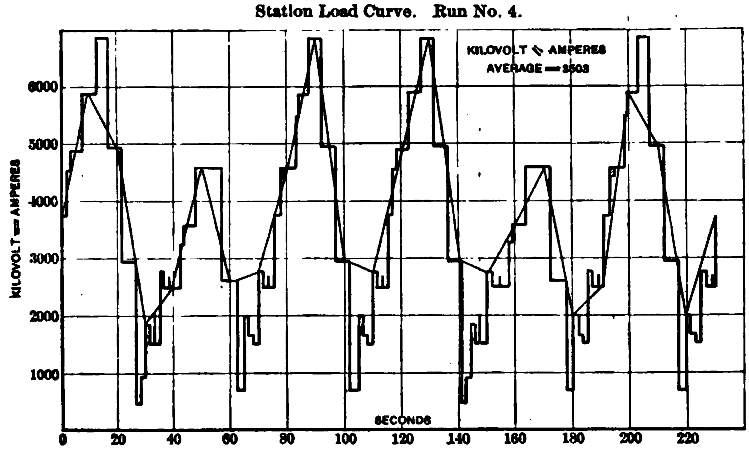


FIG. 6.

For this method of running the equipment is five 1 200-kw. generators, five 1 150-kw. engines at power-house, and four 400-kw. transformers for each sub-station, one spare unit in each case. High-pressure lines are No. 1 and No. 4 cables respectively, in duplicate. Trolley-wires are No. 000.

The loads, neglecting losses, are:

Average power on sub-station, in kilowatts	757
Average kilovolt-amperes on sub-station	914
Maximum power on sub-station	1 560
Maximum kilovolt-amperes on sub-station	1 660
Average power on generating station	3 048
Average kilovolt-amperes on generating station	3 514
Maximum power on generating station	4 680
Maximum kilovolt-amperes on generating station	4 940

This gives, including losses and drops:

Average kilowatt output of generating station..........3 320

Average kilovolt-amperes output of generating station...3 785

Maximum kilowatt output of generating station.........5 400

Maximum kilovolt-amperes output of generating station.5 600

The generators run at 79% of rated full load at average load.

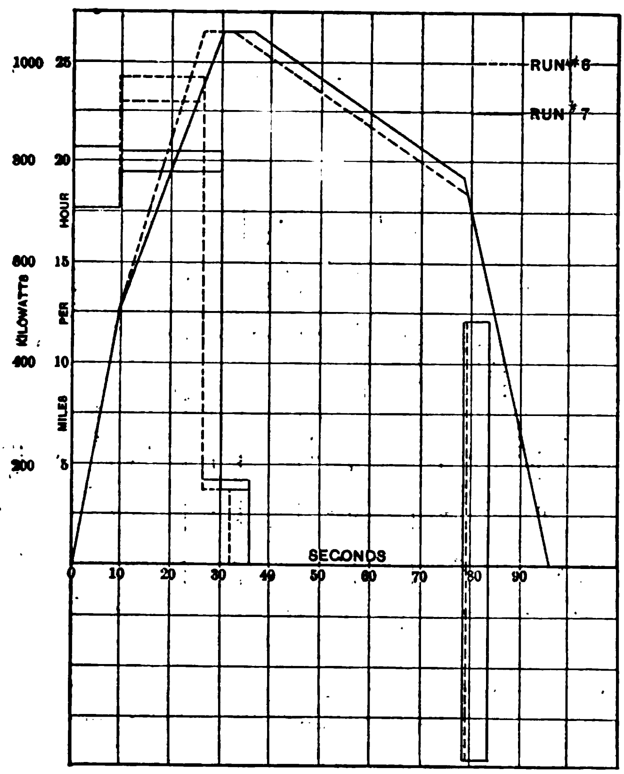


FIG. 7.

The generators run at 116% of rated full load at maximum load.

The engines run at 72% of rated full load at average load.

The engines run at 117% of rated full load at maximum load.

The ratings of apparatus in this case correspond with Mr. Berg's ratings for his direct-current project, which were slightly more liberal than for the alternating-current system.

In the calculation of cost the same prices have been used as before. Without repeating the figures in detail it is sufficient to say that the total cost, including the same items as before, is reduced in this case to $1 570 000, or 78% of the cost of the system with large air-gap motors and 25-cycle current, and 85% of that of the direct-current system.

It is evident, therefore, that when peculiarities of the three-phase motor are considered in planning the operation the strong points of the three-phase motor can be made to so far compensate for its less desirable characteristics that its operation becomes in no way inferior to that of the direct-current motor, while in many ways it is superior. This method of running is no mere theoretical speculation, but is simple to realize in practice, being regularly carried out on the Valtellina line. Limit-switches are the means employed.

Summarizing as to the above comparison, this method of running, with motors of 0.079-in. air-gap and 14-cycle current, would give the advantage of no moving apparatus at sub-stations, no commutators on motors, 8% average loss instead of 16.4%, and at a first cost of 84.5% that of the direct-current system, while entailing no disadvantages in the way of excessive load-peaks.

With the difference in cost of sub-station operation assumed as $5.00 per day, and with power at 0.008 per kilowatt-hour, assuming average load for 18 hours per day—this represents an annual difference in operating cost of about $25 000, not including interest, available to be charged against increased maintenance of bearings and of overhead conductors. That the small air-gaps and low frequency are warranted under these conditions is obvious. If with Mr. Lincoln,* we assume that sub-station attendance can be omitted altogether, the difference at $1 800 per sub-station per annum becomes about $31 000.

Experience on the Valtellina line shows that, so far as main line railways involving considerable distances are concerned, the cost of maintenance of overhead structures is not determined by the amount of actual labor required for repairs, but by the necessity of maintaining a force sufficient for regular patrolling and prompt action in emergencies. The cost of maintaining two overhead wires is therefore not greater than for a single wire under such conditions.

The method of making the run indicated in Fig. 7; that is,

* See *Electrical World and Engineer*, Dec. 12, 1903, Vol. XLII, No. 24, p. 951.

with a lower rate of acceleration for the higher speeds, is also advantageous in another respect; namely, gain in elasticity.

Thus Mr. Berg's direct-current run would allow 4.6 seconds to be made up by running up to the braking point, but by his alternating-current run only 1.35 seconds could be gained; by

Station and Substation Load Curves. Kilowatt Run No. 7. (Losses not included.)

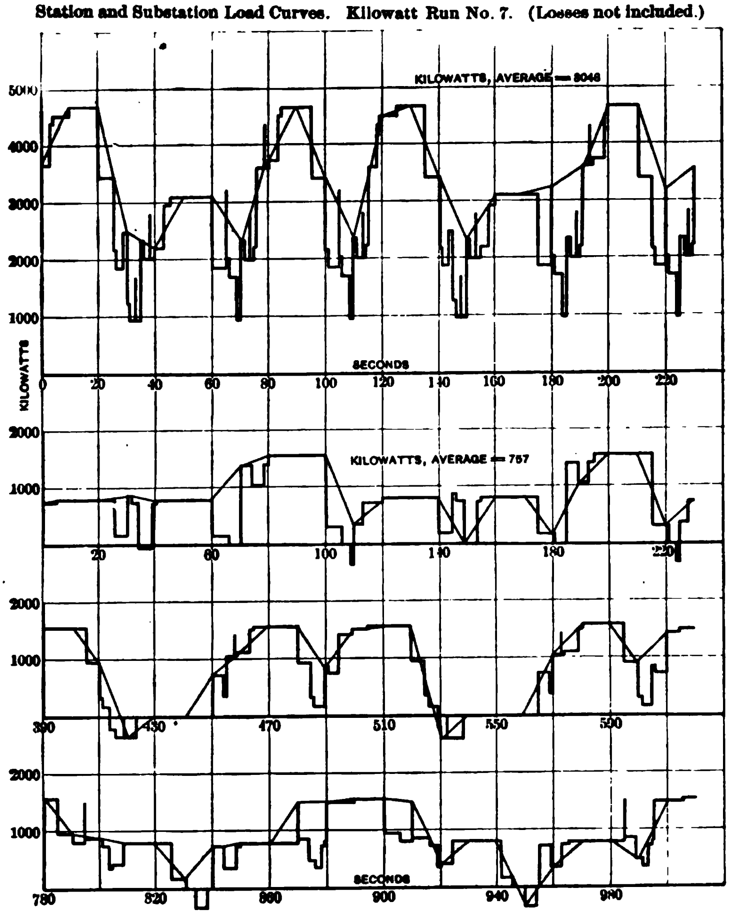


FIG. 8.

raising the acceleration to 1 mile per hr. per sec. (run No. 4) this could be increased to five seconds at the cost of very high maximums at train and central station; but, by the method of run No. 7, 5.14 seconds could be made up and with a maximum kilowatt input not greater than the direct-current motors would require. Thus in addition to lower first cost and smaller losses, run No. 7 makes an important gain in elasticity.

Rapid acceleration is comparatively unimportant except during the period when the velocity is low and the motors are

Station and Substation Load Curves. Kilovolt-Ampere. Run No. 7. (Losses not included.)

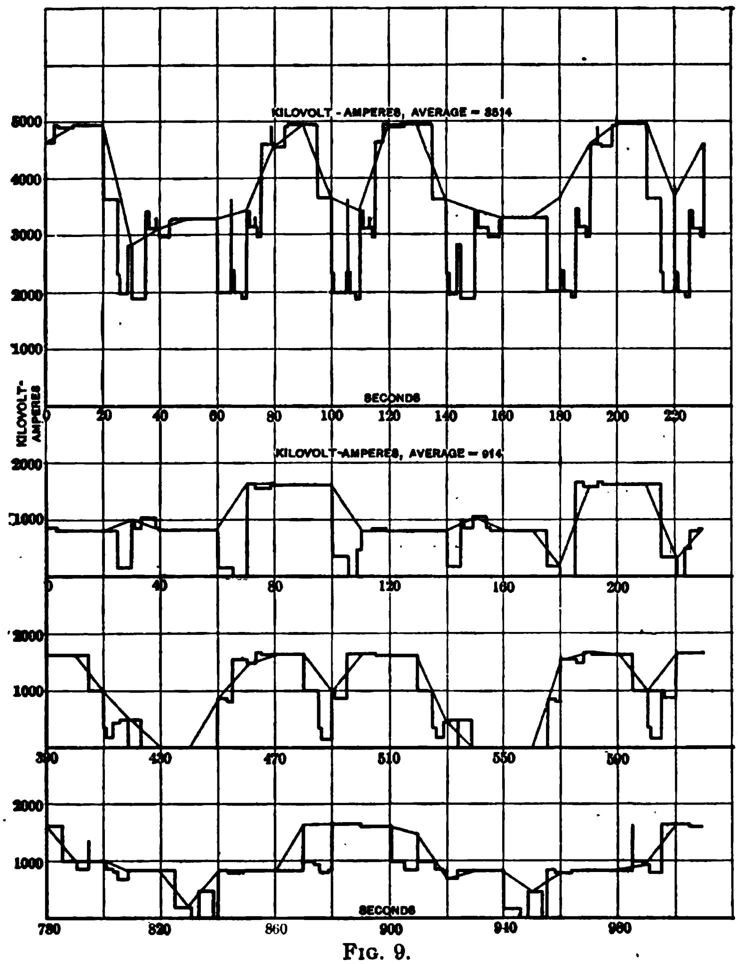


FIG. 9.

running in series or cascade connection; but during this period it should be made at the maximum rate that the tractive effort will permit. This is evident from the fact that during this time the average speed is low and the distance covered small, while the rheostatic losses are approximately one-half of the entire input. On the other hand, during the latter half the average speed is high, the distance which could be gained by higher acceleration relatively small, and the rheostatic loss about 25% of the input and hence smaller relatively to the distance covered. Thus by this method, as compared with a constant acceleration reaching the same final velocity in the

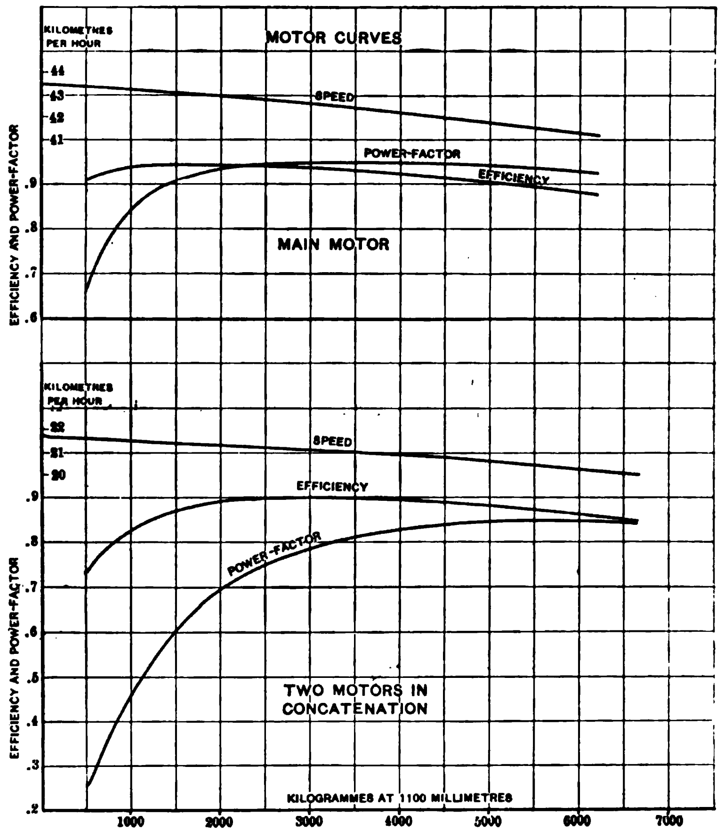


FIG. 10.

same time, the watt-hours per ton-mile rheostatic loss are less; the distance covered greater, and the maximum input less while the watt-hours per ton-mile total input are also less. This is, therefore, an important feature of three-phase operation, and quite alters many conclusions based on consideration of a constant acceleration.

Owing to the absence of the commutator, the three-phase

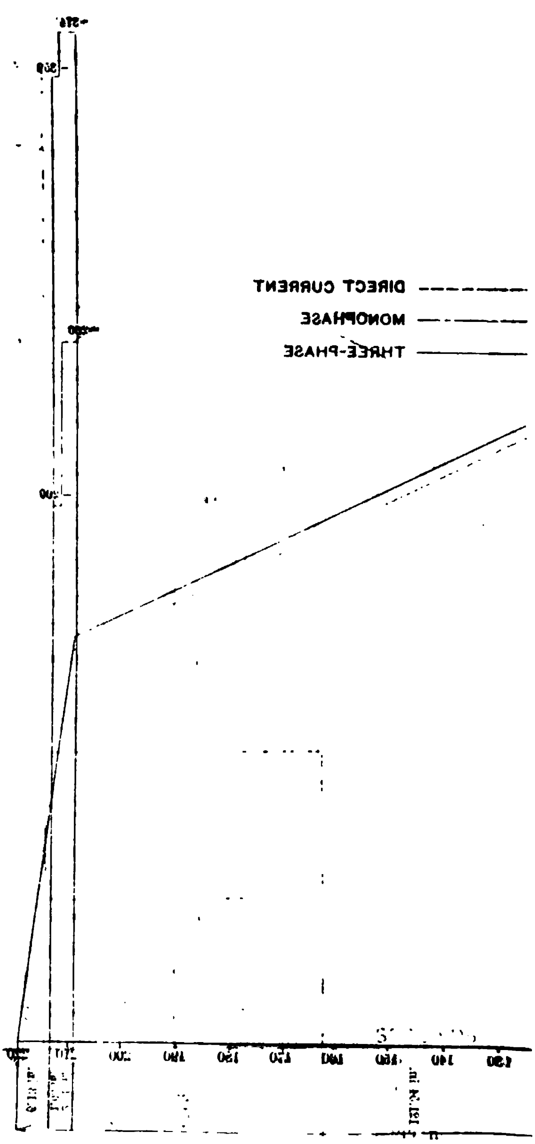
ONE-PHASE, AND THREE-PHASE PERFORMANCE,
ERS OF W. L. SLICHTER.
E A. I. E. E., January, 1904.

ltiple unit arrangement, each with two 60-h.p.

ple unit arrangement, each with two 60-h.p.

ive included, 8 motors for single, cascade, and

n: Efficiency of motors, 90%. Efficiency of not considered. Diameter of driving wheels is Length of run = 7497 ft. Time, 219 seconds.



COMPARISON OF DIRECT-CURRENT, SIN[GLE-PHASE AND THREE-PHASE ...]
BASED ON CURV[ES ...]
TRANSACTIONS OF TH[E ...]

Direct-Current—Three 25-ton cars, mu[ltiple-unit] motors.
Monophase—Three 25-ton cars, multi[ple-unit] repulsion motors.
Three-Phase—Train of 75 cars, locomot[ive] double-cascade arrangement.
Traction coefficient = 9.90 lb. per ton ... gearing, 96%. Rotating masses are ... 5.05 ft. for three-phase locomotive.

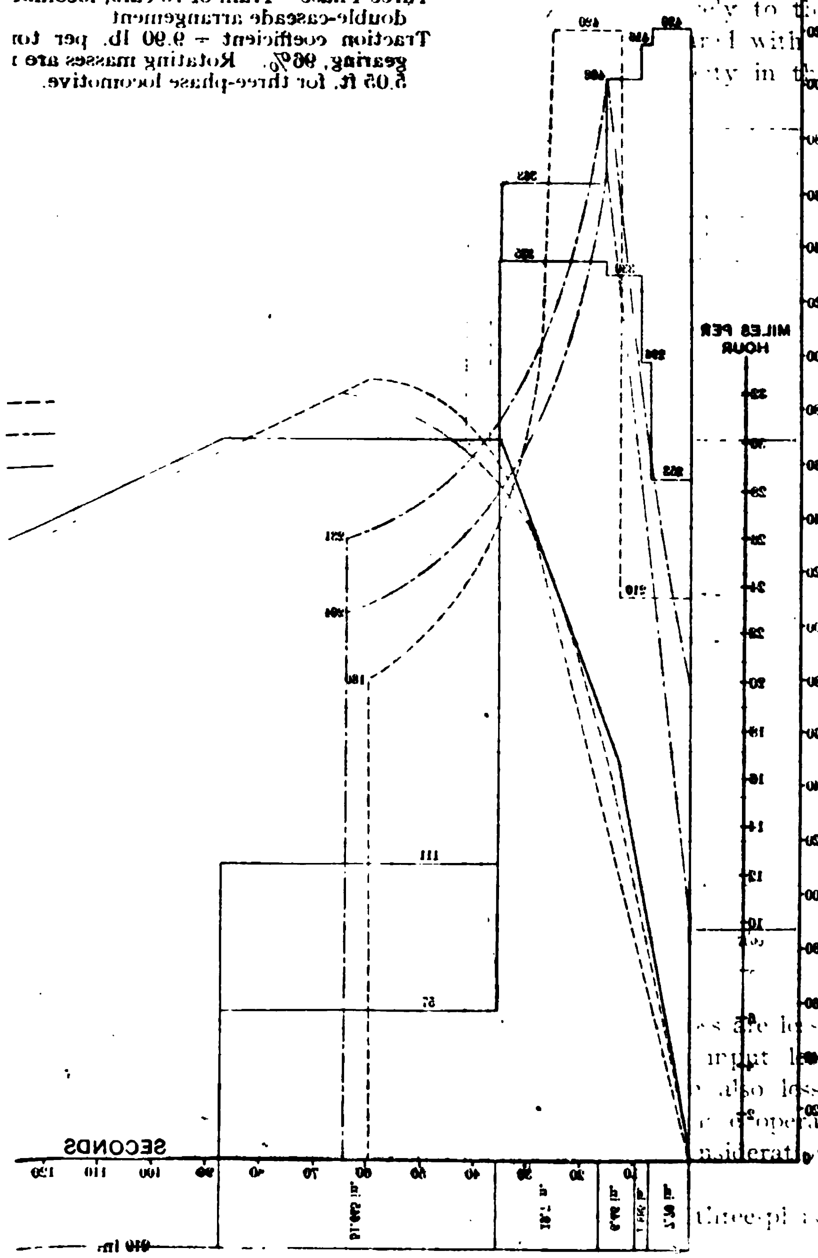


FIG. 11. (Waterman.)

motor has some peculiar features of elasticity, one of which is of interest in the consideration of the proper method of making the run. I refer to the ability to obtain a number of economical speeds with a simple and compact mechanical construction and arrangement. For projects of the kind considered by Mr. Berg this method has peculiar advantages, and should in general be used, but even had motor curves been available it would have destroyed the comparability sought in this instance. As an example of the above method of running applied in this way—and incidentally as a matter of interest in showing what might be expected of three-phase performances in comparison with single-phase—it has been thought worth while to include Figs. 11 and 12.

Fig. 11 is based upon the curves given by Mr. Slichter* in his paper read before the INSTITUTE in January, 1904, for the purpose of comparing the direct-current motor with the repulsion motor. The three-phase motors used are arranged to give four speeds, there being three motors, mounted and arranged as two structures, giving economical speeds of 9.7, 12.1, 18.3, and 30 miles per hour. They were designed by Ganz & Co. for rapid-transit service.

No change whatever has been made in the run, but multiple-unit trains have been used instead of the single cars cited by Mr. Slichter. The weight of the train is 75 tons in each case. The distance covered is 7 497 ft., the time 219 seconds, and the maximum speeds are 32.48 miles per hr. for the direct-current run, 31.92 for the repulsion motor, and 30 for the three-phase motor. The comparative results are given in the following table.

By this plan, therefore, the results with three-phase motors are not inferior to the results with either direct-current motors or the repulsion motors, but show a total input, as compared with the direct-current of 91.5%, and of 96% as compared with the alternating current motors, while the net input is only 85.5% of the direct-current and 89.5% of the single-phase.

It is interesting to note also that the maximum kilovolt-amperes input for the three-phase motor is the same as for the direct-current motor and only 104% of the single-phase motor, while the maximum kilowatt input is only 80% of the direct-current kilowatts and 91% of the single-phase kilowatts. The

*TRANSACTIONS of the A. I. E. E., Vol. XXIV., p. 61.

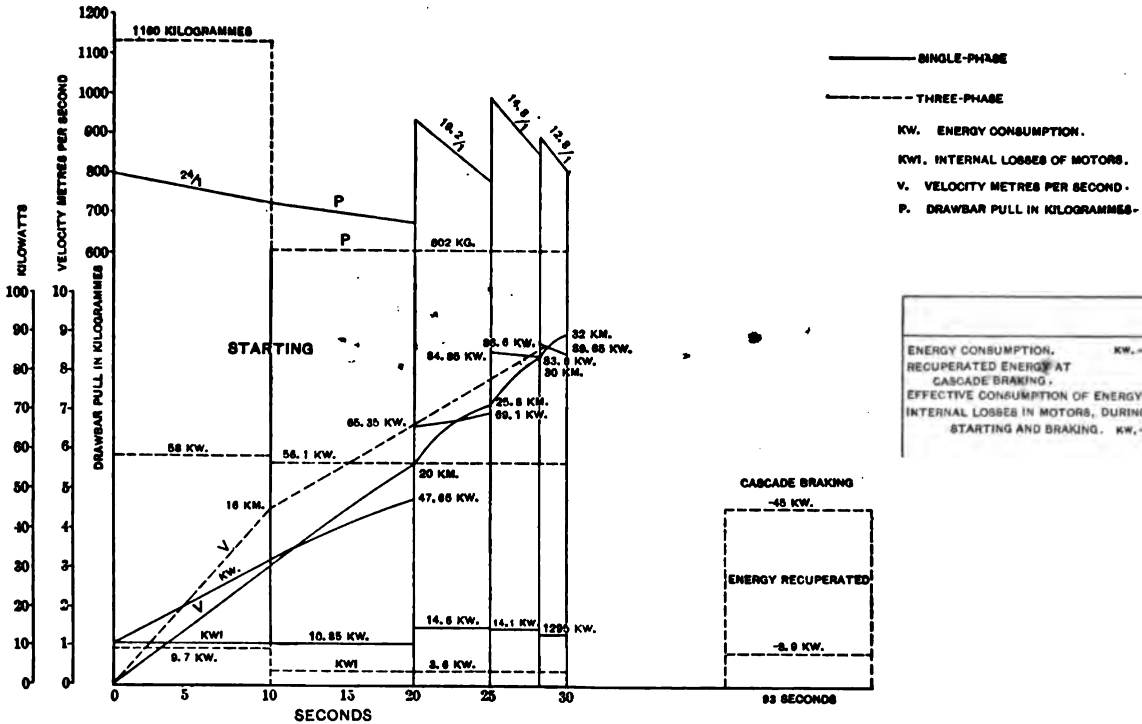
	Direct current	Monophase alternating current	Three-phase alternating current
Maximum speed miles per hour	32.48	31.92	30.
Average speed in miles per hour	23.29	23.29	23.29
Time of acceleration	60.	62.5	35.74
Time of run with motors	0.	0.	51.64
Time of coasting	149.3	146.8	121.54
Time of braking	9.7	9.7	10.07
Average acceleration on controller	.9	1.1	.84
Average acceleration during starting	.541	.511	.84
Maximum energy consumption kilowatts	420.	368.	335.
Maximum energy consumption kilowatt-amperes	420.	402.	420.
Positive kilowatts per hour	4.32	4.11	3.94
Negative kilowatts per hour			.26
Effective comparison of energy kilowatts per hour	4.32	4.11	3.68
Watt-hours per ton-mile	36.90	35.1	31.40

elimination of rheostatic losses is sufficient here to permit of a very favorable showing, while by making the run at approximately constant input the peaks even of apparent energy do not exceed those of the other systems; a result which shows that in spite of its lack of variable-speed characteristics the three-phase motor only requires to be used with due regard to its own peculiarities to yield results entirely comparable with those of the variable-speed motor, while retaining all of its own advantages.

Curve 12 (for which I am indebted to Mr. de Kando of Ganz & Co.) shows a comparison of the performance of the three-phase motor and the Winter-Eichberg single-phase motor (based on curves of the latter published in *Elec. Zeit.*,* 1903). In this case the maximum power input is only 64.7% that of the single-phase motor in reaching the same speed in the same time, the distance travelled being 1.19%, and the net energy input only 90%. The watt-hours per ton-mile input during acceleration are 176.4 for the single-phase motor and 177.9 for the three-phase motor.

The particularly interesting feature of this comparison is the relative amounts of energy which the motors have to dissipate. This is indicated by the lower curves marked $K\,w\,i$, the total energy being 345 kilowatt-seconds for the single-phase motor as against 241 for the three-phase motor. The single-phase motors must therefore be able to radiate 43% more energy

* See *Electrical World and Engineer*, Digest, p. 1016, Dec. 19, 1903; also p. 1006, same issue.



	SINGLE-PHASE	THREE-PHASE
ENERGY CONSUMPTION. KW.-SEC.	1343	1035
RECUPERATED ENERGY AT CASCADE BRAKING.	—	424
EFFECTIVE CONSUMPTION OF ENERGY.	1343	1211
INTERNAL LOSSES IN MOTORS, DURING STARTING AND BRAKING. KW.-SEC.	845	241

FIG. 12 —Comparison between Eichberg Single-Phase and Ganz Three-Phase Motors, for the starting period of a 25-ton motor car. (See Union Motor Curves, *Elektrotechn. Zeitschrift*, 1903, okt., Berlin.)

than the three-phase motors; this illustrates the fact that the higher efficiency realizable with three-phase motors has its greatest value in the lowering of motor temperatures for the same ventilation, or the greater protection of the motors which is possible with the same temperatures.

Value of Recuperation.

The practical value of the ability to restore energy to the line, possessed by the three-phase system, has been the subject, first and last, of a considerable amount of discussion, the general conclusion of American engineers apparently being that except for mountain roads with heavy traffic it is an item of comparatively small consequence. Curves 3 to 7 are interesting in this connection.

During the acceleration period the three-phase motor must run on the rheostat until full speed is reached and hence, other things being equal, the power input will be greater than with series motors in proportion as this maximum velocity is greater than that at which running on the motor-curves becomes possible. This results in greater rheostat losses. On the other hand, the return of energy in braking is said to be of little consequence because it is small, varying from a small percentage up to about 45% of the stored energy of the train, according to rate of braking. This item will, however, usually be quite comparable in magnitude with the excess rheostatic losses. For operation such as that shown by the curves given, where relatively high accelerations are used, it permits the method of making runs to be widely varied without greatly varying the total energy required. The accompanying table will enable the curves to be more readily compared in this respect.

In considering these results it should be borne in mind that the maximum speed used is alike in all cases, being that selected by Mr. Berg, and that no attempt has been made to select the most advantageous speed. This is a matter of much importance, but was considered as being outside the scope of the paper. The results are therefore to be considered only as comparative, and as limited by the specific conditions of a definite problem.

Thus it appears that the rheostatic losses are, for run No. 3, approximately 6 815 kilowatt-seconds, while for the direct-current run they are 3 100 kilowatt-seconds.* The difference is

* Motor losses deducted; efficiency of single motor without gears taken at 91%.

	Curve No. 7. Acceleration = 1.32 miles per hr. per sec., and 0.680 miles per hr. per sec.	Curve No. 6. Acceleration = 1.32 miles per hr. per sec. initial, and 1 mile per hr. per sec. average.	Curve No. 5. Acceleration = 1.32 miles per hr. per sec.	Curve No. 4. Acceleration = 1 mile per hr. per sec.	Curve No. 3. Acceleration = 0.8 miles per hr. per. sec.	Curve No. 1. Berg direct-current run.
kw-sec. accelerating	22 766	22 374	21 776	21 977	22 507	21 800
kw-sec. uniform speed	853	825	1 095	1 500	4 063	
Total input kw-sec	23 619	23 199	22 871	23 477	26 570	21 800
kw-sec. braking	-1 854	-1 634	-1 291	-1 974	-3 542	
Net input kw-sec	21 765	21 565	21 580	21 503	23 028	21 800
Average kw. per run	189	187.5	187.65	187.0	200	190
Maximum kw. per run	780	920	1 404	1 086	896	780
Maximum kilovolt-ampere per run	823	970	1 501	1 149	945	780
Watt-hours per ton-mile	69.4	68.64	68.7	68.5	73.3	70
Ratio average alternating-current kw. / average direct-current kw.	0.994	0.9868	0.9876	0.984	1.056	1
Rheostat loss	6 665	6 540	6 258	6 540	6 815	3 104
Per cent. net stored energy returned	36.44	34.3	30.4	37.4	43.9	
Per cent. energy stored at beginning of braking	31	29.3	25.9	31.87	37.44	
Minimum time for run	90.36	89.42	87.79	90.93	94.15	90.86
Maximum time saved	5.14	6.08	7.71	4.57	1.35	4.64
kw-sec. accelerating	22 766	22 374	21 776	21 977	22 507	21 113
kw-sec. uniform speed	5 531	5 924	6 624	6 150	5 672	
Total input kw-sec	28 297	28 298	28 400	28 127	28 179	28 113
kw-sec. braking	-4 364	-4 364	-4 364	-4 364	-4 364	
Net input kw-sec	23 933	23 934	24 036	23 763	23 815	28 113
Per cent. energy recoverable in terms of stored energy minus energy consumed in friction	44.8	44.8	44.8	44.8	44.8	
Per cent. total energy stored in train, returned	38.2	38.2	38.2	38.2	38.2	
Watt-hours per ton-mile	76.17	76.17	76.50	75.63	75.80	89.48

3 715 kilowatt-seconds; but the alternating-current motors after coasting for 14 seconds still return 3 540 kilowatt-seconds leaving only 175 kilowatt-seconds excess in spite of the fact that the direct-current motors accelerated at 1 mile per hr. per sec. and the alternating-current motors at 0.8 mile per hr. per sec. If the direct-current motors were limited in the same manner the three-phase motors would return considerably more than the difference in rheostat losses and have the added advantage of making the run in shorter time.

If the runs were made in minimum time, 17.5% more energy would be returned by any one of them than would be required to counterbalance the excess rheostatic losses of the worst one.

In making runs of this kind the motorman will usually overrun in order to be sure of making schedule time. He thus coasts less and brakes longer, and for each second increase he adds—in this case 300 kilowatt-seconds—to the net energy consumption; but with the three-phase motor, for each added second of braking he returns 350 kilowatt-seconds. Thus the actual results with three-phase motors in practice may be expected to vary less from the calculated than will the results with direct-current motors.

When making this run in the least time the direct-current motors save 4.64 seconds and consume 89.5 watt-hours per ton-mile. By run No. 7, however, the three-phase motors make up 5.14 seconds and consume only 76.2 watt-hours per ton-mile, or about 85% of the direct-current requirement, while in spite of the variety of ways of making the run the three-phase runs do not differ in energy consumption by more than about 1% when making the run in minimum time and the worst one takes only 85.5% of the energy required by the direct current.

To make the run in this way the direct-current motors take nearly 30% more energy than with the run made in the normal manner, while the three-phase motors take only from 3.5% to 10% more energy. The least favorable comparison therefore is on the normal run, and any departure from it results favorably to the three-phase motors. Thus run No. 7, for instance, having only a slight advantage over the direct-current motor on the normal run, takes 17.5% less energy for minimum time and saves 10% more time. The small increase of energy consumption for the runs when made in minimum time is a very interesting feature of three-phase operation.

In the normal runs as shown by the curves the effect of recuperation is less marked, but since it varies inversely as the extent of coasting it tends to equalization of energy consumption. Thus the maximum difference in total input shown by the curves is 16%, but the difference in net input is only 7%; the energy returned, exclusive of coasting, varying from 11.3% of the total energy of the train in the case of run 5 to 31% in run 3, or from 13.3% to 36.4% of the net train energy. These results show that the recuperative braking tends to give the effect of coasting from full to half speed for all runs without necessitating the sacrifice of time involved in coasting, and in general its importance increases as length of run and ratio of maximum to average speed decrease. It is of small consequence where runs are so long that acceleration energy becomes a small factor; it becomes of large consequence where acceleration is an important factor.

The percentage of the total available energy which can be returned electrically varies with the rate of braking, from 40 or 45% of the net (35 to 40% of the total) stored energy of the train for high rates of braking, down to zero where the train coasts, and the energy is all returned mechanically. Thus braking at 150 lb. per ton, about 45% of the net and 41% of the total energy would be returned by motors of good efficiency, being nearly the entire rheostatic loss. Mr. Berg's calculations showed 28% of the total energy returned after coasting for a portion of the available range, and 36% when braking from full speed; with the better motors afforded by smaller clearance and low frequency, proportionately better results, are, of course, secured, those shown above being 31 and 38% under the same conditions.

In this connection, however, it is important to note that while the favorable results shown at the trolley are due to the recuperation of energy, the discussion presupposes a density of traffic which, as in the present instance, will permit of its utilization. While therefore the usual contentions that the three phase-motor would necessarily prove itself radically uneconomical for rapid-transit service, and that it must inevitably produce a station load curve with prohibitive peaks, require modification in such cases, when the inputs alone are considered there is, superficially at least, a very different showing.

Thus run No. 7, which in all other respects is the most desirable, shows a total input of 23 619 kilowatt-seconds as against 21 800 kilowatt-seconds for the direct current, or an excess of 8% for the normal run; it is also a trifle worse for the run in shortest time. The rheostatic losses here count seriously against the system; and, with the particular equipment used they would be conclusive as to the disadvantageous power relations were it not for the difference in transmission losses.

The transmission system employed has been calculated on the general basis established by Mr. Berg and is not quite that which would be indicated for maximum economy; but even in this case the difference in transmission losses is 8.4% in favor of the three-phase system so that the motors in consuming 8% more energy at the trolley would not increase the power-house output as compared to the direct current, while the cost of the system would still be less by about 15%. The three-phase system, therefore, shows no inherent disadvantage on the score of economy under the conditions of rapid-transit service, even without taking advantage of the recuperative power, while with it a substantial gain is made which is not at the cost of any economic disadvantage.

On roads having grades the return of energy by electrical braking may, as a saving in station equipment and operating expense, be a matter of much importance; it also saves wear and tear on the brake equipment. In a proposed rapid-transit system recently calculated by Ganz & Co., (the results of which they have kindly furnished me), the profile is quite irregular, the maximum grade being 2.97%. In this case 21.5% of the total energy required was furnished by recuperation on grades and in braking, the average station power-factor at the peak loads being 0.81 and the ratio of mean kilowatt output to maximum instantaneous peak being 0.51, as indicated by the theoretical load curve (not including sub-station and transmission losses) for the period of heaviest load. Since the total rheostatic losses in this case amounted to 10.5% of the output, more than twice their entire amount was returned by the motors; and the average energy required was only 44.5 watt-hours per ton-mile at the power-house, including all losses and energy for air pumps and yard switching. The maximum speed was 19.5 miles per hour, the average distance 2·970 ft., the schedule speed 15 miles per hour, the average number of trains 35, and the minimum headway 2.5 minutes. A four-speed control was employed.

The following results of a test made on the Valtellina line by the writer to determine the effectiveness of recuperation on grades will doubtless be of interest. Owing to the official requirement of half speed on that section, the run was made with motors in cascade connection.

For more ready inspection the results are given in tabular form.

Weight of train, 125.2 tons.

Distance run, 3.39 miles.

Grade elevation, 329.45 feet.

Average grade per cent., 1.845.

Time ascending, 10.5 minutes; speed, 19.36 miles per hour.

Time descending, 10 minutes; speed, 20.16 miles per hour.

Energy, ascending (by Thomson integrating wattmeter), 43.74 kw-hr.

Energy corresponding to grade, 31.1 kw-hr.
Efficiency of motors in cascade at corresponding load, 85%.
Hence consumed in train friction, 6.1 kw-hr.
Train friction indicated, 7.26 lb. per ton.
Energy, descending (by Thomson wattmeter), 18.09 kw-hr.
Efficiency as generators at corresponding load, 83.5%.
Apparent train friction energy, 9.45 kw.
Train friction,* 11.2 lb.
Energy expended in elevating train, 36.8 kw-hr.
Energy returned in descending (total), 27.54.
Per cent. of energy returned, 75.
Per cent. of total energy required to ascend, 63.
Per cent. of total energy of grade, 88.5.
Per cent. of total energy of grade electrically returned, 58.5.

It is interesting to note that in a paper presented, Oct. 20, 1904, at the Electrical Congress at Bologna,† by the Italian engineers who made the official tests, the return of energy on this same grade and section of the road was reported at 54% as compared with 58.5 obtained in the tests made by the writer. The small difference is accounted for by the difference in train weights, the difference in efficiency as shown by the motor curves checking closely with the difference in load. The article says:

"In other words the running with motors in circuit permits making use of 80% of the energy which, in other systems, would have to be wasted in braking."

The fact must not be overlooked here, that wherever the rate of recuperation exceeds the constant losses of the system trains must be simultaneously running to absorb the energy, otherwise the whole system would tend to speed up until the losses equalled the energy returned. This is not a serious practical objection, however, as even a slight increase of speed is readily recognized by the motorman, and a light application of the mechanical brakes will reduce the returned energy to that which the system is able to absorb.

The foregoing discussion indicates that in spite of the larger rheostatic losses during acceleration the constant-speed char-

* Meters were standardized at Milan immediately before the test. The discrepancy in train frictions indicates either a slight under-registry of meters or an increase of train friction in a train descending a grade and braked only at the head.

† See *L'Electricita*, Nov. 4, 1904, No. 44.

acteristic is not without compensating features when the motor is constructed and operated with due consideration of its peculiarities. Constant speed is indeed a positive advantage as regards the maintenance of schedule, and the use of cascade regulation permits of reduction of speed on grades without in the least interfering with the exact preservation of the time-table since the reduction is by a definite and substantially constant amount. Two places are certainly not nearer together because there is a grade between them, or because the propelling motor is heavily loaded, and the desirability of getting from one place to the other in the shortest time is, of itself, in no way affected by these considerations. It is also not an advantage, from the time-table point of view, that a given run should require a variable time by reason of change of load and that therefore the schedule of runs involving grades must be laid out in view of the heaviest loads if the time is to be made. From the traffic manager's point ot view, speed should depend only upon curves and conditions of traffic; if from operating considerations the speed must be reduced by reason of grades, the safe speed over the level portions is not thereby increased and the speed for each portion should be definitely predeterminable, thus making it possible to fix definitely the amount of elasticity of the system allowed for making up time.

The view usually held in this country is, however, that the three-phase motor is inherently unfit for use on roads having irregular profiles. The experience with the Valtellina road does not appear to sustain this opinion, and the constant-speed characteristic seems again to have its own compensating features in a direction hitherto entirely overlooked by engineers in this country, so far as I know.

The Valtellina line is peculiarly irregular in profile, having many very heavy grades, most of which are short, but one is 3.5 miles long. It also has many curves of comparatively short radius. The running speed is 40 miles per hour. The train service is also not dense, so that all the conditions for extreme fluctuation of station load are present.

Fig. 13 shows sections of the load curve taken directly from the record of the Olivetti recording wattmeter at the central-station during the hours of heaviest load, 5 22 to 5 52 and 7 57 to 8 22 p.m. (17 22 to 17 52 and 19 57 to 20 22 according to the Italian system of reckoning time). During these intervals four to six trains are running, and during the first there is also usually some switching going on in one of the yards.

The extreme station peaks as shown by the curves are 1.7 to 1.8 times the average load or in other words the ratio of mean to maximum is 0.55 to 0.59 per cent. This remarkable result is due directly to the constant-speed characteristics of the motors; that is, to their dependance upon frequency. The slip of the motors with trains running at full speed is very small; the energy which they take is determined by this precise relation, being greatly influenced by very small variations of fre-

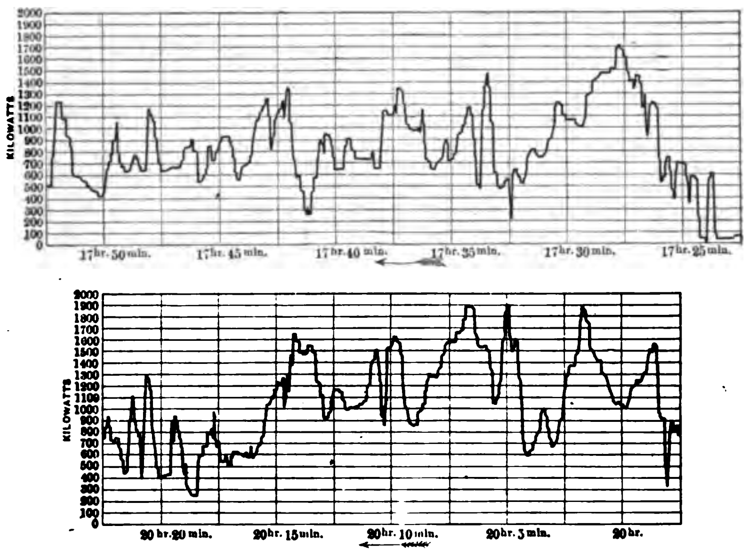


FIG. 13.

quency. The sudden application of a heavy load reduces the generator speed, and simultaneously all synchronously running trains drop their loads in a greater or less degree; if the fall in speed is equal to the slip they cease altogether to draw energy.

Since the motors usually run with a slip of hardly more than 1% and reach their full output at 2 to 2.5%, a reduction of generator speed of 1% will relieve the station altogether of the load due to synchronously running trains, while with a greater fall these will momentarily return energy, all trains gradually resuming their loads as their speed falls to proper relation with the generator speed. In a similar way all trains that are returning energy will have the rate of recuperation increased by the fall of speed. Thus all conditions tend to an equalization of load; the trains act like fly-wheels flexibly connected to the system, and the station peaks are thereby greatly modified.

Since the stable operation of alternators in parallel is most easily accomplished when a considerable fall in speed occurs between no load and full load, this property of the three-phase system may be fully utilized in practice, particularly as the fluctuation in lights which results will still be less than is inevitable with the larger line drops occurring in direct-current operation.

The effect of this equalization on the station load-curve is very marked, and is one of the first observations made in watching the instruments or examining the load curve of the Valtellina Central Station. It was for some time a very puzzling phenomenon to the writer but there is no doubt about the correctness of the explanation. Correspondence with Ganz & Co. has elicited the information that the regulation of the prime movers is purposely determined by them so as to take advantage of this effect.*

COMPARISON OF CALCULATED RESULTS AND RUN TESTS.

The figures as to performance given above, in the study of Mr. Berg's project, are of course mere calculations and, while they have been made with great care from reliable data and are believed to be realizable in practice they are naturally open to the suspicion which attaches to such computations. It will therefore be advantageous to compare the results of calculation with those of actual tests.

In the spring of 1904, the writer, on behalf of Mr. L. B. Stillwell, conducted an investigation of the performance of the Valtellina three-phase system. Some of the results of the tests are of interest in this connection. Before any tests were made, in fact before going to Italy, calculations were made from the known profile, alignment, train-weights, and motor performance-curves for consecutive runs from Lecco to Colico, a distance of about 24 miles. The profile is very irregular and there are many curves. The distance was assumed to be made in six runs varying from 10 690 to

* See also *Zeitschrift des Vereins Deutscher Ingenieure*, Vol. 49, No. 4, January 28, 1905.

31 020 feet, in each case between regular stations. Various circumstances conspired to defeat the intention of making test-runs over the entire distance thus planned, but consecutive runs were made on the portion from Lecco to Bellano and return, a distance one way of about 15 miles. The tests were made at night between the hours of regular traffic and were somewhat marred by extreme variations in frequency, due to the absence of any other load on the system, these variations being as much as 6% above and below normal.

It subsequently appeared that shortly before these tests were made similar tests had been made on various portions of the road by engineers connected with the Italian railway sys-

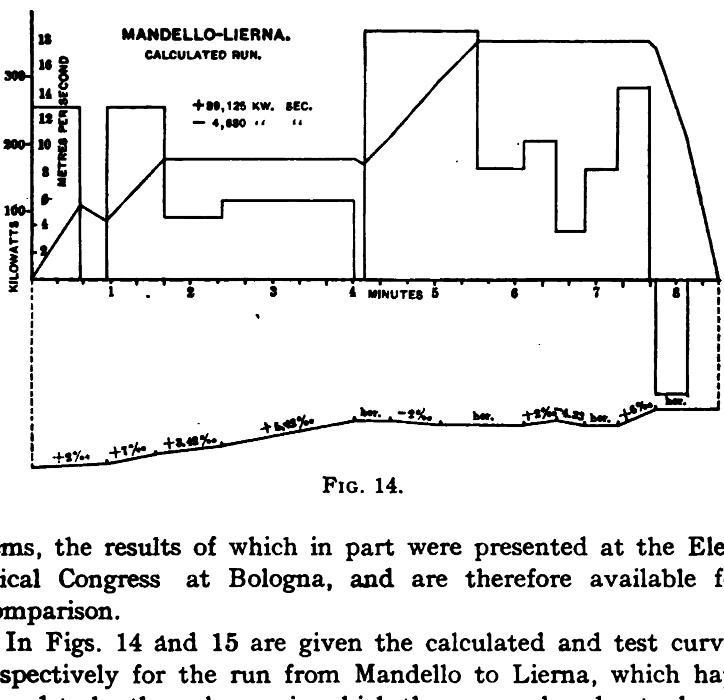


FIG. 14.

tems, the results of which in part were presented at the Electrical Congress at Bologna, and are therefore available for comparison.

In Figs. 14 and 15 are given the calculated and test curves respectively for the run from Mandello to Lierna, which happened to be the only one in which the assumed and actual running times were alike, but even in these it will be observed that there are some differences in the manner of making the run. The calculated input for Fig. 14 is 14% greater than the actual for Fig. 15, and the calculated recuperation is 50% greater, the net watt-hours per ton-mile calculated being 55 as against 51 actually shown.

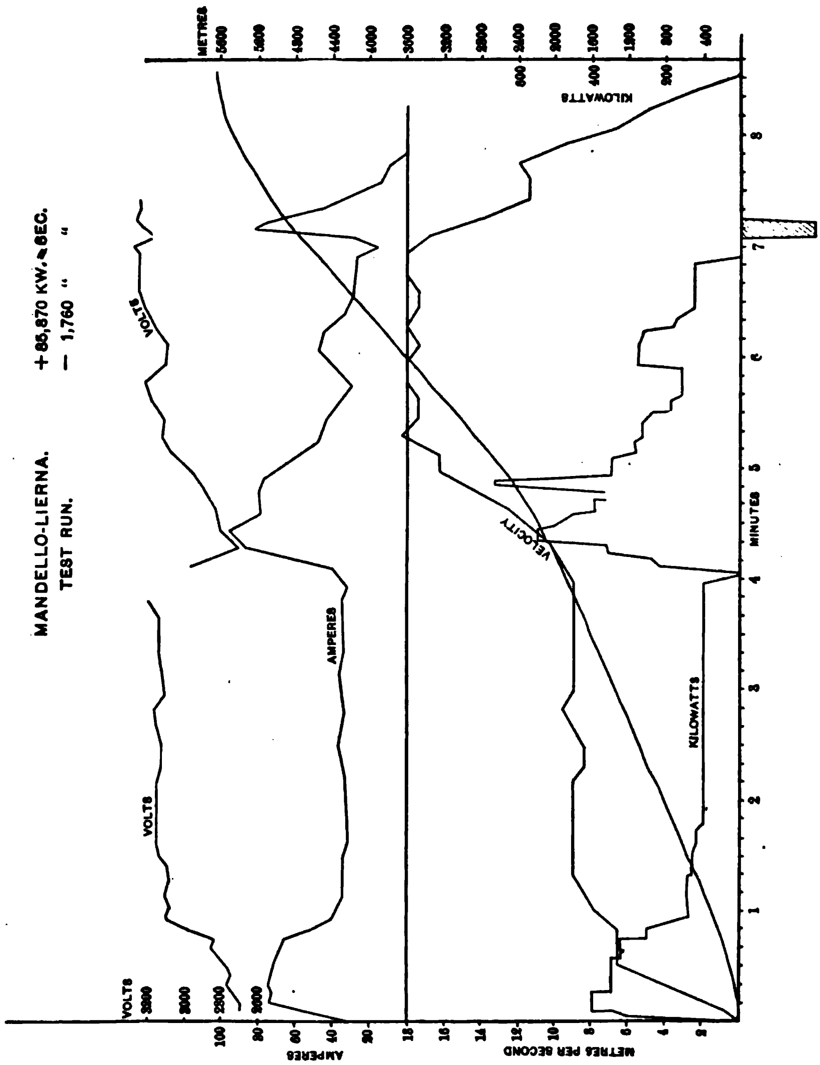

MANDELLO-LIERNA.
TEST RUN.
+85,870 KW. SEC.
− 1,760 " "
VOLTS
AMPERES
VELOCITY
KILOWATTS
MINUTES
METRES PER SECOND
METRES

Fig. 15.

Figs. 16 and 17 give the calculated and test results for the run from Lierna to Varenna, and Fig. 18 the test results for that between Varenna and Bellano. The running time in these instances exceeded the calculated time by 88 seconds and 36 seconds respectively. The total excess for all runs was only 14 seconds, but on the test runs one extra stop was made, owing to a misunderstanding of the motorman. The weight of the test train was 116 and that used in the calculations 110 metric tons. Owing to these variations the calculated and test results are not comparable in any strict sense, but they probably represent about the approximation of practice to theory which might ordinarily be realized and are therefore perhaps of greater interest.

Tables C and D give the results of test and calculation between Lecco and Bellano.

Weight of train for calculated run = 121.2 tons.

Weight of train for test run = 127.8 tons.

TABLE C.

Stations.	Distance in miles		Ton-miles	Kilowatt-seconds at train (measured)		Watt-hours per ton-mile (measured)		Watt-hours per ton-mile (calculated)	
	Between stations	Total		+	—	+	—	+	—
Lecco..........		—.01							
	4.35		555.9	100 800	—3 110	50.3	1.55		
Abbadia.......		4.34						44.8	2.43
	1.52		194.25	45 310	—3 120	64.6	4.44		
Mandello.......		5.86							
	3.53		451.1	85 870	—1 760	52.9	1.06	58.0	3.04
Lierna.........		9.39							
	4.02		513.7	74 930	—9 030	40.5	4.88	47.0	2.92
Varenna.......		13.41							
	2.03		259.4	44 360	—8 810	47.6	9.44	50.6	9.82
Bellano........		15.44							
Total from Lecco to Bellano.			1974.35	351 270	—25 830	39.4	3.63	49.1	3.66

	Actual	Calculated
Net watt-hours per ton-mile........................	45.77	45.44

The very close correspondence of these final averages is, of course, accidental.

For the return trip the test results are as follows:

TABLE D.

	Distance in miles		Ton-miles	Kilowatt-seconds at train		Watt-hours per ton-mile	
Bellano		15.44					
	2.03		259.4	50 360		54.0	
Varenna		13.41					
	4.02		513.7	83 220	—3 990	45.0	2.15
Lierna		9.39					
	3.53		451.1	71 380	—5 730	43.9	3.53
Mandello		5.86					
	1.52		194.25	37 690	—4 350	53.9	6.23
Abbadia		4.34					
	4.35		555.9	84 240	—5 930	42.1	2.96
Lecco		— 01					
Total from Bellano to Lecco			1974.35	326 890	—20 000	46.0	2.81
Net watt-hours per ton-mile							43.19
Round trip Lecco to Lecco			3 948.7	678 160	—45 830	47.6	3.23
Net watt-hours per ton-mile							44.37

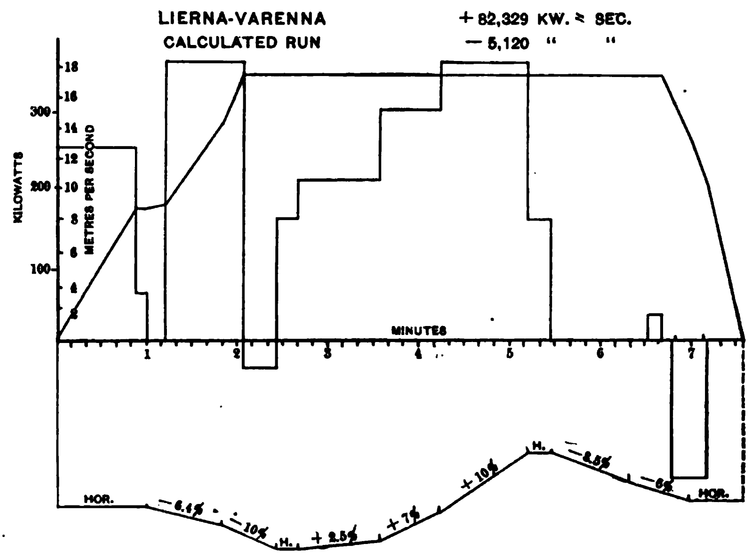


FIG. 16.

The average results calculated for the run from Lecco through to Colico was 49.25 watt-hours per ton-mile for an average length of run of 20 400 feet, the terminal stations being practically on the same level. The average for the test taken both ways was 44.4 watt-hours per ton-mile and the average length of run 16 306 feet.

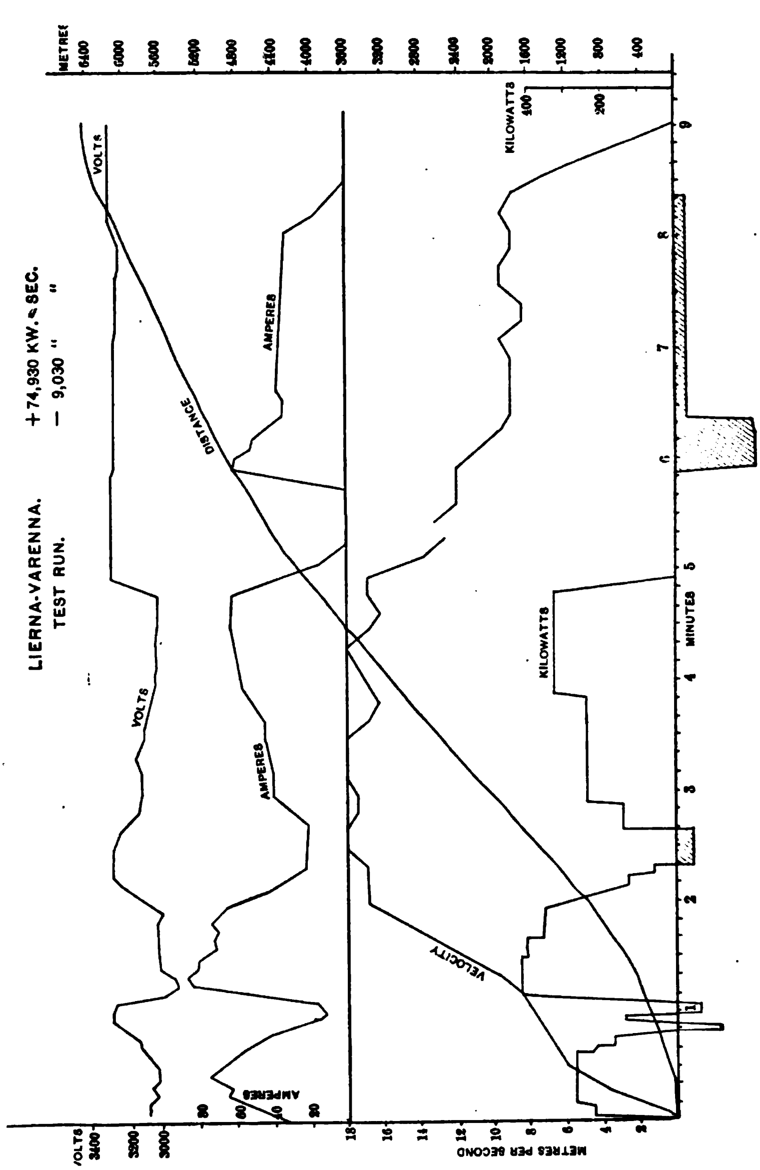

LIERNA-VARENNA.
TEST RUN.
+74,930 KW. SEC.
− 9,030 " "
VOLTS
AMPERES
DISTANCE
VELOCITY
KILOWATTS
MINUTES
METRES PER SECOND
METRES

Fig. 17.

In the paper presented at the Bologna Congress the average results of tests from a very much larger number of runs is given as 31 watt-hours per ton-kilometre (or 45.3 watt-hours per ton-mile), thus agreeing within 2% with the results obtained by the writer. The closeness of the results obtained by calculations to those obtained by test indicates that when based on reliable data the calculated results will very nearly represent actual practice.

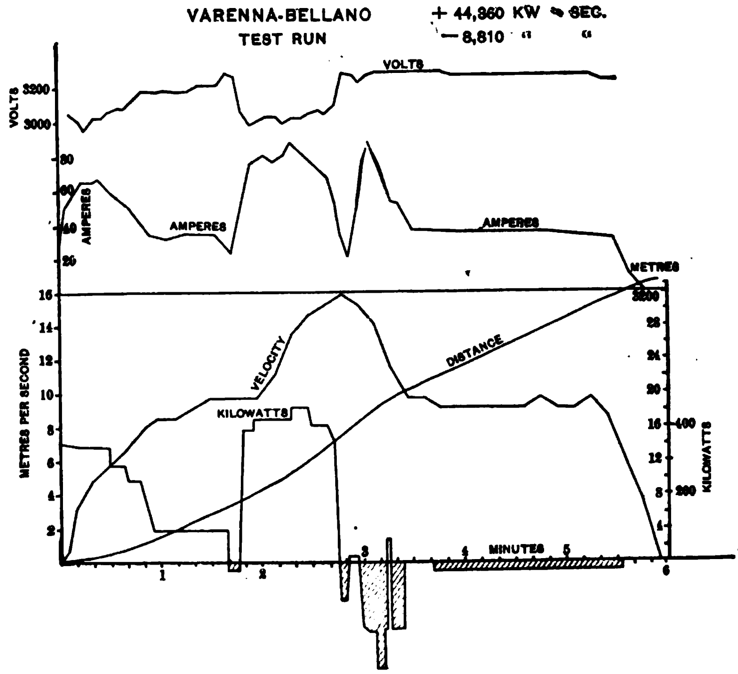


FIG. 18.

In the tests made by the writer it was found impracticable to determine by measurement the average value of the rheostatic losses; this, however, is given in the paper referred to as six watt-hours per ton-kilometre (or 8.75 watt-hours per ton-mile), as determined from the regular run between Lecco and Colico where, in a distance of 24.2 miles, seven starts have to be made. It is apparent therefore that they are not a serious item in the operating expenses.

The average station output for all purposes, including lighting and heating of trains, operating air-pumps, lighting of stations, yard switching, and power for the shops at Lecco is 64 watt-hours per useful ton-mile. It should also be stated that the Italian records of ton-miles do not include the weight of freight or passengers but simply the train weights. The power-factor is never less than 0.8 at periods of maximum loads. When it is remembered that the Valtellina motors are not modern but were designed more than six years ago, these results are seen to be particularly creditable.

The financial aspect of the operation is outside of the scope of this paper, but in passing it may be said that the average daily service is slightly under 200 000 ton-miles gross and the annual cost* per 1000 ton-miles of train weight (exclusive of locomotive weight and weight of electric equipment of motor-cars) is $0.265 including total cost of power-house, sub-station, motive-equipment, and line operation and maintenance, both mechanical and electrical.

The estimated saving as compared with operation by steam is $400 per mile of line per annum, or a trifle under 4% on the net cost of installation in spite of the low traffic density.

For the period since the new locomotives went into service the estimate is $590.00 per mile or 5.5% on the net cost. The total cost of maintenance of electrical equipment of rolling stock is $0.0135 per mile of locomotive or motor-car service.

In conclusion, a brief reference to the new Ganz locomotives, which went into service early last summer on the Valtellina Line will be of interest. No alternating-current locomotive can have the remarkable structural features and advantages of the New York Central type, but those furnished by Ganz & Co. for the Valtellina Line are in many ways equally striking, and the results of their operation up to the present time show them to be particularly successful and efficient. The following table gives the comparative dimensions.

	N. Y. Central Type	Valtellina Type
Driving-wheels	8	6
Pony-trucks	2	2
Weight (tons 2 000 lb.)	95	68
Weight on drivers (tons 2 000 lb.)	69	46
Weight per driving-axle (tons 2 000 lb.)	17	15
Rigid wheel-base	13 ft.	14 ft. 10 in.

* See *Zeitschrift des Vereins Deutscher Ingenieure*, Vol. 49, No. 4, Jan. 28, 1905.

train at a speed of 40 miles per hour between Lecco and Colico, grades as high as 1% being encountered, where the current taken rises to 160 amperes. Trains of 500 tons are moved over the same line at a speed of 20 miles per hour.

An interesting illustration of the flexibility of alternating-current operation is furnished by the performance of the new locomotives. In one instance a train of 310 tons (including locomotive) was being hauled up a 1.7% grade at a speed of 69 kilometres per hour or about 42.5 miles per hour, as measured by a tachometer. The wattmeter showed 1 120 kw. and the voltmeters and ammeters indicated 1 220 kilovolt-amperes. At this point the train was about 3 km. from one sub-station and 8 km. from the other. Since the trolley wires have an area of only 50 sq. mm. (between No. 1 and No. 0. B. & S gauge), and the regulation of the transformers is very good, this load was for the most part carried by one 300-kw. transformer. This capability for great momentary overload is of course of enormous importance; it is one of the great advantages that alternating current-systems have over the direct current.

The contract under which the Valtellina Line was constructed contained the following requirement:

"The electrical propulsion of trains will be considered satisfactory, if, during the first two years of complete operation under the new system, the difficulties encountered are no greater than are usual where steam is used, either as regards the maintenance of the schedule, elasticity and promptness in satisfying the severest demands of traffic or general reliability."

This requirement was so far met that the Rete Adriatica early began negotiations to take over the system, which were completed and the system accepted about three months before the expiration of the two-year trial period

The Valtellina line is not a trunk line but is the northern portion of the system of the Rete Adriatica and has an ordinary steam railroad service. It was chosen for the test of three-phase operation because it combined all the difficulties encountered in railroad operation, particularly those with which three-phase motors were said to be least able to contend. The contract provided that in the event of failure satisfactorily to meet the above conditions the entire equipment, with the exception of the power-house apparatus, should be removed without cost to the Rete Adriatica or to the Italian government. As with all new systems, difficulties were encountered, requiring an extended experimental period; these having been overcome the operation appears to be particularly successful, and the system constitutes a notable achievement in the records of electrical traction engineering.

In all comparisons made in this country the three-phase system has suffered. But it must be remembered that whereas in the case of direct current a fully developed and well worked out system has been taken for comparison, the data as to the three-phase system have not only not been worked down to a practical basis but have been assumed without any experience whatever as a guide. It has been taken for granted that the practical considerations found to be of importance in direct-current practice would be equally preeminent with three-phase, that the same limitations apply and the same methods of operation should be followed. European experience seems to indicate that none of these assumptions is true. Each system has its own peculiarities, both favorable and unfavorable; each must be designed and operated to take advantage of the one and to minimize the other.

Whatever may be the future of three-phase traction, the conclusion seems clearly warranted that were there no other system, all traction business that permits a private right-of-way could be handled as well and as economically as at present, and that it could be done with a smaller average cost of installation and at a cost of operation which would often be materially lower than present attainments.

There is also good reason to believe that maintenance charges would not exceed those now submitted to and that while such charges would undoubtedly be differently distributed they would not involve any reduction of equipment mileage.

Eighteen years of experience have brought the direct-current system to a high state of development, while with only one case of serious working out on a large scale, the three-phase system is showing results which, from the standpoint of effectiveness and economy, seem not inferior. The evidence of flexibility already observed gives reasonable promise that others may be expected, and it will be indeed strange if some field of utility is not found wherein pre-eminence is attained.

Since writing the above, Ganz & Company have kindly furnished motor-curves giving the performance of 3 000-volt, 25-cycle geared motors suitable for making Mr. Berg's run. They are, however, arranged for four economical speeds, the lower speeds being respectively 33, 40, and 66% of the full running speed. The motors are designed for motor-car units with multiple-unit control. With these as a basis, Mr. Berg's run has been recalculated assuming the same train-weight and friction, and, as before, neglecting the inertia of rotating parts. The gear-loss was assumed to be 3%. The results are given in the table below.

Accompanying the motor-curves was a run-curve showing how the run would be made with the limit switches of the Ganz

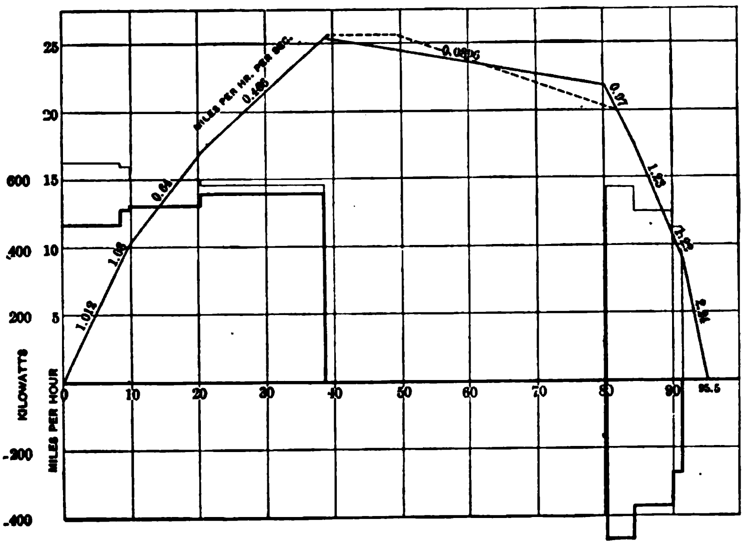


FIG. 20.

multiple-unit control apparatus set for the schedule called for by Mr. Berg's project. This curve is given in Fig. 20. The writer is indebted to Mr. de Kando, of Ganz & Co., for this courtesy.

The acceleration is automatic; that is, for this particular adjustment it cannot be made at any greater rates than shown. The rates of acceleration are noted on the curve.

The train-weight is assumed as 180 tons, the actual train-weight with motor-cars is given by Mr. de Kando as 163 tons (2 000 lb. per ton). The inertia of rotating parts is taken at 11% and gear-loss at 3%. The train-friction assumed is lower than it is customary to consider allowable in this country, being only nine lb. per ton at maximum speed and six, seven, and eight lb. respectively for the lower speeds. They are the values given by the accepted formulas used abroad.

Since these results are not directly comparable, owing to the difference in train-friction, they have been recalculated on the same basis as the others. The method of acceleration and braking has been preserved, but a run at uniform speed was of course necessitated and the results are thus materially modified. The alteration in the run is indicated by the dotted lines in the figure; the inputs have been omitted to avoid confusion.

	A.	B.	C.	D.	E.
Maximum acceleration in miles per hr. per sec.	1.08	1.08	0.8.	0.8	1.
Average acceleration on controller	0.652	0.655	0.8	0.8	1.
kw. seconds accelerating	20 965	20 340	21 160	25 100	21 800
kw. seconds uniform speed	1600	—	4399	5400	—
kw. seconds braking	—2954	—4520	—4890	—3230	—
kw. seconds total	19 611	15 820	20 670	27 270	21 800
Kilovolt-ampere seconds total	24 750	21 600	28 232	47 900	21 800
Average kw. per run	169.7	137.	179.	237.	190.
Average kilovolt-ampere run	214.	187.	244.	416.	190
Maximum kw. per run	572.	555.	912.	977.	780.
Maximum kilovolt-ampere run per	644.	650.	975.	1140	780.
Watt-hours per ton-mile	62.5	50.5	66.0	88.	70.
Volt-ampere hours per ton-mile	78.9	69.	90.	154.	70.
Ratio $\frac{\text{average alternating-current kw.}}{\text{average direct-current kw.}}$	0.89	0.72	0.942	1.26	—
Ratio $\frac{\text{average alternating-current kilovolt-amp}}{\text{average direct-current kilovolt-ampere}}$	1.125	.98	1.285	2.2	—
Average power-factor	0.793	0.733	0.733	0.57	1.
Power-factor at peak	0.80	0.846	0.91	0.60	
Average kw. at power-house (without losses)	2 715	2 190	2 865	3 800	3 040
Maximum kw. at power-house	3 632	3 300	5 309	6 000	4 400
Average kilovolt-ampere at power-house	3 425	3 000	3 915	6 650	3 040
Maximum kilovolt-ampere at power-house	4 530	3 900	5 827	10 000	4 400
Average kw. at sub-station (without losses)	679	546	716	948	760
Maximum kw. at sub-station	1 144	1 110	1 824	2 000	1 600
Average kilovolt-ampere at sub-station	856	750	978	1 660	760
Maximum kilovolt-ampere at sub-station	1 218	1 300	1 947	3 500	1 600

The foregoing table gives the results for:

A. Mr. Berg's schedule and train-friction with Ganz four-speed, 25-cycle, 2-mm. air-gap motors and automatic control.

B. Same as A, with train-friction and inertia of rotating parts as assumed by Ganz & Company.

C. Mr. Berg's run (Run No. 3, Fig. 1) with four-speed control.

D. Calculations made by Berg; 25-cycle, large air-gap motors.

E. Run made with direct-current motors as given by Mr. Berg.

It will be noted that the gain in economy by the four-speed control is very marked. When a run identical with that used by Mr. Berg is made with these motors the net energy taken is only 76% of that found by him and 94.5% of that for the direct current, notwithstanding the lower acceleration as compared to the latter. When made with automatic control the energy required is only 89% and 72% respectively of that for direct current, even with a very much lower average acceleration on the controller, as compared to 126% given by Mr. Berg. The results given do not include transmission losses in either case. When these are considered the results are of course still more favorable.

Since these runs assume motor-cars with multiple-unit control, cost comparisons are not directly possible except by assuming that the cost of cars and locomotives is not changed. On this assumption, making calculations on the same basis as before (except as to transformers, which in this instance are designed for 25 cycles) the following comparisons may be made.

	A.	B.	C.	D.	E.
Station equipment	$471 000	$423 500	$619 000	$785 000	$646 000
Sub-station equipment	22 400	22 400	32 400	57 000	312 000
Cables and trolley lines	155 500	155 500	181 000	397 000	206 000
Total for generation and distribution	$648 900	$601 400	$832 400	$1 239 000	$1 164 000
Locomotives and cars	628 000	628 000	628 000	628 000	531 000
Track and trolley construction	140 200	140 200	140 200	140 200	132 000
	$1 417 100	$1 369 600	$1 600 600	$2 007 200	$1 857 000
Average kilowatts required	2 945	2 380	3 110	4 170	3 650
Average per cent. loss	7.7	8.0	7.7	9.1	16.4
Percentage of direct-current power	81	65	85	114	100
Percentage of cost of direct-current installation	76.5	74.	86.5	107.	100.
Cost of generating and distributing system in percentage of direct-current cost	56	51.5	71.5	106	100

Therefore the small air-gap motors at 25 cycles and with four-speed control show a great superiority in performance not only over the alternating-current motors used by Mr. Berg but also over the direct-current motors. On the same basis of weight, friction, and schedule and a much lower average acceleration, these motors take 81% of the power required by the direct current (at the switchboard); they have 47% of the average losses in transmission, and cost 76.5% for the entire equipment, or 56% for generating and distributing equipment.

These results make a most interesting showing; and while arbitrary calculations of this kind have little meaning as to exact values or even as to precise ratios they are sufficiently comparative to indicate that when operated so as to utilize its advantageous features the three-phase motor is able to give a good account of itself in traction work, even of the character for which it is commonly supposed to be least fitted.

Discussion on "Three-Phase Traction."

F. N. Waterman: The presentation of this paper was prompted by the development, in the course of an investigation, of certain facts which indicated that the disadvantages of the three-phase motor for traction purposes had been very largely exaggerated, and its advantages either underestimated or overlooked. To present, in concrete form, a few of the points raised, it seemed desirable to take a specific case, and therefore that was chosen which is already familiar to the Institute, through the medium of Mr. Berg's paper read some years ago.

W. N. Smith: In my opinion the paper by Mr. Waterman is the most practical exposition yet presented of the results attained in three-phase traction. Its value as a practical demonstration, however, is somewhat limited by the fact that it illustrates the operation of but one railway, the well-known Valtellina line, which is apparently somewhat more favorable for an exposition of the capabilities of three-phase traction than would be a suburban or rapid transit system, such as is found in or about New York City, with reference to which Mr. Waterman opens his paper. One of the conclusions implied in this paper is that the engineering profession is asked to disregard some of the fundamental precedents of railroad engineering in order to make the peculiar limitations of the three-phase motor fit railroad conditions for the sake of some results which are claimed as advantages, but which in the last analysis may be of doubtful value.

As between the direct-current series motor (or its counterpart, the modern single-phase alternating-current motor) and the three-phase motor, it seems to be a question of which motor is really the better for train propulsion: a motor whose characteristic is that of furnishing relatively *constant power* with speed and torque varying inversely according to the conditions of grade and load; or a motor of practically *constant speed* whose torque and power requirements vary with the train resistance due to grade and load. Heretofore, whether considering the steam locomotive or the series railway motor, either alternating current or direct current, engineers have been considering a machine of practically fixed power-capacity, in which speed and tractive effort vary inversely with almost automatic precision. With the three-phase motor, however, it is implied that if a train is to be hauled up a steep grade at the same speed at which it runs on a level, it is only necessary to call upon the main power-station for the extra energy required and the motor will do the rest.

In my opinion this view seems to conflict with the general principle that the best engineering economy in designing any machine, whether steam or electric, is obtained by proportioning it for a certain definite average power-capacity. It may be assumed as a fundamental principle that only a fixed maximum amount of power can ever be produced from or transmitted through any mechanical appliance consisting of a given quantity of material of known resisting power to heat or to mechanical stress. Obviously, a motor whether steam or electrical, which is built to haul a train up a 2 per cent. grade, for instance, at the same speed at which it is to operate on a level (constant speed being an essential feature of the system under consideration) will have to develop or transmit from the prime mover three or four times as much energy as when working on a level. Consequently, the motor must be proportioned accordingly; and this requires that a railway motor of such type must be correspondingly larger and heavier, all because there may be an occasional call for power to ascend grades considerably heavier than the average grade to be found along the line.

The inevitable result is that an equipment designed on the principle of constant speed and varying power, is much heavier than a motor designed for the production of relatively constant power at varying speed. Furthermore, the physical dimensions of the space available for mounting a motor in a truck or locomotive are in practice just as important as the weight of equipment; and unless the motors are to be mounted well up above the wheels one cannot hope to get an amount of power capacity into the truck of a car or locomotive, in three-phase motors, that is commensurate with the amount of space available, in comparison with the present practice in the constant-power series motors hitherto so successful. Limitations of space in car-trucks are reached very quickly, and involve the necessity of equipping all four axles with three-phase motors. In the case of electric locomotives it becomes necessary to resort to parallel-rods and mechanical movements, which add to an electrical equipment one of the disadvantages of steam equipments—the complications incident to the proper balancing of the extra parts. The very latest development in steam locomotive practice; namely, the 4-cylinder balanced compound locomotive illustrates the complications which locomotive engineers are forced to introduce in order to steady the motion of the locomotive and save the track, while the absence of imperfectly balanced revolving parts has hitherto been counted as one of the greatest mechanical advantages of electric traction as compared with steam.

Referring again to the question of weight of equipment, Mr. Waterman's paper does not discuss this question in detail. If I am accurately informed, the concatenated system of control requires either two sets of motors or else a motor with practically two armatures combined in one—all this equipment being used when starting, half of it being cut out and left idle when running at full speed. In the arrangement described in Fig. 11 of Mr. Waterman's paper; that is, 3 motors practically combined as 2, giving 4 speeds, it is presumed that what may be called the primary motor is large enough to propel a train at full speed on a level and that the others have to be carried along to assist it either in starting or in going up grade, being idle the rest of the time. Question: are the original cost, and the ton-mile expense and maintenance of this extra machinery warranted by any compensating advantages?

The curves in Fig. 11, one of which illustrates the performance of the arrangement just referred to, are most interesting as is also the tabulated comparison of the results. In the last line of the table, watt-hours per ton-mile is apparently the final basis of comparison of motor performance, but there is no reference to the relative carrying capacity of the three 75-ton trains compared in Fig. 11. This comparison of three trains of different types represents fairly well the performance typical of what is required in suburban rapid transit service, but we are left to draw our own inferences regarding ratio between dead and live load in the three cases. Mr. Waterman states that the 75-ton train includes a locomotive, although he does not particularize as to individual weights of cars and locomotives. It is obvious, however, that a locomotive and three trail-cars would weigh considerably more than three multiple-unit motor-cars, particularly if the cars are to be of equally substantial construction; and that a three-phase motor train weighing 75 tons would consist of a locomotive and not more than two trailers, which could not possibly carry more than two-thirds of the paying load possible with the multiple-unit train of three motor-cars with which it is compared. Hence, there is the alternative of diminishing the gross receipts by 33 per cent.—which would probably kill the proposition at the outset from the investor's standpoint—or increasing the tonnage of the train, thereby increasing the number of ton-miles and the watt-hours per ton-mile if the same rate of schedule speed is to be maintained. This results in increasing the capacity and cost of the equipment on the electric locomotive, and, though to a somewhat less extent, the power-station capacity.

In the proceedings of the British Institution of Electrical Engineers, of 1902, will be found a paper by Professor Carus Wilson, entitled, "Electric Traction on Steam Railways in Italy." In this paper is a table which compares the weight, power, and dimensions of the polyphase motor-cars on the Valtellina line with those of the direct-current motor-cars on the Varese line. At the risk of having this table set aside, as ancient history and entirely superseded by recent developments, I would respectfully invite attention to this comparison, which indicates with at least a fair degree of precision the tremendous difference in weight efficiency, and consequently commercial efficiency, between the series type of motor and the three-phase motor.

The three-phase motor-car weighs 53 tons, the direct-current car 40 tons. The three-phase car is 57-ft. long with 56 seats, while the direct-current car is 52-ft. long with 63 seats. Each has 4 motors, of which the total maximum horse power is given in the table as 600 for the direct current and 300 for the alternating-current motors, though it may be that since this paper was published the power of the alternating-current motors has been increased; but whether it has or not, the weight of the 4 alternating-current motors was 15.2 tons, while the weight of the four direct-current motors was 10 tons, and the maximum speed on a level of the alternating-current motors was 37 miles per hour, while that of the direct-current motors was 56 miles per hour.

Therefore, it seems to me that at the very outset of the discussion of the relative merits of the three-phase type and the series type of railway motor (whether alternating current or direct current) we are confronted with a most fundamental question of commercial engineering, and I think it must be admitted by the advocates of the three-phase system that up to the present time, they have not shown that electric railway engineers would be justified in so radically abandoning the precedents hitherto followed, when such an abandonment involves such serious commercial consequences. The watt-hours per ton-mile, as between the three-phase and the other systems, have been shown on paper to give a relatively small percentage in favor of the three-phase system, but the reduction of watt-hours per ton-mile will not interest the business management of a railroad unless the ton-miles of dead load can be compared on a more favorable basis than seems possible with the facts hitherto presented. A railroad desires to carry the largest number of paying passengers for a given transportation unit, and in order to obtain the respectful attention of steam railroad men, electrical engineers must rather be prepared to demonstrate the ability of an electric system to handle a given number of paying passengers with the least possible expense per transportation unit, than to exploit a particular method because of an insignificant percentage gain in power and fuel consumption. I do not dispute the accuracy of Mr. Waterman's power computations, though I shall be interested in trying to analyze them more carefully than time has so far permitted; but we should not be spellbound by an artistic technical demonstration which, though interesting, does not of itself show the maximum financial return for a given investment.

One other question is of great importance; namely, double versus single trolley wires. This seems to have been set aside very lightly, but it is nevertheless a fact that it will cost more to construct and maintain 50 miles of working conductor than it does 25. One object of all engineering is to dispense with complications and unnecessary parts unless some paramount advantage is gained by complication (as is the case where steam locomotives are being constructed on the balanced principle in order to save wear and tear on the track, which on high-speed steam railroads is evidently such an item as to warrant some greater expenditure for motive-power maintenance to counteract it). Everything points to the ultimate adoption of a single working conductor wherever heavy electric railroading is to be expected. There are complications enough with only one working conductor at points of limited clearance to convince railway engineers of the undesirability of increasing the complications by the addition of another conductor.

The three-phase system seems to be better adapted for locomotive than for multiple-unit service. While locomotives are doubtless desirable for long-distance passenger and freight traffic, they are well known to be highly undesirable for suburban traffic, and to the best of the writer's knowledge have not been seriously considered in any of the recent developments in heavy suburban traction. In London they have been abandoned. If the three-phase system cannot compete on even terms with the series motor in multiple-unit traction, it cannot receive from railway men the consideration that would otherwise be accorded to it in the impending development of the electrification of the suburban portions of trunk lines, which is unquestionably the field where the problems of heavy electric traction are now most pressing.

The feature of returning the energy to the line while braking, is brought forward as a leading argument in favor of the three-phase system. Mr. Waterman's demonstrations in regard to this are more interesting than any which have yet appeared, and are entitled to careful consideration. It is a grave question whether its advantages are of sufficient importance in proportion to the entire question of economics for a scheme of electrical equipment involving possibly several millions of dollars. I have been informed that at the time this question was under consideration in London, it was found that not more than possibly 15 per cent. of the total energy involved would be returned to the line by braking—this being a rapid transit proposition with short runs and not very high speeds. As the carrying capacity per transportation unit is of such preponderating importance, in a rapid transit proposition, it is not surprising that a slight gain of 15 per cent. in power consumption should be outweighed by considerations of greater weight efficiency of the rolling stock. The rapid transit problem is one where the return of energy by means of braking might be of considerable advantage, provided at least 50 per cent. of it could be returned, and also provided that no *more important* consideration should be sacrificed to the development of this one. As it seems now, however, the greatest possibilities of braking are in descending long grades in runs of comparatively greater length than those commonly met with in rapid transit propositions, and I am yet to be convinced that the importance given to braking, even on long distance runs, would of itself warrant the adoption of the three-phase system, as opposed to the lighter and less complicated single-phase system.

CHAS. P. STEINMETZ: Mr. Waterman's paper is in phase with the previous paper by Mr. E. J. Berg. Mr. Berg's paper shows what the three-phase motor can do under existing conditions. Mr. Waterman's paper shows what the three-phase motor can be made to do where the constants of the system, as frequency, etc., are chosen, not according to existing conditions, but as the best values for the problem under consideration. I believe it is the purpose of the paper to reopen the discussion of three-phase versus direct-current traction, not of impressing the necessity of discontinuing the direct-current motor and choosing the three-phase induction motor. Too rapid conclusions from comparisons with individual installations must, however, be guarded against, especially with an installation like that on the Valtellina road.

There are a number of problems that will have to be solved before deciding on the best traction system, problems which have not come to the front in the Valtellina plant. After all, this line is a very small one, the total equipment, I understand, consisted of two locomotives at the time the tests were made.

With two locomotives it is true that the violent fluctuations of power incident to three-phase traction would be very greatly reduced by the train slowing down when climbing a hill and so slowing down the generator system; but I do not think it would be desirable nor feasible when a train climbs a hill in the Allegheny Mountains to take so much power as to slow down the generators of the Pennsylvania Railroad system or of the New York Central system. So it is seen that this drawing upon the momentum of the train by dropping the generator frequency may be all right in the Valtellina railroad, but it would not do on a trunk-line system. This naturally would make quite a difference in the record of tests.

There are, furthermore, some data regarding which I would like to get more information. For instance, the extremely high efficiency 96 per cent., of the induction motor, a much higher efficiency, indeed, than I ever had the pleasure of seeing, or have been able to get in any apparatus of this character that I designed.

Now I have said that a number of problems have not been solved. Look at any switchyard, for instance the New York Central yard at Forty-second Street, and see the maze of tracks. At once there will be realized the vast problem of installing in such a switchyard a system of electric power supply utilizing a single conductor, either overhead or third-rail. Now imagine what is to be done to supply this yard with 2 overhead conductors in addition to the ground return. Personally I should hesitate before accepting the responsibility of trying to solve this problem. It is, indeed, the great difficulty and the enormous complications in overhead construction or third-rail construction, in switching, which I consider one of the most serious handicaps of the three-phase system of traction.

The paper says when we come down to low frequency, to 14-cycle, and 0.079 inch air-gaps, that is smaller than railway engineering at the present time considers desirable, we can get a three-phase induction motor to be practically as good as the direct-current motor. If all that exists were swept away, and the reconstructing of the universe were at our disposal, at least in electrical engineering, all constants might be chosen to suit the particular problem in hand, and then possibly a low frequency—14 cycles—might be adopted for electric railroading. Unfortunately this is not the case, and in deciding on frequency, etc., the existing state of the art must be considered so as to adapt the requirements of the problem in hand to the established standards of the electrical industry. For an electric railway having no connection with any other electrical enterprise, we may choose 14 cycles. But such simple conditions never exist. With the exception of a few isolated instances, as the Baltimore tunnel, the New York Central, and the Pennsylvania tunnel, where special and local conditions were fundamental in bringing about a change to electric locomotion, the general trend of development is this: the steam railroad remains a steam railroad but trolley lines parallel it, first in the cities, then from the cities to the suburbs, and then, as high-speed lines, stretching farther and farther. The trolley takes away the local short-distance traffic from the steam railways. Electric express companies begin their inroads into the express business, and when the steam railroad wakes up to the danger and considers electrification, it is not merely to replace the steam locomotive by the electric locomotive, but the steam railway buys up and consolidates competing electric trolley lines, forms them into a network and organizes them systematically as feeders to the trunk-line trains, and for local and commutation traffic. That means that whatever system a steam railroad chooses for operating the main line trains and accommodation trains on the steam track, it must be able to accommodate the existing electric lines, the interurban, and the city trolley lines, as feeders of the main trunk line.

Now I do not believe there is much hope of replacing the city trolley service by any alternating-current system, whether three-phase or single-phase, because for city service the direct current is entirely satisfactory and especially with three-phase, I do not think any self-respecting city would ever permit doubling the already sufficiently ugly overhead network of trolley wires. Furthermore, the troubles from electrolysis, which are formidable now and very difficult to guard against, may be intensified by changing to a low-frequency alternating system because electrolysis exists also with low-frequency. Telephone disturbances also become more serious with an alternating trolley system. This is another problem that still waits for solution. Before low frequency can be seriously considered, one must first make sure how low-frequency, 14-cycle synchronous converters and transformers would work, or how much more expensive they would be, also how 14 cycles would operate a single-phase commutator motor. Furthermore, how the existing railway plants, which are almost always 25-cycle generation and distribution, and which no steam railway could permit to exist in competition, and which no steam railway could replace by three-phase, 14-cycle motors, or replace the converters and transformers by others, could be utilized. The problem is very much more difficult, due to the necessity of considering in the solution of an engineering problem not the particular problem alone, but its relation to everything else that exists.

So the solution of each individual problem involves the solution of a vast number of other problems, and for this reason I do not think there is much chance from the engineering point of view to consider any frequency lower than is standard now, if such a new frequency does not have advantages superior to anything existing, vastly superior to anything shown in Mr. Waterman's paper.

C. O. Mailloux: Mr. Waterman's paper contains the first complete and satisfactory data that we have been able to obtain concerning three-phase traction. The Valtellina line, which I visited twice last year, is a splendid example of the use of three-phase traction. The line itself presents ideal conditions for the application of such a system. But as I had had occasion to see other three-phase lines, I was not quite so much impressed perhaps as I would have been if it had been my first experience in that direction. In Milan, or near Milan, a comparison can be made between the direct current and the alternating-current systems. There is a direct-current (third-rail) line that starts from Milan and runs into a suburban district—the Milan-Varese Porto-Cerese line. A short distance away, at Lecco, the other may be seen (the Valtellina line). The two lines correspond to entirely different circumstances. The Porto Cerese line is a short suburban line of rapid-transit character—not rapid-transit as it is understood up here, perhaps, but certainly more rapid than is contemplated on the Valtellina system, which represents the conditions of what we would call in this country a branch line—a feeder line. The passenger service conditions are not exacting, and consequently a low acceleration will answer the purpose, and it is possible to adapt the three-phase system. The equipment itself is very well worked out. The fact that constant speed can be maintained, and energy recuperated, is of great theoretical interest, undoubtedly, but practically it is not always of so much importance. I was somewhat surprised to find that even the partisans of three-phase traction—some of the engineers of Messrs. Ganz & Co.—were not so sanguine as to the results that could be obtained with it or be expected from it, as Mr. Waterman himself seems to be. While it is theoretically true that part of the energy can be recovered with a constant-speed system, yet, could it not be done as well or better with some other system of recuperating energy? Would it not be more practical to run cars at lower speed on up grades, and do the spurting by coasting on down-grades, if one wants to make up lost time? Under these conditions all the energy which is being given to the car is recovered, with no transformation losses. This results in a pure kinetic reaction. I will not deny that the system has some qualities; it seems to me to be an idea beautifully worked out. The weak features of it seem to me, as they do to Mr. Steinmetz, to be the necessity of two lines, and more especially the limitations of these two lines in regard to potential differences. I carefully investigated that point, and found the advocates of the system would not recommend any higher working line potential than 3 000 volts. Higher voltages than that are not to be hoped for. Now, I submit that before steam lines can be successfully electrified—before locomotives of from 1 000 to 2 000 h.p. can be run—current must be delivered to a car at a higher potential than 3 000 volts, because at lower potentials the trolley line would be too large and too unwieldy. Energy cannot be delivered to a motor by means of such large current volumes. The line potential must be raised; 6 000 volts has been advocated as a suitable line potential, but even that is too low. It must be raised to 10 000 or 15 000 volts, or even more. Now, to do that, it is out of the question to attempt to use more than a one-line conductor, for feeding or contact line. There must be only one trolley wire, or if there are two, they must be at the same potential, and not electrically related to each other in the same manner as they would be in a polyphase system such as used on the Valtellina line.

Another thing to be considered is high speed. With trolley lines suspended as they are there is a serious trouble due to the beating of the current collector against the wires. I noticed, particularly at Valtellina, that the trolley lines did swing very perceptibly. I am afraid that question would be a very serious one and a difficult problem to solve, for the "catenary" suspension system is out of the question, there being already too much complication, even for a single-phase line.

The three-phase system is adapted to certain cases, but it seems to me that these cases are more frequently to be met with in Europe than here. I cannot help feeling that, all things considered, the cases that the direct-current motor will not satisfactorily meet can best be met by a monophase alternating-current system. Up to the present time there have been no cases of single-phase electric locomotives equipped with motors of relatively great size; that is, no electric locomotives of such power perhaps as the latest three-phase locomotives that have been put on the Valtellina line. This I regard as merely a question of development. I am told that manufacturing companies have recently taken steps to bring out locomotives of large power equipped with single-phase motors. I believe that when this is done these motors will do practically as well in the way of efficiency as the three-phase system, while there will be great advantages in other respects. I do not look with the same feeling of confidence on the ability to maintain a system in commercial operation, with low cost for maintenance, with such small clearances. Experience with practical railroad men leads me to believe that many of them would object to it very seriously on that ground if on no other. They consider that the clearance of the direct-current motor, large as it seems compared with such cases, is already small enough, and that it might be increased rather than decreased.

S. M. Kintner: In regard to alternating-current electrolysis: I do not know the frequencies that Mr. Steinmetz has in mind in which this action would take place. I do know that I have recently examined pipes buried in the earth, pipes that had a potential of 25 volts at 25 cycles applied to them for a period of 8 months. On examining these pipes at the end of that time I was unable to notice any appreciable loss in comparison with another pipe buried a short distance away in practically the same character of earth but not subjected to any electrical action.

Chas. P. Steinmetz: I have my information from the Bell Telephone Co., which has made a very extensive investigation of alternating-current electrolysis. I was very much surprised at the formidable destructive results observed.

H. G. Stott: In reading railroad papers I often note the great emphasis that is placed on the kilowatts per ton-mile. Now the electric lighting stations teach us that the cost of energy is not proportional simply to the kilowatts, but must have relation to the load-factor, that is to say, invariably the charge for the first hour is greater than for succeeding hours. Now the cost of producing a current per hour varies with the load-factor. Because we can save a few kilowatt-hours does not prove that one motor or the other is the better of the two. A condition to be looked at from the central-station point of view, is to get a good average load-factor, but whether the three-phase motor or the direct-current motor will give the better load-factor, I am not prepared to say.

The recuperation of power is undoubtedly a good feature. I wish to place emphasis upon this point. When one system uses 1 000 kw-hr., while another uses 1 200 kw-hr., the one find that even the partisans of three-phase traction—some of the engineers of Messrs. Ganz & Co.—were not so sanguine as to the results that could be obtained with it or be expected from it, as Mr. Waterman himself seems to be. While it is theoretically true that part of the energy can be recovered with a constant-speed system, yet, could it not be done as well or better with some other system of recuperating energy? Would it not be more practical to run cars at lower speed on up grades, and do the spurting by coasting on down-grades, if one wants to make up lost time? Under these conditions all the energy which is being given to the car is recovered, with no transformation losses. This results in a pure kinetic reaction. I will not deny that the system has some qualities; it seems to me to be an idea beautifully worked out. The weak features of it seem to me, as they do to Mr. Steinmetz, to be the necessity of two lines, and more especially the limitations of these two lines in regard to potential differences. I carefully investigated that point, and found the advocates of the system would not recommend any higher working line potential than 3 000 volts. Higher voltages than that are not to be hoped for. Now, I submit that before steam lines can be successfully electrified—before locomotives of from 1 000 to 2 000 h.p. can be run—current must be delivered to a car at a higher potential than 3 000 volts, because at lower potentials the trolley line would be too large and too unwieldy. Energy cannot be delivered to a motor by means of such large current volumes. The line potential must be raised; 6 000 volts has been advocated as a suitable line potential, but even that is too low. It must be raised to 10 000 or 15 000 volts, or even more. Now, to do that, it is out of the question to attempt to use more than a one-line conductor, for feeding or contact line. There must be only one trolley wire, or if there are two, they must be at the same potential, and not electrically related to each other in the same manner as they would be in a polyphase system such as used on the Valtellina line.

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The recuperation of power is undoubtedly a good feature. I wish to place emphasis upon this point. When one system uses 1 000 kw-hr., while another uses 1 200 kw-hr., the one that takes 1 200 kw-hr. should not be condemned because it actually may cost no more to produce 1 200 kw-hr. than to produce 1 000 kw-hr.

C. L. de Muralt: Some of the ideas brought out during the discussion are referred to in my own paper, but I should like to emphasize a few of them.

It has been suggested by Mr. Smith that a three-phase system requires a considerably larger power station, if the trains are to run up-grade at full speed. First of all, there is no reason why three-phase trains should not also make use of a lower speed when going up grade; but even if they are made to maintain the same speed over the entire line, the power-station need not necessarily be larger on this account. With conditions as they now exist on our normal steam railways, the additional energy consumed by the trains when going up grade at full speed will in most cases not be any greater than the additional energy required during the period of acceleration. The peak caused by the grade will therefore not be higher than the peak caused by the starting of a train. The starting peaks will have to be taken into consideration when designing the power-station; but it does not matter very much, whether peaks of the same sizes are used to take trains up grade at full speed, or whether lower peaks are used and consequently the speed on grade reduced.

The question was raised by Mr. Steinmetz, whether a train, climbing a very steep grade somewhere in the Allegheny Mountains, might not pull down the speed of the entire Pennsylvania system. It is easy to see that this is not so, because if there is only one train using an excess of energy against a whole lot of trains running under normal conditions, then that one train may take two or three times as much power as it will take ordinarily and yet it will not be able to affect in any way the system as a whole. It is possible under conditions which Mr. Steinmetz has called favorable, when there are only two trains running at the same time as on the Valtellina line, that one train will influence the other train to a certain extent. As a rule, however, the three-phase system will be considered only for long roads with comparatively heavy traffic, and it will therefore be reasonable to presume that in most cases several trains will be running on the level while one may be climbing a grade.

The question of comparative weight of equipment can hardly be treated in a general manner. It may be quite possible to find an exceptional case where there is a very heavy and very long grade, so that a three-phase motor, if made to climb that grade at full speed, will have to be heavier than a continuous-current motor, which is allowed to slow down on the grade. But the grades found on most of our railroads are such that the extra energy required by the motor when going up grade at full speed can be dissipated without difficulty, and the grade will therefore in no way influence the weight of the motor. On the other hand, it is well-known that for the same capacity and the same heating the induction motor will be lighter than the continuous-current motor. It is therefore safe to say that the three-phase motor will in most cases prove to be lighter and not heavier than the continuous current motor. The actual three-phase motors already built for railway purposes bear this out in every respect.

The criticism that three-phase motors, when used in concatenation, will have one of the motors dragged along useless most of the time, is also misleading. The fact is of course perfectly true, but it is no disadvantage inherent to the three-phase system; for it simply means that a certain part of the weight of the equipment is not used continually, and exactly the same thing is true of the continuous-current system. The continuous-current motor is under a very much greater load when starting than when running at full speed, and it is therefore also using its full weight only during a short period and carrying dead weight for the rest of the time. If the motor curves are examined it will be found that in this respect also the three-phase motor is superior to the continuous-current motor.

The double-contact line is undoubtedly a theoretical drawback for the three-phase system, and the only thing that can be stated in this connection is that there are now quite a number of three-phase railroads doing business, some of them for from six to ten years, and no difficulty has been met with in this respect. If you will accept a very personal proposal, I may say that I am willing to install and operate a double overhead line on whatever road you may choose, no matter how complicated it may be. Switchyards are no difficulty if properly treated. The Valtellina line mentioned in Mr. Waterman's paper has switchyards as complicated or more complicated than any I know of in this country. They are not the same in regard to size, but in regard to complication they are worse, and comparing them to the New York yard of the New York Central, for instance, would simply mean multiplying the difficulties, but not increasing them.

With reference to the highest pressure to be used on the contact line I do not quite agree with Mr. Mailloux. It is of course quite true that, if very high pressures are used, substations may be entirely avoided. But stationary transformer sub-stations are easily handled, and it seems to me to be preferable to use pressures which will allow of absolutely safe and comparatively easy insulation, as long as the current to be taken is not excessive. In most cases this can be done with lower pressures than those mentioned by Mr. Mailloux.

F. N. Waterman: The discussion of my paper indicates that it has been somewhat misunderstood. The purpose of the paper is to call attention to certain interesting facts which indicate that the disadvantages of the three-phase motor for traction purposes have been largely exaggerated, and certain of its advantages have been underestimated or overlooked. One idea that was prominently in mind was the financial value of the air-gap, and the effect of European experience, which indicates that, with three-phase motors at least, air-gaps much smaller than are used here are perfectly practicable. If bearings of equal size can be employed, the smaller air-gap should be equally available for the single-phase motor and almost equally useful.

With regard to the heating of three-phase motors; this is a question of internal losses, and since the efficiency of the motor is at least as high as that of the series motor it will not heat more. The distribution of the heat, however, will be different, and will also vary with the character of the service. In starting, the rotors will have greater iron losses than when running; although this energy has to be radiated it does not represent a proportionate increase in total loss because it represents actual torque in the motors, and hence a reduction of copper loss for the same starting effort. In running, the losses are chiefly in the primary, and occur, therefore, where they are most readily radiated. On the usual basis of rating by rise of temperature in one hour, the three-phase equipment will weigh less than the direct-current equipment by at least from 15 to 20 per cent.[1]

It is contended that any motor to be useful for traction purposes must be capable of operating with direct current. In some cases this is true, and the Ganz Co. is now equipping two suburban lines with three-phase motors designed to run with direct current through the towns along the lines. The control is not complicated, and since the same rheostats and controllers are used for both the direct and three-phase currents the weight of the equipment is not materially increased. The same motors can operate as single-phase motors at the expense of some extra weight of control equipment.

It has been said that the utility of recuperation depends upon the presence of other trains. This is true, as pointed out in the paper, provided the train returns more energy than can be absorbed by the system in making good its constant losses. Should the rate of recuperation exceed the constant losses the whole system would speed up until the losses equalled the energy being returned. The acceleration of the train is, however, readily recognized by the motorman, and a slight application of the brakes will reduce the returned energy to that which the system is able to absorb at normal speed, so that in practice this is not a serious matter.

Mr. Smith has criticised the side-bar drive as unbalanced. This is hardly germane to the subject, but a moment's reflection will show that it is not true, since every part has a circular motion and can be perfectly balanced. It is only the recip-

1. See article by H. M. Hobart, *Electrician*, London, 1904.

rocating parts of a steam locomotive that give rise to unbalanced conditions. The peculiar advantage of this method lies in the fact that it renders possible a spring support for the entire motor weight, and insures proper distribution of load between the motors.

The statement made by Mr. Mailloux, that the Valtellina line is peculiarly favorable to three-phase traction is hardly in accord with the general understanding. The one thing universally agreed upon in this country is that great irregularity of profile and the presence of many curves requiring reduction of speed mark a condition particularly unsuited to the characteristics of the three-phase motor. I understand that one of the objects in view in selecting this line was to put the system to the severest test. The remarkable uniformity of the load curve and the high average efficiency indicate that the three-phase motor has an adaptability it has not hitherto been credited with.

Mr. Steinmetz has commented on the frequency of 14 cycles as impracticable, having evidently overlooked the fact that all the calculations in the latter part of the paper are based upon 25 cycles, the cost of the generating and distributing system being only 71.5 per cent. of that for the direct current in Mr. Berg's own run, while it is reduced to 56 per cent. with the run made in the correct manner. Low frequency is by no means a necessity and it was only assumed in the earlier calculations because motor curves for 25-cycle motors were not available. Even as to the low frequency, however, there is room for a difference of opinion where the question arising is, as it was in the case of the Valtellina line, the selection of a frequency best suited for the operation of an entire railroad system. Mr. Lamme has recently expressed the opinion that a large railroad could afford to select its frequency independently of general practice.

Mr. Steinmetz has also commented on the high efficiency of the motors used. The actual efficiency of the motors of the large Valtellina locomotives is 95.6 per cent., while 96 per cent. is quite attainable. The results shown by the paper are not dependent upon such efficiencies and the calculations in the later portion are not based upon motor curves showing exceptionally high values. A lack of time and space prevented their reproduction.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

HEAVY TRACTION PROBLEMS IN ELECTRICAL ENGINEERING.

BY CARL L. DE MURALT.

It is proposed in the following chapters to consider the relative advantages presented by the various electric systems available, with a view to determine which, at the present state of the art, is best adapted to handle heavy traction on through lines.

Broadly speaking, all traction on rails can be subdivided into the following three classes:

1. Street railways, devoted almost exclusively to passenger traffic, operating over restricted areas, with single cars, at comparatively regular and short intervals and with frequent stops, the maximum speed being limited by the use of the public highways.

2. Rapid transit systems, comprising elevated railways, subways, suburban, and interurban lines, operating over their own right of way a traffic otherwise similar to that handled by street railways, the main difference being the use of somewhat larger units, higher speeds, and greater distances between stops.

3. Through lines, characterized by a combination of passenger and freight traffic, handled over great distances, in large units, at longer and not necessarily regular intervals, and with stops few and far between. This latter condition, however, is one of degree, and this class is meant to include through trains of the local as well as the express kind, but not suburban trains, which properly belong to the second class.

In street railway and rapid transit systems a very high rate of acceleration plays an important part. Therefore these systems quite generally use their motive power distributed over as many axles as possible, either in single cars or in trains under multiple-unit control. The motors used must be capable of being started and stopped in rapid succession without undue waste of energy.

In through line traffic quick acceleration is of less importance. Therefore the simpler method of concentrating the motive power in one or more locomotives is, and most probably will be, employed almost exclusively. Motors in this service are called upon to run at practically constant speeds for long periods of time.

It is quite generally recognized nowadays that electricity is the best kind of motive power for practically any proposition belonging to one of the first two classes. And more than that, it is quite generally taken for granted that the proper electric motor to be used in such instances is the continuous-current series motor, or perhaps of late sometimes the single-phase alternating-current motor of the commutator type, which motor, after all, is a very close kin to the continuous-current series motor. Whether it might not be preferable to use the three-phase alternating-current induction motor in some instances is not easy to say. At present the fact must be taken into consideration that the choice of motor is quite frequently dependent not so much on the motor characteristics as on outside circumstances, such as for instance the possibility of operating rapid transit trains over adjoining street railway tracks, etc. And it is therefore quite likely that the series motor will continue to be used in the great majority of cases belonging to the first two categories of above classification.

This paper will therefore not touch on this subject at all, but will consider only problems relating to traction on through lines. This kind of traffic has thus far been held by many to be outside the sphere of the electrical engineer, though it may prove in the end to be of even greater interest to him than either of the two other kinds.

The great variety of conditions governing all practical railroading makes it appear inadvisable to deal with this question in too general a manner. It is therefore considered essential to take an actual case, on which a detailed report was worked out some time ago, and to present the data obtained from the investigation of this specific case in such form that conclusions may be drawn which will apply to similar cases.

General Conditions. The conditions governing the case in question may be stated briefly as follows:

From a point *A* (terminal city) two lines branch out, both now operated by steam but for which electric operation is proposed. A-B is a division, 175 miles long, of a regular trunk-line system. A-C is an ore road, 49 miles long. Both lines have single track, except at some of the stations where a second track of about 3000 feet in length is installed. The total track mileage is 182 for A-B and 51.5 for A-C.

There are 16 stations between A and B, more or less evenly distributed over the entire length, and four stations between A and C. A and B are situated at about the same elevation above sea level, while C is about 550 feet higher, which gives an average grade of 0.2 of one per cent. in the direction A to C. The maximum grade on A-B is one per cent., and the maximum grades on A-C are 0.6 of one per cent. in the direction A to C and 0.2 of one per cent. in the direction C to A. The maximum curvature on either road is four degrees. The gauge is normal.

The traffic on A-B consists of eight trains per day in each direction, two local passenger trains stopping at all stations, one express train stopping at A, B, and one intermediate point, one express train stopping at A and B only, two local freight trains stopping at all stations, and two through freight trains stopping at A, B, and one intermediate point. The weight of these trains without locomotive is as follows: local passenger trains 125 tons, express trains 300 and 450 tons respectively, local freight trains 600 tons average, through freight trains 850 tons from A to B and 1200 tons from B to A. The free running speed is about 25 miles per hour for the local passenger trains, 35 miles per hour for the express trains, 17 miles per hour for the local freight trains, and 20 miles per hour for the through freight trains.

The traffic on A-C consists of three ore trains per day in each direction, those going from C to A are loaded and weigh about 3000 tons without locomotive, those from A to C are empty and weigh about 800 tons net. The free running speed of these trains is about 15 miles per hour.

It may be interesting to note that the heaviest steam locomotive now in use on these lines weighs 134 tons total, of which 83 tons are on drivers.

Train Powers. In order to calculate the tractive efforts, for which the locomotives have to be designed, it is necessary first of all to determine the values which are to be given to the various resistances opposing the movement of the trains. The following formulas were used to obtain resistances in pounds per ton of total train weight:

Friction resistance (wind and bearings) when running on level track at different speeds, $R_f = 5 + 0.008\,v^2$, where v = speed in miles per hour.

Values for R_f:		
	Slow Speeds	5
	10 miles per hour	6
	15 " " "	7
	17 " " "	7.5
	20 " " "	8
	25 " " "	10
	35 " " "	15

Resistance due to grade, $R_g = 2000\,s/100$, where s = grade in per cent.

Values for R_g:		
	on grade of 0.2 per cent	4
	" " " 0.6 " "	12
	" " " 1 " "	20

Starting resistance, $R_s = a \times 91.2 \times (1 + p)$, where a = rate of acceleration in miles per hour per second, and p = correction for fly-wheel effect of rotating parts. p in this case was found to be about = 0.08, thus making R approximately equal to $a \times 100$.

Values for R_s:		
	0.08 miles per hour per second	8
	0.1 " " " " "	10
	0.18 " " " " "	18
	0.3 " " " " "	30

The approximate weights of electrical locomotives for the proposed service were found to be: 40 tons for the local passenger trains, 75 tons for the express trains and the local freight trains, and 90 tons for the through freight and the ore trains. Adding these locomotive weights to the train weights given above, the tractive efforts for the different kinds of trains under various conditions were found to be as follows:

	Weight with locomotive. Tons.	Speed. Miles per hr.	Running tractive effort. On level.	On max. grade.	Rate of acceleration. Miles per hr. per sec.	Starting tractive effort. On level.
Local passenger trains	165	25	1 650	4 950	0.3	5 800
Express train I	375	35	5 600	13 100	0.18	8 600
Express train II	525	35	7 900	18 400	0.18	12 100
Local freight trains	675	17	5 100	18 600	0.1	10 100
Through freight train, A to B	940	20	7 500	26 300	0.1	14 100
Through freight train, B to A	1290	20	10 300	36 100	0.1	19 350
Ore train, A to C	890	15	6 200	16 900	0.1	13 350
Ore train, C to A	3090	15	21 600	34 000	0.08	40 200

The rates of acceleration used may seem low, but they are better than the rate now obtained from the steam locomotives; and even the lowest rate of 0.08 miles per hour per second will bring the ore train up to full speed in three minutes, which is perfectly satisfactory for this kind of service. The advantage of comparatively low rates of acceleration lies in the fact that the tractive efforts required for starting are in this case but slightly higher than the average full speed running efforts. The maximum possible tractive efforts, which could be obtained from the three types of locomotives with a coefficient of 25% for adhesion between rails and wheels, would be 20 000, 37 500, and 45 000 pounds per ton respectively, which is well above the efforts actually required, and which would even suffice for starting the trains on the maximum grade with a very fair rate of acceleration.

The power which the motors of the different types of locomotives will have to be capable of giving while running at full speed is found by the formula: h.p. = tractive effort in pounds per ton × speed in miles per hour/375, and the values obtained are tabulated herewith.

	Average horse power.	Horse power on max. grade.
Local passenger trains	110	330
Express train I	520	1 220
Express train II	740	1 720
Local freight trains	230	840
Through freight trains, A to B	400	1 400
Through freight trains, B to A	550	1 930
Ore trains, A to C	390	680
Ore trains, C to A	370	1 360

It will be remembered in this connection that there is an average grade of 0.2 per cent. against the trains going from A to C and in favor of those going from C to A, which makes the average power taken by these trains nearly the same, although the power taken when running at full speed on the level is 250 h.p. for trains from A to C and 860 h.p. for trains from C to A.

Preliminary Considerations. It may be well to realize that the problem under consideration can be solved in a great many different ways without encountering extarordinary difficulties from a technical standpoint. It is not at all impossible to solve it by the use of a system employing continuous-current motors connected all in series on the constant-current plan; or by a system using motor-generator sub-stations along the line, the motors of these motor-generators being of the continuous-current type and all connected in series on a constant-current circuit; or by any one of several other systems.

But in this particular instance four systems only were seriously considered:

1. Continuous-current series motors on the locomotives, fed from synchronous-converter sub-stations along the line, which sub-stations receive three-phase alternating current from the power station.

2. Three-phase alternating-current induction motors on the locomotives, fed from three-phase transformer sub-stations along the line, which receive three-phase alternating current from the power station.

3. Single-phase alternating-current motors on the locomotives, fed from single-phase transformer sub-stations along the line, which receive either single-phase or polyphase alternating current from the power station.

4. Continuous-current driving motors, fed from motor-generators on the locomotives, the latter receiving single-phase alternating current from the power station, either direct or through transformer sub-stations along the line.

Actual numerical data were available only concerning the first two of these four systems and they were therefore worked out in detail, while a comparison of the characteristics of the other two systems led to conclusions as to their applicability for the case under consideration.

Energy Consumed by Trains. The following tables show some figures obtained during the calculations made to find the actual energy consumed by the different trains during their runs between terminals. The tractive efforts and the horse power required to haul each train were obtained for consecutive points of the run according to profile of road and time table. Then with the motor diagrams the kilowatt input at each point was calculated, a load-curve plotted for the entire run and from this curve the total kilowatt-hours and the average kilowatts were obtained, as well as the number of watt-hours consumed per ton-mile.

The same rate of acceleration was used for both systems. In stoping, the trains were allowed to coast down to about half speed, when the brakes were applied so as to bring the trains to standstill with a rate of retardation of about 0.75 miles per hour per second.

Series-parallel control was employed for the continuous-current motors, and these motors were geared so as to run at point of maximum efficiency for full speed. Ordinary rheostatic control was used for the three-phase motors, and they were geared so that full speed corresponded to synchronous speed less slip.

	Continuous current.		Three-phase current.	
Local Passenger Train, 165 tons including locomotive. 25 miles per hour.				
Rate of acceleration, miles per hr. per sec.	0.3		0.3	
Total time running, seconds	26 667.		26 667.	
Average running speed, miles per hr.	23.6		23.6	
Total kw.-hr. consumed	625.44		627.76	
kw-hr. per train mile	3.57		3.58	
Watt-hours per ton mile	21.6		21.7	
Average kilowatts required running	84.43		84.70	
Express Trains I and II, 375 and 525 tons respectively, 35 miles per hour.				
Rate of acceleration, miles per hr. per sec.	0.18	0.18	0.18	0.18
Total time running, seconds	18 315.	18 157.	18 315.	18 157.
Average running speed, miles per hr.	34.3	34.6	34.3	34.6
Total kw-hr. consumed	2 202.4	3 015.3	2 162.	2 953.4
kw-hr. per train mile	12.6	17.2	12.35	16.85
Watt-hours per ton mile	33.6.	32.8	33.	32.2
Average kilowatts required running	433.	597.8	425.	585.6

	Continuous current.		Three-phase current.	
Local Freight Trains, 675 tons including locomotive, 17 miles per hour.				
Rate of acceleration, miles per hr. per sec.	0.1		0.1	
Total time running, seconds	39 014.		39 014.	
Average running speed, miles per hr	16.15		16.15	
Total kw-hr. consumed	1 939.5		1 [illegible]46.9	
kw-hr. per train mile	11.05		11.12	
Watt-hours per ton mile	16.4		16.5	
Average kilowatts required running	178.9		179.6	
Through Freight Trains, 940 and 1290 tons respectively, 20 miles per hour.				
Rate of acceleration, miles per hr. per sec.	0.1	0.1	0.1	0.1
Total time running, seconds	31 766.	31 766.	31 766.	31 766.
Average running speed, miles per hr	19.8	19.8	19.8	19.8
Total kw-hr. consumed	2 869.7	3 936.9	2 810.22	3 863.8
kw-hr. per train mile	16.4	22.45	16.05	22.1
Watt-hours per ton mile	17.5	17.4	17.1	17.1
Average kilowatts required running	325.2	446.2	318.5	437.9
Ore Trains, 890 and 3090 tons respectively, 15 miles per hour.				
Rate of acceleration, miles per hr. per sec.	0.1	0.08	0.1	0.08
Total time running, seconds	12 251.	12 345.	12 251.	12 345.
Average running speed, miles per hr	14.4	14.3	14.4	14.3
Total kw-hr. consumed	1 028.87	1 090.7	1 020.53	1 115.6
kw-hr. per train mile	21.	22.25	20.9	22.7
Watt-hours per ton mile	23.6	7.2	23.5	7.35
Average kilowatts required running	302.3	318.1	299.8	325.3
Total kilowatt-hours per day for all trains.				
4 local passenger trains	2 501.76		2 511.04	
2 express trains I	4 404.8		4 324.	
2 express trains II	6 030.6		5 906.8	
4 local freight trains	7 758.		7 787.6	
2 through freight trains from A to B	5 739.4		5 620.44	
2 through freight trains from B to A	7 873.8		7 727.6	
2 ore trains from A to C	2 057.74		2 041.06	
2 ore trains from C to A	2 181.4		2 231.2	
Total energy consumption, kw-hr	38 547.50		38 149.74	
Average daily load, kilowatts (24 hours)	1 606.15		1589.57	

It will thus be seen that there is not much difference between the two systems as far as actual energy consumed by the motors is concerned; this result appears perfectly natural when one considers the fact that, while the continuous-current motors are somewhat more efficient at starting, the energy consumed during the starting period is only a small part of the total energy required for such comparatively long runs, and when running at full speed the alternating-current induction motors have a higher efficiency than the continuous-current motors. Through the employment of cascade control for the three-phase motors, with its corresponding saving during starting and returning of energy during braking, the three-phase motors would probably show up more favorably all the way through. But in any case the difference between the two systems on this account will be extremely small and it will hardly be more than one or two per cent. one way or the other.

Line Equipment. While the amount of energy used by the two types of trains may thus be taken as being approximately equal, there is an appreciable difference in the cost of delivering this energy to the trains. First of all the contact line from which the current is collected by the moving trains can not be of the same type for the two systems. The reason for this is mainly the limit in pressure imposed on the continuous-current system by the properties of continuous-current machinery. While it is possible to build alternating-current motors for practically any reasonable pressure, continuous-current motors have thus far been limited in most cases to a pressure in the neighborhood of 650 to 700 volts. This is not an absolute limit, however, and in the present instance a pressure of 1000 volts was chosen, which would probably be found feasible for motors of the size under consideration.

Even at this pressure the current to be collected is very heavy. The express locomotive will require inputs of 1450 kw., the freight and ore locomotives inputs of 1600 kw. At 1000 volts this represents currents of 1450 and 1600 amperes respectively, which would be still further increased by the inevitable drop in pressure. Such currents can not be collected with safety from an overhead trolley line and recourse must be had to some heavier construction, either in the shape of a third rail at practically track level, or a similar rail suspended overhead over the center or the side of the track. With an alternating-current pressure of 5000 volts in a three-phase system, the maximum current in one phase will be 185 amperes, which could readily be taken from a copper overhead line of the familiar construction.

The total track mileage was given as 233.5. A third-rail equipment for this road would cost:

About 228 miles conductor rail, 80 lb. per yard, $35 per ton	$558 600.00
Fish-plates and bolts, $65 per mile	14 820.00
Insulators and fastenings, 120 384 at 50 cents	60 192.00
Bonds, $160 per mile	36 480.00
Cables for crossings, 9600 yards at $3	28 800.00
Erection, $600 per mile	136 800.00
Total	$835 692.00

and about $130 000 additional if a wooden protection for the rail is desired.

An overhead double-trolley line would cost:

Copper wire, 2×233.5 miles of No. 000, 15 cents per pound	$177 012.00
Wooden poles, 12 024, at $6	72 144.00
Brackets and special insulators, 12 024, at $10	120 240.00
Overhead switches, 42, at $80	3 360.00
Erection, $800 per mile	186 800.00
Total	$559 556.00

Sub-stations. These should preferably be spaced so as to coincide as much as possible with the railroad stations. This would mean an approximate distance between sub-stations of 10 miles. The maximum number of trains between two substations is two. Placing these two trains in the most unfavorable position and letting both take the maximum possible input, the drop in third rail will be found to be about 70% and the drop in overhead trolley line about 15%. While these values are very high, they can readily be accepted as extreme maximums, which in all probability will be reached but on very rare occasions. Should smaller maximum drops be desired, feeders may be added, which would of course be very much cheaper for the three-phase line than for the continuous-current line. It is possible to allow a greater drop in a continuous-current system, because a reduction in pressure will only affect the speed of the motors and not their torque. In an alternating-current system, however, the drop must be kept within comparatively narrow limits, because any decrease in pressure will seriously influence the torque of the motors, while the speed will not be affected.

The sub-stations in either system must be dimensioned so as to be capable of furnishing a maximum of 1200 kw. each, which corresponds to the maximum load condition represented by two of the heaviest trains approaching the sub-station simultaneously. The average load on these sub-stations is however much smaller; and as far as heating is concerned the sub-stations need only be dimensioned for the square root of the square integral of the current required. The varying density of traffic and the slight differences in distance between sub-stations, if the latter are placed conveniently near railway stations, result in slightly different capacities for the different sub-stations. With a view to ease in operation it is preferable to make them all of the same size, and the normal average capacity per sub-station was found to be about 350 kw. It is easy to design a stationary transformer of 350 kw. normal continuous capacity, which will be able to give 1200 kw. for short periods of time with a drop in pressure not exceeding six or seven per cent. The same can not be said of a synchronous converter, which could hardly be built for more than say 100 per cent. overload. It will therefore be necessary either to add storage-batteries to the continuous-current sub-stations or else to use synchronous converters capable of furnishing 600 kw. in normal continuous service and 1200 kw. for short periods of time. The latter alternative proved to be the more economical in the case under consideration. The cost of sub-stations for the two systems thus worked out as follows:

23 synchronous-converter sub-stations, complete, with step-down transformers, synchronous converters and switch gear, at \$24 000............\$552 000.00

23 transformer sub-stations, complete, with stationary transformers and the necessary switch-gear, at \$2100....................................\$ 48 300.00

Transmission Line. The high-pressure transmission line may be the same in both cases. The greater amount of energy which has to be transmitted in the continuous-current system, due to the greater losses in this system, will of course increase the drop in the transmission line to a certain extent. But we have seen above that a somewhat greater maximum drop is permissible in the continuous-current system. The high-pressure line proposed for the railroad under consideration was estimated to cost a total of $679 860.00, which amount would allow for entirely separate poles for this line. Some might suggest using the poles of the contact line in the alternating-current system. But this seems open to objections and it would appear to be advisable to make the transmission line entirely independent in either case, in order to secure the greatest possible safety against breakdown. The above amount therefore holds good for the continuous-current and the three-phase alternating-current system.

Power Station. When we finally come to consider the power station, we find that its normal capacity will be governed by the average energy which has to be supplied to the trains plus the losses occasioned by the transmission of this energy from the power station to the trains. These losses are composed of the losses in contact line, losses in sub-station machinery, and losses in transmission line. The average energy supplied to the trains was found above to be about 1600 kw. and practically the same for the continuous-current and the three-phase alternating-current system.

To calculate the losses in the contact line accurately would be an extremely tedious task on account of the constantly changing load conditions. But an approximate calculation showed the average energy lost in the third rail of the continuous-current system to be about seven per cent of the energy required by the trains, or about 7% of 1600 kw. = 112 kw., while the average energy lost in the overhead line of the three-phase system is about 2% of the energy delivered or about 2% of 1600 kw. = 32 kw.

The total losses in the synchronous converters are a combination of the friction and iron losses and of the copper losses. The first two are practically constant and correspond to about three per cent of the normal capacity of the synchronous converters, or 3% of 13 800 kw. = 414 kw. The copper losses are proportional to the energy converted and under normal conditions will represent about two per cent. of that energy, or 2% of (1600+112) kw. = 34 kw.

Similarly the transformer losses may be divided into iron losses, equal to about 1.5 per cent. of the normal transformer capacity or 1.5% of 8050 kw. = 121 kw. and into copper losses, equal to about one per cent. of the energy transformed, or 1% of (1600+112+414+34) kw. = 22 kw. in the continuous-current system, and 1% of (1600+32) kw. = 16 kw. in the three-phase system.

The losses in the high-pressure transmission line may be taken as two per cent. of the total transmitted energy in either case, though this percentage will be a trifle less in the three-phase system than in the continuous-current system. The energy to be delivered to sub-stations in the continuous-current system is 1600+112+414+34+121+22 = 2303 kw., the losses therefore 2% of 2303 kw. = 46 kw. In the three-phase system 1600+32+121+16 = 1769 kw. have to be transmitted, making the losses 2% of 1769 kw. = 35 kw.

We thus find the total average energy which has to be generated at the power station for the movement of the trains as follows:

	Continuous current.	Three-phase current.
Energy supplied to trains	1 600 kilowatts	1600 kilowatts
Losses in contact line	112	32
" " synchronous converters	448	—
" " step-down transformers	143	137
" " transmission line	46	35
Total	2 349 kilowatts	1804 kilowatts

This represents an efficiency of transmission of about 68 per cent. for the continuous-current system and of about 88 per cent. for the three-phase alternating-current system.

As compared with the average consumption of 1600 kw., the maximum energy consumption at the trains was found from the time-table to be 2475 kw., occasioned by seven trains running at schedule speed and two trains accelerating. A second peak in the load curve of 2130 kw. is caused by five trains running and three trains accelerating. The efficiency of transmission at the moment of these maximum loads will be about 71 and 89 per cent. respectively and we thus find that the power station for the continuous-current system may be called upon to furnish as a maximum 3490 kw., while the greatest demand on the power station for the three-phase system will be 2780 kw.

Adding to these values and to those found above for the average load, an amount of say 500 kilowatts for switching service and lighting of stations, etc., the total load on the power station of the continuous-current system will be about 2850 kw. on the average and 3990 kw. as a maximum, and the total load on the power station of the three-phase system will be about 2300 kw. as an average and 3280 kw. as a maximum.

In the present instance the power would be bought from an already existing water-power plant at a certain fixed sum per horse power per annum. But the cost of water-power development is known to have been $145 per horse power and for the sake of comparison this figure was used to establish the first cost of installation for the two systems. While the generators and step-up transformers could be made to stand an overload of 50 per cent. for several hours and the electric equipment can thus be dimensioned directly for the average output required, the turbines could be overloaded only about 20 per cent. and it was thus made necessary to provide for 5000 h.p. in the continuous-current system and for 4000 h.p. in the three-phase system. The cost of the power stations thus compares as follows:

Power station for continuous-current system, 5000 h.p. at $145 .... $725 000.00
Power station for three-phase system, 4000 h.p. at $145 .... $580 000.00

In the case of steam or gas power stations, the first cost of prime movers would be less. But, if the cost of fuel were capitalized and added, the total cost would be found to be about the same.

First Cost of Installation. If we now make a summary for the first cost of the complete installation for the two systems, we find:

	Continuous current.	Three-phase current.
Contact line	$835 692.00	$559 556.00
Sub-stations	552 000.00	48 300.00
Transmission line	679 860.00	679 860.00
Power station	725 000.00	580 000.00
Total	$2 792 552.00	$1 867 716.00

It will be found later on that the first cost of rolling-stock, including motor equipment, may be taken as being practically the same in either case; it is thus made apparent that the three-phase alternating-current system has a very great advantage over the continuous-current system as far as first cost of installation is concerned.

Cost of Operation. It is easy to see that the cost of operation is also far less for the three-phase system. It is not necessary to go into details in this respect, but it may be pointed out that the energy consumed will be smaller in the three-phase system, and the omission of synchronous converters will decrease both the labor item and the cost of repairs, which latter will be still further reduced in the three-phase system due to the absence of the commutator used on continuous-current motors.

The difference in cost would thus distinctly point toward the adoption of the three-phase alternating-current system. Before taking up the various objections which are sometimes urged against the employment of the three-phase motor, a comparison will be made of the characteristics of the two other systems mentioned in the beginning as being available for this work.

Single-phase Alternating-current System. This system has an advantage over the three-phase system in that it requires one single overhead conductor only, as compared with the two conductors necessary in a three-phase system. But, in the opinion of the writer, the single-phase alternating-current commutator motor, be it of the series, the repulsion or a compromise type, is not at all suitable for heavy traction work.

The torque of a single-phase motor is 30 per cent. smaller than that of a corresponding continuous-current motor, and it is not constant but varies between a maximum and zero with double the periodicity of the line current. The mean value of the torque is only half of the maximum torque when slipping wheels, which means that in cases like the above, where the tractive efforts required necessitate going to the limit of adhesion between wheels and track, a single-phase locomotive must have almost twice as much weight on drivers as either a continuous current or a three-phase locomotive. It is true that this difference holds good only for motors mounted directly on the car-axle, and it will be somewhat less if geared and spring-suspended motors are used.

The single-phase motor is restricted to a pressure at the commutator of hardly more than 200 volts. It has a lower inherent efficiency than either the continuous-current or the three-phase motor. Due to the low average flux density used, it will for the same output weigh probably 50 per cent. more than a corresponding continuous-current motor. And the difficulties of design are such that it can not, at present at least, be built in large sizes. It would probably be necessary to use six or eight motors to get 2000 h.p., and this would in all probability necessitate a double locomotive, where with continuous-current or three-phase motors a single locomotive would be sufficient. Besides this, the single-phase motor is much better suited for high rotative speeds, which means that in many cases double-reduction gear will be required. It would therefore appear that single-phase motors, as long as they are available only in the commutator type, will hardly present any advantages for heavy traction problems.

It is not at all impossible however that the single-phase induction motor may some time be so improved as to be available for railway service. Its only drawback at present is its poor starting torque. A suitable condenser would overcome this difficulty and give the single-phase motor the same starting qualities now possessed by the three-phase motor. Low-pressure condensers are extremely bulky and unwieldy and at the same time costly pieces of apparatus; but there has recently been placed on the market a condenser for use with high-pressure alternating-currents up to 50 000 volts and more. The capacity of a condenser increases with the square of its pressure, and these high-pressure condensers are therefore not only cheap but also very small, and if they fulfil the expectations placed on their reliability in continuous service, the single-phase motor might yet play an important part in railway service.

Motor-Generator Locomotives. This system using a combination of a high-speed single-phase alternating-current motor and a high-speed continuous-current generator, furnishing energy to continuous-current driving motors, with pressure control according to the Ward Leonard system, is really more useful than is generally admitted. The question of weight which is often urged against this system is only relatively important and, while it would probably be out of the question to use this system for the propulsion of single cars at high speeds, yet it deserves careful attention whenever heavy trains have to be considered. As a matter of fact it will be found that it is principally the speed desired, which decides the question whether motor-generator locomotives can be used to advantage or not, as will be seen from the following considerations.

To start a train of given weight on the level and to accelerate it at a given rate requires a certain tractive effort. In order to be able to produce this effort the locomotive hauling said train must have a certain weight on drivers. Take a train weighing 3090 tons and an acceleration of 0.08 miles per hour per second, then the tractive effort will be approximately 40 000 pounds. With a coefficient of 25 per cent. for adhesion the locomotive must have 160 000 pounds or about 80 tons on drivers.

To move this same train at a given speed on the level requires a certain amount of power. To give this power the locomotive must have an electric equipment of a certain capacity. Suppose a speed of 15 miles per hour, then the electric equipment must be dimensioned to give continuously 840 h.p.

Modern, careful design will probably result in a weight of about 60 pounds on drivers for each horse power in a continuous current or three-phase locomotive, and about 100 pounds in a motor-generator locomotive. A locomotive capable of giving continuously 840 h.p. will therefore, if designed for minimum weight, weigh about 25 tons if of the continuous-current or three-phase type, and about 42 tons if of the motor-generator type. Inasmuch as there must be 80 tons on drivers to give the desired tractive effort, it is made evident that for this speed the type of electric equipment does not influence the weight and there is no disadvantage connected with the use of the motor-generator locomotive.

Suppose however the speed were to be raised to 25 miles per hour. Then the electric equipment would have to give 2060 h.p. In this case the minimum weight for the motor-generator locomotive would be about 103 tons, while the continuous current and the three-phase locomotive could still be built within the 80 tons necessary for the tractive effort. It is easy along these lines to find out whether, for any given train weight and speed, the motor-generator locomotive is at a disadvantage as far as weight is concerned or not.

The advantages of this system lie in the use of but one overhead conductor and more particularly in the very beautiful control which it offers. Those having had actual experience with this type of locomotive will probably confirm that the starting is exceedingly smooth and does not produce any peaks in the load diagram. The regulation of torque and speed is also the most convenient imaginable and the electric braking is so easy and efficient that it will probably be used in preference to compressed air. This system is therefore a very good solution for heavy low-speed freight traffic, while for a mixed service with both light and heavy trains and for low as well as high speeds its advantages as known at the present day, are probably not great enough to warrant its adoption in preference to the straight three-phase alternating-current system.

Objections to Three-phase Induction Motor. This brings the discussion back to the relative advantages of the continuous-current and the three-phase motor, and to the objections which have been urged against the latter. It has been claimed that the three-phase induction motor is inefficient, that it weighs and costs more, that the small air-gap generally used causes trouble, that the power-factor is low, that its overload capacity is limited, and finally that its speed characteristics are wholly unsuited for railway service. Let us analyze these objections.

Efficiency. It is necessary to distinguish between efficiency when running and efficiency during the period of starting. That the induction motor *per se*, running at full speed, is a more efficient machine than the continuous-current motor, will probably be admitted by all designers. The objection made refers therefore principally to the economy in starting under railway conditions. Either motor when started alone requires the insertion of a rheostat to reduce the rush of current in the armature, and both motors are equally inefficient under these conditions. When however two or more motors are installed on the same car, it is possible with continuous-current motors to save a great part of the rheostat losses by connecting the motors first in series and then in parallel. This is not directly possible with induction motors because such reduction in impressed voltage would at the same time decrease the torque. Yet by using concatenation; viz., by connecting the secondary part (rotor or stator) of one motor to the primary part (stator or rotor) of a second motor, the same result can be obtained and exactly the same amount of energy saved, with the additional advantage that during the braking period some of the energy otherwise lost in the brakes may be recovered and returned to the line, which is not feasible with the continuous-current motor.

It is superfluous to go into details here in this respect. Granted even that the three-phase motor might in a certain case be somewhat less efficient in starting, in heavy traction problems the energy consumed during the starting period is only a comparatively small part of the total energy consumed during the run between two stations, and the greater efficiency of the three-phase motor during the rest of the run makes up for what might have been lost through poorer efficiency at the start. With other words the total energy consumed for comparatively long runs between stations will be pretty closely the same for continuous-current and three-phase motors. This was borne out by the careful calculations made in the case referred to above as will be seen from the tables showing energy consumed by trains. Through the courtesy of Messrs. L. B. Stillwell and H. S. Putnam the table below was obtained, which shows the results of calculations made in a case which is more or less typical of traffic on one of the large American trunk lines. The assumptions made were as follows

Length of line	150 miles
Number of stations	16
Length of intervals	10 miles
Number of tracks	4
Train-weights including locomotives:	
Passenger train	512.65 tons
Fly-wheel effect	41.01 "
Freight train	704.5 "
Fly-wheel effect	56.44 "
Average running speed:	
Passenger trains	40 miles per hour
Freight trains	20 " " "
One-third of trains of each kind stop only at end stations.	
Maximum traffic simultaneously on road:	
Passenger trains	15
Freight trains	15
Track level—no curves.	

The comparison was made using the same schedule for both systems and in starting the same rate of acceleration. In the three-phase system energy was recovered during part of retardation.

	Continuous current.	Three-phase current.
Local Passenger Train.		
Time of 10 mile run, seconds	955.4	955.4
Acceleration in miles per hr. per sec.	.318	.318
Average running speed, miles per hr.	37.7	37.7
Maximum speed, miles per hr.	51.75	47.6
Maximum kw. required	1 775.55	1 160.0
Average kw. required (running)	629.77	617.5
Total kw-hr. furnished	167.09	176.3
Total kw-hr. returned	0.00	12.4
Total kw-hr. consumed	167.09	163.9
kw-hr. per train-mile	16.71	16.39
Watt-hours per ton-mile	32.6	31.8
Through Passenger Train.		
Time of 150-mile run	3 hr. 21 min. 3 sec.	3 hr. 21 min. 3 sec.
Acceleration in miles per hr. per sec.	0.318	0.318
Average running speed, miles per hr.	44.67	44.67
Maximum speed, miles per hr.	51.75	47.6
Maximum kw. required	1 775.55	1 160.0
Average kw. required (running)	659.43	660.7
Total kw-hr. furnished	2 210.	2 226.3
Total kw-hr. returned	0.0	12.4
Total kw-hr. consumed	2 210.	2 213.9
kw-hr. per train-mile	14.7	14.75
Watt-hours per ton-mile	28 75	28.8
Local Freight Train.		
Time of 10 mile run, seconds	1 851.4	1 851.4
Acceleration in miles-per hr. per sec.	0.189	0.189
Average running speed, miles per hr.	19.45	19.45
Maximum speed, miles per hr.	24.3	22.6
Maximum kw. required	712.0	419.0
Average kw. required (running)	244.0	246.7
Total kw-hr. furnished	125.5	131.4
Total kw-hr. returned	0.0	4.5
Total kw-hr. consumed	125.5	126.9
kw-hr. per train-mile	12.55	12.69
Watt-hours per ton-mile	17.78	17.96

	Continuous current.	Three-phase current.
Through Freight Train.		
Time of 150-mile run	7 hr. 9 min. 9 sec.	7 hr. 9 min. 9 sec.
Acceleration in miles per hr. per sec	0.189	0.189
Average running speed. miles per hr	20.97	20.97
Maximum speed, miles per hr	24.3	22.6
Maximum kw. required	712.0	419.0
Average kw. required (running)	253.5	251.3
Total kw-hr. furnished	1 814.5	1 801.9
Total kw-hr. returned	0.0	1.5
Total kw-hr. consumed	1 814.5	1 797.4
kw-hr. per train-mile	12.09	11.98
Watt-hours per ton-mile	17.16	16.9
Daily Consumption of Energy under Average Traffic Conditions.		
32 trips of 2210 kw-hr. each	70 720	
32 trips of 2213.9 kw-hr. each		71 200
64 trips, 15 stops, of 167.09 kw-hr. each	160 406	
64 trips, 15 stops, of 163.9 kw-hr. each		157 800
16 trips of 1814.5 kw-hr. each	29 032	
16 trips of 1797.4 kw-hr. each		28 600
32 trips, 15 stops, of 125.5 kw-hr. each	60 240	
32 trips, 15 stops, of 126.9 kw-hr. each		61 000
Total consumption, kw-hr	320 398	318 600
Average daily load, kilowatts	13 350	13 290
Maximum load, kilowatts	30 923	21 420

It will be seen that these results confirm the conclusion that there is not much difference between the two systems as far as efficiency or energy consumption is concerned.

Weight and Cost. The former is affected to a certain extent by design, the latter by some other considerations. Taking identical conditions and modern, careful design for both motors, then the three-phase motor will weigh only about 0.75 times as much as the continuous-current motor. This is partly due to the smaller losses in the three-phase motor, and partly to the fact that the distributed winding and the general construction of the three-phase motor allow it to radiate heat with greater ease than is the case in the continuous-current motor where practically all the losses have their origin far from the radiating surface. In general, both iron and copper are distributed to better advantage in the three-phase motor. And, if the selling price of both motors is taken proportional to the cost of production, then the three-phase motor will certainly be cheaper than the continuous-current motor.

Small Air-Gap. This is purely a question of proper design of motor-bearings. With a large air-gap, as in the present continuous-current motor, small bearings will be sufficient. With air-gaps approaching $\frac{1}{16}$ in. the bearings have to be designed more liberally. But this does not present any difficulties, and it is perhaps worth while noting that the rotor of the three-phase motor leaves much more space available for bearings than can be found in the continuous-current motor. The fact that railway motors with such small air-gaps have now been in regular service, some as long as 10 years, without ever giving the least trouble on this account, is proof enough that the modern designer need not be afraid to use an air-gap small enough to make a good induction motor.

Low Power-Factor. A continuous-current system will always have a higher power-factor than an alternating-current system. But the power-factor in no way influences the actual energy consumed. A low power-factor simply increases the current flowing at any time by the addition of the so-called wattless current, and the current carrying capacity of transformers, transmission line, and generators will therefore have to be somewhat larger if the power-factor is poor.

A modern continuous-current plant with synchronous-converter sub-stations will have a power-factor of about 95 per cent. The power-factor of modern three-phase motors, while only about 60 per cent. at very low loads, is 90 per cent. and more for all loads above about one-fourth normal full load, and the power-factor of the entire system at the time of maximum current consumption will be about 80 per cent. While the lower power-factor will therefore increase the current flowing in the three-phase system by about 15 per cent., we have seen above that the energy required in the continuous-current system is about 25 per cent. greater than that in the three-phase system, and we thus find that even with the lower power-factor the current flowing in generators, transmission line, and transformers is not any greater in the alternating-current system than in the continuous-current system.

Overload Capacity. This again is strictly a question of design. The normal capacity of any motor is determined by the heating of its windings. The overload, which a given motor will stand is determined in the case of a continuous-current motor by the behavior of the commutator, and in the case of a three-phase motor by the fact that at a given point the influence of the currents in the induced part will reduce the magnetic field to zero.

The continuous-current motor can probably be designed to stand an overload up to about six times the normal continuous load, which is quite sufficient for railway service.

The overload capacity of the three-phase motor has been accepted by many as being about 2.5 to three times normal full load, because stationary induction mutors are generally designed in this way. This is however entirely a matter of choice and it is not difficult to so choose the point of normal full load of a three-phase motor with reference to the maximum load that it will give without trouble six or eight times its normal full load before showing any signs of approaching the maximum load point. As a matter of fact the maximum load could be made to be 10 or more times normal full load should this prove to be desirable.

The general statement will hold good that either motor can be designed for overloads greater than required in normal railway service, yet the overload capacity of the three-phase motor may be said to be unlimited, while that of the continuous-current motor is restricted by the presence of the commutator.

Speed Characteristics. It has often been said that the three-phase motor is entirely unsuitable for railway service because it lacks the so-called series characteristics. But perhaps few realize that these very series characteristics are distinctly unsuitable for problems such as the one treated above. The series motor will decrease its speed for any increase in load or decrease in line pressure, while a motor with shunt characteristics will run at constant speed independent of load or pressure.

Perhaps a comparison with the conditions found in electrically-operated machine shops will serve to illustrate this point. There we find that for hoisting and crane work, viz., for work requiring frequent starting and stopping, and working with greatly varying loads, a series motor will be pre-eminently suited. Variations in speed are permissible in such work as long as good average speed is maintained, and the fact that the torque of the series motor decreases with increasing speed, and vice versa, will enable the motor automatically to adjust its speed so that the power input will be more or less constant.

Machine tools however should be run at as nearly constant speed as possible no matter how much the load may vary from moment to moment, and we find therefore that for this kind of work the series motor has to give way to the motor with shunt characteristics, which will run at practically constant speed whether the torque increases or decreases. And this requirement for constant speed under all conditions is even more clearly indicated for the main transmission line shaft, from which a great variety of small machines may be driven. The load on this transmission will vary between wide limits as groups of machines are thrown on or off, but from the moment the shaft is started in the morning until it is shut down in the evening it should run at constant speed. A series motor for this service is entirely out of the question.

Reverting to railway conditions, it is found that the series motors will be permissible in street railway service, where the work consists practically only of starting and stopping and where it is therefore of small importance whether the running speed is constant or not. In rapid-transit systems with greater distances between stops, it is already open to doubt whether the series motor presents the best solution or not. And for through line service, for local as well as express trains, a high schedule can only be maintained if the speed between stations is as nearly as possible constant and independent of the load—in other words, if a motor with shunt characteristics is used.

The objection that constant speed under all circumstances will mean a varying load on the central power station is true enough, but the same objection holds good in the case of the machine shop, where the constant speed for machine tools and line-shaft is insisted upon even though it may cause the load on the power station to fluctuate. This is undoubtedly a point on which the interests of the electrical engineer conflict with those of the railway operating engineer. The electrical engineer wishes to have as smooth a load-curve as possible and the railway engineer must have constant speed if possible. In the great majority of cases the increase in power necessary to run trains up the maximum grades at the same speed as on the level will not be more than the power taken to start these trains, and, wherever there are a number of trains supplied from the same power station, the fluctuations reaching the latter will not be such as will cause any special difficulties. In this connection the fact may be mentioned that three-phase motors automatically return energy to the line on down grades, which series motors can not be made to do. The energy thus gained will naturally have a tendency to smooth out the load curve of the power station to a considerable extent.

As regards the ability to run any given train economically at more than one speed, both types of motors are exactly alike. The series as well as the three-phase induction motor, when run alone, have only one economical speed, and to get other speeds rheostats must be used with correspondingly lower economy. Several motors on one locomotive can be arranged to give more than one economical speed in either case. By means of series-parallel control two series motors may be run at full and half speed, four motors at full, half, and quarter speed, with equal economy at all these speeds. Two induction motors can be connected in cascade, and, if they have the same number of poles, full speed and half speed will be speeds of equal economy. If they have a different number of poles, various combinations of speed are possible. Three motors with different number of poles will give four economical speeds, and so forth. Or two or more induction motors may be combined in one motor, either by directly mounting motors of different number of poles on the same shaft, or by arranging the stator winding so that it is possible to change the number of poles by a change in connections. Thus practically any desired number of different speeds may be obtained, with the additional advantage that the rotor may be of the short-circuited rotor type, or as simple as any motor armature can be made.

The point to be borne in mind in this connection is this, that, if any service requires more than one speed, then it is best for safe operation as well as for correct maintenance of time table to have the second or third speeds have a definite relation to the normal full speed, and let all these speeds be as constant as possible.

Starting and Acceleration. We have already seen that in long distance service rapid acceleration is usually unnecessary. But if quick acceleration is desired it can be had from the three-phase motor just as well as from the continuous-current motor, inasmuch as the maximum torque of the three-phase motor can be made at least as large as that of a continuous-current motor of corresponding size. Given a certain maximum rate of acceleration, the three-phase motor will even reach full speed quicker than the continuous-current motor, because its torque is independent of speed and it can therefore carry practically the same rate of acceleration clear up to full speed, while the continuous-current motor can use the maximum rate of acceleration only up to a certain point, the point where the motor curve is reached, from which point on its torque decreases with increasing speed.

More important in heavy traction work is the fact that for slow acceleration the three-phase motor will have a lower current input than the continuous-current motor. The starting torque is in each case proportional to the product of magnetic field-times current. But the magnetic field of the three-phase motor is practically constant, while that of the continuous-current series motor is a function of the current. The exact character of this function is dependent on the design of the motor and on the magnetic properties of the iron employed in its construction. It is difficult to express this relation in a mathematical formula, but actual motor curves show clearly that the torque of a continuous-current series motor decreases much faster than the current. With other words at low current densities the three-phase motor will have a higher torque per ampere than the continuous-current motor.

This fact is made use of in practical operation and in at least one European three-phase railway system the current taken during starting is limited by rheostat control to a value about 20 to 25 per cent. above full load running current, with a resulting average acceleration of about 0.5 miles per hour per second. Curves published for some American continuous-current railways with similar rates of acceleration show considerably higher peaks in the current input.

Conclusion. From the above it would appear that, for the railroad under consideration, the three-phase alternating current system is not only cheaper to install and cheaper to operate than the continuous-current system, but the three-phase induction motor also proves itself at least equal in every respect to the continuous-current series motor and superior to the latter on several rather important points. There remains only one objection to the three-phase system as such and that is the two overhead wires which it makes necessary. That one wire is simpler to install than two is undoubtedly true. But to judge from this that a double line is impossible, or even only that it will present serious difficulties, is not justified by the actual facts. The successful operation of a good number of three-phase railways proves the feasibility of the two wire overhead line beyond doubt, and it is worthy of note that some of these roads have very complicated switching yards. The construction of the necessary aerial switches has been worked out with such complete success, that it is possible to stop a locomotive directly underneath a switch and start it in the same or the opposite direction without any trouble whatever. And these aerial switches are not very complicated either. It must of course be admitted that a double line will cost somewhat more for repairs than a single line. Yet, it will always be necessary in any electric railway system to have a repair gang ready for emergencies, and these men will be able to look after two wires as well as after one. The difference in cost is thus limited to the difference in cost of material. And it is well to remember that the cost of maintenance of contact lines is very small in any case, compared with the cost of motor repairs. In street railway systems the motor repairs cost anywhere from four to 10 times as much as the line repairs. The difference in cost which may be charged against the alternating current system on this account is therefore a small per cent. of an already small item and it is quite certain that this difference will be more than counterbalanced by the greater cost of repairs to continuous-current motors, due to the presence of the commutator which has no counterpart in the three-phase induction motor.

For this particular railroad the three-phase alternating-current system might therefore be chosen without hesitation.

As stated at the beginning, it will be difficult to reach general conclusions applicable to all possible cases. Yet by following the line of reasoning used above, it will be seen that the advantages of the three-phase alternating-current system may become somewhat less if the distances between stations are reduced and if trains are made lighter, while on the other hand heavier trains and longer runs between stations make the advantages of the three-phase system even more pronounced. And wherever there are any long grades the three-phase system presents the special advantage of relieving the power station by the energy returned from the descending trains.

As regards traffic density, it may be said that the three-phase system is preferable for light traffic on account of the smaller first cost of installation, and for congested traffic, because the constant speed of the induction motor will permit maintenance of a high speed schedule even under abnormal conditions.

The greatest advantage which can be secured in trunk line operation by the use of electricity in place of steam, lies in the practically unlimited power which can be poured into an electric locomotive. This increased power can be used to haul far heavier trains than are now customary, up steeper grades and at higher speeds if desired. The technical characteristics of the three-phase alternating-current system are such as to make it pre-eminently suited for taking advantage of this situation, and its smaller cost of installation, with corresponding lower charges for interest, amortisation, etc., allow the railway company to reap the full benefit of the resulting greater economy of operation.

The three-phase alternating-current motor is probably the most robust and thoroughly mechanical piece of electrical machinery extant, and it may well be hoped that it will be used extensively in railroad work in the future.

DISCUSSION ON "HEAVY ELECTRIC FREIGHT TRACTION."

C. O. MAILLOUX: Before beginning this discussion I want to say one word about Mr. Waterman's comment. I did not think I was to be misunderstood in stating that the conditions of the Valtellina line favored the three-phase system. These conditions would possibly be considered very unfavorable in Europe, but in this country they would certainly be considered favorable, for the curves there are not nearly so severe and the grades are not nearly so numerous as here. This brings me naturally to Mr. de Muralt's paper, and I want to state that it must not be forgotten that in all discussions of the substitution of one motive power for another, it must be borne in mind that the existing system is not merely to be replaced by something that does as well, but by something that does much more than that. Who is there that is operating electric street cars by electricity that is satisfied, or would be satisfied, with the same service from electricity that he once got from horses? Nobody. The advent of electric traction, bringing new possibilities, also increased the demands of the public. It increased the requirements that were prescribed for the electrical engineer by the railway line owners and managers. The difficulty is that the street railway has progressed marvellously, and this has happened because facilities for its development were furnished by electric traction. The same condition prevails where electricity is substituted for steam on steam roads. The railroad president or manager is not satisfied with the substitution of electricity unless the trains are run faster and cheaper. One of the other reasons why I mentioned the Valtellina line as being a favorable case is that the runs are longer than would be the case in most suburban lines, and that the acceleration required is not so great. I need not dilate on that subject because if the length of the run is decreased and the acceleration increased the comparison becomes much less favorable.

In this country there is no case where the acceleration is as low as 1 mile per hr. per sec. In most cases it is between 1 and 2 and in many cases it is above two, and even above 3 miles per hr. per sec. But I insist that steam railroads will expect electrical engineers to give them something better than they have now, just as the street railway men looked to the engineer to give them more acceleration and less cost.

On page 539 is a statement that the maximum torque of a single-phase motor is only one-half of what it would be. Mr. de Muralt has forgotten to qualify his statement by the fact that this depends on the frequency. I refer to experiments made which show that while the phenomenon exists at very low frequency, it ceases at something like 15 periods. Hence, for any frequencies likely to be considered in actual practice, the phenomena would have very little interest. In reference to the fact that the energy required in starting a railroad is a very small portion of the whole energy, this may be true where the cars start slowly and make few stops, but it is not true where rapid transit and frequent and rapid acceleration are required. In that case the three-phase motor is distinctly outclassed. That motors can be designed for large overloads cannot be questioned, but the real point is, what will be the cost? In reference to the methods of obtaining different speeds, for instance by mounting several motors on the same axle, or by having a variable number of poles on the motors, these things are all more or less possible; but in introducing them it must not be forgotten that a complication is introduced, and introducing a complication increases not only the initial cost of equipment but the cost for maintenance. Hence, while theoretically it is feasible to expect that rapid acceleration can be obtained with the three-phase system or the induction motor, yet no one is ready to do it when he has counted the full cost. To my knowledge no acceleration has been attempted above about 1.1 miles per hr. per sec. with three-phase systems in practical operation. The other questions of input, etc., are also related to cost and expediency. Several things that Mr. de Muralt says can be done are feasible theoretically, but have practically never been realized. The question of cost seems to have decided whether it can be done. So far as the saving of energy in acceleration is concerned, even the direct-current motor can still be improved if it is thought best to increase somewhat the complication of control. One can revert to or introduce many features in design, windings, etc., which have, many of them, already been tried and abandoned for the sake of greater simplicity. In the case of very large motors if it is found that there is any advantage in doing this, it can be resorted to, for the sake of increasing the economy in direct-current motor systems. The important point is that the margin for improvement in efficiency is not by any means all exhausted, in the case of the direct-current motor.

S. T. Dodd: One question in regard to the synchronous characteristics of three-phase motors run in parallel: Mr. Waterman says that the three-phase motors he has considered will run at full speed with a slip of 2.5 per cent. Take as an example, a three-phase locomotive with 4 motors; suppose one pair of drivers were 2.5 per cent. smaller in diameter than the other drivers, it would follow that the motor mounted upon this pair would run at synchronizing speed and not deliver power to the locomotives. If the difference in diameter were only one per cent. that motor would deliver to the locomotive approximately 50 per cent. of the power that any of the other three motors would deliver. I presume that in order to prevent such unbalancing certain limits in variation of driver diameters would have to be maintained; that is, that no driver on a three-phase locomotive could be allowed to vary more than, say, 0.5 per cent. in diameter from any other driver. Such an arrangement would be perfectly feasible on any single locomotive, but it would be impossible to maintain such limits of variation on all the locomotives upon a road; in other words, it would be impossible to operate indiscriminately any locomotive on the same train with any other locomotive without first checking up their driver diameters. As a consequence, by the use of three-phase locomotives there would be lost the advantage of multiple-unit operation which has always been considered one of the great advantages of electric locomotive operation.

F. N. WATERMAN: Mr. Dodd has raised a very important question, although experience has shown that it is not a practical difficulty so far as concerns single-motor cars or locomotives.

The use of side-bar connected locomotives of course eliminates it entirely by keeping the driving-wheels the same size. The discrepancy that might occur in the size of driving-wheels on different cars would be important in the use of multiple-unit control. This discrepancy is taken care of by providing as a part of the equipment a control-box by which the resistance of the secondaries is adjusted to bring them to a slip corresponding to the standard equipment. In this way trains can be made up without regard to the size of the wheels. The question is properly raised, although no attempt was made in the paper to mention all of the matters which would naturally be touched upon in a full discussion of the system. It was the intention to select only two or three important points, out of many, and treat them fully.

I want to make one comment on Mr. Mailloux's statement, that so far as he knew 1.1 miles per hr. per sec. is the highest acceleration ever proposed with three-phase motors. It is a fact that the system proposed for the London Metropolitan was based on 2.25 miles per hr. per sec. for the three-phase system and was condemned by the authorities because the acceleration was greater than people would tolerate.

C. O. MAILLOUX: What are the watt-hours per ton-mile?

F. N. WATERMAN: The watt-hours per ton-mile for a three-phase system properly handled may easily be 15 per cent. less than for direct current.

C. O. MAILLOUX: With an acceleration of 2.5 miles per hr. per sec.?

F. N. WATERMAN: Yes; higher acceleration can be had with greater advantage, provided the maximum speeds are not too high.

C. O. MAILLOUX: Referring to Mr. Waterman's statement in regard to the speeds appreciated by the English people, I had an interview with Mr. Cottrell of the Liverpool elevated system last year, in which he informed me that not only was high acceleration appreciated by the public, but that it was also found to be economical, as it had greatly increased the traffic on his line. He informed me that the acceleration was 3.5 miles per hr. per sec. on the Liverpool elevated system.

C. P. STEINMETZ: The conclusions that Mr. de Muralt has drawn from his premises are correct. There may, however, be expressed some doubt regarding the correctness of the premises. From an engineering point of view I question whether all the things promised can be realized. Mr. de Muralt states that induction motors can be built and designed to have a maximum overload capacity 10 times the rated load, which is true. But what are the power-factor and the efficiency at the rated load, and below it? There is the difficulty. Design an induction motor of a maximum capacity equal to twice the rated load only, then there results reasonable power-factor and efficiency at the rated load, and below it. Increase the overload capacity, that means that the rated load is one-tenth of the maximum output and the power-factor corresponds with that underload, that is, practically vanishes.

Furthermore, transformers can undoubtedly be built to carry 3.5 times the average load with 6 or 7 per cent. regulation, but what is the efficiency of such transformers? and incidentally what is the cost of them? I do not know whether Mr. de Muralt took into consideration, when he figured on the average efficiency and average power-factor of the system, that he had not to deal with the average induction motor, which has a maximum power-factor of 90 per cent. somewhere near the rated load, but with an induction motor that is rated at one-tenth of the maximum load. Furthermore it is true, if a very small air-gap is used, it is also necessary to use very much larger bearings. Unfortunately, anybody who has tried to design a railway motor has found that after the armature is large enough to do the work without heating too rapidly and the collectors large enough to carry the current, there is no room left for the bearings. Railway bearings are designed as they are now not because the designers are not liberal enough but because there is no more room. The question of room is the important feature in railway motor design and there is the stumbling block regarding increased liberality.

In regard to speed, it is true that any machine-shop runs the machines at a constant speed and runs the transmission at a constant speed. In a railroad train, however, it is not so necessary to run at a constant speed up hill and down; retarding on up-grades and accelerating on down-grades is permissible, and it must be done for the sake of economical operation because there it is not the question of a few horse power but of thousands of kilowatts that must be taken into consideration.

As regards the return of power by the motor: this does not smooth out the load-factor: the return of power from the motor means that the total variation of power is increased;

that is, the load-factor of the station still further impaired. To depend on the time-table, arranging trains so as to give an even load, would require that the trains always follow the time-table, which unfortunately, here in America, they do not always do. Now, as to the return of power, if power is to be returned to the line there is no reason why it could not be done with a direct-current motor just as well. It has been proposed and it has been done. Where there is a four motor equipment, which is almost always the case, it has been proposed to use one motor as an exciter and the other three motors as generators putting power back into the line. Experience shows that the complication incident to the controlling devices to return power into the line are such that the power saved does not warrant it. That is why the direct-current motor is not built to return power into the line. It may be that the three-phase motor is better in this respect. It must, however, be considered that the return of power is available only in concatenation, because appreciable power is returned only on a fairly steep down-grade and there is no desire to run then beyond maximum or synchronous speed. The return of power in concatenation takes place with a low efficiency and therefore is objectionable because of the heat. If a motor is allowed to run in concatenation, the heat dissipation must be considered in the induction motor and that, too, under conditions where the second motor is operated with an inductive secondary circuit, the first motor. Therefore the conditions are rather unfavorable for efficient production of current, and that has been the stumbling block in the application of concatenation. This matter becomes very much simpler when one follows Mr. Waterman's proposition in regard to low frequency. However, it is usually difficult to build a railway motor, in the limited space, large enough to do its legitimate work of pushing the car without excessive heating—without imposing still further duties on the motor, by using it as generator, and so still further increase its heating.

C. L. de Muralt: I heartily support the statement made by Mr. Mailloux, who said that it is necessary not only to equal what the steam railroads are doing now, but to do better. This is very true indeed, but it seems to me to be an argument in favor of three-phase traction. In coming down to Asheville in the train, I read some statistics gathered by "The Manufacturer's Record." The article showed a very interesting increase in the number of tons moved per mile of railroad since 1890, the figures given being 65 billions in 1890, 93 billions in 1897, and 170 billions in 1904. At this rate 1911 will have 300 billions of tons, which shows that the railroads of our country are nearing the limit of their capacity and that they will have to do something to increase their carrying facilities in order to meet the growth of traffic. Electricity will enable them to increase the power of the locomotive, so that heavier trains may be used, or speeds increased, or both. In either case I believe that the three-phase system is best suited to solve the problem.

The question of maximum acceleration possible with the three-phase motor is not new. During the discussion of my paper in May 1902, Mr. Mailloux raised the same point and I then expressed my doubts as to his being the correct way of looking at it. To me it appears as follows: if a certain acceleration is wanted it is necessary to provide enough power in the motor to give a certain something in excess of what is required to overcome the train resistance. The amount of that power is the same whether the motor is a continuous current or a three-phase motor. It is therefore the maximum power or the maximum torque that a motor can develop which determines the acceleration that can be obtained from it. But, the three-phase motor can exert the same or even greater torque than the continuous-current motor of equal size. There is no doubt about that. Why then should the three-phase motor not be able to give the same or even greater acceleration? Mr. Mailloux at that meeting stated that the customary acceleration in American practice was 2.5 miles per hr. per sec. I was then not able to say that such accelerations had been reached on any three-phase railroad in Europe, but I mentioned that to my knowledge rates of 1.5 miles per hr. per sec. had been obtained, and I thought that 2 miles could easily be reached. Since then I have without difficulty obtained 2.5 miles per hr. per sec., so that I am now prepared to say that this can be done, and I may add that I do not see any difficulties in getting higher rates of acceleration if they should be desired.

This brings me to Mr. Steinmetz' remark as to the desirability of choosing such high overloads for the motors. I agree with him, that, if a motor is designed with a maximum capacity equal to 10 times normal load, the power-factor at normal load will be comparatively poor. But such extreme overloads are probably never required. What I pointed out in my paper was, that higher overloads may be had from the three-phase motor just as well as from the continuous-current motor. Whether it is desirable to use them is another question, and I put the word "desirable" in my paper with the idea of saying that these overloads can be had if found necessary. I have curves in my pocket, and more at home, to show that if the motor is given an overload capacity three times the normal full load, the power-factor at all loads is very good indeed. It goes a little above 90 and stays there for some time, and at half load it is in the neighborhood of 85, which I do not think is poor.

With reference to efficiency of transformers, it is true that transformers will have a better efficiency at full or overload than at half load. But transformers have such high efficiencies anyway, that, even under one-third load for instance, the efficiency will be very good, at any rate higher than the combined efficiency of the transformer and synchronous converter in the continuous current system.

In regard to bearings, it is difficult to assert that sufficiently large bearings can always be placed in three-phase motors, especially if Mr. Steinmetz thinks that in some cases this may be impossible. I am not an expert designer of machinery myself, and I therefore do not wish to doubt that there may be cases where it is difficult to place large bearings. Yet I may mention that a German company has built some three-phase motors for direct use on a 10 000-volt circuit, which from the designer's standpoint is a particularly unfavorable condition. The bearings could easily be placed, although I believe the motor was of 450 h.p., or rather larger than the average traction motor. It is interesting to note, that the bearings in these motors are brought way underneath the rotor, which can readily be done in an induction motor, whereas the commutator prevents similar construction in the continuous-current motor. Where the width is very limited, the collector rings of the three-phase motor may even be placed outside the locomotive frame, as has been done in some of the latest motors of another company.

It is hardly worth while to say much on the subject of change of speed, because the induction motor can be made to run at different speeds just as well as the continuous-current motor. In my opinion the great advantage of the three-phase motor lies in the fact that it can and will maintain constant speed when this is desired, whereas the speed of the continuous-current motor is dependent on the profile of the road and other circumstances. From the railroad man's standpoint constant speed is desirable. Whether it is necessary is another question. But some people say that if continuous-current motor and three-phase motor run up grades at the same speed, then the continuous-current motor will run at higher speed on the level and thus make faster time. If that higher speed is permissible, however, then there is nothing to prevent the three-phase motor being designed for that higher speed on level and up the grade, and it will thus be able to make the schedule still faster. In a general way it is largely a question of taking the operating engineer's viewpoint. If you want to run a railway the way he is accustomed to run it, or the way he will think it should be run under the changed conditions of electric operation, you will find that the three-phase motor with its maintenance of speed presents a number of advantages.

In conclusion: if leaving out all other questions on which the two systems are more or less equal, there remain two things; the commutator of the continuous current system, and the second overhead wire of the three-phase system, which may fairly be compared with each other as disadvantages strictly inherent to one of the two systems. To settle the question which of the two is worse, permit me to make the following suggestion: suppose the continuous-current motor had not yet been invented and thus far all railways were operating with three-phase current and had two overhead lines everywhere. Now, somebody comes and tells us that one of the two lines can be eliminated by using a continuous-current motor, but to do this it would be necessary to put a commutator on the motor. It will hardly be doubted that those that realize the enormous difference between cost of repairs to commutator and cost of repairs to second contact line, would surely cast their votes in favor of the three-phase system.

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CHOICE OF MOTORS IN STEAM AND ELECTRIC PRACTICE.

BY WILLIAM McCLELLAN.

The rise of the new electric-traction engineer has been very rapid. Within not more than a decade men untrained in the old railroad systems have been called on to solve some very great problems in what has been called heavy traction work. With the new engineer has come new methods, which are due to the fundamental difference in the nature of the power systems. Predetermination of power conditions is necessary in any railroad system, but it is especially so in an electric system.

The steam locomotive is self-contained. In one unit is found the power-house, transmission system, and motor, usually for a very small part of the total load upon the whole system. If a mistake is made in estimating the amount of power required, it is not a serious matter to correct the error. Certainly it is in no way comparable with what would be necessary if a similar mistake were made in connection with an electric system, where the whole load is to be carried by one or two large power-houses, the energy from which must be properly distributed to the various portions of a widely-expanded area, and conveyed to the motors on a car moving at, say, from 20 to 60 miles an hour.

No engineer in the latter line of work has hesitated to adopt and use the valuable results of the many years of labor and experience on the part of the motive-power superintendents of the steam systems. But special attention has been necessarily paid to operating features that were not prominent in the older methods. New plans of attack have been invented: these are now in the trying-out process, and time alone will tell what is of value.

It is hardly more than three years, however, since the steam and electrical engineers met on common ground. Up to that time there had been little real competition, so far as motive power was concerned, in heavy traction work. As a result, the development of the electric locomotive, like that of the steam-engine, has been a slow process. We are not ignoring what has taken place in the last 80 years, but are reasoning from what is going on just now.

No electrical engineer, anxious as he may be to see a rapid substitution of electricity for steam, should fail to bear in mind the possibility that substantial improvement in steam locomotives is not at an end. Competition has served to awaken considerable dormant energy, the result of which can not be easily estimated. Probably more money is being spent this year by far-seeing men on the development of the steam locomotive than has been spent in any other year since it was invented.

In either system, the choice of a motor for a particular service is a very important matter. It is well known that the cost of power is a comparatively small part of the total expense, but there are other reasons why the choice of a motor is important, and good engineering requires in any case that the cost of power shall be as low as possible. It must be acknowledged that neither in the steam nor in the electric system is the choice of a motor determined on the basis on which we eventually hope it will be decided. Moreover, in the electric system at least, we shall not see much improvement immediately, for experimental data are the necessary foundation therefor, and such data are lacking.

A comparison between the old and the new is always worth while, and particularly so in this case. The writer purposes, therefore, to survey certain characteristic features of the motive power in the two systems, and call attention to some points that seem important.

In Tables 1, 2, 3, and 4, will be found a collection of data relating to steam locomotives. The numbers in the first column refer to different roads, the same number standing for the same road in all the tables. All the important roads of the United States and Mexico are represented. The information was furnished the writer by officials of the roads. The meaning of the "type" names used in column 2 will be found in Fig. 1. The "total weight" includes the tender and engine, ready for the train. For purposes of comparison "gross tractive effort" was calculated by assigning an adhesion of $\frac{1}{5}$; the value assumed was not checked from the cylinder dimensions and steam pressure, the proper design of these parts being assumed. The "net tractive effort," being for comparison only, was calculated on the basis of a friction loss of eight pounds per ton. In the 11th column is given the "pounds of (total) engine (weight) per pound of (net tractive) effort." The writer re-

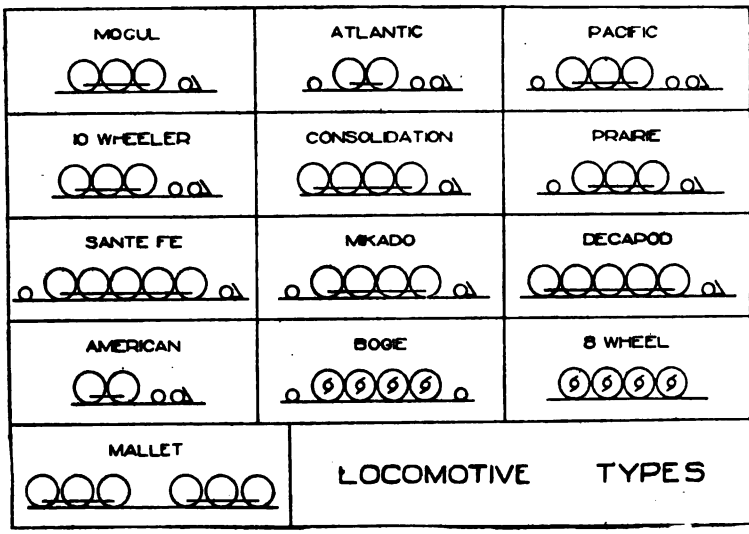

FIG. 1.

grets that the information relative to "maximum run" is not more definite and complete. It will be obvious, however, that an enormous mass of detail would have to be given to make such information of real value.

The engines referred to in the tables do not represent all the types used on the respective roads. They were selected as modern types in each of the four classes. Apparent inconsistencies are due to the different ideas the managers of the several roads have as to classification of trains.

It is evident that no complete discussion of the data given could be made unless much more were added. The train weights, alignment, grades, character of road-bed, etc., must also be known. But sufficient information is presented to justify several conclusions. A glance at any column will show that there is little or no tendency towards uniformity. To appreciate the very wide variations from any common standard, we may take the columns of "Cylinders," "Drivers," "Per cent. on Drivers," and "Pounds of Engine per Pound of Effort." The figures for the two electric locomotives cited accord quite closely, but no general conclusions can be deduced from such limited data.

The tables show, as is frankly acknowledged by motive-power superintendents, that there is no standard, nor demand for standards in locomotive practice. Some of the great railroad systems of the country have attempted in a rather desultory fashion to arrive at a standard, but have failed. Undoubtedly the difficulties in the way are great, but there should be possibility for advance in this direction. It would seem as if some of the many types still in use must be intrinsically poorer than others, and might be done away with.

The reasons why a locomotive should have a load on the drivers varying all the way from 30 to 90 per cent. of the total weight is not apparent at first sight. Every lot of locomotives ordered, whether built in the road-shops or by contract, has its designs modified to suit the ideas prevalent at the time. The new engines may be of the same class, general weight, etc., as previous ones, but numerous differences in details are sure to be introduced by the particular motive-power superintendent who is in control at the time. The only tendency towards standardization at the present time comes from the formation of great systems, whereby one superintendent has a chance to put his ideas into practice in a large number of locomotives. This problem of standardizing steam locomotives is not for the electrical engineer to solve, but he has one coming that is very similar. Much is to be learned from a study of the older field, where so much energy has been spent by some of the best engineers in the profession.

It is not necessary to give here a similar list of car-motors. There are two companies in the field, and their types are not widely different, even in details of design. Not counting alternating-current types, each company has made about 20 fundamental types of motor. Of these about 15 are modern. By fundamental types is meant, practically, types that have different frames and armature cores, shafts, bearings, and com-

TABLE 1.—PASSENGER.

No.	Type.	Profile of Road.	Cylinder.	Drivers.	Total Weight.	Weight on Drivers.	Per cent. on Drivers.	Gross Tractive Effort.	Approx. Net Tractive Effort.	Pounds of engine per pound Effort.	Fuel.	Heating Surface. Grate Surface.	MAXIMUM RUN. Cars	Tons	Miles	Miles per hour.
1	Mogul	Flat	19x26	6-72	238 000	121 500	50	24 000	23 000	10	Soft coal	68	10		206	41.8
2	American	Rolling	18½x22	4-68½	180 000	69 000	38	13 800	13 100	14	Hard coal	20				
2	American	Rolling	21x22	4-68½	184 000	73 000	40	14 600	13 900	13	Hard coal	17.5				
2	American	Rolling	21x22	4-68½	238 000	89 000	37	17 800	16 800	14	Hard coal	26				
3	American	Flat	19x24	4-75	336 000	78 000	23	15 600	14 300	23.5	Soft coal	71.7	8		202	40
4	American	Rolling	18½x26	4-80	218 000	93 500	43	18 700	17 800	12	Soft coal					
5	10 wheel	Rolling	20x28	6-68	283 000	134 000	47	26 800	25 700	11	Soft coal	78.5	10		150	50
6	American	Flat	18x24	4-70	178 000	64 000	36	12 800	12 100	15	Soft coal	80	15		154	25
7	American	Low grade	19x24	4-69	192 000	74 000	39	14 800	14 000	14	Soft coal	17	8		142	34
8	Atlantic	Flat	19x26	4-73	279 000	83 000	30	16 600	15 500	18	Soft coal	82				
9	10 wheel	Flat	19½x26	6-69	252 000	117 000	46	23 400	22 400	11	Soft coal	73	7		227	
10	Pacific	Mountain	22x28	4-77	222 500	141 000	63	28 200	27 300	8	Soft coal		12		156	36
11	Pacific	Mountain	22x26	6-69	318 000	132 000	42	26 400	25 100	13	Soft coal	73	9		270	38
12	Pacific	Flat	21x26	6-69	334 500	133 000	40	26 600	25 300	13	Soft coal	71	9		188	
12	10 wheel	Flat	21x26	6-73	292 000	142 000	49	28 400	27 200	11	Soft coal	84	9		180	
13	Atlantic	Mountain	20x28	6-81	329 000	105 000	32	21 000	19 700	17	Oil		14		250	32
14	Atlantic	Mountain	15/25x26	6-72	194 000	101 500	52	20 300	19 500	10	Coal	65				
15	Atlantic	Flat	20x28	4.74	184 000	103 600	56	20 700	19 900	9	Soft coal	54				
	Pacific	Mountain	22x28	4-70	222 500	141 000	63	28 200	27 300	8	Soft coal	61.5				
16	Pacific	Mountain	20x26	6-62	191 000	115 000	53	23 000	22 200	8.5	Soft coal	66				
5	10 wheel	Rolling	20x28	6-62	167 000	130 000	78	26 000	25 300	6.5	Soft coal	78.5				
5	Atlantic	Rolling	19x28	4-72	169 000	81 000	48	16 200	15 500	11	Soft coal	64				
17	American	Rolling	20x26	4-62	251 000	102 000	41	20 400	19 400	13	Hard coal	24				
21	Pacific	Rolling	20x26	6-62	281 000	117 000	42	23 400	22 300	13	Soft coal	60				
	Bogie	N. Y. C.		8-44	186 000	133 500	72	27 000	26 200	7	Direct-current					
	8 wheel	B. & O.		8-42	320 000	320 000	100	64 000	62 700	5	Direct-current					

TABLE 2.—FAST PASSENGER.

No. Type.	Profile of Road.	Cylinder.	Drivers.	Total Weight.	Weight on Drivers.	Per cent. on Drivers.	Gross Tractive Effort.	Approx. Net Tractive Effort.	Pounds of engine per pound Effort.	Fuel.	Heating Surface. Grate Surface.	MAXIMUM RUN. Cars	Tons	Miles	Miles per hour.
1 Atlantic	Flat	20x26	4-84½	307 400	91 200	30	18 250	17 050	18	Soft coal	68	6		206	50.4
1 Atlantic	Flat	15/25x26	4-78	183 000	95 900	52	19 200	18 450	10	Soft coal	70				
2 Atlantic	Rolling	21x24	4-84½	305 000	102 000	34	20 400	19 200	16	Hard coal	39				
2 Atlantic	Rolling	21x26	4-86	338 000	106 000	31	21 200	19 850	17	Hard coal	31				
3 Atlantic	Flat	20x26	4-78	298 000	91 000	30	18 200	17 000	17.5	Soft coal	65.[illegible]	5		202	50
4 Atlantic	Rolling	22x26	4-80	315 600	118 000	38	23 600	22 350	14.2	Coal					
5 Atlantic	Rolling	19x28	4-79	284 300	85 300	30	17 100	15 950	17.6	Soft coal	64	8		150	50
6 Pacific	Flat	23x26	6-72	343 600	142 000	41	28 400	27 000	12.8	Soft coal	94	15		196	31.8
6 Atlantic	Flat	15/25x28	4-84½	303 000	92 450	30	18 500	17 300	17.5	Soft coal	69			260	29.7
7 10 wheel	Low grade	20x28	6-67	269 000	132 600	49	26 500	25 450	10.6	Soft coal	31.5	7		156	47
8 Atlantic	Flat	21x28	4-79	328 000	110 700	35	22 100	20 800	15.8	Soft coal	65				
9 Atlantic	Flat	20x28	4-79	334 600	101 500	31	20 300	18 950	17.6	Soft coal	57	10		189	
10 Pacific	Mountain	22x28	6-77	242 500	141 300	58	28 300	27 300	8.9	Soft coal		8		156	46.1
11 Atlantic	Mountain	15/25x26	4-78	183 000	95 900	52	19 200	18 450	10	Soft coal	70	10		200	45
11 Atlantic	Mountain	19x26	4-78	232 900	74 000	32	14 800	13 850	16.8	Soft coal	78	5		160	33
12 Atlantic	Flat	20½x26	4-79	272 000	87 000	32	17 400	16 300	16.6		52	11		188	
13 Atlantic	Mountain	20x28	4-81	329 000	105 000	32	21 000	19 700	16.6	Oil	2655 h s	7		250	36 8
14 Pacific	Mountain	22½x28	6-79	216 000	147 400	68	29 600	28 750	7.5	Soft coal	67				

TABLE 3.—FREIGHT.

No. Type.	Profile of Road.	Cylinder.	Drivers.	Total Weight.	Weight on Drivers.	Per cent on Drivers.	Gross Tractive Effort.	Approx. Net Tractive Effort.	Pounds of engine per pound Effort.	Fuel.	Heating Surface. Grate Surface.	MAXIMUM RUN. Cars	Tons	Miles	Miles per hour.
1 Prairie	Flat	22x28	6–69	363 200	151 000	42	30 200	28 750	12.6	Soft coal	67				
2 Consol.	Rolling	22x30	8–61½	359 000	180 000	50	36 000	34 550	10.4	Hard coal	36				
3 10 wheel	Flat	20x26	8–63	263 800	118 300	45	33 600	32 550	8.2	Soft coal	83		1200	202	15
4 Consol.	Rolling	22x28	8–56	336 000	173 000	51	34 600	33 250	10	Soft coal					
5 Consol.	Rolling	21x24	8–56	212 700	114 700	54	23 000	22 150	9.5	Soft coal	61		2300	150	15
5 Consol.	Rolling	23/35x32	8–50	186 000	166 000	90	33 200	32 450	5.7	Soft coal	80				
5 Consol.	Rolling	21x30	8–50	173 800	151 500	88	30 600	29 900	5.8	Soft coal	51				
6 10 wheel	Flat	21x30	6–69	302 600	136 000	45	27 200	26 000	11.6	Soft coal	87		956	138	
7 10 wheel	Low grade	19x28	6–60	265 100	125 000	47	25 000	23 950	11	Soft coal	31.5	26	832	202	21
8 10 wheel	Flat	19x24	6–63	188 500	87 000	46	17 400	16 650	11.2	Soft coal	90				
9 10 wheel	Flat	20x28	6–63	259 200	122 300	47	24 500	23 450	11	Soft coal	89		1150	162	
10 10 wheel	Mountain	15½/26x28	6–69	184 200	142 400	77	28 500	27 750	6.6	Soft coal			1750		12
11 10 wheel	Mountain	22/34x28	6–62	265 800	131 800	50	26 200	25 140	10.6	Soft coal	86.13		1200	117	20
12 10 wheel	Flat	20x28	6–64½	284 000	132 000	47	26 400	25 250	11.2	Soft coal	84	80		466	
13 Mogul	Mountain	20x28	6–63	248 300	126 000	50	25 200	24 200	10.2	Oil	2.14	38		128	18
17 Consol.	Rolling	21x26	8–50	191 500	171 700	90	23 400	22 650	8.5	Hard coal	29				
18 Mogul	Flat	20x28	6–56	155 000	133 100	86	26 600	25 950	6.	Soft coal	48				
13 Consol.	Mountain	22x30	8–50	207 300	184 500	90	37 000	36 150	5.7	Soft coal	69				
14 Mikado	Mountain	18/30x32	8–57	262 000	200 000	77	40 000	38 950	6.7	Oil or coal	91				
17 Mogul	Rolling	20½x26	6–56	281 000	144 000	51	28 800	27 700	10.2	Hard coal	44				
19 Consol.		21x30	8–50	334 000	164 000	49	32 800	31 450	10.6	Soft coal	60				
20 10 wheel	Flat	21x26	6–50	300 000	122 500	41	24 600	23 400	12.8	Soft coal	80				

TABLE 4.—FAST AND HEAVY FREIGHT.

No. Type.	Profile of Road.	Cylinder.	Drivers.	Total Weight.	Weight on Drivers.	Per cent. on Drivers.	Gross Tractive Effort.	Approx. Net Tractive Effort.	Pounds of engine per pound Effort.	Fuel.	Heating Surface. Grate Surface.	MAXIMUM RUN. Cars	Tons	Miles	Miles per hour.
14 Santa Fe	Mountain	19/32x32	10-50	287 200	234 600	82	46 900	45 750	6.3	Coal	82				
1 Consol.	Flat	22x28	8-57	356 800	179 200	50	35 800	34 400	10.4	Soft coal	71				
1 Prairie	Flat	22x28	6-69	363 200	151 000	42	30 200	28 750	12.6	Soft coal	67				
2 10 wheel	Rolling	22x28	6-68½	287 000	131 000	46	26 200	25 050	11.4	Soft coal	50				
2 10 wheel	Rolling	22x28	6-68½	352 000	153 000	44	30 600	29 200	12.	Hard coal	33				
3 10 wheel	Flat	21x26	6-63	302 500	126 000	42	25 200	24 000	12.6	Soft coal	66		2000	202	10
4 Mogul	Rolling	20x28	6-62	308 900	142 900	46	28 600	27 350	11.3	Soft coal					
5 Consol.	Rolling	21x30	8-56	284 400	149 500	53	29 900	28 750	9.9	Soft coal	74		3000	150	15
6 Consol.	Flat	22x28	8-56	302 600	156 400	52	31 300	30 100	10.	Soft coal	56				
6 10 wheel	Flat	21x30	6-69	302 600	136 000	45	27 200	26 000	11.7	Soft coal	87		956	138	
7 Consol.	Low grade	21x30	8-56	288 900	159 300	55	31 900	30 750	9.4	Soft coal	45	26	832	202	21
8 Mogul	Flat	19x28	6-63	269 200	128 600	48	25 800	24 700	10.8	Soft coal	57				
9 Consol.	Flat	22x30	8-63	348 500	181 000	52	36 200	24 800	14.	Soft coal	59		2500	147	
9 12 wheel	Flat	23x30	8-57	369 000	181 400	49	36 300	34 800	10.6	Soft coal	93		2500	104	
10 10 wheel	Mountain	15½/26x28	6-69	184 200	142 400	77	28 500	27 750	6.7	Soft coal			1400		25
11 Mikado	Mountain	24x30	8-63	405 500	203 000	50	40 600	39 000	10.4	Soft coal	93		1300	106	20
12 Consol.	Flat	22x30	8-63	304 500	180 000	59	36 000	34 800	8.7	Soft coal	66	80		182	
13 Consol.	Mountain	22x30	8-57	339 800	184 000	54	36 800	35 450	9.6	Oil		31		119	12
22 Mallet	Rolling	20/32x32	12-56	477 500	334 500	70	66 900	64 900	7.5	Soft coal	72				

mutators. Each of these types has various combinations of number turns of wire per slot, field-turns, gear-ratio, current, electromotive force, etc. In consequence, about 100 different motors are proffered to the consulting engineer for his selection. In fact he can have almost any combination that he wants without the particular type selected being considered new. One type of motor may be made with as many as five or more gear-ratios, two or three numbers of turns of wire per slot, and several sets of field-turns. As a result, one particular type of motor has no less than 20 variations. The average number of combinations for any type is probably five.

It may be well to state here a reason for some of these varieties of design of electric motors, varieties that have no counterpart in locomotive design. Comparing the motor with the locomotive, we have the armature corresponding to the cylinders; the combination of gears and wheels corresponding to the driving-wheels. The locomotive designer calculates the driving-wheels on the basis of tractive effort and acceleration only; in addition to these, the electrical designer must consider heating effects, a phase of the traction problem not known to the steam locomotive designer. The locomotive can be loaded until it is stalled without being materially injured; the car motor, however, while it can be excessively overloaded, is deteriorating all the time. In a large part of car design the wheel-diameter is fixed; this item must be cared for in the choice of a gear-ratio. Some of the nicest work in connection with the choice of motors is demanded by these conditions.

Looking for standards in electric car motor design meets with little more success than with the design of steam locomotives. The motor, gears, and wheels may be considered as equivalent to the locomotive, since the electrical engineer is concerned only with weight above the trucks. As shown above, there are many variations in the motor itself for any given type; that is, variations in the armature and field-turns. This will always be more or less necessary. At first sight, it would seem that there is some uniformity in gear-ratios, but the writer has been able to count no less than 48 gear-ratios, varying from one, or gearless, to 4.78. To form these ratios, 60 different combinations of gear and pinion were used. This entails a stock, of patterns at least, of 40 gears. For a long time, 33-in. wheels have been standard for the larger portion of electric cars. With the arrival of the heavy car and rapid accelerations this size has been found too small, and there are now in use wheels of 33, 36, 40, 42, 44, 49, and 62 inches in diameter. It is not likely that many wheels larger than 62 inches will be used, for with the adoption of the gearless motor, if it is successful on the durability test, wheels will be designed strictly with reference to the room for equipment required beneath the car. Even if the future heavy motors are not gearless, the wheels will be as small as possible, in order partly to prevent the lifting of one end of the truck at acceleration and braking.

The standardizing of apparatus arranges itself naturally under two heads: desirability and possibility. From the standpoint of desirability there seems to be little room for argument, for in other lines of industry standardization has always reduced the cost of production. Standardization also means greater promptness in delivery of orders; for where parts are odd, either a large stock must be kept or pieces manufactured as they are wanted. Moreover, in the absence of standard parts little stock can be manufactured in advance of sale; that is, for new equipment. The cost of operation has always been greatly reduced by standards. Repairs and replacing of worn-out parts are greatly facilitated. The great lack of data, which we all are deploring at present, is of course due to the complexity of the traction problem. Much of this would be removed if motors were made to vary as little as possible. The same motor, with a slightly different gear-ratio, may have much greater heating effect on the same service; and it only renders this problem more complex to have all varieties of ratio unless there is some necessary reason.

As to the possibility of introducing standards into car-motor practice, there will probably be widely differing opinions. The problem is very much simpler for the electrical engineer than for the designer of the steam locomotive. The car motor is manufactured by two companies only. They have done by far the larger part of the experimental work in this line. No operating company makes any attempt to build motors. Therefore the introduction of standards is comparatively easy, and without doubt much good has already resulted from this arrangement for manufacture. Whether it will remain this way, as the great railroad systems gradually change motive power, cannot be discussed to advantage now. Certainly much of the unreasonable lack of standards in locomotive practice is due to the other plan, in which many companies or roads manufacture locomotives. Little experimenting has been done by the manufacturing companies except in machine design. Every lot of locomotives sold has been, and still is, a partial experiment. Owing to the attitude of managers and superintendents, the locomotive manufacturing companies have never been able to hold the same relation to operating companies that exists in electrical lines. No matter what the outcome is, valuable lessons can be learned from a consideration of these relations.

Considering the present methods for calculating the size of motors for a given case, it is a question whether the number of motor variations could not conveniently be reduced. There may be men who can tell to a certainty whether a gear-ratio of 3.24 or 3.28 is more advisable in certain circumstances, but the writer has not yet met them. This is an example of one case only, but it indicates what might be done in several others. There is one feature of this work that has not received all the attention it requires, and that is the personal peculiarities of motormen. There is little use in calculating speed-time curves and working out a particular motor, when the motorman is allowed to work the motors under totally different conditions. The automatic controllers will only partly obviate the trouble for they can only put on the power properly; it is taking off the power that is serious. A motorman always has it in his power to cut out the drifting portion of the speed-time curve. This is a small matter in elevated and subway work, where usually very little drifting is done, but it is vastly important elsewhere. It would seem, therefore, that there are several reasons why there should be little place for a large number of motors with slight differences. These are: 1. The small amount of information regarding operation of motors *under commercial conditions*; 2. The inability to calculate closely a motor for a given project in spite of the skill shown in speed-time curves and the like; 3. The fact that little or no precautions are taken, or even can be taken, to have the motors operated under the exact conditions by which they were calculated.

It must be conceded that too much conservatism would stifle proper experimenting, and retard real progress. Therefore the writer has in view a proper attitude of mind rather than any rapid adoption of hard and fast conditions. We must have experimental work, and the more of it the better. But it should be done rationally, that is, with an end in view which is definite. Men in authority should be perfectly sure that demands for changes in standard types are based on accurate information, and not on prejudice, whims and the like. If this position is taken, especially as large systems come and increase, there will be no danger of the semi-chaotic condition that exists in some other branches of industry.

DISCUSSION ON "CHOICE OF MOTORS IN STEAM AND ELECTRIC PRACTICE."

W. E. GOLDSBOROUGH: Mr. McClellan has brought to our attention a factor in the working out of heavy traction problems. I think that the first thing the electrical engineers will have to do, or will have to try to get steam railroad people to permit them to do, is to fix upon a standard form of electric current and electric pressure for the service of heavy locomotives. If, for instance, it were decided to deliver power to large electric locomotives uniformly at 25 cycles and 6 000 volts, single phase, it would be then possible to design quite a variety of interchangeable electric locomotives for trunk line service. There are a number of locomotive systems that have been suggested which are equally adaptable to this work. If locomotives of these systems can be arranged to be interchanged between different railroad systems, as the traffic on eastern lines increases and the western lines become electrified, the old locomotives can be put in service in the west and the electrified roads will become more or less a single inclusive system. I personally feel that it is useless for us to hope that there will be any greater uniformity in the design of electric locomotives than there has been in steam locomotives.

C. O. MAILLOUX: I do not think that this is a paper that can be very extensively discussed. I think it will be readily conceded that the author is right when he says that there is not much practical difference between the gear ratio of 3.24 and 3.28. In saying that, he expressed a warranted criticism of the methods at present in use whereby too large a variety of gear-ratios is made available, thereby causing some confusion and difficulty in the way of keeping extra parts. But there is another side to the question which the author seemed to recognize when he stated: "It must be conceded that too much conservatism would stifle proper experimenting and retard real progress." I do not believe that it is possible at the present time to do much standardizing in electric locomotives. I think it better to wait until a few electric locomotives are built and operated on steam roads before standardizing is attempted.

I remember, in my own experience, the attempts which were constantly made by manufacturers some years ago to develop standard forms of generators, and the persistence with which I refused to accept their standards. The wisdom of declining to agree with the manufacturers' wishes is demonstrated by the fact that since that time they have radically changed and improved the design of their machines.

Any attempt to standardize a thing too early may do more harm than good. The fact is that things become standardized only when they are sufficiently developed to admit of it. Standardization is gradually taking form in large alternators, and in large transformers. I do not wish to be understood as saying that nothing in connection with the electric locomotive can be standardized at the present time, but I do wish to be understood as saying that it is too early to standardize probably three-fourths of the types of electric locomotives. The statement made in the paper to the effect that no two locomotives are built alike, notwithstanding the fact that the building of steam locomotives began more than 60 years ago, is a sufficient criterion of the difficulties met with, a measure of the constantly varying requirements which make it almost impossible to standardize. Hence, I think that while gear-ratio and certain details of armature and commutator construction may be standardized—for they have been in service many years, and are more or less ripe for standardization—yet there are many things that cannot be standardized now. I think the discussion this morning showed that we are not yet prepared to standardize the "system." Some believe it ought to be three phase, some think it should be single phase, and others that direct current should be used. More experience must be had with all of these systems before attempting to standardize them. Lack of experience with high voltages suggests that no attempt be made to standardize voltage. In the meantime gear-ratios may be standardized; and their number reduced. There is no necessity for a manufacturer being required to furnish gear-ratios so near to each other as 3.24, and another 3.28. We might get along with steps of gear-ratios further apart than those available to-day, and to that extent decrease the number and complexity of standard parts. But I think that could be done more readily by adopting a standard inter-axial distance, because if a fixed distance between the armature shaft and the axle is adopted, that part is of necessity standardized since there are only certain gear-ratios that will fit in that combination. It would be almost impossible for all engineers to agree on that question, and it would probably be better and easier for the manufacturers simply to agree that they will furnish only certain standard forms, and that they will adopt certain distances between the motor axle and the gear axle; and thereby necessarily fix the possible number of gear-ratios by determining the possible numbers of teeth on the pinion and gear.

CHAS. P. STEINMETZ: As I understand it, this paper is intended to be an appeal for standardization of electric motors, especially electric locomotive motors; that is, motors intended for heavy traction. Now, I do not agree with the writer of the paper in his appeal to standardize motors, but would rather say, "don't un-standardize them," because the only thing that is in actual existence is the 550-volt motor, and, for heavy locomotive traction, the gearless motor. For that, a single-phase commutator motor is proposed, a motor supposed to run on a 6 000-volt trolley, but it is not running yet, and then a rheostatic induction motor, supporting it on a vastly lower frequency. If you want to standardize, you might as well stay where we are now and use what is here and what is known to be reliable rather than to go to new types, and so follow out the suggestion of the writer, unless such new types should be very seriously called for and become absolutely necessary.

Now, with regard to the gear-ratio which has been complained of here; this is unavoidable, but really only apparent. Gear ratios of 3.28 and 3.24 are not different but are the nearest feasible approach to the desired ratio 3.25. In the gear-ratio the number is always odd. This is a necessity because the ratio of the teeth of the pinion and the gear must be prime to get uniform wear, and in addition thereto the number of the teeth of the pinion must be as large as possible to get good wear and smooth transmission. This means that with a certain number of teeth in the pinion the nearest approach to a gear-ratio of 3.25 may be 3.24, while in a larger motor permitting a pinion with a few more teeth, the nearest approach may be 3.28. This difference is, therefore, unavoidable. What can be standardized are certain approximate gear-ratios, 3.25, 3.75, 4.25. It will never come out exactly like this, but near enough. It is therefore not a question of whether an engineer can find a difference between 3.28 and 3.24, because both ratios are intended to be the same.

C. O. MAILLOUX: I wish to take issue with Mr. Steinmetz about his reference to standardizing I do not sympathize with the idea that things which are not standard should be avoided. As a matter of fact in the present state of the art of electric traction as applied, or expected to be applied to steam and trunk lines, any system whatever should be welcomed with encouragement. I have expressed my opinion as being skeptical perhaps in regard to certain systems. These systems are not standards in the sense we would now understand them. But I would not be understood as saying that I would not want to see these systems introduced. If there are people who have sufficient money and sufficient faith in these systems to introduce them, I should very much like to see them tried. Indeed, there may be a good many good points in them that we know not of, and it is with these things as it has been in the past with many things which were supposed to be standard, and which have had to be modified, by reason of collateral types coming into existence and serving if for nothing more, to give valuable hints and suggestions to other systems which engineers have been more than pleased to appropriate and utilize. I think that the disposition to stop experimenting and to adopt standards and adhere to them *too soon* is capable of doing a great deal of harm, by retarding progress, if not stopping evolution.

H. G. STOTT: A good illustration of the lack of standardization and the result of it are found in the fact that to-day probably no manufacturer of reciprocating engines builds two lots alike.

I will give a notable instance: large engines built for the Manhattan Railway Co. had just been installed, and the last one was not running. Nine engines of exactly the same speed and capacity and style were ordered—the first castings were made about the time that the last Manhattan engine was being delivered—yet when we compared the second lot of engines with the first lot they were radically different, and that was after 60 years of development of reciprocating engines and less than one year between the building of the two lots of engines. The cylinder heads were different, the cranks were different, and the cross-heads and valve-gears were different. I think it is rather hopeless to think of standardizing electric locomotives for another 50 years. This paper is about half a century ahead of time

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

ELECTRICAL FEATURES OF BLOCK SIGNALING.

BY L. H. THULLEN.

It is only within the last decade that electricity has played any important part in block signaling. Previously to that time the only electricity used in signaling was the current from a few batteries for the track circuit, and for the operation of pin-valve magnets in the electropneumatic system of signaling and interlocking. During the last few years the use of electricity for signaling has steadily increased. Now electricity is the chief feature of all signaling apparatus. A brief sketch of the older methods of signaling will be first presented, as they are still in use, and therefore not without interest.

TELEGRAPH BLOCK SYSTEM.

The first system worthy of notice is what is known as the telegraph block system, which is yet extensively used, especially on single-track roads. In this system the road is divided into sections of a predetermined length, an average section or block being from one to three miles long. An operator is stationed in a tower at the entrance of every block, and by means of hand-operated signals gives the engineer of an approaching train a clear- caution- or stop-signal, as the case may be. Under normal conditions only one train is allowed in a block at a time. The operator allows a train to enter a block only after he has received information from the operator at the other end that all trains have cleared that block. This information can be given by means of a bell-signal, or by telegraph.

Lock-and-Block System.

A system similar to the telegraph block system, but more automatic in its action, and not depending entirely upon the vigilance of the operator, is what is known as the lock-and-block system. In this system the machine that operates the signal is locked by means of a track circuit, and is unlocked by the operator in the block in advance when all trains have cleared the section. A system of bell-signals is used in the lock-and-block system to give notice to the towerman.

Automatic Block Signaling.

The automatic block system of signaling, that does not depend in any way upon any operator for its proper manipulation, however, is coming into extensive use at the present time. In this system, as in the two systems just outlined, the road is divided into sections, or blocks. An automatic signal indicates to a train approaching a block that the block ahead is either occupied or unoccupied by a train. It is quite customary to place two signal-blades upon one post, by which two signals can be given, one signal showing the condition of the first block in advance, and the other making known the condition of the second block in advance. Or one blade only may be employed which may occupy three positions: vertical, indicating that two blocks in advance are clear of trains; an angle of 45°, or caution-signal, denoting first block clear, and second block occupied; horizontal, or danger-signal, indicating that the first block is occupied.

These signals are usually operated either by compressed air, or by electricity, although carbonic-acid gas is sometimes used. However, the electrically-operated signals are coming more and more into use, and bid fair to be the signals of the future.

Track Circuit.

All automatic signals are controlled by a track circuit as shown diagrammatically in Fig. 1. A is a source of electric energy, usually in the form of a battery of one or more primary cells, or a storage-battery of one cell. In the latter case a resistance of one ohm, to prevent an excessive discharge of current when a train is in a block, is placed between the cell and the track. When storage-batteries are used they are charged from mains extending along the track. The cells are in duplicate, one being charged while the other is in use; the batteries are switched in or out, either automatically or by the signal inspector when on his rounds.

At the other end of the block is a relay that controls the operation of the signals through a local circuit. The signals are generally operated by a $\frac{1}{8}$-h.p. motor, and 5 storage-cells each of 24 ampere-hours' capacity. The energy taken to operate most signals is 2 amperes at 10 volts for 6 seconds. When the signal has assumed the normal position, the circuit to the motor is opened and the signal held in position by an electromagnet. The current required to hold the signal in this position is only 0.01 of an ampere.

When a train enters a block the relay *B* is shunted, its armature drops and opens the local circuit, thus allowing the

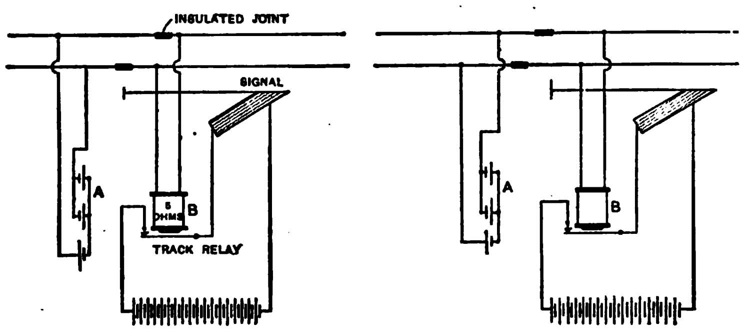

FIG. 1.

signal to move to the danger position. The signal is not cleared again until the train leaves that block.

It is interesting to note that in a block-section 4000-ft. long, when the track is covered with snow, or the ties wet with rain, and the ballast up to the flange of the rails, the resistance between the two rails will not exceed 0.5 ohm.

To the average engineer these pieces of apparatus seem quite simple, but if he stops to consider he will at once be impressed by the degree of exactness required to make them faultless, and operative under all conditions of weather and changes of temperature. In fact all parts must be practically perfect, for the lives of thousands daily depend upon the proper operation of the signals.

The signaling apparatus is so designed that no probable events or conditions will cause a clear signal when a danger signal is required. For instance, all electric circuits are closed when in the clear position; any broken wires or broken rails will put the signal to the danger position. Also, all forces are always operated against gravity, no springs or other forces being used to put the signal at danger. Under all adverse conditions the automatic signal is therefore by far the most reliable.

System on Boston Elevated R.R.

Since the adoption of electricity for motive power on steam roads great changes have been made in the art of railway signaling. On steam roads the track can be subdivided into sections equal to the length of a block, but on electric roads the rails must be continuous in order to provide for the return of the propulsion current. At first one rail was made continuous

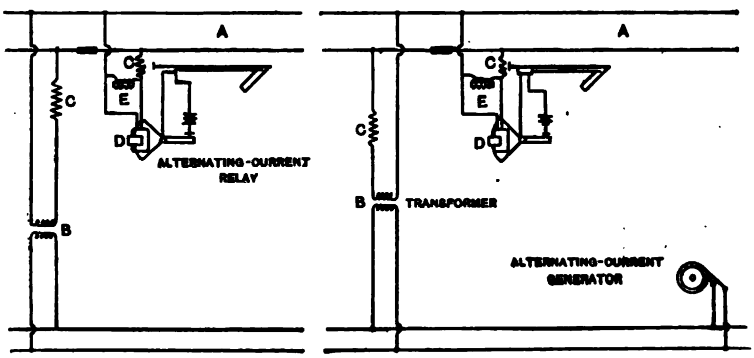

Fig. 3.

and the other subdivided into sections equal to the length of the block. A source of current was supplied to one end of the block, and a relay having a polarized armature was placed at the other end. This relay was operative only by the track current which was connected in opposition to the current traversing the subdivided rail. This system is shown diagrammatically in Fig. 2. It was installed on the Boston Elevated R.R. in 1901, and is still in use.

More Recent System.

Another system of more recent date, installed on the North Shore Railroad in California, and in the New York Subway, consists of the application of an alternating current to the track, and the use of a relay operative by alternating current only. This system is shown in Fig. 3. *A-A* are block-

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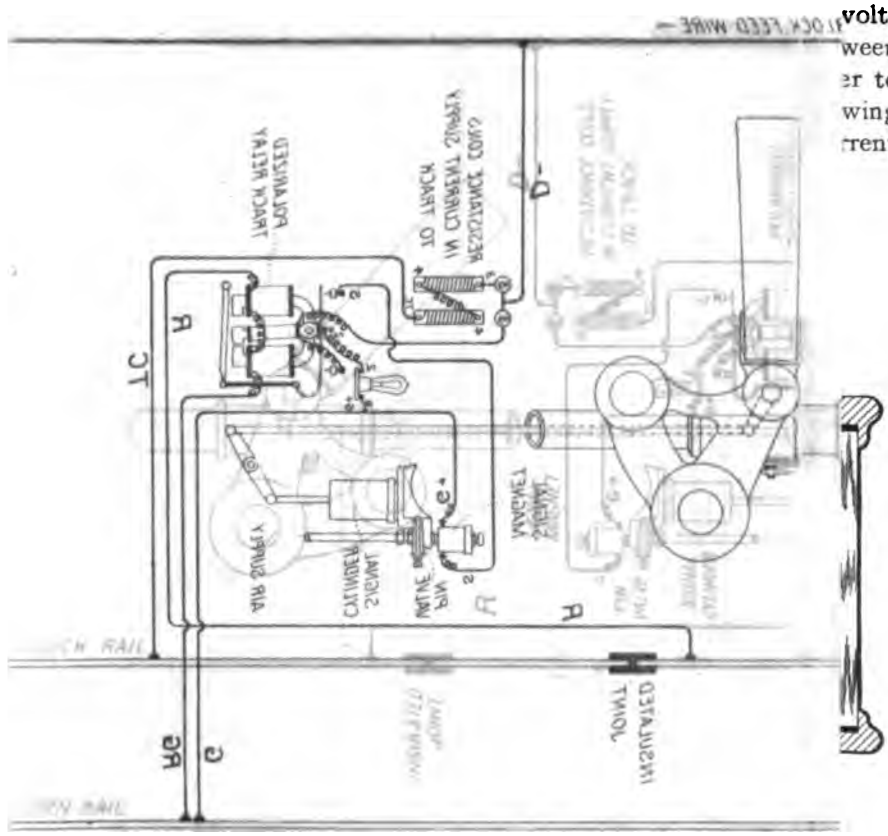

EXPLANATION
D—Dynamo
G—Ground
R—Relay
T C —Track Cur
R G—Relay Gr
S—Signal
1, 2, 3, 4—Local W

FIG. 2.—(Thullen.) Diagram of Operation of Electropneumatic B

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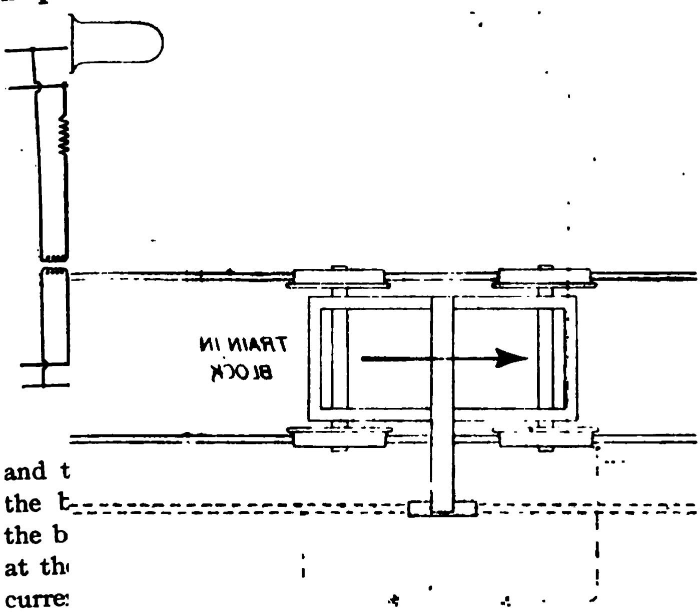

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sections. *B-B* are transformers which transform current from a high pressure—500 to 2000 volts—to about 10 volts for the track circuit. *C-C* are resistances placed between the transformer and track, and relay and track; the former to limit the amount of alternating and direct current flowing through the transformer, the latter to limit the direct current traversing the apparatus at the relay end of the block.

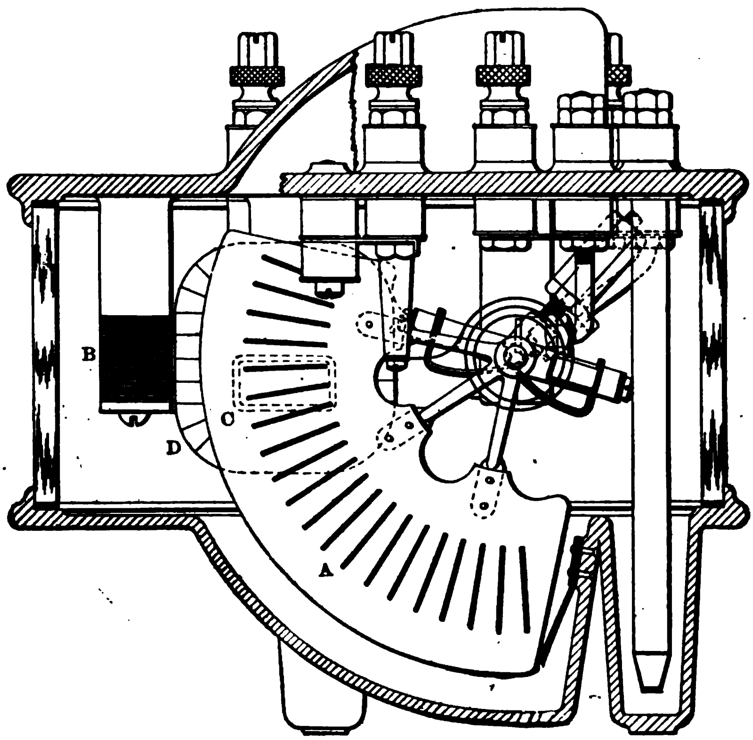


Fig. 4.

D is a relay made to operate on the Ferraris principle. This relay is shown by Figs. 4 and 5, in which *A* is an aluminum disc, *B* a laminated iron core, and *C* a copper ferrule which embraces one-half of the poles of the laminated iron core. *D-D* are the coils traversed by the alternating track-current. As can be readily seen, this relay will operate by alternating current only. Referring to Fig. 3, *E* is an impedance coil of low ohmic resistance, which offers a free path for the direct current, but is traversed by only a small part of the alternating current. The impedance coil is, therefore, a shunt to the alternating-current relay; one object of the shunt coil is to limit the direct current that traverses the relay, for the presence of direct current causes the relay to operate in a sluggish manner. As the resistance of the relay is quite high compared with that of the impedance coil, very little of the direct current will traverse the relay.

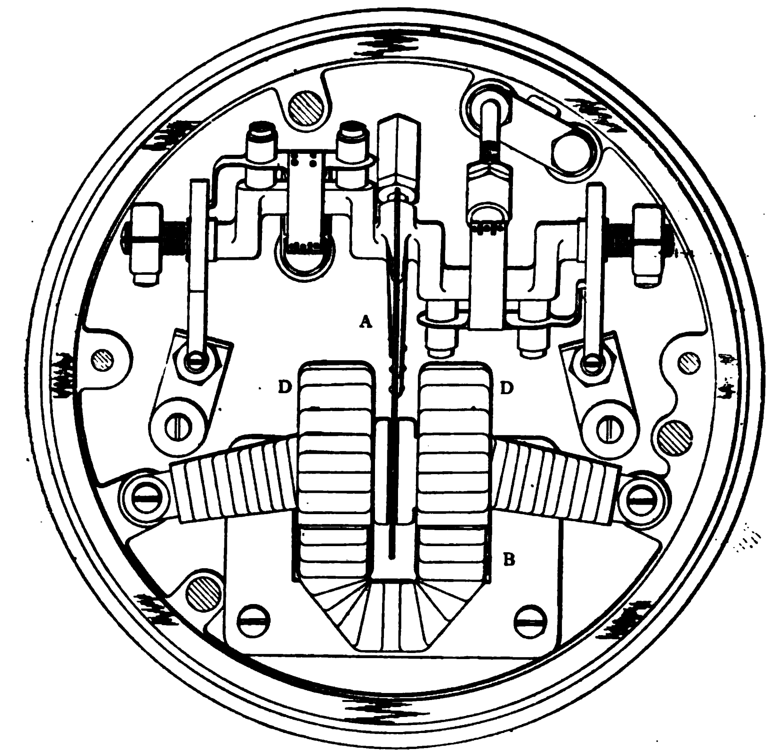


Fig. 5.

A Later System.

In the system just described only a small current traverses the sectional rail. Means more recently devised, whereby both rails can be utilized to a greater extent for the return current, are shown by Fig. 6, in which *A-A* are block-sections, from 2 000 to 4 000 ft. in length; *B-B* are inductive rail-bonds of a few turns of copper conductor of about 1 000 000 cir. mils cross-section, *C-C* are transformers supplying current to the track, and *D-D* are relays operated by alternating current only, controlling the signals through the local circuit E. They are similar to those shown in Fig. 4.

The transformer is designed to have a large amount of magnetic leakage when the secondary is short circuited by a train in the block, thereby reducing the electromotive force of the secondary and the energy absorbed at that time.

The inductive rail-bond is shown in detail in Fig. 11. The bond is composed of a few turns of bar copper, and adds but small resistance to the track-section; in fact, the actual increase of resistance in a track-section 3 000-ft. long, due to the addition of these bonds, is only one-half of one per cent.; or in other words, the efficiency of the track return is 99.5 per cent.

As shown in Fig. 5, the propulsion current traversing each rail divides and traverses the bond in opposite directions, thereby

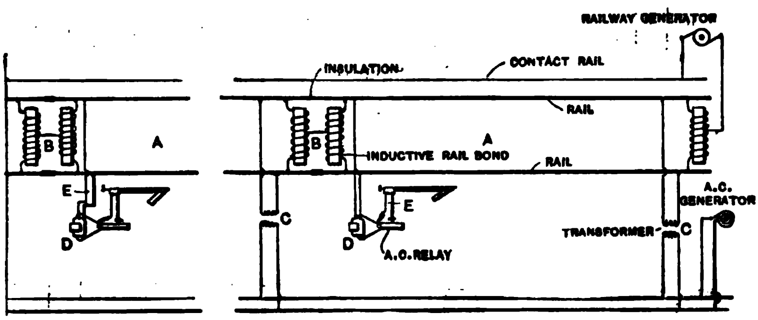


FIG. 6.

neutralizing the magnetic action of the direct current; while the alternating current traverses the bond in only one direction, making the bond inductive to the track current.

The question naturally arises: will the resistance of both rails be equal? It is not assumed that they will be, and this is taken care of by making the iron core of the inductive rail-bonds with an open magnetic circuit, the opening being so large that no excessive unbalancing of the current between the rails will change the inductive effect of the bond.

The effect of direct current on impedance coils, with and without an air-gap, is shown by curves in Figs. 7 and 8. Fig. 7 shows the same winding and iron as used in the test shown by Fig. 8, except that in Fig. 8 the iron core has an air-gap of 0.125 in. In Fig. 7, the least amount of direct current will make a great increase in the alternating current traversing

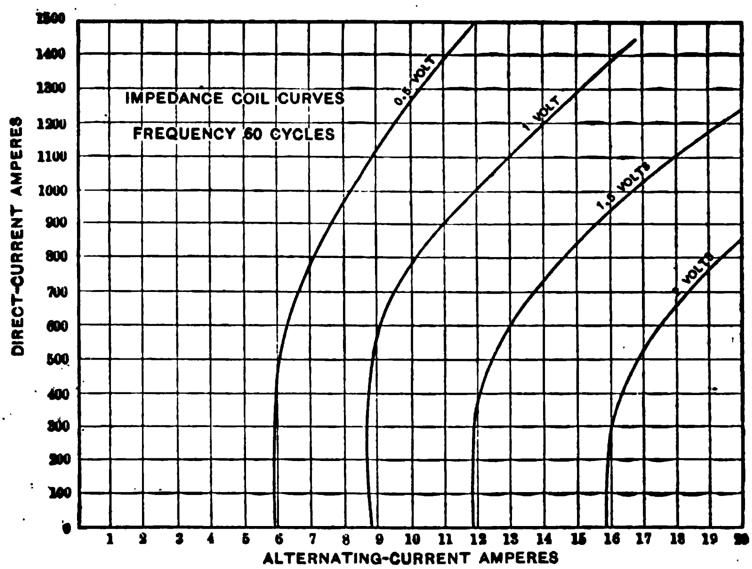

IMPEDANCE COIL CURVES
FREQUENCY 60 CYCLES
0.5 VOLT
1 VOLT
1.5 VOLTS
2 VOLTS
DIRECT-CURRENT AMPERES
ALTERNATING-CURRENT AMPERES

FIG. 7.

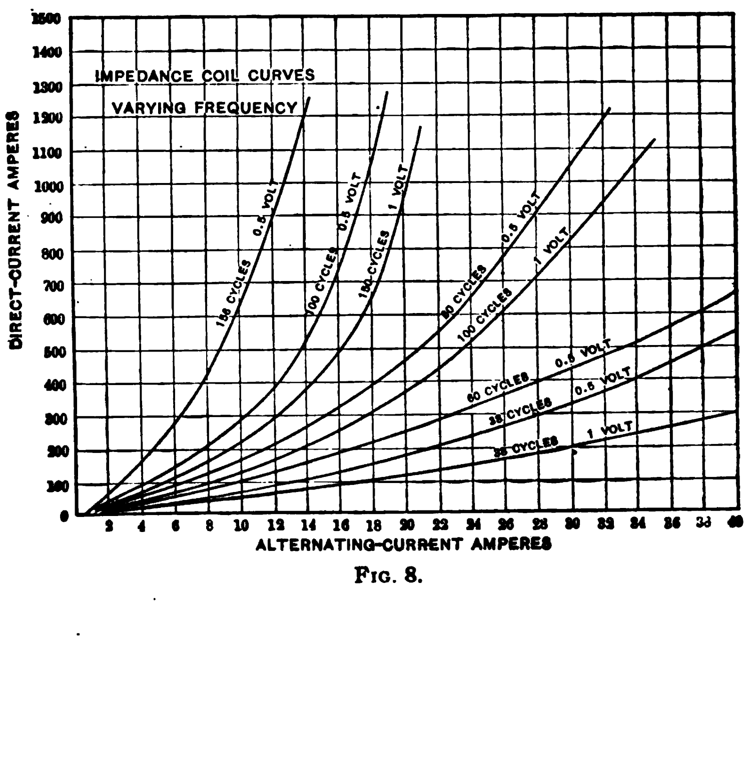

IMPEDANCE COIL CURVES
VARYING FREQUENCY
0.5 VOLT
1 VOLT
100 CYCLES
60 CYCLES
DIRECT-CURRENT AMPERES
ALTERNATING-CURRENT AMPERES

FIG. 8.

the coil, while in Fig. 8 the direct current is increased to 600 amperes without any material increase in the alternating current.

From 600 amperes to 1 200 amperes, the curvature is gradual; beyond 1 200 amperes the curves are quite flat. The air-gap may be made sufficiently long to take care of any reasonable amount of direct current, the alternating and direct current traversing the coil being nearly in proportion to the opening in the magnetic circuit. Continuity is attained between adjacent block-sections by connections made to the middle of the inductive windings. It will be seen, therefore, that the track-current from one block cannot extend into another block regardless of the impedance of the bond *B*.

A relay similar to that shown in Fig. 4 is used in this system, the only changes being of minor importance. The electromotive force at the relay is a little more than one volt. In blocks 3 000-ft. long there is a pressure of about 6 volts at the transformer, the difference being due to the high impedance of the rail with the alternating current.

The relay is placed at the entrance end of a block and the transformer at the exit end. With no train in a block, the energy absorbed by each block is approximately 50 watts. When a train enters the block at the relay end, the energy is seldom more than 75 watts, and about 300 watts when the train is exactly opposite the transformer. As the train is exactly opposite the transformer but a few seconds at a time, the average actual energy consumed is quite small.

LIGHT-SIGNALS.

In the East Boston tunnel light-signals only are used, as shown in Fig. 9. The signals have two colored lenses; red, for danger; and green, for safety. The signals are lighted by two 4 c-p., 50-volt lamps connected in multiple. The lamps are placed close together and in line with the lens, the focus of the lens being midway between the two lamps. With this arrangement very little difference is noticed in the action of the lenses. Low-efficiency lamps with a coiled filament are used; on account of their low pressure and low efficiency these lamps have long life. Being connected in multiple, both would have to be out at once before the signal would be out of commission; even then there would be no danger, as no light in a signal is considered a danger signal. The current for the lights is supplied by a separate winding on the transformer.

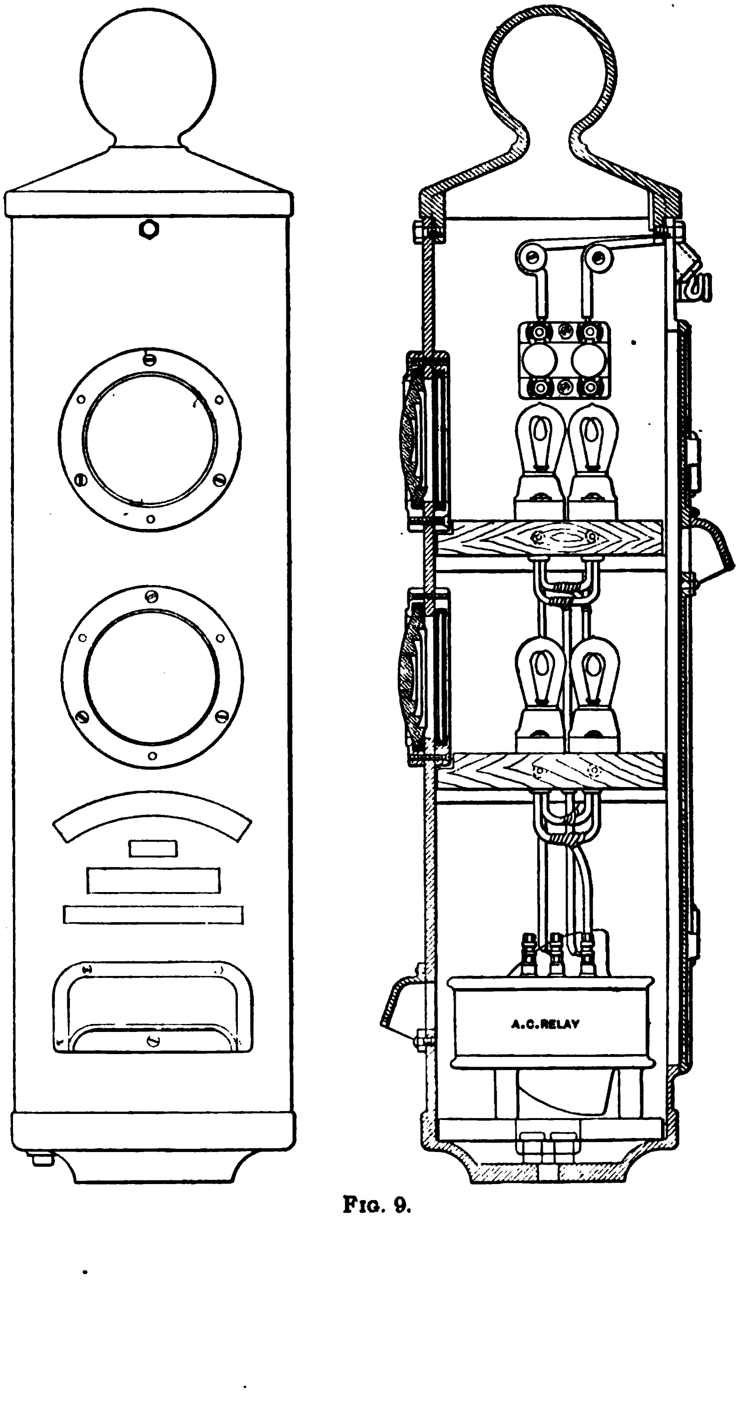


Fig. 9.

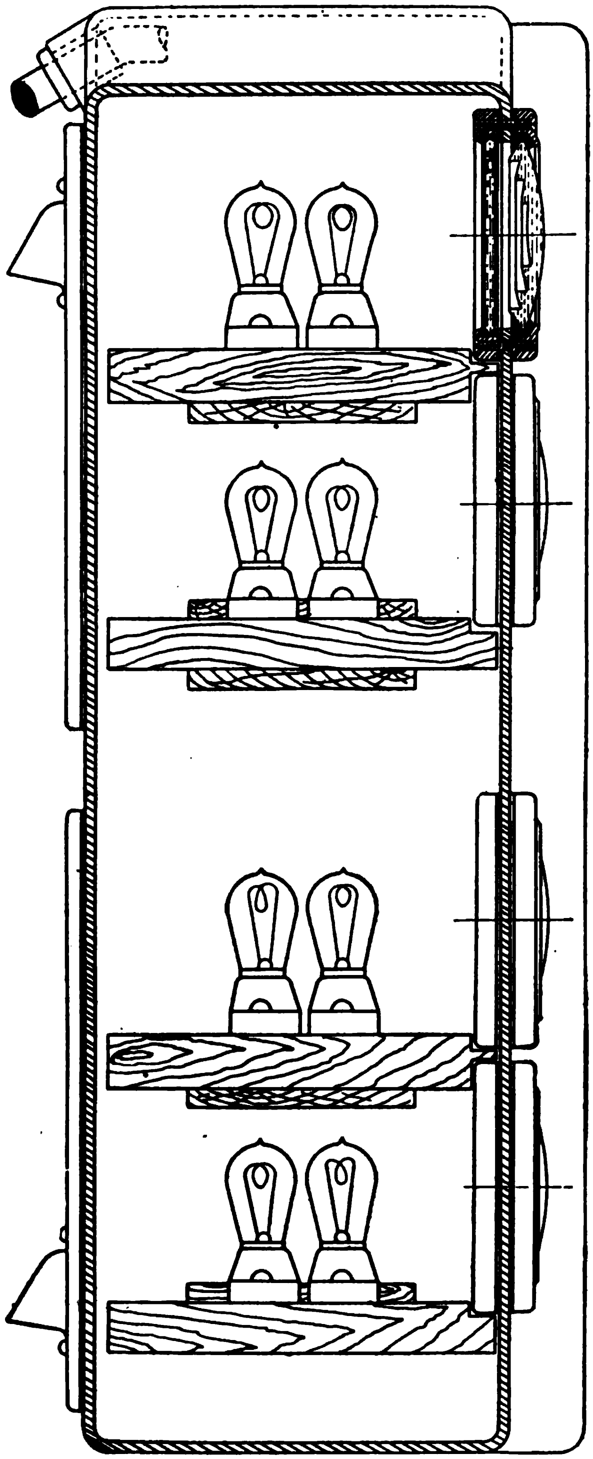


Fig. 10.

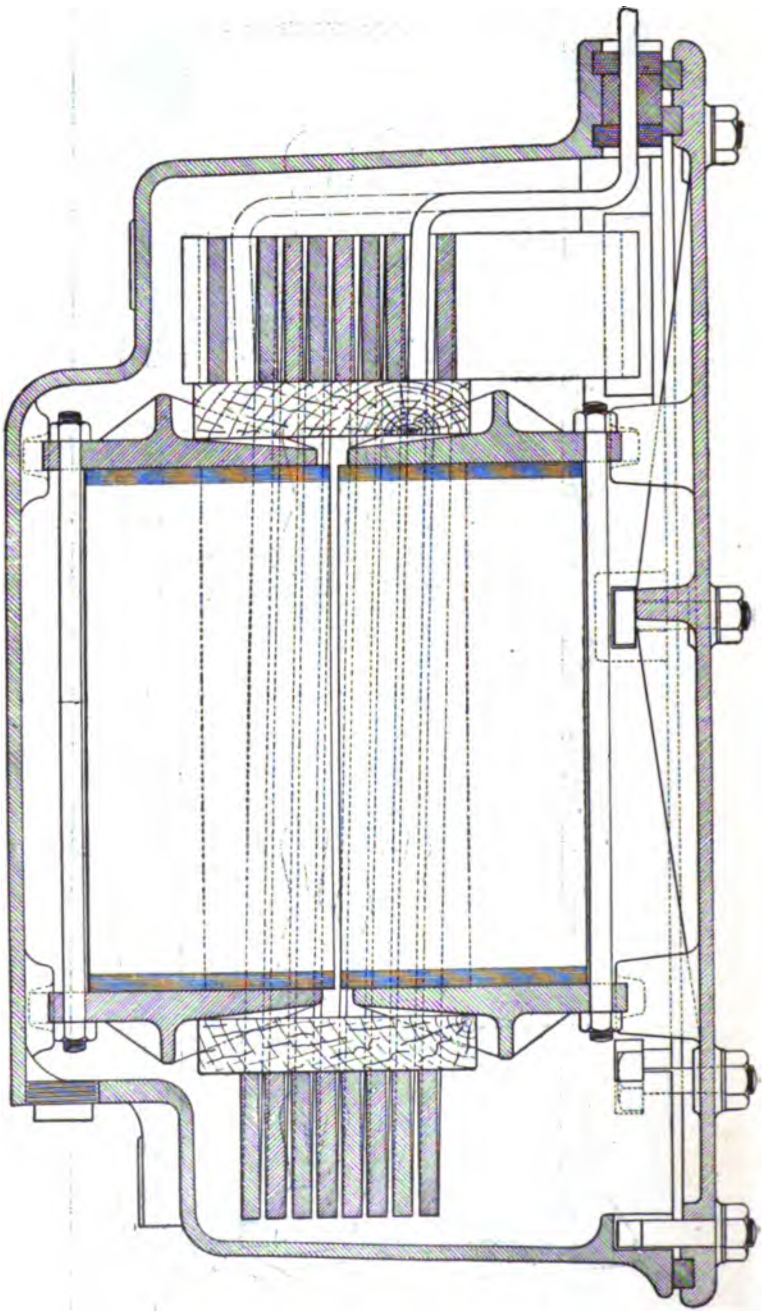


Fig. 11.

Electrically-lighted signals are fast displacing the oil-lighted ones. They were adopted on the New York Subway after very careful consideration, and their continued satisfactory working has more than justified their adoption. In an installation of this kind men are not required to fill and clean lamps. This means great saving in the cost of labor, and perhaps of life; for in a place like the Subway, where space is limited and the trains are constantly running, it is of great importance that the maintenance crew be kept as small as possible.

In the East Boston Tunnel the lamps are lighted and extinguished back of the different lenses by means of front and back contacts on the track-relays. The contacts are made between platinum and carbon, as two metals could not be used on account of the liability of fusing.

At this point it may be said that the layman usually believes that the rails of a track are less likely than any other part of the signal system to be struck by lightning, or to carry currents induced by lightning. Yet this is a condition that signal men have to contend with. The inductive discharge between rails is considerable, and numerous relays have been burned out or injured by lightning, notwithstanding that they were built in the best possible manner, and all parts tested by an alternating current of 5 000 volts as an insulation breakdown test.

Long Island Railroad Signaling System.

In the electrified subway portion of the Long Island Railroad electrically-lighted signals only are to be used. The signals are shown in Fig. 10. Four lights will be used: the two upper ones being the signals for the adjacent block, and the two lower ones for the second block in advance. The upper lens is red, danger; the one below, green, or safety; the upper one of the two lower lenses is yellow, or caution, and the lower one green, or safety.

On the elevated and surface portions of this road it is planned to use signals of the 2-arm type operated by electric motors from storage-batteries of 6 cells each, the batteries being charged by current taken from the third-rail through a suitable resistance. About 250 of these signals are to be installed. Current at 2 000 volts and 25 cycles will be furnished the signaling system by mains extending the length of the track.

DISCUSSION ON, " ELECTRICAL FEATURE OF BLOCK SIGNALING."

H. G. STOTT: I am surprised that Mr. Thullen has attempted to treat such a subject in so short a paper, because when one sees the mass of detail entering into the improved signal system it seems almost hopeless to attempt to describe it. The amount of detail looks discouraging and the expression of a number of our engineers (excepting the signal engineers) before the system was started was " How will the trains be kept running; it is so easy to stop them and so hard to get them started again? " For instance, we start out with a transmission line, a 60-cycle transmission line to the different sub-stations, and that was to supply ultimately, after passing through transformers, about 550 volts, carried to a main bus-bar running the whole length of the system. In addition to that, there are still in each sub-station motor-generator sets consisting of a direct-current motor operated from the bus-bar, and that directly connected to a small 60-cycle generator, which is held as reserve so that in case of failure of the 60-cycle power from the main power-house it can be supplied immediately from the sub-station by putting in one of the small motor-generators in each sub-station and synchronizing them. These in turn feed into the 550-volt, single-phase, 60-cycle pair of wires running the entire length of the subway. They in turn feed transformers, and these transformers supply 14-volt bus-bars running the entire length of the system. In addition to that there is another line of storage-batteries for supplying the lights and they in turn are fed from the third rail at different points. In addition to that there is a main air-pipe line which of course is controlled by the electrically operated signal system between interlocking and overlapping sections. There is such a mass of complication and detail that it seems absolutely hopeless to attempt to make any description of it. The record of performance of the 60-cycle relays in the Manhattan Railway system has been remarkably good. I think the actual record is something like 300 000 successful performances to one failure, and it is improving all the time. That in itself was on an absolutely new system when installed in the New York subway. In the subway system one track rail is used for the return current, what might be termed the traction current, and the other rail is insulated and is used only for the signal service.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

WEIGHT DISTRIBUTION ON ELECTRIC LOCOMOTIVES AS AFFECTED BY MOTOR SUSPENSION AND DRAW-BAR PULL.

BY S. T. DODD.

In a locomotive propelled by electric motors the motor action produces a set of stresses acting between the truck-frame, motor supports, and driving-wheels. The horizontal effort at the rail-head resulting from these stresses acts against the resisting forces of the locomotive, the principal items of which may be considered as:

a. The rolling friction of the wheels on the track, acting at the rail-head.

b. The resistance to acceleration due to inertia of the locomotive, and the resistance due to grades, acting at the center of gravity of the locomotive.

c. The air resistance acting at the exposed surface, particularly at the head end.

d. The resistance of the trailing load, acting at the draw-bar.

The effect of the forces here discussed, including the internal or driving forces acting between truck, motor, and wheels, and the external or resisting forces, produces a shifting or redistribution of the weight on the various wheels. In this paper an attempt is made to investigate the amount of this redistribution. The discussion is confined to locomotives drawing trailing loads, since this redistribution of weight is particularly effective in the case of a locomotive exerting a horizontal effort at approximately the slipping point of the driving-wheels. Some of the general limitations and considerations applying to this particular case must be clearly defined.

Stresses acting on a spring supported locomotive produce a compression of journal-box springs and a consequent shifting of the center of gravity of the locomotive and a redistribution of the weight on the wheels. A certain amount of redistribution of weight due to this cause may be assumed, but it has been omitted in the following discussion for the reason that it cannot be investigated without a knowledge of the elasticity of the springs.

The resistance due to inertia assumes particular importance in the case of single motor-cars subjected to high acceleration. The air resistance also is of particular importance in single high-speed motor-cars. In a purely locomotive problem such as considered here, that is, in the case of a motor-car used only for drawing trailing loads, the weight of the locomotive is often less than 10% of the weight of the trailing load. The resistances due to the locomotive itself are therefore not so important as those due to the rest of the train, and consequently no great error will be introduced into our results, and their expression can be much simplified, by leaving out of consideration the weights and resistances of the locomotive itself, and by considering the entire reaction against horizontal effort to be concentrated at the draw-bar.

Since each axle and its pair of wheels form a rigid uniform body they are always considered together; a reference to a driving-axle always is understood to include the pair of wheels attached to it.

The following calculations are based on the horizontal effort per driving-axle. Since all the motors on the locomotive are supposed to be geared so as to produce an equal torque on each driver, the draw-bar pull of the locomotive is consequently equal to the product of the horizontal effort per axle into the number of driving-axles.

In all diagrams, motion of the locomotive is considered to take place from left to right. The driving-axles are lettered from rear to front, so that the axle A is the one nearest the draw-bar and the axle D the one nearest the pilot.

The weight of the locomotive frame is assumed to be carried on springs upon the journal-boxes. With a motor suspended in the usual way, part of the stress it exerts is transmitted through the axle-bearings direct to the axle and part is transmitted through the suspension to the truck and journal-box springs. Forces transmitted from the motor direct to the axle are referred to as increase or decrease of "dead weight" and those transmitted through the frame are referred to as increase or decrease of "live weight." The sign + indicates an increase of weight, the sign − a decrease of weight.

The increase or decrease of weight on any axle due to motor and draw-bar actions is proportional to the horizontal effort per driving-axle. In what follows the term "Distribution-Factor" represents the ratio between the increase of weight on any axle and the horizontal effort per driving-axle. This distribution-factor may be either positive or negative, a negative value referring to a decrease in weight.

The alteration of weight on a driving-wheel alters the slipping point of the wheel, consequently the distribution-factor may also be considered as determining the variation in the tractive power of the driving-wheels. In other words, the change in the slipping point of the wheels due to internal actions can be easily determined by a determination of the distribution-factor as may be shown by the following considerations:

$L o$ = Original load per axle.
L = Final load due to redistribution of weights.
P = Horizontal effort per driving-axle at the slipping point
X = Coefficient of traction.
Y = Distribution-factor (may be either + or −).

At the slipping point: $P = X L = X (L o + P Y)$

Therefore:

$$P = \frac{L o}{1/X - Y} \tag{1}$$

To make this more definite by a concrete example, consider a 4-axle locomotive with a weight of 10 tons per axle and a tractive coefficient of 20%. Without considering the distribution-factor, the horizontal effort per axle is given by:

$$P = 20\,000 \times 0.20 = 4\,000 \text{ lb.}$$

Therefore: draw-bar pull $= 4 \times 4\,000 = 16\,000$ lb.

If, however, one of the axles has a distribution-factor of −0.5, applying formula (1) the horizontal effort on this particular axle is:

$$P = \frac{20\,000}{5.5} = 3\,636 \text{ lb.}$$

Since the maximum draw-bar pull of the locomotive is limited by the slipping point of any wheel, the distribution-factor on this one wheel reduces the maximum draw-bar pull on the whole locomotive from 16 000 lb. to four times 3 636 or 14 544 lb. It follows from this that Y, the distribution-factor, is a quantity which, subtracted from the reciprocal of the tractive-coefficient, gives the effective or equivalent reciprocal for any axle from which the actual slipping point can be derived

The distribution-factor has to be separately discussed for each separate design of locomotive but the symbols given in the following table are adhered to in the discussion of each type:

TABLE I.

A, B, C, D...	Driving-axles,
E, F........	Pony-trucks,
G, H, I......	Points of support of locomotive frame on equalizer system.
J, K........	Truck centers or centers of equilibrium of locomotive frame,
L, M, N, O..	Points of motor suspension or motor-noses,
P...........	Horizontal effort per driving-axle,
$2a$..........	Length of journal-box spring,
$2b$..........	Wheel-base per pair of drivers,
c............	Distance between J and K,
$2d$..........	Length of equalizer-links,
h............	Height of draw-bar,
s............	Distance between axle center and motor-nose,
t............	Height of truck-bolster,
w...........	Radius of driving-wheel.

Type No. 1 Locomotive.

Fig. 1 shows a single-truck, four-wheel locomotive with two driving-axles. The distribution of stresses on the wheels and truck are shown in the diagram; and it may be advisable in this simple case to discuss these stresses in detail in order to illustrate the method which has been applied to other types of locomotives. It will be noted that under the headings Type No. 2 to Type No. 5 this paper does not attempt to discuss the stresses in detail but simply states in a summarized or tabular form the results of a similar discussion.

The action of the motor on the driving-axle A and the reaction against the track produce a horizontal pressure P against the journal-box and a vertical pressure at L, the nose of the motor. The vertical action at L deducts from the dead weight directly on the axle an amount $P\,w/s$ and transfers to the truck frame an equal weight which is again transmitted through the journal-box springs to the axles A and B. An application of the equation of moments of forces around these two axles shows that the weight on L produces a redistribution of the weights on A and B, in the inverse ratio of the distances of L from A and B; that is, it adds a live weight, $P\,w\,(s+2\,b)/2\,s\,b$, to the axle A, and reduces the live weight on B by $P\,w\,s/2\,s\,b$.

Similarly, the action of the motor on the driving-wheel B produces a horizontal pressure P against the journal-box and a vertical pressure at M, the motor-nose. This vertical action at M adds to the dead weight upon the axle an amount $P\,w/s$

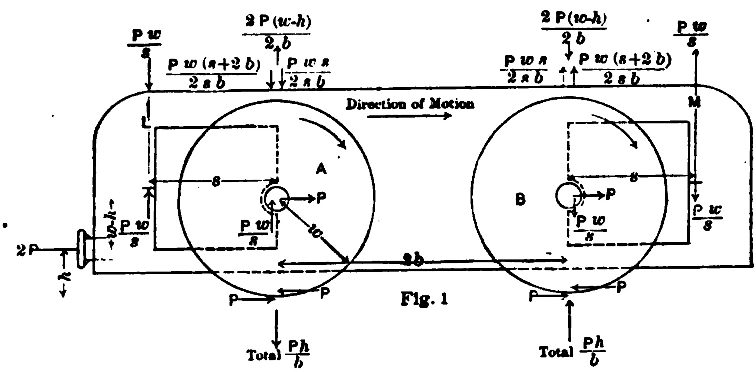


Fig. 1

and reduces the live weight at M by a similar amount. This reduction of weight again produces a redistribution of the weights on A and B in the inverse ratio of their distances, reducing the weight upon B by $P\,w\,(s+2\,b)/2\,s\,b$ and adding to A an amount $P\,w\,s/2\,s\,b$.

The total redistribution of weight due to internal or motor actions is found by adding the items above acting on A and B respectively as follows:

On A, $-P\,w/s+P\,w\,(s+2\,b)/2\,s\,b+P\,w\,s/2\,s\,b = +P\,w/b$

On B, $+P\,w/s-P\,w\,s/2\,s\,b-P\,w\,(s+2\,b)/2\,s\,b = -P\,w/b$ (2)

In addition to the motor action, the effect of the horizontal forces must be considered. The pull $2\,P$ on the draw-bar acts on the trucks at a height h above the track, and the force on the drivers acts at the journal-boxes at a height w above the track; this produces a couple acting upon the truck whose moment is $2\,P\,(w-h)$ which tends to tilt the truck and which is balanced by an equal and opposite couple of the same moment acting at the axles, but whose arm is $2\,b$ the distance between the journal-boxes.

The alteration of pressure on the axles due to draw-bar actions is therefore:

On A, $-2\,P\,(w-h)/2\,b$

On B, $+2\,P\,(w-h)/2\,b$ (3)

The total effect of the motor and draw-bar forces is therefore:

On A, $+P\,w/b - P\,(w-h)/b = +P\,h/b$

On B, $-P\,w/b + P\,(w-h)/b = -P\,h/b$ (4)

The same results will be obtained by applying the same reasoning to any arrangement or gearing of motors on a single truck. Table 2 contains a summary of these deductions.

TABLE 2.

INCREASE OF WEIGHT ON

	L	A	B	M
Produced by				
Motors direct	$+P\,w/s$	$-P\,w/s$	$+P\,w/s$	$-P\,w/s$
Stress at L		$+P\,w\,(s+2\,b)/2\,s\,b$	$-P\,w\,s/2\,s\,b$	
Stress at M		$+P\,w\,s/2\,s\,b$	$-P\,w\,(s+2\,b)/2\,s\,b$	
Total motor action		$+P\,w/b$	$-P\,w/b$	
Draw-bar action		$-2\,P\,(w-h)/2\,b$	$+2\,P\,(w-h)/2\,b$	
Total		$+P\,h/b$	$-P\,h/b$	

This result may be briefly stated by saying the distribution-factor is $\pm\ h/b$.

Considering this result still further, we note it shows that the locomotive is acted on at the axles (a distance of $2\,b$ from each other) by equal and opposite forces $\pm\ P\,h/b$, constituting a couple whose moment is therefore $2\,P\,h$. But h is the height of the draw-bar, and $2\,P$ is the force acting at the draw-bar in one direction and at the rail-head in the opposite direction. This shows that a single motor truck may be discussed as if it were a rigid body acted on by a horizontal effort along the line of the rails and a draw-bar pull at the height h above the rails.

Type No. 2 Locomotive.

This is an eight-wheel locomotive having two independent trucks, and four driving-axles. The motors are supported on the trucks, and all internal reactions due to the motors are self-contained in the trucks as shown in Fig. 2. The stresses of the draw-bar are transmitted by the truck-bolster from the locomotive frame to the truck. In addition to the dimensions discussed under type No. 1, we must take into consideration the dimension t, the height of the truck bolster, and c, the distance between truck centers. There are three sets of actions to be discussed:

1. The internal actions of the motors produce an increase of weight on the rear axle of each truck and a reduction in weight on the forward axle of the amount $P\,w/b$, as already discussed under type No. 1, formula (2).

2. Each truck is acted on by a horizontal effort $2\,P$ at the journal-boxes and an equal and opposite force at the truck-bolster; these constitute a couple that produces an increase in weight on one journal-box and a decrease on the other whose

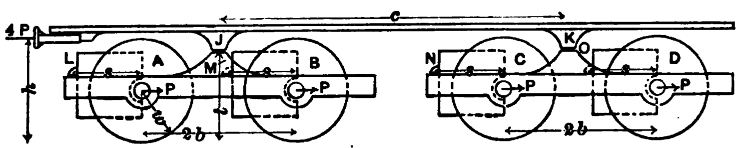


Fig. 2.

amount is $2\,P\,(w - t)/2\,b$, as already discussed under Type No. 1, formula (3).

3. The locomotive body is acted on by a couple due to the pull of the draw-bar at a height h and the pull on the truck-bolster at a height t, tending to tilt the locomotive body and increase the weight on one truck, decreasing it on the other by the amount $4\,P\,(t - h)/c$. These reactions are summarized in Table 3.

TABLE 3.

INCREASE OF WEIGHT ON

	A	J	B	C	K	D
Produced by						
Motors..........	$+P\,w/b$		$-P\,w/b$	$+P\,w/b$		$-P\,w/b$
Bolster..........	$-\frac{2\,P\,(w-t)}{2\,b}$		$+\frac{2\,P\,(w-t)}{2\,b}$	$-\frac{2\,P\,(w-t)}{2\,b}$		$+\frac{2P(w-t)}{2\,b}$
Draw-bar........	$-\frac{2\,P\,(t-h)}{c}$	$-\frac{4\,P\,(t-h)}{c}$	$-\frac{2\,P\,(t-h)}{c}$	$+\frac{2\,P\,(t-h)}{c}$	$+\frac{4\,P\,(t-h}{c}$	$+\frac{2P\,(t-h)}{c}$

Total increase of weight at $A = P(tc - 2tb + 2hb)/bc$
" " " " " $B = P(2hb - 2tb - tc)/bc$
" " " " " $C = -P(2hb - 2tb - tc)/bc$
" " " " " $D = -P(tc - 2tb + 2hb)/bc$ (5)

Since h and t are quantities of approximately the same amount and always appear in these formulas with opposite signs, and in combination with the same factor $2b$, it is evident that in general the distribution-factor is determined by the term " tc " and that therefore its amount is chiefly dependent on the ratio of the bolster height to the wheel-base.

It was said in regard to Type No. 1 locomotives that the results there obtained were perfectly general and independent of arrangement or gearing of the motors, and since a type No. 2 locomotive consists of two type No. 1 locomotives carrying a single platform or body, but with all internal actions self-contained in the trucks, the results given in formula No. 5 are also independent of arrangement or gearing of the motors.

Some applications of these formulas, using different dimensions of locomotives, are shown in Table 4, in order to indicate the approximate amount of variation of the distribution-factor in locomotives as actually constructed. These dimensions refer to locomotives actually built or designed each of approximately 100 tons' weight. Dimension No. 1 refers to a locomotive originally designed as a type No. 2 locomotive; that is, with two swivel trucks on which the motors are carried. Dimension No. 2 refers to a type No. 3 locomotive having four axles on a rigid wheel-base, each journal-box driving directly against the locomotive frame. Dimension No. 3 refers to a type No. 4locomotive with six axles, having four driving axles on a rigid wheel-base, each journal-box driving directly against the locomotive frame and having one pony-truck at each end.

For the purpose of comparison, the writer has assumed under the present head, three 8-wheel locomotives each of the No. 2 type; that is, with two swivel trucks but having otherwise the dimensions of these three actual locomotives. This may be a little unfair to the locomotives of dimensions No. 2 and No. 3, but under later heads the writer has assumed the same dimensions on type No. 3 and No. 4 locomotives, so that the results serve not only as a basis of comparison of different locomotives of the same type, but also of the same locomotive under different conditions; that is, with or without swivel trucks and with or without pony trucks.

DIMENSION No. 1.

$w = 22$ in.
$2\,b = 96$ in. or $b = 48$ in.
$c = 204$ in.
$h = 34.5$ in.
$t = 35$ in.
$s = 39.375$.

DIMENSION No. 2.

$w = 21$ in.
$2\,b = 46$ in. or $b = 23$ in.
$c = 128$ in.
$h = 34.5$ in.
$t = 35$ in.
$s = 39.375$.

DIMENSION No. 3.

$w = 22$ in.
$2\,b = 52$ in. or $b = 26$ in.
$c = 104$ in.
$h = 34.5$ in.
$t = 35$ in.
$s = 39.375$.

Applying formulas (5) to these dimensions of locomotives, we get the following results:

TABLE 4.

VALUES OF DISTRIBUTION-FACTOR FOR LOCOMOTIVES OF TYPE NO. 2

	Dim. 1	Dim. 2	Dim. 3
Wheel *A*	+0.725	+1.515	+1.335
B	-0.735	-1.53	-1.355
C	+0.735	+1.53	+1.355
D	-0.725	-1.515	-1.335

TYPE No. 3 LOCOMOTIVE.

This is an eight-wheel locomotive with four driving-axles and all journal-boxes driving directly against the locomotive frame as shown in Fig. 3. The motor-noses are suspended to the locomotive frame, which is carried upon an equalizer system. The two center points, J and K, of this system are symmetrical with respect to the forward and rear pair of axles, J distributing its weight equally between A and B, and K distributing equally between C and D.

With this type we obtain different results with different arrangement of motors, for the reason that an action having its origin at one driver is transmitted to the locomotive frame and may not react directly upon the originating axle but may be

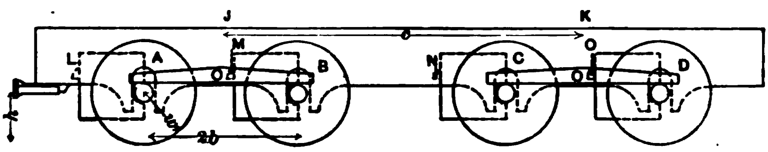


Fig 8.

distributed to other axles which are independent of the original action. All possible symmetrical arrangements of motors are shown in Figs. 3 to 9, Fig. 9 representing gearless motors. Following out the same course of reasoning as above, the results given in Table 5 are obtained.

TABLE 5.

	Wheel	Due to Motor Actions	Due to Draw-bar	Total
Fig. 3	A	$+2Pw/c$	$-2P(w-h)/c$	$+2Ph/c$
	B	$+2Pw/c$	$-2P(w-h)/c$	$+2Ph/c$
	C	$-2Pw/c$	$+2P(w-h)/c$	$-2Ph/c$
	D	$-2Pw/c$	$+2P(w-h)/c$	$-2Ph/c$
Fig. 6	A	$+Pw(c+2s-2b)/sc$	$-2P(w-h)/c$	$+P(wc+2hs-2wb)/sc$
	B	$-Pw(c-2s+2b)/sc$	$-2P(w-h)/c$	$-P(wc-2hs+2wb)/sc$
	C	$+Pw(c-2s+2b)/sc$	$+2P(w-h)/c$	$+P(wc-2hs+2wb)/sc$
	D	$-Pw(c+2s-2b)/sc$	$+2P(w-h)/c$	$-P(wc+2hs-2wb)/sc$
Fig. 7	A	$-Pw(c-2s-2b)/sc$	$-2P(w-h)/c$	$-P(wc-2hs-2wb)/sc$
	B	$+Pw(c+2s+2b)/sc$	$-2P(w-h)/c$	$+P(wc+2hs+2wb)/sc,$
	C	$-Pw(c+2s+2b)/sc$	$+2P(w-h)/c$	$-P(wc+2hs+2wb)/sc$
	D	$+Pw(c-2s-2b)/sc$	$+2P(w-h)/c$	$+P(wc-2hs-2wb)/sc$

Figs. 4, 5, 8, and 9 give the same results as Fig. 2.

It will be noted from this table that the results are independent of the motor arrangements only so long as the two motors on one pair of axles are both forward of the axles or both back of the axles. We have applied these results to type

No. 3 locomotives having the same dimensions as those discussed under type No. 2, *i.e.*, assuming that in this case there are no swivel trucks but that the locomotive journals are driving directly against the locomotive frame. The application of the formulas of table No. 5 give the results shown in table No. 6.

TABLE 6.

VALUES OF DISTRIBUTION-FACTOR FOR LOCOMOTIVES OF TYPE NO. 3.

Motor Suspension	Wheel	Dimension 1	Dimension 2	Dimension 3
Fig. 3.........	*A*	+0.338	+0.540	+0.664
	B	+0.338	+0.540	+0.664
	C	-0.338	-0.540	-0.664
	D	-0.338	-0.540	-0.664
Fig. 6.........	*A*	+0.634	+0.882	+0.945
	B	-0.484	-0.187	-0.175
	C	+0.484	+0.187	+0.175
	D	-0.634	-0.882	-0.945
Fig. 7.........	*A*	+0.042	+0.1975	+0.384
	B	+1.16	+1.268	+1.500
	C	-1.16	-1.268	-1.500
	D	-0.042	-0.1975	-0.384

It is to be noted that the results given under Dimension No. 2, Fig. 6, or Dimension No. 3, Fig. 6, or Fig. 7, could not be obtained in actual practice. It would be impossible to obtain the arrangements of Fig. 6 with a locomotive of Dimension 2, having a wheel-base $2\,b = 46$ in. and with a motor of length $s = 39.375$ inches.

Type No. 4 Locomotive.

This is a locomotive having four driving-axles and two pony-trucks as shown in Fig. 10. The locomotive frame is supported at one end at the points G, H, and I to an equalizer system transmitting the load to the driving-wheels and the pony-trucks, and at the other end to a similar system. With a load L on one end of the locomotive, the equalizer system divides the load between points of support as follows:

$$\text{Load at } G = L\,\frac{m}{4\,m + k}$$

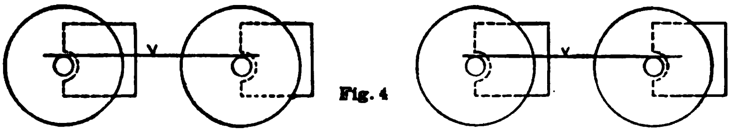


Fig. 4

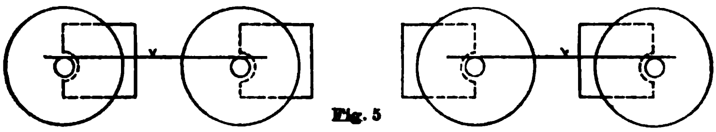


Fig. 5

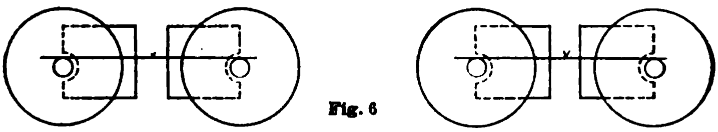


Fig. 6

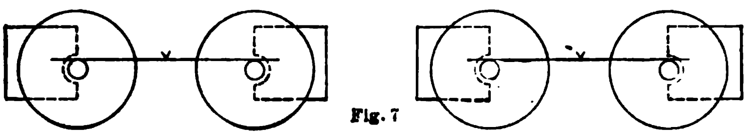


Fig. 7

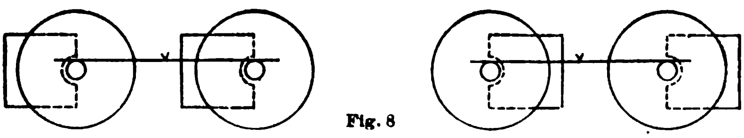


Fig. 8

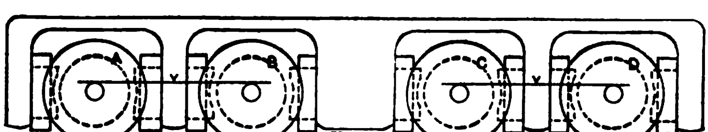


Fig. 9

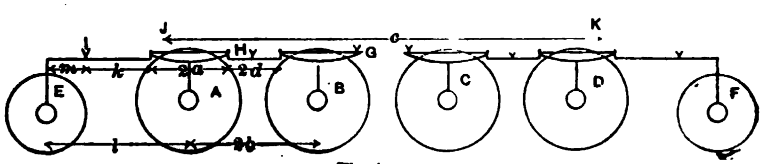


Fig. 10.

$$\text{Load at } H = L\frac{2\ m}{4\ m + k}$$

$$\text{Load at } I = L\frac{k + m}{4\ m + k} \tag{6}$$

This load is then distributed upon the wheels as follows:

$$A = L\,2\,m/(4\,m+k)$$
$$B = L\,2\,m/(4\,m+k)$$
$$E = L\,k\,(4\,m+k) \tag{7}$$

The center of equilibrium or center around which the load will turn is a point J lying at the center of gravity of the system G, H, and I; that is, a distance Z from H such that:

$$Z = k\,(d+2\,a+k+m)/(4\,m+k) \tag{8}$$

Considering now the distribution of weights due to motor actions, it will be noted that the distribution of dead weight due to motors direct to the axles is the same as already shown in table 2, and amounts to $\pm\ P\,w/s$. The distribution of live weight concentrated at J and K consists partly of internal reactions transmitted from the motors and partly of the quantity $4\,P\,(w-h)/c$ due to the tilting action of the draw-bar already discussed. For example, a locomotive of type No. 4 having an arrangement of motors shown in Fig. 2 or Fig. 3; that is, with all motors back of the axles will have stresses concentrated as shown in table 7.

TABLE 7.

	A	J	B	C	K	D
Distribution of dead weight......	$-P\,w/s$		$-P\,w/s$	$-P\,w/s$		$-P\,w/s$
Live weight......		$P\,w\,(2\,c+4\,s)/s\,c$			$P\,w\,(2\,c-4\,s)/s\,c$	
Due to draw-bar..		$-4\,P\,(w-h)/c$			$+4\,P\,(w-h)/c$	
Total live weight.		$P\,(2\,w\,c+4\,h\,s)/s$			$P\,(2\,w\,c-4hs)/s\,c$	

This live weight upon J and K is not equally divided between the driving-axles, as in type No. 3 locomotive, but is distributed between driving- and pony-axles according to formula (7).

The resultant formulas are too complicated to state in general terms but are fairly simple in a number of particular cases. The writer has applied these formulas to a locomotive of the type

No. 4 having dimensions similar to Dimension No. 3, above described under type No. 2 locomotives.

$w = 22$ in.

$2b = 52$ in. or $b = 26$ in.

$h = 34.5$ in.

$s = 40$ in.

$m = 22$ in.

$k = 45$ in.

From which by applying formulas (7) and (8), we derive the following:

Weight on $A = 0.331\,L$

" " $B = 0.331\,L$

" " $C = 0.338\,L$

" " $Z = 37.2$

" " $c = 178.4$

The distribution-factor is given in table No. 8 for a type No. 4 locomotive of these dimensions having the different arrangements of motors shown in Figs. 3 to 9.

TABLE 8.

DISTRIBUTION-FACTOR FOR LOCOMOTIVE OF TYPE NO. 4. FIG. 10, WITH DIMENSION NO. 3.

Motor Suspension	E	A	B	C	D	F
Fig. 3	+0.634	+0.07	+0.07	-0.442	-0.442	+0.1104
4	-0.1104	+0.442	+0.442	-0.07	-0.07	-0.634
5	-0.1104	+0.442	+0.442	-0.442	-0.442	+0.1104
6	+0.155	+0.702	-0.398	+0.398	-0.702	-0.155
7	+0.371	-0.187	+0.913	-0.913	+0.187	-0.371
8	+0.634	+0.07	+0.07	-0.07	-0.07	-0.634
9	+0.260	+0.256	+0.265	-0.256	-0.256	-0.260

It is to be noted, however, that the motor suspension of Figs. 5, 6, and 7, would be impossible with a motor of $s = 40$ on the short wheel base ($2b = 52$) of this locomotive.

Type No. 5 Locomotive.

This is a locomotive having three driving-axles as shown on Figs. 11 and 12. One-third of the weight of the locomotive is carried directly upon one of these axles, the remaining two-thirds is carried upon point J, the center of the equalizer system which transmits the load equally to the other two axles. Following out the same method of calculation used before and applying it to a distribution of motors as shown in Fig. 11, a locomotive of type No. 5 will have stresses concentrated as shown in table 9.

TABLE 9.

	A	J	B	
Distribution of Dead weight..	$-Pw/s$		$-Pw/s$	$-Pw/s$
Live weight...		$Pw(2c+3s)/sc$		$Pw(c-3s)/sc$
Due to draw-bar.........		$-3P(w-h)/c$		$3P(w-h)/c$
Total on J....		$\dfrac{P(2wc+3hs)}{sc}$		
Due to J.....	$\dfrac{P(2wc+3hs)}{2sc}$		$\dfrac{P(2wc+3hs)}{2sc}$	
Total.......	$+3Ph/2c$		$+3Ph/2c$	$-3Ph/c$

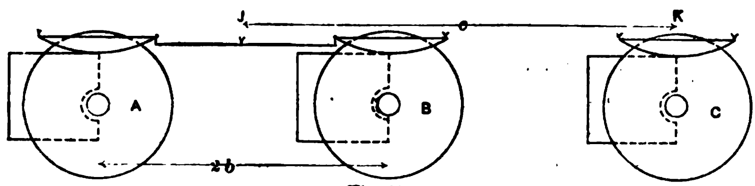


Fig. 11

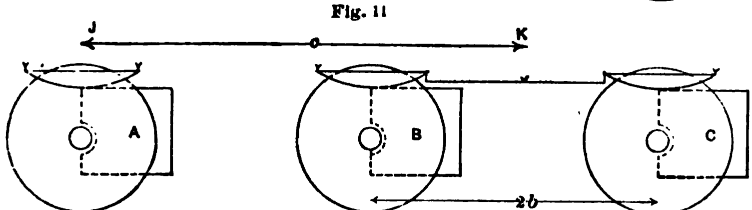


Fig. 12

Reversing the direction of motion on the same locomotive, results in an arrangement as shown in Fig. 12. The effect of redistribution will be exactly opposite to that shown in Table 9 so that the following distribution of weights is obtained:

Increase of weight on A, $+\ 3Ph/c$

" " " " B, $-\ 3Ph/2c$

" " " " C, $-\ 3Ph/2c$

These formulas have been applied to a locomotive of No. 5 type having the following dimensions:

Dimension No. 4.

$w = 30$
$s = 40$
$2b = 76$ or $b = 38$
$c = 3b = 114$
$h = 35$

Substituting these dimensions in the formulas given in Table 9, the following results are obtained:

DISTRIBUTION-FACTOR OF TYPE NO. 5 LOCOMOTIVE.

Motor Suspension.	*A*	*B*	*C*
Fig. 11	+0.46	+0.46	-0.92
Fig. 12	+0.92	-0.46	-0.46

Conclusion.

From the results given in the foregoing paper, it appears that there is an element of uncertainty in the determination of the tractive effort of electric locomotives, on account of the different distribution of weights on drivers, produced by variations in motor suspension, an element which, as far as the writer knows, has not been very closely considered heretofore. The foregoing tables show the possible amount of variation in the redistribution of weight on the drivers in various possible locomotives. To make the results more definite the writer has selected four types of locomotives which have approximately the arrangement of motors and dimensions as actually designed. In table No. 10 is tabulated the actual distribution-factor for these four locomotives.

TABLE 10.

Locomotive type	Type 2	Type 3	Type 4	Type 5
Wheel and truck diagram	Fig. 2	Fig. 3	Fig. 10	Fig. 11
Motor arrangement	Fig. 2	Fig. 7	Fig. 9	Fig. 11
Locomotive dimensions	Dim. 1	Dim. 2	Dim. 3	Dim. 4
Distribution-factor, Wheel *A*	+0.725	+0.1975	+0.256	+0.46
Wheel *B*	-0.735	+1.268	+0.256	+0.46
Wheel *C*	+0.735	-1.268	-0.256	-0.92
Wheel *D*	-0.725	-0.1975	-0.256	
Coefficient of traction				
Assumed actual	25%	25%	25%	25%
Effective	21.1%	19%	23.5%	20.4%
Reduction in draw-bar pull	15.5%	24%	6%	18.5%

Assuming that the wheels actually slip when exerting a horizontal effort of 25% of the weight on them, the reduction in this weight results in a reduction of the possible draw-bar pull; that is, a reduction of the apparent or effective coefficient of traction to some value below 25%. Table 10 shows not only the distribution-factor but the value of this effective coefficient of traction, and in the last line gives the percentage of variation in draw-bar pull due to this redistribution of weight. Since it appears from this that in actual cases the reduction in draw-bar pull may amount to anywhere from 6% to 24% of its theoretical value, it would appear that in the design of electric locomotives it would be advisable to keep in view an arrangement of motor suspension which will give the lowest possible value of the distribution-factor.

Discussion on "Weight Distribution on Electric Locomotives as Affected by Motor Suspension and Draw-bar Pull."

C. O. Mailloux: Those who have had to deal with such problems as are considered in Mr. Dodd's paper have surmised that there was a displacement of weight that altered the effective adhesion at some of the wheels. It was called to the attention of the Institute 2 years ago in Mr. Parke's paper on braking, that such a displacement occurs, and causes the tilting of the trucks when the brakes are applied. There is also a displacement of similar character due to the acceleration of the car body itself, which causes a tendency to tilt the car body backward during acceleration, and to tilt it forward during retardation. Three phenomena are presented of which only two have heretofore been recognized. Mr. Dodd has formulated the forces involved, and indicated the manner in which these forces operate, and given an analytical statement of their action and reaction upon each other.

F. N. Waterman: It seems appropriate to draw attention at this time to the fact that the subject was called to the attention of the Institute in a discussion by Mr. L. B. Stillwell. in which he recited the experience of the Manhattan Company, He found that the front wheels on the trucks of the motor cars of the Manhattan trains slipped before the others, owing to the redistribution of weight due to the effort of the motors and the resistance of the train.

C. O. Mailloux: It would be of interest if measurements were made by which the three different phenomena could be differentiated from one another. In many cases this might be difficult to do. I have myself had occasion very recently to notice the tilting of a car body due to the acceleration and retardation and also I have made experiments, in which the acceleration was measured, and have obtained charts of acceleration as a time-function. These experiments show that there is a tilting effect at the time of starting and stopping the cars, which may offset the value of the acceleration unless specific means are taken to eliminate the complication due to that phenomenon. Even in the case of motor cars there may possibly be some phenomenon like that mentioned by Mr. Dodd.

S. T. Dodd: Referring to Mr. Mailloux's remarks relatively to the value of making tests on this subject, I would only say that the paper has not attempted to take up the practical side of this question, but has been confined entirely to the theoretical side. Of course, the great difficulty of making accurate experiments of this character is realized. Aside from the difficulty of obtaining, for testing purposes, locomotives of approximately the same capacity, but with different arrangements of motors and wheels, the variations in draw-bar pull, due to the variations of the actual tractive coefficient acting between wheel and rails are so great as to make very difficult any accurate measurements which could be made on variations of draw-bar pull, due to redistribution of weights.

The friction of rest between steel and steel measured by laboratory tests runs from 30 to 40 per cent. varying with the pressure between the surfaces in contact. With a weight of 5 or 10 tons, as in a locomotive wheel concentrated on the surface in contact between the wheel and rail-head, there exists a condition of the surface in contact, which, as far as I know, has not been approximated in laboratory tests, and there is a good deal of uncertainty as to the actual value of the friction of rest between such surfaces. Locomotives have been tested which show a tractive coefficient as high as 33.3 per cent., and the coefficient varies from that value down. In ordinary cases on successive tests, under, as nearly as can be seen, identically the same conditions, one may expect to obtain values of the coefficient varying from 15 to 25 per cent. With bad conditions of rail the coefficient will fall as low as 6 or 10 per cent., and with slipping wheels it falls to about half those values. Under such conditions it would be very difficult to obtain accurate quantitative experimental data on different locomotives of variation in draw-bar pull produced by the redistribution of weight such as has been discussed in this paper, where this redistribution would produce a theoretical variation of from 6 to 25 per cent. of the draw-bar pull.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

LIMITS OF INJURIOUS SPARKING IN DIRECT-CURRENT COMMUTATION.

BY THORBURN REID.

In a paper read before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS in December, 1897, the author advanced the hypothesis that the injury done by sparking at the brushes of a direct-current dynamo was not due, as was then commonly supposed, to the current jumping across the gap between the segment and the brush, but was done while the brush was in contact with the segment, the copper of the segment being first melted and then volatilized by the concentration of current energy at one or the other of the segment edges. Perfect commutation was also defined as such a change in the current in the coil under commutation that the current density over the contact surface between the brush and the segment would be constant and uniform, and that perfect commutation would result if the coil impedance were negligible as compared with the brush contact resistance. It was also shown that with perfect commutation the total energy developed over the contact surface would be a minimum and that every part of the contact surface would receive an equal amount of energy. On this principle the question of sparking is simply a question of the temperature of the segment while it is under the brush.

In order to make this whole subject clearer and also to render this principle applicable to practical commutator design, it will be of advantage to consider in detail what happens to a commutator segment while the machine is running.

As the segment comes under the brush it receives a sudden accession of energy both by friction and by current. This energy is developed mainly on the surface of the segment and immediately begins to be conducted away, partly down into the body of the segment and partly into that of the brush. When the segment has passed out from under the brush and until it reaches the next brush, energy is both conducted and radiated away from its surface. Thus the surface temperature of the segment oscillates between a maximum just as it leaves the brush and a minimum just before it enters under the next brush.

Consider first the temperature variation of the segment surface while it is under the brush. If the commutation is perfect, energy is developed at a constant rate during the whole period of commutation and every part of the segment surface will receive the same amount of energy. As soon as any part of the segment surface comes under the brush it begins to receive energy at the rate $I^2 R/A$ per square inch—I being the brush current, R the brush contact resistance, and A the brush contact area—and its temperature begins to rise, the rise of temperature in a given time depending on the rate at which energy is being developed as compared to the average rate at which it is being transferred from the contact surface by radiation and conduction. More specifically, the rise in temperature during a given time is directly proportional to the difference between the heat developed and the amount radiated and conducted away during that time. As the temperature rises the rate of dissipation of energy also increases and the curve of temperature rise is therefore convex upward, tending towards a maximum temperature at which the rate of radiation and conduction is just equal to that of development of heat energy. The time of commutation, however, is so short (from less than 0.01 to less than 0.001 seconds) that this maximum is not even approached; it will, therefore, be sufficiently accurate to assume that the temperature rise of any part of the segment surface while under the brush is proportional to the watts per square inch multiplied by the time of commutation; that is, it is proportional to the joules per square inch developed during commutation.

The contact energy consists partly of friction energy and partly of $I^2 R$ loss. The friction energy is distributed uniformly over the whole contact surface, and with perfect commutation the $I^2 R$ energy would also be thus uniformly distributed; but with imperfect commutation as it exists in actual machines this is seldom if ever the case, the self-inductance of the coil under commutation causing the energy density to increase all the way from the front to the back edge of the segment; and since the energy at the back edge may under certain conditions be many times greater than will exist with perfect commutation, it is essential that the law of variation of this energy density should be determined.

In the writer's 1898 paper the fundamental differential equation of current in the coil under commutation was given as follows:

The $I\,R$ drop between the brush and the entering segment equals the $I\,R$ drop between the brush and the receding segment, plus the $I\,R$ drop in the coil under commutation, plus the inductance drop in this coil, plus the reversal electromotive force—all of these pressures being given their proper signs. This is equation (1) in Appendix A at the back of this paper, where will be found the analysis by which it was integrated and by which the law of the variation of energy density was determined. Those who may wish to follow the analysis in detail are referred to that appendix; the general method followed will merely be indicated here.

The fundamental differential equation is

$$i_1\,r_1 = i_b\,r_b + i_2\,r_2 + L\,\frac{d\,i_b}{d\,t} + E_r \tag{1}$$

in which subscript 1 refers to the entering segment, subscript 2 to the emerging segment, subscript b to the coil under commutation; t is time reckoned from the beginning of the commutation period, i is current, r is resistance, L the self-inductance, and E_r is the reversal electromotive force due to the flux from the field.

This equation is based on the assumption that but one armature coil is under commutation under each set of brushes at any one time; that is, that the width of the brush contact surface is not greater than that of one segment plus the thickness of the insulation between two adjacent segments. It takes no account of the interior resistances of the brushes and segments, as these resistances are entirely negligible as compared with the brush contact resistance. This equation also assumes infinite resistance between two adjacent segments and between the segment surface and that part of the brush surface not in contact with it. It will appear later that this last assumption is not strictly true for some cases of commutation, and for this reason certain modifications will have to be introduced in the final results.

Assuming the contact resistance to vary inversely with the contact area and substituting for i_b, i_2 their values in terms of i_1, equation (1) may be written,

$$i_1 = \frac{t}{T} I + \frac{\frac{r_b}{2R} t (T-t)(T-2t)}{T^2 + \frac{r_b}{R} t (T-t)} I - \frac{\frac{L}{R} t (T-t)}{T^2 + \frac{r_b}{R} t (T-t)} \frac{d i_1}{d t} + \frac{t (T-t)}{T^2 + \frac{r_b}{R} t (T-t)} E_r \qquad (4)$$

in which the first term represents the variation of i_1 for perfect commutation, that is, when $\frac{r_b}{R}, \frac{L}{R}$ and $\frac{E_r}{R}$ are so small as to be negligible and the current is entirely governed by the contact resistances. The second term represents the variation from perfect commutation due to the coil resistance alone, the third term that due to the coil inductance, and the fourth term that due to the reversal electromotive force.

In order to simplify the application of the final equations to practical problems, the writer has substituted for current, time, etc., various ratios — m for the ratio of instantaneous currents to full brush currents, n for the ratio of elapsed time to the time of commutation, e_p for the ratio of the reversal electromotive force to the average $I R$ drop across the contact surface, and p for the ratio $T R/L$, T being the time of commutation, R the resistance of the total contact area per stud, and L the self-inductance coefficient of the coil under commutation. Substituting these values and neglecting r_b as compared with R, equation (4) may be reduced to

$$m_1 = n - (1 - p e_p) \left(\frac{1-n}{n}\right)^p \int \frac{n^p}{(1-n)^p} d n \qquad (8)$$

Simple as this integral appears to be, the writer spent many days trying to integrate it before he discovered that it could only be integrated by means of an infinite series that was not capable of being expressed in any general form. The problem was finally solved, however, by giving to p certain numerical values which covered nearly the whole range of practical work and made it possible to determine with sufficient accuracy for practical purposes the values of the curves lying outside the range of values thus determined.

The equation was found to be integrable for integer values of p; equations (14), (15), and (17) in Appendix A show the integral of the last term of the equation for values of p equal to 1, 2, and 3. Equation (18) shows how the integrals may be written by analogy for higher integer values of p. It was also found possible to integrate the equation for values of p equal to 0.5 or multiples of 0.5. Equations (10) and (12) show the integral equations for values of p equal to 0.5 and 1.5.

It will be noticed that for integer values of p the integral contains a logarithmic term and for fractional values of p it contains circular functions, and while both these forms of functions may sometimes be expressed as exponential functions of the logarithmic bases, the writer has not been able to discover any general form by means of which both sets of equations could be expressed.

Returning now to equation (8), if $e_p = 0$; that is, if there is no reversal electromotive force, the equation becomes

$$m_1 = n - \left(\frac{1-n}{n}\right)^p \int \frac{n^p}{(1-n)^p}\, d\, n.$$

From equation (1), if E_r, L, and r_b are so small compared with the contact resistance R as to be negligible, we have $m_1 = n$, which is evidently the equation for perfect commutation. Now making $(f\,p) = \left(\frac{1-n}{n}\right)^p \int \frac{n^p}{(1-n)^p}\, d\, n$, we have $m_1 = n - (f\,p)$ when there is no reversal electromotive force. $(f\,p)$ represents, then, the amount by which the self-inductance of the coil causes the current to differ from the value it would have if the commutation were perfect. Equation (8) then becomes $m_1 = n - (1 - p\, e_p)\ (f\,p)$. Now if $p = \frac{1}{e_p}$. we have again $m_1 = n$. That is, if the reversal electromotive force equals $\frac{I\,L}{T}$, the current behaves as though there were neither reversal electromotive force nor self-inductance, and perfect commutation results.

Fig. 1 shows the curves of current for various values of $\frac{L}{R\,T}$ when there is no reversal electromotive force, assuming the coil resistance to be negligible as compared with the brush contact resistance; the curves of the left-hand side of the figure show the condition when the contact area of the segment is increasing, and those of the right-hand side the condition when the contact area is decreasing. The straight lines inclined at 45 degrees to the horizontal represent the current variation for perfect commutation; that is, when the coil reactance is negligible as compared with the brush contact resistance.

The wavy line crossing these 45-degree lines at their centers shows the form of the current curve when the coil inductance is negligible and the coil resistance is equal to the brush contact resistance. It is evident that under these conditions the coil

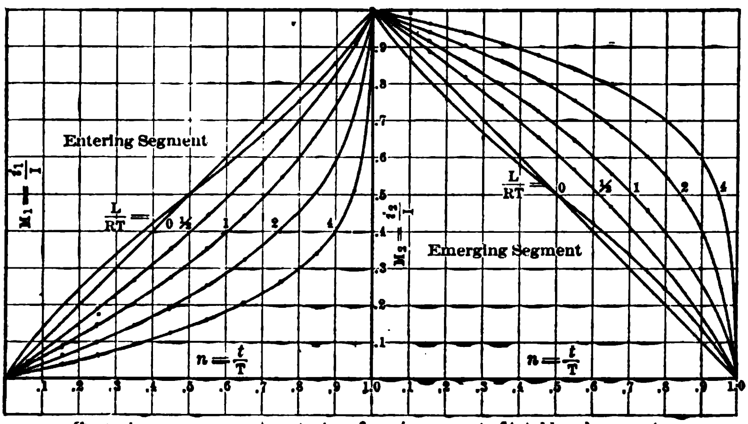


FIG. 1.

resistance will have very little effect to distort the actual current curve; and since in any machine ever examined by the writer the coil resistance has never approached this value, he feels justified in neglecting it. The curve for $\frac{L}{R\,T}$ equal to 4 was obtained by a step-by-step method from the differential equation, but is quite as accurate as the others which were obtained from the integral equations.

Referring to the form equation (8) takes when $E_r = 0$; namely, $m_1 = n - (f\,p)$ and $m_2 = 1 - n + (f\,p)$, the curves of this figure show that $(f\,p)$ is represented by the amount that the actual current deviates from the 45-degree line representing perfect commutation

Fig. 2 shows the current densities for the currents of Fig. 1. The main interest in this figure lies in the right-hand curves. It will be noticed that for all values of $\frac{L}{R\,T}$ equal to or greater than unity the current density goes to infinity just before the segment emerges from under the brush. It was this phenomenon that led Messrs. Arnold and Mie to the conclusion that with any values of $\frac{L}{R\,T}$ equal to or greater than unity, sparking must ensue.

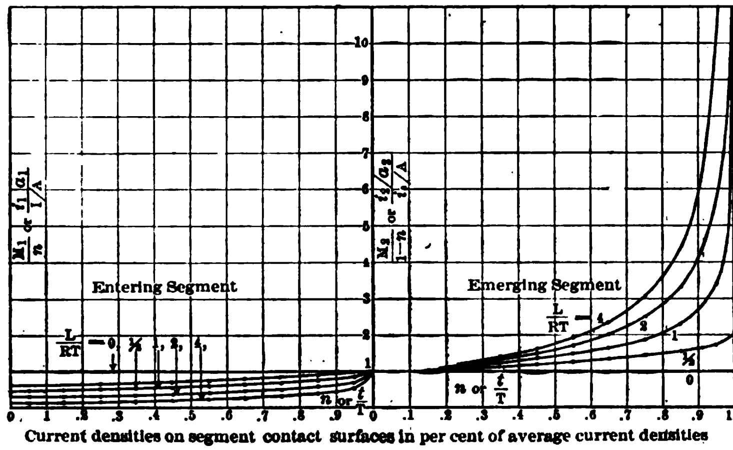


FIG. 2.

That a spark will be present under such conditions seems probable, although, as the writer will show later, this spark is not necessarily injurious nor is it certain that there will be any spark at all, despite the fact that the density will still reach infinity theoretically for all values of reversal electromotive force less than $\frac{I\,L}{T}$ if $\frac{L}{RT}$ is equal to or greater than unity. It is also of interest that the final values of the current densities for values of $\frac{L}{R\,T}$ less than unity are equal to $\dfrac{\frac{T\,R}{L}}{\frac{TR}{L}-1}$

It was deduced from equation (8) that a reversal electromotive force equal to $\frac{I\,L}{T}$ exactly neutralized the effect of the coil inductance and produced perfect commutation. Assuming that this reversal electromotive force remains constant while the current taken by the brushes is reduced to zero, a current will be produced in the short-circuited coil by reversal electromotive force alone. This current will be in the same direction as the brush current in the entering segment and in the opposite direction in the emerging segment. Fig. 3 shows the form the current curves will take under these conditions, the curves of current in the emerging segment being for convenience plotted as positive although in reality they are negative.

Fig. 4 shows the corresponding current densities; it will be noticed that again the current densities in the emerging

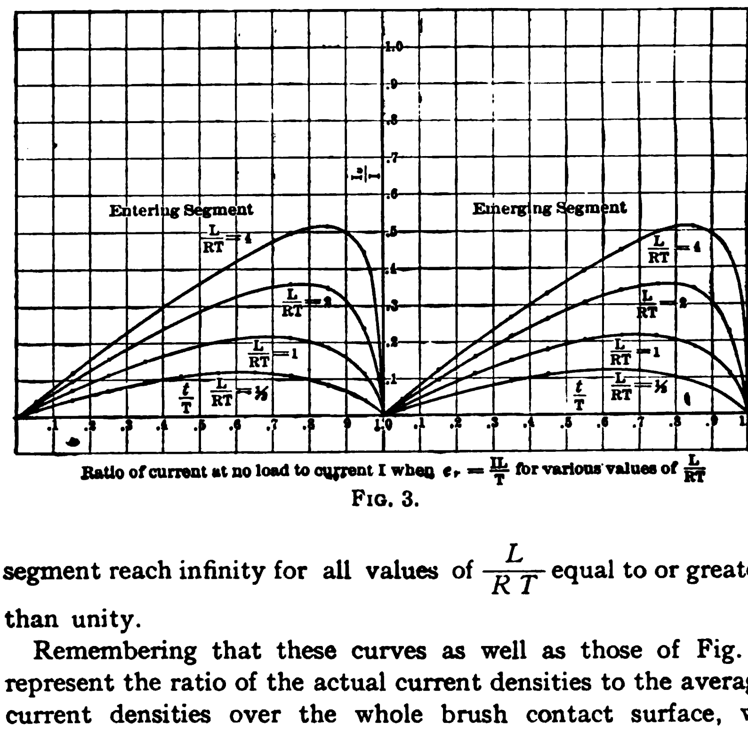


FIG. 3.

segment reach infinity for all values of $\frac{L}{RT}$ equal to or greater than unity.

Remembering that these curves as well as those of Fig. 2 represent the ratio of the actual current densities to the average current densities over the whole brush contact surface, we reach the following conclusions for the conditions assumed when $\frac{L}{RT}$ is equal to or greater than unity.

1. If there is no reversal electromotive force, the current density will reach infinity just before the segment emerges from under the brush for every value of brush current except zero,

2. For any value of reversal electromotive force less than $\frac{I\,L}{T}$ the current density will reach infinity just before the segment emerges from under the brush for every value of the brush current except zero.

3. If the reversal electromotive force equals $\frac{I\,L}{T}$ and I have any value greater than zero, the current density at no load will reach infinity just before the segment emerges from under the brush.

From these three conclusions we finally conclude:

4. That when $\frac{L}{R\,T}$ is equal to or greater than unity, the

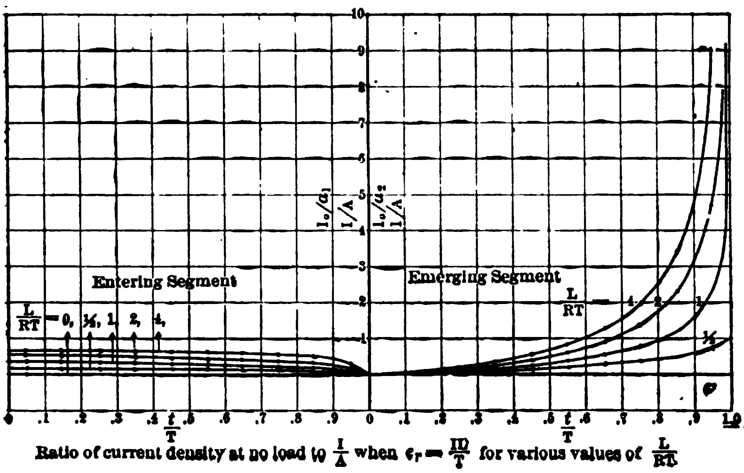


FIG. 4.

current density will reach infinity just before the segment emerges from under the brush for all loads greater than zero load if E_r is less than $\frac{I\,L}{T}$ and for any value of E_r at no load. From this it follows that when $\frac{L}{R\,T}$ is equal to or greater than unity, the current density can be prevented from reaching infinity only by so proportioning the load and reversal electromotive force that $E_r = \frac{I\,L}{T}$. If then we assume that sparking will necessarily occur when the current density tends to infinity, it will be possible to prevent sparking under these conditions only by causing the reversal electromotive force to vary directly with the load and to be always exactly equal to $\frac{I L}{T}$; since this is a condition that it is impossible to create in practice it follows that for any machine in which $\frac{L}{R T}$ is greater than unity sparking can not be prevented at any load except by accident.

Several machines whose constants the writer has examined commutate satisfactorily with a value of $\frac{L}{R T}$ greater than unity and without movement of the brushes; it is certain that such a machine would run sparklessly at light loads with no reversal electromotive force, or would admit of a certain range of load with constant reversal electromotive force without sparking. A further consideration of the curves will indicate an explanation of this seeming inconsistency.

As the current density increases, the $I R$ drop across the contact surface increases until it reaches a point sufficient for it to cause surface leakage across the insulation between two segments under the brush. This leakage allows the current to have a larger value when the contact is broken between the segment and the brush than would otherwise be the case, and the current must therefore either continue to flow across the segment insulation to the receding brush or must jump through the air, or both. Now although the current density may be very high, the amount of current flowing may be very minute, so minute in fact as not to produce a visible spark even if it jumped through the air, and a surface leakage across the segment insulation need not be either visible or audible. But even if there be a visible spark from this cause, it does not follow that this spark is injurious. On the contrary, we have numberless experiments to prove that it is not injurious to any appreciable extent, if at all.

Many thousands of sparks may flash between the two points or knobs of a Ruhmkorff coil without any evidence of injury to the points or knobs. Many of you have doubtless seen the brilliant display of sparks on the commutator of the old Thomson-Houston open-circuit arc dynamo, which did little, if any, injury to the commutator. It is not necessary to go as far afield as this for examples of sparking without injury. There are, or used to be, many direct-current generators which sparked continuously without resulting in visible injury to the commutator. In fact, all of our information on this subject goes to show that ~~such~~ a spark injures, not the conductor, but the insulation that it pierces or disrupts. The main energy of such a spark must clearly exist in the space across which it jumps, since practically the whole difference of pressure exists in this space. When this space is filled with air, it is the air that receives the energy of the spark; if it is occupied by some solid insulating medium, it is this insulation that receives the energy and is pierced or disrupted. The lightning stroke injures only the insulators in its path unless the volume of current be too great.

In order that the segment copper may be worn away it is necessary that energy be developed in the copper itself, not in the insulation or in the space between the receding segment and the brush. A reference to the curves of Fig. 5 will show clearly how the energy necessary to accomplish this is developed.

Referring first to Fig. 1; the line between the two sets of curves represents the point at which the back edge of the segment first comes under the brush; that edge remains in contact with the brush while the current has the values shown in the right-hand set of curves, and the current density on the back edge will be that corresponding to the right-hand curves of Fig. 2. The same is true also for Figs. 3 and 4. The electrical energy developed per square inch in the back edge of the segment during commutation will then be the summation of the $I^2 R$ losses per square inch for the right-hand curves of Figs. 2 and 4, and this will be the maximum energy density that will occur anywhere on the segment. The curves of Fig. 5 show how this energy density varies with the values of $\frac{L}{R\,T}$ for values of the reversal electromotive force varying from zero to $\frac{I\,L}{T}$, the dotted curve showing the energy density at the back edge of the segment at no load when $E = \frac{I\,L}{T}$.

These curves are not theoretically accurate, as it was manifestly impossible that the energy density should ever reach infinity. They were plotted from the average of 10 equidistant values of n ranging from 0.05 to 0.95. The area thus excluded is small in any case. For $\frac{L}{RT}$ equal to unity the theoretical energy density is 3.29 (see appendix A) while the curve gives 3.15, a difference of only about 4%.

The analysis in Appendix A also shows that the energy density in the back edge of the segment for $\frac{TR}{L}$ equal unity will be a minimum when $E_r = 1.645 \frac{IL}{T}$, that the minimum energy density ratio is 0.584, and that the energy density in

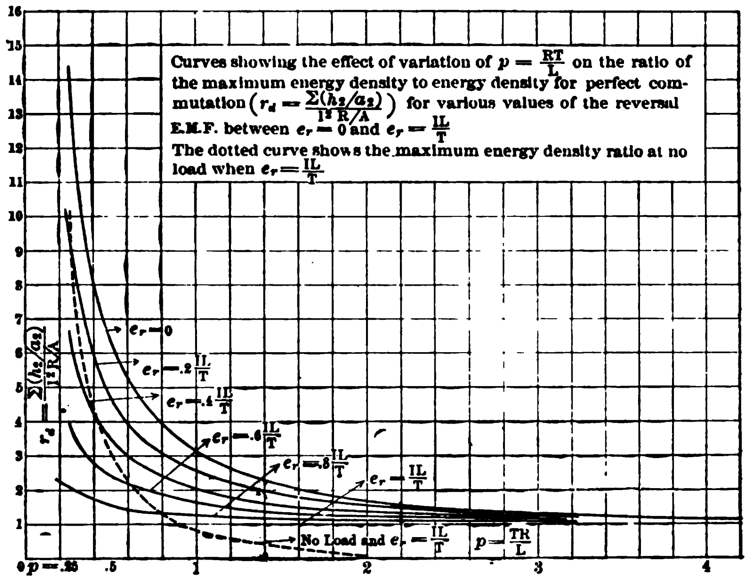


FIG. 5.

the back edge of the segment will begin to increase again if the value of E_r increases beyond this value. The curves also show that the energy density ratio at no load for $E_r = \frac{IL}{T}$ is unity for $\frac{TR}{L} = 0.9$. It is theoretically unity for $\frac{TR}{L} = 1$ (Appendix A).

It will be noticed that the curves of energy density rise very rapidly for values of $\frac{TR}{L}$ less than unity until for $\frac{TR}{L}$ equal to 0.25 and $E_r = 0$ the energy density at the back edge of the segment is 14 times the average and for $\frac{T R}{L}$ equals 0.5 it is 6 times the average. Also the energy density at no load for $E_r = \frac{I L}{T}$ is nearly 10 times the average for $\frac{T R}{L}$ equal 0.25 and 3 times the average for $\frac{T R}{L}$ equals 0.5. Thus when $T R/L$ equals 0.25 if sufficient reversal E is supplied to bring the energy density down to the average at full load, it will be nearly 10 times the average at no load.

Although the coil inductance increases the energy density in the emerging segment and decreases it in the entering segment, the total energy of commutation is increased by the coil inductance (see Appendix A,) by an amount equal to

$$\frac{(f p)^2}{n (1 - n)}.$$

If there is no reversal electromotive force the ratio of the actual total $I^2 R$ loss to that of perfect commutation is about 2 when $\frac{T R}{L}$ is 0.25; 1.43 for $\frac{T R}{L}$ equal to 0.5; 1.15 for $\frac{T R}{L}$ equal to 1, and 1.04 for $\frac{T R}{L}$ equal 2. It is now possible to apply these curves in the determination of a practical criterion for injurious sparking.

The friction energy per stud equals a constant times the brush pressure times the number of brushes per stud times the speed of travel of the commutator surface times the length of the period of commutation; the friction energy density will equal the friction energy divided by the area of contact surface.

The current watts per stud for perfect commutation equals the square of the current per stud times the contact resistance per stud. For actual commutation this quantity must be multiplied by a factor depending on the self-inductance of the coil under commutation and on the reversal electromotive force.

Consider first the case when the brushes are set at the neutral point and there is no reversal electromotive force. The maximum current energy density will then occur at the back edge of the segment and its ratio to the energy density for perfect commutation can be ascertained from the curves of Fig. 5 for $E_r = 0$ after the ratio $\frac{T R}{L}$ has been calculated. Adding to this the friction energy density, we obtain the total energy density at the back edge of the segment where the energy density is a maximum.

Secondly, when the brushes are given a forward lead for generators or a backward lead for motors, so that the effect of self-inductance in increasing the energy density is reduced or even entirely eliminated by means of the reversal electromotive force set up by the flux from the field, the actual maximum energy density will lie somewhere between that of perfect commutation and that for no reversal electromotive force, depending on the ratio of E_r to $\frac{I\,L}{T}$, and if the value of E_r is known, the increase of energy density corresponding to the known value of $\frac{T\,R}{L}$ and E_r can be obtained from the curves of Fig. 5.

Thus the curves of Fig. 5 furnish a means for the conditions assumed of determining the maximum energy density for any part of the segment contact surface, and since the maximum rise of temperature of any portion of this contact surface while under the brush is directly proportional to the maximum energy density under the conditions of practical working a means is also obtained of ascertaining the maximum rise of temperature. Before proceeding further in this branch of the investigation, it is necessary to consider another condition affecting, not the rise of temperature of the segment while under the brush, but its total rise of temperature above the surrounding atmosphere.

As the segment passes out from under the brush its surface begins to cool, and as the rate of dissipation and transfer of heat decreases as the temperature falls the rate of cooling will also decrease and the curve of temperature of the segment surface between brushes will be concave upwards, tending toward a minimum, the temperature of the surrounding atmosphere.

When the machine has been running long enough at constant load for the temperatures to have reached a stable condition, it is evident that the fall of temperature between brushes must equal exactly the rise of temperature while under the brush. As a corollary of this statement, all the heat energy developed on the segment surface while under the brush must have left that surface when it reaches the next brush. Also the curve representing the fall of temperature will be represented by the temperature of the different parts of the commutator surface from one set of brushes to the next while the machine is running under load.

If therefore it be possible to take the temperature of the commutator surface at various points between brushes while a machine is running under load, points on this curve will be determined together with the maximum rise of temperature of the segment while under the brush, and its minimum temperature just before entering under the brush. Sufficient data are not available to determine points on these curves by analysis, but some light can be thrown on the problem by a consideration of the little that is known pending further experiments.

The melting point of copper being in the neighborhood of 2 000° fahr., this temperature must be reached at some point of the contact surface in order that the copper may be melted and volatilized. That this temperature must be confined to an exceedingly thin stratum of the segment follows from a consideration of the specific heat of copper and the energy developed during commutation. Taking the specific heat of copper as 0.095 B.t.u. per degree fahr., one joule will raise the temperature of one cubic inch of copper 1/32 of a degree fahr. The maximum energy density the writer has found so far in actual machines is less than 0.7 joules per square inch developed in about 0.003 seconds; this amount of energy could raise to a temperature of 2 000° fahr. from say about 200°, about 0.00001 of a cubic inch, and the heat required for fusion would reduce still further the amount of copper that would be melted. Some of this heat is also conducted up into the brush, and the whole rise of temperature does not take place during one commutation period so that it is not possible to say just how much of the segment may be melted at each spark, but these figures show how very small the amount must be.

Although this energy is practically all developed at the contact surface, such a high temperature as this would result in a very rapid flow of heat by conduction down through the segment. In attempting to determine how rapid this flow would be the writer was unable to find any experimental results on the flow of heat under such conditions. The rate of flow of heat through various metals (including copper) between two planes a known distance apart and at a *constant difference of temperature* has been determined, but the writer has been unable to find any data as to the rate of flow between two planes *whose difference of temperature is constantly changing* by reason of the intermittent applications of heat energy to one of them.

The use of the constants given for constant difference of temperature between the two planes gave such incongruous results that the writer was led to the conclusion that there was present under such circumstances a property similar to inertia in the case of the flow of liquids, or to self-inductance in the case of the flow of electricity. That some such inertia phenomena are present is also a natural deduction from the fundamental theory of heat as a mode of motion, since on this theory if the temperature of a body be raised the speed of vibration of its molecules is increased and time is required to overcome the inertia of these molecules. In view then of the lack of data on this phase of the subject the rise of temperature of the segment under the brush does not seem to be capable of analytical determination, but can probably be ascertained by means of the experiment indicated by the writer—that of obtaining the temperature of the commutator surface at various points between two sets of brushes while the machine is running under load.

It is probable that very shortly after a machine is stopped the temperature of the whole commutator surface is practically uniform. It is certain that the subsequent rate of cooling of this surface is entirely too low to account for a fall of temperature of anything like 1800° fahr. between the time the load is shut down on the machine and the time its temperature is taken by thermometer, a fall of temperature which must have taken place during that period if the segment surface has risen in temperature to the melting point of copper. However, if the load is taken off a sparking machine and the brushes immediately raised off the commutator, there will be a very rapid flow of heat from the hot surface down through the segment by conduction as well as from the hotter portions of the surface to the cooler portions that will soon bring the temperature of the whole commutator copper very nearly to uniformity. After this condition of uniformity is reached the subsequent cooling takes place almost entirely by radiation, the internal thermal resistance of the copper for the short distances concerned in a commutator being but a small fraction of the external thermal resistance of radiation. Consequently the flow of heat from the hotter to the cooler parts of the commutator will be many times as rapid as the dissipation of heat from its surface. The time required, therefore, to reduce the temperature of the commutator to uniformity will be but a very small fraction of the time that will be required to reduce its temperature by radiation by the same amount, as the temperature of its hottest portion is reduced by conduction in the process of reducing the temperature of the whole commutator to uniformity. The rate of cooling of the commutator surface after the machine has been shut down furnishes therefore no information of value for determining the distribution of temperatures while the machine is running under load.

The heat energy present at and near the surface of the segment as it leaves the brush is transferred partly by radiation and partly by conduction. The rate of radiation will be directly proportional to the difference of temperature between the segment surface and the surrounding air, but the law governing the rate of conduction through the segment is, as has been already indicated, not so easily determined.

It may be possible to approximate this law empirically by determining a series of points on the curve of temperature of the commutator surface between brushes. Another method which would perhaps be of more practical value would be to determine for a number of machines the energy density at which sparking commences and to plot from these results a curve of sparking limits with maximum energy densities as ordinates and frequency of commutation periods as abscissas.

If we may assume the fall of temperature per second of the segment surface between brushes to be constant per degree rise of temperature, the equation expressing the maximum temperature of the segment as it leaves the brush may be expressed thus (see Appendix B for the deduction of this equation):

$$\tau = b\, H_d \frac{e^{a\, T_b}}{e^{a\, T_b} - 1} \tag{29}$$

in which a and b are constants, H_d the maximum joules per square inch developed during commutation (including also friction energy), T_b is the time between brushes and e is the base of the Naperian system of logarithms. An analytical determination of the constants a and b does not seem possible, but they can probably be approximated by tests on actual machines in the manner that has been indicated; that is, by determining on a running machine the temperatures of the emerging and entering segments, b being determined by the consideration that the difference between these temperatures is equal to $b\, H_d$, and the maximum rise of temperature being equal to τ the equation can be further solved for a.

If the exponent of e in this equation is a very small fraction $e^{a T_b}$ approximates the value $1+a T_b$ and equation (29) becomes approximately $\tau = b H_d \frac{1+a T_b}{a T_b}$, or since $a T_b$ can be neglected as compared with unity, equation (29) becomes $\tau = \frac{b H_d}{a T_b}$. This means that if the fall of temperature between brushes is small, the maximum rise of temperature of the segment surface above the atmosphere will vary directly with the maximum energy density times the frequency of commutation periods; that is, it would vary with the maximum energy density in joules per second developed on the commutator surface or with the maximum watt density. In other words, the temperature of any given part of the segment surface will be nearly constant throughout a revolution, the rate of transfer of heat from that part would be nearly constant, and the temperature would be that necessary to transfer each second the average amount of heat energy generated per second.

Again the term $e^{a T_b}$ increases very much more rapidly in value than does its exponent. Thus for $e^{a T_b}$ equal to 100, $a T_b = 4.605$ nearly. Thus if $a T_b$ has a value say as high as 5, equation (29) may be reduced approximately to the form $\tau = b H_d$. This means that almost the whole rise of temperature would take place during each commutation period and the temperature of the segment surface would fall nearly to that of the atmosphere between each commutation period. Considering the very small value of T_b it is probable that the conditions conform much more nearly to the former of these hypotheses than to the latter; that is, the true equation may approximate the form $\tau = \frac{b H_d}{a T_b}$.

If experiments should prove this to be the case; that is, that there is no great difference of temperature between the corresponding parts of the commutator segments between two brushes, the problem of sparking would be merely a question of the maximum watt density on the commutator surface; and a more or less accurate criterion of sparking would be determined for all classes of direct-current commutating machines by a determination of the watt density that produces sparking on a single machine.

Whatever may be the truth with regard to these hypotheses, the maximum temperature will depend on H_d and T_b. For any particular frequency of commutation periods, therefore, freedom from injurious sparking will depend on a certain maximum energy density not being exceeded, and that maximum energy density will be the same for all machines of the same class and with the same frequency of commutation.

That this critical value must be more or less inaccurate is a necessary result of practical conditions. The actual point where sparking commences is difficult to determine, and no two observers will agree as to this. Both friction energy and the contact resistance depend on the condition of the commutator and brush surface and on the force with which the brush is pressed down on the commutator surface. The contact resistance is also a function of the temperature.

In many cases only a part, sometimes a very small part, of the brush surface is in contact with the commutator. But while these conditions prevent scientific accuracy in the determination of this criterion, they do not destroy its value for practical work, because these imperfections are bound to occur in practice and the criterion finally established must be such as to leave a reasonable margin of safety for such imperfections and inaccuracies. The best method then would be to use for this purpose machines engaged in actual commercial work and then choose a limiting value which leaves a sufficient margin of safety.

Unfortunately the data at the writer's disposal, while stating what machines did or did not spark at full load, included but a small number of machines in which the actual sparking limit was determined. The tests were the ordinary commercial tests made on the machines before they were shipped from the factory, and no attempt was made to determine the value of the reversal electromotive force.

Another, though less important, source of inaccuracy lies in the difficulty of calculating with any degree of accuracy the self-inductance of the armature coil. The comparative unimportance of this source of inaccuracy is due to the fact that in most cases the ratio $\frac{T\,R}{L}$ is so great as not to increase the energy density to a material extent, and a large variation in its value does not much change the maximum energy density.

Considering now the conditions when reversal electromotive force is present, the energy density at full load will be a minimum when $E_r = \frac{I\ L}{T}$, since commutation is perfect when this relation obtains. Any further increase in the reversal electromotive force increases the maximum energy density, but transfers its locality from the back to the front edge of the segment. Such further increase in the reversal electromotive force also increases the energy density at no load and at all intermediate loads so that it is detrimental in every respect. It is in fact customary in practice to move the brushes from the neutral point only so far as may be necessary to prevent sparking at the maximum load at which the machine is required to run sparklessly, and no farther. If then the machine will run sparklessly at this load with any value of the reversal electromotive force, it will do so when the reversal E reaches such a value as to produce perfect commutation. It is a fair assumption then that in commercial work the reversal electromotive force will not exceed this value.

On the other hand, sparkless commutation may be secured with a value of reversal electromotive force less than this critical value, since every increase in reversal electromotive force from zero to this critical value decreases the maximum energy density, and in most cases of sparkless running it will probably be found that the critical value of reversal electromotive force is not reached.

The minimum value of the maximum energy density is the value for perfect commutation, and if this maximum energy density is not too great sparkless commutation may be achieved at full load, provided sufficient reversal electromotive force be available.

The actual value of reversal electromotive force that will allow of sparkless commutation at full load can be determined by means of the curves of Fig. 5 if the sparking density is known. Having determined the friction energy density, the remainder, after subtracting this from the energy density that will produce sparking, will be the allowable current energy density. This divided by the current energy density for perfect commutation gives the energy density ratio that must be attained by means of the reversal electromotive force. Find the ordinate in Fig. 5 corresponding to the value of $\frac{T\ R}{L}$ for the machine, and on that ordinate find the point corresponding to the energy density ratio already determined. If this point lies on one of the curves, the value of E_r for that curve is the value sought; if the point lies between the curves, the required value of E_r may be obtained with sufficient accuracy by interpolation.

The dotted curve of Fig. 5 shows the energy density ratio at no load for $E_r = \frac{I\,L}{T}$ and if E_r equals any fraction of $\frac{I\,L}{T}$ the energy density ratio at no load will be reduced in the same proportion. If this energy density is below the sparking limit the machine will then run sparklessly at no load as well as at full load.

This is based on two more or less inaccurate assumptions: one that the reversal electromotive force is not affected by the armature ampere-turns; that is, it remains constant while the load changes from full load to no load; the other that the density of the reversal flux is uniform in the field swept over by the coil under commutation during the commutation period.

The effect of the armature reaction on the strength of the reversal flux field is a matter of much importance. It is a matter that lies outside the scope of this paper and deserves a separate investigation. Its solution would serve to increase the accuracy of the method outlined above since thus the reversal electromotive force and therefore the energy density at no load corresponding to the reversal electromotive force required and obtained at full load could be accurately determined.

That the density of the reversal flux is not uniform in the field swept through by the coil during commutation has been shown by experiment, but owing to the short period of commutation the variation is not very great and need not affect seriously the accuracy of equations based on the assumption that it is uniform.

Finally there may be cases in which the ratio $\frac{T\,R}{L}$ is so small that sufficient reversal electromotive force can not be obtained to produce perfect commutation at full load. If the effect of the armature reaction in lessening and distorting the reversal flux could be neglected, such a condition would probably never exist in any practical machine. This again, however, is a question outside the scope of this paper.

In only a few machines have I found values of $\frac{T\,R}{L}$ less than unity and those were commercial machines that ran satisfactorily as regards sparking. On the other hand, the writer has found that most of the machines which sparked badly had values of $\frac{T\,R}{L}$ less than unity, in some cases as low as 1/15, which is evidence of the truth of the hypothesis set forth in his 1897 paper—that injurious sparking is not necessarily due to the jumping of the current from the brush to the segment after contact is broken.

Occasionally in practice the reversal electromotive force is made to exceed the value $\frac{I\,L}{T}$, for the reason that under this condition the maximum energy density occurs at the front edge of the segment; and although the commutator may be and often is thus worn away at its front edge, no spark will at first give evidence of that fact, for the reason that the copper is not volatilized; no arc is formed and the melted copper is merely drawn over the surface of the segment by the brush. Eventually, as the surface is thus worn down, the energy density will increase until sufficient copper is melted to follow the brush until it leaves the segment when the current will flow through this film of melted copper, volatilize it and form an arc which appears as a spark.

In conclusion, it will be well to consider carefully the limitations imposed upon the reasonings and conclusions contained in this paper on account of the approximations involved and the neglect of the effect of various conditions that are present in reality and which further study may show to have an influence sufficient to affect appreciably the accuracy of the deductions.

In most machines the brushes cover more than one segment and its insulation, so that two or more coils are commutating at once; the inductance effect of one coil is thus complicated by the mutual inductance of an adjacent coil, the latter commutating during part at least of the commutation period of the former.

Experimental investigations of which accounts have been published indicate that while this factor has an appreciable influence on the distribution of the current, it is not great enough to require material correction in the criterion of sparking that may be established by tests on machines running under the conditions assumed in this paper.

The idea has so long been accepted that the current's jumping from the receding segment to the brush; that is, the current's not being completely reversed at the end of the commutation period, was the real cause of sparking that no attention has been paid to the distribution of *energy* over the contact surfaces. The problems that follow in the wake of this conception are new and difficult to solve.

Probably the most difficult problem thus presented concerns the transfer and dissipation of heat energy from the contact surface both during and between commutation periods. Data on which to base an analysis seem to be lacking and, even if this were not so, the problem is sufficiently complicated to point to direct experiment as the only practical means of solving it. Since the frequency of commutation periods ranges from about 15 to 100 per second the conditions appear to be comparable to those obtained in an incandescent lamp fed by an alternating current of a frequency low enough to cause a visible variation in the light. In the case of the incandescent lamp the surface of the filament is so large and its area for the conduction of heat is so small as compared with its volume that the greater part of the heat is probably radiated rather than conducted away. On the other hand, the area of conduction in the case of a commutator is comparatively very great; the thermal resistance of copper is much less than is that of carbon, and the external thermal resistance of both carbon and copper is many times greater than is the internal thermal resistance. It is therefore probable that there would be a large variation of the temperature of the commutator segment at a frequency much higher than would cause an appreciable variation in the light of an incandescent lamp.

The distorting and weakening of the reversal flux by the armature ampere-turns and the variation in the reversal flux density during commutation are also more or less uncertain factors in the problem, although some work has been done towards investigating them.

An investigation of the temperature of the different parts of the commutator surface while running, and after the load has been steady long enough for these temperatures to have become stable, should tend to show the accuracy of the deductions contained in this paper, especially if a machine with a low frequency of commutation periods is chosen for the test, and from such a test there might be deduced a criterion of sparking more accurate than is at present available.

APPENDIX A.

DERIVATION OF EQUATIONS OF CURRENT AND ENERGY AT BRUSH CONTACT SURFACE.

NOTATION.

i_1 = instantaneous current across contact surface of entering segment.

i_2 = instantaneous current across contact surface of emerging segment.

i_b = instantaneous current in coil under commutation.

I = brush current per stud.

t = elapsed time reckoned from start of commutation period of active coil.

T = time required for reversing current in active coil.

r_1 = instantaneous resistance of contact surface of entering segment.

r_2 = instantaneous resistance of contact surface of emerging segment.

r_b = resistance of active coil.

R = total contact surface resistance per stud.

E_r = reversal electromotive force.

L = coefficient of self-inductance of active coil.

$$m_1 = \frac{i_1}{I},\ m_2 = \frac{i_2}{I},\ e = \frac{E_r}{I\,R},\ n = \frac{t}{T},\ p = \frac{T\,R}{L}$$

$(f\ p)$ = difference between actual instantaneous current with no reversal electromotive force and the instantaneous current for perfect commutation.

w_t = total instantaneous watts per stud in both segments.

W_t = total average watts per stud.

w_2 = instantaneous watts in emerging segment.

H_d = energy density per square inch in joules on emerging segment.

r_d = ratio of actual H_d to H_d for perfect commutation.

Assuming but one coil commutated at a time, brush thickness equal to width of one segment plus width of one insulation between segments, and neglecting the internal resistance of brush and segment, we have as the fundamental differential equation of electromotive forces by Kirchoff's law,

$$i_1 r_1 = i_b r_b + i_2 r_2 + L \frac{d\,i_b}{d\,t} + E_r \tag{1}$$

and since $i_b = \frac{I}{2} - i_1$ and $i_1 + i_2 = I$.

$$i_1 r_1 = r_b \frac{I}{2} - r_b i_1 + r_2 I - r_2 i_1 - L \frac{d\,i_1}{d\,t} + E_r \text{ or}$$

$$i_1 (r_1 + r_2 + r_b) = I \left(r_2 + \frac{r_b}{2} \right) - L \frac{d\,i_1}{d\,t} + E_r \tag{2}$$

and since $r_1 = \frac{T}{t} R, r_2 = \frac{T}{T-t} R$

$$i_1 \left\{ \frac{T^2 R}{t\,(T-t)} + r_b \right\} = I \left\{ \frac{T R}{T-t} + \frac{r_b}{2} \right\} - L \frac{d\,i_1}{d\,t} + E_r \text{ or}$$

$$i_1 = \frac{t\,T\,R + t\,(T-t)\frac{r_b}{2}}{T^2 R + r_b\,t\,(T-t)} I - \frac{L\,t\,(T-t)}{T^2 R + r_b\,t\,(T-t)} \frac{d\,i_1}{d\,t} +$$

$$\frac{t\,(T-t)}{T^2 R + r_b\,t(T-t)} E_r \tag{3}$$

or

$$i_1 = \frac{t}{T} I + \frac{t\,(T-t)\,(T-2\,t)\frac{r_b}{2}}{T^2 R + r_b\,t\,T\,(T-t)} I - \frac{L\,t\,(T-t)}{T^2 R + r_b\,t\,(T-t)} \frac{d\,i_1}{d\,t} +$$

$$\frac{t\,(T-t)}{T^2 R + r_b\,t\,(T-t)} E_r \tag{4}$$

If $\frac{r_b}{R} = 0$, we have $i_1 = \frac{t}{T} I - \frac{L t}{T^2 R} (T - t) \frac{d i_1}{d t} + \frac{t (T - t)}{T^2 R} E_r$ (5)

or

$$m_1 = n - \frac{n (1 - n)}{p} \frac{d m_1}{d n} + n (1 - n) e_p \tag{6}$$

which is to be integrated.

Multiplying both sides by $p \frac{n^{p-1}}{(1 - n)^{p+1}}$ we have

$$\frac{d m}{d n} \frac{n^p}{(1 - n)^p} + p \frac{n^{p-1}}{(1 - n)^{p+1}} m_1 = p \frac{n^p}{(1 - n)^{p+1}} + p e_p \frac{n^p}{(1 - n)^p}$$

Since the left-hand term is the complete integral of

$$m_1 \frac{n^p}{(1 - n)^p} d n$$

and since

$$\int \frac{n^p}{(1 - n)^{p+1}} d n = \frac{n^{p+1}}{p (1 - n)^p} - \frac{1}{p} \int \frac{n^p}{(1 - n)^p} d n, \text{ we have}$$

$$m_1 \frac{n^p}{(1 - n)^p} = \frac{n^{p+1}}{(1 - n)^p} - (1 - p e_p) \int \frac{n_p}{(1 - n)_p} d n \tag{7}$$

or

$$m_1 = n - (1 - p e_p) \frac{(1 - n)^p}{n^p} \int \frac{n^p}{(1 - n)^p} d n \tag{8}$$

in which

$$(f p) = \frac{(1 - n)^p}{n^p} \int \frac{n^p}{(1 - n)^p} d n$$

so that $m_1 = n - (1 - p e_p) (f p)$ and $m_2 = (1 - n) + (1 - p e_p) (f p)$

For no load from equation (5) we have

$$i_b = \pm \frac{n (1 - n)}{p} \frac{d i_b}{d n} + n (1 - n) \frac{E_r}{R} \text{ or } i_b = \pm (1 - p e_p) (f p)$$

$(f p)$ can only be integrated for all values of p by means of an infinite series, but for practical purposes it will be sufficient to integrate it for values of $p = 1/2, 3/2, 1, 2,$ and 3

For $p = \frac{1}{2}$

Let $1 - n = x^2$. Then

$$\int \frac{n^{\frac{1}{2}}}{(1-n)^{\frac{1}{2}}}\,d\,n = -\int \frac{(1-x^2)^{\frac{1}{2}}}{x}\,2\,x\,d\,x = -\int 2\,(1-x^2)^{\frac{1}{2}}\,d\,x = -$$

$$x\,(1-x^2)^{\frac{1}{2}} - \sin^{-1} x + \text{constant} = -(1-n)^{\frac{1}{2}}\,n^{\frac{1}{2}} - \sin^{-1}(1-n)^{\frac{1}{2}} + \frac{\pi}{2} \tag{9}$$

$$\text{And }\ (f\,p)_{\frac{1}{2}} = \frac{(1-n)^{\frac{1}{2}}}{n^{\frac{1}{2}}}\left\{\cos^{-1}(1-n)^{\frac{1}{2}} - (1-n)^{\frac{1}{2}}\,n^{\frac{1}{2}}\right\} \tag{10}$$

$$p = \frac{3}{2}$$

$$\int \frac{n^{\frac{3}{2}}}{(1-n)^{\frac{3}{2}}}\,d\,n = -n^{\frac{3}{2}}\,(1-n)^{-\frac{1}{2}} + \frac{3}{2}\int n^{\frac{1}{2}}\,(1-n)^{-\frac{3}{2}}\,d\,n$$

$$= -n^{\frac{3}{2}}\,(1-n)^{-\frac{1}{2}} + 3\,n^{\frac{3}{2}}\,(1-n)^{-\frac{1}{2}} - 3\int n^{\frac{1}{2}}\,(1-n)^{-\frac{1}{2}}\,d\,n$$

$$= \frac{2\,n^{\frac{3}{2}}}{(1-n)^{\frac{1}{2}}} + 3\,(1-n)^{\frac{1}{2}}\,n^{\frac{1}{2}} + 3\sin^{-1}(1-n)^{\frac{1}{2}} - \frac{3\,\pi}{2}$$

$$(f\,p)_{\frac{3}{2}} = \frac{(1-n)^{\frac{3}{2}}}{n^{\frac{3}{2}}}\left\{\frac{2n^{\frac{3}{2}}}{(1-n)^{\frac{1}{2}}} + 3\,(1-n)^{\frac{1}{2}}\,n^{\frac{1}{2}} + 3\sin^{-1}(1-n)^{\frac{1}{2}} - \frac{3\,\pi}{2}\right\} \tag{12}$$

$$= 2\,(1-n) - 3\,\frac{1-n}{n}\,(f\,p)_{\frac{1}{2}}$$

$$p = 1$$

$$\text{Let } x = 1 - n \text{ then} \int \frac{n}{1-n}\,d\,n = \int -\frac{d\,x}{x} + \int x\,d\,x$$

$$= -\log\,(1-n) + \text{constant} = -\log\,(1-n) - n \tag{13}$$

$$(f\,p)_1 = -(1-n) - \frac{1-n}{n}\log\,(1-n) \tag{14}$$

$$p = 2$$

$$\int \frac{n^2}{(1-n)^2} d\,n = \int \left\{ -\frac{d\,x}{x^2} + \frac{2\,d\,x}{x} - dx \right\} = \frac{1}{1-n} + 2 \log (1-n)$$

$$-(1-n) \quad (f\,p)_2 = \frac{(1-n)^2}{n^2} \left\{ \frac{n\,(2-n)}{1-n} + 2 \log (1-n) \right\} \quad (15)$$

$$p = 3$$

$$\int \frac{n^3}{(1-n)^3} d\,n = \int \left\{ -\frac{d\,x}{x^3} + \frac{3\,d\,x}{x^2} - \frac{3\,d\,x}{x} + d\,x \right\} = \frac{1}{2\,(1-n)^2} -$$

$$\frac{3}{1-n} - 3 \log (1-n) + (1-n) + \frac{3}{2} \quad (16)$$

$$(f\,p)_3 = \frac{(1-n)^3}{n^3} \left\{ \frac{-3\,n + 4.5\,n^2 - n^3}{(1-n)^2} - 3 \log (1-n) \right\} \quad (17)$$

And by analogy for integer values of p.

$$(f\,p)_p = \frac{1-n}{(p-1)\,n} \left((n - p\,(f\,p)_{p-1} \right) \quad (18)$$

Total watts in both segments

$$w_t = i_1^2\,r_1 + i_2^2\,r_2 = \left(\frac{m_1^2}{n} + \frac{m_2^2}{1-n} \right) I^2 R \quad (19)$$

$$\frac{w_t}{I^2 R} = \frac{\{n - (1 - p\,e_p)\,(f\,p)\}^2}{n} + \frac{\{1 - n + (1 - p\,e_p)\,(f\,p)\}^2}{1-n} =$$

$$1 + \frac{(1 - p\,e_p)^2\,(f\,p)^2}{n\,(1-n)} \quad \frac{W_t}{I^2 R} = 1 + (1 - p\,e_p)^2 \int_0^1 \frac{(f\,p)^2}{n\,(1-n)} d\,n \quad (20)$$

Energy density at back edge of segment.

$$H_d = \int_0^T \frac{w_2}{a} d\,t = T\,\frac{I^2 R}{A} \int_0^1 \frac{m_2^2}{(1-n)^2} d\,n$$

$$= T\,\frac{I^2\,R}{A} \int \left\{ 1 + \frac{2\,(1 - pe_p)(f\,p)}{1-n} + \frac{(1 - p\,e_p)^2\,(f\,p)^2}{(1-n)^2} \right\} d\,n$$

$$= T\frac{I^2 R}{A}\left\{n+2(1-p\,e_p)\int_0^1 \frac{(f\,p)}{1-n}d\,n+(1-p\,e_p)^2\int_0^1 \frac{(f\,p)^2}{(1-n)^2}d\,n\right\} \tag{21}$$

$$r_d = \int_0^1 d\,n+2\,(1-p\,e_p)\int_0^1 \frac{(f\,p)}{1-n}\,d\,n+(1-p\,e_p)^2\int_0^1 \frac{(f\,p)^2}{(1-n)^2}\,d\,n \tag{22}$$

r_d for $p = 1$

$$(f\,p) = -(1-n)\left\{1+\frac{\log(1-n)}{n}\right\}$$

$$r_d = \int_0^1 \left\{1-2\,e\left(1+\frac{\log(1-n)}{n}\right)\right.$$

$$\left.+e^2\left(1+\frac{\log(1-n)}{n}\right)^2\right\}d\,n \text{ where } e = 1-p\,e_p$$

$$= \int_0^1\left\{(1-e)^2-2\,e\,(1-e)\,\frac{\log(1-n)}{n}+e^2\frac{\log^2(1-n)}{n}\right\}d\,n \tag{23}$$

$$\int \frac{\log^2(1-n)}{n^2}\,d\,n = -\frac{1-n}{n}\log^2(1-n)-2\int\frac{\log(1-n)}{n}$$

$$r_d = (1-e)^2\,n-e^2\,\frac{1-n}{n}\log^2(1-n)-2\,e\int\frac{\log(1-n)}{n}\,d\,n$$

Since $-2\,e\displaystyle\int\frac{\log(1-n)}{n}\,d\,n = 2\,e\left\{n+\frac{n^2}{2^2}+\frac{n^3}{3^2}+\frac{n^4}{4^2}+\text{etc.}\right\}$

$$r_d = (1-e)^2\,n-e^2\,\frac{1-n}{n}\log^2(1-n)+2\,e\left\{n+\frac{n^2}{2^2}+\frac{n^3}{3^2}+\frac{n^4}{4^2}+\text{etc.}\right\}$$

+ constant. When $e_p = 1$, $e = 0$ and $r_d = 1$ $\therefore$ constant $= 0$ and we

have $r_d = (1-e)^2+2\,e\left\{1+\dfrac{1}{2^2}+\dfrac{1}{3^2}+\dfrac{1}{4^2}+\text{etc.}\right\} = (1-e)^2$

$+2\times 1.645\,e$ (Legendre's values) or $r_d = 1+1.29\,e+e^2$ (24)

When $e_p = 0,\ r_d = 3.29,\ \dfrac{d\,r_d}{d\,e} = 1.29+2\,e = 0,\ e = -0.645,\ e_p = 1.645$

and r_d is a minimum when $e_p = 1.645$ and the minimum value of r_d is 0.584

Current Density.

$$\frac{i_1}{a_1} = \frac{m_1}{n}\,\frac{I}{A} \therefore \frac{\dfrac{i_1}{a_1}}{\dfrac{I}{A}} = \frac{m_1}{n} \tag{25}$$

and

$$\frac{\dfrac{i_2}{a_2}}{\dfrac{I}{A}} = \frac{m_2}{1-n} \tag{26}$$

No load energy density for $p = 1 \quad E_p = 1$

$$(f\,p) = -(1-n)\left(1 + \frac{\log(1-n)}{n}\right)$$

$$r_d = \int_0^1 \left\{1 + \frac{2\log(1-n)}{n} + \frac{\log^2(1-n)}{n^2}\right\} d\,n$$

$$r_d = n + 2\int \frac{\log(1-n)}{n}\,d\,n - \frac{1-n}{n}\log^2(1-n) - 2\int \frac{\log(1-n)}{n}\,d\,n$$

$$= n - \frac{1-n}{n}\log^2(1-n) + \text{const.} \quad \text{When } n = 0,\ r_d = 0 \text{ and const.} = 0.$$

$$\text{Therefore } r_d = n - \frac{1-n}{n}\log^2\ 1-n)\Big]_0^1 = 1 \tag{27}$$

APPENDIX B.

DEDUCTION OF EQUATION FOR THE FINAL MAXIMUM RISE OF TEMPERATURE OF THE COMMUTATOR SURFACE.

τ_m = maximum difference between the temperature of the segment surface and that of the surrounding atmosphere after temperatures have become stable.

τ_c = rise of temperature while the segment is under the brush. τ = difference between the temperature of the segment surface and that of the surrounding atmosphere at any time reckoned from the end of the commutation period.

τ_2 = difference of temperature of the segment and the atmosphere just before the segment comes under the brush.

T_b = length of time between commutation periods.

a = degrees fall of temperature per second per degree difference of temperature between the segment surface and the surrounding atmosphere (assumed to be constant).

$$-d\tau = a\tau\,dt \text{ or } \frac{d\tau}{\tau} = -a\,dt \text{ or } \log \tau = -at + \text{constant}.$$

When $t = 0$, $\tau = \tau_m$ and constant $= \log \tau_m$

$$\therefore \log \frac{\tau_m}{\tau} = at \text{ or } \frac{\tau_m}{\tau} = e^{at}$$

When $t = T_b$, $T = T_2$ and we have $\frac{\tau_m}{\tau_2} = e^{aT_b}$

$$\text{But } \tau_m - \tau_2 = \tau_c \;\therefore\; \frac{\tau_m}{\tau_m - \tau_c} = e^{aT_b}$$

$$\text{or } \tau_m = \tau_c \frac{e^{aT_b}}{e^{aT_b} - 1} \tag{28}$$

$$\text{and } \tau_2 = \frac{\tau_c}{e^{aT_b} - 1} \tag{29}$$

If τ_c varies directly with the energy density H_d then $\tau_c = b\,H_d$ and we have

$$T_m = b\,H_d \frac{e^{aTb}}{e^{aTb} - 1} \qquad (30)$$

Discussion on "Limits of Injurious Sparking in Direct-Current Commutation."

Gano S. Dunn: Mr. Reid's paper gives us a theory to account for the phenomenon which I think is the best we have so far although to my mind it does not explain all of the facts that we observe. The theory that the blackening of the commutator bars is due to volatilization of the copper is confirmed by the following fact: when the sparking has not been too severe there is a very delicate layer of copper deposited on the under side of the brush which layer I have observed may be completely removed from one brush and deposited upon a brush of opopsite polarity if, for instance in the case of a generator, the polarity of the generator be reversed. The fact that this layer of copper changes its brush when the current changes its direction, implies that the action is electrolytic, and we know it could be electrolytic only if the copper were volatilized. I cannot account for sufficient energy in the contact of the brush with the copper bar to produce this volatilization in the manner Mr. Reid points out. I have run a carbon brush at enormous densities on plain brass and copper rings and have not had such deposits. I think the deposit is the result of some change in the brush after the machine has started running. It is an old maxim with me that all new brushes are good brushes. Whenever new brushes are put upon machines and freshly sandpapered, they work well. Blackening of the commutator, which occurs after the machine has been running some time, I have always attributed to excessive action commencing at the edge of the brush and causing an eating back of its contact surface. The depth affected may be only 0.001 of an inch, but the eaten or burned area travels back under the brush until it gets one-eighth or one-quarter inch back and then the forces that cause it balance with other forces and it stops. Evidence of this is seen in many brushes which, taken out of the machine, show a perfectly polished surface at the entering edge and a rather dull surface at the leaving edge, these two surfaces being sharply separated from each other by exactly straight lines parallel with the mica. These peculiar markings are also found on brushes, sometimes in several degrees. There will be a bright surface, then a dull surface, then a surface of different texture. I therefore think that these surfaces may indicate that the brush is not making such good contact at one place as at another place. I do not mean it is out of contact, but the pressure of contact may be very much lighter at some than at other areas. Such lighter contact might account for sufficient energy to volatilize the copper at that point. The reason why I think this is so is the result of experiments recently made with brushes of greatly increased contact resistance. A brush of this kind has been devised by Mr. F. W. Young, and when used on machines which previously performed as Mr. Reid has described, the phenomenon he observed has been absent. I attribute it to the fact that the increased contact resistance gained by the two extra contact surfaces actually prevent the excessive current density usually present at the edge of a plain brush, which excessive current density is responsible for the peculiar change of surface, whatever it may be. The dead brush, I believe, is a new principle in commutation. The method of getting a force which we have not had before to turn over our coil and its results are very interesting.

Chas. P. Steinmetz: Mr. Reid's paper further extends the theory proposed by him some years ago that the damage done by commutation is to be looked for by the action under the brush, and not beyond the brush at the leaving point. When Mr. Reid proposed this theory it met with considerable criticism. Now, I believe that most engineers familiar with commutating machines are agreed that the damage by faulty commutation is to be looked for in the distribution of the current under the brush. There is, however, one quantity in the equation given by Mr. Reid to which I desire to draw attention, and that is the contact resistance per unit area of the brush contact. This resistance is not a constant quantity, but a variable one. It increases somewhat with the increase of peripheral velocity, and decreases with the increase of brush pressure. The most important condition, however, is that it varies with the current density under the brush and over a wide range almost in inverse proportion thereto. That is, the voltage consumed by the brush contact is approximately constant over a considerable range, and equals about one volt. That means that the contact resistance does not appear like a true resistance, but has arc characteristics. The voltage consumed per unit area is fairly independent of the current density. If the potential drop at the brush contact is determined as a function of the current density, it is found that it starts with zero, rises in a straight line, then begins to bend, becomes horizontal, and looks somewhat similar to a saturation curve. A series of equations involving and considering this characteristic feature of the contact resistance would be interesting. The actual condition probably will lie somewhere between the two conditions, a constant contact resistance and a constant contact voltage.

W. L. Waters: The conclusions which Mr. Reid comes to in his paper appear to fit in very well with practical results. In practice it is found that low current density in the brushes is always conducive to good operation. This agrees well with Mr. Reid's suggestion that it is the energy liberated per unit area on the commutator surface that is responsible for the damage to the commutator. It is also found that when a machine sparks, the temperature of the commutator is greatly increased, thus showing that the energy dissipated in sparking is often greater than that lost by friction and resistance drop.

So that it may easily be understood that there is enough energy dissipated in sparking to volatilize some of the copper. I hardly think, however, that Mr. Reid's suggestion that the value of the expression $\frac{L}{R\,T}$ should be used as a criterion of sparking tendency by practical engineers is a good one, but the general suggestions outlined in his discussion of the subject are likely to be useful in practical work.

THORBURN REID: Mr. Dunn describes a phenomenon that I have not noticed in my experience, that the deposition of the copper took place on one brush when the current was in one direction and on another brush when the current was reversed. I hesitate to try off-hand to make the statement agree with my theory, but would suggest that the copper, in order to be deposited, must be first melted or volatilized in some way, and the deposition on one brush or the other would then depend on the direction of the current, but after the copper has already been separated from the segment; in that way it would agree with my theory. In that connection, Mr. Dunn did not seem to think that there was sufficient energy available for melting the copper. When the ratio $p=0.25$ the energy density at the receding edge of the segment is 14 times the average, which seems to be sufficient energy to raise the temperature to the melting point of copper and even with $p=0.5$ the ratio was 7 for the energy density. If the average density would raise the temperature, say, 50 or 75 degrees fahr. then a density 14 times as great, should easily raise it to the melting point of copper.

Mr. Steinmetz' suggestion in regard to taking into consideration variation in the contact resistance is one I had already thought of. The reason it was not included in my equations was twofold: first, because I did not know of any equation that would express that variation of contact resistance with any amount of accuracy; secondly, because it was sufficiently difficult to solve these equations when the contact resistance was assumed to be constant, and when it came to trying to express contact resistance as a variable, I was not able to accomplish it. However, if the law Mr. Steinmetz has suggested can be assumed—that the contact resistance is inversably proportional to the current density—that gives rather a simple equation that it may be possible to solve.

In regard to the use of the ratio p, or $\frac{L}{R\,T}$, in practical design, it can be used and will be used by engineers, at least to some extent, although perhaps not to the degree of refinement indicated in the paper. To a certain extent it is indirectly used now, in that the inductance of the armature coil is kept within arbitrary limits, determined mainly by experience, and it is kept within these limits simply in order that the ratio shall be kept down. The current density in the brush contact surface is generally limited to a certain definite amount; the depth of the armature slots and the number of turns of the coil are also limited, which is the same thing as limiting the various values in this term p. Now, the calculation of the self-inductance of the coil cannot be made very accurately in the present state of our information. It can be done with sufficient accuracy for practical purposes, however, and it seems worth while for engineers to do it, as it is not a complicated matter to measure the inductance with a great deal more accuracy than is now customary, and it will increase the definiteness of the commutator design greatly at a slight cost of time.

GANO S. DUNN: I do not wish to attribute wholly to electrolytic effects the picking up of copper referred to in Mr. Reid's paper which Mr. Waters has mentioned. Copper may be picked up from other causes, but I did mean to point out emphatically that the copper on the brush is affected by the polarity of the current; I have made numerous observations in which copper has changed from a brush of one polarity to another when the direction of the current has been changed. This seems significant and tends to prove the soundness of Mr. Reid's conclusions—that blackening of the commutator is due to some volatilization of the copper. What really happens when the brush gets very coppery, is that the thin film of copper suddenly forms at some point into a very tiny bead, and as soon as this bead is formed it short-circuits the high contact resistance of the brush and invites the current to pass through it into the commutator. When this commences the commutator cuts and copper may then appear almost equally at the positive and the negative brushes.

CHAS. P. STEINMETZ: Which one of the brushes picks up copper, the positive or the negative?

GANO S. DUNN: In the incipient stage when the copper picked up is not in the form of beads, but as though the brush had been slightly electroplated so that if held to the light it looks coppery, it is the negative brush.

CHAS. P. STEINMETZ: That means the copper is carried in the direction of the negative current?

GANO S. DUNN: It is a question of whether it is a motor or a generator. If it is a generator the current goes out of the machine at the positive brush and the deposit is on the positive brush, but if the current comes into the machine at the positive brush, as in the case of a motor, then the deposit is on the negative brush.

J. N. DODD (by letter): To the designer the subject of commutation is of great interest. In its definition it is simple, but in all its bearings it is exceedingly complex. Mr. Reid is I think the first to point out that the heat evolved causes the trouble, and that effort must be made in the direction of discovering the watts lost during time of commutation and the distribution of this energy.

I would, however, suggest a practical difficulty; it is with reference to the resistance of the brushes—the quantity called R. This is a quantity of which one can say that it is impossible to calculate it with any degree of exactness. It varies, of course, with the quality, setting, and pressure of the brush, and with the current density, temperature, commutator speed and condition of the commutator surface. In looking up the records of identically similar machines—machines tested under the same conditions—I have found that the brush resistance of one machine is very often double the resistance of the other, and sometimes even five times that of the other.

Moreover, after a machine is on load until thoroughly heated; that is to say, when it has reached stable conditions, the resistance per square inch of brush surface is not the same over the entire face, and the equations page 635, following equation (2) are not correct.

All engineers are familiar with the relation between brush contact surface resistance and current density. The resistance seems to vary inversely as the density. According to Mr. Reid's paper the density may vary from its average value to an almost infinite value. While one cannot say that the resistance per square inch will vary from its usual value to zero, it is perhaps safe to say that it varies from fairly high value to a very low value. In other words, the resistance between the brush and the emerging segment does not vary inversely as $T - t$, as Mr. Reid states, but at a very much lower rate. The resistance per square inch of the brush surface may be taken as about 0.03 ohms per square inch. According to Mr. Reid's paper the resistance between the brush and the entering segment may be said to have this resistance. The current density, however, between the brush and the emerging segment has a value much higher than the average, rising from the average to, as I have said, often an almost infinite value. The resistance per square inch of the brush contact surface for the emerging segment will then, according to most curves published, vary from the average value to an extremely low value.

This will to a certain extent vitiate Mr. Reid's train of reasoning. It introduces an error from the very beginning; see page 635 following equation (2). The time during which the resistance is low lasts of course for only a very short time, and it is to be hoped that it does not seriously alter the result obtained.

In Mr. Reid's fundamental equation (1) pages 613 and 635, he gives the quantities that affect commutation; these quantities are resistance of various parts of the circuit, the current commutated, the voltage of self-induction, and the reversal electromotive force. As one always runs with the brushes either in the neutral or the reverse field these strike one as eminently the only factors of importance. On page 633 Mr. Reid also brings in the effect of the distorting and weakening of the reversal flux by the armature ampere turns. In this he appears to bring in a needless complication. In other words, sparking is the result of too high a voltage between two consecutive bars. This voltage can be caused by only one thing; that is, the coil cutting magnetic lines. These magnetic lines constitute the field. This field is a resultant of two fields, one due to the field winding, and the other to the armature winding. The sparking of the machine at any load may be considered as due to two causes. In the first place the sparking due to the external field which he has already taken into consideration under the title of the reversal electromotive force and in the second place the sparking due to the field set up by the armature. That is, this latter is due to the voltage set up in the armature coil by the armature coil cutting the lines which have been set up by the current flowing through the armature coils. This, however, is what is meant by self-induction. That is, the quantities inserted in the fundamental equation, pages 613 and 635, are entirely sufficient. Stated differently, the stability factor or ratio between armature ampere turns and field turns for the air-gap is not a factor of first importance. What must be done in designing machines is either to keep down what is called the self-induction or reactive voltage, or to provide a reversing field sufficient to render it innocuous.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

THE DESIGN OF INDUCTION MOTORS.

WITH SPECIAL REFERENCE TO MAGNETIC LEAKAGE.

BY COMFORT A. ADAMS.

At the last International Electrical Congress,* the writer presented a paper on the "Leakage Reactance of Induction Motors," in which a new leakage element was described, with results of experiment and calculation. A method of calculating the other leakage elements was also outlined. This method, based upon fundamental principles, was checked by a long series of experiments, and while not new fundamentally, may have some points of novelty in its details. In the present paper this method will be more fully developed and applied to the design of Induction Motors. The leakage elements will be expressed in a novel form and a new method will be employed for the calculation of the power factor. A method of calculating the exciting current will be given with corroborative data. Some new design constants will also be developed.

POWER-FACTOR.

One of the controlling elements in the design of an induction motor is its *power-factor*; but an intelligent design takes account of the fact that in some cases it is important to have the maximum power-factor occur at full load, in others at less than full load, and in others beyond full load. This last applies to a squirrel-cage motor to be started at reduced pressure from a compensator.

The power-factor is dependent largely upon the magnetizing component of the exciting current, and the reac-

* St. Louis, 1904, Section B.

tive drop of pressure due to the leakage fluxes. For any given value of the slip, the power-factor may be expressed in terms of the leakage and exciting reactances (or equivalent constants), or the *maximum* power-factor may be very simply expressed in terms of the " leakage-factor " (which is approximately the ratio of total leakage reactance to exciting reactance).

For purposes of design, the writer has developed another method, in which the leakage reactance e.m.fs. are expressed in terms of the induced or counter e.m.f. E_1', Fig. 1, and the magnetizing current in terms of the torque current (the effective or energy component of the secondary current).

The advantages of this method are: the results are *explicit*, in that they enable two machines to be compared directly, without further reference to output or pressure, the comparison applying not only to the leakage as a whole but to each ele-

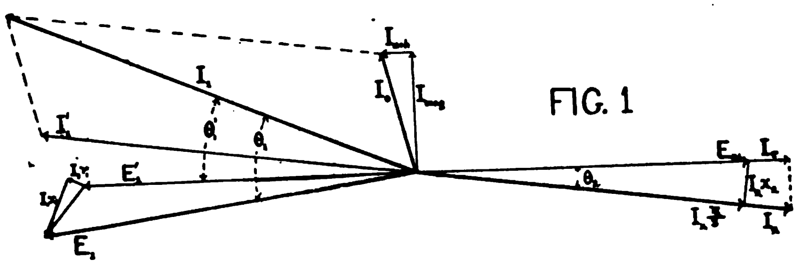


FIG. 1

ment thereof; the full-load power-factor, the leakage-factor, and the maximum power-factor are easily obtained by simple calculations, all being expressed in terms of the *design constants** in such a manner that the latter may be so chosen at the beginning of a design, that the power-factor for any desired load will have its maximum possible value, for the given capacity, pressure, frequency, and mechanical limitations; or the design constants may be so chosen as to make the leakage reactance a minimum, this being in some cases much more important than a low leakage factor.

Referring to Fig. 1, and assuming all secondary quantities reduced to primary turns,—

r_1 and r_2 are the primary and secondary resistances.

x_1 and x_2 the primary and secondary leakage reactances.

I_1 and I_2 the primary and secondary currents,

* See page 330.

E_1, the primary impressed e.m.f.,

E_1', that part of E_1 required to balance the e.m.f. induced by the mutual flux,

$E_{20} = E_1'$, the secondary induced e.m.f. divided by the slip, s,

$\frac{r_2}{s}$, the equivalent secondary resistance,

$I_T = I_2 \cos \theta_2$, the torque current,

I_0, the exciting current,

I_m, the magnetizing current,

I_{e+h}, the core loss energy current,

$I_1' = I_2$, that part of I_1 which balances the m.m.f. of I_2.

Let

$$q_m = \frac{I_m}{I_T},\quad q_{x1} = \frac{I_1 x_1}{E_1'},\quad q_{x2} = \frac{I_2 x_2}{E_{20}},\quad q_{r1} = \frac{I_1 r_1}{E_1'},\ \text{and}\ q_c = \frac{I_{e+h}}{I_T}$$

$$\text{then } \tan \theta_1' = \frac{q_m + \dfrac{q_{x2}}{\sqrt{1 - q_{x2}^2}}}{1 + q_c} = q_1'$$

$$\text{and the power-factor} = \cos \theta_1 = \frac{1}{\sqrt{1 + \left(\dfrac{q_1' + q_{x1}\sqrt{1 + q_1'^2}}{1 + q_{r1}\sqrt{1 + q_1'^2}}\right)^2}} \quad (1)$$

Although the calculation of the power-factor from Equation (1) is not a tedious operation, there are several approximations which are quite satisfactory for comparative purposes, *e.g.*;

$$\text{power-factor} = \frac{1}{\sqrt{1 + \left(\dfrac{q_{x1} + \dfrac{q_{x2} + q_m}{1 + q_c}}{1 + q_{r1}}\right)^2}} \quad (2)$$

$$\text{power-factor} = \frac{1}{\sqrt{1 + \left(\dfrac{q_{x1} + q_{x2} + q_m}{1 + q_c}\right)^2}} \quad (3)$$

$$\text{power-factor} = \frac{1}{\sqrt{1 + (q_{x1} + q_{x2} + q_m)^2}} \quad (4)$$

Equation (2) gives results too high by about 0.2% or 0.3% in a good motor;

Equation (3) gives very close results;

And equation (4) gives results too low by from 0.5% to 1%, except in very poor motors, where the error is greater.

Design Constants and Output Equation.

During the last six years the writer has used the following rational output equation. Its development is obvious, as is the slight change necessary to adapt it to other types of dynamo-electric machinery. It is, for a three-phase induction motor:

$$K = 2.4 \times 10^{-10} B\, v\, \Delta\, d\, l = k_0\, d\, l \tag{5}$$

where

K is the output in kilowatts;

d and l the gap diameter and length of the core in inches;

B the maximum superficial gap density in maxwells per square inch;

v the synchronous peripheral velocity in feet per second; and

Δ the full-load peripheral current density (ampere conductors per inch of periphery) due to the torque current, I_T.*

B, v and Δ may be called the *major design constants*, since they determine the general proportions of the machine.

k_0 is called the "output coefficient;" it is the reciprocal of the "Steinmetz coefficient."

In metric units equation 5 becomes

$$K = 2.0 \times 10^{-9} B\, v\, \Delta\, d\, l \tag{5a}$$

where v is in meters per second.

Copper Heating Constant.

Let m = circular mils per ampere in the secondary active conductors, and m_1 = the same for the primary.

Then, since it happens that the hot resistance (60° cent.) of one circular mil inch of copper is almost exactly one ohm, $\frac{\Delta_1}{m_1}$ is the watts primary copper loss developed under each square inch of gap surface, and $\frac{\Delta}{m}$ the same for the secondary. This will be called the *copper heating constant* and will be designated by h.

---

* On some accounts it would be more convenient to use Δ_1 (corresponding to I_1), but on the whole Δ seems to be more satisfactory. I_T is so nearly equal to I_2 in a reasonably good motor that the difference (about one per cent.) may be neglected. I_1 is from 7% to 15% larger than I_2.

The writer has used this constant for a number of years in connection with all types of dynamo-electric machinery, and has found it very convenient, since it is a rough measure of the heating. Its permissible value depends upon the ratio of pole-arc to pole-pitch, the core loss, and ventilation.

In motors with average core losses and average ventilation, h_1 should not exceed 0.6 watts, 0.5 being a good average; with very good ventilation h_1 may reach 0.8. For the secondary it may be somewhat higher, since the secondary core loss is small. For very well-ventilated direct-current or alternator armatures h may be as high as 1.

Also, $\Delta\, m$ is the total copper section (in circular mils) per inch of periphery, and is thus a measure of the depth of slot, other things being equal. Therefore if h is to be kept constant, m will be proportional to Δ and $\Delta\, m$ to Δ^2; therefore the depth of slot will increase very rapidly as Δ increases. On this account there is in a given machine a fairly definite limit for Δ which thus proves to be a valuable design constant.*

Slot Constants.

Let b'' = ratio of slot-width to tooth-pitch (at gap),
d_s = depth of slot in inches, and
f_s = space-factor for the slot.

Then

$$b''\, d_s\, f_s = \frac{\pi}{4}\,\frac{\Delta\, m}{10^6}$$

or

$$d_s = \frac{.7854}{10^6}\,\frac{\Delta\, m}{b''\, f_s}$$

but

$$\frac{\Delta}{m} = h$$

and

$$d_s = \frac{.7854}{10^6}\,\frac{\Delta^2}{h b'' f_s} \qquad (6)$$

where Δ, h, b'', and f_s may be easily and closely approximated in any given case.

It should be noted that f_s will, in general, increase somewhat as Δ and d_s increase; and that on the rotor (other than squirrel-cage) of an induction motor, or on the armature of a direct-

* Although these relations must have been employed in a general way by numerous designers, the writer has never seen them definitely expressed.

current machine, b'' will decrease slightly as d_s increases, especially on a machine of small diameter. This further emphasizes the limit to Δ.

Magnetizing Current.

Tooth Fringing. Although the air-gap of the induction motor is short, there are many cases where the tooth fringing plays an important part. The following method of dealing with this subject has given excellent results.

Referring to Fig. 2, consider a strip of gap-section one inch wide perpendicular to the plane of the paper (or parallel to the shaft), and divide this strip into three parts: *one* immediately under the tooth tip; the *second* extending outward from the edge of the tooth-tip a distance equal to the radial depth of the air-gap, δ; and a *third* extending from this last point to a point half-way across the slot opening. Assume that in this third part, the flux lines are circular as shown in Fig. 2.

It is proposed to find the equivalent increase in gap-section (or in the width of the tooth-tip) produced by the permeance of the second and third parts above mentioned (*i.e.*, by the fringing), in terms of δ. To this end the unit of permeance may be taken to suit the system of units employed.

The permeance of the "*second*" *part* of the gap-section is not easily determined with any degree of accuracy, but may be taken as approximately equal to 0.6; *i.e.*, the *equivalent average* width of this portion of the fringing path is approximately 0.6 δ.

The permeance of the "third" part is found by an obvious integration. It is:

$$\frac{2}{\pi}\int_{x=\delta}^{x=\frac{s_0}{2}} \frac{dx}{x} = \frac{2}{\pi} \log_\epsilon \frac{s_0}{2\,\delta} = 1.47 \log_{10} \frac{s_0}{2\,\delta}$$

and the total fringing permeance is

$$f = 0.6 + 1.47 \log_{10} \frac{s_0}{2\,\delta} \tag{7}$$

In Fig. 6 "f" is plotted against $\frac{s_0}{2\,\delta}$.

A little consideration will show that when s_0 is less than $2\,\delta$, equation (7) will not be satisfactory. This is allowed for in Fig. 6 by continuing the curve from the point $s_0 = 2\,\delta$ to the origin, in a straight line.

The fringing is thus equivalent to increasing the width of the tooth-tip by $f\,\delta$ on each of the two edges which are parallel to the shaft.

If the width of the actual tooth-tip be designated by t_t, the equivalent tooth-tip will be

$$t = t_t + 2\,f\,\delta \tag{8}$$

and all calculations of gap reluctance may be made on this basis.

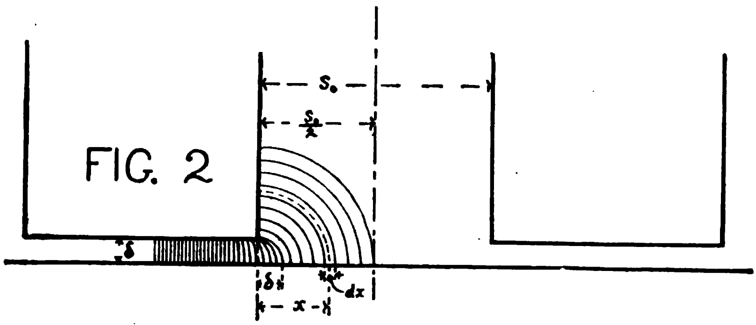


FIG. 2

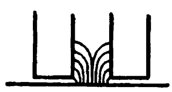


FIG. 2a

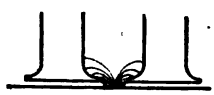


FIG. 2b

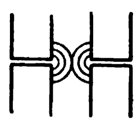


FIG. 2c

For rough calculations, f may be taken = 1, although in many cases it differs considerably therefrom.

Sources of Error. (1) If the slots are straight, as shown in Fig. 2, the fringing will extend farther back on the side of the tooth and the fringing permeance will be slightly greater than given by the above integration (see Fig. 2A). (2) If the slots are overhung by thin tooth projections, the fringing permeance will be slightly less than that given above (see Fig. 2B). (3) Whenever there are slot openings on both sides of the gap, there will be short periods during which f will be less than above, owing to the greater length of fringing path (see Fig. 2c). These errors are usually small and can be easily approximated for any given case.

End Fringing. There is also a fringing at the ends of the core and in the ventilating ducts, which is of minor importance. For ordinary purposes, it may be taken as equivalent to an increase in core length equal to δ for each core-end or side of duct; and when great accuracy is not desired, it may be neglected.

Average Gap-Section. Consider as before one unit length parallel to the shaft. Referring to Fig. 3, t_1 and t_2 are the equivalent tooth-tips including fringing, and λ_1 and λ_2 are the corresponding tooth-pitches. Consider the average overlapping area per tooth of smaller pitch during a movement equal to one-half of the larger pitch.

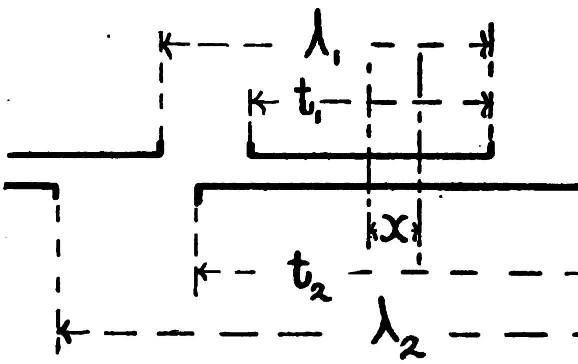


FIG. 3

$$
\text{a} \begin{cases} \text{From } x = 0 \text{ to } x = \tfrac{1}{2}(t_2 - t_1) \\ \text{Overlap} = t_1 \end{cases}
$$

$$
\text{b} \begin{cases} \text{From } x = \tfrac{1}{2}(t_2 - t_1) \text{ to } x = \lambda_2 - \tfrac{1}{2}(t_2 + t_1) \\ \text{Overlap} = \tfrac{1}{2}(t_2 + t_1) - x \end{cases}
$$

$$
\text{c} \begin{cases} \text{From } x = \lambda_2 - \tfrac{1}{2}(t_2 + t_1) \text{ to } x = \tfrac{1}{2}\lambda_2 \\ \text{Overlap} = (t_1 + t_2) - \lambda_2 \end{cases}
$$

Integrals

(a) $\frac{t_1}{2}(t_2 - t_1)$

(b) $\int_{x=\frac{1}{2}(t_2-t_1)}^{x=\lambda_2-\frac{1}{2}(t_2+t_1)} [\tfrac{1}{2}(t_2+t_1) - x]\,dx = (\lambda_2 - t_2)\left(t_1 - \frac{\lambda_2 - t_2}{2}\right)$

(c) $\left[(t_1+t_2) - \lambda_2\right]\tfrac{1}{2}\left[(t_1+t_2) - \lambda_2\right] = \tfrac{1}{2}\left[(t_1+t_2)^2 + \lambda_2^2 - 2\lambda_2(t_1+t_2)\right]$

$$(a) + (b) + (c) = \frac{t_1 t_2}{2}$$

$$\text{Average overlap} = \frac{\frac{t_1 t_2}{2}}{\frac{\lambda_2}{2}} = \frac{t_1 t_2}{\lambda_2}$$

$$\text{Average \% overlap} = \frac{t_1 t_2}{\lambda_1 \lambda_2} = a_1\, a_2 = \underline{K_1} \qquad (9)$$

where $a_1 = \frac{t_1}{\lambda_1}$ and $a_2 = \frac{t_2}{\lambda_2}$, which may be calculated from equations (7) and (8).

Thus $K_1 = a_1 a_2$ is the ratio of effective gap-section to superficial gap-section. In calculating the *superficial* gap-section, use the gross length of core minus air-ducts. No appreciable reduction in effective gap-section results from the presence of the spaces between laminations, because these are small when compared with the radial depth of gap; moreover they are almost wholly covered by the burring of the edges of the core-discs.

The actual maximum gap-density is then, $\frac{B}{K_1}$, where B is the superficial density corresponding to the superficial gap-section as above.

Peripheral Magnetizing Current Density. For general or comparative purposes, it is convenient to express the magnetizing current in terms of the corresponding peripheral current density (ampere-conductors per unit of periphery).

Let Ni_g represent the ampere-turns consumed in the single air-gap at the point of maximum flux density;

δ, the air-gap in inches;

λ_p, the pole-pitch in inches;

Δ_m, the peripheral magnetizing current density (root mean square).

Then

$$Ni_g = 0.313 \frac{B}{K_1} \delta$$

and

$$2\, Ni_g = 0.9\, \Delta_m\, \lambda_p$$

This assumes sinusoidal distribution of the peripheral magnetizing current density.

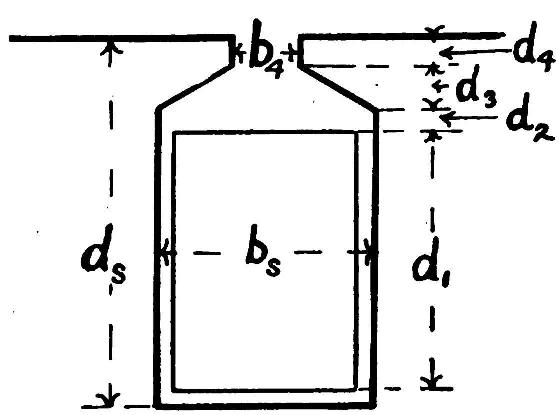


FIG. 4

$$\therefore \Delta_m = \frac{0.695\, B\, \delta}{K_1\, \lambda_p}$$

or

$$\Delta_m = 0.695 \frac{B\, \delta}{K_1\, K_2\, \lambda_p} \qquad (10)$$

where K_2 is a constant less than unity which takes account of the *ampere-turns consumed in the iron* part of the magnetic circuit. K_2 varies from 0.8 to 0.9 in 60-cycle motors, and is in general smaller for lower frequencies, because of the longer flux-paths and higher densities in the iron.

Where reasonable accuracy is desired, it is advisable to calculate carefully the ampere-turns consumed in the iron.

For the purposes of this paper equation (10) will be written:

$$\Delta_m = 0.116 \frac{B \delta n}{K_1 K_2 v} \tag{11}$$

where n is the frequency, cycles per second, and v is the synchronous peripheral velocity in feet per second.

or, in metric units—

$$\Delta_m = 0.0353 \frac{B \delta n}{K_1 K_2 v} \tag{11a}$$

all in centimeters except v, which is in meters per second.

The actual magnetizing current in amperes is readily obtained from (10) or (11); it is:

$$I_m = \frac{\Delta_m}{N'} = \frac{0.695}{K_1 K_2} \frac{B \delta}{N' \lambda_p}$$

where N' is the number of primary conductors per inch of periphery.

Expressed in *terms of the torque current*, the *Magnetizing Current is*:

$$q_m = \frac{\Delta_m}{\Delta} = \frac{0.116}{K_1 K_2} \frac{B \delta n}{\Delta v} \tag{12}$$

The above described method may seem to some unnecessarily complicated, but those who have carefully studied this subject will appreciate the necessity of care in making these calculations. After spending several weeks time in the observation and calculation of air-gap reluctance by numerous methods, the writer feels confident that with reasonable care in the determination of air-gap and tooth dimensions, the magnetizing current may be readily determined within 5%.

A method such as that employed by Mr. Hobart in his excellent book on Electric Motors, gives very fair results when applied to machines with small slot openings, but falls far short when applied to machines with open slots.

Comparison with Test Data. The above method of calculation has been applied to a series of machines with a wide variety of slot openings and air-gaps, with the results shown in Table I. The stator and rotor numbers refer to the machines fully described in the Congress paper referred to on page 327. All important dimensions were measured with great care. The observed exciting current was multiplied by *sin* θ to obtain the magnetizing current. It will be noticed that the machines are partly of the open-slot type, where the air-gap reluctance is most difficult to calculate.

The method employed to measure δ was such as to give results too large, which is indicated by the consistent positive error in most of the calculations. A change in the quality of the iron might have shifted the above errors by three or four per cent.; but it would not have altered the consistency of the results.

Most of the refinements of the method here recommended were only adopted after a careful study of the results of the above series of tests, in which it was discovered that the ordinary methods gave exceedingly unsatisfactory results, and that the introduction of some apparently insignificant refinement would add much to their consistency. No refinement mentioned in this paper has proved so insignificant that it did not add materially to the parallelism of the observed and calculated data.

Had Mr. Hobart's[1] method of calculating the maximum superficial gap density and the corresponding magnetizing current been employed, the errors attributed to his method in table I would be reduced by 3.5%.

Leakage Reactance.

Slot Leakage. Referring to Fig. 4, the flux leakage per ampere-inch of slot is

$$\phi_s = 3.2 \left(\frac{d_1}{3\, b_s} + \frac{d_2}{b_s} + \frac{2\, d_3}{b_4 + b_s} + \frac{d_4}{b_4}\right) \qquad (13)$$

or, per ampere centimeter—

$$\phi_s = 1.26 \left(\frac{d_1}{3\, b_s} + \frac{d_2}{b_s} + \frac{2\, d_3}{b_4 + b_s} + \frac{d_4}{b_4}\right) \qquad (13a)$$

[1] Electric Motors, by Henry M. Hobart. Whittaker & Co., London, 1904.

TABLE I.

Stator No.	Rotor No.	a_1	a_2	k_1	δ	Apparent B	CALCULATED. Δ_{gap}	Δ_{iron}	$\Delta_m = \Delta_{g+i}$	Observed Δ_m	% Error.	HOBART'S METHOD. k_1	Δ_{gap}	Δ_m	% Error.
1	4	0.82	0.90	0.736	0.0112	31200	60.7	21.6	82.3	78.3	+5.1			$1.12 \times \Delta_g$	
2	4	0.625	0.90	0.563	0.0112	31700	80.0	19.2	99.2	95.	+4.4				
3	4	0.92	0.90	0.83	0.0112	29300	50.0	15.6	65.6	66.4	—1.2				
1	1	0.86	0.88	0.757	0.0216	29000	104.7	23.8	128.5	125.4	+2.5	0.79	100.5	112.5	—10.3
2	1	0.68	0.88	0.598	0.0216	22900	104.6	14.4	119.0	115.8	+2.8	0.678	92.2	103.0	—11.0
3	1	0.94	0.88	0.827	0.0216	27200	90.	18.8	108.8	105.5	+3.1	0.865	86.	96.3	—8.7
1	2	0.86	0.745	0.64	0.0214	27300	115.7	22.2	137.9	134.4	+2.6	0.692	107.	120.	—10.7
2	2	0.68	0.745	0.507	0.0214	22600	120.6	14.1	134.7	132.7	+1.5	0.582	105.	115.5	—13.0
3	2	0.94	0.745	0.70	0.0214	26900	104.5	18.3	122.8	120.	+2.3	0.768	95.3	106.7	—11.1
1	3	0.86	0.695	0.598	0.0210	28900	128.6	24.3	152.9	151.	+1.3	0.692	111.0	123.3	—18.3
2	3	0.68	0.695	0.473	0.0210	22550	126.8	14.1	140.9	138.	+2.1	0.582	103.3	115.5	—16.3
3	3	0.94	0.695	0.653	0.0210	26900	109.5	18.6	128.1	122.8	+4.3	0.768	93.2	104.4	—15.0
1	4	0.86	0.930	0.80	0.0210	30200	100.5	20.9	121.4	117.2	+3.6	0.81	95.5	106.8	—8.9
2	4	0.68	0.930	0.632	0.0210	23900	100.7	13.3	114.	113.8	+0.2	0.7	88.	98.5	—13.5
3	4	0.94	0.930	0.874	0.0210	28900	88.0	15.4	103.4	103.8	—0.4	0.886	89.	94.	—9.4

Equation 13 may be written—

$$\phi_s = k_s \frac{d_s}{b_s} \tag{14}$$

where

$$k_s = \frac{3.2}{d_s}\left(\frac{d_1}{3} + d_2 + d_3 \frac{2\,b_s}{b_4+b_s} + d_4 \frac{b_s}{b_4}\right) \tag{15}$$

This will be called the *slot constant*, and will prove useful, as it is fairly constant for a given type of slot (it decreases slightly as d_s increases).

k_s varies from 1.2 to 2.5, the higher values for closed or nearly closed slots. 1.5 is an average value for open slots and 2 for nearly closed slots.

Let N_s = conductors per slot.

Let N' = conductors per inch of periphery.

Then the inductance per inch of slot (conductors in series), is

$$L_s'' = \phi_s N_s^2\, 10^{-8}$$

and the corresponding reactance

$$x_s'' = 2\,\pi\, n\, \phi_s N_s^2\, 10^{-8}$$

$\frac{N'}{N_s}$ = slots per inch of periphery.

Let $b'' = \frac{N'}{N_s} b_s$ which is the total slot width per inch of periphery.

Then, since $\frac{\Delta}{N'}$, = torque-amperes per conductor, the *Reactance e.m.f.* per inch of slot is

$$E''_{xs} = \frac{6.28}{10^8}\,\frac{N_s\, n\, k_s\, d_s}{b''}\,\Delta \tag{16}$$

There will be induced in the same conductors by the mutual (or gap) flux an e.m.f.

$$E'' = \frac{12}{\sqrt{2}\, 10^8}\, k\, v\, B\, N_s$$

where k is the differential factor and is 0.95 for a three-phase motor. Then

$$E'' = 8.05\, v\, B\, N_s \times 10^{-8}$$

and the *Reactance e.m.f. of slot leakage is, in terms of the induced e.m.f.*

$$q_s = \frac{E''_{xs}}{E''} = 0.78 \frac{k_s\, d_s}{b''} \frac{\Delta\, n}{v\, B} \tag{17}$$

In metric units this becomes

$$q_s = 0.037 \frac{k_s\, d_s}{b''} \frac{\Delta\, n}{v\, B} \tag{17a}$$

Substituting d_s from (6) gives

$$q_s = \frac{0.612}{10^6} \frac{k_s}{h\, b''^2 f_s} \frac{\Delta^3\, n}{v\, B} \tag{18}$$

But, k_s will usually decrease and f_s increase as Δ (and therefore d_s) increases, and although there is no exact relation, it will be sufficiently accurate for a general analysis to write

$$\frac{k_s}{f_s}\,\Delta = \text{a constant } (k_d).$$

Then

$$q_s = \frac{.612}{10^6} \frac{k_d}{h\, b''^2} \frac{\Delta^2\, n}{v\, B} \tag{19}$$

For final calculations (17) or (18) should be used, but (19) gives the most accurate conception of the manner in which Δ affects q_s.

The *total* for *primary and secondary* is

$$q_s = \frac{.612}{10^6} \left(\frac{k_{d_1}}{h_1\, b_1''^2} + \frac{k_{d_2}}{h_2\, b_2''^2}\right) \frac{\Delta^2\, n}{v\, B} \tag{20}$$

Tooth-Tip or "Zigzag" Leakage.

The calculation of the permeance of the leakage path over the top of a slot by way of an overlapping tooth on the other side of the gap is, in the general case, a complicated process; but it will be sufficiently accurate for all practical purposes to consider the case where the tooth-pitch is the same in the primary and secondary, and then to apply it to any other case by substituting the average tooth-pitch of that case.

Referring to Fig. 5, t_1 is the primary tooth tip *plus the fringing*, t_2 is the same for the secondary, λ is the common tooth pitch, and x is the displacement of the center of the secondary tooth from the center of the primary slot opening.

Consider the series permeance from t_1 to t_2 and back to the next primary tooth-tip, neglecting the iron* part of the path. This permeance takes account of the *total tooth-tip leakage primary and secondary.*

Consider one inch of core length parallel to shaft.

The left hand overlap is

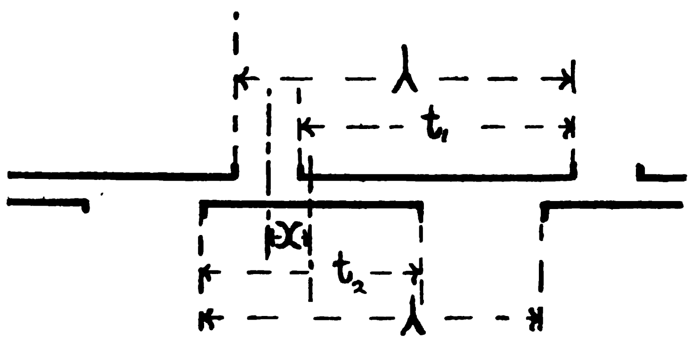


FIG. 5

$$\frac{t_2}{2} - \frac{\lambda - t_1}{2} - x = \lambda\left(\frac{t_1 + t_2}{2\lambda} - \frac{1}{2}\right) - x = m - x$$

The right hand overlap is $m + x$

and the series reluctance† is

$$.313\left(\frac{\delta}{m - x} + \frac{\delta}{m + x}\right) = .313\left(\frac{2\,m\,\delta}{m^2 - x^2}\right)$$

The *series permeance* † is then

---

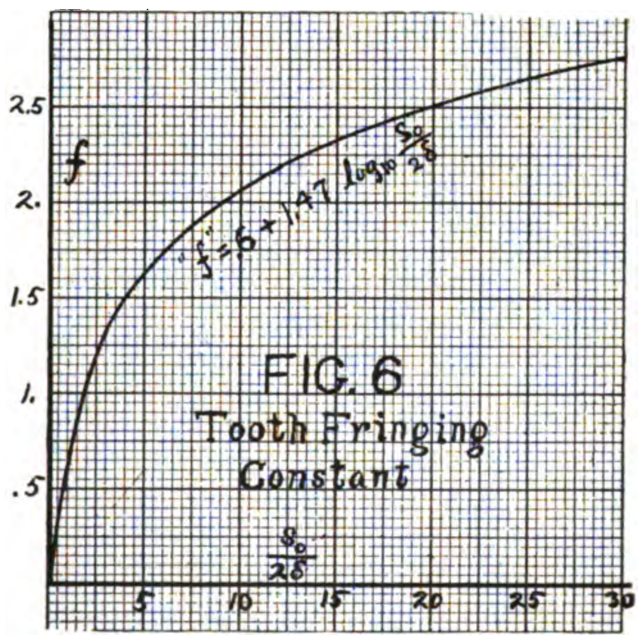
* The saturation of the tooth corners may introduce quite an appreciable reluctance and cause the above method of calculation to give too large a value of the tooth-tip leakage.

† These are expressed in units corresponding to the ampere-turn.

$$3.2\,\frac{m^2 - x^2}{2\,m\,\delta}$$

and its average value is

$$\phi_t = \frac{3.2}{2\,m\,\delta}\;\frac{2}{\lambda}\int_{x=0}^{x=m}(m^2 - x^2)\,d\,x = 2.13\,\frac{m^2}{\delta\,\lambda}$$



But

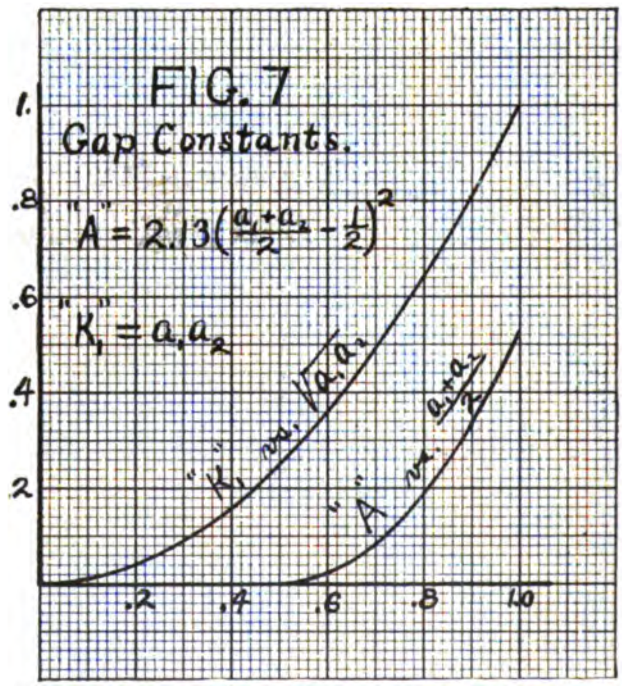
$$m = \lambda\left(\frac{t_1 + t_2}{2\,\lambda} - \frac{1}{2}\right) = \lambda\left(\frac{a_1 + a_2}{2} - \frac{1}{2}\right)$$

and therefore

$$\phi_t = 2.13\,\frac{\lambda}{\delta}\left(\frac{a_1 + a_2}{2} - \frac{1}{2}\right)^2 = \frac{\lambda}{\delta}\,A \qquad (21)$$

This is the flux linkage per ampere-inch of slot.

In Fig. 7, A is plotted against $\frac{a_1 + a_2}{2}$, the average value of the per cent. exposed iron, including fringing. On the same sheet, K_1 is plotted against $\sqrt{a_1 a_2}$ which is nearly equal to $\frac{a_1 + a_2}{2}$, when a_1 and a_2 differ but little. These curves will prove very useful in analyzing the effect of a change in slot opening. From the standpoint of magnetizing current, K_1 (and therefore a_1 and a_2) should be as large as possible; while from the standpoint of tooth-tip leakage, A (and therefore a_1 and a_2)



should be as small as possible. There is for each case a best value of a_1 and a_2.

When the tooth-pitches of primary and secondary are not the same, their average value may be substituted for λ in (21).

The tooth-tip inductance per inch of slot (conductors in series) is then

$$L_t'' = \phi_t N_s^2 10^{-8}$$

the corresponding reactance

$$x_t'' = 2 \pi n \phi_t N_s^2 10^{-8}$$

and the reactance e.m.f. due to the torque current

$$I_T\, x_t'' = \frac{\Delta N_s^2}{N'}\,\frac{2\,\pi\,n}{10^8}\,\frac{\lambda}{\delta}\,A$$

But

$$\frac{N'}{N_s} = \frac{1}{\lambda}$$

$$\therefore\ I_T\, x_t'' = \frac{2\,\pi}{10^8}\,\frac{\Delta\, N_s\, n\, \lambda^2}{\delta}\,A$$

The e.m.f. per inch of slot induced by the mutual flux is

$$E'' = 8.05\, v\, B\, N_s\, 10^{-8}$$

and

$$q_t = \frac{I_T\, x_t''}{E''} = .78\ \frac{\lambda^2\,\Delta\, n}{\delta\, v\, B}\,A \tag{22}$$

But $\lambda = \dfrac{6\,v}{N_{sp}\,n}$ where N_{sp} = slots per pole

$$\therefore\ q_t = 28.1\ \frac{\Delta\, v}{n\, B}\ \frac{A}{\delta\, N_{sp}^2} \tag{23}$$

or, in metric units

$$q_t = 92.2\,\frac{\Delta\, v}{n\, B}\ \frac{A}{\delta\ N_{sp}^2} \tag{23a}$$

As noted on page 342, this takes account of the total tooth-tip leakage, primary, and secondary.

Coil-End Leakage.

Designate by ϕ_f the equivalent flux per ampere-inch of free length or coil-end, where "*coil-end*" is understood to include all the conductors of a phase-belt-bundle, or the conductors per pole per phase.

For a given shape of coil-end, ϕ_f depends largely upon the ratio of the pole-pitch to the diagonal of the section of a coil-end, and is approximately proportional to the logarithm of that ratio. But for a given type of winding and a given number of phases, this ratio is fairly constant, and its logarithm still more nearly a constant.

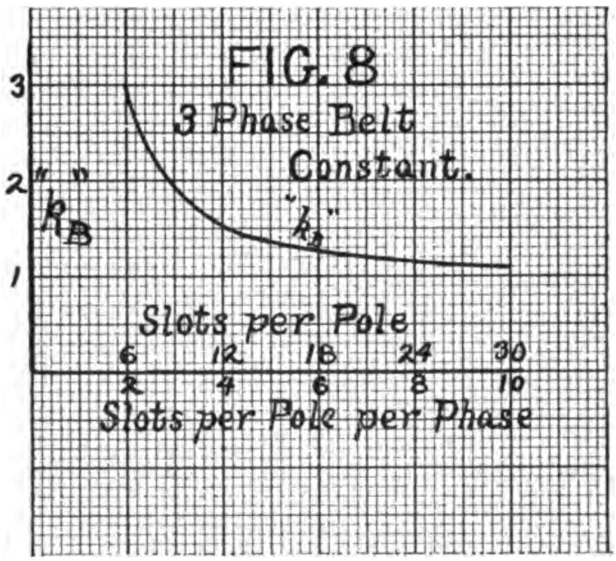
A method of calculating ϕ_f was outlined in the Congress paper referred to on page 327. In this method ϕ_f cannot be expressed in a simple manner without the introduction of empirical constants, and as ϕ_f itself varies so little, it may for our present purpose be taken as a constant.

Let λ_p = pole-pitch in inches.

then $\lambda_p = 6\,v \div n$

Let $k_s = \lambda_p \div l$

and k_f = ratio of free length (per conductor) to pole-pitch.



Then $k_s\,k_f$ = ratio of free length to active length,

and $\dfrac{N'\,\lambda_p}{3}$ = conductors per phase belt.

∴ Inductance per free inch of belt (conductors in series) is

$$\phi_f\,\frac{N'^2\,\lambda_p^2}{9}\,10^{-8}$$

The corresponding reactance is

$$2\,\pi\,n\,\phi_f\,\frac{N'^2\,\lambda_p^2}{9}\,10^{-8}$$

But for every inch of active belt there are $k_s\, k_f$ inches of idle or free belt, therefore the reactance of the free belt per inch of active belt is

$$x_f'' = 2\,\pi\,n\,\phi_f\,k_f\,\frac{\lambda_p}{l}\;\frac{N'^2\,\lambda_p^2}{9}\;10^{-8}$$

but $I_T = \frac{\Delta}{N'}$, = torque amperes per conductor. Therefore the corresponding reactance e.m.f. for free length, per inch of active belt, is

$$I_T\,x_f'' = 2\,\pi\,n\,\phi_f\,k_f\,\frac{\lambda_p^3}{l}\;\frac{\Delta\,N'}{9}\;10^{-8}$$

The e.m.f. induced in one inch of active belt by the mutual flux is

$$E'' = 8.05\,\frac{v\,B}{10^8}\,\frac{N'\,\lambda_p}{3}$$

and

$$q_{f_1} = \frac{I_T\,x_f''}{E''} = 0.26\,\phi_f\,k_f\,\frac{\lambda_p^2}{l}\,\frac{\Delta\,n}{v\,B} \tag{24}$$

But $\lambda_p = 6\,v \div n$, $l = \dfrac{K \times 10^{10}}{2.4\,B\,v\,\Delta\,d}$ (See equation 5)

and $d = \dfrac{720\,v}{\pi \times r}$ where r = synchronous rev. per min.

$$\therefore\; q_{f_1} = \frac{51.7}{10^8}\,k_f\,\phi_f\,\frac{\Delta^2\,v^3}{K\,r\,n} \tag{25}$$

or

$$q_{f_1} = \frac{0.86}{10^8}\,k_f\,\phi_f\,\frac{\Delta^2\,v^3\,p}{K\,n^2} \tag{26}$$

where p is the number of pairs of poles.

In metric units (25) is

$$q_f = \frac{5}{10^8}\,k_f\,\phi_f\,\frac{\Delta^2\,v^3}{K\,r\,n} \tag{25a}$$

where ϕ_f = flux per ampere-centimeter, r = revolutions per second and v = peripheral velocity in meters per second.

For primary and secondary (25) becomes

$$q_f = \frac{51.7}{10^8} (k_{f_1} \phi_{f_1} + k_{f_1} \phi_{f_2}) \frac{\Delta^2 v^3}{K r n} \tag{27}$$

Belt Leakage.

This has been completely expressed in the Congress paper already referred to; for a three-phase motor, it is, in English units

$$q_B = \frac{I_T x_B}{E_1'} = 0.03\, k_B K_1 K_2 \frac{\Delta v}{\delta n B} \tag{28}$$

or, in metric units

$$q_B = 0.0985\, k_B K_1 K_2 \frac{\Delta v}{\delta n B} \tag{28a}$$

where k_B is a constant depending upon the number of slots per pole (see Fig. 8).

It should be remembered that these equations include the total belt leakage, primary and secondary.

It will be noted that equation 28 is of the same form (as regards the major design constants) as equation 23; but this was to be expected, since these two leakage elements are of the same nature, the one (tooth-tip leakage) taking account of the leakage over the individual slots, which does not link with any of the opposing current; while the other (belt leakage) takes account of a similar flux which links with equal portions of both primary and secondary currents.

Summary of Results.

Assembling equations 12, 20, 23, 27, and 28, and abbreviating the coefficients,

$$q_m = \frac{0.116}{K_1 K_2} \frac{B \delta n}{\Delta v} = a \frac{B \delta n}{\Delta v} \tag{29}$$

$$q_s = \frac{0.612}{10^6} \left(\frac{k_{d_1}}{h_1 b_1^{n_2}} + \frac{k_{d_2}}{h_2 b_2^{n_2}} \right) \frac{\Delta^2 n}{v B} = b \frac{\Delta^2 n}{v B} \tag{30}$$

$$q_{tB} = q_t + q_B = \left(\frac{28.1\, A}{N_{sp}^2} + 0.03\, k_B K_1 K_2 \right) \frac{\Delta v}{B \delta n} = c \frac{\Delta v}{B \delta n} \tag{31}$$

$$q_f = \frac{0.517}{10^6}\left(k_{f_1}\phi_{f_1} + k_{f_2}\phi_{f_2}\right)\frac{\Delta^2 v^3}{K r n} = d\,\frac{\Delta^2 v^3}{K r n} \qquad 32)$$

or, the total reactance e.m.f. due to the torque current, is (in terms of E_1')

$$q_x = q_s + q_t + q_B + q_f = \Delta\left(b\frac{\Delta\, n}{v\, B} + c\frac{v}{B\,\delta\, n} + d\frac{\Delta\, v^3}{K r n}\right) \qquad (33)$$

A very interesting fact here brought out is, that of the four leakage elements, three (q_t, q_B and q_f) are inversely proportional to the frequency. A careful study of these equations will yield numerous other interesting relations, some of which will be developed in connection with the analysis which follows.

Referring to equation 4, it will be remembered that q_{x_1} and q_{x_2} applied to the total primary and secondary currents, whereas q_x applies to only the torque current. On this account, the substitution of q_x for $q_{x_1}+q_{x_2}$ in equation 4 will give a larger value of power-factor and will a little more than neutralize the error due to the approximation of equation 4. We then have approximately

$$\text{power-factor} = \frac{1}{\sqrt{1 + (q_x + q_m)^2}} \qquad (34)$$

which will do very well for purposes of comparison. Moreover, (34) applies not only to full load, but to any load, Δ and K being altered accordingly. The only point in the development of any of the above equations, at which full load conditions were assumed, was in connection with q_s, when the constants h and m were introduced, and although it would be possible to adjust these to suit the load, it will be more satisfactory to obtain q_s from equation 17, whenever less than full load is considered. For the present consider full load only.

A rough inspection of (29) and (33) will show that in general they are affected reciprocally by the major constants and by δ, and that an increase in the one means a decrease in the other. There is evidently therefore a particular value for each constant or a set of values for them all which will make $q_m + q_x$ a minimum and the full load power-factor a maximum.

If a particular machine be considered, rather than the choice of constants for a machine as yet undesigned and of which the dimensions are considered as variables, equation (33) may be written—see equations (17) and (24)

$$q_x = .78\left(\frac{k_{s1}\,d_{s1}}{b_1''} + \frac{k_{s2}\,d_{s2}}{b_2''}\right)\frac{\Delta\,n}{v\,B} + \left(\frac{28.1\,A}{N_{sp}^2} + 0.03\,k_s\,K_1\,K_2\right)\frac{\Delta\,v}{B\,\delta\,n}$$

$$+\ 9.36\,(k_{f1}\,\phi_{f1} + k_{f2}\,\phi_{f2})\,\frac{\Delta\,v}{B\,n\,l} \qquad (33a)$$

where q_x is directly proportional to Δ, *i.e.*, to the load; but as q_m is inversely proportional to Δ, there is a particular value of Δ and of the load which makes q_m+q_x a minimum and the power-factor a maximum; moreover, this is obviously the value which makes $q_m = q_x$. If then in any given motor, q_m is greater than q_x at full load, the condition of equality will be reached at overload, where will be found the maximum power-factor; and if q_x is greater than q_m at full load, the maximum power-factor will occur at underload.

Thus when q_m and q_x are known for full load, it is immediately apparent whether the maximum power-factor occurs at underload, full load, or overload; moreover, the per cent. of full load at which the maximum power-factor occurs is easily shown to be

$$\sqrt{\frac{q_m}{q_x}}.$$

THE "LEAKAGE-FACTOR."

If the "leakage-factor" be desired, it may be obtained as follows:

Let $x = x_1+x_2$ = total leakage reactance;

$$q_x = \frac{I_T x}{E_1'} \quad \text{and} \quad x = q_x\,\frac{E_1'}{I_T} = q_x\,\frac{2.85\,E_1'^2}{K}$$

The exciting reactance is $x_0 = \dfrac{E_1'}{I_m}$ and $I_m = q_m\,I_T$. Therefore $x_0 = \dfrac{E_1'}{q_m\,I_T}$ and the "leakage-factor" is approximately

$$\sigma = \frac{x}{x_0} = q_x\,q_m \qquad (35)$$

For this purpose, q_x is most convenient in the form of equation (33a).

$$q_x = .78\left(\frac{k_{s1}\,d_{s1}}{b_1''} + \frac{k_{s2}\,d_{s2}}{b_2''}\right)\frac{\Delta\, n}{v\,B} + \left(\frac{28.1\,A}{N_{sp}^2} + 0.03\,k_B K_1 K_2\right)\frac{\Delta\, v}{\delta\, B\, n}$$

$$+\ 9.36\,(k_{f1}\,\phi_{f1} + k_{f2}\,\phi_{f2})\,\frac{\Delta\, v}{l\,B\,n}$$

Let

$$\frac{k_{s1}\,d_{s1}}{b_1''} + \frac{k_{s2}\,d_{s2}}{b_2''} = S$$

and

$$(k_{f1}\,\phi_{f1} + k_{f2}\,\phi_{f2}) = F$$

Then

$$\sigma = q_m\,q_x = \frac{0.0905\,S}{K_1 K_2}\,\delta\,\frac{n^2}{v^2} + \frac{3.26\,A}{K_1 K_2 N_{sp}^2} + 0.0035\,k_B$$

$$+\ 1.085\,\frac{F}{K_1 K_2}\,\frac{\delta}{l}$$

but

$$\frac{n^2}{v^2} = \frac{36}{\lambda_p^2}$$

and

$$\sigma = \frac{3.26}{K_1 K_2}\left(S\,\frac{\delta}{\lambda_p^2} + \frac{F}{3}\,\frac{\delta}{l} + \frac{A}{N_{sp}^2}\right) + 0.0035\,k_B \qquad (36)$$

In metric units this is

$$\sigma = \frac{3.26}{K_1 K_2}\left(S\,\frac{\delta}{\lambda_p^2} + \frac{F}{1.18}\,\frac{\delta}{l} + \frac{A}{N_{sp}^2}\right) + 0.0035\,k_B \qquad (36a)$$

where S and F are also in metric units.

S varies from 6 to 12 for nearly closed slots, and from 4 to 10 for open slots. F varies little from 3.

K_1, S and A are all smaller with open slots, K_1 decreasing more than S but less than A. There is thus for each case a best percentage of slot opening and corresponding values of K_1, S, and A; usually K_1 and A should be given their maximum values.

The only way of changing λ_p (for a given frequency) is by changing v, but other things being equal, l is inversely proportional to v^2 and therefore to λ_p^2. There is thus a fairly critical value of v (and therefore of λ_p), and σ will increase rapidly if v departs much from that value.

Equation (36) is a rational formula for σ, and takes into account all important elements of design and gives excellent results, although the writer prefers the treatment which involves q_m and q_x explicitly.

Examples.

As examples, there have been chosen the two motors in Hobart's "Electric Motors," of which complete data and test results are given.

All the constants entering into the equations employed, are here given and may be easily checked by referring to the data given in Hobart's book.

The two motors are: a 100-h.p., 500-volt, 500 rev. per min., 50-cycle, Westeras motor, and a 500-h.p., 5000-volt, 100 rev. per min., 25-cycle Alioth motor. They will be referred to as A and B respectively.

		A	B
Fringing constant	f_1	0.6	0.51
	f_2	0.6	0.34
Equivalent tooth-tip, %	a_1	0.922	0.942
	a_2	0.9	0.94
Equivalent % exposed iron, K_1		0.83	0.885
Tooth-tip constant, A		0.36	0.415
Equivalent length of armature = gross length of core minus ducts plus fringing (inches)		13.35	29.6
Radial depth of gap, δ		0.059″	0.0689
Iron constant, K_2		0.90	0.88
Maximum superficial gap density, B (computed from counter-e.m.f.)		18950	18800
Synchronous peripheral velocity, v, ft. per sec.		75.	51.3
Frequency, n		50.	25.
Peripheral torque-current density, Δ		480.	460.
Slot constant	k_{s1}	1.56	1.6
	k_{s2}	1.66	2.33
Depth of slot inches	d_{s1}	.985	2.24
	d_{s2}	.846	0.866
% breadth of slot	b_1''	.685	0.625
	b_2''	.62	0.53
Slots per pole	N_{sp1}	15.	15.
	N_{sp2}	18.	24.
	Average N_{sp}	16.5	19.5
Belt constant, k_B		1.3	1.2
Idle ÷ active wire, $(k_{f_1}+k_{f_2}) \div 2$		1.5	1.5
Maxwells per ampere inch of free length of phase-belt bundle, $\phi_{f_1} = \phi_{f_2}$		1.	1.

Kilowatts output, K	74.6	373.
rev. per min., r	500.	100.
q_m	0.240	0.204
q_m (observed from $I_0 \sin \theta_0$)	0.234	0.194
q_s	0.0593	0.0892
q_{t+B}	0.0430	0.0428
q_f	0.081	0.0477
$q_x = q_s + q_{t+B} + q_f$	0.183	0.18
$q = q_m + q_x$	0.423	0.384
Full load power factor $= \dfrac{1}{\sqrt{1+q^2}}$	0.922	0.933
Observed full load power-factor	0.92	0.935
Maximum power-factor as calculated by Hobart	0.895	0.922
Approximate leakage-factor, $\sigma = q_m q_x$	0.044	0.0367
Corresponding maximum power-factor $= \dfrac{1}{1+2\sigma}$	0.9185	0.932
Leakage-factor as calculated by Hobart	0.058	0.042

Conditions for Maximum Power-Factor at Full Load.

It will be interesting now to investigate the values of the design constants which make the power-factor a maximum for any given type of machine.

The total quadrature component is approximately

$$q = q_m + q_x = a\frac{B\,\delta\,n}{\Delta\,v} + b\frac{\Delta^2 n}{v\,B} + c\frac{\Delta\,v}{B\,\delta\,n} + d\frac{\Delta^2 v^3}{K\,r\,n} \quad (37)$$

and

$$\text{power-factor} = \frac{1}{\sqrt{1+q^2}} \quad (38)$$

It is thus necessary to study the conditions which make q a minimum.

The quantities entering into equation (37) may be divided into several classes: K, n, and r are ordinarily to be classed as *specifications*; B, v, and Δ, will be termed the *major design constants*, since they together with the specifications completely determine the general proportions of the machine; the remainder may be called *minor design constants*, (since they have to do with the details of design), although they are none the less important.

The problem is then to so choose these various constants that q will have the lowest possible value consistent with a reasonable first cost, heating, efficiency, regulation, and mechanical and electrical reliability.

These latter considerations place certain limitations upon the constants (major and minor), which limitations will be considered at each step, as far as possible in a broad treatment of this kind.

Unless otherwise specified the machines considered will be of the wound rotor type.

The Best Value of δ.

$$\frac{dq}{d\delta} = 0 = a\frac{B\,n}{\Delta\,v} - c\frac{\Delta\,v}{B\,n}\frac{1}{\delta^2}$$

$$\delta_{q\,min.} = \sqrt{\frac{c}{a}}\,\frac{\Delta\,v}{n\,B} \tag{39}$$

where

$$\frac{c}{a} = \frac{K_1\,K_2}{0.116}\left(\frac{28.1\,A}{N_{sp}^2} + 0.03\,k_s\,K_1\,K_2\right)$$

K_2 varies only moderately in different machines and may be taken = 0.88; assume slots closed and K_1 = 1.0; then A = 0.52 (see Fig. 7); take n = 30 and v = 60; then λ_p = 12 in; N_{sp} (average of primary and secondary) may be 15 and k_s = 1.35; take Δ = 400 and B = 20 000.

Then $\frac{c}{a}$ = 0.763 and δ = 0.035 in.

This is not at all an impracticable air-gap from the mechanical standpoint, even for a machine of moderate size, and is considerably larger than mechanically necessary for small machines.

With open slots, K_1 and A would both be smaller and δ would probably be below the mechanical limit; but as the minimum is a flat one, a moderate increase in δ will not increase the total q by any considerable amount.

With higher frequencies the best value of δ is usually below the mechanical limit, but with very low frequencies, such as 15 cycles per second, it is easily within that limit in many cases.

Substituting (39) in (37) gives as the minimum of q

$$q_{min.\,s} = 2\sqrt{a\,c} + b\frac{\Delta^2\,n}{v\,B} + d\frac{\Delta^2\,v^3}{K\,r\,n} \tag{40}$$

A further reduction in q may obviously be brought about by decreasing Δ or by increasing B; but either of these changes involves a reduction of δ (equation 39) which may carry it below the mechanical limit.

As v enters in numerator and denominator in (40), there is a particular value of v which makes (40) a minimum. It is

$$v_{q\,min.} = \sqrt[4]{\frac{b}{3d} \cdot \frac{n^2 r K}{B}} \tag{41}$$

Thus the best value of v varies slowly for moderate changes in the other constants.

This value of v will usually be found too low for a reasonable value of the output coefficient k_0, and so low that when substituted in (39) the resulting value of δ will be below the mechanical limit; but under these conditions the last term in (40) is usually so small that a considerable increase in v does not seriously increase the total q, although the last term in (40) may be doubled or trebled.

The Best Value of B. Assuming now that the conditions are such as to place the choice of air-gap on a mechanical basis, it will be interesting to investigate the effect of changes in the major constants.

The value of B which makes q a minimum is obtained in the ordinary manner by placing the first derivative of (37) with respect to B equal to 0. It is

$$\frac{d\,q}{d\,B} = 0 = a\,\frac{\delta\, n}{\Delta\, v} - \frac{1}{B^2}\left(b\,\frac{\Delta^2 n}{v} + c\,\frac{\Delta\, v}{\delta\, n}\right)$$

and

$$B_{q\,min.} = \Delta\sqrt{\frac{b}{a}\cdot\frac{\Delta}{\delta} + \frac{c}{a}\cdot\frac{v^2}{\delta^2 n^2}} \tag{42}$$

Substituting this in (37) gives as the minimum value of q

$$q_{min\,B} = 2\sqrt{a\left(c + b\,\frac{\delta\,\Delta\, n^2}{v^2}\right)} + d\,\frac{\Delta^2 v^3}{K\,r\,n} \tag{43}$$

As Δ enters only in the numerator, it is desirable from the standpoint of power-factor to reduce it; but this means a more than proportional reduction in $B_{min.}$ (see equation 42) and therefore a reduction of the output coefficient k_0 more than in proportion to the square of Δ. Δ will therefore have a fairly definite lower limit depending upon the relative importance of power-factor and first cost.

On the other hand, the larger Δ the larger $B_{q\,min.}$ and the larger k_0. When the power-factor is of relatively small importance, the upper limit of Δ is determined by the heating. This, in fact, is the average condition, since the gain in power-factor made by a reduction of Δ much below the heating limit, is usually small in comparison with the sacrifice in the output coefficient.

The Best Value of v.

$$\frac{d\,q_{min.\,B}}{d\,v} = 0 = \frac{-2\,a\,\dfrac{b\,\delta\,\Delta\,n^2}{v^3}}{\sqrt{a\left(c + b\,\dfrac{\delta\,\Delta\,n^2}{v^2}\right)}} + 3\,d\,\frac{\Delta^2\,v^2}{K\,r\,n}$$

and

$$v_{q\,min.\,B} = \sqrt[4]{\frac{2\,a^{\frac{1}{2}}\,b\,\delta\,r\,K\,n^3}{3\,d\,\Delta\sqrt{c\,v^2 + b\,\delta\,n^2\,\Delta}}} \tag{44}$$

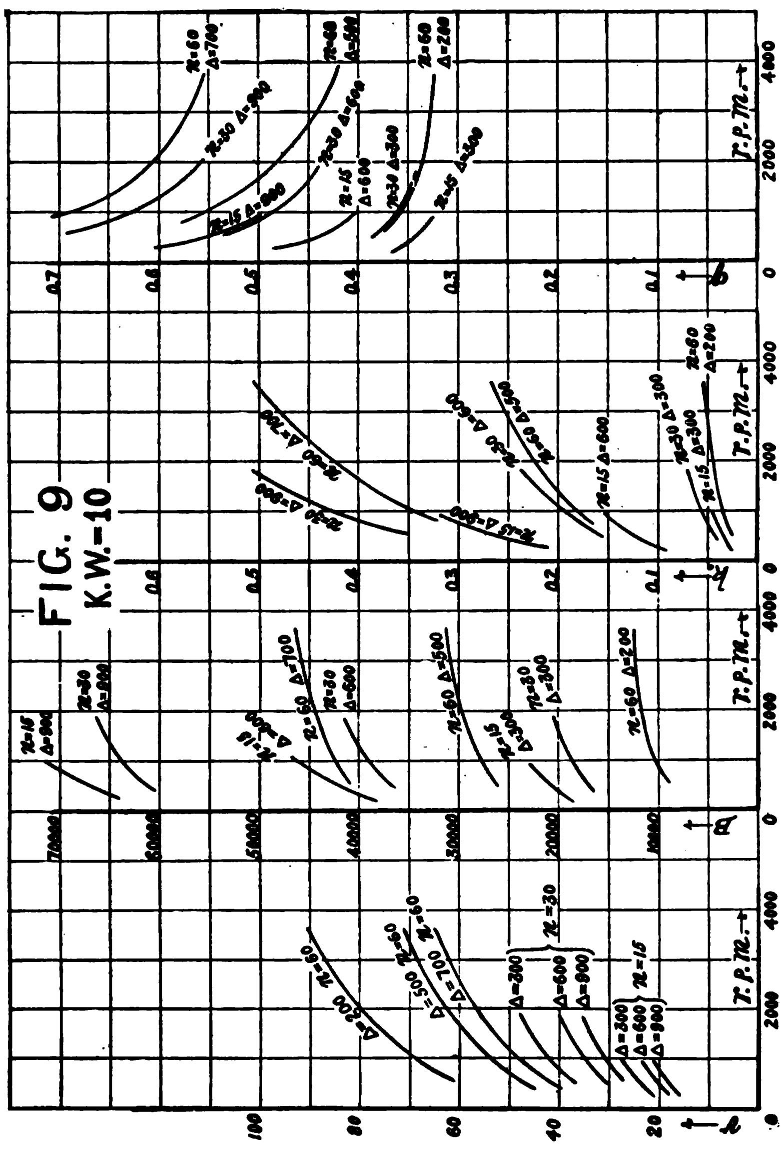
This is not a complete solution but is easily applied to numerical problems, since a considerable error in the value of v assumed for the denominator makes a comparatively small error in the resulting approximate solution.

It is clear that $v_{q\,min.\,B}$ increases with r, K and n, and decreases as Δ increases.

Applications.

In Figs. 9, 10, 11, and 12, are shown the results of applying equations 42, 43, 44, and 5 to three machines of 10,-100,- and 1000-kw. output respectively, it being assumed that they all have nearly closed slots, and four slots per pole per phase. This last would not be the case in the larger machines with higher v. The air-gap is taken from the following formula: $\delta = 0.012\ \sqrt[3]{K.W.}$ This gives rather shorter gaps for large machines than is common practice, although within mechanical limits. The other constants would correspond to a moderately good high voltage motor, and might be considerably improved for low voltages, especially on the larger machines.

Some of the peripheral velocities on the large machines are considerably beyond modern practice, but although the v minimum is sharp for large values of Δ, with moderate values of Δ, a moderate change in v may be made without seriously increasing q. It is obvious that it is the last term in equation 37 (which represents the coil end leakage) that sets the upper



R.P.M.
0
2000
4000
100
80
60
40
20
70000
60000
50000
40000
30000
20000
10000
0.7
0.6
0.5
0.4
0.3
0.2
0.1

FIG. 9
K.W.-10

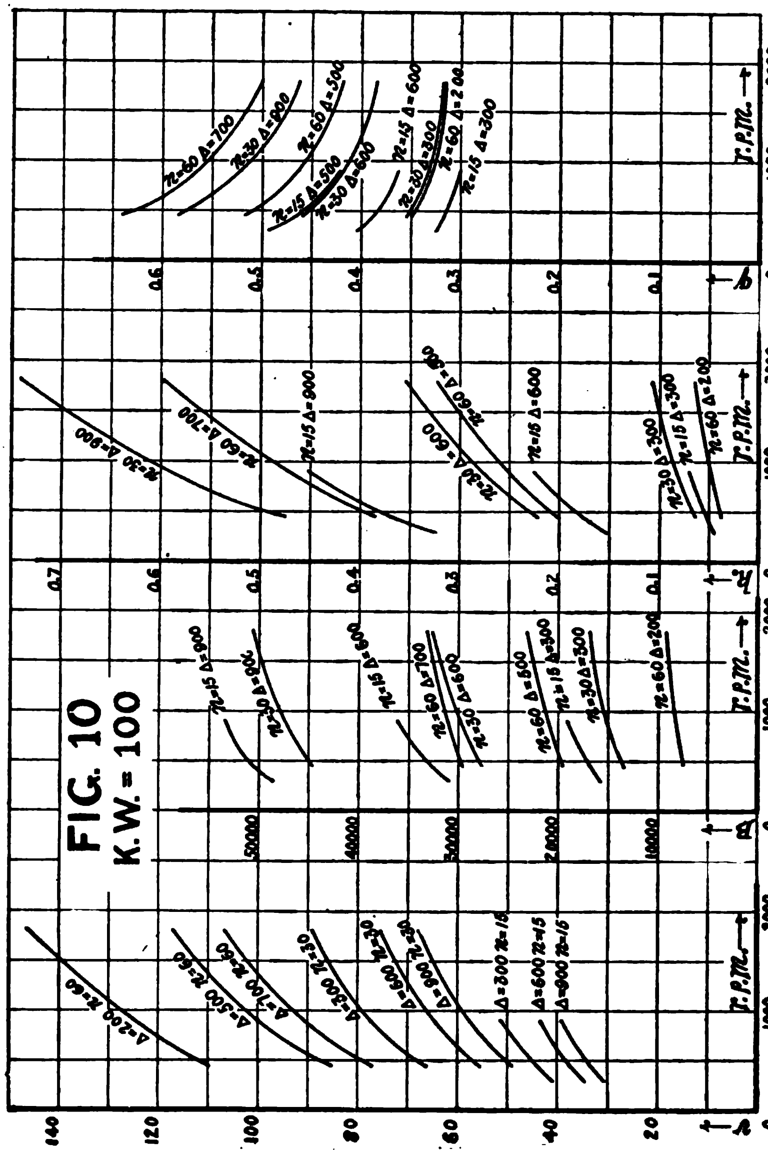


FIG. 10
K.W. = 100

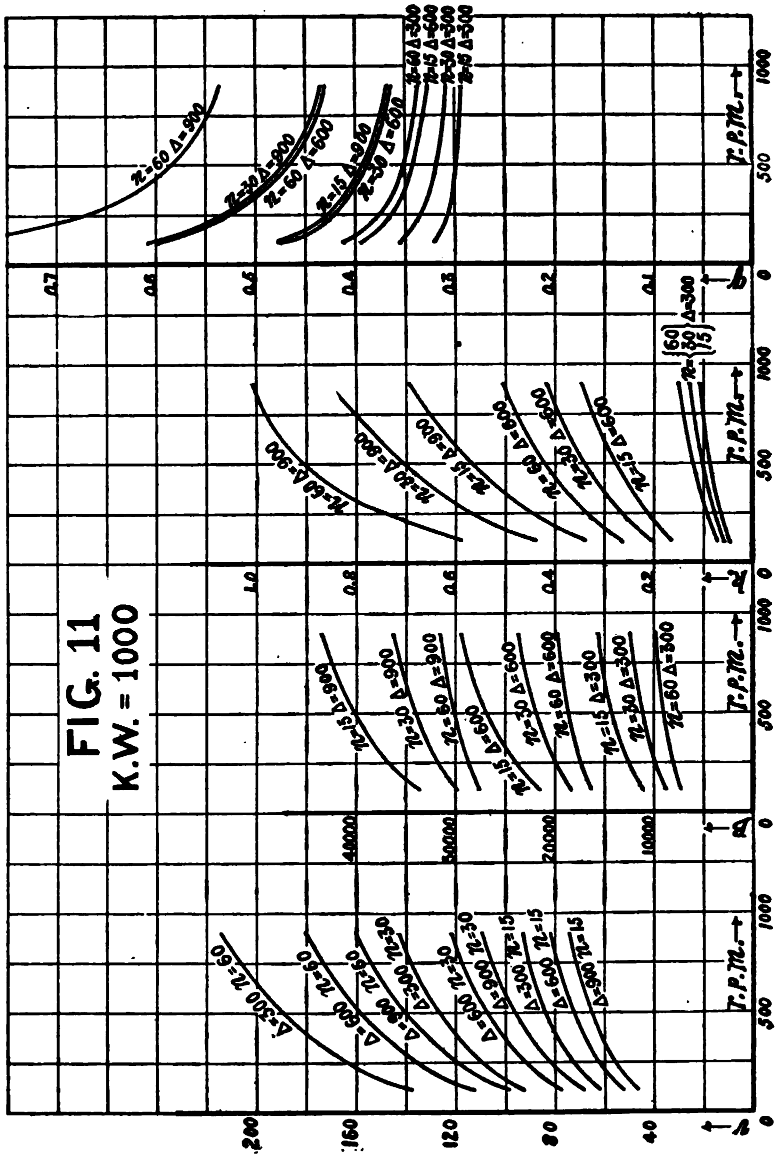


FIG. 11
K.W. = 1000

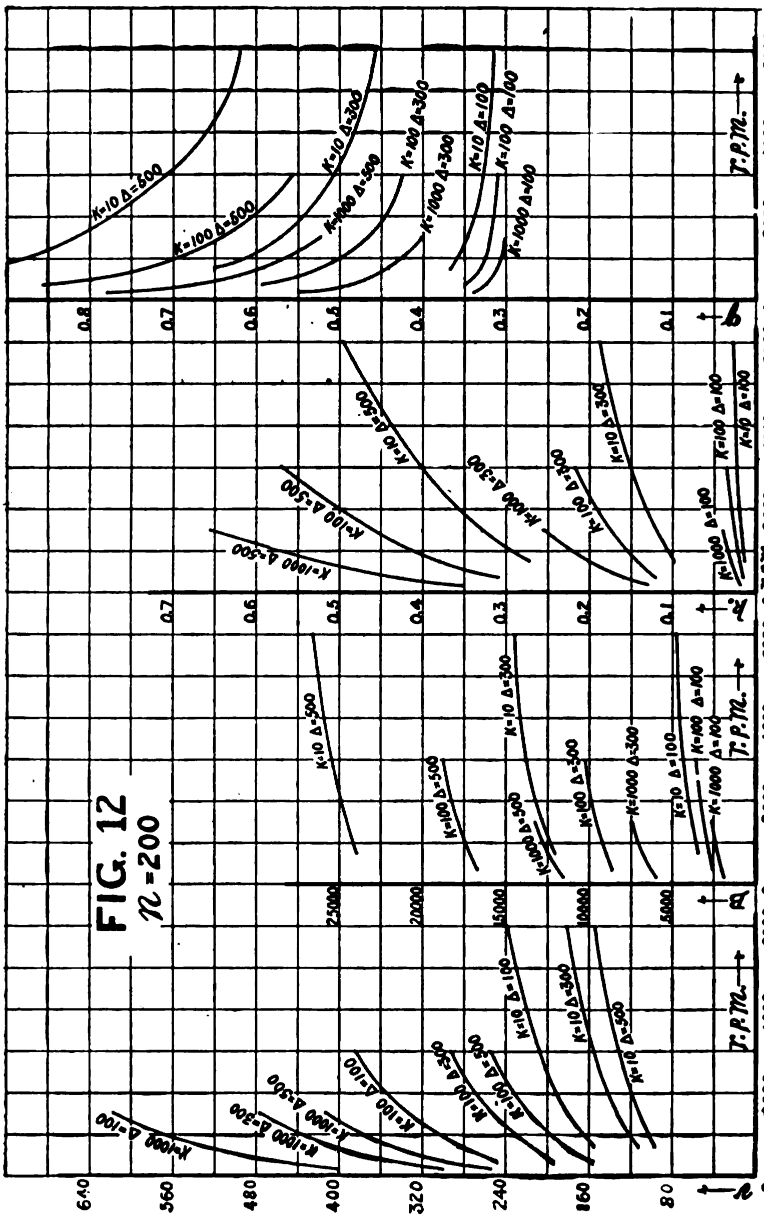


FIG. 12
n=200

limit of v. The B minimum is a relatively flat one and will allow a moderate variation in B.

The k_0 curves show clearly the limitations due to the first cost, since the latter is roughly inversely proportional to k_0, and the q curves the power-factor limitations.

Taken as a whole, the curves bring out clearly several important points: the advantages of large rev. per min.; the comparatively narrow range of Δ, (for any given n and rev. per min.), within which the power-factor and first cost are both acceptable; the lower peripheral velocity which accompanies low frequency checks the otherwise increase in pole-pitch, which thus increases only slowly as the frequency decreases; and the fact that the relatively large value of Δ required in low frequency motors on the score of first cost partly offsets its natural advantage in the line of power-factor. A study of the curves of Fig. 12 will be interesting in this connection, as they show the possibilities in the design of high-frequency motors.

The curves are not to be regarded as exact, since they correspond to certain assumed constants which may be considerably stretched in any particular design; but it is believed that this method of analysis is sufficiently inclusive of the important elements affecting leakage, to make the results useful in showing some of the limitations of induction motor design, and it is hoped that it may also serve as a step in making the design of this class of machines a little less empirical.

Effect of Open Slots. The effect of open slots is to decrease K_1 and A, and therefore to increase a and decrease c (equation 37) and b. This will bring about an increase in v (equation 44) and a decrease in B (equation 42).

Example. Take as an example a 10-kw., 60-cycle, 1200-rev. per min. motor. Let $\Delta = 500$. $\delta = 0.0258$.

Referring to Fig. 7, it will be apparent that reducing $\frac{a_1 + a_2}{2}$ below a certain point (0.7) does not save much on the score of tooth-tip leakage, "A," while it does decrease K_1 and increase the exciting current very considerably; neither would such a change reduce the slot leakage materially. But with $a_1 = 0.7$, straight sided slots would be very wasteful of winding space and give a large slot-leakage. Therefore if the primary is to have straight slots for form wound coils with $a_1 = 0.6$, the secondary, of lower pressure, could be bar-wound with more nearly closed slots say $a_2 = 0.9$; then $K_1 = 0.54$ and $A = 0.13$. The same end could be obtained by overhanging the slots only slightly on both primary and secondary, although this might involve a loose formed coil slipped through the opening, one or more wires at a time. This has the advantage (over straight slots) of a considerably larger possible b'' and less *slot* leakage, despite the overhanging tooth.

With the above constants and $K_2 = 0.88$, we have (see equation 37)

$a = 0.244$

$b = 0.01$

$c = 0.0253 + 0.0213 = 0.0466$

$d = 1.53 \times 10^{-6}$

From (44), (42), etc., the following values have been calculated. These are tabulated with the corresponding values for a similar machine with nearly closed slots, from Fig. 9. The latter will be labeled " *A*," and the former " *B*."

	Δ	v	B	k_0	q_m	q_x	q	p.f.	
"*A*"	500	56	28300	0.19	0.218	0.315	0.533	88.3	Slots nearly closed.
"*B*"	500	58.2	16300	0.114	0.211	0.317	0.528	88.5	Open slots.
"*C*"	500	70	22600	0.19	0.244	0.421	0.665	83.3	

Thus it is possible to get as good a power-factor with open as with closed slots, but at the expense of weight, size, and first cost; or, in order to raise k_0 for the open slot machine to equality with that of the nearly-closed-slot machine, it is necessary to sacrifice the power-factor, the quadrature component q being 26% larger in the latter case (Row " C ").

Squirrel-Cage Motor. The effect of a squirrel-cage secondary is to reduce the secondary slot leakage slightly; to increase the secondary slots per pole and therefore to reduce c; and to reduce k_{f_2}, the equivalent idle length being relatively small.

This paper, together with that mentioned on page 327, are the results of a very large amount of experimental work and calculation, and although the results are in some respects incomplete, the method has proved so satisfactory in dealing with widely differing types of induction motors, it was thought that it might prove useful to others interested in design problems. It is with this hope that this paper is presented.

The writer wishes here to express his appreciation of the kindness of Dr. A. E. Kennelly and Mr. G. A. Anderegg in reviewing this paper.

DISCUSSION ON "A STUDY IN THE DESIGN OF INDUCTION MOTORS."

W. L. WATERS: The main point in Professor Adams' paper, that strikes the practical designer is that the calculations are made with such exactness. Practical design is at best only an approximation, as the quality of material and the actual dimensions obtained in the shop vary in different machines. An important example of this is the dimensions of the air-gap in an induction motor. With the small air-gaps required in such machines, a variation of 25% among a number of machines sent through the shop at the same time, is not by any means uncommon.

I hardly think that Professor Adams emphasized sufficiently the difference between the open and closed slot in an induction motor. The difference in the magnetizing current and leakage factor is from 20% to 50%; this is the reason why manufacturers have to a great extent done away with the open slot and have sacrificed the advantage of using form-wound coils.

I think Professor Adams' method of calculating the leakage of an induction motor is much too complicated for practical work. An experienced designer can make a conservative guess that will probably be more accurate than any possible calculation. But in any case I think that the question of power-factor will not be so important in the future as it has been in the past. The difference between a power-factor of 93% and one of 88% makes all the difference between an expensive and a cheap design of motor; and at the same time it has practically no other effect on the generator and system than that of reducing their capacity about 5%; because, as regards the inductive effect on the system, there is practically no difference between 100 ampere load at 93% power-factor and 100 ampere load at 88% power-factor. I think, in the future the competition in induction motor manufacture being much more severe, the manufacturers will have to take into consideration every feature that tends to cheapen the design of such machines.

C. P. STEINMETZ: I do not agree with Mr. Waters that this method of calculation of the leakage is too complicated for practice, because in practice such a method is used, except that every operation is not gone through separately, but inserted in a formula, which is still further abbreviated when fixed types of apparatus are under consideration. But the calculation is actually done by the principles stated here. I would like to say further that it *is* material whether the power-factor is 93 or 88 per cent. It is true that it is only a difference of 5 per cent.—and if the motor is always run at full load, 5 per cent., more or less, would perhaps not matter—but the motor of 93 per cent. power-factor at full load will have a power-factor of 85 per cent. at an average load that varies between full load and one-third load; while a motor at 87 or 88 per cent. power-factor at full load goes down into 50 per cent. power-factor at the average running load. It is not the full load conditions, but the average running conditions, that count. This is fully recognized in the alternating-current transformer, where at full load the core loss does not matter so much, but transformers are not run at full load, but at average load, and then any increase of core loss, which is a constant loss, is very serious in lowering the all day efficiency. So on average load the wattless current counts a good deal more than it appears from the full-load value.

COMFORT A. ADAMS: Mr. Stanley's question can best be answered by referring to the examples given on pages 674-675 The several leakage elements when expressed in per cent. of the total leakage, are:

	Slot Leakage	Tooth-Tip Leakage	Belt Leakage	Coil-End Leakage
Motor	$100 \frac{q_s}{q_x}$	$100 \frac{q_t}{q_x}$	$100 \frac{q_B}{q_x}$	$100 \frac{q_f}{q_x}$
A	32.4	13.2	10.2	44.2
B	49.6	12.4	11.4	26.6

The large *coil-end leakage* for *A* is due to its high peripheral velocity, and the large *slot leakage* for "*B*" is due to its very deep slots.

The *belt leakage* for *A* is unusually high for a 50-cycle motor; this is due to the high peripheral velocity.

The tooth-tip leakage is low for both machines, because of the large number of slots per pole, due to the large pole-pitch; this in turn is the result of the high peripheral velocity in *A* and of the low frequency in "*B*." In this connection it should be noted again that the equations upon which are based the curves of Figs. 9 to 12, do not take account of this relation between v, n, and N_{st}, but assume N_{sp} constant.

Referring now to Mr. Waters' remarks, consider first the air-gap and the calculation of the magnetizing current. Assuming that variations of 25 per cent. do occur in the air-gaps of a set of similar machine built at the same time from the same design, the speaker cannot appreciate the point of view from which it appears that a saving of 10minutes in the design of a machine is sufficient to warrant the addition of a 15 per cent. calculation error to the above possible 25 per cent. constructional error. The cry of " too complicated for practical work" is only rational when the gain in accuracy is negligible, since the practical designing engineer is the one above all others who cannot afford to be inaccurate.

As Mr. Steinmetz has pointed out, the above equations will be much simplified when applied to a particular type of machine, and if the work is properly systematized, the extra labor of calculation is negligible.

Referring to the relative merits of open and closed slots, Mr Waters will find, by examining more carefully the example given on the last page of the paper, that the machine " C " which is figured on the basis of the same first cost as " A," has a leakage factor $(q_m q_x)$, just 50% greater than that of " A". What was said in this connection, is that a machine with wholly open slots on the primary, or with half open slots on both primary and secondary, can be designed with the same power-factor but at greater first cost; such a one is machine " B " of the example referred to.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

LIMITATIONS IN DIRECT-CURRENT MACHINE DESIGN.

BY SEBASTIAAN SENSTIUS.

The purpose of this paper is to present a system of design, not based upon the cut-and-try method associated with the use of an output constant, but directly upon general experimental data and the commercial guarantees of the machine; and to deal with the limitations imposed upon the development of large machines by the quality of brushes obtainable.

The author hopes that the paper may contain information of value to the consulting engineer, particularly in the way of preventing the introduction of impracticable requirements into specifications relating to direct-current dynamos.

The problems involved have not been attacked from the point of view of the physicist, but from that of the engineer. They are considered under the following heads:

Reactance Pressure: 1. Reactance pressure of the single-commutator machine; 2. Reactance pressure of the double-commutator machine.

Commutator and Brush Sparking, Spitting, Glowing, and Picking up Copper: 1. Probable causes; 2. Experimental data.

Designing an Armature.

Conclusions: 1. Discussion of the formulas; 2. Limiting sizes of direct-curent machines; 3. Note on direct-current turbo-generators.

REACTANCE PRESSURE.

§ 1. *Reactance Pressure of the Single-Commutator Machine*: Fig. 1 represents the position of the armature coils undergoing commutation, with reference to the field-magnet poles. Assuming an armature-coil pitch of 180 electrical degrees, it is seen that the lines of force set up in the embedded portion by the ampere-turns of one coil are interlinked with the embedded part of the other coil. Thus if a is the number of lines per unit length set up in and around a slot by one ampere-turn, then $2a$ will equal the lines per unit length per ampere-turn interlinked by mutual induction with one embedded side of the coil under consideration. Let

a = lines per ampere-turn per embedded unit length,

b = lines per ampere-turn per free unit length.

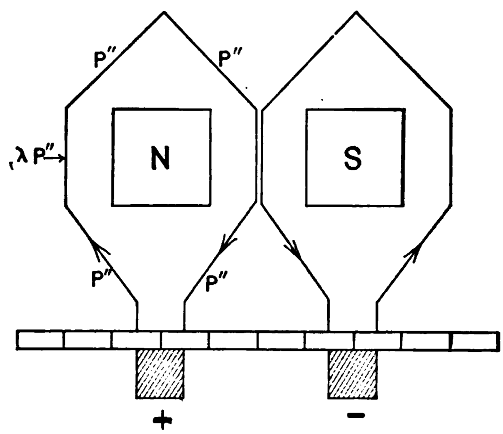


Fig. 1.

p = pairs of poles,

D = diameter of armature.

$\frac{D}{p} = P,$

$l = \lambda P$ = armature length, assumed to be equal to the axial length of the pole-shoe,

$4P$ = approximate length (per turn) of the free ends,

t = number of turns per armature coil;

then, the total lines per ampere-turn interlinked with the coil will be

$$2\lambda P \times 2a + 4P \times b = 4P(\lambda a + b);$$

hence, the coefficient of self-induction per coil is,

$$4P(\lambda a + b)\, t^2 .\, 10^{-8} \text{ henries.}$$

In a $2\,p$-polar armature with $2\,p_1$ circuits the number of coils short circuited in series under one brush is equal to $\frac{p}{p_1}$ coils, assuming that the width of the brush equals the width of one commutator segment.

The total coefficient of self-induction L of the coil short circuited by one brush thus becomes,

$$L = 4\frac{p}{p_1} \times (\lambda\, a + b) \times P\, t^2 \times 10^{-8} \text{ henries} \tag{1}$$

Assuming that the reversal of the current takes place at a constant rate (as a linear function of the time of commutation), we obtain for the rate of reversal of the current from $+\frac{I}{2\,p_1}$, to $-\frac{I}{2\,p_1}$, in the time T:

$$2 \times \frac{I}{2\,p_1} : T = \frac{I}{T\,p_1},$$

in which I = total current of the machine,

$\frac{I}{2\,p_1}$ = current per conductor,

T = time of reversal or commutation,

The reactance pressure v is

$$v = L\frac{I}{T\,p_1} \times 10^{-8} = 4\,\frac{p}{p_1} \times (\lambda a + b)\frac{I}{T\,p_1} \times P\, t^2 \times 10^{-8} \tag{2}$$

The time of commutation is the time required for the commutator to move the width of one brush. Since the brush has been assumed to be of the same thickness as a commutator bar, the time of commutation becomes,

$$T = \frac{60}{2\,p\,s\,N} = \frac{60}{S N} \tag{3}$$

where

s = number of coils and number of commutator segments per pole.

$S = 2\,p\,s$ = total number of commutator segments.

N = number of revolutions per minute.

If a brush covers more than one bar the reactance pressure is increased directly as the number of coils short circuited; but owing to the increased time now allowed for commutation the reactance pressure is decreased; in short, the effect, is compensatory.

Combining (2) and (3), v becomes

$$v = \frac{2\,p\,s\,N}{15} \times \frac{p}{p_1} \times (\lambda\, a + b) \times P \times \frac{I}{p_1} \times t^2 \times 10^{-8} \qquad (4)$$

or

$$v = \frac{S\,N}{15} \times \frac{p}{p_1} \times (\lambda\, a + b) \times \frac{I}{p_1} \times P\, t^2 \times 10^{-8};$$

and writing l for $\lambda\, P$ = armature length,

$$v = \frac{a + \dfrac{b}{\lambda}}{15} \cdot \frac{p}{p_1} \cdot \frac{I}{p_1} \cdot l\, S\, N\, t^2 \,.\, 10^{-8} \qquad (5)$$

This formula is undoubtedly familiar to designers. It is convenient for determining the reactance pressure of armatures that have been already designed, but it is of little use in predetermining new machines. To fill this want the following transformation of formula (5) has been devised: Assume that

E = generated electromotive force,

F = flux per pole,

B = air-gap induction at the pole-face,

α = percentage of the pole-face embrasure,

$O = E\,I$ = generated power,

$\frac{\pi D}{2\,p}\,\alpha\, l$ = pole-face area,

then:

$$F = \frac{\pi\, D}{2\,p} \,.\, \alpha \,.\, l \,.\, B$$

$$E = F\,S \,.\, 2\,t \,.\, \frac{p}{p_1} \cdot \frac{N}{60} \,.\, 10^{-8}$$

$$= \frac{\pi \,.\, \alpha}{p} \cdot \frac{p}{p_1} \cdot \frac{l\,N\,S}{60} \,.\, t \,.\, D\,B \,.\, 10^{-8}. \qquad (6)$$

Dividing (5) by (6),

$$\frac{v}{E} = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{I\,t}{B\,D} \cdot$$

$$v = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{E\,I\,t}{B\,D} \cdot$$

and finally,

$$v = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{O\,t}{B\,D} \cdot \qquad (7)$$

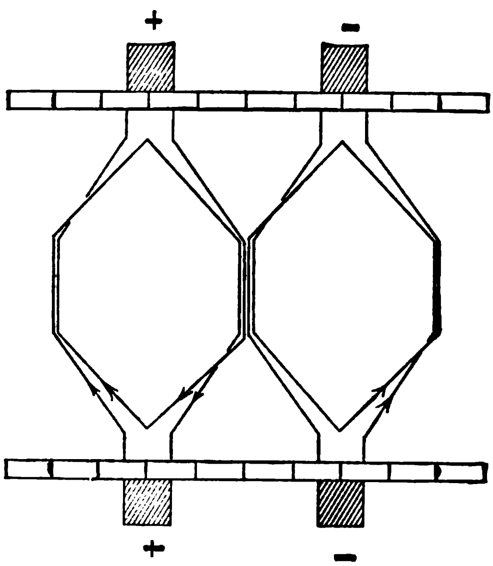


Fig. 2.

§ 2. *Reactance Pressure of the Double-Commutator Machine*: There are two varieties of double-commutator armatures; first, the double-commutator armature with two independent windings, each connected to a separate commutator; secondly, the double-commutator armature with one winding connected to two commutators.

The Double-Winding Armature: Fig. 2 represents the position of the short-circuited coils. As before

t = number of turns per coil,

,nut.

I' = the total current per commutator.
The coefficient of self-induction of one coil is

$$L = 4\frac{p}{p_1} \cdot (\lambda a + b) \cdot P t^2 \cdot 10^{-8} \text{ henries} \tag{1}$$

The current commutated in one coil is $\frac{I'}{2 p_1}$.

Two coils are simultaneously under commutation. The total current commutated then is $2 \cdot \frac{I'}{2 p_1}$; and the reactance pressure per coil

$$v = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{2 E I' t}{B D}$$

$$\text{or} \quad v = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{O t}{B D},$$

which is the same as (7).

Whether the two commutators work in series or in parallel, the total current commutated remains the same, and thus the reactance pressure remains unaltered.

If the commutators, working on different circuits, deliver the currents I_1 and I_2, then the total current commutated is $\frac{I_1 + I_2}{2 p_1}$ and the reactance pressure is

$$v = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{I_1 + I_2}{B D} \cdot E t \tag{8}$$

If one winding has t_1 turns, the other t_2 turns per coil, and if the currents on the commutator are I_1 and I_2, the internal electromotive forces E_1 and E_2, the result is:

$$v_1 = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{I_1 t_1 + I_2 t_2}{B D} \cdot E_1 \tag{9}$$

And in general

$$v_n = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{\Sigma\ (I t)}{B D} \cdot E_n \tag{9a}$$

Or, if the pairs of circuits are different on the two windings,

$$v_n = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot p \cdot \frac{\Sigma \left(\frac{I\, t}{p_1}\right)}{B\, D} \cdot E_n \tag{10}$$

From formula (9) it is seen that in case commutator No. 1 does not deliver any current, just the same there is a reactance pressure of the short-circuited coil belonging to that commutator,

$$v_1 = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{I_2\, t_2}{B\, D} \cdot E_1 .$$

so that sparking may occur even on the non-loaded commutator.

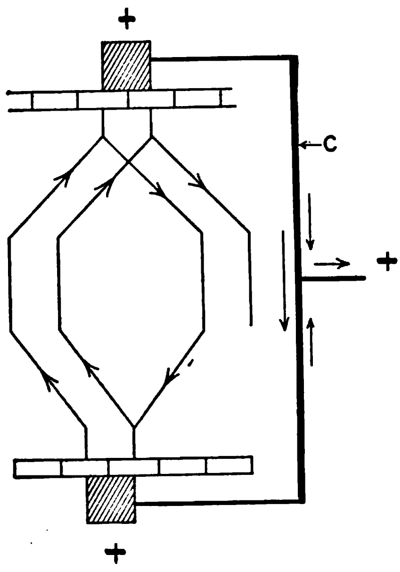


Fig. 3.

The Single-Winding Armature: The reactance voltage between the terminals of the short-circuited coil does not depend upon the current collected by the brush, but merely upon the current $\frac{I}{2\, p_1}$ to be reversed in the coil; now, referring to Fig. 3, the reactance pressure in this position would remain the same if the current were collected on only one side of the commutator, thus:

$$v = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{O\,t}{B\,D}$$

which is the same as (7).

Given the output and the number of turns per coil, the use of two commutators will not therefore decrease the reactance pressure.

In case of commutation in a non-neutral position of the coil,

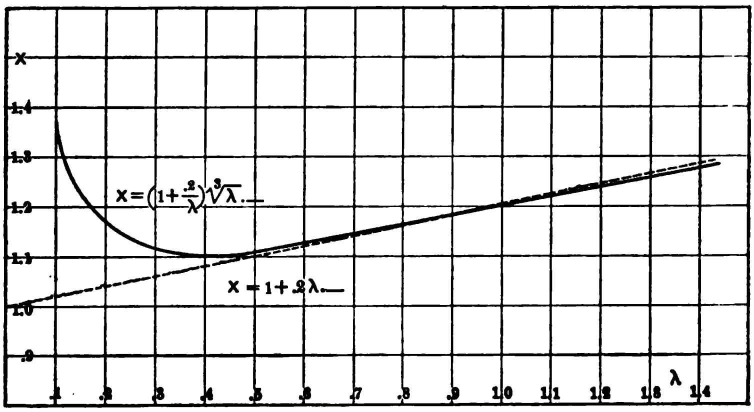


FIG. 4.

the electromotive force generated in the coils is short-circuited by the cross-connector C of the brushes. This phenomenon is practically independent of the load; depending upon its magnitude, it might cause burning of the brushes and disturb commutation.

COMMUTATOR AND BRUSH SPARKING, GLOWING, SPITTING, PICKING UP COPPER.

§ 1. *Probable Causes:* These phenomena offer a great field for speculation. Nothing definite is yet known about the causes that produce them; for this reason the writer will limit himself to stating when they are likely to take place, the statements being based on his experience with a large number of machines.

Sparking: Bright, white sparks usually can be traced to a too-high reactance pressure. This kind of sparking does not seem to be harmful to the commutator.

Glowing: Glowing of the brushes appears when the armature ampere-turns per pole, and therefore the armature reaction, exceed a certain limit; this glowing increases with the pole-pitch. The armature reaction may be caused by the working current, and in addition by unbalanced currents going from one brush-stud to other brush-studs of the same polarity. In a particular case the ammeter registered at no-load 300 amperes between brush-studs of the same polarity, whereas the full-load current was but 500 amperes.

Spitting: This phenomenon seems to be the combined effect of high reactance pressure and considerable armature reaction. The sparks become yellow or greenish, small explosions (spitting) take place under the brushes, causing carbon particles to escape into the air; the commutator loses its glassy appearance and becomes blackened.

Picking up Copper: The picking up of copper at the contact-surface of the brushes has received scant consideration in technical publications. The author does not possess any definite data concerning this phenomenon. Experiments are now in progress which thus far only show that probably in most cases the picking up of copper is not due to electrolytic action, but simply to the polishing action of the brush contacts. This is possible only if the brush material has a much greater hardness than the commutator copper. And since copper becomes softer at higher temperatures, we should, therefore, take current densities and brush pressures at the contact surface such as to keep the commutator as cool as possible.

It is within the ability of the designer to prevent commutator troubles of the kind described; it can be done by taking conservative values for the reactance pressure, the armature reaction, the current densities at the brush contact, and the peripheral speed of the commutator. Below are given data obtained from tests for average conditions of brush shifting, mechanical accuracy in assembling, etc.

§ 2. *Experimental Data. The Reactance Pressure*: According to

Hobart* the average number of lines of force set up per ampere-turn per embedded unit length in slots, with a ratio of depth to width not exceeding 3.5, equals 4 lines per centimetre per ampere-turn, or 10 lines per inch per ampere-turn. The number of lines set up in the free ends equals 0.8 lines per centimetre per ampere-turn, or 2 lines per inch per ampere-turn. We have, in inches,

$$a = 10 \qquad b = 2 \tag{11}$$

$$a + \frac{b}{\lambda} = 10\left(1 + \frac{0.2}{\lambda}\right).$$

In modern machines λ varies between 0.9 and 1.4 causing $\left(1 + \frac{.2}{\lambda}\right)$ to vary between 1.222 and 1.143, with an average of 1.18. Hence, contrary to the statements made by Hobart, the self-induction of the end-connections influences commutation only to a limited extent.

Substituting (11) in (5) and (7) we obtain the general formulas:

$$v = 0.067\left(1 + \frac{0.2}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{I}{100\,p_1} \cdot \frac{l}{10} \cdot \frac{N}{100} \cdot \frac{S}{100} \cdot t^2 \tag{12}$$

$$v = \frac{12.6}{\alpha}\left(1 + \frac{0.2}{\lambda}\right) \cdot \frac{p}{p_1} \cdot \frac{O\,t}{B\,D} \tag{13}$$

which gives for series windings:

$$v = 0.067\left(1 + \frac{0.2}{\lambda}\right) \cdot \frac{pI}{100} \cdot \frac{l}{10} \cdot \frac{N}{100} \cdot \frac{S}{100} \cdot t^2 \tag{14}$$

* "Electric Motors," by H. M. Hobart. Whittaker & Co., N Y., 1904, page 42.

"Modern Commutating Dynamo-Machinery," with special reference to the commutating limits. Paper read by H. M. Hobart before the Int. Eng. Congr., Glasgow, 1901. Journal of PROCEEDINGS Inst. E. E.. 1901, vol. xxxi., also *Engineering*, London, Feb. 14. 1902.

$$v = \left\{ \begin{array}{c} \frac{12.6}{\alpha} \left(1 + \frac{0.2}{\lambda}\right) \\ \text{roughly} \frac{15}{\alpha} \end{array} \right\} \cdot p \cdot \frac{O\,t}{B\,D} \tag{15}$$

and for parallel windings:

$$v = 0.067 \left(1 + \frac{0.2}{\lambda}\right) \cdot \frac{I}{100\,p} \cdot \frac{l}{10} \cdot \frac{N}{100} \cdot \frac{S}{100} \cdot t^2 \tag{14a}$$

$$v = \left\{ \begin{array}{c} \frac{12.6}{\alpha} \cdot \left(1 + \frac{0.2}{\lambda}\right) \\ \text{roughly} \frac{15}{\alpha} \end{array} \right\} \cdot \frac{O\,t}{B\,D} \tag{15a}$$

In the above formulas

Armature-coil pitch = 180 electrical degrees.

v = reactance pressure.

v_s = spark pressure = the value of the reactance pressure when self-induction sparking begins.

D = armature diameter.

l = gross iron length = iron length + insulation.

p = pairs of poles.

p_1 = pairs of circuits.

$\lambda = \frac{D}{p\,l}$ with an average of 1, 1.

I = total armature current.

N = revolutions per minute.

t = number of turns per coil.

S = number of commutator segments = number of armature-coils.

α = average pole-face enclosure.

B = induction at the surface $\frac{\pi\,D\,l}{2\,p} \cdot \alpha$

At the point of almost sparkless operation the spark pressures of more than 30 machines, calculated by formula (12), gave the following averages:

$$\left. \begin{aligned} v_s &= 1.6 - \text{(estimated) National graphitized brush} \\ &= 2.5 - \text{Partridge brush.} \\ &= 3.2 - \text{National Columbia brush.} \\ &= 3.4 - \text{Le Valley Vitae brush.} \\ &= 3.8 - \text{Dixon pure graphite brush} \end{aligned} \right\} \tag{16}$$

For sparkless operation, we evidently must have

$$v < v_s \tag{17}$$

The limits given apply to generators with a maximum brush-shift of 10% and to motors with practically no brush-shift. The limits are the same for small as for large machines, machines varying from 0.3-kw. to 2500-kw. capacity.

Brush-Contact Density. To minimize the picking up of copper, the maximum densities at the brush-contacts should be:

$$\left.\begin{aligned} \text{Maximum density} &= 55 \text{ amperes per sq. in. National graphitized} \\ &= 35 \text{ amperes per sq. in. Partridge.} \\ &= 27 \text{ amperes per sq. in. National Columbia} \\ &= 25 \text{ amperes per sq. in. Le Valley Vitae} \\ &= 22\text{–}25 \text{ amperes per sq. in. Dixon graphite.} \end{aligned}\right\} \tag{18}$$

The maximum density for the National graphitized brush is still doubtful. The author does not possess conclusive experimental data concerning it.

Armature Reaction. The maximum permissible armature reaction was found to depend upon the pole-pitch, therefore upon the value of $\frac{D}{p}$.

For

$$10 \text{ in.} < \frac{D}{p} < 15 \text{ in.}$$

$$5000 < \frac{I}{2p_1} \cdot \frac{S}{2p} < 6500 \text{ ampere-turns per pole} \tag{19}$$

Definite limits for smaller values of $\frac{D}{p}$ are still lacking: $\frac{D}{p} = 15$ in. should be taken as a maximum.

The following experiments are pertinent to the subject, and of interest at this point:

Two 45-in. by 12-in. armatures A and B, were wound for a 6- and an 8-pole frame. A had 8 000 ampere-turns and B 5 750 ampere-turns per pole. The percentage of pole-enclosure on both was nearly the same, and also the speed and pressure.

The inductive sparking on B was less than on A. Spitting and glowing were observed only on A, and after a 10-hours' run A's commutator was badly marked and blackened and some of its brushes were eaten away. On the other hand, B's commutator was bright and glossy and its brushes showed a smooth contact-surface.

A third armature 45-in. by 15.5 in. was wound for 7 800 armature ampere-turns per pole. This armature was of the same general mechanical structure as armature called A. Spitting and glowing were absent, and the commutator was in good condition. This is unusual; it does not affect materially the relations shown in equation (19).

Commutator. To prevent chattering of the brushes the peripheral speed of the commutator should be kept below 3 600 ft. per min. To insure a well-balanced collection of the current, the length of the commutator bar should not exceed 18 inches.

If the above considerations fail to throw light on some commutator troubles, it must be remembered that the mechanical construction of the machine also affects commutation. In order to show how many conditions affect commutation the writer quotes the following list, published by H. M. Hobart*:

1. High ratio of pole-arc to pitch, which results in too narrow a commutating zone.
2. A number of commutator segments for multiple windings, not of a multiple of the number of poles.
3. Inequality of the air-gap.
4. Inequality in the material of the magnetic circuit.
5. Unsymmetrically assembled commutator bars.
6. Unsymmetrically assembled brush-gear.
7. Unsuitable type of brush-holder.
8. Incorrect brush tension.
9. Inexact alignment of brushes.
10. Insufficient brush surface.
11. Brushes not suitably bedded.
12. Unsuitable quality of carbon brush.
13. Hard mica segments.
14. Soft commutator segments.
15. Insufficiently rigid machine foundations.
16. Insufficiently rigid shaft.

*In the paper mentioned before.

17. Insufficiently rigid commutator construction.
18. Eccentricity of the commutator.
19. Insufficiently clean commutator surface.
20. Inequality in angular speed of the prime mover.
21. Too large lag of the current in the short-circuited coil.

Designing an Armature.

Rating. 200 kilowatts, 600 volts, 575 revs. per min.

Guarantees. A sparkless operation at full load, and a maximum temperature rise of 35° cent. on any part of the machine. A fairly good commutation at 150% load, and after a 2-hour run no part of the machine shall have a temperature rise of more than 55° cent. above the room temperature.

Preliminary Design: Assume the use of Le Valley Vitae brushes for which

$$v_s = 3.4$$

In order to obtain almost sparkless operation with an overload of 25% the reactance pressure must be $\frac{3.4}{1.25} = 2.7$ volts.

With $B = 60\,000$, $v = 2.7$, $\alpha = 0.72$, $t = 1$, and a multiple winding, we obtain from the approximating formula (15a)

$$D = \frac{15}{0.72} \cdot \frac{200 \times 1}{60 \times 2.7} = 25.7 \text{ in.}$$

Take $D = 25$ inches. At full load the end-connections should have a temperature rise of not more than $\frac{55°}{1.5^2} = 25°$ cent. With a peripheral speed of 3 750 ft. per min. the maximum number of ampere-turns per inch of the circumference is, for 25° rise, about 325 ampere-turns per inch. The total number of ampere-turns then is $\pi \times 25 \times 325 = 25\,600$. As long as the frequency is kept below 25 or 30 cycles, there will be no trouble in limiting the temperature rise of the embedded part.

The problem arises whether to make a 2-, 4-, or 6-pole armature. With a 6-pole multiple winding the current per conductor will be 55.5 amperes and the number of bars 460. Assuming a minimum segment-pitch of 0.19 in., we obtain a 28-in. commutator with a peripheral speed of 4 200 ft. per min., which is prohibitive. A 2-pole armature would give 12 800 ampere-turns per pole, which is also prohibitive. We therefore have to make it a 4-pole machine. The current per conductor being 83.5 amperes, the number of commutator-bars will be about 308, giving with a 0.19 segment-pitch an 18.5-in. commutator and a peripheral speed of 2 800 ft. per min., which is permissible. An armature reaction of 6 400 ampere-turns per pole is rather high (see equation 19). Since $\frac{D}{p} = 12.5$ in., we make the reaction about 5 500 ampere-turns. Now we wish to have:

Three coils per slot—a number of slots, divisible by the number of poles—a number of bars divisible by five or six (for cross connecting every fifth or sixth bar)—a brush with a 30-degree bevel and covering only a little less than either three or two bars per stud—a commutator with a maximum peripheral speed of 3 200 ft. per minute and a maximum face of 15 in. These considerations lead to 84 or 88 slots and to a 0.625-in. or a 0.563-in. brush thickness.

Assume the following: 84 slots, 252 bars, 0.625-in. brush thickness, 19-in. commutator diameter and 12.5-in. commutator-face.

Final Calculation: Estimate the armature drop at 20 volts.

Induced pressure = 620 volts; number of coils = number of bars = 252;

Turns per coil = 1, multiple winding;

84 slots 0.4 in. by 1.45 in. with sticks;

6 conductors per slot each 0.075 in. by 0.5 in.;

Pole-face enclosure = 72% — width of top of tooth = 0.535 in.;

Width of root of tooth = 0.425 in.;

6 brushes per stud each 0.625 in. by 1.75 in. (equation 18);

Commutator 19 in. by 12.5 in.;

Le Valley Vitae brushes with 30-degree bevel.

With a maximum induction at the root of the tooth of 150 000 lines per square inch and $\alpha = 0.72$, the flux per inch of iron length = 960 000 lines. The flux required to generate 620 volts is 12.8 megalines. The armature iron length then is $\frac{12.8}{0.96} = 13.25$ in. Allowing 10% for insulation between the laminations makes the gross iron length $\frac{13.25}{0.9} = 14.75$ in., approximately 15 in. Allowing three ventilating ducts between the the lamination and two at the ends, each 0.5-in. wide, makes the total armature length 17.5 in., and the pole-shoe axial length 16 in. The induction of the pole-face becomes 56 700. Summing up

$\lambda = 1.2$; $p = 2$, $p_1 = 2$; $I = 333$ amperes; $l = 15$ in.;

$S = 252$; $t = 1$; $N = 575$ rev. per min., $O = 620$ by $333 = 207$ kw.

$D = 25$ in.; $v_s = 3.4$; $\alpha = 0.72$.

$$B = \frac{12\,800\,000 \times 4}{\pi \times 25 \times 0.72 \times 15} = 60.7 \times 10^3$$

$$v = 0.067 \left(1 + \frac{0.2}{1.2}\right) \cdot \frac{333}{100 \times 2} \cdot \frac{15}{10} \cdot \frac{575}{100} \cdot \frac{252}{100} \cdot 1 = 2.82 \text{ see} \quad (14a)$$

and as a check

$$v = \frac{12.6}{0.72} \cdot \left(1 + \frac{0.2}{1.2}\right) \cdot \frac{207}{60.7 \times 25} = 2.82 \quad \text{see (15a)}$$

The maximum load with almost sparkless commutation is

$$\frac{v_s}{v} \times 100 = \frac{3.4}{2.82} \times 100 = 120\%.$$

Armature reaction = 5 250 ampere-turns per pole. see (19)

With an armature inside diameter of 10 in., it will be found by calculating the watts per square inch on the armature surface that the heating effect is within the specified limits.

The Kapp output factor defined by $\dfrac{O - \text{watts}}{D^2\, l\, N}$ is 0.037, which is fairly high, considering the size, the pressure, and the guarantees.

CONCLUSIONS.

§ 1. *Discussion of the Formulas. The Armature Reaction.* For peripheral speeds ranging from 1 500 ft. per min. to 7 000 ft. per min.; for a coil depth (not slot-depth) of 1.25 in. and a temperature rise of the end-connections not exceeding 25° cent., the number of ampere-turns per inch of armature circumference varies as a straight line from 260 ampere-turns per inch to 400 ampere-turns per inch. The maximum permissible armature reaction being about 6 500 ampere-turns for really good operation, therefore the maximum pole-pitch falls between 25 in. for the slow-speed and 17 in. for the high-speed machines.

The maxima values of $\frac{D}{p}$ become

$$11 \text{ in.} < \frac{D}{p} < 16 \text{ in.}$$

for machines of large outputs.

The Volt-ampere Density of a Brush. From formula (16) we have

$v_s = 1.6$	2.5	3.2	3.4	3.8

from formula (18) the densities are:

$d = 55,$	35,	27,	25,	22 to 25
$v_s\, d = 88,$	87.5,	86.5,	85,	85 to 95

with an average of

$$v_s\, d = 87 \text{ volt-amperes per square inch} \qquad (20)$$

Conclusion 1. The volt-ampere density $v_s\, d$ or the product of spark pressure and maximum permissible current per square inch of contact surface, is the same for all carbon brushes.

As will be seen later, the volt-ampere density enables us to determine the largest size of direct-current machine that can be made.

The Reactance Pressure. The reactance pressure for multiple windings was found to be

$$v = \frac{12.6}{\alpha}\left(1 + \frac{0.2}{\lambda}\right) \cdot \frac{O\, t}{B\, D} \qquad \text{(see 15a)}$$

It may seem rather strange that the reactance pressure should be a function of the product $\alpha.B.D.$ It simply means that the larger $\alpha.B.D.$, the larger will be the flux, the fewer the commutator bars, the longer the time of commutation, and the lower the reactance pressure.

Assuming $\alpha = 0.72$, $\lambda = 1.1$, as an average, we have

$$v = 21 . \frac{O\, t}{B\, D}$$

Conclusion 2. The reactance pressure of a machine of given output diameter, gap induction, and turns per armature coil is entirely independent of its speed and practically independent of its armature length.

In large machines t usually equals 1 and B maximum equals 65 000 lines per sq. in.

Substituting this in the last formula and assuming $v_s = 3.2$ we obtain

$$D_{min.} = \frac{O-\text{kilowatt}}{10} \text{ inches} \tag{21}$$

a formula, very useful both for designers and consulting engineers.

Conclusion 3. At the point of almost sparkless operation (with Columbia brushes), the armature diameter equals one-tenth of the kilowatt output: this applies to self-inductive sparking only.

To guard against spitting and glowing, and in order to keep the size of the machine down we should have $\frac{D}{p} \leqq 15$, or substituting in (21).

$$\text{No. of poles} \geqq \frac{O-\text{kilowatt}}{75} \tag{22}$$

Since $\frac{D}{p}$ depends upon the degree of ventilation of the armature, it follows that as the ventilation increases the number of poles increases.

§ 2. *Limiting Sizes of Direct-current Machines.*

Equation (21) seems to indicate that the maximum output of a machine depends wholly upon the largest permissible armature diameter. That this is not so will now be shown.

Let w = width of brush.

b = axial length of brush-contact.

I being the total current, $\frac{I}{p}$ is the current per stud and $\frac{I}{p\,w\,b}$ the current density at the brush-contacts. Assuming this density to be the maximum that the brush can practically stand, we get from formula (20)

$$\frac{I}{p\,w\,b} \cdot v_s = 87.$$

And remembering that

$$v_s = \frac{21\,O\,t}{B\,D}$$

we have

$$\frac{I}{p} = \sqrt{\frac{87}{21} \cdot \frac{w\,b}{t} \cdot \frac{B}{E} \cdot \frac{D}{p}}$$

or

$$\frac{O}{p} \text{ max.} = \sqrt{4,1 \, . \frac{w\,b}{t} \, . \, B \, . \, \frac{D}{p}} \times \sqrt{E} \qquad (23)$$

This formula contains the following factors:

Limiting the reactance pressure and the picking up of copper:

$$v_s\,d = 87.$$

Limiting the length of the commutator, b.

Limiting the armature reaction and the heating of the end-connections, $\frac{D}{p}$.

To get an idea of the maximum output, we will assume the limits to be

$w = 0.75$ in. to 1 in.; $b = 16$ in.; $t = 1$; $B = 60\,000$; $\frac{D}{p} =$ 13 in., hence

$$\left.\begin{aligned} \frac{O}{p} \text{ max.} &= 6.7\sqrt{E} \text{ kilowatts} \\ \frac{J}{p} \text{ max.} &= \frac{6700}{\sqrt{E}} \text{ amperes} \end{aligned}\right\} \qquad (24)$$

Conclusion 4. The maximum output per pair of poles increases with the square root of the pressure, and the current per stud is inversely proportional thereto. This is in agreement with Hobart's contention that the building of large high-voltage machines offers less difficulties than the building of large low-voltage machines.

He also states that there appears to be no practical difficulty in the way of making 1 500-volt machines, or machines of even higher voltage. Basing the electrical design only upon the reactance pressure, as he does, will lead to this conclusion. See equations (15a) and (21).

The writer's experience is that the effect of the armature reaction may not be overlooked. Assuming 6 700 armature ampere-turns per pole as a maximum, the number of commutator bars per pole from equation (24), becomes $2\sqrt{E}$ and the pressure per bar $0.5\sqrt{E}$. The brush-pitch will not be more than 18 in., assuming a smallest bar thickness of 0.2 in. The largest number of bars per pole is 90, also equal to $2\sqrt{E}$. From this we obtain 2 000 volts as the maximum pressure at the maximum output. This output would be $6.7\sqrt{2\,000} = 300$ kw. per pair of poles.

The current = 150 amperes per stud, the reactance pressure equals $\dfrac{21 \times 300 \times 1}{60 \times 13} =$ about 8. No brushes are available sustaining a spark-pressure of 8 volts.

Difficulties are encountered even with 600 volts. In this instance, maximum output per pair of poles $= 6.7\sqrt{600} =$ 165 kw.; the current per stud = 275 amperes; the reactance pressure equals $\dfrac{21 \times 165 \times 1}{60 \times 13}$ = approximately 4.5. As before, there are at present no brushes sustaining a spark-pressure of 4.5 volts. Thus, in order to obtain the maximum output per pair of poles, at any pressure E, the spark-pressure of the brush must be approximately

$$v_s \geqq \frac{21 \times 6.7\sqrt{E}}{60 \times 13} = 0.18\sqrt{E} \qquad (25)$$

From the above we derive that Le Valley Vitae brush is adapted to pressures up to 350, and the Partridge brush pressures up to 190 volts; this applies to the maximum output per pair of poles only. At present the high cost of graphite brushes practically prohibits their use. The table below contains data for the largest commercial machines that can be built to meet the rigid guarantees applicable to smaller machines, considering the brushes that are available at moderate prices.

The assumptions have been made that

a, the engine manufacturer purposely avoids building engines with speeds lower than 75 rev. per min. b, the peripheral speed of the commutator has reached its limit; c, the brush-pitch is,

LIMITING SIZES OF DIRECT-CURRENT MACHINES

Guarantees	Full Load: Temperature rise below 35° cent., sparkless, no glowing nor spitting: no picking up of copper.			
	Overload. 25% almost sparkless.			
Rating	Pressure	125	300	600
	Output in kilowatts	1 175	1 800	1 450
	Rev. per min	75	75	75
	Amperes	9 400	6 000	2 420
Dimensions, etc.	Armature Diameter	230 in.	240 in.	180 in.
	Length of Laminae	5.75 in.	8.25 in.	11.5 in
	No. of Slots	494	560	600
	No. of Poles	38	40	30
	Diam. per pair of poles	12.1 in.	12 in.	12 in.
	Arm. ampere-turns per inch	340	338	345
	Commutator Diameter	155 in.	155 in.	155 in.
	No. of Bars	988	1 680	2 400
Limits	Reactance pressure at 100%	2	2.72	2.72
	Reactance pressure at 125%	2.5	3.4	3.4
	Arm. ampere-turns per pole at 100%	6 450	6 350	6 500
	Current per sq. in. at contact 100%	35 Partridge	25 Le Valley Vitae	24 Le Valley Vitae
	Brushes per stud 30° bevel	(8) $\frac{7}{8}$ in. by $1\frac{3}{4}$ in.	(8) $\frac{3}{4}$ in. by $1\frac{3}{4}$ in.	(6) 9/16 in. by $1\frac{3}{4}$
	Commutator Pace	16.5 in.	16.5 in.	12.5 in.
	Peripheral Speed of Comm.	3 040 ft. min.	3 040 ft min.	3 040 ft. min.
	Kapp's output constant	0.0515	0.0505	0.052

for the low-voltage machines, the smallest possible with reference to the thickness of the brush and the heating of the commutator. The author wishes to call attention to the moderate armature reaction combined with the high output constant, which shows that these factors are not always antagonistic.

The generators presented in the table are not intended to pass for commercially perfect machines; indeed the 125-volt and the 300-volt generators would prove financial failures. They are, however, well to illustrate the effect of overload guarantees on the price of large units. In the 125-volt generator λ equals 0.475. Keeping the cylindrical colume $D^2 l$ constant let us see how a variation of λ affects the design.

λ = ...	0.475	0.625	0.845	0.99	1.175
D = ...	230 in.	210 in.	190 in.	180 in.	170 in.
$l.$ = ...	5.75 in.	6.9 in.	8.4 in.	9.4 in.	10.5 in.
v = ...	2.00	2.04	2.11	2.16	2.23
Guar. spark-limit in % =	125%	125%	125%	125%	125%
Spark-limit =	125%	122.5%	118.5%	115.5%	112%
Deficiency =	0%	2.5%	6.5%	9.5%	13%

As the table shows, allowing a deficiency of only 2.5% decreases the diameter by 9.5%; and by allowing 9.5% the reduction in diameter is 27.5%, which means a considerable saving in the cost of manufacture and erection, and an increase of the efficiency. In a lesser degree the same may be said of the 300-volt and the 600-volt generators. We will now show in a general way how λ affects the reactance pressure when the cylindrical volume $D^2 l$ of an armature is kept constant.

According to Kapp*, the relation of output, cylindrical volume, and speed can be expressed by the formula

$$O = q \times D^2 \times l \times N \text{ watt.} \tag{26}$$

in which q is the output factor, and fairly constant for large machines.

For our purpose, we prefer the form

$$O = q \,.\, L^3 .\, \lambda \,.\, \frac{N}{p}$$

$$\frac{1}{D} = \sqrt[3]{\frac{q\,\lambda\,N}{O\,p}} \tag{27}$$

and substituting (27) in (7)

$$v = \frac{1.26}{\alpha} \cdot \left(a + \frac{b}{\lambda}\right) \sqrt[3]{\lambda} \times \frac{p}{p_1} \cdot \frac{t}{B} \cdot \sqrt[3]{\frac{O^2 q N}{p}}$$

For $a = 10$, $b = 2$

$$v = \left(1 + \frac{2}{\lambda}\right) \sqrt[3]{\lambda} \times \frac{12.6}{\alpha} \cdot \frac{p}{p_1} \cdot \frac{t}{B} \cdot \sqrt[3]{\frac{O^2\, q\, N}{p}}$$

*G. Kapp.—Dynamo Construction, Electrical and Mechanical. London, 1900 keeping

$$\frac{12.6}{\alpha} \cdot \frac{p}{p_1} \cdot \frac{t}{B} \cdot \sqrt[3]{\frac{O^2\, q\, N}{p}} = C, \text{ a constant,}$$

and

$$v = \left(1 + \frac{.2}{\lambda}\right) \sqrt[3]{\lambda} \times C \tag{27a}$$

In Fig. 4 is given the curve for equation:

$$x = \left(1 + \frac{.2}{\lambda}\right) \sqrt[3]{\lambda} \tag{27b}$$

Between $\lambda = 0.5$ and $\lambda = 1.4$, the curve is nearly a straight line. λ in practice never falls below 0.7; thus we may write with sufficient accuracy

$$v = \frac{12.6}{\alpha}\left(1 + 0.2\,\lambda\right) \cdot \frac{p}{p_1} \cdot \frac{t}{B} \cdot \sqrt[3]{\frac{O^2\, q\, N}{p}} \tag{28}$$

which means: a large change of λ effects the reactance pressure but very little; on the other hand, such a change reduces or increases the cost of the machine considerably. Whenever possible we should take λ between 1 and 1.3.

§ 3. *Note on Direct-Current Turbo-Generators.*

The writer desires to compare in a general way the commutation of slow-speed generators with that of the high-speed generators. To understand the difficulties confronting the designer of turbo-generators we have to refer to the approximate reactance pressure equation:

$$v = 21\,\frac{O\,t}{B\,D}$$

Let us consider a 1 500-kw. generator, running at 1 800 rev. per min. The number of turns per coil cannot be less than 1; the number of poles 4; the induction in the air-gap approximately 45 000 lines per sq. in.; the peripheral speed of the armature approximately 14 000 ft. per min., and the diameter 35 in., from which

$$v = 21 \times \frac{1\,500 \times 1}{45 \times 35} = 20 \text{ volts.}$$

Since only copper brushes can be employed, and since the spark-pressure of copper may be estimated at about 1.2 volt, on the basis of the reactance pressure alone commutation of this generator is 20/1.2 = 17 times as difficult as commutation of a slow-speed generator. Adding to this the high peripheral speed of the commutator (between 7 000 and 10 000 ft. per min.) and an armature reaction of about 12 500 ampere-turns per pole, corresponding to 450 ampere-turns per inch of armature circumference, some idea may be gathered of the difficulites encountered. To summarize, these difficulties are, from the standpoint of commutation:

a, excessive reactance pressure; b, high peripheral speed of the commutator, causing chattering of the brushes; c, high armature reaction.

Objections *a* and *c* can be overcome, for any practical speed, by compensation, and compensated machines can be proportioned for good commercial operation.

DISCUSSION ON "LIMITATIONS IN DIRECT-CURRENT MACHINE DESIGN."

GANO S. DUNN: Fourteen years ago or so, when all generators were small and about the time when Mr. Parshall was at work upon the 1 200 kw. machines for the Chicago World's Fair, he stated as a law what Mr. Senstius has just put in excellent form; namely, that the amperes per pole in a direct-current generator were a limited quantity. While I agree with the general method by which Mr. Senstius arrives at his limitations, I do not agree with the actual values of the limitations which he reaches. For instance, his value of 1 175 kw. for a 125-volt machine is too high; 1 800 kw., for a 300-volt machine, seems about right, and 1 450 kw. for a 600-volt machine is altogether too low. I should like to ask Mr. Senstius, if he is free to speak upon the subject, how he harmonizes his limit of 1 800 kw. at 300 volts with the existence and good operation of a certain 3 500-kw., 325-volt direct-current generator in Cincinnati. It would seem that the conclusions which he reaches in his paper are not confirmed by that machine. The fact that there is a limiting size for direct-current machines, particularly in the lower voltages, ought to be better known than it is. Manufacturers are constantly receiving inquiries for generators of these lower voltages several times larger than it is possible to construct.

W. L. WATERS: I agree with Mr. Dunn in his remarks on the limitation of maximum size of direct-current generators, as given in the paper by Mr. Senstius. I think his limitation of size of a 600-volt generator is considerably too low. There are some 2 700-kw., 600-volt machines in Boston which run very well, and I think it feasible to build 4 000-kw. or 5 000-kw. generators with that voltage.

Mr. Senstius takes his reactance voltage formula as a basis for estimating the maximum possible size of a machine that can be built, but this formula is not accurate when used within wide limits. If it is found that a certain machine at a given speed will just commutate 100 amperes and the speed then be doubled, it should, then, according to Mr. Senstius' formula, commutate only 50 amperes; but by actual test it is f und that it will usually commutate about 75 amperes. The limiting current that can be commutated by any machine is not directly proportional to the time of commutation. This is an experimental result, and from which it is found that a much higher reactance voltage is allowable in large machines than in small, the reason being that the frequency of commutation is much higher in large than in small machines.

I have always regarded the picking up of copper by the brushes on the commutator as a purely mechanical operation, due to the employment of either too soft commutator bars, or too hard brushes, or too heavy a tension on the brushes, and I heard for the first time to-day the electrolytic explanation from Mr. Dunn. I cannot express any opinion as to its accuracy, but I know that very often it is possible to stop the picking up of copper by weakening the tension of the brushes or by using a softer grade of carbon.

CHAS. P. STEINMETZ: I believe the value of Mr. Senstius' paper lies more in the discussion regarding the limitation of direct-current design, which it brings before us, than in the given numerical values. I should greatly hesitate to accept the deductions arrived at in the paper, for the reason that, in endeavoring to cover such an enormous field as the direct-current commutating machine, it is more or less unavoidable, in the conclusion, to draw deductions and express them more broadly and generally than warranted by the facts, or than by the premises on which the conclusions are based. As the result thereof there are in successful commercial operation machines which are far outside of the limits given in this paper. For instance, the Mohawk type of locomotive, which was discussed yesterday, has an armature reaction several times higher than the limits given in this paper. Many steam-turbine generators and synchronous converters have commutator speeds and general commutator constants far out of the limits of the range considered in the paper, and they are successful. If I remember right there are several 5 000-hp. commutating machines running successfully in Chicago, at 250 volts. Hence the deductions are expressed in this paper more broadly than warranted.

To illustrate, the first equation on page €£1 that of self-induction of commutation, is correct for only one particular type of armature winding, that is a full-pitch winding, which is practically feasible only with multiple-wound machines, or machines having just as many circuits as poles. In the matter of fractional pitch winding, regarding which I may refer you to Mr. Lamme's paper of a few years ago, this equation does not apply, since in a fractional pitch winding the reversing flux of commutation does not surround two armature coils, since they do not lie in the same slot, as assumed in this paper, but in different slots. In this case—which is most common in larger machines—the equation would have to be modified by replacing the factor 4 by 2, and the term b with $2\,b$; that is, the inductance will be more or less essentially reduced. Now in all series multiple-wound armatures, or armatures having a number of circuits different from the number of poles, the number of slots on the armature is practically never divisible by the number of poles, and in this case therefore strictly full pitch winding, that is, winding where the coil has a spread of 180 electrical degrees, is not feasible, and with such windings, therefore, the coils that commutate simultaneously cannot be in the same slot, and this formula of inductance cannot apply. Furthermore, practically always, the commutator brush covers several commutator segments, and for reasons of design several coils are enclosed in the same armature slot, that is, the number of armature slots is less than the number of commutator segments. That means that no armature coil is in a slot by itself, but in the same slot in which it lies there are other armature coils which are partly or wholly short-circuited by the brushes and therefore form a short circuited secondary to the coil which enters or leaves commutation, and essentially modifies or reduces the self-inductance so that this formula of induction as given in the equation is not even approximately correct.

What I desire to show is that the general deductions of the paper must be in detail further discussed and investigated safely to draw conclusive results therefrom. So, for instance, the data on the permissible maximum current density of brush contact on page 700 are exceeded by many good machines and can safely be exceeded. The maximum average density of the brush contact has as a rule no direct bearing on the commutation. The actual maximum density or density at the edge of the brush contact surface as discussed by Mr. Reid in his paper is important. With perfect commutation the maximum density at the brush surface may be equal to the average density, while with imperfect commutation it may be several times higher. Since the actual maximum density on the brush surface is of importance, the permissible average density may be higher or lower, according to the character of commutation. Furthermore, in considering commutator brushes, the character of the brush and of the machine enters as of essential importance. For instance, low resistance graphite brushes may be superior and carry much larger currents per square inch area in one type of machine, while in another type of machine they may be entirely inoperative, and a brush of higher resistance would actually carry far more current sparklessly than a graphitized brush. The reverse may be the case under other conditions. What I desire to call to your attention is that all such very general deductions require further special investigation before being applicable for an individual designing case.

Sebastiaan Senstius: I may say to Mr. Dunn that I have not seen a single machine yet, of 1 500 kilowatts, that as regards sparkless operation, can be compared with smaller machines. It seems to me, the operating engineer requires of small units much better sparkless characteristics than of large ones. Experience justifies this.

I have seen a number of large generators with cylindrical and also with disk-type commutators. Several of these spark at three-fourths load and at even less, but the commutators remain in a satisfactory condition. I am not able to give reasons for this. Now in the case of the large generators in Cincinnati, made by different companies, they all spark and the operators have a good deal of difficulty in adjusting the brushes in such a way as to have them operate more or less satisfactorily.

The limiting sizes of direct-current machines, given in the table, are designed to require but one single adjustment of the brushes and such an adjustment, that there will not be any sparking at no load, at full load, and at 25 per cent. overload. As regards the large machine of 2 700 kw. in Boston, I would like to know, whether that machine was actually sparkless without readjusting the brushes?

W. L. Waters: Practically sparkless.

Sebastiaan Senstius: With the brushes adjusted at no load?

W. L. Waters: It carried 4 000 kw. with no appreciable sparking.

Sebastiaan Senstius: The actual time of commutation certainly is dependent upon different factors. It depends largely upon the field in which the current is commutated. But this cannot be taken into account in the formula, which is for average conditions only. As regards the time of commutation being dependent upon the number of bars short circuited, I have said at the top of page 692

"If the brush covers more than one bar, the reactance pressure is increased directly as the number of coils short circuited, but owing to the increased time now allowed for commutation, the reactance pressure is decreased; in short, the effect is compensatory."

Now, about the maximum density of the brushes, Mr. Steinmetz applied it to the sparking of the commutator, whereas I meant to apply it only to the picking up of copper. I know some instances of pure graphite brushes having a density something like 50 amperes without causing the machine to spark, but my experience has always been that there would be a collection of copper at the contact surface. About a month ago there was a remarkable case of a generator, where we tried two kinds of brushes; one extremely thin, something like $\frac{3}{8}$ in., and the other $\frac{5}{8}$ in. Just because, as I believe, the density of the thin brush was very high, the collection of copper was something tremendous; with the $\frac{5}{8}$ in. brush, there was hardly any copper collected, the commutator was in fine condition, the contact surface was very bright.

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SYNCHRONOUS CONVERTERS AND MOTOR-GENERATORS.

BY W. L. WATERS.

At the present time the alternating-current motor in a motor-generator set of 100-kw. capacity ,or more, is practically always a synchronous motor; an induction motor is rarely used for this purpose. The reason for this is threefold: the lagging current taken by an induction motor makes the motor undesirable at the end of a long line; from an operating standpoint the mechanical construction of an induction motor makes it less reliable than a synchronous motor; and the cost of induction motors has heretofore been considerably higher than that of synchronous motors. The usual objections to the synchronous motor—that it has a low starting torque and that it requires external excitation—do not apply to the case of a synchronous motor used in a motor generator set; a high starting torque is unnecessary in this case, and there is always some way of exciting the motor whether it is coupled to a direct-current or to an alternating-current generator. Thus it has become standard practice to use synchronous motor-generator sets in all sizes except where the output is too small for a standard synchronous motor. This being the case I shall only consider synchronous motor generator sets in addition to synchronous converters.*

Motor-generators and synchronous converters can be dis-

* As defined by the Committee on Standardization: "A converter may be either: * * * (*b*) A synchronous converter, formerly called a rotary converter, converting from an alternating to a direct current, or vice versa." * * * See TRANS. A. I. E. E., Vol. xix, 1902, p. 1077. Synchronous converters are still perhaps most often termed "rotary converters" by engineers, and for brevity, they are frequently referred to as "rotaries," and sometimes simply as "converters." Following the definition prescribed by the Committee on Standardization, the term "synchronous converter" is generally used in this paper, although the shorter term "converter" is frequently employed where its use can cause no doubt as to what kind of converter is meant.—[EDITOR.]

cussed from two points of view; that of the operating engineer, or that of the designer and manufacturer. As the operating point of view is probably most familiar to engineers, that will be considered first.

The main points that concern the engineer when installing transforming machinery are its first cost and reliability and flexibility of operation. Incidentally, the efficiency of the outfit, the floor space it occupies, and sundry other things have tc be taken into consideration. The cost of a motor-generator or of a synchronous converter, or rather the price at which it is sold by the manufacturer, depends upon the output and speed, and incidentally upon the keeness of the competition among the firms that are trying to obtain the business. The choice of speed for either machine usually being left to the manufacturer, it is as high as is consistent with good mechanical and electrical design. The following table gives speeds that may be regarded as more or less standard for such machines for different outputs, frequencies, and pressures.

25 CYCLES.

KILOWATTS	MOTOR-GENERATORS		SYNCHRONOUS CONVERTERS	
	250 volts	600 volts	250 volts	600 volts
250	750 rev. per min.	750 rev. per min.	500 rev. per min.	750 rev. per min.
500	500 "	500 "	300 "	500 "
1 000	250 "	250 "	187 "	250 "
1 500	214 "	214 "	150 "	214 "
2 000	187 "	187 "	125 "	167 "

60 CYCLES.

KILOWATTS	MOTOR-GENERATORS		SYNCHRONOUS CONVERTERS	
	250 volts	600 volts	250 volts	600 volts
250	720 rev. per min.	720 rev. per min.	720 rev. per min.	900 rev. per min.
500	514 "	514 "	450 "	600 "
1 000	240 "	240 "	225 "	300 "

In comparing the cost of motor-generators and converters it may be assumed that it will always be necessary to use transformers with the latter in order to get the comparatively low alternating-current pressure required. With motor-generators, on the other hand, the motor can be wound to take the high-tension current direct without the interposition of transformers, unless the line pressure exceeds 15 000 volts. In estimating the costs of motor-generator sets it is assumed that no transformers are necessary.

In general, any table of relative costs of motor-generators and synchronous converters should be accepted with a certain amount of reserve. Each individual installation should be considered by itself and the costs of the various items compared. The cost of the switchboard and cables should also be considered; in this respect the motor-generator is usually much cheaper than the converter.

The following table gives the cost, efficiency, and the floor space needed for synchronous converters and motor-generators of different outputs. The converters are assumed to operate in connection with three single-phase, 6600-volt transformers. The motor-generators are assumed to run on 6600 volts without transformers. The efficiencies are the combined efficiencies of the sets—converters and transformers in the one case, and motors and generators in the other. In the case of converters, under the head of cost and floor-space, the first figure refers to the converter and the second figure to the transformers.

500 KILOWATTS, 600 VOLTS, 25 CYCLES.

	SYNCHRONOUS CONVERTER	MOTOR-GENERATOR
Cost...............	$4500+2700=$7200	$9000
Efficiency 1.25 load	91.5	88.
1 "	91.5	87.5
" 0.75 "	91.0	85.5
0.05 "	88.5	81.0
Floor space.........	60+50=110 sq. ft.	85 sq. ft.

500 KILOWATTS, 600 VOLTS, 60 CYCLES.

	SYNCHRONOUS CONVERTER	MOTOR-GENERATOR
Cost...............	$4700+2300=$7000	$8700.
Efficiency 1.25 load	90.5	88.
" 1 "	90.5	87.5
" 0.75 "	89.5	85.5
" 0.50 "	86.5	81.
Floor space.........	70+50=120 sq. ft.	90 sq. ft.

1500 KILOWATTS, 275 VOLTS, 25 CYCLES.

	SYNCHRONOUS CONVERTER	MOTOR-GENERATOR
Cost..............	$18 000+6 300=$24 300	$21 000
Efficiency 1.25 load	93.5	90.5
" 1 "	93.5	90.
" 0.75 "	92.5	88.
" 0.50 "	90.5	85.
Floor space.........	240+125=345 sq. ft.	320 sq. ft.

These are the selling prices free on board at the factory, and, therefore, do not include freight or cost of erection. They do include, however, all necessary rheostats and shunts, but not induction regulators for the converters.

In all three cases it will be noticed that the combination of a synchronous converter with transformers is the more efficient, the difference in efficiency being about 3% at full load and about 6% at half load. The value of this difference in efficiency has to be decided in each case by the cost of producing the extra kilowatt-hours. In a water-power plant the efficiency is an unimportant feature; in a steam plant, where the cost of fuel is high, it may be quite important.

The floor-space taken up by a synchronous converter and its transformers is about 25% greater than that taken up by a two-bearing motor-generator set. The floor space is only of importance in the case of a sub-station in a city where real estate is valuable; in such cases the transformers could be placed in a gallery over the converters. As the converters themselves only take up about two-thirds the floor-space of a motor-generator set the advantage would, with this arrangement, be in favor of the converters.

The relative desirability of synchronous converters and motor-generators from the operating point of view depends upon the question of their reliability and flexibility of operation. As regards flexibility, the motor-generator is, of course, by far the better. With motor-generators the power-factor of the motor may be adjusted to unity, or, if desired, a leading current may be introduced into the line without affecting the operation of the motor. The voltage on the direct-current side may be adjusted within wide limits either by use of the shunt rheostat, or by compounding. Neither of these adjustments can be applied conveniently to a converter.

In a synchronous converter the ratio of the voltage on the direct-current side to that on the alternating-current side is practically constant; that is, any drop or rise of voltage on the line affects proportionally the direct-current voltage of the converter. In trying to regulate the power-factor of the converter or to introduce leading or lagging currents into the line by varying the field strength one is liable to alter the alternating-current voltage at the end of the linc, and hence to affect the direct-current voltage of the converter. Variation of the shunt current within wide limits is also objectionable, because it sometimes has a tendency to produce hunting.

Theoretically a synchronous converter can be compounded or over-compounded, or rather the line can be over-compounded, producing the same effect as if the synchronous converter were over-compounded. This may be done by introducing an artificial self-induction into the line, and producing in the line, by means of a series winding on the converter fields, a leading current approximately proportional to the load on the converter This leading current will boost the pressure of the line because of the self-induction present. This compounding is, however, at best only a rough method and can only be used on systems in which exactness of pressure is not important. It is somewhat difficult to adjust the self induction and the series winding to give the required compounding. The power-factor of the converter and that of the system are varied within wide limits as the load varies. And a change of pressure on the line affects all other machinery on the line, so that the cases are limited in which this method can be used to regulate the direct-current voltage on a converter.

A method of voltage control with synchronous converters is used on some of the Edison systems. An induction regulator is inserted in the alternating-current circuit between the transformer and the converter, and is usually controlled from a switchboard by means of a pilot motor. Such a regulator increases the cost of the apparatus about 20%, decreases the total efficiency about 1%, needs about one-third the floor space that the transformers require, and adds to the complication of the system. Usually, therefore, the necessity for employing an induction regulator is a strong argument against the use of converters in such an installation.

A synchronous converter is more liable to hunt and to flash-over, and is a somewhat more complicated piece of apparatus than a motor-generator set. On the other hand, a synchronous motor wound for a pressure of over 6 600 volts is not so reliable as a transformer wound for the same pressure. Generally speaking, from the point of view of reliability of operation, there is little choice between 25-cycle converters and 25-cycle motor-generators, although in a 60-cycle installation the advantage is decidedly in favor of the motor-generator. There is no doubt that satisfactory 60-cycle converters can be made up to 600 volts, but their design is so much more difficult than that of 25-cycle converters that it is natural they should require more attention than motor-generator sets.

Motor-generators have another advantage over synchronous converters in that the former are not so liable to hunt as the latter. Of course, hunting can be prevented, but not without usually introducing some corresponding disadvantage; for example, dampers may be placed on the pole-faces, but with the disadvantage of causing some loss in efficiency; or substantial uniformity of engine speed may be obtained at the expense of a heavy fly-wheel; finally, to insure the small line-drop that is usually found necessary for the reliable operation of converters in parallel is a matter of considerable expense for conductors. Synchronous motors are not nearly so liable to hunt as converters, and the conditions that are good enough to insure the proper operation of alternators in parallel are usually all that are required to prevent hunting in synchronous motors.

From the operating engineer's standpoint, a motor-generator is preferable to a synchronous converter in almost every respect except as to efficiency and cost; and even as to cost a motor-generator is decidedly the cheaper for low voltages and large outputs. Consequently, when comparatively cheap medium-size units are wanted, and if close voltage regulation is unimportant, synchronous converters are used. But when large units are desired, and the voltage regulation is important, as in incandescent lighting, motor-generators are employed. This applies to both 60 and 25 cycles.

Heretofore the writer has referred mainly to synchronous converters for transforming from alternating current to direct current. In regard to inverted converters; that is, converters for transforming from direct current to alternating current, almost the same remarks apply. In addition, inverted converters are subject to another disadvantage—

the power-factor of the load on the alternating-current side affects the magnetic flux, which, in turn, affects the speed and frequency of the converter. A heavy inductive load on the alternating-current side tends to make the converter run away. This, of course, can be prevented by a speed-limit device, or by separately exciting the converter from an under-saturated exciter driven from the converter, or by making the armature of the converter very weak in comparison with its field magnet. But none of these devices can keep the speed absolutely constant under these conditions. And when the speed varies it causes the speed of all induction motors and synchronous motors on the line, fed from the converter, also to vary, which is highly objectionable. This, combined with its other faults, makes an inverted converter in many instances less desirable than a motor-generator.

Generally speaking, the higher the speed of a machine the less is its cost, so that it is to the interest of the manufacturer to run at as high a speed as possible. The possible speed for an alternator is limited only by mechanical considerations. The maximum speed at which a direct-current generator or a synchronous converter of a given output can be run is limited by sparking. Given the approximate speed at which a direct-current machine will run, the number of poles that the machine should have is fixed within narrow limits by sparking and cheapness of design. As the number of poles and speed determine the frequency of a machine, it is easily seen how the choice of speed at which a converter of given output, frequency, and voltage may be run is limited.

Suppose a 1 000-kw., 25-cycle, 600-volt converter is to be designed: to insure the cheapest machine the number of poles must be as few as possible so that the speed can be high. There are 1 670 amperes to commutate; this, to a great extent, determines the number of poles. On laying out the design of the machine, it is found that 10 poles will suffice, but that 12 poles will be better. Let 250 rev. per min. be decided upon. Assuming a pole-pitch of 21 in., we obtain an armature diameter of 80 in., 24 slots per pole, two coils per slot, and a length of armature core of 13.5 in. The slots are comparatively narrow, only 0.4-in. wide, so that solid pole faces can be used. This makes a very good machine. Fig. 1 shows a 1 000-kw. converter of similar design to that just described.

If a 1 000-kw., 600-volt motor-generator is to be designed, the number of poles on the direct-current generator can be taken care of, and the speed may be made as high as is consistent with good commutation. The speed may be as high as 300 rev. per min., but, just as in the case of the converter, a better machine would result if the speed were kept down to 250 rev. per min. Twelve poles is the correct number, and as a somewhat better sparking constant is wanted than in the converter, the armature is built with a slightly larger diameter. An armature of 86-in. diameter, with 16 slots per pole and three coils per slot is satisfactory. The width of slot is not limited as

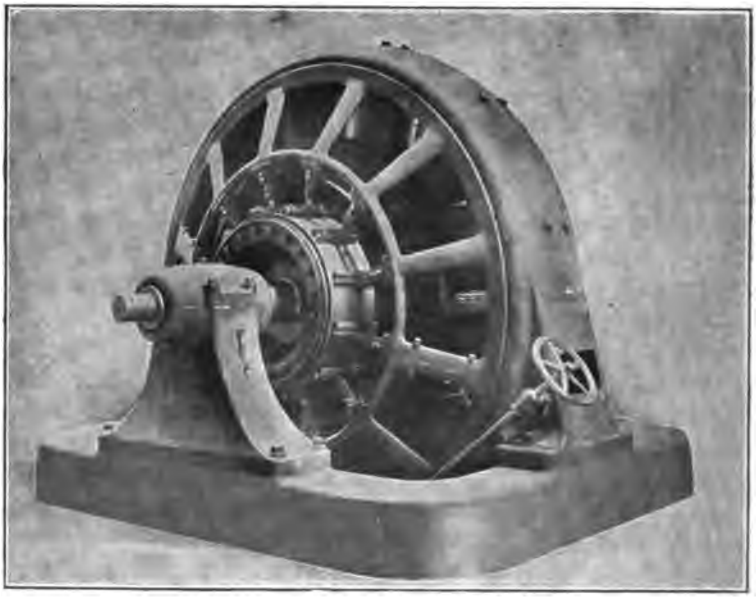


FIG. 1.—1000-kw., 600-volt, 25-cycle, 250-rev. per min. Synchronous Converter.

laminated pole-faces are to be used. This gives an armature length of 10.5 in. This also makes a very good machine.

This is one instance in which we find that the synchronous converter and motor generator will run at the same rate of speed and have the same number of poles. Of course, in this case, the cost of the converter and transformers will be considerably less than the corresponding motor-generator set.

Suppose, on the other hand, a 1 500-kw., 275-volt, 25-cycle machine is to be designed. It is found that the minimum number of poles for a direct-current machine of this output and pressure is about 20. This gives a 20-pole converter at 150 rev. per min., and an armature 130 in. diameter, 13 in. long, 24 slots per pole, one coil per slot.

The corresponding generator for the motor-generator set may be run at 214 rev. per min. by making it with 20 poles. This gives: armature 120-in. diameter, 9.5-in. long, 14 slots per pole, two coils per slot. In this case the cost of the motor-generator will be considerably less than that of the corresponding converter and transformers, simply on account of higher speed at which the motor-generator can be run.

Speaking generally from the designer's standpoint, there is not much to choose between the difficulty of designing a synchronous converter and that of designing a direct-current generator of the same output, speed, and voltage. The design of a converter is subject to more limitations than that of a direct-current generator. The number of commutator segments per pair of poles must be divisible by the number of phases, and the number of slots per pair of poles should also be divisible by the same number. The relative dimensions of the slot and air-gap are limited by the fact that eddy currents must be avoided in the solid pole-faces or copper dampers, which are usually employed to prevent hunting. On the other hand, however, the absence of armature reaction in a synchronous converter, is considerably in its favor as regards sparking when the machine is running with fixed brushes.

Investigating the conditions at the point of commutation in a direct-current generator by means of a pilot-brush when the machine is running at its full rated output with brushes set in the normal position, it is generally found that resistance commutation is taking place; that is, that the brushes are advanced just far enough for the armature field to neutralize the direct field due to the magnets at the point of commutation. Now as the load on the machine is increased, the increased armature reaction causes the resultant field at the point of commutation to become of the opposite sign to that which would be required for perfect commutation, thus tending to make the brushes spark. At the same time the increased current, which has to be commutated, also has a tendency to make the brushes spark unless the resistance of the brush contact is sufficiently high. Assuming that the maximum current is being taken out of the machine that the brushes could commutate by the varying resistance of their contacts if they were in a zero resultant field, any increase of load on the direct-current generator will cause the brushes to spark, for two reasons: first, because of increased armature reaction; secondly because the current becomes too great to be taken care of by resistance commutation, even assuming no armature reaction.

In a synchronous converter, on the other hand, the armature-reaction effect is not present, and the brushes may be assumed at all times to be either in a neutral field or in one that is helping the commutation. The result of this is that a direct-current machine run as a synchronous converter will carry, as regards sparking, heavier overloads with fixed brushes than will the same machine used as a generator. The sparking does not seem to increase so quickly in a synchronous converter as the load is raised. The result of this is that the sparking-constant in a converter is usually permitted to be about 25% higher than in a generator, under which circumstances a synchronous converter may run at a lower peripheral speed and with a longer armature core than the corresponding generator.

There being no resultant armature reaction in a synchronous converter some manufacturers design such machines with a high armature reaction and low volts per commutator-bar; that is, with a strong armature and weak fields, the idea being to save material in the construction of the machine and to lower its cost. This saving in cost however is not so pronounced as one might think at first sight, as the labor is increased quite materially when the number of coils on the armature and the number of bars on the commutator are increased. In addition, a strong armature is not conducive to good operation in a synchronous converter; it tends to make the brushes flash badly or even to flash over when starting from the alternating-current side, and it reduces the synchronizing power of the machine and tends to make it flash badly when hunting. Considering the question from all points of view, it is usually found that it is best to design synchronous converters with about the same armature reaction and volts per bar as the corresponding direct-current machines.

The copper loss in the armature of a polyphase synchronous converter is usually considerably less than in the case of the corresponding direct-current generator, so that such converters are sometimes designed with a much smaller cross-section of copper than would be used in a generator. This is bad practice. The copper loss in a synchronous converter armature is not equally distributed, the loss in the bars nearest the collector leads being usually much greater than in those midway between the leads. And although the difference in temperature at the end of a temperature run cannot generally be detected by a thermometer, the difference is very appreciable in the case of sudden overload at a low power-factor. And cases are on record where the armature bars connected to the leads in a large converter have been fused before the other bars got dangerously hot. For railway work the section of the copper in a converter armature ought to be at least equal to that in the corresponding generator.

As regards heating, six-phase synchronous converters have a slight advantage over two- or three-phase converters. But six-phase machines call for such extra complications in the cables and switchboard that they are seldom employed. In any case a six-phase converter may have to operate three-phase at some time, so it should be designed simply as a three-phase machine with three extra collector-rings. This being the case, the remarks before made in regard to the section of the armature copper and heating of conductors also apply to two- and to three-phase machines.

An important feature in the design of the armature of a synchronous converter is often overlooked, and that is equality or balancing of the phases. If the windings of the different phases on a converter armature are not all exactly equal and not all placed on the armature in an exactly similar and symmetrical position with regard to one another, then the phases will be unbalanced, with the result that the load will not be balanced among the phases and that there will be a greater tendency to hunting. If the three ammeters in the three phases of such a rotary are watched the load can be seen changing from one phase to another.

This is the reason why synchronous converters with series wound armatures are usually unsatisfactory. It is often impossible to balance the phases. A 6-pole, three-phase converter with a series wound armature with 224 coils, must have the rings connected to coils 1–26–51. An 8-pole three-phase converter with a multiple-wound armature with 520 coils, must have its rings connected to coils 1–44–86. The phases of both these armatures are unbalanced. To get the phases perfectly balanced the number of commutator bars per pair of poles should not only be divisible by the number of phases but the number of slots per pair of poles should also be divisible by the same number. The reason for this is that to get the different phase windings all symmetrically and similarly placed on the armature all the coils that are connected to the phase leads must be in the same relative positions in their slots.

Synchronous converters are more liable to hunt than synchronous motors. Generally speaking, conditions of operation and design that will enable two alternators to run satisfactorily in parallel without hunting will also enable one of them to run satisfactorily as a synchronous motor when driven by the other machine under the same conditions. A single converter driven from an alternating-current system will not operate under given conditions quite so well as regards hunting as a motor-generator. The armature reaction of a synchronous converter is considerably higher in proportion than that of a synchronous motor. Therefore, its synchronizing power is less and the fact that the direct-current side is so intimately connected to the alternating-current side makes it peculiarly sensitive to hunting.

But the main difficulties with converters in regard to hunting are experienced when two or more converters are running in parallel on the same alternating-current system and feeding into the same direct-current system. These difficulties are especially marked when the converters are running in parallel upon the same alternating-current and the same direct-current bus-bars. Under similar conditions motor-generators are no more sensitive to hunting than under the conditions of singly operated units. But the difficulties with converters are often so serious that operating engineers have found it necessary to insist that manufacturers provide all such machines with damping or anti-hunting devices.

Artificial damping devices of various types and forms have been tried, but the only one in use at the present time is a heavy grid of cast copper imbedded in the pole face. Another construction now in use for accomplishing the same result consists in solid pole-faces so shaped, and with the armature slots and air-gap so proportioned that eddy currents due to the teeth are avoided. As far as can be seen from practical operation, these two methods of preventing hunting seem equally effective. They both enable converters to be run in parallel satisfactorily, so long as the variation in speed of the engines and the pressure drop in the feeders is not excessive.

As regards the relative effects of a copper-grid damper and a solid pole-face upon the efficiency under working conditions it is difficult to speak within any degree of accuracy, so much depends on the uniformity of speed of the engines; but it is probable that there is often a constant loss in the copper-grid damper, as it is sometimes applied, with large armature teeth and small air-gaps.

Solid pole-faces call for a larger air-gap or smaller slot, which in turn demands more copper on the magnet. This is especially the case in 60-cycle converters. On the other hand, from a mechanical point of view it is a nuisance to have to fix auxiliary copper grids or dampers on any pole-face. The cost of the dampers is not insignificant. Generally speaking, then, there is little choice between solid pole-faces and auxiliary dampers, so it would perhaps be best to advise the use of solid pole-faces in all cases, as they are simpler and more mechanical.

Though synchronous converters have been used for quite a number of years yet their detail design seems to have received less care than has been given to generator design. A converter in a sub-station carrying a street railway load is usually subjected to pretty rough treatment, and consequently should be of robust design. All parts should be as accessible as possible in order to facilitate repairing.

Two features in the design of converters that are often faulty are the alternating-current collector gear and leads, and the starting resistance used for starting from the direct-current side. The alternating-current end of the machine is often designed similarly to the old revolving-armature alternators; that is, the leads are strap-copper soldered to the armature conductor and fixed to the armature end-plate with cleats. The collector-rings are mounted solid upon the shaft and separated and insulated by fiber or wood discs and bushings, the leads being imbedded in this insulation where they pass through or are connected to the rings.

This construction is shown in Fig. 2. It is unsatisfactory for heavy railway work. Solid copper leads cleated to the armature end-plates are liable to break due to vibration, and soldered joints are liable to melt under over loads. Collector rings mounted solid on the shaft are liable to break down due to warping or cracking of the insulation and to get hot on overloads due to poor cooling facilities. And when the rings are insulated by wooden discs projecting between the rings they cannot be easily turned off when they become cut or grooved by the metal brushes. The most substantial construction is to use cable for the leads and to connect them to the armature winding by special lugs riveted and silver soldered to the armature conductors. The rings should be carried on arms projecting from a cast-iron spider and should be freely open to the air all round for cooling, and be easily accessible for turning off whenever they become grooved or uneven from wear. In fact they should be designed exactly like the collector gear of

FIG. 2.—Synchronous Converter Armature and Collector Rings.

a revolving-field alternator. When this construction is adopted a temperature rise of over 10 degrees is rarely attained on normal load. Such collector rings are shown in Fig. 3.

Regarding a starting resistance for starting a converter or a motor-generator from the direct-current side, it is often forgotten that starting such machine is a much more severe operation than starting a motor. A converter or a motor-generator has to be run up to speed and then synchronized and when synchronizing the speed has to be exact. If the pressure on the direct-current system is varying, it often takes several minutes to synchronize a machine, and if it is varying suddenly the speed can only be adjusted by means of the starting resistance because shunt control is not quick enough. Starting resistances for converters or motor-generators should be designed so that the last steps can be kept in circuit for at least five minutes without overheating. An oil-cooled starting resistance that has been designed for this work is shown in Fig. 4. The resistance coils are of iron wire supported on porcelain insulators and connected to heavy brass terminals. The resistance is designed so that the temperature rise of the oil will be 150° cent.

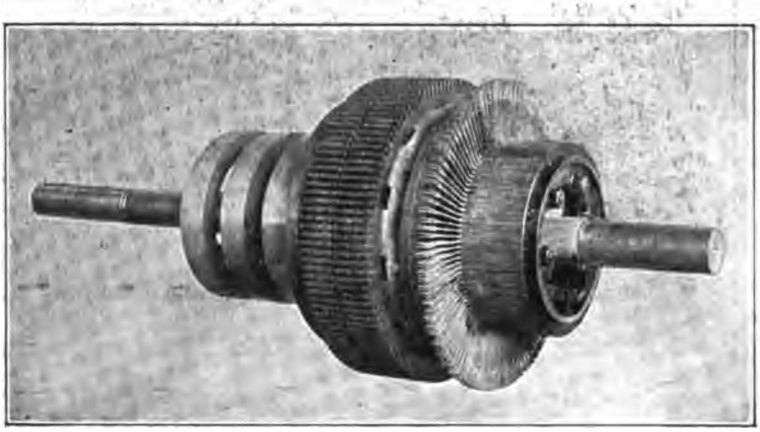


FIG. 3.—Collector Rings for Synchronous Converter.

in five minutes with all the coils carrying their maximum rated current. This type of resistance gives excellent results and has the additional advantages of being quite cheap and almost fireproof.

The usual starting switch, with overload and no-load release, is neither necessary nor desirable for synchronous converter work; it is too complicated and expensive and not reliable enough for such work. A standard multiple-contact switch is all that is required. Such a switch requires very little space and may be mounted on the converter panel.

This paper has not been written with the idea of advocating the use of synchronous converters instead of motor generators, or vice versa, but more with the idea of comparing them generally, their advantages and disadvantages, and of pointing out some of the characteristic features of each machine. The question as to which type of machine ought to be used in any given case can only be decided after every feature of the situation has been duly considered. Broadly speaking, however, the tendency to-day is toward motor-generator sets in lighting systems and synchronous converters on traction systems. This seems to be perhaps the most rational conclusion.

Motor-generators and synchronous converters, all things considered, are really considerably more difficult to design and build than the ordinary standard engine-type generator. They

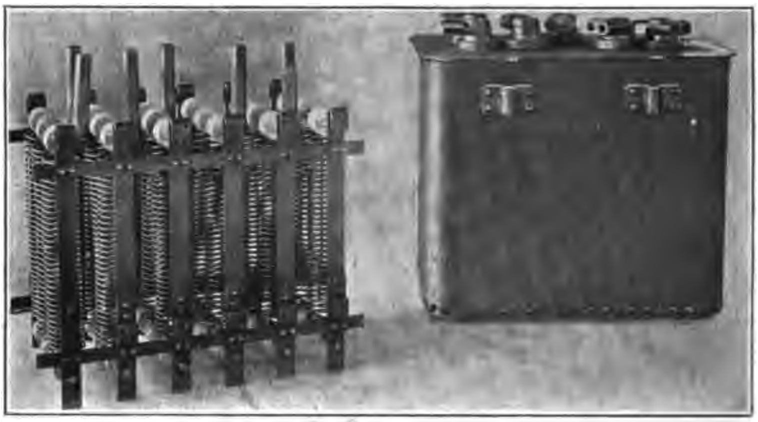


Fig. 4.—Starting Resistance for 1 000-kw. Motor-Generator Set.

are high-speed machines and usually run in sub-stations where the conditions of operation and the supervision are not of the best. The question of their reliability in continuous operation should therefore receive the most careful consideration from the designer and manufacturer. Suggestions and criticisms from operating engineers are of the utmost value to the manufacturers, and should always be welcomed and investigated to see whether or not they contain features valuable enough to warrant the alteration of standard designs.

Discussion on "Synchronous Converters and Motor-Generators."

Gano S. Dunn: I am very glad to see that motor-generators are beginning to get their due. When synchronous converters were first brought out their theoretical and apparent advantages were so great that too much attention was paid to them and it has taken us a long time to recognize the very great advantages that motor-generators possess. The relative costs that have been pointed out by Mr. Waters to-day, which were also pointed out by Mr. Eglin in a paper before the St. Louis Congress, and by Mr. Stott and others, are having the effect of drawing more attention to the availability of motor-generators. As I look at the tables on page 719 and especially with reference to the 500-kw., 600-volts, 60-cycles comparison, I see the motor-generator, costing under those conditions only 5 per cent. more. I would like very much if Mr. Waters would define what he means by the word "cost" in this table. There are so many things that may be included or excluded that the simple word alone does not give any information. He speaks of the motor-generator costing 20 per cent. more than the synchronous converter. Does that include any regulating device for the synchronous converter, also does it apply to machines set up or simply f.o.b. at the station; also are both machines three-phase?

It is often objected when motor-generators are proposed for railway load, that the fluctuations on the direct-current end are so serious as to interfere to a dangerous extent with the excitation of the synchronous end by the direct current, and therefore it is considered by some that a separate exciter driven by the same machine, is required. Of course if this separate exciter is required, it adds to the cost of the motor-generator as compared with the cost of the converter. I should like to have an expression of opinion as to what effect the fluctuating of the railway current has upon the excitation of the motor-generator. Whether these fluctuations are, after all, serious enough to throw the tide in favor of converters, or to make us feel that we ought always to use a separately excited synchronous motor.

F. G. Proutt: I do not quite agree with Mr. Waters in his elimination of the induction motor as a factor in motor-generator sets of large sizes. Where motor-generator sets are to be located in central-stations, it seems to me the induction motor is in every way preferable to the synchronous motor, and as nearly all lighting and power companies are now taking up induction motor loads in sizes varying from two to 200 h.p., a large number being of 50-h.p. capacity, it would seem as if a large number of these motors would be just as objectionable as a station load as several large motor-generator sets equipped with induction motors; the only objection in either case being the bad power-factor of the induction motor load and its effect on the general regulation of the system.

The first thing to consider in any central-station equipment is to have it as nearly as possible proof against harm from careless or unskilful operators, because continuous operation is, after all, of greater importance than efficiency. Apparatus that it is practically impossible for operators to get out of order present as nearly ideal a condition as can be obtained, and it can be said more truthfully of induction motors than of either synchronous converters or synchronous motors that they fill the conditions ideally.

The question of power-factor is only one of the many points that should be considered, and even with a synchronous motor outfit, there are very few occasions where the power-factor is actually unity, while with induction motors there is a good power-factor on anything over half load, and on light loads, even though the power-factor be low, the current taken by the motor is so small that the actual results, as far as regulation goes, will be much the same whether the induction motor be run on heavy load with good power-factor, motor taking large amount of current from primary generator, or with light load, and small amount of current from primary generator, at much lower power-factor.

From considerable experience with induction motor-generator sets of as high as 500-kw. capacity, and from experience in operating large number of induction motors on a distributing power service, my opinion is that the induction motor, from the standpoint of the central-station operator, should be used in a very large number of cases in preference to the synchronous motor for driving motor-generator sets.

Chas. P. Steinmetz: I agree with Mr. Waters in his preference for the motor-generator over the converter for 60-cycles. I also agree with his preference for the synchronous converter over the motor-generator for small 25-cycle units. But I cannot see why, for large 25-cycle machines, the synchronous converter should not also be preferable, except perhaps in special cases. The reason why Mr. Waters and I disagree on this point may possibly be due to difference of opinion regarding the designing constants of the synchronous converter. I do not agree with Mr. Waters that in synchronous converters low armature reaction is preferable. My experience has led me to the opposite conclusion, that high armature reaction is desirable. The advantage of high armature reaction is not the smaller size of the machine, which is offset by the copper on the armature being much more expensive than on the field, but the greater stability. A machine with extremely low armature reaction it is practically impossible to operate without serious surging, while high armature reaction reduces the tendency to surging. This I consider as one of the main reasons why a 60-cycle converter is not as good as a 25-cycle converter, because it is not possible with the limited pitch of 60-cycles to get as high armature reaction as is possible with 25 cycles. Both types of machines, converters as well as synchronous motors, occasionally hunt, but synchronous motors are practically always provided with some anti-hunting device in the field poles, while synchronous converters nowadays are practically not so provided. Only in special cases are anti-hunting devices used nowadays. The reason is the higher armature reaction of the converter feasible by the use of higher current densities in the armature which gives the synchronous converter a stability which the synchronous motor does not share to the same extent. The higher armature reaction and lower mechanical momentum, and thereby reduced tendency to surge, are the main reasons for utilizing in converters the high nominal current densities which are permissible due to the two currents neutralizing each other more or less completely, but not to the attempt to save copper. In the converter there obtains the stability of high armature reaction, without the distortion of the field, since magnetically the alternating-current and direct-current armature reactions neutralize one another. The result is that a synchronous converter can carry an overload without appreciably dropping its voltage, which no direct-current generator, designed with equally conservative constants, can carry. Therefore, the overload capacity of the synchronous converter is higher, and I doubt whether, by any other means, automatic regulation of voltage could be secured as perfectly as by the standard system of long-distance railway transmission by means of a series of sub-stations with over-compounded synchronous converters controlling the transmission-line voltage by the effect of current lead and lag on reactance, or as it is called, by phase control.

L. C. Marburg: The most probable explanation for the general preference of European engineers for the motor-generator may be found in the fact that a frequency of 50 cycles has been more or less standardized in Europe, while in this country 25 cycle current is used in all railway and power work. Our experience with 60-cycle converters substantially agrees with that of European engineers with 50-cycle apparatus of this description. Particularly does this apply to railway converters in which, on account of the high voltage, the number of commutator bars has to be large, although the distance between adjacent poles and, therefore, adjacent brush holders is small. This naturally results in thin segments, high voltage between segments, and a tendency to flash over. It seems that this point has been overlooked when Europeans speak of American practice in the use of converters, and when they state that converters always spark.

Referring to the superiority of the motor-generator due to the possibility of regulating its direct-current voltage by means of the field excitation. As far as city railway work is concerned, where the variation of load is small due to the fact that the individual cars are small compared with the capacity of the sub-station, there seems but little necessity of providing special means for keeping the direct-current converter voltage constant under varying loads. A light car, weighing in the neighborhood of 15 tons and fed from 500- or 1 000-kw. converters, will naturally affect the converter voltage but little when starting up. This is different with interurban roads operating 30- or 40-ton cars from 300- or even 200-kw. converters, but here automatic regulation can be obtained by means of reactive coils and compound winding.

In respect to hunting, Mr. Waters states, on page 728:

> "The main difficulty with regard to hunting is experienced when two or more converters are running in parallel on the same alternating-current system and feeding into the same direct-current system."

No difficulty should be experienced operating converters in parallel in this way as long as they are fed from independent banks of step-down transformers. Two converters in the same station will hunt in synchronism; that is, their speed will increase at the same time and will decrease at the same time, showing that the parallel operation is not the cause of the hunting. This fact was demonstrated very clearly in some tests made a few years ago.[1] Round disks with black and white sectors were fastened to the ends of the shafts of two converters located in the same station and were illuminated by alternating current arcs connected to the system supplying the converters. Obviously, as long as a converter is entirely in synchronism; the different sections will appear stationary provided the number of black and white sections is properly chosen, while as soon as it begins to hunt, the sections will move back and forth. In this way it was observed, that no hunting occurred between the two converters, but that they always hunted absolutely in synchronism.

The following explanation of the phenomenon seems reasonable. Hunting can not occur when the synchronizing power (the tendency of the cross currents flowing between machines out of synchronism to pull them into synchronism) is sufficient. With small resistance between machines, naturally the cross current will be heavy and, therefore, the tendency to hunt is slight; while with a large resistance between machines much smaller cross-currents will be caused by a certain angular displacement between the two armatures, so that, other things being equal, the danger of hunting will be greater. Hunting between converters in the same station, seems, therefore, improbable. It may be that the difficulty Mr. Waters has found in running converters in parallel was due to the fact that when he put the second machine in parallel and increased the total load, the drop between the main

1. Tests conducted by Mr. John B. Taylor.

station and the sub-station was increased so much that the converters at the sub-station hunted with generators at the main station or with converters in another sub-station. No difficulty, however, should be expected from the fact that the two machines are operating in parallel.

H. G. STOTT: A paper read by me before the INSTITUTE in March, 1901, contained a number of similar comparisons to comparisons given in Mr. Waters' paper. The efficiencies correspond quite closely in the two papers. I found that the costs, including all the different regulating devices, such as induction regulators required on a synchronous converter, brought the synchronous converter up to practically the same point as the motor-generator, and so I think they are about even on that point. I would like to call attention to the fact that a fluctuating load can be got from a synchronous converter without affecting the power-factor, and this cannot be done with a motor-generator. The reason is this: with a motor-generator set a fluctuating load on the direct-current generator changes the power-factor and a sudden increase in the load decreases the power factor, and that demagnetizes the field of the generator, so there is perhaps at least double the fluctuation repeated back on the generator. That effect is very marked. Now by using the compound winding on the synchronous converter and adjusting it to the proper point, the power-factor at the power-house and at the sub-station, under any condition of load from zero to full load, or any overload, can be held at unity, which in itself is a very important factor in the regulation.

MORGAN BROOKS: I would inquire of operating engineers whether motor-generators are not more satisfactory than synchronous converters under abnormal conditions, such as a short circuit on a street-railway feeder? That is, whether by using a motor-generator we may not rely upon the circuit-breakers to confine such trouble strictly to the direct-current side, and so prevent a complete shutdown, which I understand has sometimes resulted with converters from a comparatively small initial trouble.

PRESIDENT LIEB: In the operation of synchronous converters in large systems, it has been found necessary to provide synchronous converters with speed-limit devices, to guard against disaster to the converters when a short circuit occurs. In a large system with which I am familiar, two or three converters have been wrecked, owing to the absence of such devices. The speed-limit devices that were available when this system was first put in operation were crude and unreliable, so that a special type of speed-limit device had to be developed, using as a basis the Schaeffer and Budenberg tachometer. When a violent short-circuit or other disturbance came on the system there was a tendency on the part of the operator to disconnect the converters, partly from fear that if that were not done they would run away and be wrecked. It has been found that the operation of the improved speed-limit devices has not only saved converters in a number of cases, but has also given the operators such confidence that they have allowed the converters to remain connected with the system and to follow up the fall and rise of voltage without fear of disaster. Under these conditions converters have given good results, but it has also been found necessary to apply devices to prevent hunting when the system is lightly loaded. Under conditions of heavy load, with several generators in parallel, the necessity for anti-hunting devices disappears, and we have found on a large system there is no difficulty with parallel operation. One of the effects on a large system, when a heavy short circuit occurs, is to burn the commutator and collector brushes; in several cases the short circuits have been so violent as to produce quite serious effects on conductors that were near together and carrying heavy currents. When the short circuits occurred the series copper connectors of the storage batteries would momentarily carry large amounts of current, 10 000, 15 000, 20 000 amperes, and the result has been in several cases to force the copper bars out of their supports, break the insulators in which they were held, and throw the bars half way across the room. It has therefore been found necessary to provide against the repulsion which takes place in contiguous copper conductors, when carrying heavy currents due to short circuits by extra bracing and clamping of the conductors.

Gano S. Dunn: Were the three or four converters you describe, wrecked when acting as inverted converters? Was the short-circuit that caused the wreck on the alternating-current side or on the direct-current side?

President Lieb: As a general thing the short circuit is on the alternating-current side and in almost all cases it is due to mistakes of the operators. In a case that occurred several years ago, which completely wrecked a converter, stripping the winding, and wrecking the commutator, two parts of the system were operating from independent sources of current supply, one from an equipment of large capacity and one of small capacity. On a distant part of the system an operator by mistake threw the two sources of supply together without synchronizing, or without voltage adjustment, with the result that a converter not equipped with speed-limit device at a distant part of the system was wrecked.

L. C. Marburg: It would be interesting to learn if any of the members know of the runaway of a motor-generator under such conditions. If the generator is compound wound, it would seem as if the danger of such an occurrence would exist for reasons similar to those that cause compound converters to run away, although, of course, in the case of a converter an alternating-current short circuit on the line might result in a strong lagging current, which, by weakening the field of the converter would tend to increase the speed more than would be likely with a motor-generator. The possibility of a run-away, however, seems to exist with a motor generator set also.

CHAS. P. STEINMETZ: A synchronous converter, as long as it is connected on the alternating-current side with an alternating system of a power, large compared with the power of the synchronous converter, cannot run away under any conditions whether the current reverses or not. But if it disconnects from the alternating side, then it may run away, and the motor-generator set, whether a synchronous motor or an induction motor, will do the same. A motor-generator set disconnected from the alternating side and fed from the direct-current system into which it connects, may run away probably quicker than the synchronous converter, because the direct-current generator probably has a more powerful series field than the converter, and this series field reverses and demagnetizes. However, with a reverse-current circuit-breaker on the direct-current side, no running away is possible in either case, except by a failure of the circuit breaker, and against this a speed limiting device must guard.

L. C. MARBURG: I have made observations recently that I think may be of interest in connection with the operation of 60-cycle converters run alternately from a three-phase generator and from a 600-volt direct-current generator. I have run the converter on a railroad circuit carrying a locomotive that had a capacity very much larger than the converter itself. I have seen the circuit-breaker operate on the direct-current end of the converter at 350 amperes while, when the load of the rotary is 362, the converter was held absolutely steady up to that. The converter is provided with a reactive coil and series winding. I have been able to set the power-factor, what I call the minimum average load, at about 85 or 90 per cent. I had to take that by observation. I did not have a power-factor indicator. I found the regulation excellent. Not having engine power behind it, I did not get the regulation desired.

Speaking of inverted converters with inductive load, I would like to ask Mr. Waters where he thinks that danger of running away would occur? I have had it up to one-third load on incandescent lighting and have put in an arc system with low power-factor, and have been unable to notice any increase in speed of the converter or any fluctuation in voltage at all. Up to what point that would be the case I have not been able to determine, but up to one-third or one-half load I have been unable to notice any variation in voltage whatever, whereas the same load on an alternating-current generator not provided with an automatic generator regulator would have to regulate by hand very rapidly.

In connection with the speed-limit device which is a speed-switch on the alternating-current end of the converter set for an excess speed of 300 rev. per min., or 1 200 revolutions on the converter, we have not had it go above that. The increase in speed is not appreciable.

GANO S. DUNN: Dr. Steinmetz' remark that the motor-generator would run away as soon as the synchronous converter, seems to me not strictly correct. It would take more kilowatts in the short-circuit on its alternating side to make the motor-generator run away than the converter. For instance, an inductive short circuit involving very few kilowatts on the alternating side of the converter would cause demagnetization of its field sufficient to make it run away; but a similar short circuit on the alternating side of a motor-generator would cause so small a back current to flow through the series fields of the direct-current side that the speed would be increased only a little and there would not be a runaway and a wreck.

The motor-generator would also be more likely to burn out a short-circuit on the alternating side and save itself than would a converter.

W. L. WATERS: The costs given in the table are selling prices f.o.b. at the factory, and include the necessary rheostats or shunts, but do not include induction regulators. If induction regulators are included, then as Mr. Stott has said, there will be practically no difference between the cost of a motor converter outfit and a motor-generator.

In regard to the necessity for a separate exciter for a motor-generator when the load on the direct-current side is fluctuating very quickly: the only effect of the fluctuating load would be to cause the direct-current voltage to vary somewhat, which would vary the excitation of the synchronous motor. This means that the current in the alternating-current lines would also vary. But under ordinary circumstances there would be absolutely no danger of the motor falling out of step, so long as the voltage on the direct-current side did not vary more than 40% or 50%.

I agree with Mr. Steinmetz that the synchronous converter is more capable of carrying overloads than is a motor-generator. And as I have remarked in my paper, I also think that the application of synchronous converters is confined more to traction installations where they have to carry heavy overloads and where exact voltage regulation is not of importance.

In regard to converters running away, the only machines that can run away are those with compound field winding. A shunt-wound motor-generator or converter cannot run away, and as the tendency nowadays is towards shunt windings for generators, I cannot see that this danger is very serious, at any rate in the case of motor-generator sets. Of course in an inverted converter with shunt windings, an inductive load on the alternating current side will cause the speed to rise and the extent to which the speed rises is merely a question of the design of the machine. Usually, however, the synchronous converters can be designed so that the rise in speed is not serious and can be taken care of by a speed-limit device.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19–23, 1906.

A NEW INSTRUMENT FOR THE MEASUREMENT OF ALTERNATING CURRENTS.

BY E. F. NORTHRUP.

The instrument and methods of measurement described in this paper were developed to meet the frequent need of means for easily and accurately calibrating alternating-current instruments—ammeters and voltmeters, whatever their capacity; also to suggest an inexpensive method of measuring with high precision very large alternating currents regardless of their wave form or frequency. Incidentally the instrument and methods should prove sufficient for the accurate measurement of currents of very high frequency where ordinary methods would not be applicable.

A further object kept in mind was to make it possible to utilize an installation of a direct-current potentiometer outfit, to measure alternating currents and pressures with nearly equal facility and precision.

The instrument and the methods of using it have been successful because the following important features have been realized: (*a*) It is used as a *zero instrument*, and does not depend upon any calibration or determination of any constant of the instrument; (*b*) it operates with extreme sensitiveness, and being perfectly "dead-beat" is adapted to work with fluctuating currents; (*c*) it may be used with or without low-resistance shunts; when used with them, it has an unlimited upward range of current measurement; and when used without them, its lower range is down to from two to five milliamperes; (*d*) as the operation of the instrument depends upon the heating effect of currents, it is wholly independent of wave-form and frequency.

The cuts and descriptive matter in the following pages describe the instrument clearly. Referring to Fig. 1, two small wires, *A B*, of No. 33 hard-drawn silver wire when shunts are used, lie parallel to each other at a distance of 0.158 in., being held near their extremities by ivory clamps, *C C*. Each of the ends of the two wires are connected to binding posts through the medium of heavy leads and soldered joints.

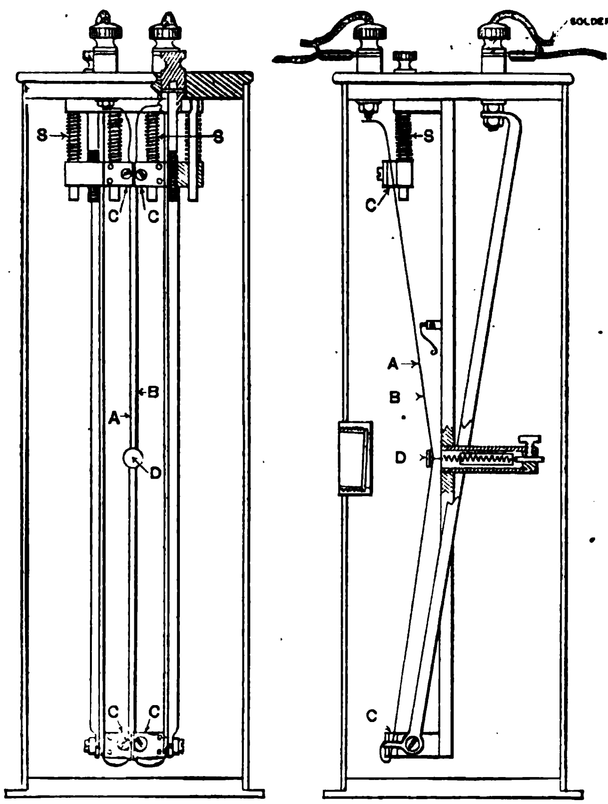


Fig. 1.

One face of a small circular disk of ivory, *D*, rests against the two wires at their middle point, a 0.5-in. circular mirror being fastened to the other face. Fastened at the center of the ivory disk, and half way between the wires, when the disk is in position on the wires, is a small hook. To this, through the medium of a thread, is fastened a small adjustable spiral spring. The small ivory disk maintains its position by friction and the tension of the spring. The wires bend back under the tension of the spring about 0.875 in. from the vertical. The ivory disk does not rest directly upon the wires but bears upon each wire through the medium of a small agate stud shaped like the head of a screw, each wire being in the slot of the agate stud which rests upon it

The two ivory clamps holding the wires near their upper extremity are made separately adjustable in a vertical direction by means of thumb-screws which pass through the hard-rubber

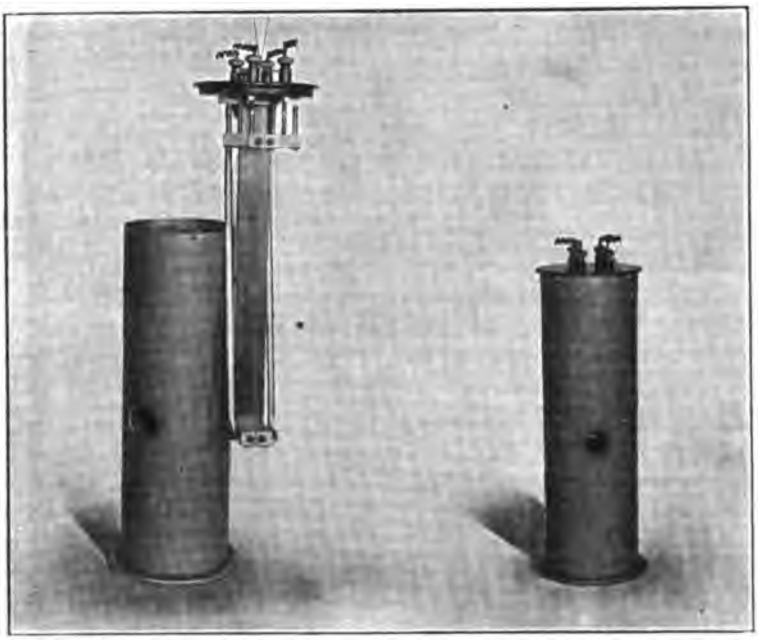


FIG. 2.

top of the instrument. Springs *s s* prevent lost motion when the ivory clamps are screwed up or down.

The arrangement of parts above described is supported by a brass frame and a circular hard-rubber top. This frame drops into a circular nickel-plated brass case. (Fig. 2). The case has a window in it directly in front of the mirror on the small ivory disk. Fig. 2 shows clearly the arrangement of parts and the appearance of the instrument.

By means of the adjusting screws the tension of the two wires may be so adjusted that the plane of the mirror will be vertical to a line drawn in the direction of the spring which holds the mirror against the wires. Now if any elongation occurs in the wire on the right, that side of the mirror will be drawn down or back by the spring, or a deflection to the right is obtained. Likewise, if an elongation takes place in the wire on the left, the mirror will deflect to the left. If, however, an exactly equal elongation occurs in both wires at the same time, the plane of the mirror will not tilt but simply move back keeping parallel to itself.

If the mirror is observed with a telescope and scale, say at a distance of one meter, very minute angular deflections of the mirror will be easily observed, while a sinking back of the plane of the mirror away from the scale will not be observable.

Now if an alternating current of unknown strength be sent through the wire A, the wire will elongate, deflecting the mirror toward the left. Pass an adjustable direct current, which can be measured, through the wire B, until the deflection is reversed and brought back to zero on the scale. If when the deflection is zero, and certain precautions to be stated later have been observed, the strength of the direct current is known, the strength of the alternating current will also be known; for it is exactly equal to the direct current. This, however, is on the assumption that equal currents through the wires A and B produce equal elongations of the wires. Previously to comparing the currents, connect the wires A and B in series, and send a current through the circuit; if under these conditions the mirror be not deflected at all, or only slightly, it proves that the two wires are practically equally elongated by the same current strength. The limit of this possible small deflection may be taken as the true zero of the instrument. If this zero is maintained under working conditions, it means that the strength of the alternating current in the wire A, is equal to the strength of the adjustable and measured direct current in the wire B.

The instrument, however, if limited to such currents as could be passed directly through its wires, would have comparatively little value. We shall show how it may be used with shunts so as to measure alternating currents, however large.

The arrangement of the complete circuits for measuring a large alternating current, for the purpose of calibrating an alternating current ammeter, A; is shown diagramatically in Fig. 3. An important accessory to the instrument is a quick-acting double-throw switch, marked S in the diagram. W_a and W_d represent the two wires of the instrument and m the mirror. R is a low-resistance shunt, preferably of manganin, having a negligible temperature coefficient, furnished with tap-off points c and d, between which the resistance R has previously been determined. The ammeter indicated in the diagram will measure from one to two amperes of direct current; r_2 is a slide wire resistance along which a slider p may be moved, thereby varying the pressure difference at a–b from zero to the value of the electromotive force of the storage-battery.

The points a, b, on the direct-current side of the circuits have leads attached to them which go either to an accurately calibrated direct-current laboratory standard voltmeter, or to a

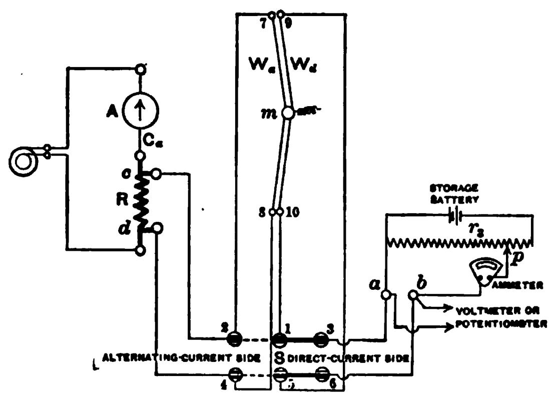


FIG. 3.

potentiometer. It will appear later that except for the highest possible precision it is more convenient to employ the standard voltmeter, but assume for the present that a potentiometer is employed to give the potential difference between a and b.

When the instrument is installed a permanent adjustment of the resistances, at any convenient temperature of the wires and leads, must be made as follows: (see Fig. 3.)

$$\text{The resistances, } 9 \text{ to } 10 = 7 \text{ to } 8,$$

$$10 \text{ to } 1 + 9 \text{ to } 5 = 8 \text{ to } 4 + 7 \text{ to } 2 \text{ and}$$

$$2 \text{ to } c + 4 \text{ to } d = 3 \text{ to } a + 6 \text{ to } b.$$

Thus while this gives the over-all resistance from a through the wire W_d to b equal to the over-all resistance from d through the wire W_a to c, the different portions of the circuit must be matched in resistance as stated above.

It will be observed that if the switch S is closed on the alternating-current side the two wires W_a and W_d are thrown in parallel, that the two parallel-connected circuits have the same resistance, by construction, and that to these parallel circuits at the points 2 and 4 is applied the same potential difference, this potential difference being the drop on the low resistance R carrying the alternating current. The drop over R, inasmuch as it is a low resistance, is only slightly lowered by being shunted by the two wires of the instrument and their leads, and this lowering of the potential is not appreciably greater when the two wires in parallel shunt the resistance R than when only one wire with its leads shunts this resistance. Disregarding the slight lowering of the potential, which, as will appear later is of no consequence, we observe that both wires will now have passing through them equal currents, each current being nearly the same as would pass through the one wire W_a if the switch S were open, and only this wire could receive current.

With the resistances of the parallel circuits correctly adjusted to equality, both wires will get equal currents, both will elongate equally or very nearly so, and the mirror m, instead of rotating will move back, maintaining its plane parallel to the position which it has with no current passing.

When the switch S is thrown to the direct-current side, the potential drop over the resistance R is now applied to the wire W_a only; and the direct potential difference between the points a and b is applied to the wire W_d. This drop between a and b can be varied by the slider p and measured by a voltmeter or potentiometer applied at a, b. The ammeter gives the current taken by the wire W_d.

The shunt resistance R may be designed to carry any current, however large. The same resistance R, or a combination of resistances, may be designed with several tap-off or potential points, so that the instrument may always have approximately the same potential applied to its alternating-current side, whatever the strength of the current to be measured. This potential drop is best made between 0.25 and 0.5 volt. The necessary drop of potential being so low, the energy dissipated in the shunts is small, and therefore they may be of very moderate size. It is also easy to make them practically non-inductive.

Consider now the circuits to be arranged as above described, and that a standard voltmeter is used, calibrated to give a full-scale deflection for about 0.75 volt, to indicate the direct potential between a and b. Then proceed to take measurements to calibrate the alternating current ammeter A, (which may have any current carrying capacity whatever above one ampere), as follows:

A shunt R and tap-off points are first so placed that when the ammeter reads a full-scale deflection, the drop on the shunt R from c to d, varies from 0.25 to 0.6 of a volt, but preferably 0.5 of a volt. If the ammeter is known to read approximately correct, and since the value of R is known, we can gradually increase the current through the ammeter and shunt resistance until the proper potential drop is obtained; that is, the drop that will properly sensitize the alternating-current instrument. If, however, the ammeter gives no guide to the true value of the current, the switch S may be left in its open position; the alternating-current instrument can then be read as a deflection instrument. In this case the current through R should be increased until the alternating-current instrument deflects to the end of the scale, when the drop over R will be about right for the condition of good sensitiveness.

The adjustment being made, the switch S is closed on the alternating-current side, when the alternating-current instrument will take a steady zero position; and if carefully made and adjusted, exactly the same zero position as when no current is passing.

The zero position is now carefully noted and the switch S is then thrown to the direct-current side. The instrument will at once deflect until by moving the slider p the direct potential between a, b, balances the alternating potential between c, d, when the instrument will return to zero position. This adjustment can be made with great exactness, say to within $\frac{1}{10}\%$. The switch S may now be thrown across the alternating-current and the direct-current side, alternately, to prove that the adjustments have been correctly made; this will be the case if no permanent deflections result. The voltmeter is read, also the direct-current ammeter, and the alternating-current ammeter A being calibrated. These readings give all the data for making a very exact calibration of one point on the scale of the ammeter under test. Other points on the scale can be similarly taken by varying the alternating current, and also the shunt resistance R. Inasmuch as, by varying this latter, we can read a small current with the same precision as a large one, the low points on the scale of the instrument under calibration can be determined with as great precision as the high points.

In practice the direct-current ammeter is omitted. A preliminary set of readings is taken to determine its indications corresponding to the different potentials that may be produced between a and b. With a given instrument and set of working wires and leads and voltmeter, the current in the circuit $p\,b$, Fig. 3, is a function of the potential difference between a and b. This function may therefore be found by trial and plotted as a curve. This having been done, it only becomes necessary in calibrating an ammeter to take readings, in addition to the instrument being calibrated, of a voltmeter, and the zero position of the alternating-current instrument. The expression which gives the value of the alternating current C through the ammeter A is

$$C_a = \frac{r-R}{r\,R} E + c = K\,E + f\,(E) \tag{1}$$

where r is the resistance of the voltmeter, R the value of the shunt used, E the potential read on the voltmeter, and c the current in the circuit p. K is a constant, and as ten values of R will cover all currents from 1 to 1000 amperes, the values of K can be calculated once for all. Furthermore, by properly choosing the values of R, K can be made to assume the convenient values 10, 100, etc. $f\,(E)$, the function of E, is readily taken from a curve and added to the product $K\,E$. $f\,(E)$ is usually small compared with $K\,E$ and need not be accurately known.

Formula (1) is obtained as follows:

Calling x the resistance of the circuit from c to d, Fig. 3, through the wire W_a, we shall also have the resistance from a to b through the wire W_d equal to x, when it carries a current equal to that carried by W_a. This assumption is sufficiently correct in practice, for the two circuits are adjusted to be equal in resistance at the temperature of the room, and as the two circuits are constructed of precisely similar wires, the equality of their resistance will be closely maintained when warmed by the passage of equal currents. We then have

$$C_a = \frac{E_a}{R} + C^1$$

where E_a is the drop from c to d and C^1 is the current through W_a.

Now when the alternating-current instrument is balanced, $E_a = E$, where E is the electromotive force read on the voltmeter.

Calling C_1 the current through W_d, when the instrument is balanced, C_2 the current through the voltmeter, and C the current through the ammeter, we have $C = C_1 + C_2$;

but r being the resistance of the voltmeter $\frac{C_1}{C_2} = \frac{r}{x}$,

hence $$C_1 = \frac{r}{r+x} C.$$

Also $$\frac{E}{x} = C_1 \text{ or } x = \frac{E}{C_1},$$

which gives $$C_1 = \frac{cr - E}{r}.$$

When the instrument is balanced equal currents flow through the wires W_a and W_d, hence $C^1 = C_1$ and we have

$$C_a = \frac{E}{R} + \frac{Cr - E}{r} = \frac{r - R}{rR} E + C.$$

$\frac{r-R}{rR} = K$, a constant, and C is a function, $f\ E)$, of E, so we can write

$$C_a = KE + f(E).$$

Dividing numerator and denominator of the expression $\frac{r-R}{rR}$ by r we have

$$\frac{1 - \frac{R}{r}}{R}$$

which is equal to $\frac{1}{R}$ when r is infinite; therefore if a potentiometer be used to read the potential at a, b instead of a voltmeter, the value of C_a is

$$C_a = \frac{E}{R} + C = \frac{E}{R} + f_1(E) \tag{2}$$

Here $f_1(E)$ is the function that c is of E, when no current is shunted through a voltmeter, and, as in the use of a voltmeter, it may be determined by trial, and plotted as a curve.

It is possible to measure E more accurately with a potentiometer than with a voltmeter, and the alternating-current instrument is at least four or five times as sensitive in its indications as a large laboratory standard Weston voltmeter. It is

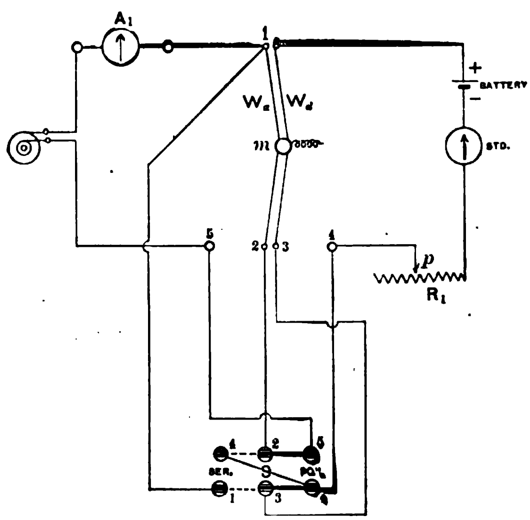


FIG. 4.

therefore desirable, where great precision is required and the alternating current being measured can be held steady, to use a potentiometer instead of a voltmeter. For all ordinary calibration purposes, however, the latter instrument is quite sufficient, and easier to read. If the current to be measured is less than about 1.5 amperes, it can be passed directly through the instrument, no shunts being required.

For the measurement of small currents a modification in the connections and method of measurement is desirable. We have found the connections shown in Fig. 4 to be most convenient for this purpose.

In this diagram A_1 is any alternating-current instrument to be calibrated that does not take more than 1.5 or 2 amperes, and Std. is any form of standard instrument that will accurately measure a small direct current. Now when the switch S is thrown to the side Ser., the wires W_a and W_d are so connected that the same current from the cell B will pass through them in series. This current may be regulated by the rheostat R_1. When the switch is thrown to the side *Pa'l* the alternating current will pass through the wire W_a and the direct current through the wire W_d.

With the switch in the position Ser. the differential zero of the instrument is noted. This zero, by careful construction and choosing of the working wires, may be made to differ not more than a fraction of a scale division from the no-current zero. The switch is now thrown to the position *Pa'l*, and the rheostat R_1 is adjusted until the instrument shows no deflection from the zero position found when the switch was in the position Ser. The switch may now be swung from side to side once or twice, the rheostat R_1 being more finely adjusted until there is not the slightest deflection. The value of the alternating current; that is, the square root of its mean-square value, is now equal to the direct current as read by the standard instrument, Std. The accuracy of this comparison can be made very great. If the alternating current is perfectly steady for a period sufficient to read the instruments, an accuracy of a $\frac{1}{10}$ of 1% is not too much to expect if the current being measured has a value which is such as to give the instrument a good sensitiveness.

If it is required to read very small currents, it becomes necessary to change the wires in the instrument, using finer wires suited to give the necessary sensitiveness, which is always obtained if, when passing the current to be measured through one wire only, the instrument gives nearly a full-scale deflection.

The following analysis will assist in a proper understanding of the most suitable circuit arrangement and wires to use for different kinds of measurements and current values.

Referring first to Fig. 5a, let *a-p-b* be the no-current position of one of the wires viewed from the side, that is, along a line perpendicular to the normal to the face of the mirror, and to the wire. Let Fig. 5b represent the two wires viewed along a line normal to the face of the mirror. For small deflections the angle θ through which the mirror turns when the wire $a\ b$ expands will be

$$\theta = \frac{x_1 - x_0}{d}. \tag{3}$$

d being the distance between the wires and $X_1 - X_0$ the distance that the expanded wire moves back under the tension of the spring.

Taking the meaning of the symbols to be as shown in the diagram, Fig. 5a, we have

$$x_1 - x_0 = (l_1^2 - l^2)^{\frac{1}{2}} - (l_0^2 - l^2)^{\frac{1}{2}} \tag{4}$$

This equation does not lead to any simple expression, and shows that the instrument does not follow any simple law when used as a deflection instrument. Equation (3) shows that the

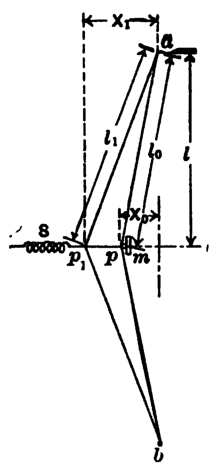


Fig. 5a.

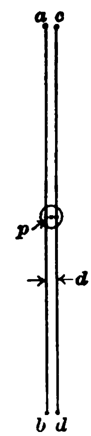


Fig. 5b.

sensibility will decrease in direct proportion to the distance separating the two wires.

We shall now determine the best kind of wires to employ when the instrument is used with shunts, and also when the entire current is to be sent through its wires.

Let δl_1 be the increase in the length of the wire per unit of length due to the increase in its temperature produced by the flowing of the current. If l_0 is the length of the wire, $\delta l = \delta l_1 l_0$ is the total increase in the length of the wire.

Let $T = t_1 - t_0$ be the increase in the temperature of the wire above its surroundings, t_0 being its temperature with no current and t_1 its final temperature with current flowing.

We will then have, if λ is the coefficient of expansion of the wire,

$$\delta l \propto T l_0 \lambda \tag{5}$$

T will reach a steady state when the rate at which heat is generated in the wire equals the rate at which it is dissipated. In the absence of experimental data, the most reasonable assumption to make in regard to the rate at which heat is dissipated from the wire is that the rate is proportional to the difference of temperature $(t_1 - t_0)$ and to the exposed surface of the wire. Heat will be generated at the rate, $c^2 r$, when c is the current in the wire and r is its total resistance.

Therefore, when the temperature is steady,

$$c^2 r = k \pi l_0 d (t_1 - t_0)$$

Where k is a constant, and d is the diameter of the wire. This relation may be written in the more simple form

$$c^2 r \propto l_0 d T \tag{6}$$

or

$$T \propto \frac{c^2 r}{l_0 d}.$$

Substituting this value of T in (5) we have

$$\delta l \propto \frac{c^2 r \lambda}{d} \tag{7}$$

Since $r \propto \frac{l_0 \rho}{d^2}$, ρ being the specific resistance of the material from which the wire is drawn,

δl becomes, $$\delta l \propto \frac{l_0 \rho \lambda}{d^3} C^2 = \text{current formula} \tag{8}$$

This expression for the elongation shows that when the current is passed directly through the wire to obtain the maximum effect with a given current and wires of given length, wires of high specific resistance, large coefficient of expansion, and small diameter should be used. Kruppin wire 0.025 mm. diameter, 387 ohms to the foot, has been used with great success, and will give deflections of several scale-divisions with two to five milliamperes. The deflections are astonishingly quick, taking place in about ⅓ second, and the return to zero is accurate and dead-beat.

If the instrument is to be used with a shunt, only a certain limited electromotive force, E, can be applied to the terminals of the wires. In this case wires of entirely different character need to be employed. For we have

$$C^2 = \frac{E^2}{r^2} \alpha \frac{E^2 d^4}{l_0^2 \rho^2}$$

Putting this value for c^2 in (8), we have

$$\delta l \alpha \frac{d \lambda}{l_0 \rho} E^2 = \text{electromotive force formula} \tag{9}$$

Here it is seen that the diameter of the wire should be large and its specific resistance low. Experiments show that if the diameter be made too great the instrument becomes too sluggish in its movements, creeping back slowly to its final zero. Therefore it is desirable to keep down the diameter of the wire, and obtain the necessary sensibility by choosing λ large and ρ small. As the result of many trials, using wires of different sizes and materials, such as copper, manganin, brass, steel, phospho.-bronze, platinum, and silver, it is found that No. 33 hard-drawn silver wire gives the best and entirely satisfactory results. An electromotive force of about 0.5 of a volt applied to the terminals of a No. 33 silver wire gives a full scale deflection at a meter distance, the wire getting just perceptibly warm.

By means of equations (8) and (9), and knowing the sensibility that is obtainable with any one wire, and the constants λ and ρ, one can calculate pretty closely the sensibility that can be obtained with any other wire of any diameter d.

Experimental instruments were constructed and tested before the final form illustrated in this paper was designed. The experiments were continued over a period of three months; many arrangements were tried that cannot be here described, although some interesting phencmena were observed. Many difficulties were at first encountered, due to improper construction, but in the final instrument these were entirely overcome. As now constructed it is very simple to adjust and use. At first it was thought that to insure a uniform action of the wires it would be necessary to fill the case with a thin transparent oil. The instrument works well with the wires in oil, but on account of the great rate at which oil dissipates the heat, a much greater current is required for a given deflection with the wires in oil than when in air.

Ordinarily the instrument is used with the wires in air; but if the instrument is to be used to measure a current passed directly through it that is somewhat too great for its capacity with a given pair of wires in air, its capacity can be greatly increased without changing the wires by simply filling the case with kerosene oil, the case being constructed oil-tight for this purpose.

The following are a few sample measurements made with the instrument. Experiments on the measurement of direct currents were made, some of which are here given, because direct currents could be accurately measured by passing them first through a standard low resistance, the drop in which could be read by a potentiometer, and thus give an accurate check on the results obtained by the alternating-current instrument.

Example I. Direct current passed through the resistance R (Fig. 2).

(1) True value of current =	7.097	
$R=0.1\ \Omega$, current measured =	7.093	error = 0.056%
(2) True value of current =	7.392	
$R=0.1\ \Omega$, current measured =	7.392	error = 0.000%
(3) True value of current =	50.920	
$R=0.01\ \Omega$, current measured =	50.928	error = 0.016%

Example II. Alternating current passed through resistance, R, and measured by a 100-ampere Kelvin balance; $R = 0.01\Omega$.

(1) Current by balance =	49.92	
Current by instrument =	49.90	Dif. = 0.050%
(2) Current by balance =	49.460	
Current by instrument =	49.498	Dif. = 0.077%

The last results, as far as the alternating-current instrument is concerned, could have been made still closer. But as the current was not steady, and the Kelvin balance not a dead-beat instrument, it could not be read with certainty closer than $\frac{1}{20}$% to $\frac{1}{10}$%, a fact which incidentally shows the superiority of the alternating-current instrument for making accurate calibrations.

Example III. In this experiment, a direct current was first passed through a standard resistance and measured by a potentiometer; it was then passed through a commutator that changed it into an alternating current. The alternating current was then measured by the instrument, the resistance R being 0.1 Ω.

The results were as follows:

The current, when direct and as measured by the potentiometer, was 8.365 amperes.

The current alternating, and as measured by the instrument, was 8.359 amperes.

The per cent. difference being thus but 0.070%.

In order to prevent sparking at the commutator segments, two condensers of one microfarad capacity each were connected across the circuits. This had the odd effect of making the alternating current appear about one per cent. higher than the direct current, due to surgings set up in the circuits, which the alternating-current instrument took account of and measured, but which the potentiometer failed to show. This experiment very forcibly illustrates the power of the instrument to measure the entire current flow in a circuit.

Example IV. The instrument was fitted with Kruppin wire, 0.025 mm. diameter, to make it sufficiently sensitive to measure the current from the high-pressure winding of a 7-inch induction coil. At first great difficulty was encountered due to the intermittent character of the induction coil discharge, the mirror rapidly oscillating from side to side in an irregular manner. This difficulty was readily overcome, however, by placing back of the mirror a brass strip about 0.063 in. thick, 0.75 in. wide and 3.5 in. long, with its greatest length at right-angles to the instrument wires. The strip was supported from a hook a few inches above it by a fine thread. The case of the instrument was filled with kerosene. Thus great inertia and damping were obtained, and it was easy to get a fairly accurate measure of the mean value of the induction-coil current, which was about 30 milliamperes.

It should be easy to obtain with the aid of this instrument an accurate measurement of the currents of a high-frequency coil, or the high-frequency currents now being used for many experimental purposes, that are produced either by special high-frequency dynamos, or by interrupted electric arcs.

It may be remarked finally that this instrument has the following useful features: it is inexpensive as compared with a Kelvin balance or with the Siemens electrodynamometer, which, when constructed for measuring large currents, is very costly to make and to calibrate. It is simple and easy to understand and manipulate. It is not delicate, and is uninfluenced by the proximity of iron or other ordinarily disturbing influences. Unless very accurate results are required, it is easy to substitute a pointer for the mirror, and thus make the instrument portable. It is not affected by ordinary mechanical vibrations. If any injury happens to the working wires, they can be quickly replaced.

Discussion on "A New Instrument for the Measurement of Alternating Currents."

E. F. Northrup: Before speaking directly on the subject of this paper, a few general remarks may not be out of place.

Electrical measuring instruments may be divided into two classes, which for convenience I shall call primary and secondary instruments. The secondary instruments usually give their indications by means of a pointer or by dials. This class of instruments answers certain requirements that are not called for in the primary instruments. The secondary instruments, voltmeters, ammeters, and the like, should, as a rule, be robust, giving their indications directly, but not necessarily with a high precision. The primary instruments, potentiometers, the instrument which is the subject of this paper, and the like, are used to calibrate the secondary instruments. They do not necessarily need to be portable and often it is not required that they be direct reading, or specially convenient as they are generally used in a laboratory. It is very essential, however, that they be accurate and give precise indications.

But these primary instruments must, themselves, be calibrated. In calibrating them reference must be made to the concrete standards of resistance, capacity, self-induction, etc. The trustworthiness of the commercial instruments rests upon the accuracy of the primary instruments, and these in turn upon the precision of the concrete standards available. It is a very fortunate circumstance for engineers that there is now at Washington the National Bureau of Standards, a bureau that furnishes all instrument makers manufacturing primary instruments with entirely reliable certificates for the values of the concrete standards of resistance, capacity, self-induction, etc.

The interest of engineers in general in the primary instruments must rest upon the value of these instruments as a means of accurately calibrating the secondary instruments which they use. These primary instruments now have an added value to the engineer, as the instrument maker is now able to obtain concrete standards from the National Bureau at Washington, standards which a few years ago could only be obtained from abroad.

H. G. Stott: Is there not a slight twisting due to electrodynamic action of the two currents in the sides of the instrument? It seems to me that there must be an attraction or repulsion as the case may be. In determining the zero point by putting the alternating current through both wires in multiple and afterwards using it with alternating current in one wire and direct in another, would not the impedance be changed under those conditions?

F. N. Waterman: In the use of hot-wire instruments the time required to heat and cool has been a very troublesome feature in the reading of varying currents. I would like to ask Mr. Northrup whether the very low temperature at which this instrument is operated obviates that difficulty, and if so, why we could not have a rough-and-ready instrument accurate up to one-half of one per cent. for commercial purposes in which the great inconvenience of the time-lag would not exist.

H. W. FISHER: From the construction of the instrument, I think it would be difficult to have very much insulation between the wire carrying the alternating current and that carrying the direct current; therefore the difference of potential between said wires should be small; and how can the instrument be used to measure very high voltages?

E. F. NORTHRUP: Referring to Mr. Fisher's question, do the wires have to have the same resistance, I would answer, no. They can differ quite a good deal in resistance, but if the resistance of the two wires are different then when the two wires are joined in parallel, the instrument will not give the same zero that it has with no current passing. This does not make the slightest difference, however, in the accuracy of the measurements; and it is rather a convenience than a necessity to have the wires of equal resistance. It is, however, perfectly easy to give them the same resistance, likewise the lead wires, in the manner indicated on page 745. There are two portions of the circuit that must have the same resistance. Referring to the figure on page 745 the lead wire from a to 3 plus the lead wire from b to 6, must equal in resistance the lead from 2 to c plus 4 to d. These resistances are permanently adjusted by the maker.

In making high voltage measurements with the instrument it would be desirable to ground one side of the alternating-current circuit in such a manner that the instrument itself would not be subjected to the high potential. The potential drop can be made to take place over a high resistance before the instrument is reached. We have not in our laboratory facilities for obtaining very high voltages, and the measurement of extremely high voltages has not been actually tried. Everything else stated about the uses of the instrument has been carefully tested by experiment. It is believed, however, that the practical and successful application of the instrument to the measurement of very high potentials could be made.

The instrument was used to measure the current from a high-frequency coil. The high-frequency current jumped a 2-in. air-gap before it passed to the instrument. It then went through one wire and back to the coil. The deflection which was produced by this current was noted. The high-frequency current was then replaced by an adjustable direct current. This was varied until the same deflection was obtained as the high-frequency current gave. The particular current measured was 76 milliamperes. The current given by a large induction coil was also successfully measured and was found to be about 37 milliamperes.

A large number of experiments have been made to determine the action and value of the instrument when used as a deflection instrument. It can be used in this way with a fair degree of accuracy, but it is necessary to calibrate the scale because the instrument does not follow any regular law precisely in its deflections. With very fine wires the deflections are very rapid, a full scale deflection occurring in about one-third of a second.

In regard to Mr. Stott's question, as to whether the instrument has any twisting moment: there is no twisting moment but when direct current is passed down one wire and alternating current down the other wire, there is a slight tendency, if the currents are abnormally large, for the mirror to be set into a fine vibration, slightly blurring the scale. This is sometimes somewhat annoying, but in nowise affects the accuracy or quickness of the measurement. There is at the zero of the scale a small black disk, and if the mirror vibrates this disk changes into two overlapping discs and it is easy in setting to zero to note when the cross-hair of the telescope crosses the intersection of these overlapping discs, which is the zero that would be seen if the scale were not disturbed. This blurring of the scale does not occur, however, with such currents as are normally used in the wires. The force of the spring drawing the mirror against the wires is several ounces and the system is quite substantial.

In regard to the impedance of the leads and instrument wire it may be stated that these are practically non-inductive. The current enters by one path and returns by another not anywhere far removed from the first. The effect of the inductance was proved to be negligibly small by very careful experiments in which the instrument indications were compared with those of a Kelvin balance. The only limitations to the test of accuracy of the instrument were found in my ability to read accurately the Kelvin balance. This instrument not being a dead-beat instrument is continually oscillating with fluctuating alternating current.

Mr. Waterman asked in regard to the time-lag. The deflections are rather rapid. If the current is fluctuating it is easy, as the instrument is dead-beat, to catch the precise moment it passes the zero point and read the alternating-current instrument being calibrated at that moment. If the current is very fluctuating it has no definite value to measure and no instrument will measure it. Ordinary commercial circuits, however, are suitable for making calibrations with perfect ease.

One application of the instrument should be especially mentioned and that is its adaptability to determine the ratio of transformation of a series transformer in which the primary is carrying a very large current, as 4 000 amperes, and the secondary a small current, as 5 amperes. The ratio can be very accurately determined by the instrument.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

EDDY CURRENTS IN LARGE SLOT-WOUND CONDUCTORS.

BY A. B. FIELD.

The object of the present paper is the discussion of the more important causes of eddy currents in heavy conductors carrying alternating currents and surrounded on three sides by iron.

In the case in which the slots are in the periphery of a circular core, and there is a more or less radial field rotating relatively to this core, as in direct-current armatures, stators of alternators and induction motors, potential regulators, etc., the causes of the eddy currents may be conveniently divided into two general classes comprising: 1, those involving directly the current in the conductor itself, or in conductors in the same slot; 2, those involving magnetic flux due directly to external agencies.

The latter will, in some instances, produce results of considerable magnitude, but it is the first-mentioned group that is most generally productive of serious eddy currents, and this one only is considered in the present paper. In many types of apparatus the two are characterized by giving rise to losses which are, respectively, proportional to the square of the load, and nearly independent of the load. Hence the first losses are generally grouped in a vague way under the title "Load Losses" along with many other much more obscure, and often less important, ones; and on account of the difficulty of estimating and measuring them, they are generally omitted in giving and checking efficiency guarantees.

The existence of this cause of heating is recognized in a general way in designs, and various methods of stranding, laminating, or interweaving the conductors adopted. The writer believes, however, that on account of the somewhat complicated way in which frequency, and the slot and conductor dimensions, are involved, it is advantageous for the designer to have detailed information at hand, and for this reason ventures to put forward the approximate curves below; they may be of service to those who have not prepared similar curves for themselves.

As regards the magnitude of the effects, it is not at all uncommon to find commercial apparatus, even of modern type and of low frequencies, in which the eddy currents under discussion increase the $I^2 R$ loss in the active part of the conductor to several times that due to the load current; while 60-cycle alternators wound for low, or fairly low pressures may frequently be seen, in which this eddy-current loss in the active part of the outer layer of conductors considerably exceeds the load-current loss. The increased demand at present arising for high-speed, large-output alternators for steam-turbine work, where deep slots are necessarily involved, renders the matter of increasing importance.

On the other hand, it should be observed that a comparatively large percentage of the mean length of turn is taken up by the end connections in alternator and similar windings. Hence an additional loss equal, say, to the load $I^2 R$ in the active part of the outer layer of conductors of a two-layer solid-bar winding, and to 13% of this in the inner layer, will generally increase the total $I^2 R$ loss only 20–40 per cent.

Again in some cases it may be very desirable from other points of view to use a solid conductor of considerable depth, and be good policy to put up with fairly heavy eddy currents for the sake of simplicity. In all such cases, however, it is well to know roughly the extra losses involved.

A short consideration of the matter will show that the eddy currents under discussion are produced by flux crossing the slot transversely from tooth to tooth through the body of the conductor, and that they take an elongated form, tending to flow along the top edge of the conductor throughout the length of the core, and return along the edge nearer the slot-root. The eddy currents themselves will produce magnetic flux which will react upon the whole system of currents, and the net result in the conductor will be a current varying in density and phase at different depths. It will also be seen that the density of transverse flux at any depth is practically determined by the slot-width and total current in the slot below the transverse path considered; and that generally the tooth saturation, even when carried high up, will have quite an insignificant effect. This is due in large measure to the fact that the flux, which is responsible for the saturation of the teeth, passes down both teeth in the *same* direction. Under actual working conditions the transverse flux will combine with the main flux in an obvious way, but the above considerations will still stand.

The results given below have been worked out on this basis, and taking a straight path across the slot for the transverse flux. Actually the flux will bow outwards slightly at the top of the conductors, and hence in the case of wide slots the current density here will be a little less than given, and the loss also a trifle less. We are not however interested in knowing the losses to an accuracy of a few per cent.

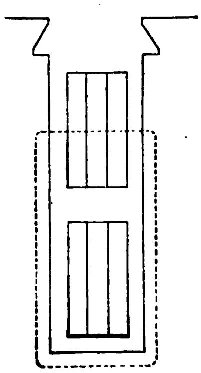
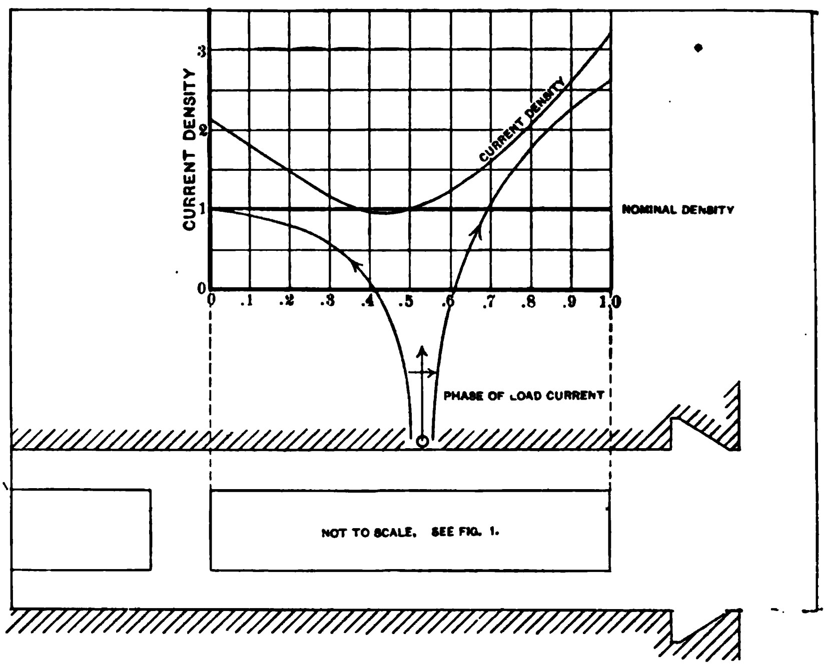


Fig. 1

In order to assure ourselves, in a rough and practical way, of the order of magnitude of these effects, without any analysis, let us consider the case of the two-layer, low-pressure winding shown in Fig. 1. where the conductor consists of three 0.1-in. by 0.6-in. strips and the slot is 0.5-in. wide. Suppose we have a load current flowing corresponding to a density of 1 000 amperes (root mean square) per square inch, then omitting any disturbance of the uniform current density, we have for the current enclosed by the magnetic path indicated in the figure, 270 amperes. This would correspond to a magnetic density across the centre of the conductor of $3.192 \times 270/0.5 = 1\,720$ root mean square lines per square inch. Taking this as the average density across the upper conductor, we have a total flux through the 0.6-in. depth, per inch length axially, of 1 030 lines. With a frequency of 60 cycles, this will tend to produce a difference of potential between the top and bottom edges of the solid conductor of 3.9×10^{-3} volts per inch length. Now the $I\ R$ drop due to 1 000 amperes per sq. in. is approximately 7×10^{-4} volts per inch, so we see that this induced voltage would be balanced by a difference of current density between the two edges of 5.57 times the nominal density in the conductor.

The actual state of affairs, taking into account the changed



Density and phase of current in solid conductor at 60 cycles. Slot, 0.5 in. wide. Conductors, 2-3 (.1 in. by .6 in.).

Fig. 2

magnetic distribution corresponding to the modified current distribution is, of course, considerably different from this simple result. It is shown approximately in Fig. 2 where the resultant root mean square current density at various points of the cross-section of the outer conductor is plotted as a curve. A second curve has been drawn to show at a glance the way in which the phase of the current varies from point to point, the *direction* of this curve indicating the phase; *i.e.*, a tangent drawn at any point to the curve, directed as shown by the arrow-head, may be taken as indicating the direction of the clock-diagram vector representing the current density at that point in the conductor.

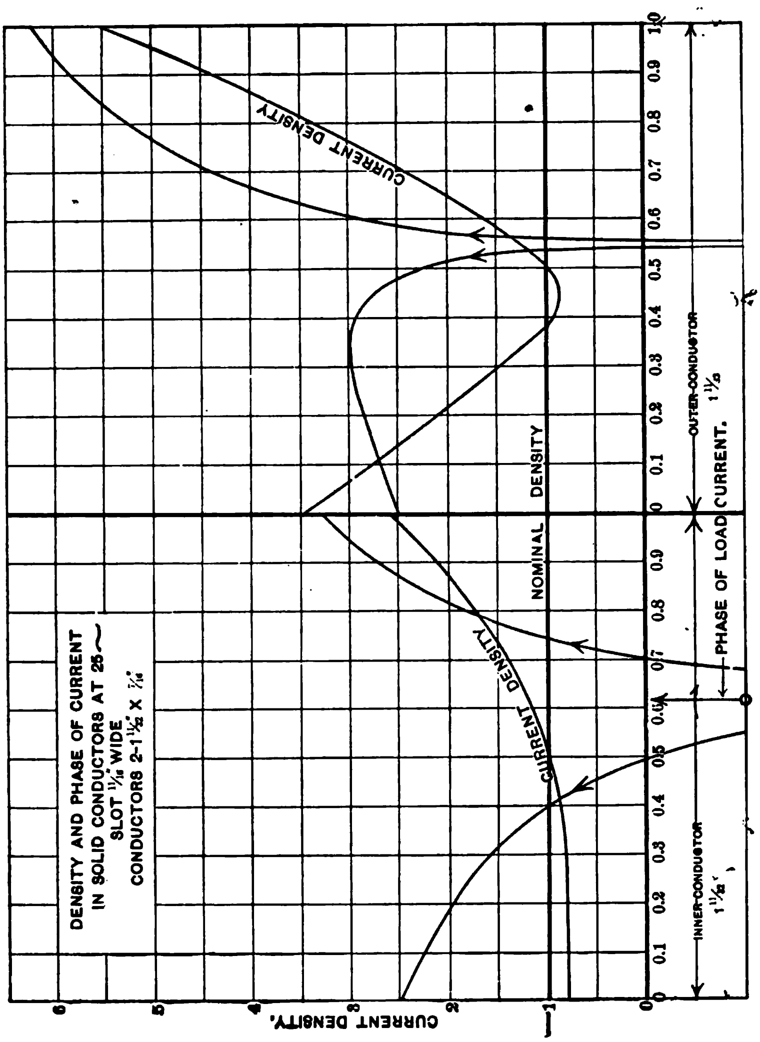


Fig. 8

We see from these curves that, with a load current corresponding to 1 000 amperes per square inch, the resultant density at the inner edge is approximately 2 120 amperes per square inch, lagging 81° behind the mean current, and at the outer edge 3 160, leading the mean—or actual load current—by 57.5°, so that there is a difference of phase of 138.5° between the current at these two places in the conductor. At a depth of 47% the current is in phase with the load current.

Similar curves for 25 cycles are given in Fig. 3 for the case of two $1\frac{13}{32}$ in. by $\frac{7}{16}$ in. conductors in an $\frac{11}{16}$ in. slot (Fig. 9), a combination of some historical interest as having been used, the writer believes, 10 years ago in the first Niagara 3 500-kw. generators. The arrangement used a few years later in the extensions is shown in Fig. 10 and entails considerably less loss although the conductor is 2 in. deep, on account of the use of a single layer only. In the still later machines, installed in the second power-house, pressed stranded conductors were used. Referring to Fig. 3, the very large effect of the eddy currents in the outer conductor will be observed, the current density nowhere being appreciably below the nominal density, and rising to as much as five and a half times this at the outer edge. The total loss in the active part of the outer layer here amounts to approximately six or seven times that due to the load current only; it would actually be diminished by removing say, 70% of the metal of this conductor, although the resulting maximum temperature rise might be greater. That such excessive losses can be dissipated, even from a 30-in. to 40-in. armature, without prohibitive temperature rise, will be found when it is remembered that the thermal conductivity of copper allows of the transference of heat at the rate of about 10 watts per square inch section for a temperature gradient of 1° cent. per inch. The resulting conduction to the end-connections largely assists the other dissipative actions at work. Some allowance was made in calculating the above curves, for the 1-in. ventilating ducts in the core.

Before considering the matter analytically it may be well to give in general terms the results obtained, and some examples of their application, together with a few of the more common means of overcoming the troubles.

It was pointed out above that within the limits of practical accuracy the density of transverse flux depends only on the width of slot and the total number of ampere-conductors behind the point considered, and hence it is possible to construct curves for solid conductors, giving the $I^2 R$ factor in terms of an extremely simple quantity involving only the frequency, depth of conductor, and the ratio of total net copper thickness

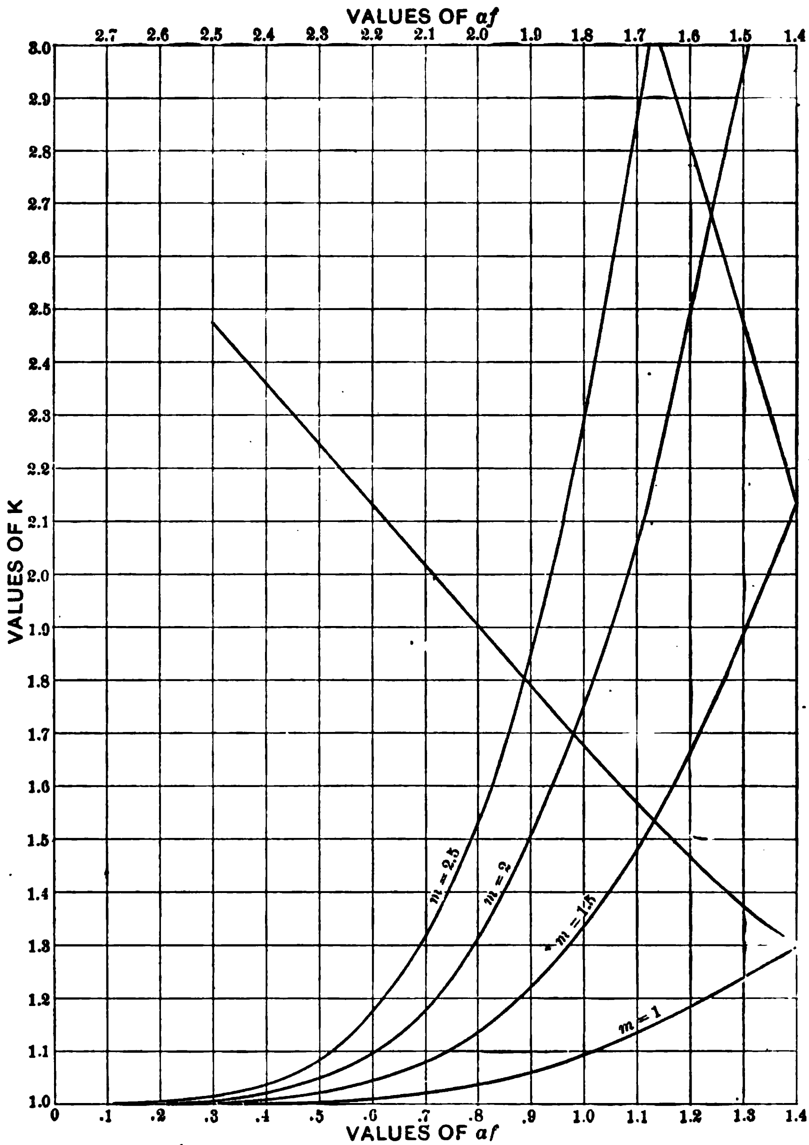

VALUES OF af
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
VALUES OF K
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
$m = 2.5$
$m = 2$
$m = 1.5$
$m = 1$
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
VALUES OF af

Fig. 4a

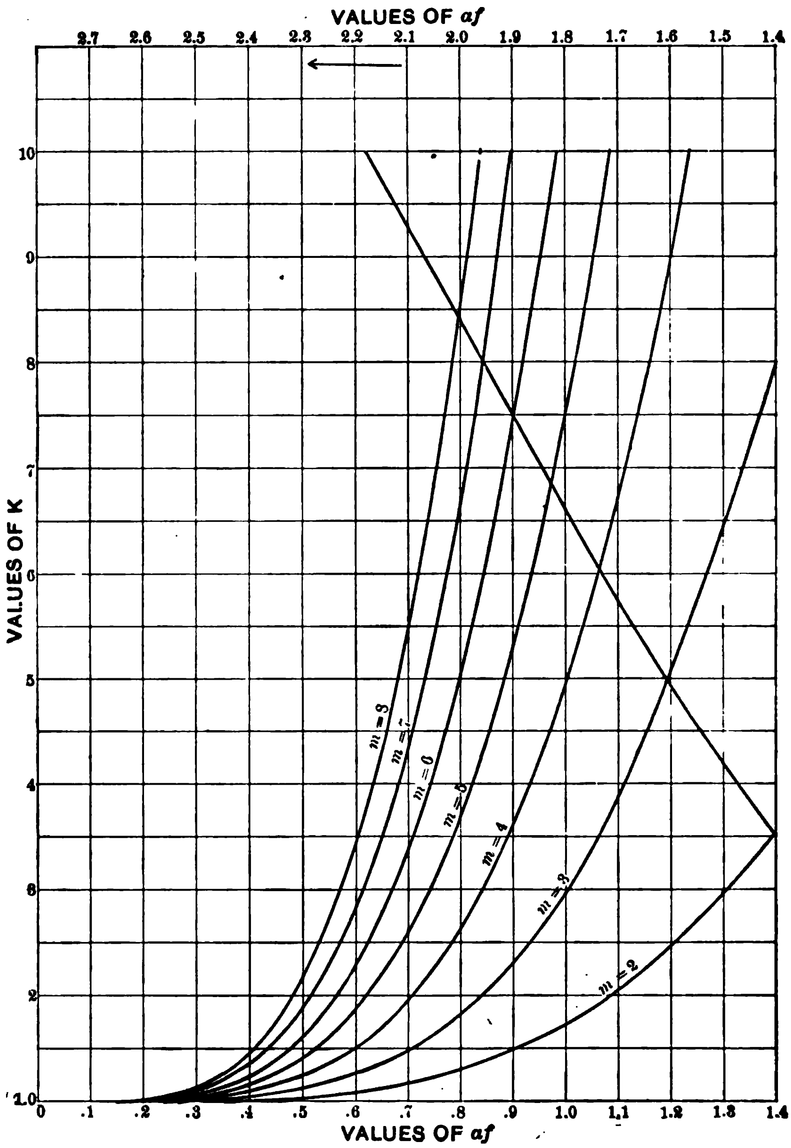

VALUES OF af
2.7 2.6 2.5 2.4 2.3 2.2 2.1 2.0 1.9 1.8 1.7 1.6 1.5 1.4
VALUES OF K
10
9
8
7
6
5
4
3
2
1.0
$m=8$
$m=7$
$m=6$
$m=5$
$m=4$
$m=3$
$m=2$
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4
VALUES OF af

Fig. 4b

measured across the slot to the slot-width, a quantity which is calculated for any case in a few seconds. It is further shown below that the same curves, with a slightly different interpretation, are immediately applicable to various other windings in every-day use, in which the eddy currents discussed take the form of cross currents between the strands of a stranded conductor. The results are not applicable to the case of a direct-current armature conductor, where the interval between reversals is so long in comparison with the time of reversal; indeed, in this case the eddy currents due to the main field are likely to be of more interest than the commutation ones.

The curves are given in Fig. 4 and reference must be made to the analysis for their full significance. The ratio of actual to nominal $I^2 R$ loss is represented by the ordinates (K); the abscissas correspond to the quantity denoted by $\alpha\, f$ where

f = depth of conductor in centimetres (if a laminated conductor take the gross depth).

$\alpha = 0.145 \sqrt{\sim r_1/r_2}$

r_2 = practically unity for solid conductors, and for laminated conductors is generally equal to the ratio of half the mean length of turn to gross length of core.

r_1 = for solid conductors, the ratio of net copper measured across the slot, to the slot width, and for laminated conductors generally the same multiplied by ratio of net to gross conductor depth.

Counting the number of layers of conductors from the bottom of the slot upwards, we refer to the curve drawn for a value of m corresponding to the layer in question; *i.e.*, $m = 1$ for the bottom layer, $m = 2$ for the second, and so on, and obtain a value of K by which the $I^2 R$ loss due to the load current must be multiplied to give the total $I^2 R$ loss in that part of the winding.

For a bar winding with laminated conductors, the value of K applies for the length of conductor between points at which laminae are connected together. For a winding with laminated conductor in which the strands are continued from layer to layer, and only joined together at the beginning and end of the coil, we obtain a value of K applicable to the whole coil by referring to the curve drawn for $m = 0.5 +$ half the number of layers per slot, if the winding is one in which there are twice as many slots as coils. For the case in which each slot carries parts of two coils, one above the other, we take instead the curve for which $m = 0.5 +$ one-quarter the number of layers per slot. The distinction between these two cases is explained more fully later. For a one-layer winding in which the conductor is twisted over in the middle of the coil (*e.g.*, Figs. 11, 13) we take $m = 1$ but refer to a point corresponding to $0.5\,\alpha\,f$ instead of $\alpha\,f$, and so on.

It is interesting to note the effect of splitting up or laminating a solid-conductor winding. In general this diminishes

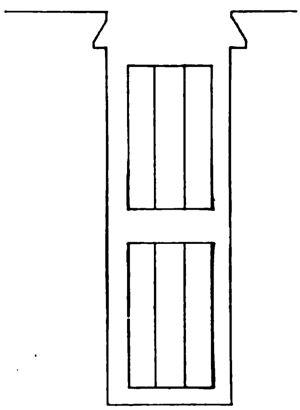


Fig. 5

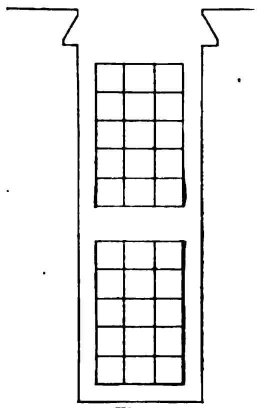


Fig. 6

FIG. 5.

Slot 0 65-in wide

Conductors 2–3 (0.14 in by 0.75 in.)

Bar wound	60 cycles	25 cycles
K for top conductor	5.9	2.1
K for bottom conductor	1.6	1.14
K for whole coil	2.1	1.25

FIG. 6.

Slot 0.65-in. wide.

Conductors 2–15 (0.144 in. sq.)

Bar wound.	60 cycles	25 cycles
K for top conductor	2.0	1.18
K for bottom conductor	1.13	1.02
K for whole coil	1.56	1.10

the loss in the active part, increases it in the end-connections, and diminishes the total loss of the half turn; but in some extreme cases the total loss may be increased by such lamination instead of decreased; *e.g.*, in a winding in which the gross core length is 40% of the half mean length of turn, the total loss of a first- or second-layer conductor is increased by lamination if $\alpha\,f$ is greater than 3. Such increased losses at first sight appear paradoxical but a moment's consideration will show that they

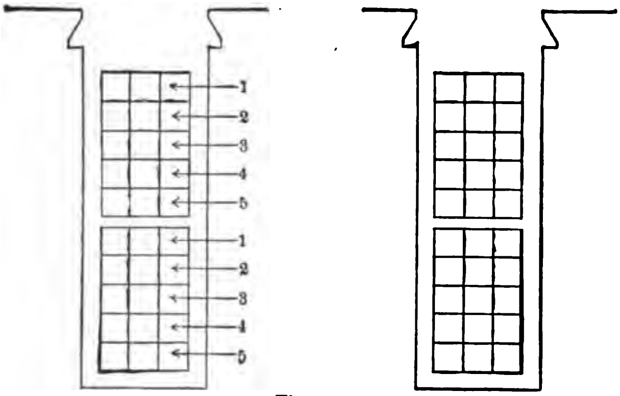


Fig. 7

FIG. 7.

Slot 0.65-in. wide.

Conductors 2–15 (0.144 in. sq.)

2-turns-per-coil winding

	60 cycles	25 cycles
K for whole coil	1.45	1.08

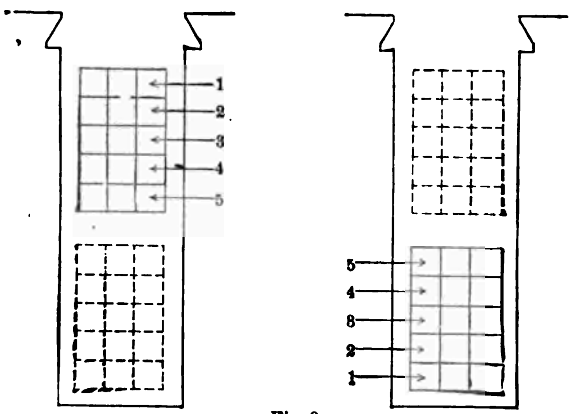


Fig. 8

FIG. 8.

Slot 0.65-in. wide.

Conductors 2–15 (0.144 in. sq.)

1-turn-per-coil winding.

	60 cycles	25 cycles
K for whole coil	1.13	1.02

are to be expected. A somewhat similar case is to be found in the increased loss that may occur in a mass of iron, subject to an alternating magnetomotive force, if the iron be laminated instead of solid.*

Again, if a given total depth of copper per slot is to be employed it will in all practical cases involve less loss to adopt a two-layer than a one-layer arrangement (not necessarily a less temperature rise), but in extreme cases this becomes reversed.

It should also be pointed out that for large values of αf, say over two or three, the $I^2 R$ loss is practically proportional to $\sqrt{\sim}$ (as in a large class of other eddy current phenomena), and to f the depth of conductor; but for the cases within everyday experience, where αf is much smaller, these quantities are involved in a more complicated way, and a slight increase of conductor depth may mean a largely increased loss.

As illustrations, a few diagrams are given below, in Figs. 5–11, of slot and conductor arrangements, with the corresponding approximate $I^2 R$ factors, both for the active part, and for the whole winding (assuming a ratio of active length to half mean turn length of 0.4 in Figs. 5–8.)

With regard to the methods of eliminating these additional losses, many are self-evident. Where the ratio of depth to breadth of conductor is not too great, pressed stranded conductors of the usual well-known type may with advantage be used. Conductors of this class have generally a net copper cross-section of 75 to 85% of their gross cross-section, according to the extent to which they have been compressed. It will be noticed that if a concentrically stranded cable be the basis from which the conductor is made, the conditions are little better (from our present point of view) than obtain with a laminated conductor twisted over in the middle of its length. As already stated, such a twisted conductor, in a single-layer winding, has the same $I^2 R$ factor as an untwisted one of half the depth; but this halving of the effective depth will generally be found in practical cases to reduce the eddy losses from a very serious quantity to entirely negligible dimensions. For the second and successive layers, of a multiple-layer arrangement, the twisted or pressed stranded conductor is very much better than an untwisted one of half the depth. In many practical cases

* *Journal Inst. Elec. Eng.*, London, Vol. 33, "Eddy currents in solid and laminated iron masses," by M. B. Field

of two-layer windings using a pressed stranded conductor, it will be found satisfactory to leave the lower conductor solid, the losses in this layer being comparatively slight, even when excessive in the top layer (see curves).

For conductors having a large ratio of depth to breadth,

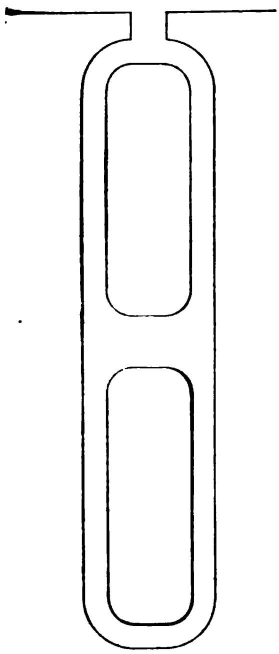


Fig. 9

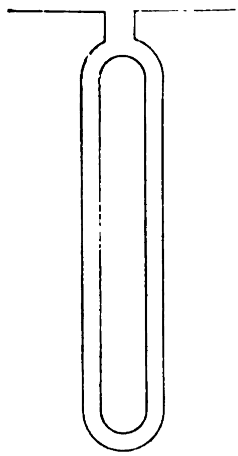


Fig. 10

FIG. 9.		FIG. 10.	
Slot 0.687-in. wide.		Slot 0.406-in. wide.	
Conductors 2-1 (1.344 by 0.4375 in.)		Conductor 1 (2 in. by 0.2185 in.)	
Bar wound.	25 cycles		25 cycles
K for top conductor	6.6	*K* for active conductor	2.5
K for bottom conductor	1.7		

which would be difficult to form in the way described above, a woven tube or stocking of fine wire, closed flat, has been used by W. S. Moody. Such a conductor has the disadvantage that it changes shape if subjected to tension. A similarly shaped conductor, but with a simple lay and having a soft idle core, has been proposed by C. A. Parsons (U. S. Patent 782 463), in connection with direct-current turbo-generators. The primary object here appears to be the reduction of the inductance of the bar by increasing its perimeter—and hence

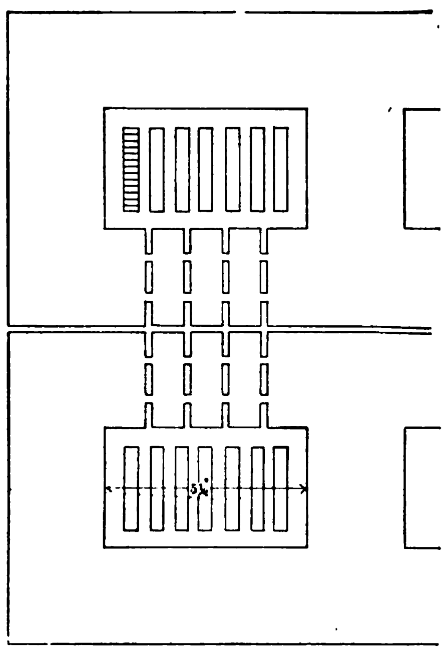


Fig. 11

FIG. 11.

Slot 5.25-in. wide.

Conductors 7-19 (0.27 in. by 0.10 in.)

7-turns-per-coil winding. (r_2 = 1.87)

	60 cycles	25 cycles
K for whole coil (untwisted conductor)	2.5	1.5
K for whole coil (twisted conductor)	1.3	1.05
K for equivalent solid conductor (act: part)	3.2	2.
K for ditto (whole coil)	2.2	1.53

improvement of commutation—but with such an extended conductor it becomes necessary to strand to avoid eddy currents. The soft core here doubtlessly tends to prevent deformation to some extent.

A neat conductor has been developed by E. D. Priest for use more particularly in railway-motor armatures, to avoid the eddy currents produced by the working flux which enters the slot-mouth. Fig. 12, reproduced from the patent drawing, shows the construction. The conductor is formed from a single strip split longitudinally for part of its length, the two halves being then transposed for half the core length and crushed into one another at the crossings, so that the completed conductor takes up only the same space as the original strip. The two parts are separated by a small piece of mica at the crossings. Such a conductor would probably be too expensive for general use in alternators.

In the case of a bar winding, two conductors deep, some improvement is achieved by using a laminated conductor, the losses being diminished and distributed over the end connec-

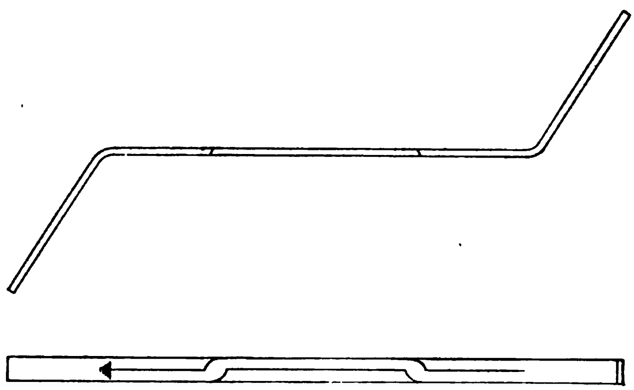


Fig. 12

tions as well as the active length (compare Figs. 5 and 6). A still greater improvement results if the stranding be continued between the top and bottom layer (Fig. 7). or better still if the conductor be twisted over between these layers (Fig. 8). This last case would generally be used, rather than the previous one, and corresponds to a half-formed bar winding; it is unnecessary (from the point of view of the present discussion) to keep the strands insulated further than throughout the complete turn length; *i.e.*, the connecting clip may join conductors together, all strands at once.

In Figs. 13 and 14 are shown two types of winding which Moody has used for low-pressure " reactances," where excessive losses would occur in solid strips; the section of the coil shown in Fig. 13 has already been given in Fig. 11. For such a winding, a conductor 20 strands or so high and measuring over-all some 2.25 in. by as little as 0.25 in. may be comparatively easily wound directly on a former, the whole conductor being twisted over in the middle of the winding as shown in the figure. By a varnish and japan treatment the strands may be conglomerated to form a rigid conductor. In the case in which a similar two-layer winding is required, both layers may be wound at

Fig. 13

once and so connected together strand by strand as to produce the same result as the previous twist, see Fig. 14. In all these cases in which any type of stranding is adopted, it is advisable to pay somewhat more attention to the mechanical support of the conductor, particularly the end-connections, to prevent distortion under excessive loads and short circuits.

The above remarks are not intended in any way as a comprehensive account of the methods in general use, and proposed, for obviating eddy currents, a few examples only being cited.

There is another aspect of this subject deserving a little attention. In estimating the (leakage) reactance of armature windings and the like, it is usual to take into account the flux crossing the slot, below the top of the coil, by a term involving one-third the depth of the winding, which is approximately correct for a coil wound with small conductors. In the case of deep solid conductors, however, the effective crowding of

Fig. 14.

the current to the outer edge materially changes this. The modified value of the reactance may be calculated from the results given later, but as the matter is not of much practical importance, on account of the small proportion of the whole reactance which is dependent on this slot flux, and the futility —as some hold—of attempting to calculate the whole reactance at all, no general formulas have been given. A numerical example will, perhaps, be the best illustration.

Taking the exaggerated case of Fig. 9 (25 cycles), we find that that part of the reactance, per unit length, which is due to flux penetrating the conductors, is reduced 29% by the effects in question; that part due to other flux is unchanged. The actual distribution of current in the various cases, and the derivation of the results already given, will now be considered in a little more detail.

There are several different types of winding which require, to some extent, independent treatment. There is, first, the case of one or more layers of conductors per slot, the current being free to distribute itself differently in the different layers; *e.g.*, windings with solid conductors, or laminated-bar windings in which the laminae are all joined together at the bar-to-bar connection. In other cases the stranding* is continued from layer to layer, so that the current in the strand of one layer is necessarily the same as that in the corresponding strand of the other layers; and we then have a further distinction according as the order of strands is retained or reversed in passing from the layers of the upper half of the slot to those of the lower half. In all cases we take the *load current* in all the conductors of any one slot to be in the same phase, and to be represented by a sine function of the time.

Consider, then, the first case mentioned above, and a slot measuring a by b centimetres, and carrying n layers of conductors, *i.e.*, reckoned in the direction of the depth of the slot (Fig. 15).

Using the ampere, volt, centimetre, second, and corresponding units, let

X, x = distance measured in the direction of the depth of the slot outwards.

(The large letter is used for general relations, the small one in connection with the individual conductors.)

---

* The type of stranding referred to here, and throughout this paper except in connection with "pressed stranded conductors," is that shown in Figs. 16, 17. That is to say, the strands are not twisted or woven together at all within the active length of the conductor. It should also be noticed that the laminating of the conductor is not to be taken as affecting the number of "layers," but that the term "layer" is here used to denote a conductor or group of strands which together carry a definite total current, the "load current;" *i.e.*, the integral of current density taken over the cross-section of the group is equal to this load current. The number of conductors side by side in the slot is of no consequence as regards the eddy currents under consideration except as far as it affects the value of r_1 (below). The figures are all drawn showing one conductor wide for simplicity.

f = gross depth of each conductor.
n = number of layers of conductors per slot
$n\,s$ = net copper section per slot.

$r_1 = \frac{s}{a\,f}$ or in the case of solid conductors, r_1 represents the ratio of net copper measured across the slot, to the slot-width.

r_2 = the ratio of half the length of the eddy current path, to the length of the active† part of the conductor included within this; *i.e.*, for solid conductors r_2 may generally be taken as unity, and for laminated bar windings as equal to the mean length of turn divided by twice the gross length of core, and so on.

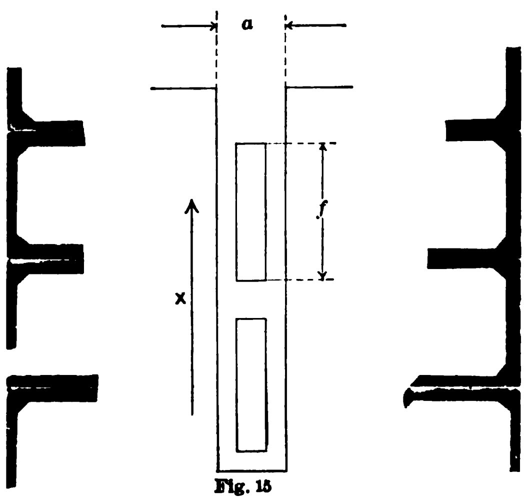


Fig. 15

Δ = net current density at any point of the conductor (instantaneous value).

$\Delta_0 \sin p\,t$ = nominal current density in the conductor (*i.e.*, ignoring eddy currents), so that $\frac{\Delta_0}{1.414}$ is the nominal root mean square current density.

Δ_1 = root mean square value of Δ (the mean with regard to x as well as time).

† The "active" part may generally be taken as equal to the gross length of core between clamping heads, including ventilating ducts, the presence of the ducts being similarly ignored in considering the length of eddy current path.

ρ = specific resistance of the conductor material.

V = electromotive force (instantaneous value) induced in the strand (or in an imaginary strand) at X by the transverse flux, per unit length of conductor, across the slot. V is measured positively in the same direction as the current.

B = transverse magnetic induction at X (inst: value).

K = ratio of actual to nominal, $I^2 R$ loss in active part of conductor.

On the hypothesis that the transverse flux, which would be produced by the current in conductors of the slot in question in the absence of other magnetomotive forces, would pass straight across the slot, and that the effective reluctance of the iron part of the magnetic circuit be small in comparison with that of the air part, we have for the actual conditions, and for the type of conductor under consideration:

$$\frac{d}{d X}(V - r_2 \rho \Delta) = 0$$

and

$$\frac{d^2 V}{d X^2} = +10^{-8} \frac{d^2 B}{d X d t} = 10^{-9}\, 4 \pi r_1 \frac{d \Delta}{d t}$$

Or, eliminating V

$$\frac{p}{2} \frac{d^2 \Delta}{d X^2} = \alpha^2 \frac{d \Delta}{d t} \tag{1}$$

where

$$\alpha^2 = 10^{-9}\, 2 \pi \frac{p r_1}{\rho r_2} = 0.021 \frac{\sim r_1}{r_2} \text{ for copper at } 45^\circ \text{ cent.}$$

The current density in the m^{th} layer, situated at $x = 0$ to $x = f$ will therefore be of the form:

$$\Delta = \delta_1 e^{-\alpha x} \sin\left(p t - \alpha x + \beta_1 - \frac{\pi}{4}\right) + \delta_2 e^{\alpha x} \sin\left(pt + \alpha x + \beta_2 - \frac{\pi}{4}\right) \tag{2}$$

subject to the two conditions

$$\frac{1}{f} \int_0^f \Delta \, d x = \Delta_0 \sin p t \tag{3}$$

and

$$r_2 \rho \left(\frac{d\Delta}{d\lambda}\right)_{x=0} = \left(\frac{dV}{dx}\right)_{x=0} = 10^{-8} \left(\frac{dB}{dt}\right)_{x=0}$$

$$= 4\pi 10^{-9} r_1 \, (m-1) f p \Delta_0 \cos pt \tag{4}$$

Inserting in the above the value of Δ (equation 2), we have:

$$-\delta_1 \sin (pt+\beta_1) + \delta_2 \sin (pt+\beta_2) = \sqrt{2}\, \alpha \, (m-1) f \Delta_0 \cos pt$$

or

$$\delta_1 \cos \beta_1 - \delta_2 \cos \beta_2 = 0 \tag{5}$$

$$\delta_1 \sin \beta_1 - \delta_2 \sin \beta_2 = -(m-1) A \tag{6}$$

where A has been written for $\sqrt{2}\, \alpha f \Delta_0$

And similarly from (3)

$$\sqrt{2}\, \alpha f \Delta_0 \sin pt = \delta_1 e^{-\alpha f} \cos (pt - \alpha f + \beta_1) - \delta_2 e^{\alpha f} \cos (pt + \alpha f + \beta_2)$$

$$-\delta_1 \cos (pt+\beta_1) + \delta_2 \cos (pt + \beta_2)$$

giving in conjunction with (5) and (6)

$$\delta_3 \cos (\beta_1 - \alpha f) - \delta_4 \cos (\beta_2 + \alpha f) = 0 \tag{7}$$

$$\delta_3 \sin (\beta_1 - \alpha f) - \delta_4 \sin (\beta_2 + \alpha f) = -m A \tag{8}$$

where δ_3 has been written for $\delta_1 \, e^{-\alpha f}$

and δ_4 has been written for $\delta_2 \, e^{\alpha f}$

To obtain the total $I^2 R$ loss in the conductor we require the mean Δ^2 value, viz.

$$\frac{p}{2\pi f} \int_0^{\frac{2\pi}{p}} dt \int_0^f \Delta^2 \, dx$$

and calling this value Δ_1^2, shall have, as the ratio of total to nominal $I^2 R$ loss in the conductor under consideration.

$$K = 2 \frac{\Delta_1^2}{\Delta_0^2}$$

From (2) we have

$$\Delta^2 = \tfrac{1}{2}\delta_1^2 e^{-2\alpha x}\left[1-\cos 2\left(pt-\alpha x+\beta_1-\frac{\pi}{4}\right)\right]$$

$$+\tfrac{1}{2}\delta_2^2 e^{2\alpha x}\left[1-\cos 2\left(pt+\alpha x+\beta_2-\frac{\pi}{4}\right)\right]$$

$$+\delta_1\delta_2\left[-\sin(2pt+\beta_1+\beta_2)+\cos(2\alpha x+\beta_2-\beta_1)\right]$$

Hence, dropping terms having zero mean value, we obtain from the remainder after integration:

$$\Delta_1^2 = \frac{1}{2\alpha f}[(\delta_1\delta_3+\delta_2\delta_4)\sinh\alpha f+2\delta_1\delta_2\sin\alpha f\cos(\alpha f+\beta_2-\beta_1)] \quad (9)$$

We can obtain the value of this expression without the labor of solving equations (5), (6), (7), and (8), for $\beta_1, \beta_2, \delta_1, \delta_2$, etc., and substituting their values, by the following elimination. By squaring and adding the four equations (5) to (8) we obtain (10), and by multiplying together each side of equations (5) and (7), and similarly (6) and (8), and adding, we have equation (11) below:

$$(\delta_1\delta_3+\delta_2\delta_4)\cosh\alpha f-2\delta_1\delta_2\cos\alpha f\cos(\alpha f+\beta_2-\beta_1) = (m^2-m+\tfrac{1}{2})A^2 \quad (10)$$

$$(\delta_1\delta_3+\delta_2\delta_4)\cos\alpha f-2\delta_1\delta_2\cosh\alpha f\cos(\alpha f+\beta_2-\beta_1) = (m^2-m)A^2 \quad (11)$$

The three equations 9, 10, 11, now involve the six quantities $\delta_1\ \delta_2\ \delta_3\ \delta_4\ \beta_1\ \beta_2$ in the same way, we can therefore immediately eliminate these, obtaining:

$$\begin{vmatrix} -2\alpha f\Delta_1^2 & \sinh\alpha f & \sin\alpha f \\ (m^2-m+\tfrac{1}{2})A^2 & -\cosh\alpha f & \cos\alpha f \\ (m^2-m)A^2 & -\cos\alpha f & \cosh\alpha f \end{vmatrix} = 0$$

Or

$$\Delta_1^2\, 2\alpha f(\cos^2\alpha f-\cosh^2\alpha f) =$$

$$= A^2(m^2-m)(\sinh\alpha f\cos\alpha f+\sin\alpha f\cosh\alpha f)$$

$$-A^2(m^2-m+\tfrac{1}{2})(\sinh\alpha f\cosh\alpha f+\sin\alpha f\cos\alpha f)$$

The ratio of actual to nominal $I^2 R$ loss is thus given by the equation

$$\frac{K}{\alpha f} = \frac{4\,(m^2 - m)(\cosh\alpha f - \cos\alpha f)(\sinh\alpha f - \sin\alpha f) + (\sinh 2\alpha f + \sin 2\alpha f)}{\cosh 2\,\alpha f - \cos 2\,\alpha f} \tag{12}$$

This equation gives an interesting set of curves which have been plotted in Fig. 4 for several values of m. The curves at small values of αf cross the corresponding members of the family

$$K = \alpha f\,[2\,(m^2 - m) + 1]$$

and for larger values reapproach these straight lines and follow them to infinity, oscillating backwards and forwards across

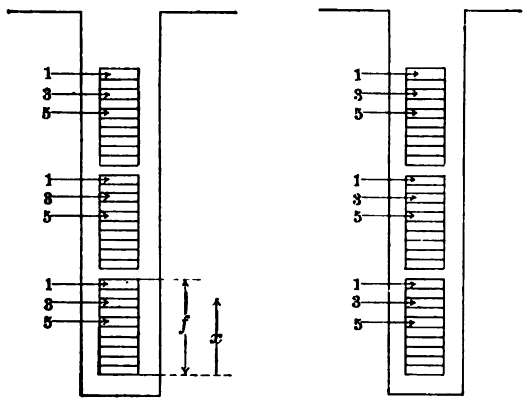


Fig. 16

them, but keeping so close as practically to coincide with them.

The curves corresponding to $m = 1$ and $m = 2$ are the two cases perhaps most commonly useful, corresponding to the inner and outer conductors respectively of a two-layer winding. The curves however for higher and fractional values of m have also been given to cover the cases of other types of winding and applications. For any negative value of m say $-m_1$, we take the curve corresponding to $m = 1 + m_1$, which is evidently identical with the $-m_1$ curve.

The value of K so obtained is to be applied only to that part of the conductor in which the eddy currents exist; for solid conductors this may generally be taken as a length equal to the gross length of core, including ventilating ducts, per half turn of winding, the remainder having normal loss. For a laminated bar winding in which the laminations are connected together only at the bar-to-bar connection, K will refer to the whole winding, but its value will be less than for the case in which the laminations are joined together immediately at the ends of the active portion, on account of the increased value of r_2.

We now come to the cases in which a stranded (laminated) conductor is used, wound up into a coil, so that the same stranding is continued from layer to layer. In such a winding the current in the conductor of one layer is no longer free to so distribute itself throughout the section of that conductor as

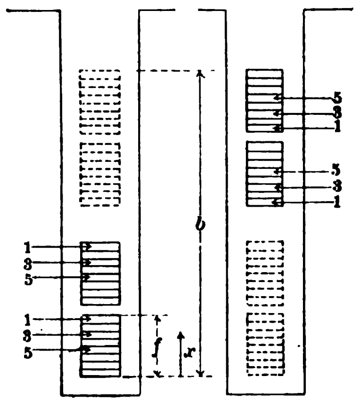


Fig. 17

to cause the rates of change of electromagnetic and $I\,R$ electromotive forces to balance per unit length, or per conductor length, since the current in any strand is restrained to take the same value throughout the whole coil.

There are two principal cases, exemplified by Figs. 16, 17, and corresponding generally to windings in which there are (1), half as many coils as slots, and (2), the same number of coils as slots. The distinction between the two cases is due to the fact that the conductor is twisted over between the two straight portions of the coil in the latter type of winding, while no such twist occurs in the former; this is indicated in the figures by the numbering of the strands.

Consider first the case of an n layer per slot coil wound with a well stranded conductor, the strands being joined together at each end of the coil, and appearing *in the same order* in all the layers, see Fig. 16 (the figure shows three layers).

The density Δ will here be a periodic function of X and, with the same notation as before, we have at once:

$$\sum_{q=0}^{q=n-1} \left(\frac{d\,V}{d\,X}\right)_{x+q\lambda} - r_2\, n\, \rho \frac{d\,\Delta}{d\,x} = 0 \text{ between } x = 0 \text{ and } x = f \quad (13)$$

and

$$\frac{d^2\,V}{d\,X^2} = +10^{-8}\frac{d^2\,B}{d\,X.d\,t} = 10^{-9}\,4\,\pi\,r_1 \frac{d\,\Delta}{d\,t} \quad (14)$$

where λ is the distance between corresponding strands in consecutive layers. From (14) we see that $d^2\,V/d\,X^2$ is a periodic function of X, since Δ is so, and hence as would be expected, the fundamental equation obtained from (13) and (14) is the same as for the simple case (equation 1), and the limiting conditions are:

At $x = 0$

$$r_2\, n\, \rho \left(\frac{d\,\Delta}{d\,x}\right)_{x=0} = 10^{-9}\,4\,\pi\,r_1 \Big\{ 1 + 2 + 3 + \ldots$$

$$+ (n-1) \Big\} \frac{d}{d\,t}\Big(f\,\Delta_0 \sin\,p\,t\Big) = 10^{-9}\,4\,\pi\,r_1\,n\,(n-1)/2\; p\,f\,\Delta_0 \cos p\,t \quad (15)$$

and

$$\frac{1}{f}\int_0^f \Delta\,d\,x = \Delta_0 \sin p\,t \quad (16)$$

Comparing these with equations (4) and (3) respectively, we see that the solution for this case will be the same as for the original one with a value of m equal to our present $(n+1)/2$; that is, to obtain the value of K for the entire coil we refer, in Fig. 4, to the curve drawn for this value of m.

Take next the case indicated in Fig. 17 (four layers shown), in which there are again n layers per slot, but in which the order of the strands in the lower $n/2$ layers is the reverse of that in the remainder, so that the current distribution in half the slot is the optical image of that in the other half.

We have here in the same way as before:

$$\sum_{q=0}^{q=\frac{n}{2}-1}\left\{\left(\frac{dV}{dX}\right)_{x+q\lambda}-\left(\frac{dV}{dX}\right)_{b_1-x-q\lambda}\right\}=r_2\,n\,\rho\frac{d\Delta}{dx}$$

$$\text{between } x = 0 \text{ and } x = f \tag{17}$$

which together with

$$\frac{d^2V}{dX^2} = 10^{-9}\,4\,\pi\,r_1\,\frac{d\Delta}{dt}$$

gives the same fundamental equation (in x) as originally (equation 1), but the limiting conditions are now:

At $x = 0$

$$r_2 n\,\rho\left(\frac{d\Delta}{dx}\right)_{x=0} = 10^{-9}\,4\,\pi\,r_1\left[\{1+2+\ldots+(n/2-1)\} - \{n+(n-1)+\ldots+(n/2+1)\}\right]\frac{d}{dt}[f\,\Delta_0\sin pt]$$

Or

$$r_2\,\rho\left(\frac{d\Delta}{dx}\right)_{x=0} = -\,10^{-9}\,4\,\pi\,r_1\,\frac{n+2}{4}\,f\,p\,\Delta_0\cos pt \tag{19}$$

And

$$\frac{1}{f}\int_0^f \Delta\,dx = \Delta_0\sin pt \tag{20}$$

We therefore use the curve (Fig. 4) drawn for $m=(-n+2)/4$ or, as this is a zero or negative quantity, $m=(n+2)/4$, and obtain a value of K which applies to the whole of the copper.

Many other cases occur in practice which we cannot enter into here, they can generally be approximately handled in a similar way to those indicated above, arbitrary allowances being made when necessary, according to the extent to which the conditions differ from our hypothetical ones.

In the above, the $I^2 R$ losses have been determined without solving the equations for the general distribution of current in the conductors. In some practical problems however it is of value to gain an idea of the actual distribution, and therefore the values of the constants in equation (2), to satisfy the boundary conditions (3) and (4), are given below, the algebraical work being omitted. The solution is immediately applicable to the other types of winding discussed above, by inserting the proper value of m as described in connection with the $I^2 R$ estimation.

The solution is given by equation (2) with the following values of the constants:

$$\delta_1 = \alpha f J_0 \left\{ \frac{y_1^2 + y_3^2}{\cosh 2 \alpha f - \cos 2 \alpha f} \right\}^{\frac{1}{2}}$$

$$\tan \beta_1 = \frac{y_1 \cos \alpha f . \sinh \alpha f + y_3 \sin \alpha f . \cosh \alpha f}{y_1 \sin \alpha f . \cosh \alpha f - y_3 \cos \alpha f . \sinh \alpha f}$$

where

$$y_1 = (m-1)\, e^{\alpha f} \cos \alpha f - m$$

$$y_3 = (m-1)\, e^{\alpha f} \sin \alpha f$$

and δ_2 β_2 are obtained from these expressions by reversing the sign of α.

As an illustration the curves already given, Figs. 2, 3, may be referred to. The phase curve is plotted with ordinates equal to

$$\int_0^x \cot \phi \, d x$$

where ϕ is the angle by which the actual current at any point of the conductor leads the load current. Hence the direction of this curve at any point indicates the phase of the resultant current there.

In conclusion the writer would point out that although in this paper he has confined his attention to the one case of eddy currents in slot-wound conductors, he recognizes that in some cases, especially where several conductors connected in parallel have to be arranged side by side in the slot, very considerable cross currents may be produced by the working flux entering the slot depthwise, unless suitable precautions be taken. He regrets that at the present writing he is unable to offer any test results confirming or otherwise the views put forward, but the few tests he has made, while confirming generally the results of calculation as to the order of magnitude involved, are not sufficiently detailed to warrant quotation.

A paper presented at the 23d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1906.

WATER-POWERS OF THE SOUTHEASTERN APPALACHIAN REGION.

BY FREDERICK A. C. PERRINE.

Three great mountain ranges run north and south through the United States, dividing it into distinct territories. They are the Appalachians, the Rockies, and the Sierras. Each of these ranges has its distinguishing characteristics and determines the character of the country in its neighborhood. Their influence is determined by their form, and by the climatic conditions to which their elevation and location contribute.

On the west side of the continent the Sierras rise from a high plateau on their eastern side, and descend on their western side sharply, almost to the level of the sea, enclosing with the Pacific Ocean a country of great fertility and marked by equability of climate.

The rainfall on the plateau to the east is very small and irregular, and, in consequence, on that side few rivers are fed by the run-off from the Sierras, such rivers as there are often sinking into the sands of the desert and never reaching the ocean.

Between the Sierras and the Pacific the rainfall is more plentiful but occurs in periods distinctly seasonal—a period of at least three months in the summer yielding no important amount of precipitation; in consequence, although many of these peaks rise to great heights, comparatively few of them are snow-capped.

The rivers which they feed are steep in slope, and rapidly deliver the run-off with great variation of flow between the wet and the dry season. By reason of their sharp descent, these mountain rivers afford many sites for power-plants of exceedingly high heads, and the glacial valleys lying high among the peaks afford locations for storage-reservoir sites which may be used to supplement the low run-off of the dry season.

While the Rockies are not so steep as the Sierras, they are as high or higher; and, rising from high plateaus on both sides, they form a wide rugged backbone to the Continent.

The rainfall on these mountains is not great, but the coldness of the climate of that region tends to hold back the winter rains and to give a more regular run-off from the year's rainfall.

Many of the rivers are of sharp descent while many others flow through great mountain valleys which afford opportunities for reservoirs with high dams.

While the rainfall in the Rockies is abundant, that in the surrounding regions is small and, in consequence, the streams of the Rocky Mountain region are largely employed for irrigation purposes, as a result the conflicting interests of water-power development and irrigation often interfere with the employment of the water for power purposes, particularly as the minimum run-off is during the winter months and the maximum in the summer, when the water is most useful for irrigation purposes, and, therefore, is not available for storage.

The Appalachian Mountains are neither as high nor as rugged as either of the two ranges before mentioned; indeed their tops are approximately on a level with the plateau between the Rockies and the Sierras. Most of them are rounded hills, covered with earth and vegetation to their summits, and none of them reaches up to the snow line; they form, however, the fountains for watering the fertile plains below, which on both sides lie at their base.

The chain extends from Maine to the Gulf, and comprises the White and the Green Mountains of the north, the Adirondacks and Alleghenies in the Middle States, and the Shenandoah, Greenbrier, Blue Ridge, Black, and Great Smoky mountains of the south, with many auxiliary ranges. In the States of Virginia, North Carolina, and South Carolina, they lie massed on the western border, and about the northern border of Alabama and Georgia, and form the eastern boundary of Tennessee, Kentucky, and West Virginia. In consequence of their location they form an important element in the life and industries of each one of these states, which for fertility have been renowned, and no unimportant element in their fertility is due to the water that flows from the mountains. As in the past the agriculturists of the south have blessed the waters, so to-day, and in the future, the manufacturers of the south will praise the mountains for the waterfalls furnishing power and forming one of the most important elements in the rebuilding and new development of the Southern States.

In this paper the writer has confined himself to the consideration of the powers in the states of Virginia, North Carolina, South Carolina, Georgia, and Alabama, since in these states the most wide-reaching effect seems to wait upon the development of these waters.

Here are the cotton fields, and here are springing up the great cotton factories. The people of these states have most thoroughly grasped the importance of the problem, and are showing the greatest results from the developments they have so far effected.

To the west of the mountains some of the best water-powers of the whole region are found and for some of them there is an abundant market. The region is indeed well worthy of study, but, as it is the study of a region separate and distinct in most of its characteristics from the country to the east and south of the mountains, one may be pardoned for not attempting its study at the present time, and may be allowed to consider only the country through which we have recently traveled, as far as Asheville, without it being assumed therefrom that, either for engineering or commercial reasons, the western region is less worthy of development.

On account of the physiographic characteristics, which have already been touched upon, this region is preeminently a water-power country. The rainfall over its entire extent is in no part less than an average of 35 in., increasing to 60 in. in the mountains. This precipitation does not occur in a wet season of limited duration, but is well distributed throughout the year. The soil itself is generally porous, and for those streams from the head waters of which the forests have not been cut the rainfall is retained, and neither the floods nor the low waters are as serious difficulties as are encountered in the middle states.

Ice and snow are not important elements in the problem, which is not only a condition favorable to hydraulic development, but also to the problems of transmission-line maintenance. The rivers draining this territory fall rapidly to a well-defined fall line where they enter the plains along the sea-coast, and in some cases become navigable; above the fall line they present many opportunities for power development, of high head in the mountain region, and of low head between the mountains and the fall line along which portions of their course they flow over many rapids which in that region are called "shoals." The greatest difficulties to be encountered are those due to lightning storms, which are frequent and severe over the whole territory and present a serious problem to the designing engineer.

On account of the generally loose character of the soil throughout almost the entire territory the rivers carry immense quantities of silt, which must be considered in planning canals and other hydraulic work. Commercially the fact that southern industries rarely operate more than 11 hr. per day requires a most careful study of the opportunities for storage, which will enable the full use of the river during this working period of each day. There are few locations presented in this region for storage-reservoirs sufficiently large to enable the full use of the average yearly run-off.

The most serious commercial problem present in this region is that of competition. On account of the abundance of water and the number of power sites, there are few, if any, powers in the entire region so situated as to be immune from dangers of competition from powers of equivalent cost of development and equal accessibility to the market.

This condition seems to require in this region, more than in any other part of our country, the development and distribution of the powers from many plants under one common management. If attacked in this manner the solution of the water-power distribution in the Southeastern Appalachian region offers great opportunities of commanding success, and by duplication of plants reduces the necessity for duplication of lines and tends to make the power more useful and reliable.

Such a procedure also tends to aid in the solution of another problem presented by the long period of minimum flow common to the rivers of this region. While the period of minimum flow is long, the steadiness of a flow 50 to 100 per cent. above the minimum may be generally depended upon for certain seasons of the year, and in the successful plant this excess flow must be utilized.

The manufacturers of the south, as in New England, have for many years been accustomed to appreciate the value of water-power to their steam plants, and of the steam plant as an auxiliary to the water-power; in consequence, a market for power beyond the amount of the minimum stream-flow is readily obtained, and should always be considered in planning for developments in this territory. The particular importance of this will appear as we proceed to a study of the different drainage areas, and realize that a great proportion of the plants in this territory are constructed directly at the dam-site, with little or no canal or penstock construction required, and entailing little expense for the development of excess power except the actual cost of the machinery and its foundations, with the necessary covering roof for including it in the power-house.

The principal rivers of the Southeastern Appalachians, whose drainage basins need to be considered in studying the water power opportunities offered, are the James, Roanoke, Staunton, and Dan Rivers, in Virginia; the Cape Fear, Yadkin, and Catawba, in North Carolina; the Catawba, Broad, Saluda, and Savannah, in South Carolina; the Oconee, Ocmulgee, Flint, and Chattahoochee Rivers, in Georgia; and the Talapoosa, Coosa, Tuscaloosa, and Tombigbee Rivers, of Alabama.

Each of these rivers has many tributaries of importance, and in the enumeration of the rivers in this region a difficulty is presented by the fact that some of them change in names as they flow from source to mouth. For example, the Catawba river of North Carolina is the Wateree river of South Carolina, and flows into the ocean after its junction with the Congaree, as the Santee; similarly, the Mobile river of Alabama is formed by the junction of the Tombigbee and the Alabama, and although the former retains its name to its source, in spite of being joined by the Tuscaloosa, the Alabama above Montgomery becomes the Coosa, and the Talapoosa and the Coosa at Rome split into the Etowah and the Coosawattee.

The northernmost region that we have selected for study is the drainage basin of the James river, having at Richmond an area of about 10 000 square miles. This river gathers its waters from streams flowing northeasterly and southwesterly among the Allegheny, Shenandoah, and Blue Ridge Mountains and, carrying them entirely across the State of Virginia in a general easterly direction, empties them into Chesapeake Bay. The fall line is not reached till at Richmond, where there is an abrupt descent of 84 ft. to the tide level just below the city. The James drains an old well-cultivated portion of the country, having an average rainfall of about 41 in., and varying from 35 to 45 in.

The minimum run-off, which is as low as 0.20 sec-ft. per square mile, generally occurs in October and November, and the maximum, which reaches about 20 sec-ft. per square mile, occurs generally in the months of February, March and April. The average run-off falls to about 0.25 sec-ft. and an average run-off of not more than 0.35 sec-ft. may be expected during three months with considerable regularity.

Toward the head waters the variation of flow is even greater than nearer the mouth, on account of the fact that the mountains here are low and little snow falls upon them, and, furthermore, these mountains are largely denuded of their trees.

The average fall of the James from Richmond to the head waters is nearly five feet to the mile, or about 4.25 ft. per mile, excluding the sharp fall at Richmond; in consequence of this rapid flow, exhibiting many opportunities for power development, as the fall is uniformly distributed along the river.

The Roanoke river, which empties into Albemarle Sound, in North Carolina, drains the western portion of Virginia south of the watershed of the James, and at Clarkesville, Va., is formed by the Staunton and Dan rivers. These two rivers rise in the Blue Ridge Mountains, the Dan lying altogether to the east of the mountains, while the head waters of the Staunton cross the eastern range in a gap and penetrate into the interior valleys, being in that portion of its course called the Roanoke. The Roanoke crosses the fall line of North Carolina at Weldon, 120 miles from the mouth of the river, where the total drainage area of the watershed is about 9000 square miles. Near Weldon there is a sharp fall of over 100 ft. in less than five miles; otherwise, both the Staunton and Dan rivers flow with insignificant grades till near their headwaters.

The rainfall along the upper Roanoke and the Staunton averages about 46 in., and along the watershed of the Dan about 47 in. In spite of this very satisfactory rainfall and a satisfactory distribution through the year, the run-off from these rivers is very variable on account of their draining, principally table-land and receiving little from the mountains. The minimum flow falls as low as 0.16 sec-ft. per square mile, while the maximum runs up to about 10 sec-ft. The floods are of great moment along these rivers on account of the suddenness of their rise.

A run-off as low as 0.30 sec-ft. must be contemplated at any time between June and November, and a greater average flow than 40 sec-ft. cannot be expected during three months, although the run-off from the Satunton is heavier per square mile than the run-off from the Dan, apparently on account of the greater drainage from mountain territory.

South of the Dan river basin the Cape Fear river drains a region in the centre of North Carolina, flowing to the southeast and entering the Atlantic near Wilmington. Although the watershed of the Cape Fear is principally covered with clay and sand and comprises pine and oak forests and agricultural land, and in spite of the fact that there are no great falls in its course, except at Smileys Falls, about 20 miles above Fayetteville, where it crosses the fall line and reaches the level of tidewater, still it is one of the most completely developed power rivers of the south.

The rainfall over this watershed averages 50 in., the greatest fall being in the spring and summer; these being the growing seasons and the territory largely agricultural the total run-off is small and is particularly low in the fall when it has gone as low as 0.07 sec-ft. per square mile, with a monthly average run-off of not more than 0.12 sec-ft. Indeed for the last six months of the year an average as low as 0.3 sec-ft. must be allowed for.

On the other hand, as in all such regions the floods are very severe, running from as high as 15 sec-ft. in May to 20 sec-ft. in January. That a stream with these difficulties to be encountered should have been so well developed shows plainly the importance of a ready market in problems of power development, and the effect of even an unreliable water power in developing manufacturing in a country where the conditions of market, raw material, and satisfactory labor are favorable.

The Yadkin river of North Carolina, or the Great Pedee of South Carolina, drains above where it crosses the fall line at Cheraw, S. C., a territory of about 9 700 square miles. This river flows from the base of the Blue Ridge Mountains in North Carolina to the Atlantic near Georgetown, S. C. At first it flows for about 60 miles in a northeasterly direction almost parallel to the Blue Ridge Mountains, from which many streams come down to augment its volume. At the northeast corner of Yadkin County it turns to the south and crosses the state into South Carolina; soon after entering this state it runs over its rapids at the fall line and reaches the level of the tide. Excepting in the rapids at Cheraw and at the Yadkin Narrows 55 miles above, there are no important falls, though there are on the watershed a number of opportunities for development by high dams forming storage reservoirs. The rainfall in the mountain region along the headwaters of the Yadkin averages in excess of 55 in., but over the greater portion of the watershed it amounts to about 46 in. The distribution of the rainfall is similar to that in the Cape Fear region, but as the river drains a greater proportion of mountain territory the run-off does not fall relatively as low, the minimum record being at the rate of about 0.25 sec-ft. per square mile. For the average year the run-off is at a rate no lower than 0.32 sec-ft. and the average for the minimum months is not less than 0.4 sec-ft. The floods are exceedingly severe, frequently running as high as 30 sec-ft.; they have been recorded as high as at a rate of 38 sec-ft.; but they are of short duration, being largely over in about 48 hours and few monthly averages rising above 5 sec-ft. per square mile.

The course and drainage area of the Catawba are much similar to those of the Yadkin. Like the Yadkin it changes its name on entering the state of South Carolina; there it is called the Wateree. From its source, running northeasterly, it receives numerous tributaries from the Blue Ridge Mountains and then turns almost south delivering its waters into the Atlantic through the Santee. Near Camden, S. C., it crosses the fall line; just above are not only the customary rapids but a few miles farther north one of the most remarkable power sites in the South, a total fall of over 150 ft. being available for development.

The fall of the river is not so gradual as the Yadkin but concentrated in falls many of which are available for developments of considerable size. The drainage area at Camden is about 5 000 square miles; in the upper half of this territory the rainfall averages about 50 in. and in the lower half about 45 in. Almost the whole territory is heavily wooded and in consequence the run-off is comparatively uniform, never having been found to fall below a rate of 43 sec-ft. in the upper half of the drainage area, or about 0.35 sec-ft. over the whole. As the minimum is large so also is the flood flow which on several occasions has risen to a rate of 50 sec-ft. The minimum flow may be expected at any time from July to November and the maximum in the spring months.

West of the watershed of the Catawba lies the Broad river. This river rises in the Blue Ridge mountains a short distance east of Asheville and flows in a southeasterly direction to Columbia, where it joins the Saluda to form the Congaree. The latter flows into the Wateree and forms the Santee. Unlike the two previous rivers, there is no branch running parallel to the mountains, but in the upper part of its watershed the tributaries spread out fan-like and deliver the headwaters to the main river at about the point where it crosses the South Carolina border. There is no point at which the Broad crosses the fall line but it lies altogether in the uplands. The slope, however, is great, averaging about 4.5 ft. per mile for the total length 140 miles from its mouth. A number of favorable opportunities are presented for development, notably near Alston, S. C., and near Gaffney, S. C. The drainage area at Gaffney is approximately 2 000 square miles and at Alston about 4 600 square miles; the total drainage area of the watershed is about 4 900 square miles. On the northern portion of the watershed, which lies in North Carolina, the rainfall is in excess of 55 in. annually; in that section of the watershed lying south of Gaffney the rainfall is about 46 in. The soil over the watershed is generally sandy and a large portion is wooded; in consequence the run-off is well distributed, not having been found to fall below 0.35 sec-ft. per square mile, and probably not so low in the northern portion of the watershed. The floods commonly rise to 25 sec-ft. per square mile and must be expected up to a rate of 30 sec-ft. The dry season is generally in the summer or fall, though a rate of 0.5 sec-ft. must be expected in any month except during the spring.

While the watershed of the Saluda directly to the west of the Broad is similar in character to that already described, still, on account of its relatively greater length in proportion to its width, the reliability of the water flow is not so great. With a total length of about 135 miles the area of the watershed is only about 2 000 square miles; in consequence, neither the maximum flood rate or the minimum run-off rate is as high as on the Broad. In the upper half of the drainage area the annual rainfall is about 53 in. per annum and about 45 inches in the lower half. A minimum run-off of 0.28 sec-ft. per square mile has been observed though it probably falls as low as 0.25 sec-ft., and a run-off no greater than 0.4 sec-ft. must be contemplated during the last half of the year. The maximum which rises to about 20 sec-ft. per square mile may occur at any time from January to July.

The Savannah river, which at Augusta drains a territory of about 7 300 miles located almost equally in South Carolina and Georgia, promises to become the source of some of the most important water powers in the south, not only on account of the fact that the stream flow is good and the shoals well adapted to development, but more particularly on account of the favorable economic situation of the water-power sites. The territory on both sides of the river is an important cotton-growing section and its adaptability for mills has been well proved; in fact, Augusta, Ga., is the largest cotton manufacturing city in the whole south. The industries of that city have been built up about a 50-ft. fall in the Savannah, at that point where the river crosses the fall line. The minimum flow at Augusta is about 0.30 sec-ft. and at Calhoun Falls 40 miles above where the drainage area is 2 700 square miles it is about 0.35 sec-ft. The maximum flood rate is about 25 sec-ft. per square mile. A monthly average must be expected as low as 0.50 sec-ft., and this average minimum may be expected for from four to six months of each year. The minimum may occur in July, October, or November, and the maximum during the first six months of the year.

The middle portion of the State of Georgia is drained by the Oconee and Ocmulgee, which, at Milledgeville and Macon respectively, cross the fall line—a territory of about 6 000 square miles. These two rivers are very much alike in origin and character, rising in the southernmost extension of the Blue Ridge mountains, where the mountains become flat, rocky hills gradually sloping off to the fall line. The rivers are comparatively steep and present a number of opportunities for power development. The flow in these rivers is comparatively low, often during several months of a year falling to as low as 0.2 sec-ft., and a rate as low as 0.1 sec-ft. is probably reached, though for the northern portion of this watershed this rate of minimum run-off is approximately doubled. The low flow generally occurs in the late summer or early fall. The maximum flow of 20 sec-ft. occurs in the spring.

To the southwest lies the drainage area of the Flint river which crosses the fall line at Albany and follows the Blue Ridge mountains practically to the end in a rapid flow. The run-off falls to about 0.20 sec-ft. and rises to about 15 sec-ft.

maximum. Although the maximum run-off is not at so high a rate as other streams still they are formidable elements in the engineering problem. This river presents the anomaly of frequently being at its lowest during November, a great disadvantage in a power river, as the yearly load curve of most industries is generally rising at that time.

The last four watersheds described headed in the Blue Ridge mountains which run southwest through Georgia. Across the mountains and running parallel to them is the watershed of the Chattahoochee river which runs rapidly down between the lower extensions of the Blue Ridge and Great Smoky mountains; in consequence of being located almost entirely in the mountains it presents many desirable characteristics as a power stream. The minimum run-off which occurs in the summer falls to a rate of 0.25 sec-ft., but a rate not exceeding 0.4 sec-ft. must be expected for more than one month during the latter half of the year. The flood flow which occurs in either December of the spring months amounts to about 20 sec-ft.

To the west of this territory lies the great drainage area of the Mobile watershed covering practically the whole of the state of Alabama, and extending into the northwestern corner of Georgia and the northeastern corner of Mississippi. The greater portion of this watershed is mountainous and well wooded; in consequence there are many valuable water-power sites. Some of the highest heads available in the eastern states are to be found in this territory.

Commercially, the development of the coal and iron mines and the types of manufacturing to which these raw materials give rise have furnished opportunities for the power market, though the presence of coal mines renders caution necessary in the selection of sites for development.

In this watershed there have been reported sites for power development aggregating 150 000 h.p., many of the sites being within close competitive distance of one another. Although the country is mountainous, still it is so far south that these mountains carry no snow and the evaporation is high; hence the minimum rate of run-off is never high. Certainly a minimum rate of 0.2 sec-ft. per square mile will be found in any important Alabama river. The flood flow tends to be a maximum at about the rate of 20 sec-ft. per square mile.

In this short review of the water powers of the southeastern

Appalachian region an attempt has been made to convey some impression of the wide distribution of water power in this territory. Already the development of a few of the available sites has had a powerful influence on the commercial life of the South, and in the contest for industrial supremacy which is continually being waged between sections of our country the ready availability of water power in the South is certain to play no unimportant part. The conditions, it must be observed, are in all respects different from the conditions in other sections of the country. There is no location which can command the field, and within a comparatively short distance of each plant there is another location which may be developed and probably offer competition. The minimum flow is everywhere small and the floods heavy, varying from 75 to 150 times the minimum. But, on the other hand, a class of manufacturers are at hand who appreciate the value of water power even when it is variable, and are accustomed to providing themselves with steam auxiliaires for allowing the use of surplus water power. These conditions are on the whole favorable to the development of water power on a large scale, but point to the necessity for effective management and a comprehensive plan for the development of a section of territory rather than of a single power.

With efficient business management and careful engineering we may expect the water powers of the Southeastern Appalachian region to prove to be one of the most valuable assets of that wealthy section of our country.

Discussion on "Water-Powers of the Southeastern Appalachian System."

Ralph W. Pope: One of the chief considerations in the transmission of power is a market. There is plenty of power available at many points where there is no place to which it can be economically transmitted to meet a commercial demand. This necessitates the development of industries to utilize the powers. Many railroads, especially through mountain districts, follow streams. In 1892, when I was at Denver, at which time we had not thought very much about operating railroads by electricity, it appeared to me that there was power going to waste along the line of railway up the Clear Creek Canyon, that would operate the whole system. Coal was brought from Utah, possibly 500 miles.

Having in view that the object of transmission is to convey power to a market, here the power is developed right alongside of the market, and the day has already arrived when there is talk of operating trunk lines by electricity. A few days ago I made a trip through western Massachusetts from Great Barrington, and the same thoughts occurred to me regarding the Housatonic River, which parallels the road for about 60 miles. Part of this power is now being transmitted to the Naugatuck Valley, 20 miles away. I think that is doing the wrong thing with the power, not only for the reason that it is a misuse as far as the valley is concerned, but it is causing serious trouble for the telephone companies. This is of such importance that a corps of telephone engineers made experiments at the power-plant with the high-tension current to see what could be done to eliminate the troubles. It may be said that there is not enough power to operate the railroad at all seasons of the year. While that might be true as far as both freight and passenger service are concerned, there might be sufficient power to operate the passenger trains, and consequently there would be a reserve of locomotives all the time, in the freight service, which could be used for the passenger trains when the power was not sufficient for the latter. While this might be a temporary return to the existing evil, it would not be so bad as it is now. Conditions would be improved, and as will be seen at once, the problem of reserve power, which is one that is encountered by almost every factory in New England operated by water power, would be met.

I think there is hardly a mill in New England, operated by water power, that does not have a steam plant in reserve; and the steam reserve on a railroad fits in very nicely for the purpose stated above. In fact, now that there is a possibility of operating railroads by electricity, this appears to be the natural course of development. Here is a water power running alongside a railroad, and here is the market right at hand, and it is for the electrical engineers to develop and apply the power of the one and for the railroad managers to obtain a pecuniary reward for the undertaking from the other.

C. E. WADDELL: Among the industries of the Southern States, Dr. Perrine mentions the cotton factories. Their growth has been something unprecedented; in a recent circular the Southern Railway states that there are more than 1 000 cotton mills located along its lines. The adjunct to the cotton mills—the finishing plant—is however not found in the South; consequently the product of the mills is sent North previous to marketing. The clear and pure water necessary for finishing is to be had in the mountains, and doubtless in the near future this important branch will be added to southern industries. The absence of anchor ice in the southern streams is an important feature and is conducive to better service than in localities so troubled.

Two classes of power are generally furnished by southern power companies, the regular day service, and secondary power available during the night; the latter is sold at a much lower rate but tends to raise the load-factor of the plant. In the majority of cases in the South the practice of working in harmony with existing city plants has been resorted to by distant powers entering a town; synchronous converters are installed, and the benefit is mutual, the local company getting a low rate and the water company a steam auxiliary.

The question of labor and capital is not paramount in the South as elsewhere, and the class of labor to be had is superior to many other localities.

In the past the difficulty experienced in financing southern enterprises has handicapped to a large extent the southern engineer, the problem has been not the development of a power in the most desirable manner, but in the cheapest way possible.

L. S. RANDOLPH: There are two points which Dr. Perrine has not mentioned, although he has covered the ground very thoroughly. One is the time of the occurrence of the minimum rainfall, which sometimes comes in winter, in some years in January and February; occasionally it comes late in the summer, sometimes early in the summer. At other times there is an exceedingly uniform distribution throughout the year.

Another point is that there are excellent sites well back in the mountains. Dr. Perrine refers to the fall-line through Richmond and Danville, etc. There are a decidedly greater number of sites for water powers in the western section well up in the mountain ranges, as at Roanoke, Freeze, and many other places.

In regard to anchor ice, some figures in regard to temperature may be interesting. Along the summits of the mountains there is during two or three months in the year considerable zero weather, but where power-plants can be built zero weather seldom lasts more than 24 hours, rising in the middle of the day to 14, 15, and 30 degrees, going to zero at night, and keeping this up for a week at a time. This gives little or no trouble with anchor-ice.

A. M. SCHOEN: The question of southern water powers appeals very strongly to all electrical engineers in this part of the country. We have long looked forward to the day when streams in the South might be developed and the energy that has so long lain latent put into service. It was some 12 or 13 years ago when I first had occasion thoroughly to look over electrical industries in the South and at that time but little headway had been made in developing the water powers in this section. Since that time, however, thousands of electrical horse power have been put at the service of man, and the industries of the South have profited accordingly. There are transmission lines extending as far as 30 miles from the generating plant to the points where it is utilized, and other high-tension, long distance systems are constantly being promoted.

In this connection, if I am not out of order in referring to Mr. Waddell's paper, which, it seems to me, is closely allied with that of Dr. Perrine, the most serious question to-day is the denudation of the water-sheds of their forest growth, and in consequence the sweeping away of the natural barriers and storage reservoirs which nature has erected to regulate the flow of the streams. This removal of the forests from such places tends to destroy entirely the efficiency of these powers.

I regret very much that Dr. Perrine did not present in his paper a comparative statement showing the difference between the high and low water marks and the periods of drought and freshet of to-day and say of 10 or 15 years ago. Had he looked into this matter I think he would have found that there has been a very decided change in these periods and that the normal conditions of the streams to-day show a difference totally unwarranted, considering the time which has elapsed.

It seems to me that this, as a national body of electrical engineers, should go on record in some way in regard to the constant destruction of the forests and the resulting injury to the reservoirs provided by nature to hold in abeyance the water which comes from the rain and snow, and thus keep the water powers in normal condition. I believe in many instances it will be found to-day that the normal condition of many streams will not remain more than three or four months out of the year, the remainder of the time the condition being that of either flood or drought, and the future promises that these conditions will augment rather than decrease.

F. A. C. PERRINE: Mr. Randolph has called attention to the fact that some of the streams have their minimum flow in the winter, stating that sometimes the minimum is in December and January. I have in mind one river in the South that has this characteristic; it is the Flint River of Georgia, which has its minimum flow in November, but I have been unable to ascertain any river in the South that has its minimum flow later than November. There are some rivers that have a low flow in December and January, but none, so far as I know, that then have absolutely minimum flow.

Mr. Randolph has also called attention to the fact that on some of the water-sheds the minimum flow is uniformly distributed, and that on some it is not. This is true, but engineers should be cautioned against understanding by this statement that the run-off which is useful for water power is proportionate to the distribution of the rainfall. With a uniform rainfall throughout the year, there is a uniform run-off. On the contrary, dry summers and wet falls and springs produce a uniform run-off. If there is a uniform rainfall there results a minimum run-off in the fall; for the reason that if it is dry late in the spring and during the summer, the vegetation is partly killed and is not so vigorous and does not use so much of the water, and there is a greater proportion of the run-off in the fall when the water is otherwise low. It may be expected that the run-off from a river will be uniform during a year when the rainfall is heavy in the early spring, light in the late spring, almost absent in the summer and heavy in the fall. Whereas during a year when the rainfall is uniformly distributed there will be an extremely low run-off during the fall, because the vegetation during the summer has used up the water. This can be seen not only as regards individual years, but as regarding some of the territories which have the worst average of run-off, they having actually the best distribution of rainfall.

CARL HERING: The papers and discussions at this session have shown us the great value of water power development in this region and I therefore think the present a very good occasion for the INSTITUTE to consider the following resolution:

Whereas, the destruction of the forest growth on the watersheds and the consequent impairment of the natural storage capacity promises to injure seriously the water power possibilities of the streams finding their sources therein; and

Whereas, the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS recognizes the serious loss to the electrical interests of the community which might result therefrom; therefore

Be it Resolved, that it is the opinion of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS that all practicable means should be adopted for the preservation to all such locations, of the integrity of their natural resources for the development of their territory.

And further, *Be it Resolved*, that a committee be appointed by the President for the collection of information concerning this matter. And a recommendation to the INSTITUTE of such action for the dissemination of information concerning the attitude of the INSTITUTE on this subject as may seem desirable.

F. A. C. PERRINE: I second the motion.

PRESIDENT LIEB: You have heard the motion; it is now before you for discussion.

F. A. C. PERRINE: This is an exceedingly serious matter, not only for this region, but for all parts of the country; not only on account of the destruction of our forests, and its influence on our power streams, but on account of the futility of the methods that have been used by our government, and the Department of Agriculture as representing that government, for the preservation of such interests. The difficulty due to the destruction of our forests, and all our other natural resources dependent thereon, is fundamental and requires broad treatment. The only solution that has been offered by our government is a very feeble attempt at the establishment of small territories in which it is supposed that no indiscriminate wood cutting can be carried on. But all of these territories are, in spite of the fact that they are established as forest reserves, laid open to the danger from forest fires, which is far worse than the direct danger from the lumberman. It is an incidental danger to lumbering, and the fact that our government allows such injudicious methods of lumbering as to leave the whole country cut over subject to danger from forest fires is a disgrace not only to our national Department of Agriculture, but to the government of every state in the Union. If this resolution should be transmitted to the Department of Agriculture, it ought equally well to be transmitted to the legislature of every state in the United States; for it is absurd that the jurisdiction over the lands which are not excepted as forest reserves should remain under the states which will allow conditions resulting in forest fires able to spread to and to destroy the infinitesimal reservations separated out for federal control. The whole question, is one of the utmost importance not only to the water power resources of our country, but to the development of many of our other resources. We are destroying one of the greatest of our natural sources of wealth without any adequate compensation and without any protection for it.

I think that the INSTITUTE should go on record at this time as protesting against this condition. I do not think that the INSTITUTE should by implication indorse the methods that have been used, but in a dignified way should call attention to the fact to all people, not only to the federal government, but to the state authorities and to individuals, that we are ruthlessly destroying these natural resources, and such methods as are being used at present are inadequate for their proper protection.

PRESIDENT LIEB: Under the original motion no further action would result, excepting that possibly communities and localities, in pressing their own case, might use the INSTITUTE's resolution in calling the attention of the authorities, either state or national, to the matter.

GANO S. DUNN: I arise to indorse those resolutions and to say that we have had a larger convention than this and we have had conventions differently located, but I know that this one will go down in the history of the INSTITUTE conspicuous for the warmth of good feeling and hospitality with which we have been surrounded.

We have met here and been entertained by the corporations and individuals whose names have been read in a way that has shown the genuine pleasure they have taken in doing it. It is but little that we can do in thanking them, but I am sure in seconding these resolutions and in giving my own personal thanks to the committee and to the others, I am but poorly expressing what is in the mind of everyone. We shall go back feeling that we have left many friends in the South and that now traditional Southern hospitality means an altogether new thing to us.

I wish to offer an amendment to the original resolution, following right on with the clauses that Mr. Hering read, the clause to the effect that a committee be appointed to see to the proper dissemination of this resolution.

CARL HERING: I accept the amendment as an original proposer.

F. A. C. PERRINE: I accept the amendment as seconder.

Motion to adopt the resolutions as amended put to vote and unanimously carried.

[The amendment appears as the last clause in the preceding resolutions].

Fig. 1.—(Nunn) Birds-Eye View of Niagara Falls, Showing Cat

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A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

THE DEVELOPMENT OF THE ONTARIO POWER CO.

BY P. N. NUNN.

The development of electrical power at Niagara Falls has long attracted widespread attention and interest. Since the first installation upon the American side descriptions and discussions of its works and methods have been granted a conspicuous place in technical records and scientific press. It is not so well known, however, that four other developments, each larger than the pioneer, are now drawing or preparing to draw power from Niagara River. These differ so widely and so apparently as to type and character and express such differences of conception and method as to suggest even to the casual visitor a doubt as to unity of purpose. It seems fitting therefore at this time, when the largest of these is about to enter the active field, to present before the INSTITUTE, and through the channels of its PROCEEDINGS to the technical world, a statement of the purposes which have obtained and of the considerations which have led to so fundamental a departure from the type of construction hitherto characteristic of Niagara Falls, as well as briefly to describe a few features which may prove to be advances in the art of power-plant design.

Standing upon the upper steel-arch bridge and facing the Canadian falls, one may observe at the foot of the cliff forming the right-hand wall of the gorge, a long but unobtrusive building, its farther end obscured by spray from the great cataract. It is of modest though massive design and its colors almost blend with those of the overhanging cliff. This is the power-house or generating station of The Ontario Power Company. To the right, high above and behind the power-house, upon the bluff overlooking both gorge and cataract, may be seen another great structure, less massive but more ornate, which on account of its commanding position is by far the most prominent landmark of the Canadian side. This is the distributing station of the same company, from which the power generated below is controlled, measured, and transmitted. Away to the left, around the bend of the river and hidden by the trees of Goat Island, are the walls, abutments, and buildings of the intake and head-gates through which the water from Niagara River is diverted for use below. In the park between these extremes, seen just beyond Horse Shoe Falls, stands the power-house of The Canadian Niagara Power Company, while to its left another power-plant, that of The Electrical Development Company, is rapidly building.

From the head-gates of the Ontario company three great steel-and-concrete tunnels or conduits beneath the surface of the park, will convey nearly 12 000 cubic feet of water per sec. to the top of the cliff above the power-house. Thence it will pass through 22 steel penstocks in shafts and tunnels down and out through the cliff to an equal number of horizontal turbines in the power-house below. From the generators the electrical cables turn back through tunnels to the 22 banks of switches, transformers, and instruments of the distributing station above and to the transmission lines beyond, completing an equipment for more than 200 000 h.p.

The intake-works for the entire 200 000 h.p. are now finished. One of the three main conduits is completed, while for the second and third, portals and head-works have been installed and a portion of the excavation made. Six of the 22 penstocks are already in place within their shafts and tunnels and two others are building, while the power-house is nearly prepared for the concomitant apparatus. The distributing station is completed for the switchboard of the entire 22 units, for the transformers of 8, and for other apparatus of 14. As to equipment, the coming month will witness one complete unit being operated, a second being tested, a third being installed, and a fourth being completed at the factories, with other units to follow as equipment of such size can be manufactured and installed.

The purposes and methods followed in the development of the pioneer plant and the environment and natural conditions at Niagara Falls have become so well known that interest in

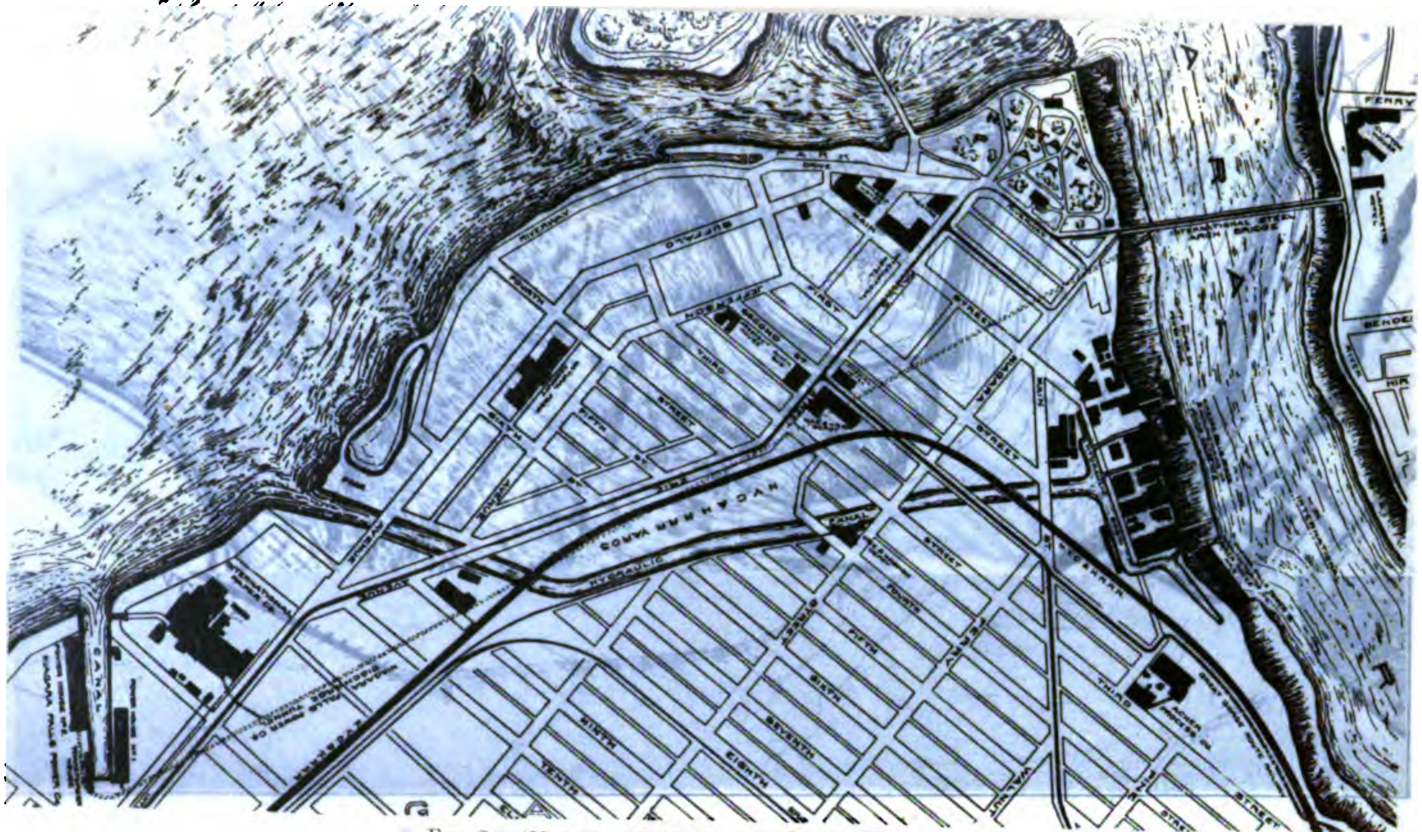


Fig. 2.—(Nunn.) Map Showing Power Developments.

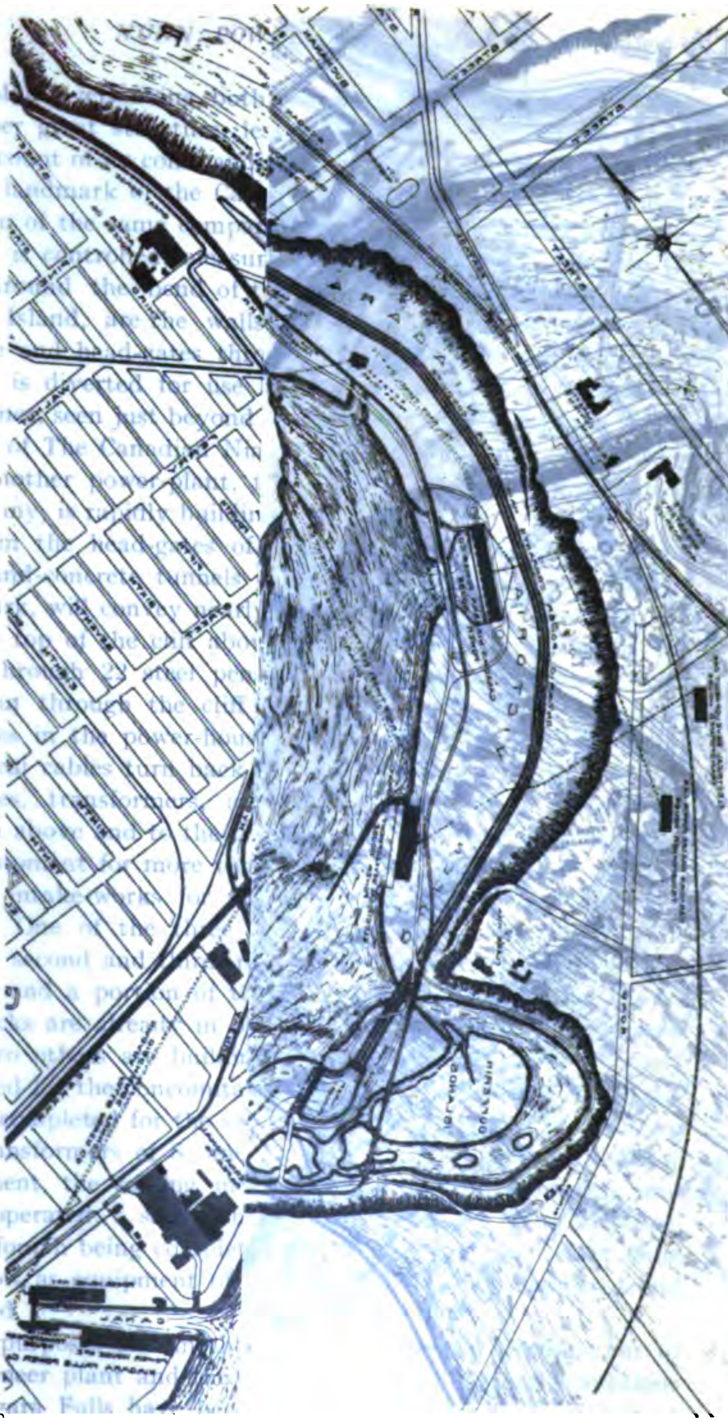


Fig. 2.—(Nuun) Map Showing Power Developments

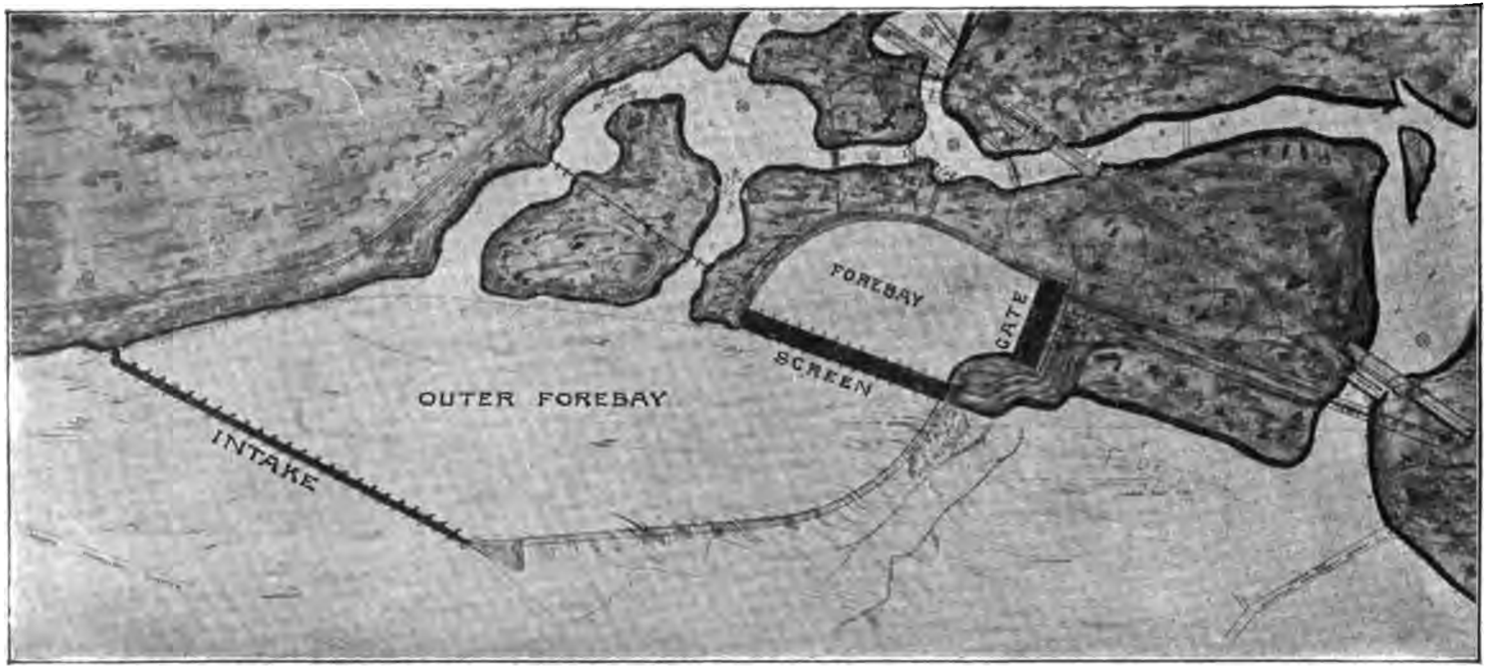


Fig. 3.—Plan of Ontario Company's Intake Works.

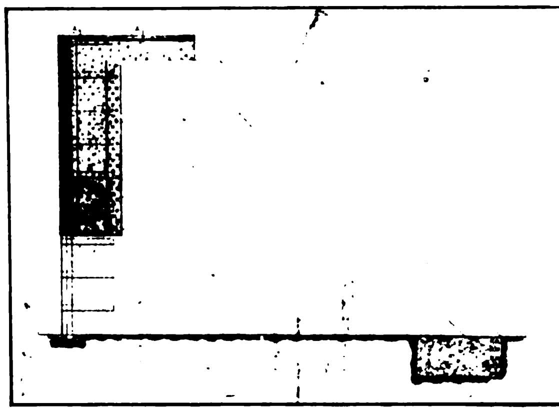


FIG. 4.—Section through Intake.

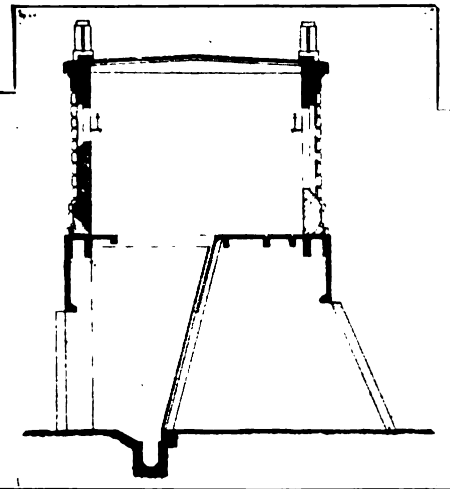


FIG. 5.—Section through Screen-House.

FIG. 6.—Section through Gate Structure.

this younger development necessarily centers in its salient features or in those most likely to represent advance in engineering. The more important of these are the arrangement of intake-works, the design of main conduit and spillway, the horizontal-shaft units, the symmetry of arrangement, the centralization of control, and the protective isolation of apparatus.

The intake-works have been located and designed with especial reference to the ice difficulties which have been the limiting factor in the success of Niagara power. Cake-ice in enormous quantities floats down for weeks at a time from the Great Lakes, and mush-ice is formed in the turbulent rapids primarily by the freezing of spray and foam and secondarily by the disintegration of cake-ice. To avoid the latter the intake is located in the smooth but swift water just above the rapids; to exclude the former the following features have been introduced. A long and tapering forebay protected at its entrance by the main intake terminates at its narrow, down-stream end in a deep spillway. Upon the river side it is enclosed by a submerged wall, while the other side adjacent to the spillway is occupied by the main screen structure leading to the inner bay and to the portals and head-gates of the three conduits.

The intake, nearly 600-ft. long, stretches across the inlet or bay at Dufferin Island, almost parallel with the current in the river. Throughout its length a concrete curtain-wall extends down 9 ft. into the water, here 15-ft. deep, so that the gate openings beneath admit only deep water, and this at right angles to the swift exterior surface flow which, sweeping the full length of the curtain, carries the floating ice to the rapids beyond. At the main screen this operation is repeated. This structure, 320-ft. long in 20ft. of water, lies across the entrance to the inner bay and parallel with the direction of flow in the outer bay. Again a curtain, formed by the front wall of the enclosing superstructure, admits to the screens only deep water, here also at right angles, while it excludes ice with the surface currents maintained through the forebay by a voluminous spill of surplus water.

At the gate structure, where the water is 30 ft. in depth, the tapering portals leading to the electrically operated Stoney head-gates are protected with wide-mesh screens which are also enclosed and safeguarded by a curtain carried by the front wall of the gate-house. The bay in front of the curtain communicates with the river by an ample ice-run. Substantial concrete buildings shelter both head-gates and main screens. In each case an open canal between curtain and screen spills into a gravity ice-run emptying into the river. Both buildings are supplied with steam for heating and thawing from an underground boiler-plant situated in the common abutment.

Thus the water before entering the conduits must pass in succession three automatically selective steps, each excluding surface water and its floating ice; and two screens, each behind ice-runs in heated buildings containing live steam for emergencies. Serious trouble is not believed possible while these provisions are maintained with reasonable care.

Screen frames are removable by an electric crane for cleaning and changing. On account of its location in the public park, the top of the long, narrow screen house, approached at either end by broad steps and landings, is finished as a promenade. From this point of vantage one may have a superb view of the upper rapids. The islands and channels made in the course of this work give great opportunity to make this portion of the park most picturesque.

The height of the water in Niagara River, and therefore the volume here available, is dependent upon the surface elevation of Lake Erie, the erosion of the river bed, and such temporary causes as ice gorges, storms, etc. From calculations based upon comparative observations extending over a number of years and upon government reports of Lake Erie levels for nearly 50 years, the elevations of the intake have been so selected that at extreme low water and most adverse conditions a full supply of water should be secured.

The main conduits are of 0.5-in. riveted and reinforced steel imbedded in concrete, 18 and 20 ft. in diameter, 6 500-ft. long, and are buried within the rock and soil of the public park. Through them the water flows at a velocity of approximately 15 ft. per sec. Just beneath the top of the cliff behind the power-house, within a long underground chamber, the arched roof of which supports the conduit above, 9-ft. diameter branches pass from the under side of the conduit through gate-valves and become the penstocks, each supplying water at 10 ft. per sec. to a single turbine. Each penstock has two expansion joints, a massive thrust anchorage in the power-house foundations, and an automatic relief-valve and a stone-catch discharging into the river. The 9-ft. valves are electrically operated under distant control from the power-house below, and

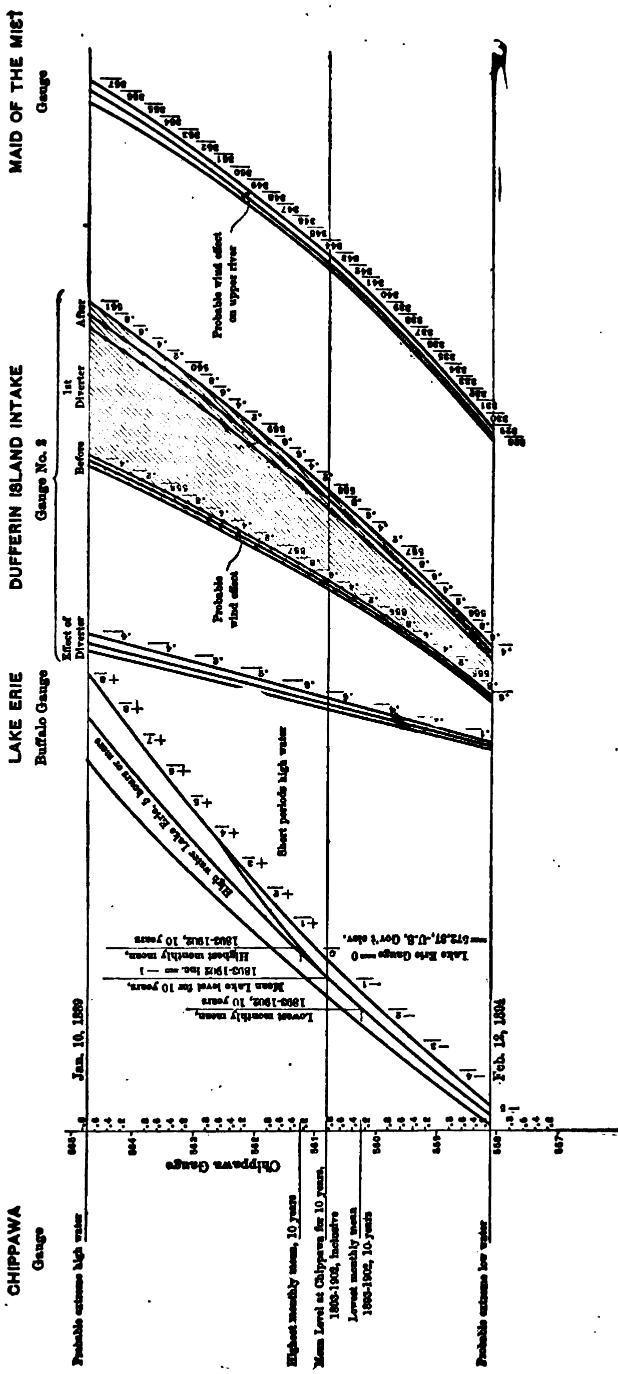


FIG. 7.—Relative Water Levels on Lake Erie and Niagara River.

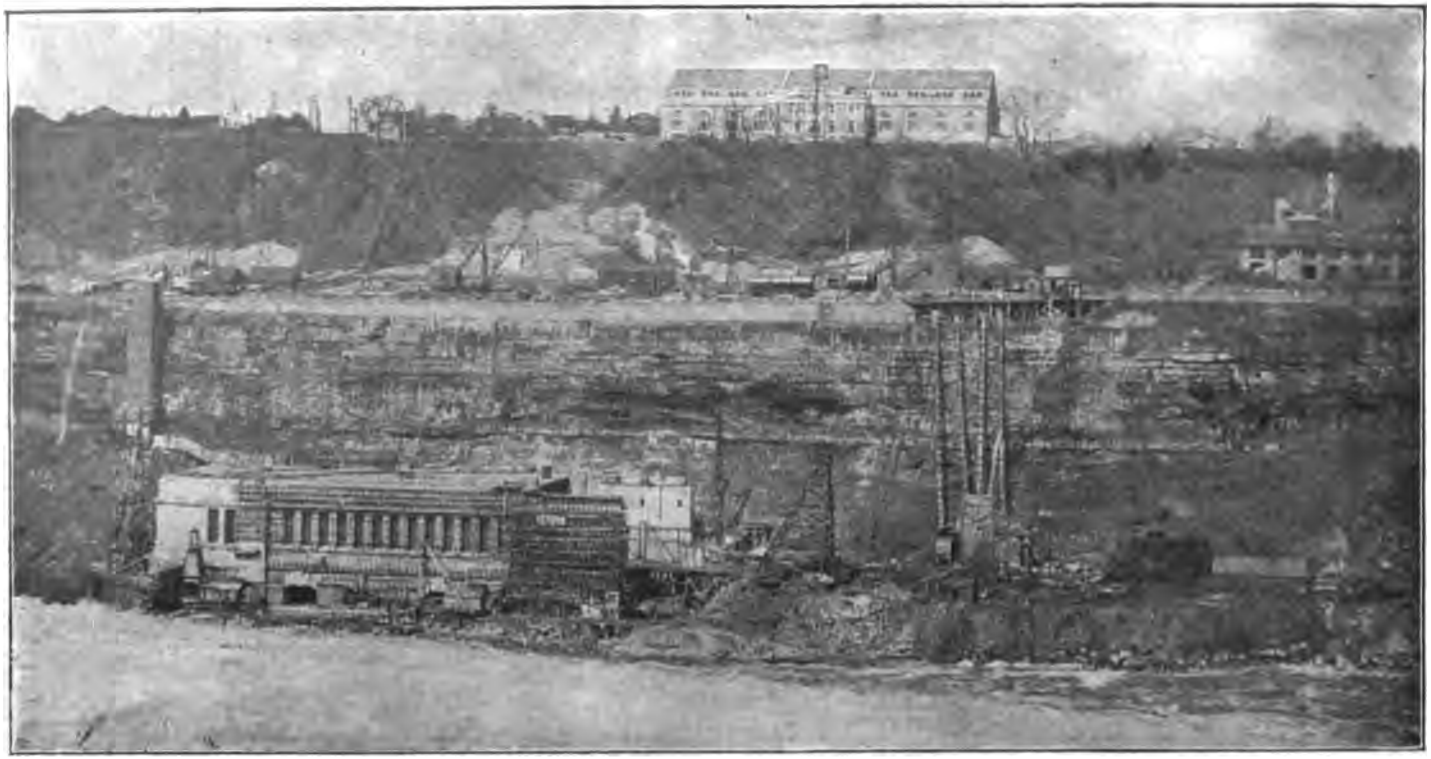


Fig. 8.—Generating and Distributing Stations During Construction.

are so constructed that all working parts may be removed for attention while the penstocks are in service.

The spillway at the end of the conduit, to prevent water-hammer in case of sudden loss of load, is little more than the enlarged and elevated end of the main conduit equipped with an enclosed weir and underground discharge. Its peculiar features are its adjustable weir and helical discharge-tunnel which, after a steep initial pitch in the taper from the weir, follows a uniform grade and symmetrical curve while circling about to reach the river, thus preserving a smooth unbroken water column of highest velocity and least expenditure of energy. The purpose here is to prevent erosion, restricted flow, and excessive air-suction, the latter on account of the

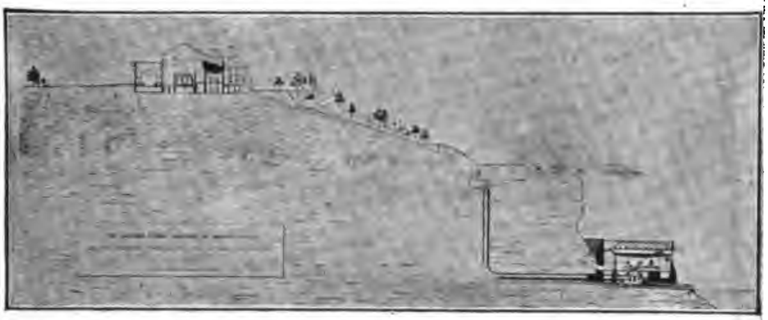


Fig. 9.—Sectional Detail through Generating and Distributing Stations.

danger of formation of ice from spray under forced circulation of air.

The generators are of conventional horizontal-shaft type, three-phase, 25-cycle, and deliver 12 000 volts at 187.5 rev. per min. The turbines are of Francis or inward-flow type, double, central-discharge or balanced twin turbines designed to deliver 12 000 h.p. under 175-ft. head. Their shafts are 24-in. maximum diameter and each carries two 78-in. cast-steel runners of "normal" reaction. Housings are of reinforced steel plate, 16 ft. in diameter, spiral in elevation and rectangular in plan. Gates are of the wicket or paddle type, and the rotating guides forming them are carried by shafts which project through stuffing-boxes to an external controlling mechanism, thus freeing the casings from the objectionable interior gate-rigging and leaving their approaches to the guides symmetrical and open. While the velocities in housings and draft-tubes are high, corresponding losses are avoided by nicely modulated changes of both velocity and direction and by symmetrical and liberal curves free from abrupt angles or obstructing projections.

Of the 175-ft. head, 20 ft. is in the 10-ft. diameter draft-tubes, because the floor of the power-house has been elevated 26 ft. above mean water level to provide for the excessive variations to which the water in the gorge is subject. While bearings are self-oiling, all are equipped with water-cooling system, and for still greater insurance a piping system for the changing

FIG. 10.—Main Conduit During Construction.

of oil has been so connected that in emergency it is instantly available for forced lubrication. Believing that disorders of bearings and journals, like those of people, are usually the culmination of gradually increasing ailment, each bearing is supplied with an automatic record-making thermometer providing the superintendent with a daily record, not only of the temperature of the bearing but also of the temperament of the attendant as well.

Although entirely feasible to use the vertical-shaft turbine and although restricted space at the power-house requires

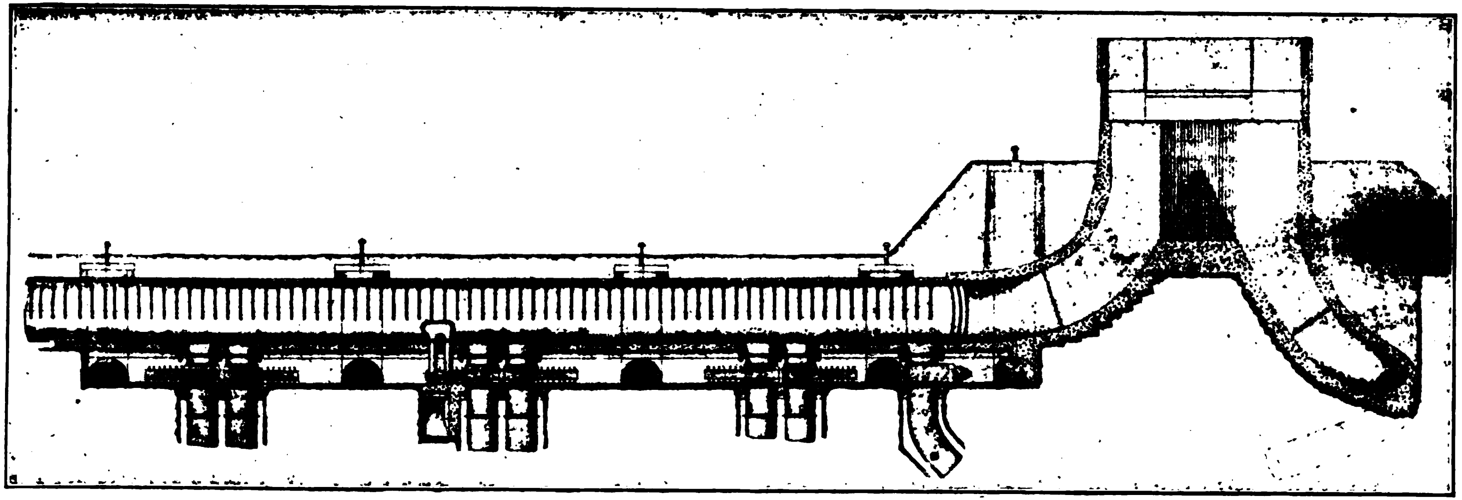


Fig. 11.—Section through Valve Chamber and Helical Spillway.

greatest floor economy, nevertheless horizontal units are employed on account of their freedom from step-bearings, their higher efficiency, and their greater accessibility. While step-bearings in certain places are entirely successful, as long since proved by screw propellers and more recently by vertical steam turbines, yet at best they entail much auxiliary apparatus requiring especial care and frequent adjustment. With high-head turbines they have an uncertain record to be shunned wherever continuity of service is essential.

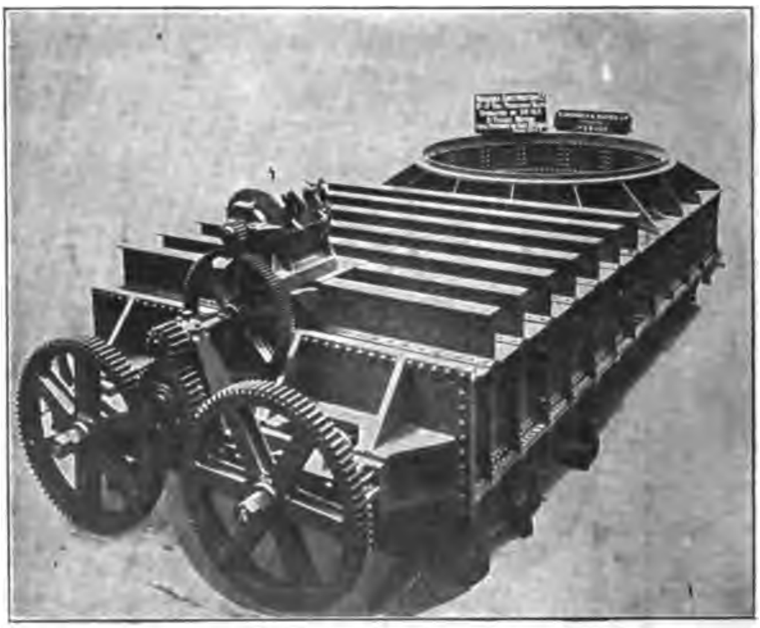


FIG. 11b.—A 9-ft. Penstock Valve.

To reduce load upon the step-bearing, the vertical unit is usually of highest permissible speed. While efficiency at the generator is favored by this high speed, the effect upon the turbine is diametrically opposite and usually many times greater. This is because highest efficiency and durability seem to require "normal" reaction—a radial relative direction of bucket entry—and narrowly limited relative dimensions of runner. At such reaction peripheral velocity of runner (the components of which—diameter and rotation—are inversely proportional) is fixed by head. At such relative dimensions power is pro-

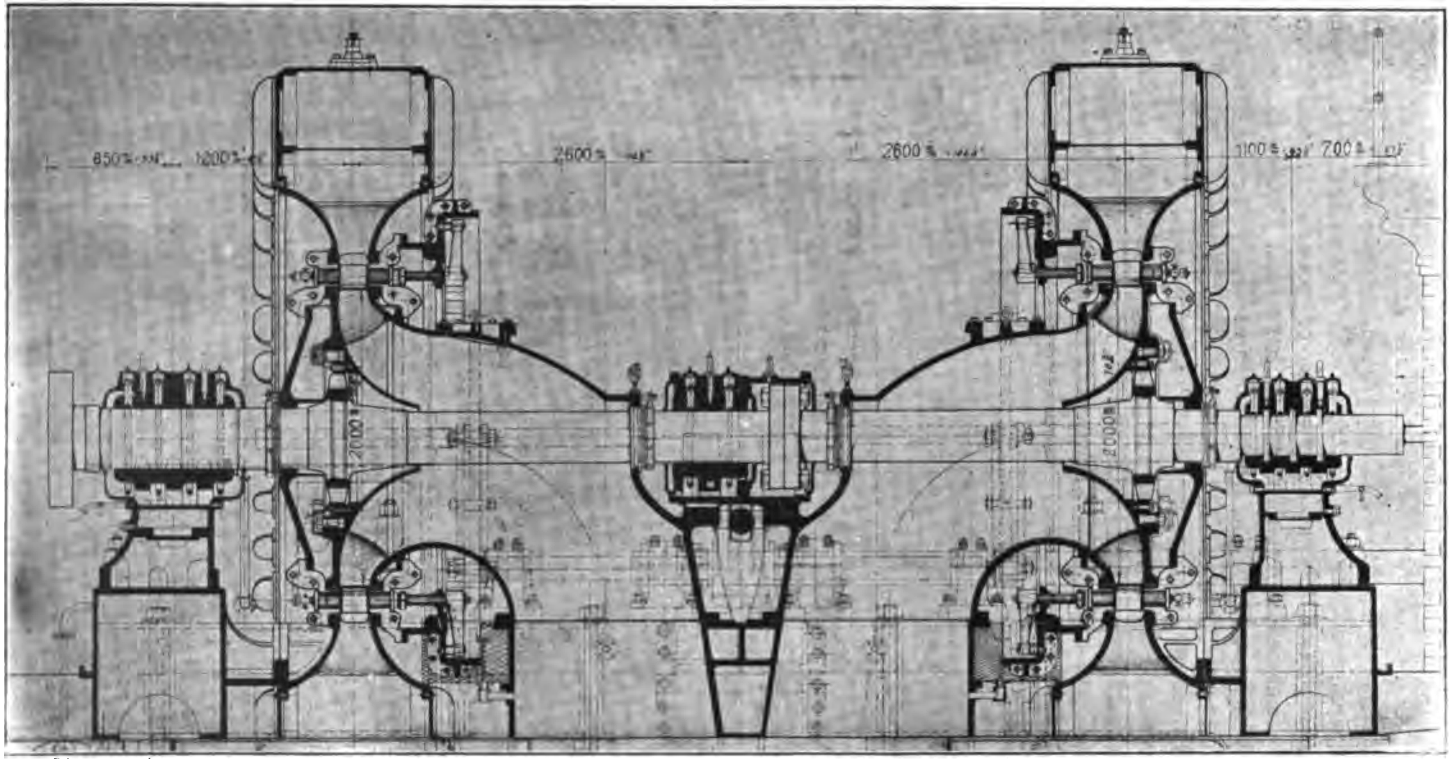


FIG. 12.—Section Detail of Horizontal Turbine.

portional to square of diameter; hence, inversely proportional to square of rotation. Increase of rotation, therefore, means disproportionately great decrease of power or abandonment of ideal reaction and relative dimensions. When carried to the extremes usual with vertical units, it results in inefficiently high reaction and reduced area of discharge, unfavorably abrupt changes of direction in buckets, and a wastefully distorted and overworked wheel. To such an extent is this distortion carried to meet special conditions that it is rare to find a high-head turbine possessing nearly the efficiency or durability possible if correctly proportioned. In the present case the speed selected

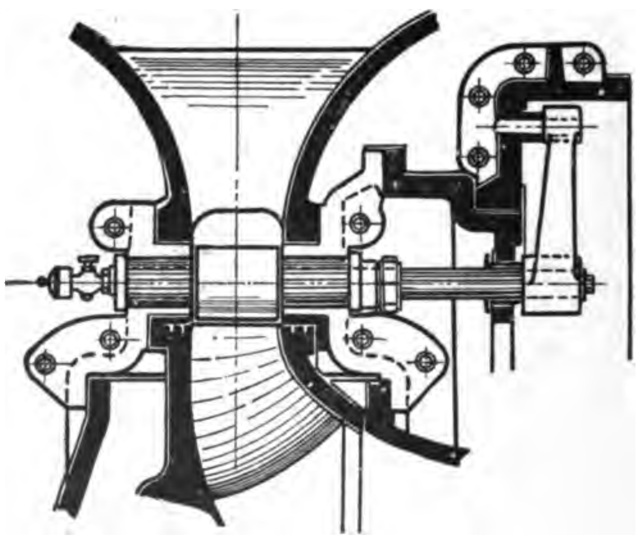


FIG. 12b.—Detail of Gate and Mechanism.

permits almost exact "normal" reaction and ideal proportions without sacrifice at the generator.

Gratifying accessibility has been obtained by compact arrangement of generators and turbines with ample clearances and good light, upon the main floor of the station and in full sight not only of the immediate attendant but also of the chief operator from his post upon the gallery above. As explained, the entire gate-rigging is external, therefore accessible for lubrication, adjustment, or repair. Excepting runners and gates, every moving part is in plain sight and, by the ready removal of a single ring, even the guides themselves are exposed for cleaning or replacing. This arrangement, in strong contrast with that of the vertical type with its several floors, intervening stairs, and dark corners, will, it is believed, appeal to every power-house operator.

In the general arrangement of the works, symmetry and centralization of control are predominant characteristics. The generating and distributing stations are parallel and nearly 600-ft. apart with 260-ft. difference in elevation. On account of limited space the generating station is but 76-ft. wide, though when completed it will be nearly 1 000-ft. long. Down the center of this building, side by side in a single row, stand the

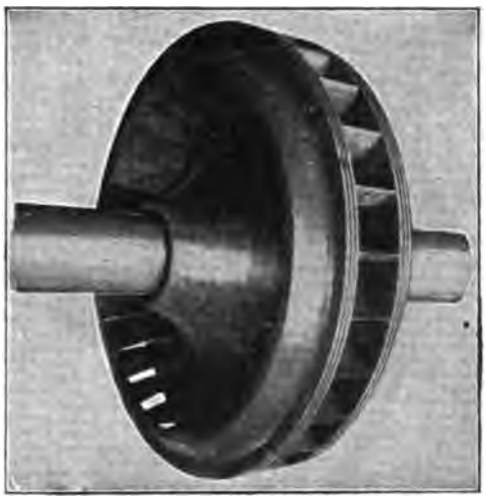


Fig. 13.—A Turbine Runner.

generating units with turbines next their source of supply. The space between them and the rear wall is occupied by a gallery upon which stands the row of oil-pressure governors, each almost over the end bearing of its turbine.

The distributing station, wider and shorter than the power-house, is divided into three longitudinal bays or five main sections. The narrow front bay contains the switches, bus-bars, etc., at generator pressure; the wider rear bay contains those at transmission pressure. Between these stretches the main middle bay divided transversely by a three-floor switch-board-section into two long transformer-rooms. The projecting central section provides space for operating offices. Along the center of these two rooms the transformers stand in groups of three corresponding in position and capacity to their respective generators. Thus similar apparatus is arranged in rows parallel one with another and with the generating units.

At the generating station three inclined cable-tunnels, one already built, carrying clay ducts, begin at the rear wall beneath the gallery and extend up through the cliff and, as standard subway, on to the distributing station. The main cables, except as diverted by these tunnels, follow the shortest and most direct routes from generators to transformers. They do

FIG. 14.—Swivel-Gates, Exposed by Removal of Cover Plate.

not converge for the accommodation of switchboard at one or more centers where congestion, which in many installations causes the most disastrous accidents, prevents separation or adequate insulation. On the contrary they are laid quite regardless of switchboard, the switches and instrument tranformers of which are then placed as required by the cables.

Unit values, corresponding to the generators in capacity and position, are maintained throughout. Thus each generating unit has its individual cables, switches and switchboard, section of bus-bars, transformers, interrupters, and high-pressure switches complete to the transmission, enabling independent operation as an isolated power-plant or, through the selector switches and duplicate sectional bus-bars the operation of all units in any combination of groups as readily and perfectly as their operation in parallel. To this end a unit length of distributing station of similar relative position is devoted to the circuit and apparatus corresponding to each generator.

From the above it may be seen that the arrangement is in

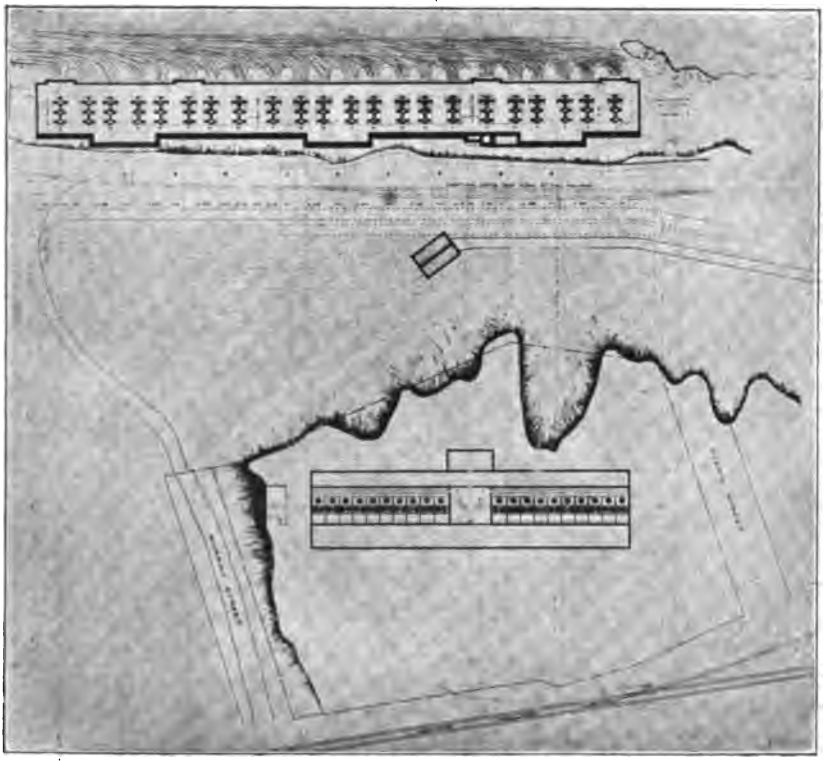


FIG. 15.—General Plan of Generating and Distributing Stations.

parallel courses; that like apparatus is arranged in rows or courses parallel with the long axis of the generating and distributing stations; that the main circuits and the unlike apparatus performing the successive functions of these circuits form 22 courses transverse to the same, and that the courses of the two directions form, as it were, a rectangular or checker-board figure covering an area nearly 1 000-ft. square. The arrange-

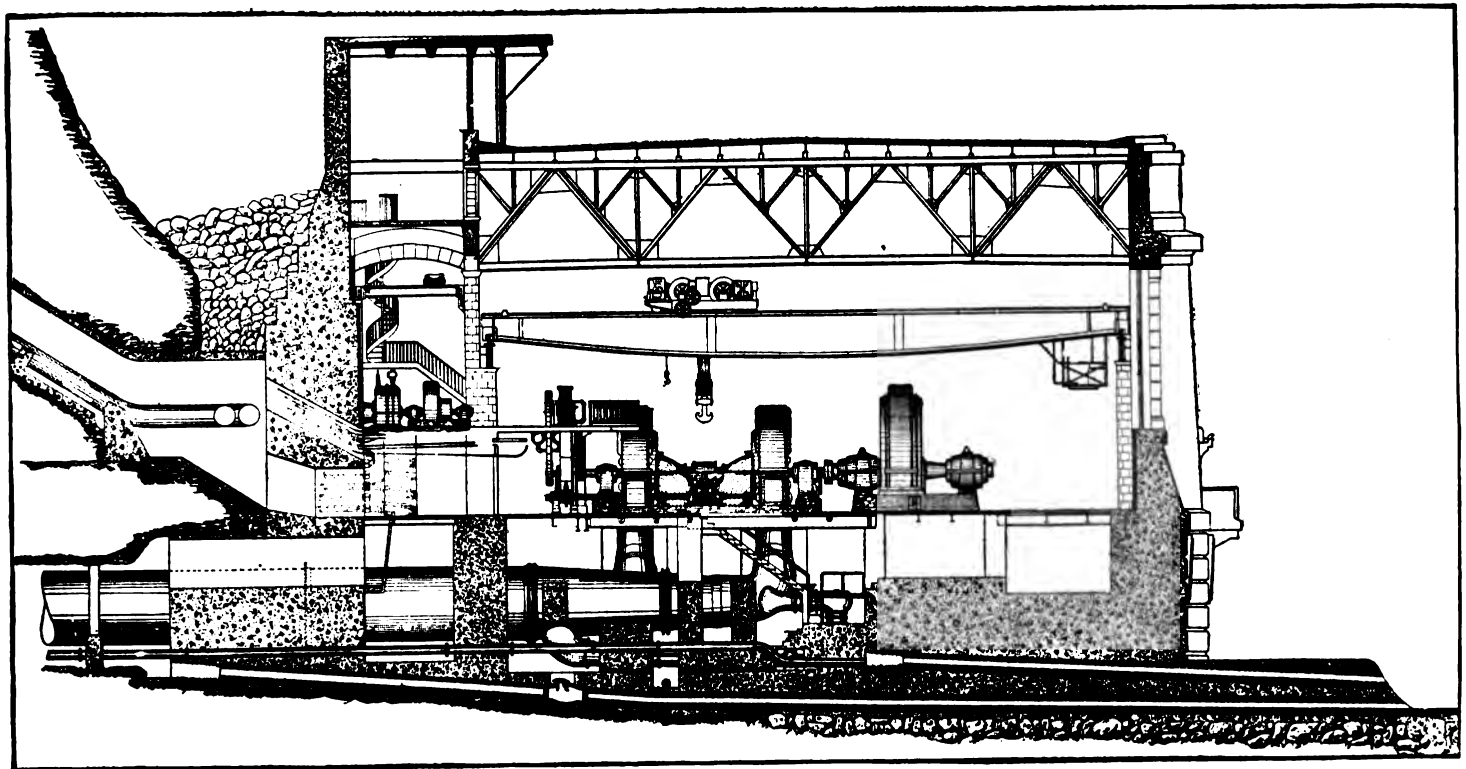


Fig. 16.—Section through Generating Station.

ment of these courses in logical sequence provides the short and direct route for the main cables previously mentioned. Such symmetry of arrangement, while difficult to attain in a crowded plant or at points of congestion, is of marked value in emergency, especially in a plant of many units, and becomes vital when the units are of such dimensions that the accidental crippling of one costs the output of many smaller plants.

Where the cable tunnels commence, the power-house and gallery are widened toward the cliff. Immediately above the tunnel entrance are the main generator switches, and on one side the duplicate turbine-driven exciters and their governors, and on the other the motor-actuated main field rheostats. In front of the switches are a few panels of switchboard carrying exciter rheostats and switches, controls for actuating penstock valves,

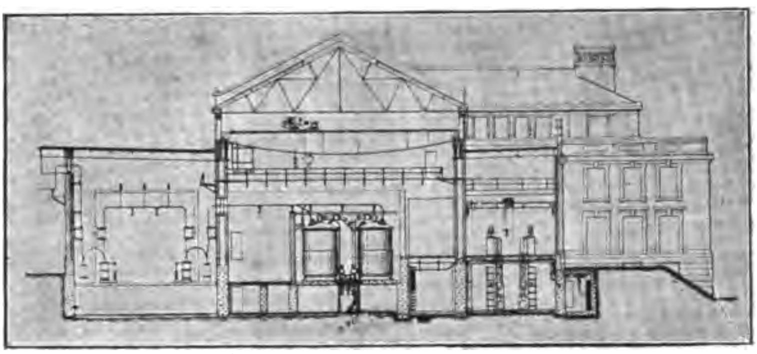


Fig. 17.—Section through Transformer Room.

and the necessary circuits and apparatus for a limited local distribution. Relief-valves and small drainage-pumps are the only operating machinery beneath the main floor, while upon it, in addition to the generating units, there are only duplicate electrically driven pumps supplying the storage-tank and transformer cooling-coils at the distributing station. For air circulation and ventilation and to avoid dampness from spray as well as to insure cool generators in hot weather, a cold-air supply to each generator is provided from a sub-floor chamber communicating with external shafts and heated air escapes through large roof ventilators.

At the distributing station the low-pressure bay contains upon the main floor the 12 000-volt automatic oil circuit-breakers in double column and, in the chamber beneath, on the sectional duplicate bus-bars and their immediate connections. In the transformer-rooms the transformers stand in pits six feet below main floor level, and parallel with them adjacent to the high-pressure bay are corresponding pits for static interrupters or other protective apparatus. Beneath both and between

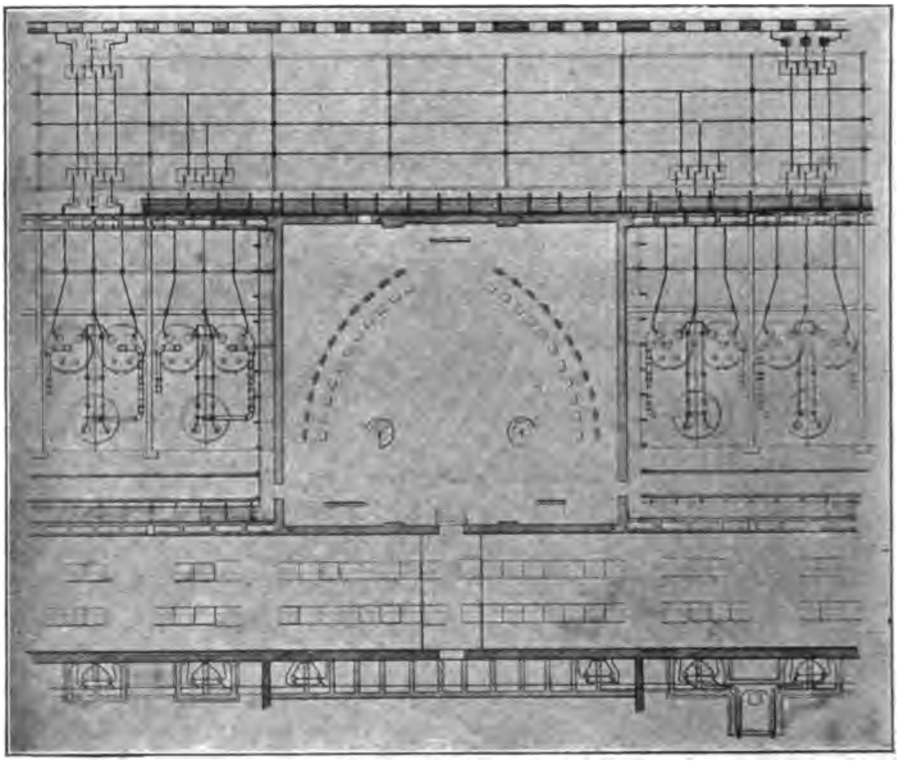


FIG. 18.—Plan of Central Portion of Distributing Station.

their foundations are accommodated the several systems of water-, oil- and drain-piping, and the main cable-ways to the transformers above. Each transformer is fitted with a record-making thermometer giving the continuous history of internal economy.

The switchboard section occupying the center of the distributing station has four floors of which the basement serves as a center for the piping systems and gives room for conduits and cableways for wiring. On the main and the mezzanine or gallery floors, marble slabs carry record-making and integrating instruments, terminal boards with fuses for the control cables, and other adjuncts of the switchboard above. Upon the upper floor is the switchboard and control-chamber, and here instrument-stands and control-pedestals supplant both the conventional marble slabs and the later bench-board. Each of the 22 instrument-stands, which are arranged approximately in a semicircle about a central point, corresponds to a definite unit, carries nine indicating instruments, and faces its 12-point control-pedestal. Doors upon the four sides lead to balconies in the four other divisions of the building of which this room is the center; those at the sides to balconies extending the full length of the transformer-rooms.

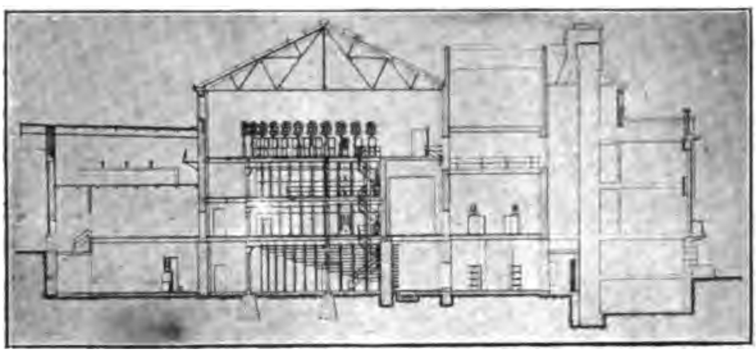


FIG. 19.—Section through Control Chambers.

Centralization of responsibility and authority, at defined points within the immediate personal care of a minimum number of chief operators, is, next to simplicity of arrangement, the prime requisite of efficiency of organization and of economy of operation. It is frequently possible so to arrange small plants of a few units as to centralize at a single operator, but with a plant of this scope that result is manifestly impossible. Two alternatives are then open; the division of the plant into several parts, each about its sub-center constituting virtually a complete plant in itself and the whole dependent upon successful coöperation for unity of result; or classification and centralization of responsibility according to kind. In this case the latter has been adopted, and notwithstanding that the number

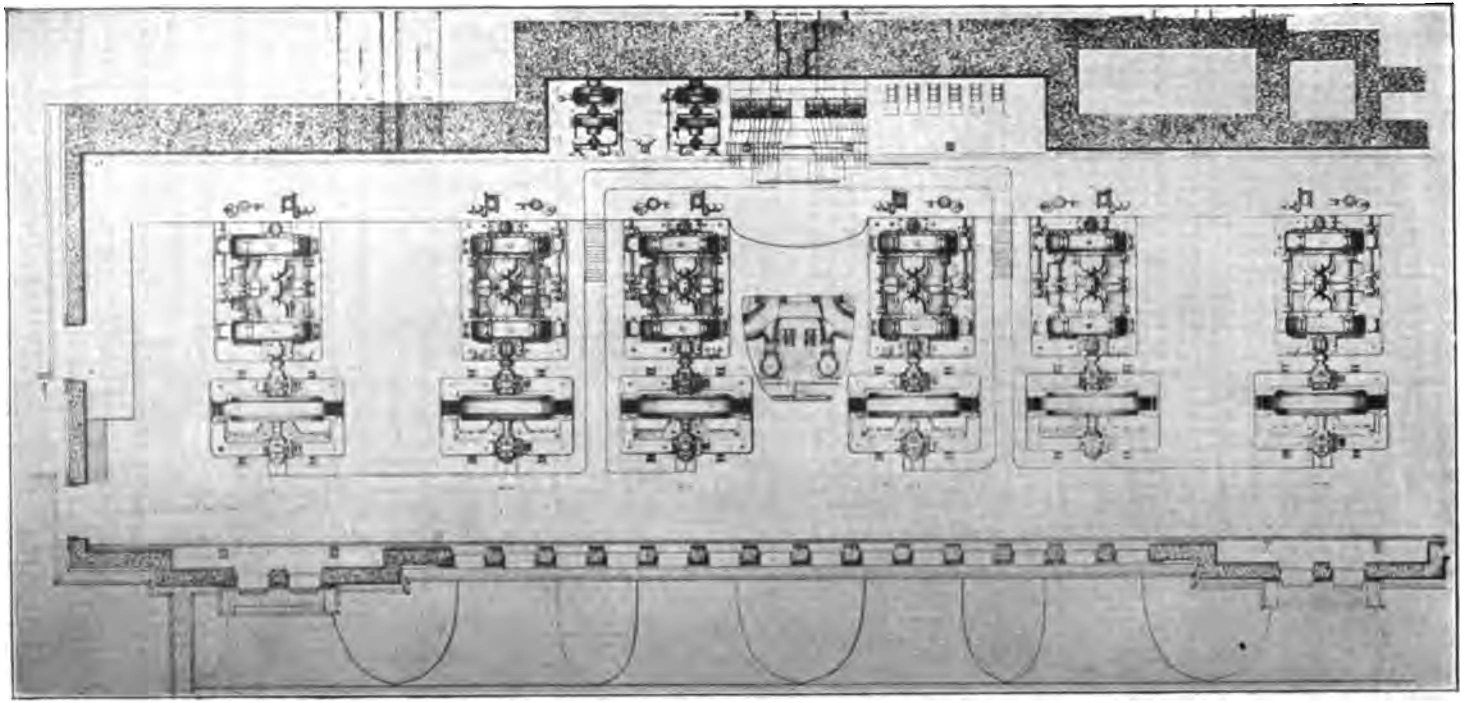


Fig. 20.—Plan—First Section of Generating Station.

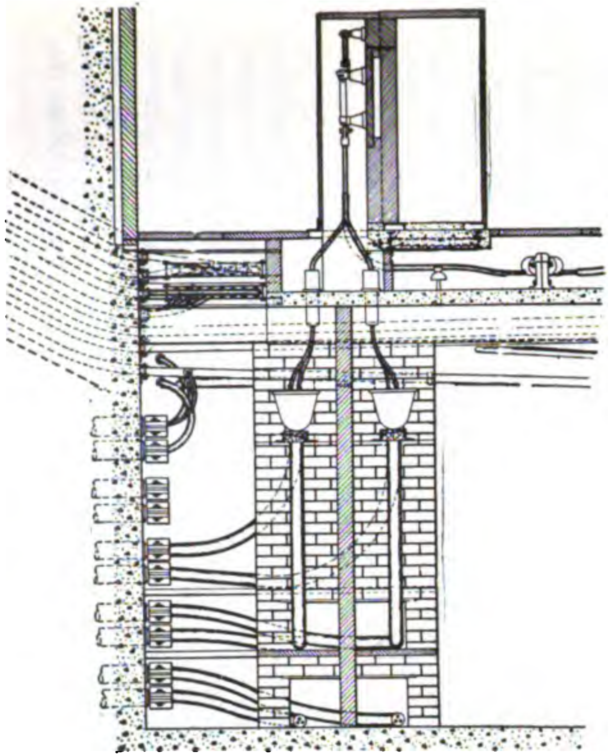


FIG. 21a.

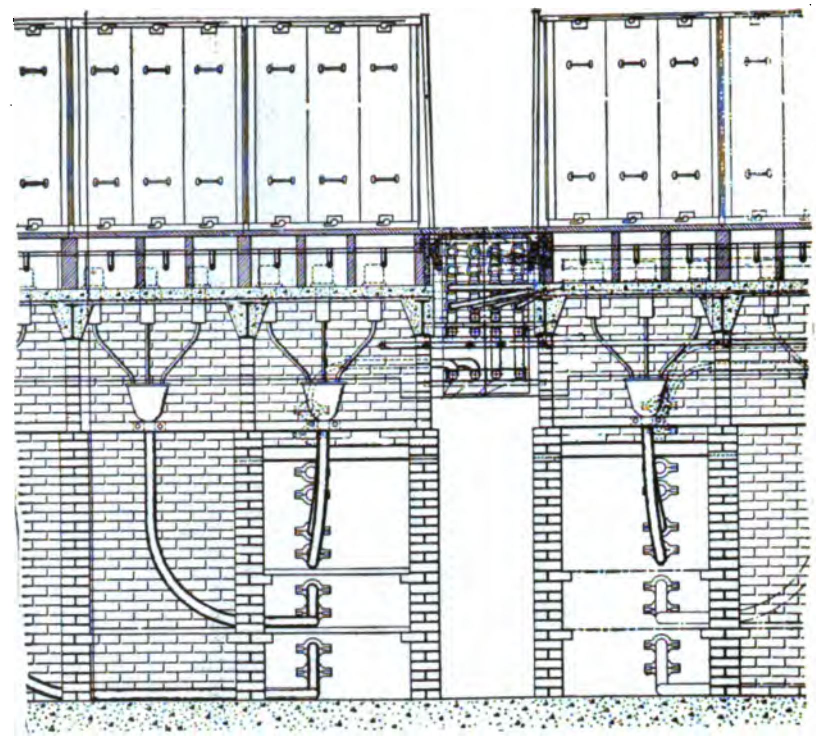


FIG. 21b.

Cable Bell, Compartments and Barriers.

of units and aggregate of power involved have opposed high merit in this respect, a promising result has been obtained.

The concentration within a single room of all instruments and control—the brain of electrical operation—provides the operator in a quiet and secluded place both full information, and perfect control of every electrical circuit and situation of the system, and enables him to stop, start, regulate, or synchronize each unit; to throw its output through its transformers to its transmission as if from a complete isolated plant or to throw it upon either bus-bar while supplying its transformers from the same or the other bus-bar. The location of this room high up at the geometrical center of the distributing station

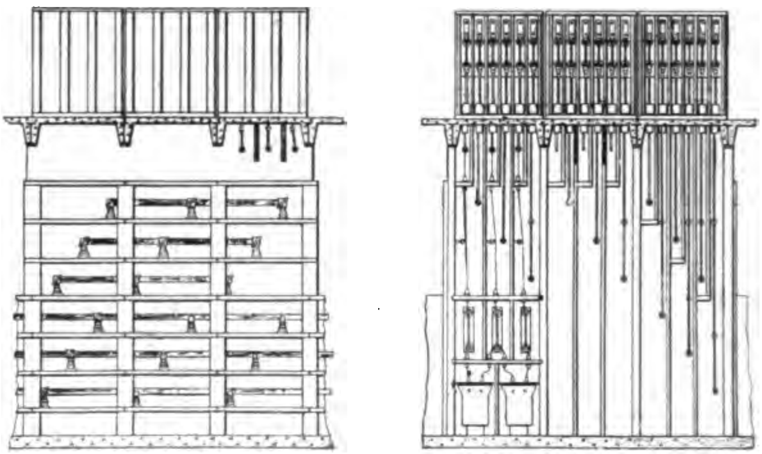


Fig. 22.—Front and Rear of Bus-Bar Structure and Switches.

places the operator at a point of vantage surrounded by four classes of apparatus. Thus located he may with few steps survey his entire field; look down upon switches, bus-bars, and arresters of the high-tension; see at a glance every low-pressure switch, or watch trouble in either transformer-room.

At the generating station the corresponding vantage-point is the gallery, where on one side the operator has the motor-driven rheostats and a few paces distant the commutators and governors of the exciters, and on the other side in plain sight the row of main governors with their adjuncts; while from the little switchboard before him he has electrical control of pen-stock gates and, when necessary, manual control of turbine speeds, exciter pressure, and field charge. Moreover from this position he can see all generators and turbines and, by signal at least, can direct his assistants; little, in fact, is likely to call him to the main floor unless it be an occasional refractory journal or collector brush.

In accomplishing the centralization of switchboard simultaneously with the broad and symmetrical distribution of main circuits and switches already described, distant electrical measurement and control have necessarily been employed to an unusual extent. Pressure and current transformers, essential to the many instruments and relays beyond those necessary at generating station and high-pressure room, are mounted in the bus-bar chamber. The innumerable and long conductors, necessary to extend over the intervening distance from those to the many instruments of the switchboard and to convey back the power from relays and control-buttons to automatic switches, have been gathered into substantial cables and laid in metal conduit.

The basement of the central bay along the side next the low-pressure side forms a wiring-chamber supporting a railway track upon the main floor above. Through this wiring-chamber transverse to the general direction of the main cables and opening at its center into the control section, these cables and those for both continuous and alternating current local service are carried into the basement beneath the control section and, rising through the recording floors, end at terminal boards below their respective instruments and relays. Carried thus far, distant control has been still further applied by the use of motor-driven rheostats for both generators and exciters, electrically operated circuit-breakers for field circuits, and speed-controllers for governors whereby, as previously mentioned, turbines may be started, stopped or regulated from the control chamber as well as from the gallery at the generating station.

The isolation of electrical apparatus and conductors by incombustible walls or barriers against spread of oil or arcs, for protection from fire and from each other, is of importance proportional to the power and investment involved. Neglect of this precaution has caused many of the most disastrous electrical accidents and has recently taught several bitter lessons. Some rather extreme measures here taken for its more complete application may be of interest. The five sections or rooms, heretofore mentioned, forming the distributing station, are of concrete-and-steel fireproof construction, separated by full-height masonry walls with intervening air-spaces. No windows and but few doorways (these latter protected by fireproof doors generally closed) penetrate these walls.

The transformer-pits already mentioned, each containing a bank of three transformers, are isolated and extended to a height of 23 ft. by masonry fire-walls. Each individual transformer is in a boiler-iron casing designed to withstand 150 lb. per sq. in. explosive pressure. Each case communicates through an 8-in. pipe from its top with a special drain for free vent in case of accident, as proposed before the INSTITUTE some time ago; but here the supply is cold oil instead of water as then proposed. With these precautions it is believed that the transformers have been surrounded with an environment unprecedented as to safety.

The power from each generator is conducted to its switch through three single-conductor braided cables carried by line-insulators and isolated by shelf-barriers in a subway beneath the floor. From the switches the three conductors pass to a bell chamber where between individual barriers they are united into two parallel three-conductor lead-covered and armored cables before entering the tile ducts of the cable tunnel. Around the few bends at manholes each cable remains always within its compartment, between horizontal or vertical barriers as required. At each point where a circuit enters the distributing station, a manhole maintaining the same segregation and communicating with the bus-bar chamber is provided for the change from three-conductor to single-conductor cable. After entering the building the cables pass between vertical barriers as before, beneath and through the floor to the switches above.

Bus-bar structures are composed entirely of concrete with mortised reinforced-concrete shelf-barriers between bus-bars. Connecting leads pass through the wall forming the center of the structure, and thence in compartments formed by vertical barriers of the same material, directly up to the switches above. Instrument transformers are also installed within similar individual compartments and these whole structures like those of the switches are closed by fireproof doors. Control cables are laid in metal conduit throughout their courses except in the wiring-chamber beneath the track where they are arranged upon metal shelf-pans filled with dry sand into which connecting conduits dip.

Of the features here presented, it is believed that the type of intake, the symmetry of arrangement, centralization of control, and almost perfect isolation of apparatus represent, to some degree at least, distinct advances in power-plant design; and while few works of such dimensions may be built for many years, if ever, it is possible that in a way some of the purposes and methods thus briefly presented may, until superseded by the next advance, be of some service as suggestions to other designing engineers of similar works. The unusual, even enormous volumes, both of water and of power, involved not only in the individual units but also in the aggregate, have presented new problems heretofore unprovided-for in standard sizes of apparatus, thus necessitating the development of larger capacities and the creation of new types. Hence the work of designing and building has been burdened with incessant test, re-design, and adaptation unknown in more conventional engineering. Therefore, it is believed that upon no similar work in this country, since that of the Niagara Falls Power Company years ago in the infancy of electrical power, has devolved such a burden of investigation, invention, and original design.

It has been suggested by an officer of the INSTITUTE that any account of this work would be incomplete without mention of those mainly responsible for it. Justice to all is here impossible, but a few may be named. Mr. O. B. Suhr has from the beginning been in charge of the engineer corps and to him is largely due the harmony of design. Mr. V. G. Converse, Mr. C. H. Mitchell, and Mr. J. B. Bailey are chiefs of the electrical, mechanical, and field departments respectively, and Mr. J. R. Harsch of the clerical work of the engineers. But more than all else in the establishment of this great and daring enterprise stands out the attitude maintained toward their engineers by Messrs. J. J. Albright and Edmund Hayes, the originators and majority owners, who, in strong contrast with the harassing interference by which uninformed investors frequently spoil the best efforts of engineers, have in this case given not only absolute freedom of action but also steadfast support.

DISCUSSION ON "THE DEVELOPMENT OF THE ONTARIO POWER CO."

GANO S. DUNN: On page 812 of Mr. Nunn's paper, he assumes from calculations of Lake Erie's level for nearly 50 years that the elevations of the intake have been so selected that at extreme low water and most adverse conditions a full supply of water should always be obtained. While he has been speaking, it has occurred to me to inquire what view the promoters and owners of this great development at Niagara Falls take of the possible withdrawal of the water at other places, such as the tapping of the great lakes at Chicago. The outlet of the great lakes, it is well known, used to be at Chicago, and the divide there is only 14 or 15 ft. high. Recently with the reversal of the flow of the Chicago River to give that city a deep-sea waterway and a pure water supply from the lake there has been taken out of the great lakes and consequently robbed from Niagara about 8 per cent. of the water that formerly went over the falls; and the Chicago people are talking of making still greater withdrawals of water from the lakes. There is a great inducement to do this, because in addition to other uses the water already taken is furnishing 40 000 h.p. The question is more than a State one, since it is outside of the territory of New York; it is an international one. I should like to know what view the engineers take of the possible diversion of this water which would make the levels much lower than would be necessary to run the plants.

W. E. GOLDSBOROUGH: One thing that has impressed me particularly in connection with the description of the new plant at Niagara, is the fact that one man apparently can supervise and control the commercial delivery of 200 000 h.p. A line drawn from the upper end of Goat Island out into the center of the stream indicates the possibility of a wall being constructed in such a position as to deflect somewhat more than one-half of the water of the Niagara River over toward the American side, thus giving the Americans the greater share of the available water. In considering the 3 installations on the Canadian side, the company that Mr. Nunn represents has evidently looked well to the future in establishing their intake so far up stream. With the wall that I mention thrown out into the river, any water passing the extreme end of it will necessarily have to distribute itself over the whole bed of the river, and I question whether or not the 2 power plants that are situated further down stream on the Canadian side might not if such a wall were built, be left with little or no available source of water supply. Of course this all depends upon the actual head conditions that prevail, regarding which I am not advised, but concerning which Mr. Nunn may be able to enlighten us.

H. G. STOTT: I think from the slight knowledge I have of the operation of water power plants, that the most interesting feature of the future will be whether the provisions made in the intake, the forebay, the spill, and the screen-way, will take care of the ice. That is the great trouble with nearly all our Northern water powers, as the cost of keeping ice from the power plants is probably equal to the entire operating expenses per annum. That gives an idea of what a problem it is for about 3 months in the year. The chief point of difference between the plant described by Mr. Nunn and that of the Niagara Falls Power Co. is the location of the generators. The generators here are located at the bottom, practically at the water level, whereas in the plant of the Niagara Power Co. they are practically on the ground level and connected tò the water-wheels by long vertical shafts. Otherwise the switchboard apparatus and diagrams are now approximately standard work with some particulars, perhaps, a little in advance.

P. H. Thomas: This paper affords an opportunity of studying the general tendency in the development of our large water-power plants. The engineers who laid out this system have had the benefit of the designs and experience of the Niagara Falls Power Co., as well as wide experience of their own in high-tension work, and it may therefore be assumed that the differences between the plans of the old company and those of the new indicate the direction in which development is tending. The most notable step taken is the isolation of units and the subdivision of the plant into what is practically a series of small plants, any one being able to operate in spite of accidents to the other. For instance, instead of carrying all cables through a single duct, or placing all transformers in a single room, under which arrangement an accident to one is likely to interfere with the operation of all, the generators, cables, transformers, and switches are installed in isolated groups. It is conceivable that the utter destruction of a third of the plant might not render unserviceable any considerable portion of the remainder.

C. A. Greenidge: In central New York there is a small plant of 7 500 h.p. operating under a heap of 265 ft. The four turbines are of the vertical-shaft, outward-flow, reaction type, direct connected to revolving-field, 60-cycle generators. With the exception of Niagara Falls this is the only installation of this kind in the country. Five-eighths of the weight of the revolving parts are supported by the water pressure, and the remainder is carried by a flat step-bearing through which 4 gallons of oil per minute are circulated under a head of about 30 ft. During the last 3 years this plant has been in almost constant operation with an average load for 1903 of 65 per cent., and for 1904 of 70 per cent. of the rated capacity. Thus far the step-bearings have given no trouble; in fact there has been little occasion for examining them.

The first wheels installed were of foreign design, but after being in operation for about a year they proved unsuitable and were replaced 2 years ago by wheels of American design. Although they have been in almost constant operation the tool-marks are still visible, proving that under this head a vertical-shaft reaction turbine can be worked satisfactorily. The only place where any wear takes place is in such ports as have been partly clogged by pieces of wood, which causes a high velocity in the open portion. These wheels showed on test an efficiency of at least 76 per cent. at full gate. For driving the exciters the reaction-type of turbine has not proved satisfactory, because of the small size of ports, and turbines of this kind have been replaced by impulse-wheels of the Gerard type. With these wheels a roller step-bearing is used, which under 24-hr. test without oil has showed an increase in temperature of only 16° fahr.

P. N. NUNN: It has been said upon excellent authority that the rights now granted to use water from Niagara River involve about 25 per cent. of the normal flow. Less than half of this amount has so far been utilized. The variation in flow from week to week, sometimes from day to day, is nearly 40 per cent., and that variation is hardly noticed by tourists. If 40 per cent. variation does not materially injure the scenic effect, an additional 25 per cent. for power purposes cannot be very serious.

The collecting wall, which it has been suggested should be built from the head of Goat Island, need not materially affect the Canadian power-plants, because there is a natural trend of the river directly toward the intakes of those works which seems to become more pronounced each year.

While the works of the Ontario Power Company have been built very substantially, yet it can hardly be said that they have been built for all time. Scientific progress has been such for the last 50 years that there is no assurance that electric plants will be in existence 200 years hence, or that water-powers will be needed.

While the general arrangement of the plant is such as to enable operation with minimum attendance, and while the distant control has been so arranged as to centralize in one chief electrical operator at the distributing station the responsibility and control of electrical conditions throughout the entire plant, it does not follow that this operator will never need assistance. Moreover, the mechanical operator at the generating station, while free from all electrical manipulation, will always require sufficient assistants to maintain perfect mechanical conditions.

The difference in the location of the generators, mentioned by Mr. Stott, is perhaps a controlling factor in the whole design; and it is possible that the necessary departure from conventional lines of development has materially contributed to the general result by requiring distant control and more liberal room at the distributing station.

There has been no purpose in the paper to disparage the turbines of other plants. Vertical wheels may be made entirely satisfactory. The purpose has been to point out the greater difficulties and dangers incident to the use of vertical wheels, both in efficiency and operation. The conditions at Trenton Falls are unusually favorable; the head is high and the units are small. Results would have been different had units several times larger been employed.

PHILIP P. BARTON (by letter): The relative importance ascribed by Mr. Nunn to the structures erected at the head-works for the protection of the plant against ice indicates that this subject has received careful study by the engineers of the Ontario Power Company. The ice problem is one that has been encountered by the writer every winter for a number of years, and for this reason he has been especially interested in the solution proposed by the engineers of the Ontario Power Company. As stated by Mr. Nunn, the Niagara River is filled for many weeks every winter with floating ice. The forming of the material designated by Mr. Nunn as "mush-ice," and which is also in various forms elsewhere designated as anchor-ice, frazil, or slush-ice, is not confined to the rapids. It is formed in the upper river and in Lake Erie whenever the temperature drops several degrees below the freezing point, and whenever there is a snow fall of any magnitude. This material floats down the river in great masses and penetrates wherever water flows with any considerable velocity. It is only in comparatively still water that it remains at the surface. It is the opinion of the writer that the safeguards provided by the Ontario Power Co. will protect quite effectively against floating cake-ice; but his experience with Niagara ice conditions cautions him to beware of predicting the probable efficacy of these works with respect to slush-ice. He is inclined to believe, however, that little trouble will be experienced from this source in producing amounts of power that are likely to be delivered commercially from this plant for some years to come. If trouble does develop, probably it will be most serious during northeasterly storms when the wind forces floating ice towards the Canadian shore, and at the same time lowers the water in the river by driving it towards the west end of Lake Erie.

In general, it seems likely that the power developments on the Canadian side of the river will have less trouble from ice than those on the American side, for the reasons: (1), that the prevailing southwesterly winds tend to force all floating ice towards the American shore; (2), that the greater depth and velocity of the water sweeping past the intakes of the Canadian plants afford a far better opportunity to divert and get rid of ice that may be encountered. In the plans for the Canadian power developments, the ice problem has been recognized from the outset as a serious factor, and all of these plans embody well considered provisions for meeting the ice conditions that are expected to arise. The adequacy of these provisions will depend largely on the correctness of the assumptions made as to the conditions of the problem. On the American side of the river, the ice conditions affecting the plants of the Niagara

Falls Power Company could not be foreseen when the plants were located and no plans for dealing effectively with them were carried out until the actual problem was developed in concrete form in the commercial operating of the plant. Probably much useless expenditure was thus avoided. However this may be, the actual solving of the ice problem of the Niagara Falls Power Company has been a process of carrying out year by year plans and methods suggested by experience as best adapted to meet the conditions known to exist. The result of this process has been that for a comparatively small expenditure methods of protection against ice in and about the intake of the Niagara Falls Power Company have been adopted that have brought about almost complete immunity, for several winters past, from interruptions of service due to ice. This period includes the severest winter on record for many years.

The primary causes of the ice difficulties experienced at the plant of the Niagara Falls Power Company were: (1), the absence of any effective means of disposing of ice that might come into the inlet canal and, (2), the shallowness of the river over a considerable area adjacent to the canal entrance. An extensive field of solid ice always forms in the river adjacent to the head of the canal, and accumulations of slush-ice drawn under this ice field by the water flowing into the canal formed ice jams, which, if left undisturbed, restricted seriously the flow of water into the canal. The opening of channels through these jams resulted in filling the canal and forebay with ice that could not readily be disposed of, and it therefore clogged the turbines and at times seriously diminished their output.

The construction of a vertical shaft at the lower end of the canal, leading to the discharge tunnel and equipped at the top with a weir gate opening from the canal, provided a very efficient spillway for disposing of ice and has effectively overcome the first difficulty. The second has been relieved by judicious dredging in the river adjacent to the canal entrance. Suitable barrier and deflecting booms, moreover, have been constructed in the river. These measures, with the application of methods of handling the ice situations that arise from day to day, developed by experience, have resulted, as stated above, in almost complete immunity in recent winters from interruptions to service due to ice, and in reducing to a comparatively small amount the annual cost of handling the ice. Their success, with the plant loaded to 80 per cent. of its ultimate output, encourages the belief that with very small additional expenditure for protective measures, the constantly increasing and ultimate load of the plants can be carried with a degree of continuity equally satisfactory.

The solution of this ice problem, it will be observed, is being worked out by meeting conditions actually experienced. The results of a solution devised and carried out before the local conditions have been developed by actual experience will be awaited with much interest.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

A NEW CARBON FILAMENT.

BY JOHN W. HOWELL.

I have the pleasure of presenting to you some data on a new carbon filament, which has characteristics so differing from those of any previously known filament as to seem to indicate that it is a new form of carbon. Beside being very interesting on account of its physical characteristics, this filament is of considerable value on account of its much better life or efficiency, as compared with the carbon filaments heretofore known. This new filament is the result of work done in the Research Laboratory of the General Electric Company, and in the laboratory of the Lamp Works, at Harrison, N. J.

In briefest outline, the new characteristics of the filament may be said to be due to the *proper* application of excessively high temperatures to the ordinary carbon filament. The value of the product is determined by the conditions under which the high temperatures are applied.

It is well known that an ordinary incandescent filament in an evacuated lamp may be heated to excessive temperatures by the application of high current without producing any beneficial change in the filament. To produce the effects described in this paper the heat is externally applied to treated filaments at atmospheric pressures. The simple application of the highest attainable temperatures to the plain carbonized cellulose fibre, *i.e.*, the so-called "filament base," is incapable of producing any considerable change in the filament. This high temperature treatment of the base is, however, a beneficial step in the process here described.

Before describing the new process, it may be well to recall the steps by which the standard filaments are made. A solution of cellulose is squirted through a die into a liquid that hardens the cellulose. The resulting fibre is dried, then shaped into the desired form for the finished filament and heated in a muffle until carbonized. In this process the highest temperature of a gas-furnace is employed. The product at this point is called a "base filament." The base filaments are usually separately heated by a current passed through them while they are surrounded by an atmosphere of hydrocarbon vapor, and in this way a coat or shell of graphite is deposited upon them. They are then said to be *treated* filaments. The best quality of standard carbon incandescent lamps of to-day owe their superiority to the use of treated filaments.

In attempting to graphitize carbon filaments it was discovered that treated filaments undergo very remarkable changes when subjected to the highest possible temperature of an electric resistance furnace. The furnace consisted of a carbon tube, held at the ends by large water-cooled copper clamps; the tube was imbedded in powdered carbon to prevent its combustion. The filaments were packed in small, cylindrical carbon boxes, which were fed into the heated tube. The temperature was usually between 3000 and 3700° cent.

Under such firing the ordinary treated filament changes in appearance; its graphite coating looks as though it had been melted, and its specific resistance is greatly reduced. The resistance of one of these filaments, measured at ordinary temperature, may be reduced as much as 80% by the firing.

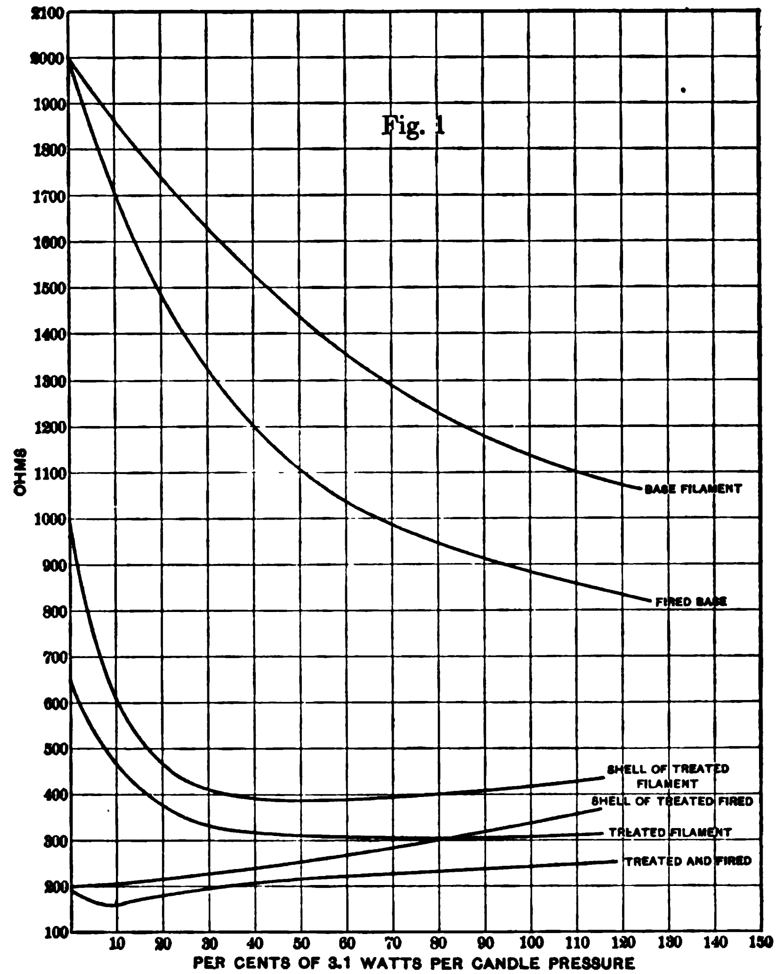
The curves representing the resistance at different temperatures are also remarkable. Fig. 1 shows curves of resistance and temperature of a regular base filament, a base filament fired, a regular treated filament, a treated filament fired, a shell of regular treated filament, and a fired shell.

The resistance in ohms is plotted against the temperature, as indicated by the percentage relation of the pressure on the filament to the normal pressure at which the filament has an efficiency of 3.1 watts per candle.

The curves show a more rapid fall in resistance of the base filament after firing, but little change in the character of the curve.

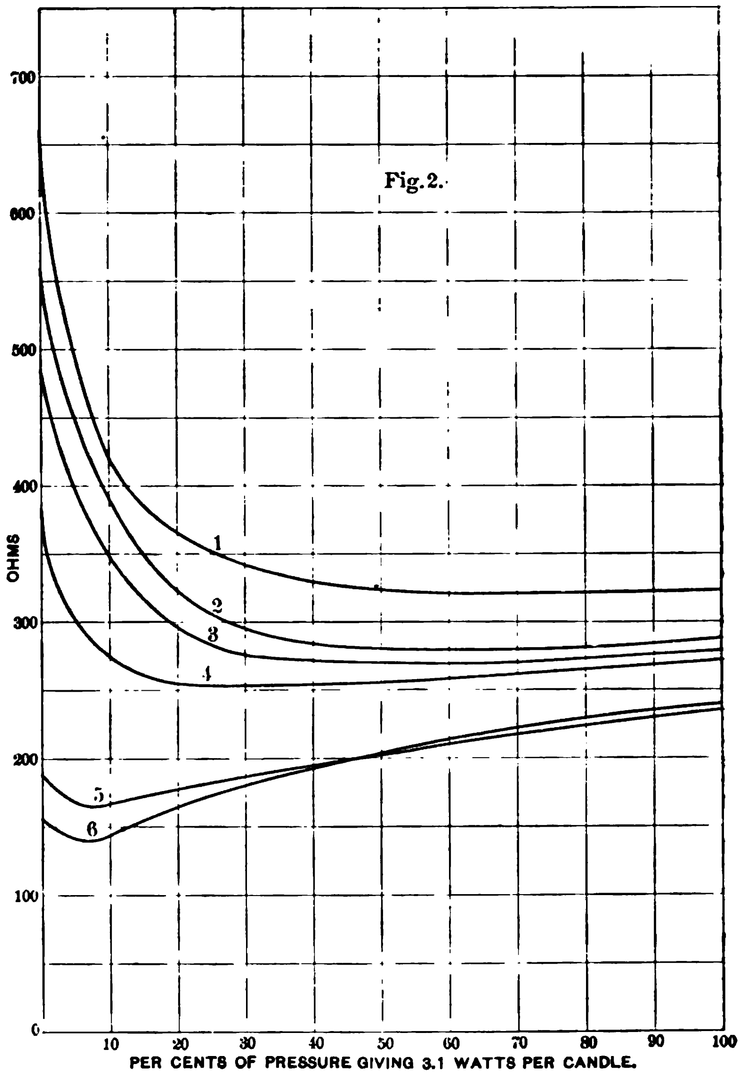
The change produced in the treated shell by firing is very great, the cold resistance being reduced from 1000 to 200 ohms, while the great change in the character of the curve of the fired shell brings the hot resistance of the two shells nearly together.

The resistance curve of a fired treated filament depends upon the relative thicknesses of base and coating and upon the temperature of firing. Figs. 2 and 3 show curves of filaments



fired at five different temperatures and of a similar filament that has not been fired. In Fig. 3 the reistances are shown in percentages of the cold resistances, and in Fig. 2 the actual resistances are shown.

These filaments were heated in the carbon-tube resistance furnace. They were enclosed in a cylindrical carbon box, placed inside the tube, one end of which was left open for observation. An indication of the temperature was obtained by looking



directly into the open end of the tube at the box holding the filaments, and holding in the line of vision the filament of an ordinary 50-volt lamp, the temperature of which was adjusted until the filament became invisible against the incandescent carbon box. The pressure on the lamp was then observed and the box of filaments taken out.

Curve No. 1 is the resistance curve of a regular treated filament.

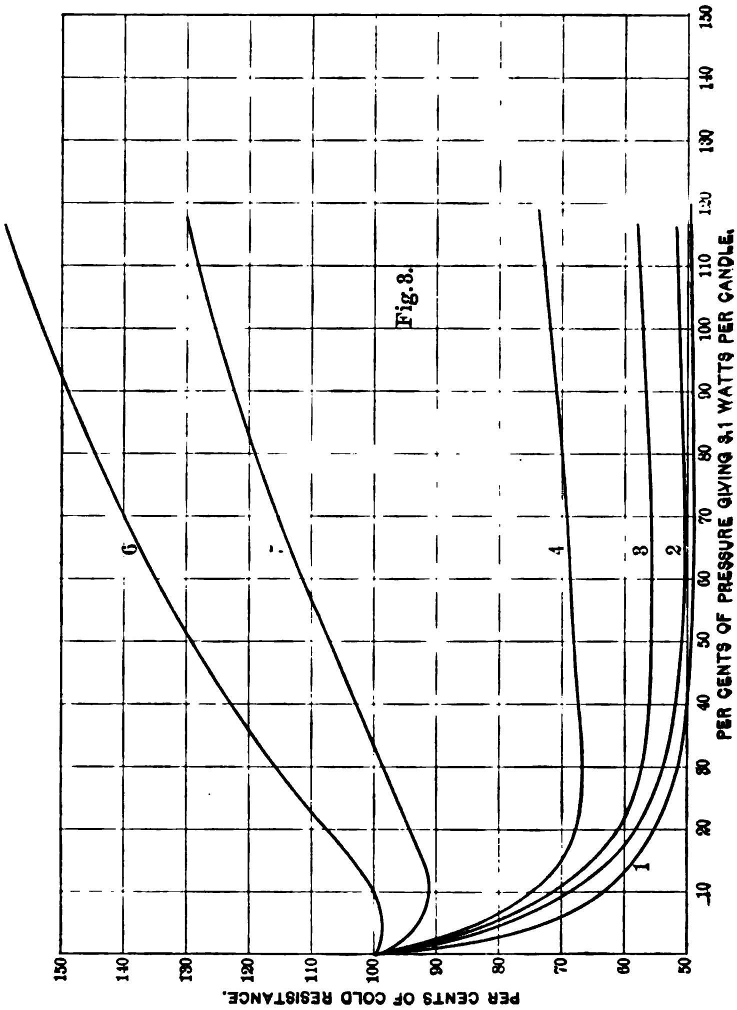


Fig. 8.

Curve No. 2 is the curve of a similar filament heated in the tube to a temperature corresponding to the temperature of a carbon filament operating at 153% of its normal pressure, or at 125 candles for a normally 16-candle-power lamp.

Curve No. 3 is the curve of a filament fired at a temperature corresponding to the temperature of a lamp at 161% of its normal pressure, or at 163 candles.

Curve No. 4, 183% of normal pressure, or at 230 candles.

Curve No. 5, 200% of normal pressure, or at 280 candles, for a 16-candle-power lamp.

Curve No. 6 is the curve of a filament heated hotter than No. 5. The temperature was not measured by this method for fear of breaking the comparison lamp.

An attempt was made to measure the temperatures by means of an optical pyrometer (Wanner) which indicated temperatures up to 3700° cent. at the highest heats.

Fig. 4 shows the resistance curve of a filament made from a thin base having quite a thick treatment; this shows a resistance increasing to 250 per cent. of its cold resistance.

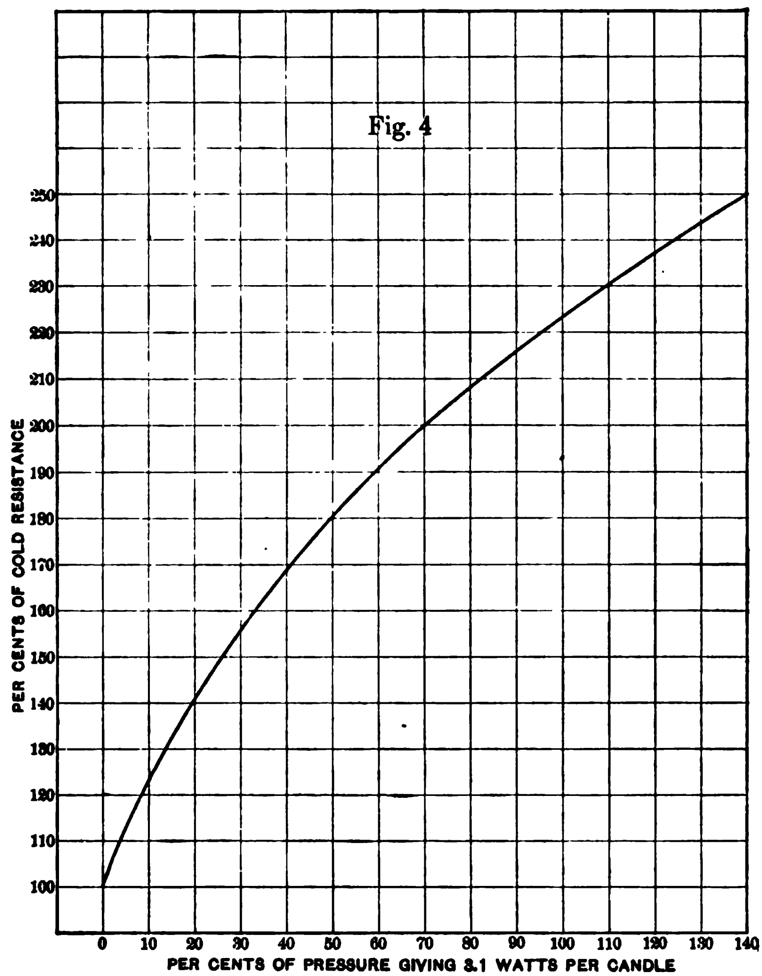
The change in the resistance curve of this coating from negative to positive seems to be due, in part at least, to the action upon the shell of some substance driven out of the base filament by the high temperature. This is indicated by the considerable change in the curve of a treated fired filament produced by heating the base filament to the same high temperature before it was treated and then reheated.

Fig. 5 shows resistance curves of carbons fired at the same temperature after treating, but with the base fired at different temperatures before treating. The base filament in Curve A was unfired; in B, C. D, and E the base was fired at successively higher temperatures.

It will be observed that the curves made from filaments, the bases of which have been heated to high temperatures before being treated, are much less positive than the others. The conclusion that the effect is produced by material being driven out of the base seems to be borne out by the fact that during the preliminary heating of the base at high temperatures it loses practically all of its mineral ash constituents, and also by the fact that, if some of the elements that the base loses in its high heating be separately placed in the furnace with the treated filaments, effects are produced similar to those observed when the base has not been previously heated.

The effect of some agency beside heat is also indicated by the fact that the lamp filament used in the temperature observations, although maintained at the same temperature as the filaments in the furnace, and for a sufficiently long time, showed no indications of such a change as was produced in the filaments in the furnace.

The appearance of a filament fired both before and after treating is very different from that of one fired after treat-



ing only. The former has a slightly pebbled appearance, as seen through a microscope, and a rather dull-gray color.

The single-fired treated filament is generally very much blistered, many blisters extending outward a distance greater than the diameter of the filament. These blisters indicate an out-flow of gas from the base when the shell was in a soft condition. The surface of the filaments is highly lustrous.

The specific-resistance of the highly heated coating (measured) has been found to be as low as 0.00006 ohms per cubic centimeter which is very much lower than the specific resistance of any other known form of carbon or graphite.

Its specific gravity is also much higher than it was before heating.

Its changed nature is also indicated by its toughness and flexibility. The coating of a double-fired filament may be pulled off in short tubular sections, which if pressed flat, will

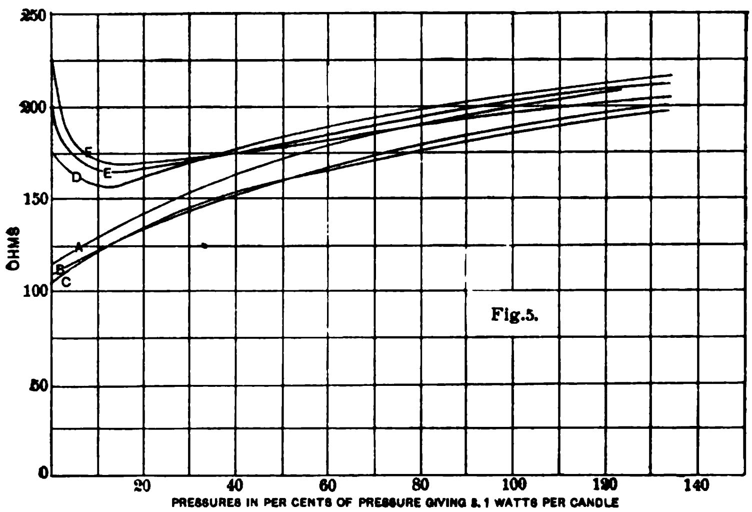


Fig. 5.

spring back to their original form when the pressure is removed. The same coating before being fired is comparatively brittle, and will break with very little pressure. On account of the positive resistance curve and physical characteristics of these filaments, they have been given the name "metallized filaments."

The treated coating on filaments, even before firing, is graphite, as determined by the chemical test established by Berthelot—the production of graphitic acid (a yellow insoluble substance) when treated with a mixture of anhydrous nitric acid and potassium chlorate. Ordinary carbon is dissolved by these reagents. The coating on the treated filament has also the greasy feel of graphite, and gives the characteristic mark of graphite on white paper.

After being heated to high temperatures in the electric resistance furnace these characteristics continue and the chemical action is much more marked.

Metallized filaments blacken the lamp-bulb very much less than ordinary filaments. This may be due to the removal from the former of practically all the mineral ash and other impurities, or it may be due to the changed character of the carbon itself.

Bamboo, coated by dipping in a solution of asphalt, is altered by firing, the coating changing to graphite and giving the characteristic positive curve.

Silk dipped in a sugar solution also gives the same result.

The base of a metallized filament, from which the treated coating has been removed, when mounted in a lamp has been found to give the resistance curve of a fired base. Pieces of the coating, about 1.5-in. long, mounted in lamps, have been found to give the strongly positive resistance curve that is characteristic of the metallized filament. These observations show that the change is practically all in the treated coating and not in the base.

Metallized filaments, as above described, are much more stable at high temperatures than ordinary carbon filaments.

The most effective carbon filament lamp now in general use operates at 3.1 watts per candle and under accurate test conditions gives a useful life (to 80% of its initial candle-power) of about 500 hours. At the present time metallized filaments that give the same useful life at about 2.5 watts per candle are being produced with a fair degree of uniformity.

Discussion on " A New Carbon Filament."

H. N. Potter: The lamp here presented is the challenge of carbon to the many rivals that are clamoring for recognition. It is to be regretted that no curve is given showing the change of candle-power during the life of the lamp, as this is a most important characteristic and one wherein a difference from the ungraphitized filament might be expected. The curves given are not in such form as to show whether this graphite filament is longer than the filaments of lamps now in use or not.

The chemistry here concerned does not seem to be novel. The changes occurring appear to be those characteristic of graphitization. This much-studied molecular change depends on several factors; the physical structure of the carbon to be graphitized, the temperature reached, the duration of the high temperature, and the presence or absence of elements other than carbon. The presence of foreign elements promotes graphitization—a distinction recognized by Acheson as distinguished from Moissan, and an explanation presumably of the observed difference in the behavior of the filament in the pyrometer lamp, and the similar filament in the electric furnace noted in the paper before us.

The treatment carbon in a filament is different physically from the carbon of the core because it is not porous but continuous. It is therefore in condition to be graphitized more quickly than the porous core. Graphitization is probably a rearrangement of the number of carbon atoms in the molecule, which rearrangement or polymerization can also be effected in the porous core carbon, though it requires a longer time than in the treatment carbon, which is devoid of pores.

J. W. Howell: In answer to Mr. Potter's questions: the filaments will not, as he intimates, be longer than the present type of filament, on account of their lower specific resistance, because the resistance is lower only when cold. At working temperature the specific resistances of the 2 filaments are nearly the same. The new filaments, however, will be materially shorter because of their higher efficiency. The 16-c-p. filaments of the new type will be about the same length as a 10-c-p. filament of the old type.

No chemical data are given in the paper because knowledge of the chemical reactions that takes place is quite incomplete at the present time.

Regarding the graphitizing of the base by time, success in graphitizing the base has been only partly successful at the highest temperature that could be produced by the furnace, because its life at this temperature was too short. Probably with a differently constructed furnace a sufficiently high temperature may be maintained long enough to accomplish this result. The changes in the shell seem to be independent of time; a few minutes in a hot tube seem to be sufficient to accomplish the result.

Regarding the characteristics of the time and candle-power curve, they are only slightly different from those of an ordinary lamp, except that it takes about four times as long to produce the same loss of candle-power.

In answer to President Lieb's question: little has been said in the paper about commercial prospects. I have made the statement that 2.5-watt lamps are being made at present.

Referring to the observations of temperature given in the paper, it was a remarkable incident to see the filament of a lamp look black if interposed between the heated furnace and the eye, when the furnace was hotter than the filament, although the latter was burning under nearly double normal voltage.

The process of matching the color of the filament with the color of the furnace is quite delicate. If the voltage on the filament is reduced only two or three volts below that at which the temperatures seem to be the same, the filament will look like a black line across an incandescent surface, whereas when the filament is raised a few volts above the voltage of matching it will look like a bright line across a less bright surface.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

ALTERNATE CURRENT MACHINERY—INDUCTION ALTERNATORS.

BY WM. STANLEY ASSISTED BY G. FACCIOLI.

In the following pages it is proposed to discuss some of the elementary phenomena found while studying the performance of alternators excited by alternating currents. In a second paper the writer intends to deal with the practical application of the principles here described.

It occurred to the writer a number of years ago that if the field of an alternator is made by alternating instead of continuous currents, the variations of current in the armature, both in value and phase, due to changes of resistance or inductance in the work circuit of the machine, would produce corresponding changes in the value and phase of the field currents, because the value of the field producing currents under these conditions is determined by the inductance of the field circuit, and this inductance is varied in value by armature reaction. And, because the writer long ago devised the following simple rule for predicting the flow of periodic currents in circuits, where the phenomena of distribution were not entirely clear at first sight; namely, that periodic currents attempt to flow in a network of connected circuits, or in circuits possessing mutual induction, so as to produce the least possible magnetism, (flow at such time and value as to destroy each other's fields).

The alternators to be described have their rotors and stators wound with distributed windings. The rotor circuits are supplied with very low-frequency multiphase currents, as shown in Fig. 1. These currents produce a field, or fields, which move around the rotor at a speed proportional to the frequency of the magnetizing or exciting source.

If the connection of the multiphase exciter circuits is such as to produce a clockwise electromagnetic rotation of the field (rotor), the rotor structure of the alternator may then be mechanically revolved either in the same or in an opposite direction.

Let n be the frequency of the exciting circuit and n_1 the frequency of mechanical rotation; then if the electromagnetic and mechanical rotations are in the same direction the speed of the flux will be proportional to $n_1 + n$; if they are in opposite direction to $n_1 - n$, and, as will be shown, these two relative arrangements produce very different phenomena.

Call $n_1 + n$ or $n_1 - n = n_{11}$ = the frequency of the currents induced in the stator or armature conductors of the machine; evidently when $n = n_1$, $n_1 - n = 0$, and there is a stationary field in the space opposite to the stationary armature conductors; consequently, no electromotive force is induced.

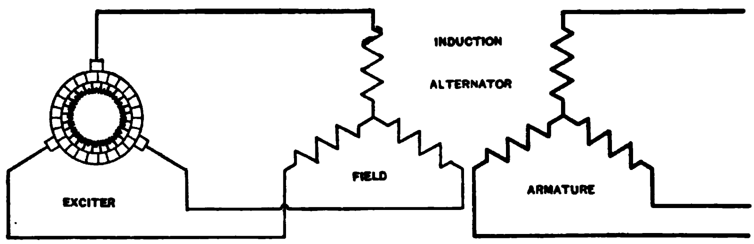


FIG. 1.

Suppose, however, that n is small compared to n_1; for example, let the exciting frequency $n = 1$ cycle, while the frequency of rotation $n_1 = 61$ cycles; then

$n_1 - n = 60$ cycles,

$n_1 + n = 62$ cycles.

Consider the first case for a moment. Suppose the stator, or armature, of the alternator is supplying current to an external circuit; then, if we have a clockwise rotation (revolutions per minute) of 61 cycles and a counter-clockwise electromagnetic rotation (exciting current) of 1 cycle, the effective field rotation is clockwise and 60 cycles; consequently, the armature (stator) currents are also of 60 cycles frequency. But these stator currents produce a field in the air-gap of the machine and this field revolves synchronously with the rotor induction, *but not* synchronously with the rotor conductors, for they (the conductors) are going faster, viz., at the rate of 61 cycles. They are therefore *constantly overtaking* the stator-produced field, and *passing through* it. That is to say, cutting it, and they therefore have electromotive force induced in them of a frequency = 61 – 60 cycles = 1, = *n*, the exciting frequency; the final result being that an electromotive force of the same frequency as that of the exciting current is produced in the rotor (field) conductors, by simply loading the alternator in the usual manner.

This " stator induced electromotive force " in the rotor conductors (so we call it) is evidently proportional to, and in quadrature with, the stator current. It is zero when the stator current is maximum; maximum when the stator current is zero, etc. It is of the utmost importance in the phenomena to be described, for if the rotor circuit be of low resistance (great time-constant) the " stator induced electromotive force " in the rotor will produce a current (called " stator induced current ") approximately *equal* in value, nearly *opposite in phase* to the stator current and, consequently, competent to neutralize the magnetomotive force of the armature or stator circuit and to destroy almost completely the magnetization due to the stator winding. In such an alternator there should be, then, no armature reaction, no back magnetization, no distortion of the field of the machine.

At first sight it would seem that these machines should give a constant electromotive force at all loads; when excited at constant potential they do not do this, but they give, when properly designed, a gradually rising potential at power-factor = 1 with a slight drop of potential for lower power-factors down to power-factor = 0.

In Figs. 2 and 3, Mr. Faccioli has represented the phase relations of the electromotive force, currents, etc., when (Fig. 2) the effective frequency of the alternator is equal to the difference between the rotational and magnetizing frequencies, and (Fig. 3), when it is equal to their sum.

In the diagram here given the ratio of the rotor to the stator turns is assumed to be 1:1; the ohmic and inductive resistance of the exciter is zero, that is to say, the exciter is assumed to maintain a constant terminal potential.

In the case of Fig. 2 ($N_{II} = N_I - N$) the flux of the alternator rotates in one direction regarding the rotor and in the opposite direction regarding the stator; therefore Diagram 2 is supposed to rotate in the direction R regarding the rotor and in the direction S regarding the stator.

v is the leakage coefficient of the rotor; that is, the ratio between the flux produced by the rotor which enters the stator and the total flux set up by the rotor. The leakage coefficient of the stator is assumed to be equal to the leakage coefficient of the rotor.

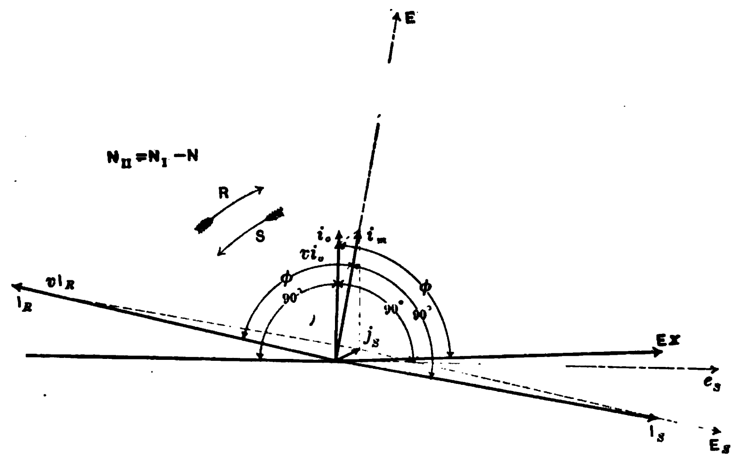


FIG. 2.

E_x represents the electromotive force of the exciter (low frequency) which is supplied to the terminals of the rotor and is assumed as constant for any load of the machine. i_0 is the

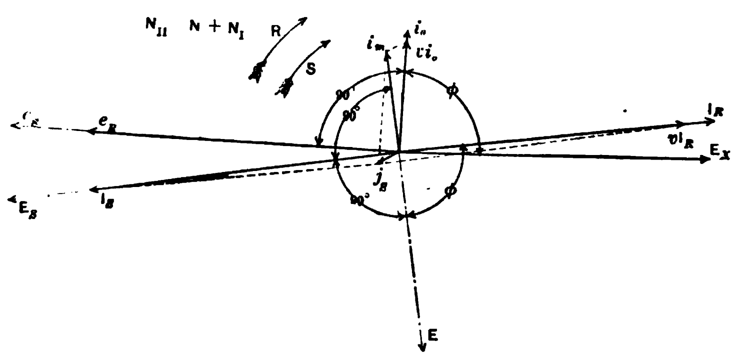


FIG. 3.

magnetizing current of the machine at no load and lags behind E_x by the angle ϕ; ϕ being a function of the resistance of the rotor and the frequency of excitation.

At no load the flux set up by i_0 will induce an electromotive force e_R ,at the terminals of the rotor; a part of the same flux proportional to vi_0, will induce an electromotive force e_S at the terminals of the stator.

Now consider the case in which the machine is loaded by the current I_s at power-factor 1. The current I_s of the stator (armature) induces at the terminals of the rotor (field) an electromotive force in the direction E, proportional to the frequency of excitation of the machine. The electromotive force E produces in the rotor a current I_r which lags behind E by the angle ϕ. I_s and vI_r give a resultant j_s, whose magnetomotive force is superimposed on the original magnetomotive force vi_0, giving a resultant magnetomotive force i_m, which is in quadrature with I_s. The electromotive force of the stator is E_s in quadrature with i_m and therefore in phase with I_s.

In the case of Fig. 3 when ($N''_{\text{II}} = N+N_1$), the diagram rotates in the same direction regarding the stator and the rotor. The same symbols represent the same quantities as in Fig. 2. In this case the electromotive force e_s and e_r have the same direction, and the resultant magnetomotive force j_s has such direction as to decrease the original magnetization vi_0 of the machine; while in the case of Fig. 2, the magnetomotive force j_s, due to the load currents, has the effect of increasing the no-load magnetization of the machine.

When, therefore, the generated frequency of the machine is equal to the difference of the frequency of rotation and the frequency of excitation the magnetization of the machine may be higher when loaded with non-inductive load than when running free; this result being principally due to the resistance of the rotor or field, which prevents the current I_r from lagging exactly 90° behind E and consequently neutralizing the magnetomotive force of I_s.

On the other hand, the resistance of the rotor when the generated frequency is equal to the sum of the frequency of rotation and the frequency of excitation, has the effect of decreasing the magnetization of the machine when loaded with non-inductive load.

If the rotor of the machine had zero resistance and perfect mutual induction, then the rotor current I_r would lag exactly 90° from its electromotive force in both Fig. 2 and Fig. 3, and would be exactly equal and opposite to the stator current I_s. There would be no resultant magnetomotive force due to the load and therefore j_s would be equal to zero and the machine would have constant electromotive force at any load and at any power-factor.

It then appears that if a machine of this type; that is, a machine with almost perfect mutual induction and very low resistance, could be built, there would be very little difference in its regulation when excited by forward and backward running fields. The principal difference would consist in the fact that with a forward running excitation the exciter would supply energy to the alternator in proportion to the ratio of the exciting to the generated frequency, while with the backward running excitation, the exciter delivers no energy to the alternator but receives energy from it.

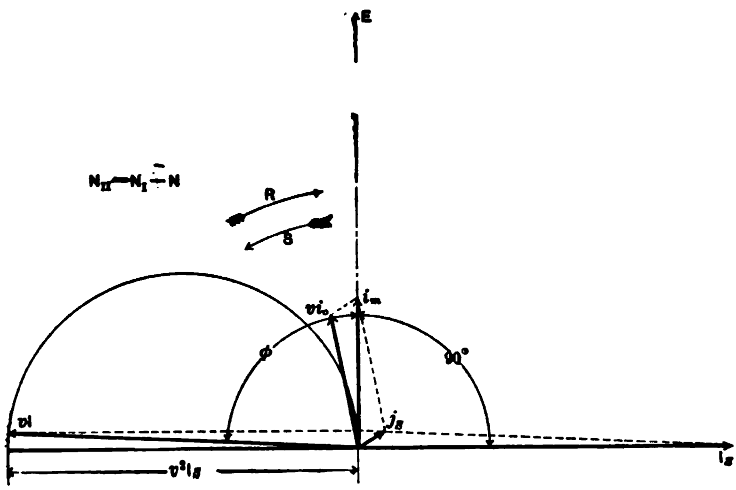


FIG. 4.

It is interesting to study the regulation of the system at power-factors less than unity and examine the effects of variation of exciting frequency. This has been set forth by Mr. Faccioli in the following diagrams:

First, take up the case of the backward rotation of the field. In Fig. 4, I_S is the load current of the machine. The electromotive force E induced by vI_s at the terminals of the rotor is proportional to the frequency of excitation f.

$$E = wLvI_s$$

where w equals $2\pi f$ and wL is the inductive resistance of the rotor at the frequency f.

The superimposed load current in the rotor is:

$$I_R = \frac{E}{\sqrt{R^2 + w^2 L^2}}$$

R being the ohmic resistance of the rotor.

$$v I_R = \frac{v^2 I_s \, w L}{\sqrt{R^2 + w^2 \; L^2}} = v^2 \; I_s \sin. \phi$$

ϕ being the angle of lag of I_r behind E.

The locus of vI_r is therefore a circle of diameter equal to $v^2 I_s$ as represented in Fig. 4. In Fig. 5 this circle is drawn directly upon I_s.

If the constants of the rotor are known we have the angle ϕ

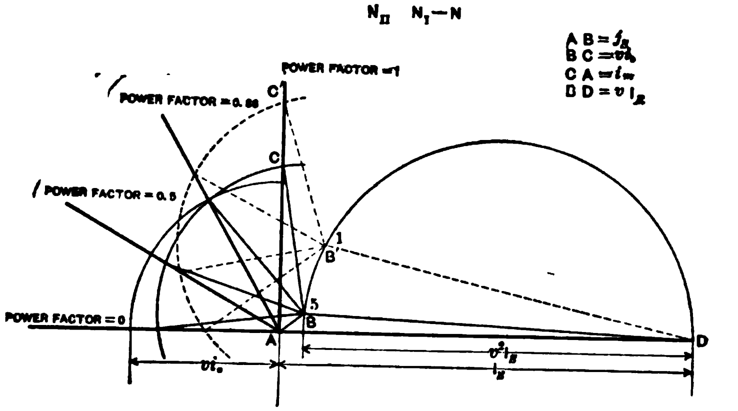


FIG. 5.

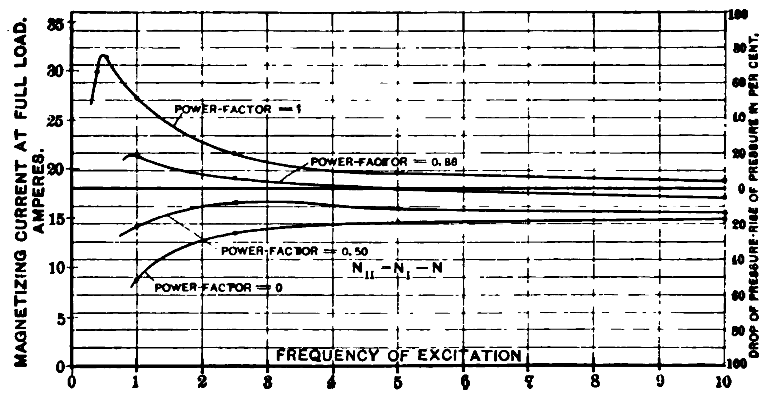
in function of the frequency of excitation. It is then possible to draw vI_r and j_s. We suppose E_x and i_0 constant and neglect the ohmic drop of the stator winding.

The resultant of j_s and vi_0 must be inclined on I_s by $90°$ plus the angle of lag of the load current I_s behind the terminal electromotive force E_s of the armature. If therefore, with centre on the terminal of vI_r and radius $= vi_0$, we cut the power-factor lines (Fig. 5), we obtain the resultant magnetomotive force i_m effective at the stator terminals for a given ampere load of the machine at any power-factor and any frequency of excitation.

The terminal electromotive force of the alternator will be proportional to i_m if the saturation and ohmic drop of the stator winding are neglected.

Fig. 6 shows the regulation of the induction alternator at different frequencies of excitation. The curves belong to a 100-kw., 8-pole, 60-cycle, 900 effective rev. per min. machine built by the Crocker-Wheeler Co. for experimental purposes; Figs. 2, 3, 4, and 5 refer to the same machine. The curves of Fig. 6 are in perfect accord with the actual tests made on the machine, the results of which are given later on.

This Fig. shows that for each machine, that is, for each combination of resistance and leakage in any machine, there is a certain frequency of excitation below which trifling changes



100 kw.—900 Effective rev. per min.—60 Cycles.

FIG. 6.

in the constants of the alternator produce great changes in its potential characteristics. For small high-frequency machines an exciting frequency of about five cycles may be required, while on large machines in which the resistance and leakage may be relatively lower, the exciting frequency may be as low as one cycle.

In a similar way it is possible to study the influence of the variations in the exciting frequency in the case of the forward rotation of the field. The locus of vI_r is in this case a circle, as shown in Fig. 7. Fig. 8 gives the regulation of the same 100-kw. alternator at different power-factors for different frequencies of the field.

NOTE.—Since this machine was designed experience has taught us to design with much less variation of potential for changes of load and power-factor.

The curves in Fig. 8 show that in the case of forward rotation of the field the potential of the alternator will drop at any power-factor, due to the effect of the resistance and leakage;

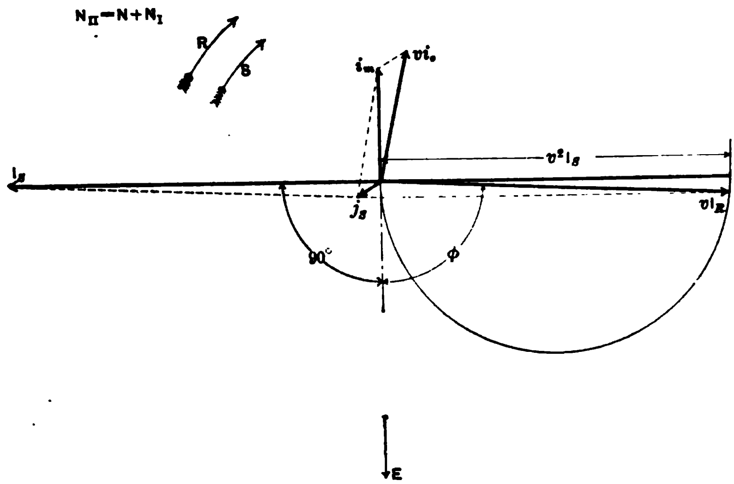
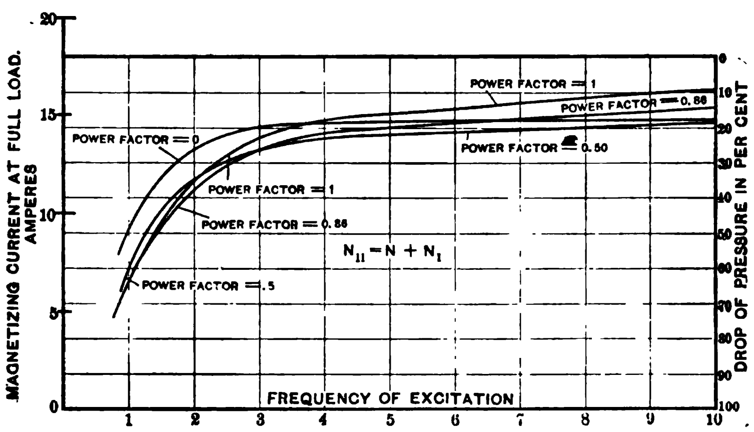


FIG. 7.

but the difference in regulation between power-factor unity and lower power-factors is very small in comparison, with the results obtainable with the alternators of standard type. (The phe-



100 kw.—900 Effective rev. per min.—60 Cycles.

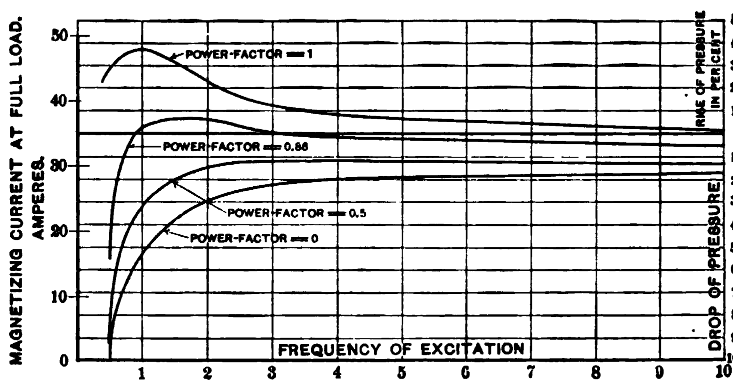
FIG. 8.

nomena in this machine are magnified by the high resistance of the rotor.)

The variation of the air-gap in these machines has a peculiar influence on their regulation. In Fig. 6 are shown the curves of a 100-kw., 8-pole, 60-cycle, 900 effective rev. per min. induction alternator having an air-gap of 0.0625 in. (single).

Curves of Fig. 9 give again the resultant magnetizing current effective at the terminals of the armature at constant ampere load (full load) and different load power-factors for the same machine with an air-gap of 0.125 in.

Figs. 6 and 9 both refer to the case of a backward rotating field $(n_1 - n)$. Doubling the air-gap of the same machine has affected very little its regulation at the frequency which is used for its excitation (about five cycles). This is due to the fact that any increase in the air-gap involves an increase in



100 kw.—900 Effective rev. per min.—60 Cycles.—(Double Air-Gap.)

FIG. 9.

the no-load magnetizing current of the machine, and an increase of the leakage coefficient v, and these two phenomena have conflicting influences on the regulation of the alternator.

When, however, the leakage of the machine is comparatively low, as in the case of high-speed alternators with a small number of poles, and the no-load magnetizing current is high (large air-gap) then something is gained in regulation by increasing the length of the air-gap. For instance, this is the case with turbine alternators where a large air-gap is required for mechanical reasons.

Considering now the phenomena of the system, the following general conditions are found: the current in the exciting circuit is composed of two parts or components. First, that due to the exciter electromotive force, which is the no-load magnetizing current; secondly, the current due to the electromotive force generated in the field (rotor) conductors by the stator load current. The first of these, the no-load magnetizing current, (volt-amperes) is, for any given capacity of the alternator, inversely proportional to its speed; that is, is proportional to the number of poles of the alternator for any given generated frequency, or is proportional to the frequency of the alternator driven at constant speed.

This magnetizing apparent energy is therefore small with high-speed machines of given frequency, and small with low-frequency machines of given speed; consequently, it is smallest in low-frequency turbine alternators and is larger in slow-speed direct-connected high-frequency machines. It is to be remembered, however, that the magnetizing current is only a fractional part of the full-load current in the exciting circuit; therefore it is not necessarily a limiting condition and does not determine the size of the exciter.

The second component of the exciting current is the superimposed component, and is approximately equal in total amperes to the armature current of the alternator. The electromotive force of the exciter is proportional to the electromotive force of the alternator multiplied by the ratio of the exciting to the generated frequency. The two components of the exciting current (the magnetizing and superimposed) have the following phase relations.

When the alternator is delivering current at power-factor unity, the magnetizing and superimposed components are nearly in quadrature; when the alternator delivers current at power-factor zero, the components are nearly in phase.

If we call M the no-load magnetizing volt-amperes of the exciter, N_1 the frequency of excitation, N_{11} the generated frequency of the alternator, w the capacity of the alternator in kilovolt-amperes, we have the size of the exciter approximately proportional to:

$$\sqrt{M^2 + W^2 \frac{N^2_1}{N^2_{11}} + 2\,M\,W \frac{N_1}{N_{11}} \sin \phi}$$

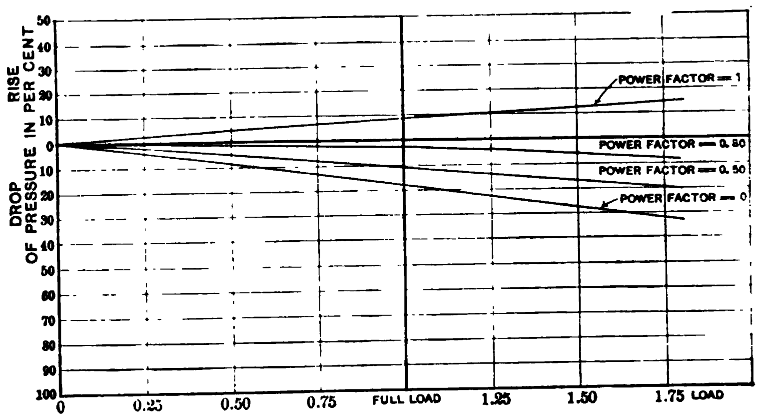
ϕ being the maximum angle of lag of the current that the alternator is called upon to deliver.

NOTE.—The size of the exciter can be exactly calculated by taking from Fig. 5 the value of the total current of the exciter for any given load and power-factor (the right phase displacement between no-load magnetizing current and load-superimposed exciter current being taken into consideration).

Thus, if the alternator is a 100-kw., 25-cycle machine excited at a frequency of 2.5 cycles, and the no-load magnetizing volt-amperes are five kilovolt-amperes, and if the alternator is called upon to deliver its full-load current at power-factor 0.5, the size of the exciter is:

$$\sqrt{5^2+\left(100\,\frac{2.5}{25}\right)^2+2\times5\times100\,\frac{2.5}{25}\times0.86}=14.5 \text{ kilovolt-amperes}$$

It will then be seen that the exciter is called upon to carry a current practically equal in total amperes to the load current of the alternator, the apparent energy of which is dependent on the frequency of excitation; consequently, the aim of the



100 kw.—900 Effective rev. per min.—60 Cycles.

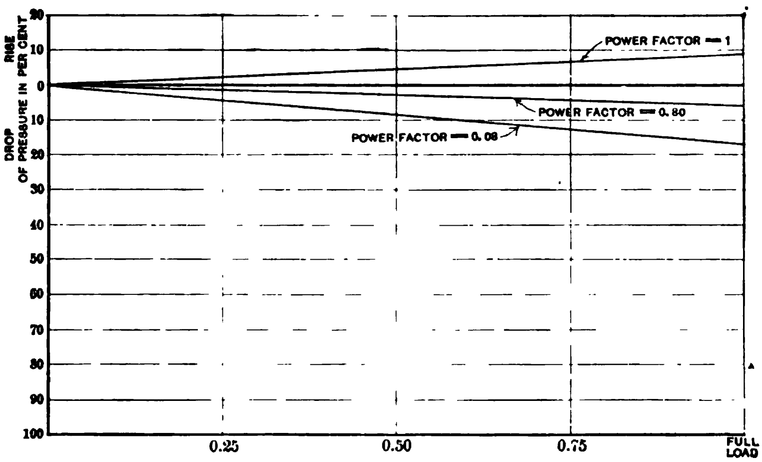
FIG. 10.

engineer is so to design his machines that they will require the minimum exciting frequency.

The following examples give the regulation characteristics of alternators of different capacities and speed when excited by alternating currents and the relative size of their exciters.

Fig. 10 shows the regulation curves of the 100-kw., 8-pole, 60-cycles, 900 effective rev. per min. alternator above mentioned, in function of ampere load of the machine when its field is excited by 5-cycle currents at constant potential (backward rotating field). For full load of alternator at power-factor 0.8 the size of the exciter is 13 kilovolt-amperes, or 13% of the size of the alternator.

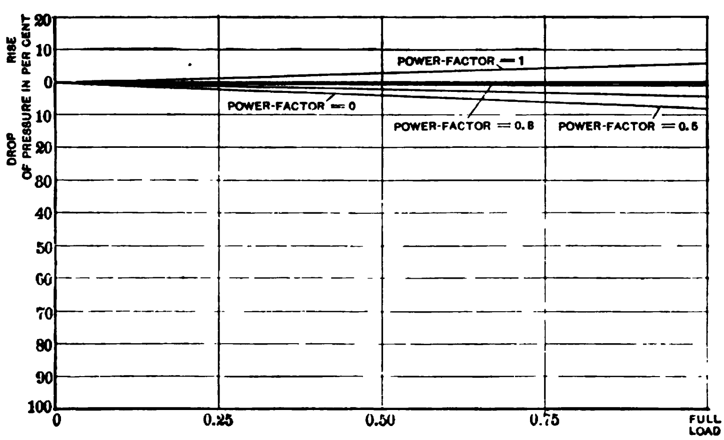
Curves of Fig. 11 give the results of tests of this 100-kw. machine, results which agree very closely with the calculated characteristics of the alternator as set forth in Fig. 10.



100 kw.—900 Effective rev. per min.—60 Cycles.—(Tests.)

Fig. 11.

Fig. 12 gives the regulation curves for a 500-kw., 100-effective rev. per min., 25-cycle alternator. (The ohmic drop of the stator is not considered.)

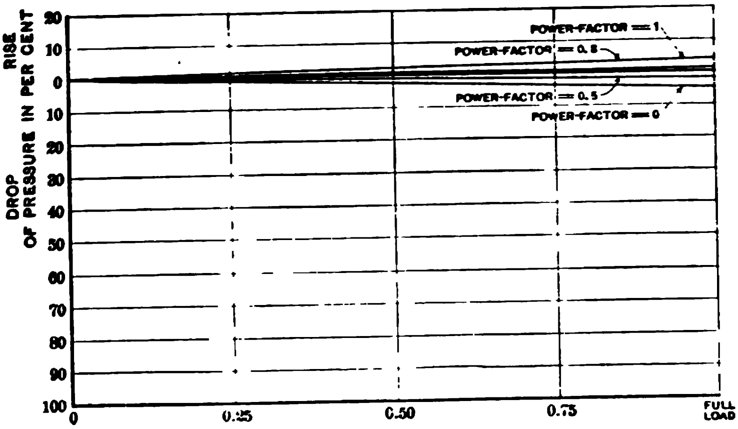


500 kw.—100 Effective rev. per min.—25 Cycles.

Fig. 12.

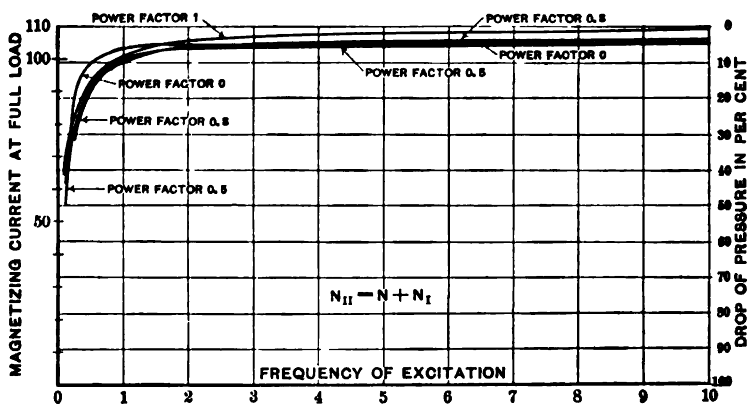
In this case the frequency of excitation (backward rotating field) is as low as 0.75 cycles. At full load of the alternator at power-factor 0.8 the size of the exciter is 42 kilovolt-amperes or 8.5% of the size of the alternator.

Fig. 13 gives the curves for a 500-kw., 60-cycle, 514 effective rev. per min. type alternator (backward rotating field. The frequency of excitation is two cycles, and the size of the exciter at full load of the alternator, power-factor 0.8, is 41 kilovolt-amperes; that is, 8.2% of the size of the alternator.



500 kw.—514 Effective rev. per min.—60 Cycles.

FIG. 13.

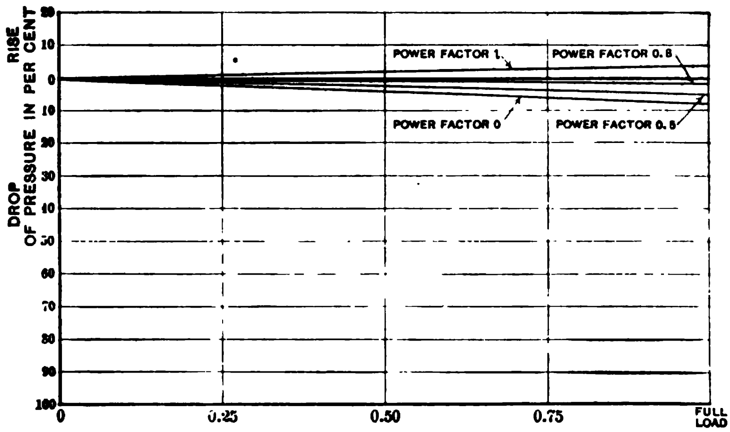


500 kw.—514 Effective rev. per min.—60 Cycles.

FIG. 14.

Fig. 14 gives the regulation curves of the same 500-kw., 60-cycle, 514 effective rev. per min. machine in the case of the forward rotating field. Note the small difference of regulation curves for different power-factors.

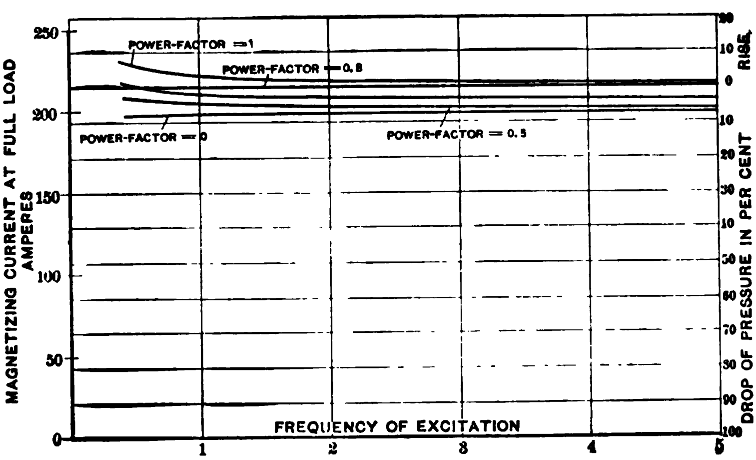
Figs. 15 and 16 refer to a 1500-kw., 25-cycle, 1500 effective rev. per min. turbine alternator. The frequency of excitation is 0.75 cycles and the exciter at full load of the alternator,



1500 kw.—1500 Effective rev. per min.—25 Cycles.
FIG. 15.

power-factor 0.8, has a capacity of 95 kilovolt-amperes; that is, 6.5% of the size of the alternator.

For all the above curves the abscissas represent either the



1500 kw.—1500 Effective rev. per min.—25 Cycles.
FIG. 16.

amperes of load or the frequency of excitation of the alternator, while the ordinates represent the resultant magnetizing current

If the saturation of the machine could be neglected this resultant magnetizing current would be directly proportional to the terminal voltage of the alternator.

Fig. 17 gives the exciting watts for different loads of the 100-kw., 60-cycle, 8-pole, alternator (at unity and lower power-factors). As shown by these curves the energy delivered to the alternator at no load is small and positive. As the alternator-load increases, the current in the rotor magnetizing circuit increases, but the watts fall to zero and reverse; that is, the current in the rotor-exciter circuit lags until

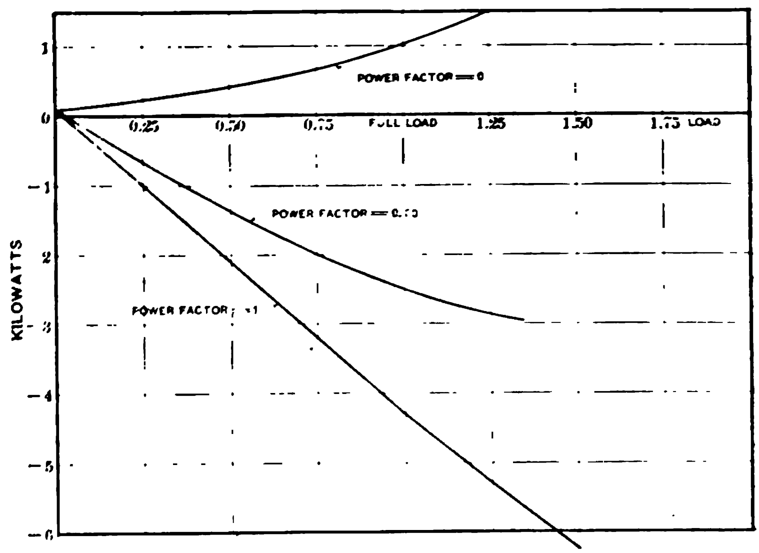


FIG. 17.

it exceeds 90° behind the exciter electromotive force; it therefore flows through the exciter against the exciter's electromotive force, just as a current delivered by a generator flows through a motor circuit against the counter electromotive force of the motor.

The all important factor in the design of induction alternators is then the excitation.

At first sight, the designing of an efficient and economical exciter to deliver multiphase exciting currents of five cycles or lower frequency, would appear to be an almost hopeless undertaking; for if an exciter of, say, 3-cycles frequency and 50 kilovolt-amperes is necessary to furnish the field and controlling current for a 500-kw. alternator, working on old lines, we should be compelled to design a 2-pole machine of 180 rev. per min. to deliver 50 kilovolt-amperes at power-factor zero to power-factor 1.

The manufacture of such a machine would ruin any going concern. We are therefore compelled to: 1, find such a method of generating the exciting currents as will permit the use of normal speeds and consequent reduction of size of the exciter; that is, the exciters must be designed to give low frequencies at high speed; 2, to produce the desired potential gradient on the alternator, we must so design the exciter that it will have a characteristic complementary to that of the natural characteristic of the alternator it excites. These are severe conditions to impose upon any machine, but they have been met in a novel manner in the machine about to be described.

It is evident that if the field of an ordinary direct-current machine is slowly alternated, corresponding alternations in the electromotive force of the armature will occur. Such a machine could evidently be driven at any speed and would give alternating current through its commutator and brushes corresponding in frequency to the frequency of its field, but it could furnish single-phase currents only.

It is evident also that two such machines could be coupled on the same shaft, each machine having its field excited by low-frequency and phase-differing currents; and such an arrangement would generate from the two armatures two phase-differing currents, whose frequency is independent of the speed of rotation.

If now these two fields are combined in one machine; that is, if the field is a Ferraris or rotating field, instead of a simple periodic field, it is evident that a single armature with a simple commutator and four brushes placed in quadrature around the commutator will deliver two sets of alternating currents, differing in phase by the angle of the brush displacement, and at the same frequency as the rotating field, and that the figuring of the generated currents will be independent of the speed of rotation.

Such an arrangement is shown in Fig. 18, where the stator consists of a 4-pole structure having energizing coils diametrically located on opposite poles and connected to a two-phase source of excitation, while the armature and commutator deliver two-phase currents to external circuits. But this arrangement presupposes and employs a third element to furnish the original exciting current of the exciter. That device might be called a frequency setter. It tends, however, to complicate the system and add an unnecessary element.

In order to make the exciter self exciting and self contained, and to reduce the apparatus to the simplest terms, the following scheme for excitation has been devised, Fig. 19. First let us notice that the usual method of self exciting a machine of the continuous current type is to connect the armature terminals, that is, the brushes collecting currents from the armature, to a field coil so located with reference to these brushes that currents in the coil will increase the electromotive force and current the brushes deliver; thus a cumulative action between armature and field coils continues (in ordinary practice) until limited by the saturation of the iron of the machine.

In the machine here described, a pair of brushes correspond-

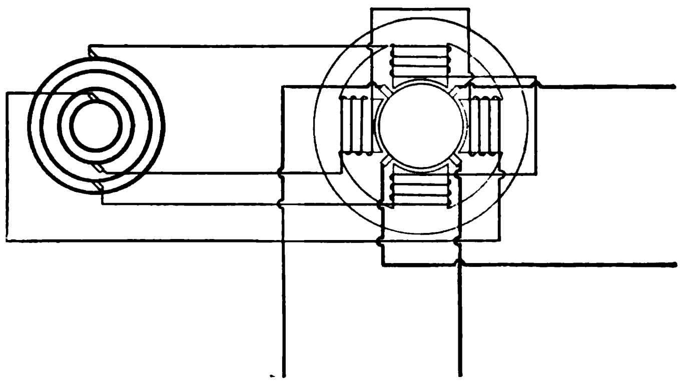


FIG. 18.

ing to those of an ordinary generator is connected to a field coil, so located with reference to these brushes that the flux it produces will be displaced by a predetermined angle, dependent upon the number of phases desired. Thus for a two-phase machine a pair of brushes is connected to a field coil so located as to produce a flux, by means of which and by rotation an electromotive force is generated upon the *other* pair of brushes, while the second pair of brushes is connected to a coil so located as to produce a flux that will generate an electromotive force on the first pair of brushes. This is shown in Fig. 19, which illustrates the connection and operation of self excitation by means of two- and three-phase currents.

Let the residual magnetism of the machine be as shown in the diagram. Then, on rotating the armature, an electromotive force will be developed on brushes 2–4. These brushes are connected to the field winding at X–X¹ instead of at Y–Y¹, as is usual in exciting continuous-current machines, consequently a current will flow, say from X through *a–a* to X¹, producing a flux through the armature at 90° to the residual magnetism. A resultant field will therefore lie between the points Y–X and Y¹–X¹, but this field will generate an electromotive force on brushes 1–3 and these brushes will deliver a current through Y–*a–a*–Y₁ in such a direction as first to *oppose* the residual magnetism and afterward to reverse its direction. At the instant that the residual magnetism is zero the only field operating in the machine is that due to the currents from the brushes

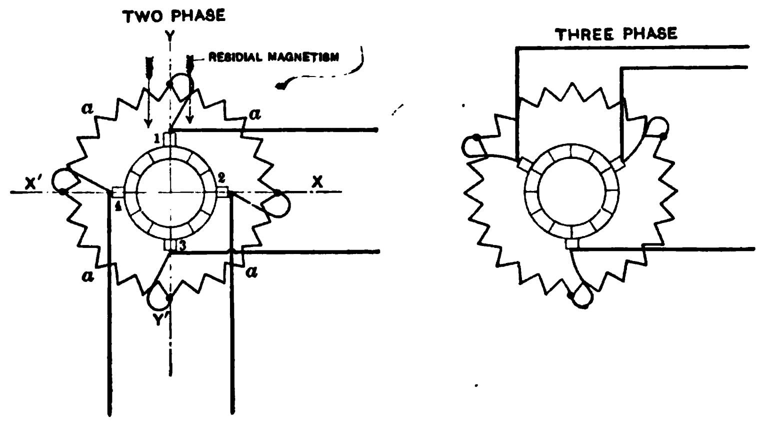


FIG. 19.

2–4; subsequently this field combines with the vertical reversed field to brushes Y–Y₁, producing a resultant with polar line between X–Y¹. These operations being cyclic, they recur at periodic intervals, and the phenomena become continuous.

As the resistance of the energizing circuit *a–a* is low in comparison with its inductance the currents delivered from each pair of brushes lag nearly 90° behind the electromotive forces, and therefore little energy is wasted in field excitation. This process of excitation presents many curious and interesting features. If, for example, one of the magnetizing circuits, such as X, be disconnected from the armature, the field immediately dies out, even if there is *no current in circuit* at the instant of the breaking.

The approximate calculation of the frequency of self excitation as given by Mr. Faccioli will be found by considering for a moment the physical phenomena that occur.

Assume the speed of rotation of the armature to be n_1; let the machine be a single magnetic-circuit machine with x conductors in the armature, and Y conductors on the stator. A moment's consideration of the laws of induction will show that the direction of the currents delivered by the armature to the field must be such as to produce a field rotating in the same direction as the rotation of the armature.

Let the frequency of this rotating field be N, then evidently the effective frequency of the armature conductors will be:

$$N_1 - N = N_{11}$$

We therefore have X armature conductors cut by the flux of the machine at frequency n_{11}, and Y conductors of the field cut by the same flux at frequency N, therefore there will be two electromotive forces; one on the rotor and one on the stator, for each magnetizing circuit; and as is evident the condition of equilibrium of current flow will be obtained when these two electromotive forces are equal and opposite to each other.

This condition of equilibrium will always be fulfilled for a certain frequency of self excitation; such in fact as will make:

$$X N_{11} = Y N$$

But $$N_{11} = N_1 - N$$

so $$Y N = X (N_1 - N)$$

and $$N = N_1 \frac{X}{X+Y}$$

That is, the frequency of self excitation will be equal to the frequency of rotation times the turns on the rotor divided by the sum of the turns on the rotor and stator.

By this formula we can easily determine the winding of a machine for a given frequency of self excitation; for instance, in the case of a two-pole machine in which the speed of rotation is 900 rev. per min. (15 cycles) the number of armature conductors is 200 and the frequency of self excitation desired is three cycles, we find that the number of turns required on the stator is:

$$\frac{200\,(15-3)}{3} = 800$$

Evidently these results are only strictly true when the resistance and leakage of the machine are zero, or not considered, as these quantities have a slightly modifying effect.

When the windings are similarly disposed in rotor and stator, it is not necessary to take into consideration the winding distribution coefficients, but the proper coefficients should be employed when the stator has salient poles.

This type of machine satisfies, therefore, the first condition laid down as necessary for a commercial exciter; for it produces low-frequency multiphase currents at normal speeds. It also fulfils the second condition—that it should deliver zero and negative power-factor currents at constant or rising potential

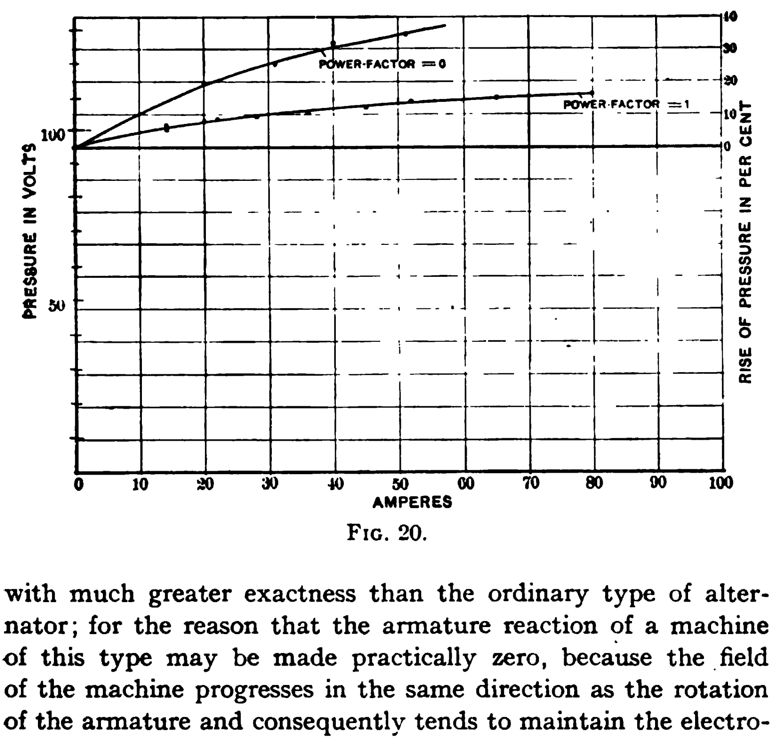


FIG. 20.

with much greater exactness than the ordinary type of alternator; for the reason that the armature reaction of a machine of this type may be made practically zero, because the field of the machine progresses in the same direction as the rotation of the armature and consequently tends to maintain the electromotive force at low power-factor loads, and because it may be compensated to give a positive, potential gradient.

Fig. 20 gives the voltage characteristics of a 10 kilovolt-ampere exciter in function of the amperes of load for power-factor = 1, and power-factor = 0. The frequency of self-excitation of this machine, when run at 900 rev. per min., is five cycles.

An examination of the characteristic curves of the induction alternator $(n_1 - n)$ type curve 10 shows that the potential gradient of these machines is positive for load currents of unity power-factor; zero for load currents of (about) power-factor = 0.8 and negative for currents of power-factor = 0.

If, therefore, the exciter is given such a characteristic that the electromotive force of the exciter will be slightly lower when the alternator is full loaded with power-factor = 1 currents, and slightly higher when the alternator is delivering low power-factor currents, the potential of the alternator may be maintained practically constant for any variation in load or power-factor.

It is to be remembered that the exciter, when used with $(n_1 - n$ type of alternator) is *never* called upon to *furnish* power-factor unity currents, but to *receive* them, and that the magnetizing reaction of such currents upon the exciter field is exactly the reverse of that found when the power-factor unity currents are delivered; therefore, the exciter should be so designed, when used with this machine, as to give an increase of potential when delivering power-factor unity currents (that it may have a *negative potential gradient when receiving them*), as well as a slight increase of potential when delivering power-factor zero currents.

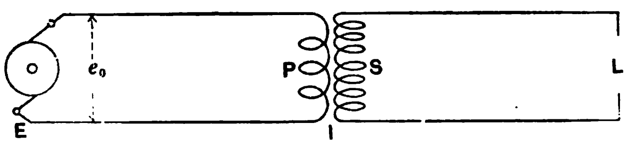
As stated in the first paragraph of this paper, the writer purposes to describe later the application of the phenomena here given to various new types of alternators. He hopes to be able to convince the members of the INSTITUTE that machines excited by continuous currents cannot compete with those employing alternating-current excitation, as the latter possess distinct advantages in simplicity, performance, and cost.

NOTE.—The phenomena accompanying this type of machine are of great interest and will be offered to the INSTITUTE in a subsequent paper.

DISCUSSION ON "ALTERNATE-CURRENT MACHINERY—INDUCTION ALTERNATORS."

CHAS. P. STEINMETZ: The machine by Mr. Stanley is of great interest, and remarkable by reason of its reactions, which permit, without change of excitation, an automatic compounding or over-compounding; that is, a rise of voltage with increase of load. Perhaps the internal reaction of the machine and its mode of operation may be made a little clearer by looking at it from another point of view; namely, as a frequency-converter. The machine is an induction machine containing primary windings connected with an impressed electromotive force, of low frequency in this instance, and secondary windings connected to an external circuit as load, and movable relatively to the primary windings. Now, in the simplest form this can be shown diagrammatically in Fig. 1.

Fig. 1



P is the low frequency primary winding of the induction machine, in inductive relation to the secondary winding S. The secondary winding S connects to the load L, while the primary winding connects to a source of constant impressed electromotive force, e_0, the terminal voltage of the synchronous or commutating machine E, or "the nominal induced electromotive force," as I called it, when operating the synchronous machine E at constant field excitation.

It is seen then that the diagram is nothing but an ordinary transformer diagram, or rather, since primary P and secondary S are movable with regard to each other, the diagram of the general alternating current transformer, as described and discussed by me in an INSTITUTE paper some years ago. In such an induction machine or frequency converter, not only voltages but also frequencies are transformed.

In an induction machine, frequency converter, induction motor, etc., the frequency or slip equals the difference between the impressed frequency and the speed; that is, if N_0 = primary impressed frequency, that is frequency of E, N_1 = secondary frequency or frequency supplied to the load L, and N = frequency of rotation, or speed, it is

$$N_1 = N - N_0$$

And the primary electric power P_0, the mechanical power P, and the secondary electrical power P_1 are proportional to the respective frequencies:

$$P_0 : P : P_1 = N_0 : N : N_1$$

Applying these induction motor relations now to Mr. Stanley's machine, the impressed frequency = 4, the secondary frequency: $N_1 = 60$. Two cases are possible: the primary impressed frequency may produce a revolving field in the same direction as the rotation: $N_0 = +4$, or it may produce a revolving field in the opposite direction: $N_0 = -4$. In the former case, the machine is driven in the direction of the rotating impressed field; that is, at over synchronous speed; in the latter case it is driven against the impressed rotating field or in backward rotation. In the former case, to get $N_1 = 60$, requires a speed $N = 64$, and in the latter case a speed $N = 56$. In the former case, at over synchronous rotation, P_0 and P_1 both are positive; that is, the machine produces electric power as generator in primary and in secondary; that is, E is a motor receiving power from the induction machine, and the flow of the power is as shown by the arrows in Fig. 2, from the induction machine I outwards in both directions. This is the well known case of an induction machine driven above synchronism, when it becomes a generator.

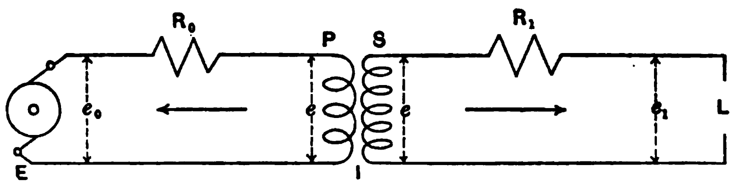


FIG. 2.

In the second case: $N_0 = -4$, P_0 is negative, *i.e.*, the primary P of the induction machine produces negative electric power; that is, receives power, and the exciter E is a generator, the flow of power is from E to I to L.

The strange compounding effects of such a frequency converter connected to a source of electromotive force e_0 are now quite obvious. Considering first the case of over synchronous rotation. In this case the primary and the secondary are both generating power, which flows outwards, the primary power into the motor exciter E, the secondary power in to the load L (Fig. 2), both powers being proportional to each other. In the primary exciter circuit, there is, however, an electromotive force e_0 which is constant (or varied in any desired manner, automatically or by hand). With increasing load L, that is, increasing secondary current in S, and therefore, increasing primary current in P, there is an increasing drop of voltage in the resistance R_0 between the induced electromotive force e in the induction machine I and the electromotive force e_0 of the motor exciter, and since e_0 is constant, e rises with increasing load, since the induction machine has no definite voltage of its own, but excites itself to whatever voltage is required by the circuit conditions. The increase of the induced electromotive force e of the induction machine with the load, primary as well as secondary induced electromotive force, since both are proportional to each other, therefore is proportional to the load and the primary resistance R_0; just as in any electric circuit, as a transmission line, the increase of generating voltage required to produce a constant voltage at the other end of the line must be proportional to the load and to the line resistance or rather impedance.

Of the induced electromotive force e of the induction machine I a part is consumed by the secondary resistance R_1; the rest appears as terminal voltage e_1. It is seen then that with increasing load, at constant exciter electromotive force e_0, or constant excitation of the synchronous machine E, the induced electromotive force e of the induction machine I increases proportionally to the primary resistance R_0, and the secondary terminal voltage e_1, or output voltage of the machine, falls below the induced electromotive force e proportional to the secondary resistance R_1.

If then the secondary resistance drop R_1 is greater than the primary resistance drop R_0, the terminal electromotive force e_0 falls with the load; if the resistance drop R_1 is less than in R_0, the voltage e_1 rises with the load; that is, the machine over compounds, and if the drop in R_1 and R_0 is equal, the voltage e_1 remains constant; that is, the machine compounds for constant voltage, and by varying or adjusting the resistance R_0 of the primary or exciter circuit, such a machine may be made to compound or over compound in any desired manner, within certain limits. An increase of the exciter resistance, therefore, increases the secondary; that is, the output voltage. A serious difficulty, however, is met with when considering the effect of the reactance of the motor circuits, on wattless currents of the load. Due to the over synchronous rotation, a lagging secondary produces a leading primary current. A leading secondary current reaches its maximum later; that is, while the rotor has been driven further forward, therefore, produces a primary current which reaches its maximum further forwards or earlier. In consequence thereof, with a leading secondary current; that is, an inductive load, the terminal voltage e_1 is less than the induced voltage e by the reactance drop of the secondary circuit. The corresponding primary current which flows into the exciter E is leading, hence the voltage rises in the direction of the flow of power, in the primary reactance, or e_0, the secondary electromotive force of the motor exciter, is higher, by the reactance voltage, than the impressed or induced electromotive force e, and with lagging current load, the voltage in the system drops from e_0 to e by the primary reactance voltage, from e to e_1 by the secondary reactance voltage; that is, the terminal voltage e_1 falls off with increasing load of lagging current. Inversely with increasing load of leading current, the terminal voltage e_1 rises, by the sum of the reactance voltages of primary and secondary circuits. It means, then, that the compounding is wrong with wattless currents, by the reactance drop of the system, and, assuming constant terminal voltage e_0 in the exciter circuit, the secondary terminal voltage e_1 at the load varies between 90° lag and 90° lead, by twice the sum of the reactance voltages of primary and secondary of the induction machine.

Hence such a machine does not automatically compound for constant voltage at varying power-factor, but can be made to compound automatically only for a constant power-factor of the load (provided this power-factor is not too low) or the voltage e_1 of the exciter must be varied in correspondence with the power factor of the load.

In the second case, or backward rotation, the exciter E is a generator, and with increasing load the voltage falls from the constant voltage e_0 to the induced voltage e, by the impedance drop of the primary circuit, and from the induced voltage e to the secondary terminal voltage e_1 by the impedance drop of the secondary circuit; that is, the variation of voltage of the machine with the load correspondence to the impedance of the primary and secondary circuit; that is, the internal impedance of the induction machine, exactly in the same manner as in any transformer or similar apparatus. Hence no more automatic compounding, with constant excitation e_0, can take place.

As you see all the phenomena of the machine become plain and intelligible by merely considering the direction of the flow of power, and taking in view that the voltage drops in the direction of the power flow, but is held constant in the primary circuit by the exciter e_0.

COMFORT A. ADAMS: I should like to ask Mr. Stanley if any tests have actually been made with this exciter, and if so, what the results of those tests were, as to the regulation of the alternator under loads of various power-factors.

MORGAN BROOKS: I should like to know how the machine acts as a motor. I understand it is a generator as described.

W. E. GOLDSBOROUGH: Dr. Stanley has brought to our attention a piece of apparatus that gives constant potentials at practically all loads.

I believe I once presented before the INSTITUTE the results of an experimental demonstration in which the reactance of an armature tended to compound the machine instead of diminish the potential at the brushes, even though the machine was excited with a direct current. The question uppermost in my mind is, whether the machine described by Mr. Stanley is one that is going to be of practical utility at this stage of the art because of giving a constant potential. In the power developments of to-day 5 000-kw. machines, and even **10 000-kw.**

machines are common, and 20 000-kw. machines promised. In the case of such large units is automatic regulation important? Do not the load fluctuations fairly compensate one another in the case of these large units? In stations that include small units, and in isolated plants, automatic regulation may be important, but in stations equipped with only large units hand regulation will in general suffice.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

NOTE ON A SIMPLE DEVICE FOR FINDING THE SLIP OF AN INDUCTION MOTOR.

BY CHAS. A. PERKINS.

There are a number of devices for finding the slip of an induction motor, but the following device, adopted more than a year ago in the laboratory of the University of Tennessee, is more simple and inexpensive than any other accurate device known to the writer. It does not even require the contact-maker and voltmeter described by B. F. Bailey in the *Electrical World* of April 22, 1905.

The device consists of a strip of sheet-iron clamped at one end to an iron base, leaving the other end free to vibrate. An electromagnet is mounted on the same base with its pole near the free part of the strip. When an alternating current is passed through the electromagnet, in series with one or more lamps, the strip will be thrown into vibration, if it has about the same period of vibration as the driving current. The adjustment of the time of vibration of the strip is readily made by giving it such a length as shall cause it to vibrate a little too rapidly and then loading it by a small copper wire which may be slid along the strip until approximate synchronism is obtained.

On the shaft of the motor is placed a cardboard disc, pierced by as many equally-spaced holes as there are north poles on the motor. The iron strip, with the electromagnet, is now placed in a good light and set into vibration by the supply current, and viewed through the holes in the rotating disc. If the hole comes at each revolution in front of the eye when the current is in a certain phase, the vibrating strip will also be in the same phase at each view, and will apparently be standing still. As the motor slips backward, the strip is seen at successively later phases of its vibration, and seems to be slowly vibrating, making one complete vibration when the motor has lost one complete cycle. By this method the slip may be counted up to about 300 cycles per minute, serving for all cases excepting for small motors with heavy loads, or on high-frequency currents.

The holes in the disc may be of generous size. In the disc that the writer is using they have a diameter equal to about one-eighth the circumference of the disc, without troublesome blurring; therefore it is easy to view the strip from a convenient distance, without stooping to the level of the disc. The frequency of the supply current may be taken from the speed of the motor, adding the correction for the slip; or if the iron strip is provided with a definite sliding weight whose position is calibrated for different periods of vibration, as described by Kinsley in the *Physical Review* for April, 1899, the frequency of the supply current is read off directly from the position of the slider, and the speed of the motor is then found from its slip. This requires a more careful adjustment of the slider and the use of a weaker current in the electromagnet, so as to avoid producing a forced vibration of the strip.

It is possible that a strong current in the electromagnet may reverse the magnetism of the core, giving the strip a period of vibration double that of the current. If the ear cannot decide from the pitch, a disc having twice the number of holes may be placed on the motor-shaft. If the image of the strip is still clear, the vibration is double the frequency of the current.

The rotating disc on the shaft of the induction motor is a convenient device for producing a number of stroboscopic effects. Thus, if an alternating arc is projected on a screen through the holes of the disc, the arc is observed to go through all its different phases. The brightening of the poles during the maximum and their cooling during the minimum are conspicuous. A soft cored carbon has a bright point on the hard shell during the positive maximum, and a lighting up of the core at the negative maximum. The arc nearly or quite dies out in the case of a hard carbon, while with a low-tension flame carbon the arc simply changes a little in size. Of course these changes may be used for counting the slip of the motor, but the motion of the iron strip is usually more convenient.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

NOTES ON THE POWER-FACTOR OF THE ALTERNATING-CURRENT ARC.

BY GEO. D. SHEPARDSON.

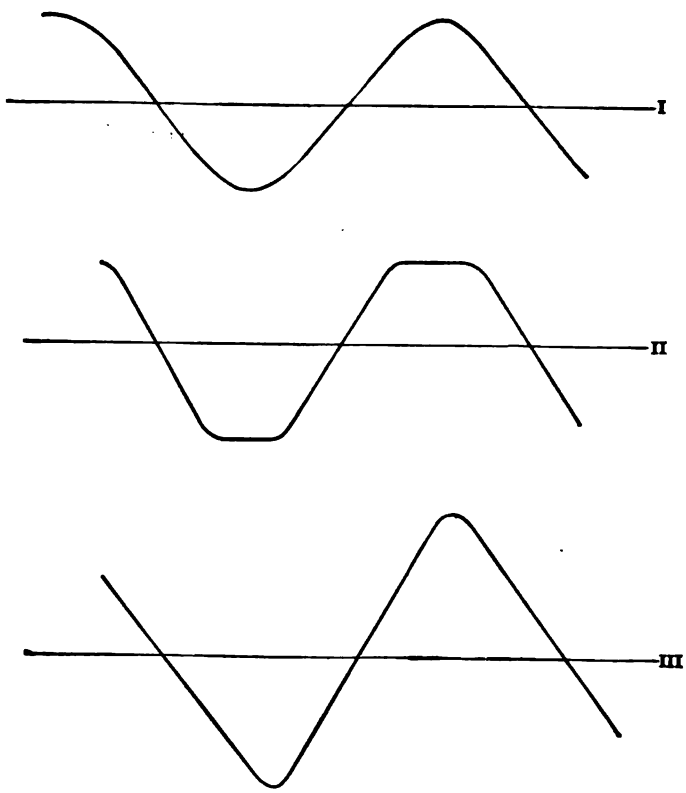
The alternating-current arc presents a wide field for research because of the many variable elements. During the last year the effect of the wave-form of electromotive force applied to the terminals of a standard enclosed arc-lamp, and the elements affecting the power-factor, were studied in connection with the graduating thesis work of Messrs. L. S. Billau, C. B. Gibson, E. H. LeTourneau, and R. Morris at the University of Minnesota. Some of the results obtained seem of sufficient interest for presentation before the INSTITUTE.

Electromotive forces having sine, flat-topped, and peaked wave-forms, Fig. 1, were obtained from a 7.5-kw., 60-cycle, General Electric double-current machine provided with three interchangeable sets of pole-pieces. Another wave-form, shown in the oscillographic curves in Figs. 5 to 8, was obtained from the circuit of the local lighting company. Current from these sources was sent through an enclosed constant-pressure lamp of standard manufacture, or through a hand-feed lamp having in series the reactance and feeding coils of the standard lamp. With the latter, all the conditions of a standard lamp are reproduced, except that the length of the arc is controllable.

For part of the experiments, wave-forms were recorded by a modified Duddell oscillograph; unfortunately this broke several times during the progress of the work, and many of the tests had to be made without oscillographic records.

Much difficulty was experienced from lack of uniformity in the carbons, although these came from a well-known maker of high-grade carbons and were supposed to be of the best quality.

In fact, the irregularities in the carbons entirely masked some of the variables which were being studied, and led to results so erratic that only a small part of the investigation gave results worthy of confidence. Variations in the performance of the carbons affected the candle-power of the light more than did changes in wave-form.



ELECTROMOTIVE FORCE WAVE-FORMS

FIG. 1.

Study of the power-factor of the arc under varying conditions shows that it is practically independent of the form of the electromotive force applied to the lamp terminals. The power-factor of the enclosed arc with soft cored carbons is found to be practically constant for current strengths between 4.5 and 8.5 amperes with 7/16-in. carbons, varying between 95 and 99 per cent. See Fig. 2. The power-factor of the whole lamp-circuit, including reactive coil and feeding coil, is practically independent of the wave-form of impressed electromotive force, being higher for small currents and lower for large currents. The change in the power-factor of the lamp-circuit, from 76 to 43 per cent. in this case, is evidently due to the smaller resistance of the arc with larger current, the reactance of the circuit being sensibly constant within the range considered. With the same grade of soft cored carbons and with open arc, the power-factor of the arc increases from 94 per cent. with 5.5 amperes to 99 per cent. with 8.5 amperes, Fig. 3, being independent of wave-form of impressed electromotive force, at

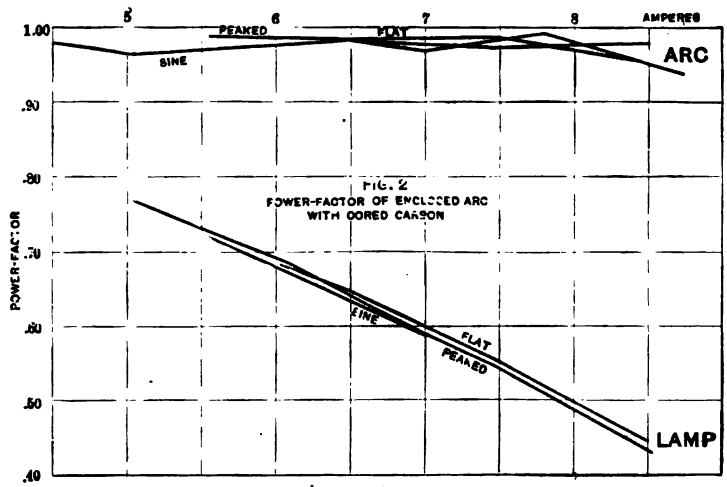
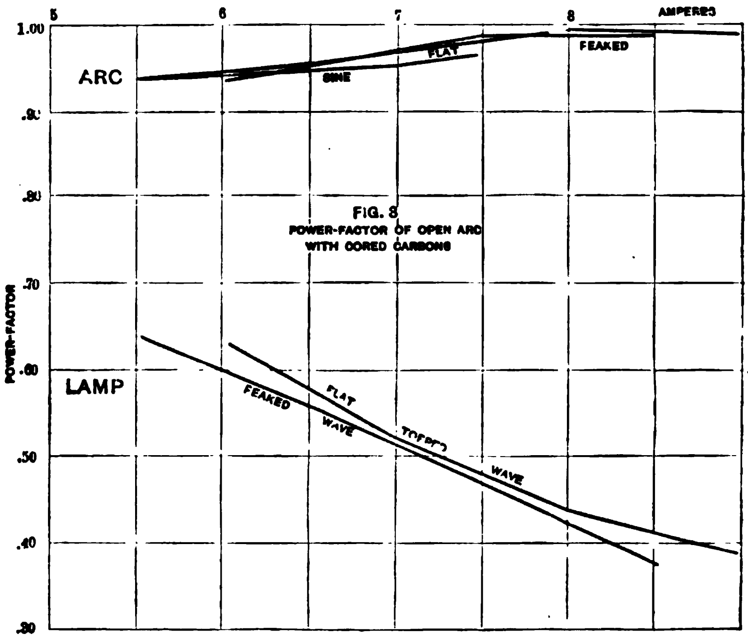


FIG. 2.

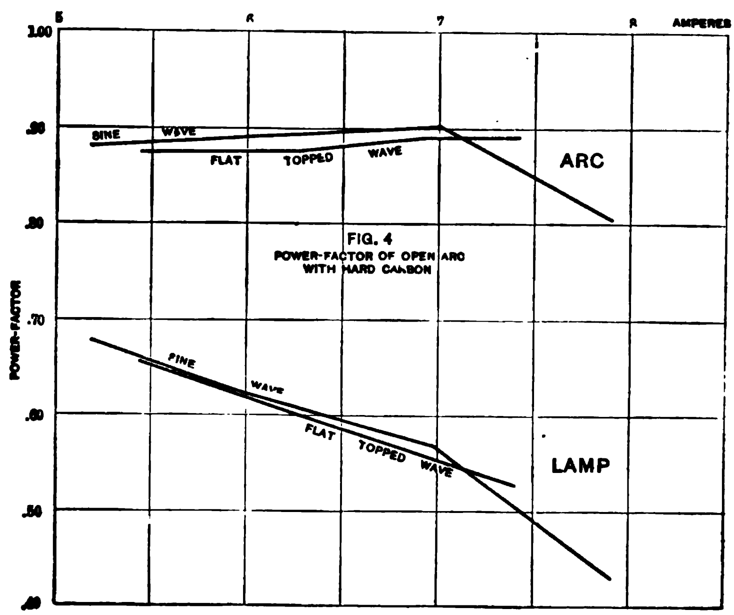
least within the limits of accuracy available. With open arc and with copper-plated hard carbons, such as commonly used with open arcs, the power-factor of the arc varies from 80 to 90 per cent. See Fig. 4.

The power-factor of the arc is found to remain constant when the arc pressure is constant, whatever the range of current and whatever the wave-form of impressed electromotive force. Likewise when the length of the arc (measured by the image thrown by a lens) is maintained constant, the power-factor of the arc is independent of changes in current and in wave-form of electromotive force applied to the lamp terminals. The quality of the carbons and the exposure of the arc to the air affect the



5
6
7
8
AMPERES
1.00
.90
.80
.70
.60
.50
.40
.30
POWER-FACTOR
ARC
FLAT
SINE
PEAKED
FIG. 3
POWER-FACTOR OF OPEN ARC
WITH CORED CARBONS
LAMP
PEAKED
WAVE
FLAT
TOPPED
WAVE

FIG. 3.



5
7
AMPERES
1.00
.80
.70
.60
.50
POWER-FACTOR
SINE
WAVE
FLAT
TOPPED
WAVE
ARC
FIG. 4
POWER-FACTOR OF OPEN ARC
WITH HARD CARBON
WAVE
FLAT
TOPPED
WAVE
LAMP

FIG. 4.

power-factor of the arc considerably. The distortion of the current wave-form doubtless affects the wave-form of electromotive force developed by the transformer or by a small generator.

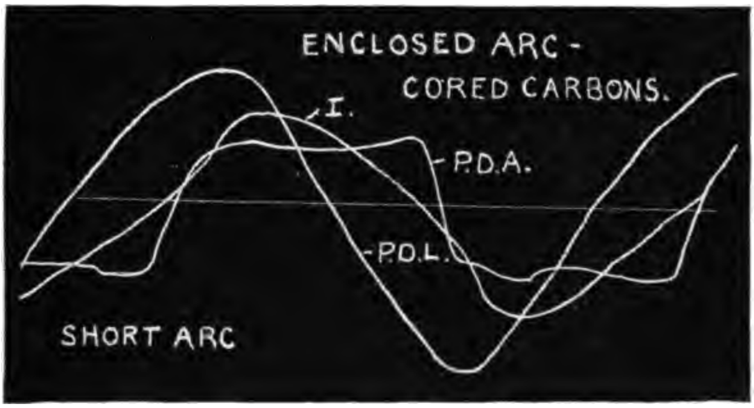


FIG. 5.

The effect of the lamp coils doubtless tends to make all impressed electromotive force waves alike when they reach the arc. Future investigations are expected to determine the wave-form of

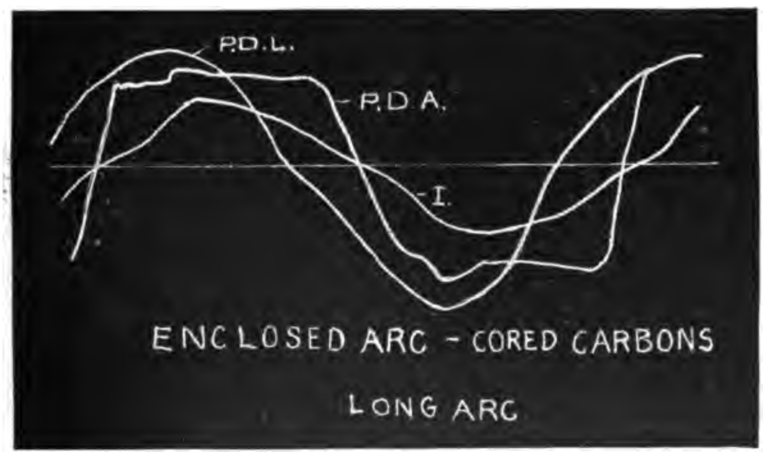


FIG. 6.

electromotive force actually applied to the arc under varying circumstances, the effect of changing it, and the reactions of the arc upon the source of electromotive force.

By means of a modification of the Duddell oscillograph, curves were obtained showing the variations in the instantaneous values of line pressure, arc pressure, and current. The de-

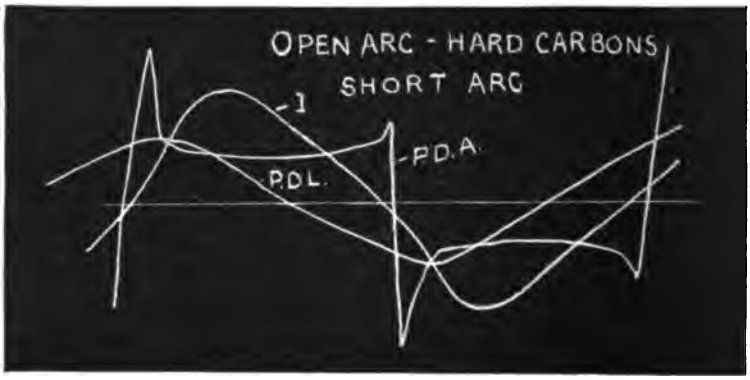


Fig. 7.

parture of the arc power-factor from unity is evidently due to distortion of the current and electromotive-force curves, there being little if any phase difference. In some of the records

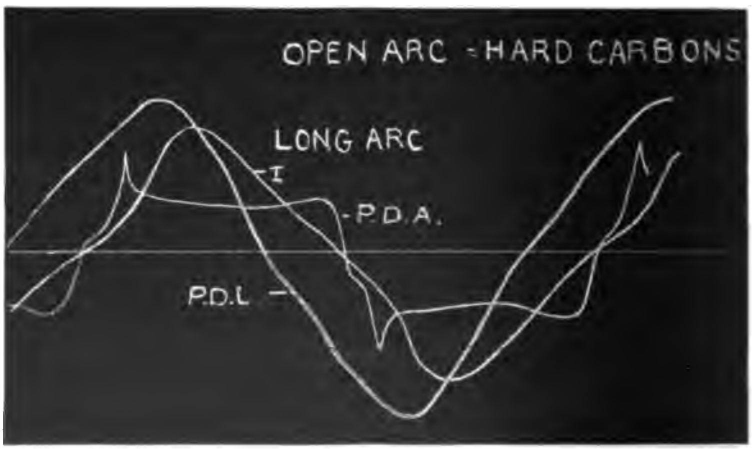


Fig. 8.

there is a slight unsymmetrical displacement of zero values. Duddell and Marchant show similar displacement of zeros in their paper before the British Institution of Electrical Engineers[1].

1. *Jour. Inst. Elec. Eng.*, vol. 28, pp. 60 to 86, 1899.

This phenomenon seems not to have been explained satisfactorily, and suggests a field for fruitful investigation.

The hard carbons show a much more sudden rise in the difference of potential around the arc than do the soft cored carbons or soft solid ones. Characteristic of the soft cored carbons is the secondary peak on the arc potential curve, occurring nearly simultaneously with the maximum current value and thereby raising the power-factor. Differences between the positive and negative loops are probably due to slight differences in the composition of the carbons. The more gradual growth of the current wave with the long arc will be noted, probably being due to the more rapid cooling of the arc gas during the extinction. With long arcs there is a tendency toward a double peak on the front of the potential wave. This portion of the wave changes greatly with the condition of burning and with irregularities in the carbons. With the short arc the potential wave rises to a marked peak at the rear. The current waves are concave to the axis when rising and convex when falling, due to the resistance being less in the hot vapor of the decreasing arc than in the cooler vapors of the increasing arc. The effect of the inductive action of the reactive coils is plainly seen in the lag of the current (marked " I ") and arc potential (marked " P. D. A.") waves behind that of the impressed electromotive force (marked " P. D. L.") in Figs. 5 to 8. With the hard carbons and open arc, the arc potential waves vary considerably with the length; with short arc the potential rises almost vertically to a high peak, is nearly horizontal on top, and rises to a peak at the rear; with the long arc, the peaks are not so prominent and the potential wave does not rise so rapidly.

A paper presented at the 22d Annual Convention of the American Institute of Electrical Engineers, Asheville, N. C., June 19-23, 1905.

THE PRESERVATION OF THE SOUTHERN APPALACHIAN STREAMS. A FOREST PROBLEM.

BY CHARLES EDWARD WADDELL.

To the south of the Shenandoah Valley in Virginia, and occupying portions of North Carolina, Tennessee, and Virginia, lies the high plateau commonly known as the Southern Appalachians. This plateau attains its greatest width, a distance of some 70 miles, in North Carolina, and has an average elevation of about 3 000 ft. It includes 275 peaks that exceed 5 000 ft. in height, and 36 summits of over 6 000 ft., among them Mount Mitchell, which is the highest point east of the Rockies, and the oldest land on the continent.

The eastern and western boundaries of the plateau are, respectively, the Blue Ridge and the Unakas. The slope of the Blue Ridge toward the Atlantic is gradual, and forms the rich agricultural Piedmont section. The Unakas, on the other hand, are higher and more rugged, and are cut into numerous deep gorges through which flows the rivers; it is a peculiarity of this region that all the streams, those flowing both east and west, take their rise on the slopes of the Blue Ridge.

Lying between the Blue Ridge and the Unakas are numerous cross-ridges, the general direction of which is northwest, and which divide the plateau into a number of valleys, and direct the course of the rivers.

This vast plateau constitutes the apex of the drainage area and serves as a source for magnificent rivers flowing to the four points of the compass. The largest and most important of these rivers are the New, which eventually becomes the Kanawha, the Yadkin, Catawba, Saluda, Broad, Toxaway, Tallulah, Chattahoochee, Pigeon, Watauga, Hiwassee, Little Tennessee, French Broad, Nolichucky, and Holston, having a combined drainage area of over 78 000 square miles. The majority of these rivers flow through excellent agricultural lands and possess fine water-powers; in fact all large water-power developments in the South to-day are located on streams rising in the Appalachians. Therefore, any influence that affects these rivers is far-reaching in its consequences and is of vital importance. The value of a river as a water-power depends upon its uniformity of flow rather than upon its quantity; regularity of flow is influenced by erosion of the hill-sides, and floods.

The rainfall in western North Carolina is heavy, approximating in some localities to 70 in. per annum. On steep slopes where the land has been cleared one violent precipitation could do more damage than would be caused in years if the same land were covered with forests.

To illustrate the serious nature of erosion the following data were collected. Beaverdam Creek is a small tributary of the French Broad River, and previous to the impounding of water by the dam of the Weaver Power Company it flowed into the French Broad through rocky banks a few hundred yards above the dam. The creek drains an area of some 14 sq. miles, all cleared land, and flows through gently undulating valleys. It is a representative but conservative type of mountain stream. The dam was completed just a year ago, and of course created a body of still water at the mouth of the creek. The run-off for the year, calculated from the recorded rainfall, and from averages of other measured streams, was 46 000 000 cu. ft.; by actual measurement the amount of sediment deposited was 12 000 cu. yd. It must be borne in mind that last year was exceptionally deficient in rainfall. In time of floods erosion is at its worst; then mountain torrents eat away their channels, and carrying down stones and other débris and depositing them on some rich agricultural land or in the pond of some developed water-power. Hence it is all important to prevent rather than to direct these floods. It is estimated that in 1901 the loss on the Catawba alone amounted to nearly $1 500 000. Property 200 miles from the mountains was damaged. The total loss for the year on all streams exceeded $10 000 000.

The government gauging stations report an increasing irregularity in the streams of the Southern Appalachians, and investigation as to the cause leads to the conviction that it is on account of the removal of the forests. Originally these mountains were covered to their summits with forests, but in the last few decades the lumbermen have made ruthless inroads with deleterious consequences. It is especially noticeable that some of the smaller streams, whose headwaters have been denuded, at certain seasons dry up altogether.

Experience in this locality together with that obtained elsewhere, notably the German and French Experiment Stations, indicates that the forests exert a potent and direct influence on stream flow; to form a clear conception of the nature of this influence it is necessary to consider the manner in which streams are formed and the methods by which they derive their supply. It must be noted that surface run-off is the cause of rapid fluctuations, while the perennial springs and underground drainage furnish the permanent supply; therefore, regularity of flow is secured if the run-off is diverted into storage. This is the part the forest performs. Its factors of conservation are lower temperature, shade, capacity of the humus, and the retarding of evaporation by protection from strong air currents. Benefit is also derived from the mechanical action of the trees in breaking the fall of the rain drops, thereby protecting the soil, and to the obstruction offered by the roots to the rapid run-off of the precipitation.

The roots further assist by increasing percolation through keeping the ground open and porous. The forest cover protects snowfall from rapid melting, and the snow in turn protects the earth from freezing, thereby keeping it open and susceptible to filtration when the snow does melt. Evaporation is much more rapid from bare tracts than from wooded areas; this is especially true of the mountains as the greater the altitude the greater the effect in preventing evaporation.

The stream preservation of the Southern Appalachian depends solely on the forests; in this respect it differs from New England, where glacial deposits and the lakes coöperate with the streams. Unfortunately in the south both the deposits and the lakes are lacking. The expedient of planting grasses that have been found to flourish in New England, and to protect the soil subsequent to the removal of forests, is not successful in the South, due doubtless to the greater heat and consequent parching effect.

Consideration of the foregoing beneficial action of the forests convinces one that the woods at the headwaters of the streams should never be removed. Valleys alone are suited to agriculture. Cleared mountain sides yield at most four or five crops, then the land becomes so impoverished that it is valueless. Nor should the lumber industries be permitted to destroy all standing timber. Protection of the forests does not imply that lumber is not to be cut; on the contrary it is beneficial to the forests to remove lumber, but it should be removed in an intelligent manner, in a way that will protect young trees. The present wholesale methods of removing forests should be stopped.

Next to the lumbermen the greatest enemy of the forests is the fires. These are especially bad on the southern exposures, due to the greater dryness, and they work the dual harm of damaging the standing timber and killing the seedlings.

In 1892 the first practical forestry in the United States was started on the Biltmore Estate. The methods in vogue consist of mapping the tracts of timbered lands, making accurate surveys of the extent and character of the forests, noting trees that have reached maturity, and reforesting bare tracts. Conservative methods of lumbering are pursued, the trees being so removed as not to destroy the younger growths, and plantings of seedlings taking the place of matured trees.

On steep declivities where the forests have been previously removed, and where erosion has ensued, the hills are first staked in belts at regular intervals of some four feet, and artificial obstructions such as rhododendron and kalmia roots are introduced which result in the formation of new soil. After sufficient time has elapsed to insure permanency and desired richness, the hillsides are planted with very small trees of a kind especially adapted to the locality. The results of these methods are to-day apparent in the condition of the brooks and streams. The deposit of sediment is materially less than on the streams not so protected, and the streams are not so turbid subsequent to heavy rains.

The French Broad river with its tributaries above Asheville drains the Biltmore Estate, and the fact that statistics show the French Broad to vary less than any other stream in the South Atlantic States may be attributed to the protection the river receives in the manner just outlined.

A paper presented at the 199th Meeting of the American Institute of Electrical Engineers New York, September 22d, 1905.

STANDARDIZATION OF ENCLOSED FUSES.

BY H. O. LACOUNT.

The object of this paper is to describe: 1. The necessity of standardizing enclosed fuses. 2. The work of standardizing such fuses. 3. The result of this work, namely: the specifications for the National Electric Code standard enclosed fuse. 4. The tests of fuses designed to comply with the specifications.

Necessity of Standardization.—Prior to about 1896, the fuses in use in this country were largely of the so-called "link" type. These consisted of a strip or wire of fusible metal, such as lead-alloy, soldered to copper terminals, which were made to fit under binding-screws or nuts on the cut-out blocks. The aluminum fuses of different forms should also be included in this class. Cut-out terminals were in the early days mounted on wood; but later, slate and porcelain were used for this purpose. The link cut-outs were frequently mounted in the open, though as time went on the use of cut-out cabinets became more and more general, because it was found necessary to prevent the flash, and melted metal produced when the fuses were blown, from being thrown out and igniting nearby combustible material.

The open link fuse has always been objectionable, not only from the standpoint of fire hazard but also from that of danger to person. The latter objection has possibly been greatest in the case of switchboards thus equipped, especially the larger boards where a considerable number of these fuses were used either on the front or back of the boards. With low-voltage boards repairs or changes are frequently made while the boards are in use. The wiremen are thus exposed to a possible flash and shower of hot metal, which might be serious, if, for example, the metal were thrown in the face. When the fuses are on the front of the board with the switches, as is frequently the case, the attendant may be severely burned or even blinded by the blowing of fuses when the switches are closed, if there happens to be a short circuit on the line at the time. The menace increases, of course, as the capacity of the fuse and the voltage of the circuit are increased.

While considering the early types of fuse, an exception to the link-fuse should be noted—the so-called Edison plug-fuse, which consisted of a fuse wire enclosed in a casing designed to screw into a receptacle in the cut-out base. This fuse was quite satisfactory in both the respects above noted; in fact, with some slight improvements it is still freely recommended for use, and has been adopted as a part of the standard fuse referred to later.

Another feature of the link fuse has been a somewhat variable carrying capacity, depending upon the way it was installed and the treatment it received later. The specifications for link-fuses have required that they be "stamped with about 80 per cent. of the maximum current that they can carry indefinitely;" and in the specifications the melting point of fuses up to, say, 500-ampere rating has been estimated to "be the minimum current which will melt them in about 5 minutes." This is the time usually necessary for a practically maximum temperature to be attained under this condition. While the approved makes of link-fuses will meet the requirements just mentioned, if connected to terminals of the usual size and held free in the air at ordinary temperatures, their carrying capacity will be materially changed if they should happen to be connected with very large or very small terminals as is frequently the case; or what is more important, if the fuse strip itself is in contact with surrounding objects, such, for example, as the porcelain part of the cut-out block. Many cases have been noted where the fuse, originally properly installed, has become heated by an overload, and softened sufficiently to sag until it struck the cold cut-out base, was then immediately chilled, and its carrying capacity thereby greatly increased.

In order to overcome the above-mentioned objections to the open-link fuse and obtain a fuse free from flash and the expulsion of hot metal, and also to obtain a fuse that could be more accurately rated and that was less affected by exterior conditions, the enclosed fuse was developed. It consisted of a fusible strip, more or less tightly enclosed in a strong fibre tube, at the ends of which terminals were provided for connecting the fuse with the cut-out blocks. The space between the fuse proper and the tube was filled with some non-combustible material, generally a powder, to break the arc formed when the fuse melted, and also to absorb or chill the gases and thereby prevent rupture of the tube.

In 1896, before enclosed fuses were placed on sale in this country, at least in any considerable quantity, the writer witnessed a series of tests upon fuses of this character, which demonstrated their ability to open safely the circuit under short-circuit conditions. The early history of this work is very interesting and shows a large amount of patient and persistent effort by those who have manufactured satisfactory enclosed fuses. Soon after this type of fuse appeared on the market other concerns brought out more or less complete lines of enclosed fuses, and after a few years at least 5 companies were engaged in their manufacture. Each company, however, adopted dimensions of its own, and also various types of terminals, so that the fuses of one manufacturer would generally not fit blocks made by other concerns unless constructed upon special order. There has always been some difference of opinion as to the exact reason for this action on the part of those companies that entered the field at a later date. Some persons contended that the motive was a selfish one, on the ground that these later companies anticipated that if the dimensions of their fuses were somewhat different from those of fuses then in use a definite market for their fuses would be created later to supply all cut-outs of their own make that might be installed. On the other hand, it has been claimed that the dimensions chosen were based entirely upon a consideration of successful operation, and that the difference in dimensions was accidental rather than premeditated. In any event, the result was a large number of types and sizes, few of which were interchangeable; in consequence of which supply houses found it necessary to maintain a very large stock in order to have on hand even only a few fuses of each particular design and capacity.

At the beginning of 1903, at least 5 manufacturers were doing considerable business in this line, and each averaged at least 4 different types of enclosed fuses. There were generally several classes in each type, so that the total number of fuses having either different dimensions or different styles of terminal, or both, was very large; for example, there were from 20 to 25 different 10-ampere fuses for use on circuits up to 250 volts, so that unless the customer knew exactly what make and type of fuse he required there were 20 chances to 1 that he would get the wrong fuse—a fuse, which he would later find out, would not fit the cut-out that he had installed.

In practice this large number of non-interchangeable fuses became a real fire hazard, also a source of great inconvenience and annoyance to both customer and dealer, because of the difficulty found in procuring the right fuse for the cut-out that happened to be installed. The supply houses found it impracticable to keep a full line and frequently could not furnish the fuses desired, so that either the customer or supply house was obliged to send to the manufacturer for a supply of the particular fuses needed. In the meantime some dangerous substitute for the proper fuse was generally provided, in the form of copper wire, wire nails, fuse wire, etc., because it was out of the question to cut out circuits until such time as the desired fuses could be obtained. As it was considered permissible to use in most places the enclosed fuse without a cabinet, the hazard was at once apparent when any of the above substitutes were employed in place of the enclosed fuses, because the combustible surroundings were at once directly exposed to the flash and melted metal produced when such a substitute fuse melted. Moreover, the use of such substitutes as have been mentioned was objectionable because of the liability to overfuse the circuits.

The only solution of this difficulty seemed to be to secure a standardization of this class of fittings whereby fuses of the same capacity would be interchangeable with reference both to dimensions and style of terminal. The considerable hazard that had thus been brought about and its apparent remedy were recognized at the same time by different insurance and municipal interests; in fact, several of them wrote independently to the different manufacturers, calling attention to the condition of affairs, offering to assist in bringing about an interchangeable fuse. In some places conditions had become so serious that definite action against the further use of enclosed fuses was contemplated; had it not been for the proposal to standardize the fuse at that time, this action would certainly have been taken. The writer was one of those who addressed the manufacturers, and it was soon discovered that others in different parts of the country were of the same mind. The Switch and Cut-out Committee of the Underwriters' National Electric Association, of which the writer was chairman, had already under consideration the question of the rating of enclosed fuses. It became evident at once that the question of standardizing the fuses could be best taken up by the committee in connection with its other work on the subject, especially as the results would undoubtedly have a more universal acceptance, because the committee represented in its membership the insurance and municipal interests, as well as the principal testing bureaus of the underwriters. The membership of the committee consisted of James E. Cole, Chief Inspector, Wire Department, Boston; Wm. H. Merrill, Jr., Secretary, Underwriters' Laboratories, Chicago; Ralph Sweetland, Inspector, New England Insurance Exchange, Boston, and E. V. French and the writer, of the Associated Factory Mutual Fire Insurance Companies, Boston. This plan was promptly outlined to several members of the Electrical Committee of the Underwriters' National Electric Association, who thought favorably of it, and the sub-committee, therefore, at once made arrangements to undertake this work in addition to the other matters already in hand. This was in July, 1903, and the manufacturers were definitely asked to make suggestions regarding the proposed standardization.

Work of Standardization: The problem was at first taken up with the manufacturers of approved enclosed fuses; but later suggestions from other parties were requested; in fact, the committee welcomed advice from anyone interested in the subject. The work of tabulating in detail the several fuses then on the market with regard to the type and dimensions was promptly begun; and on September 17, 1903, after some preliminary correspondence on the general subject, the first conference with the manufacturers was held in Boston. The situation was carefully gone over, and the necessity for the proposed standardization was outlined. The difficulties in the way of accomplishing it were at once evident, as it would require manufacturers to make a considerable change in stock, and in dies, and in shop methods to some extent, all of which would entail a large expense to each manufacturer. The question of bringing about a change in practice from the fuses in general use to others of a different design was also a prominent factor, as there were many thousands of enclosed fuses and corresponding cut-outs already in service. In addition to these difficulties came the greater difficulties of determining just what style of terminal and what dimensions should be adopted for the standard. The manufacturers, however, were willing to give their aid in the matter and made definite recommendations for the standard, all of which was of great assistance because their data, obtained from innumerable tests and close observation of the operation of the fuses in practice, were available.

As a result of the coöperation of the Switch and Cut-out Committee and the manufacturers, the committee was able to report, in December, 1903, at the annual meeting of the Underwriters' National Electric Association, an outline for the proposed standard enclosed fuse; the report was adopted and the committee was given authority to complete the details.

Further conferences were held in June, 1904, several of the manufacturers submitted more or less complete lines of fuses made to conform to the proposed specifications for the standard enclosed fuse. About 300 of these fuses were tested in Boston with special reference to their operation under short-circuit conditions. The large currents necessary for the work were obtained at the stations of the Edison Electric Illuminating Company and the Boston Elevated Railway Company. The complete results of the tests were incorporated in a report, dated July 14, 1904. In general the tests were satisfactory, and showed conclusively that the proposed specifications for enclosed fuses were, as a whole, practicable. The specifications, as far as completed, were therefore printed and promulgated in a pamphlet dated July 1, 1904, entitled "Enclosed Fuse Supplement to the 1903 edition of the National Electrical Code."

Since July, 1904, the work has been continued with the view of securing a list of manufacturers prepared to make the standard fuse in a satisfactory manner, which has required a further series of tests on nearly 600 fuses. Part of the work has been done at the Underwriters' Laboratories, Chicago; but the larger part has been carried on, in Boston, by the members of the committee residing there, who have not acted in this work, however, as the Switch and Cut-out Committee but as engineers. The work of the committee has technically been confined to the preparation of the specifications. The work, however, gave the committee additional data from which they were able to complete and perfect the specifications given in the July supplement. The last series of tests also required very large currents under conditions where short circuits could be made, and, like the earlier tests, were conducted at the stations of the Edison Electric Illuminating Company of Boston and the Boston Elevated Railway Company.

The later tests were reported in full to the respective manufacturers, under date of November 30, 1904. The fuses gave better results in certain respects than at the June tests, and on the whole a considerable improvement was noted. A number of the makes were, therefore, approved and were included in a special edition (dated July, 1905) of the pamphlet "Approved Electrical Fittings," issued by the Inspection Department of the Associated Factory Mutual Fire Insurance Companies. The approval of these fuses was also bulletined by the Underwriters' Laboratories to all subscribers.

Result of the Work of Standardization:

THE NATIONAL ELECTRICAL CODE STANDARD ENCLOSED FUSE.

The result of the work of standardizing and tests for approval of the enclosed fuse, which has been in progress for nearly 2 years, is given in the National Electrical Code of 1905, and in the List of Approved Fittings of April, 1905. The completed specifications are appended to this paper. It may be of interest to note some of the main features of the standard fuse.

Terminals.—The form of terminal to adopt was one of the most difficult problems to solve. Every one of the several terminals in use had advantages and disadvantages, and in the conferences there were strong advocates for the adoption of each. The screw-and-washer type, though probably the simplest and possibly the best electrically, offered also a ready means for wrong re-fusing with wires; in fact, such use was of everyday occurrence. This form of terminal had been used for fuse connections from the beginning of electrical installations, and everybody was accustomed to clamp the fuse wire under the screws, so that such a terminal would at once suggest this method of fusing, which would manifestly be improper where the cut-outs had been installed for the use of enclosed fuses. The merits of this type, however, were discussed at considerable length.

Several suggestions were made for an entirely new terminal, and two or three models were constructed. Of course, none of them had had the test of practical use, and it was soon decided to recommend some one of the forms that had been found reasonably satisfactory in practice.

The spring-clip and knife-blade terminals were finally chosen. Neither of these was especially new, as both had been in use for some time, particularly the spring-clip type These forms of terminals seemed to remove the temptation to wrong re-fusing as far as it was practicable to do so by mere form of contacts. Just how successful such terminals will be in this respect is yet to be determined as the standard fuses come more and more into general use.

Probably no fuse better illustrates the points that it was desired to secure than the old Edison plug; nevertheless this plug can be sadly misused. Inspectors and others have undoubtedly seen Edison plug cut-outs from which the plugs have been removed and pieces of fuse wire run over the top or along the sides of the cut-out and connected under the screws at the wire terminals. Sometimes the plugs have even been filled with type metal, and afterwards naturally "gave no trouble from blowing out and interrupting the circuit." In other instances where the attendant was somewhat less ignorant or more interested in the safety of the equipment, "blown" plugs have been re-fused on the premises with much larger wire than the plug was designed for, "in order to prevent it blowing again." It has also been found that bent hairpins, wads of tin-foil, etc., can be crowded into the Edison plug cut-out in place of the proper fuse plugs and carry the current all right. All such expedients are, of course, most dangerous.

While the Edison plug has been subjected to all these abuses, the total number of such cases is believed to be insignificant compared with the millions of plugs that have been properly used. This, however, cannot be said of the screw-and-washer type of terminal. The right use of the plug is probably due to: (1) the rules of the underwriters and their inspection bureaus; (2) the readiness with which they can be secured in almost any location; (3) the reasonably low price at which the plugs can be bought; (4) the convenience in replacing them in the cut-outs and (5) the difficulty frequently found in re-fusing them. The wrong use of the screw-and-washer type of enclosed fuse cut-out can probably be charged to: (1) the cheapness of fuse wire; (2) the adaptability of a single spool of wire to cut-outs of widely different capacities, and (3) the familiarity of wiremen with the use of link fuses and fuse wire in similar cut-out blocks.

The spring-clip and knife-blade terminals were believed to have as many of the advantages of the Edison plug and as few of the disadvantages of the screw-and-washer terminals, with respect to wrong fusing, as could be obtained and still retain other desirable features.

Another point in favor of the terminals that have been adopted is that the fuses may be inserted and removed without the aid of screw-drivers or wrenches, which many times have accidentally been the cause of serious short circuits when fuses were being replaced on live circuits.

Dimensions.—The dimensions for the fuses finally chosen were not those of an entire line of any one of the several manufacturers. In fact, many, if not most of them, were somewhat different from the dimensions of fuses then in use. At the start it was pointed out, on the one hand, that the dimensions must not be so small that the standard fuse would thereby be limited to a certain particular construction in order to successfully meet the other requirements, such as test, rating, temperature rise, and thus become a serious handicap to other manufacturers, who might find it necessary or desirable to use some different form of construction; and, on the other hand, that the dimensions must not be so large as to make the fuses unnecessarily bulky, as this would require, among other things, larger cut-outs, larger switch and panel boards, and more room in cabinets, all of which would tend to increased cost, not only in the installation of the devices but probably also in the manufacture and shipping of the fittings themselves. As it was considered that the manufacturers had to a great extent the data necessary to show the safe and reasonable limits for these dimensions, they were looked to for suggestions, with the caution that they keep in mind the points above mentioned.

After definite conclusions had been reached it was of considerable interest to compare the results of the several conferences, and the large amount of study that had been given the matter, with a table that had been prepared at the beginning and before any of the problems had received much attention. The table was based on the dimensions of the fuses then on the market, and gave for each classification what seemed to be average dimensions without special reference to any type or make. In many cases the average dimensions in the table were exactly the same as finally recommended for the standard fuses, and in practically all of the classes the differences were only small fractions of an inch. The average variation between this table and the table of dimensions finally adopted was only 12 per cent. The new dimensions are, therefore, not radically different from those of fuses that have been in use for several years.

Rating.—As already pointed out, the previous specifications of the underwriters required that the fuses be marked with 80 per cent. of the maximum current they could carry indefinitely. This was an arbitrary rating, since theoretically the rating would be 100 per cent. or, in other words, the maximum current the fuse could carry indefinitely. The reason for the above rating was to take care of irregularities of manufacture, and especially to guard against blowing of fuses exactly proportioned to the existing load when, for example, the voltage happened to be slightly increased or another lamp added; in other words, the rating was intended to provide a reasonable margin for irregularities in manufacture and ordinary fluctuations in service conditions, including changes in temperature of the surrounding air. In many cases it is believed that this precaution prevents interruption of service caused by unnecessary blowing of fuses, and thus appreciably lessens the temptation to put in larger fuses, which many times would be much heavier than required. On the whole, therefore, better protection is secured by this rating.

While this rule was retained for link fuses, it was slightly modified in the specifications for the standard enclosed fuse, which as originally proposed required that the fuse must carry 10 per cent. more current than that for which it was rated, and must melt with 15 per cent. current above its rating. The melting point of the fuse was, therefore, between 10 and 15 per cent. overload. The 25 per cent. overload necessary to melt a link fuse was thus reduced to from 10 to 15 per cent. for the standard enclosed fuse. This smaller margin between the rating and the maximum carrying capacity was considered sufficient, as it was claimed by manufacturers that the enclosed fuse could be rated more accurately than the link fuse, and possibly would be less affected by surroundings. The latter point, however, is perhaps open to some question.

In order to be sure that the fuses would melt in a reasonably short time with an appreciably greater overload, a third requirement was made that with 50 per cent. overload the fuses must open the circuit within a specified time, ranging from 30 seconds for the 30-ampere class to 10 minutes for the 600-ampere class, the test starting with the fuse cold, that is, 75° fahr.

The above figures were almost entirely a suggestion of the manufacturers, who were sure that they could meet such a specification for rating. In tests of a large number of fuses made later it seemed to be evident that it was going to be difficult, if not impracticable, to manufacture commercially a fuse complying with the first two parts of the rule, and the 15 per cent. limit was increased to 25 per cent., which is now required in the completed specifications. As the minimum melting point and the maximum carrying capacity are practically the same thing, the ratings of link fuses and enclosed fuses may be nearly alike regarding their overload capacity. The actual performance of the enclosed fuse is, however, more definitely defined.

The rule for rating also has an especially important requirement, viz., that with the 25 per cent. overload the temperature of the fuse must not be sufficient to injure the tube or the cut-out terminals. To keep the fuses reasonably cool is obviously an important matter and, therefore, an additional requirement has been made regarding it.

Temperature Rise.—Excessive overheating of the fuses may mean ignition of lint or other readily inflammable material on or near them and would be almost sure to char the fuse tube sufficiently to weaken it seriously, so that it might give way when the fuse is blown, especially if on a bad short circuit or under other severe conditions. Although accurate tests have not yet been made regarding this point, it would seem from what has already been done that the present approved fuses will meet this requirement satisfactorily.

Test.—Regarding the operation of the enclosed fuse, it is evident that it should successfully open the circuit according to the requirements for rating under the most severe conditions liable to be met in actual practice, and this should be done without liability of igniting nearby combustible material, since the fuses are intended for use outside of cabinets in almost any convenient place. The specifications, therefore, require satisfactory operation in both respects when one fuse is blown on a short circuit on a system of large generating capacity. There may be a difference of opinion as to what this capacity should be, but in the specifications the minimum limit of 300 kw. was designated to guard against testing on a system of such small capacity that poor fuses could stand the test.

The amount and kind of resistance in the testing circuit are undoubtedly of considerable importance in such tests, for it has been found by actual test that a fuse that will operate well on a circuit having what would ordinarily be considered a small resistance and connected to almost unlimited generating capacity, such as a large storage-battery, may be blown to pieces on a 300-kw. generator, if connected to the machine by only a few feet of wire of liberal conductivity. The ideal specifications, therefore, should probably also call for a definite resistance in the fuse circuit, but just what resistance should be used has not yet been fully determined. It is believed, however, that it should not be so small that fuses suitable for use practically everywhere, except in the stations themselves, will be condemned.

If the fuses are made to withstand station conditions, the cost must necessarily be greater than if a less severe test were required, and this increased cost would fall on the general public, whose equipments, except in rare cases, do not require such heavily constructed fuses either for safety or for successful operation. Undoubtedly the present users of enclosed fuses will agree that they already cost enough, and any additional rule beyond the requirements of safety that would increase this cost would probably result in greatly reducing the number that otherwise would be in service. Therefore, in laying out the tests for fuses submitted for approval such conditions were chosen as seemed best to represent the severer conditions of the average equipment, without expecting that the fuses submitted would be satisfactory for station use. For such service stronger fuses would undoubtedly be required.

Tests of Enclosed Fuses Made under the Specifications.

In addition to the two series of tests already mentioned, in which 900 fuses were tested, 200 more tests were made, in February and April, 1905, on improved samples of those makes and sizes that had not operated satisfactorily in the previous tests. The testing facilities previously given by the Edison

Electric Illuminating Company of Boston were again available for the greater part of the third series of tests, although quite a number of the tests were made at other places where approximately the same conditions could be obtained.

In all the short-circuit tests the available generating capacity was much larger than 300 kw. mentioned in the specifications. While undoubtedly the 300 kw. would have been sufficient for the smaller fuses, it would not properly represent conditions under which the larger fuses are used in practice, and it is believed that this point should be kept in mind when considering the present specifications for test. The minimum limit of 300 kw. was intended more for the smaller fuses, say 60 or 100 amperes, depending somewhat on the voltage for which the fuses are designed. For the larger fuses, however, it is believed that greater capacity is necessary, if commercial conditions are to be represented, and for a general rule it is suggested that the available capacity back of the fuse under test be, say, 10 times that at which the fuse is rated.

The 250-volt fuses, of 100 amperes and smaller current capacity, were tested on a regular commercial building service of the Edison Company, and the larger fuses were connected to a sub-switchboard fed through large cables from the main power-station about 4 000 ft. distant. There was, therefore, no question but that the tests were made under actual service conditions.

It was necessary to test the 600-volt fuses on a special testing circuit, so that the question of a proper resistance had to be considered. In most of the tests the total resistance of the circuit, with switches closed and the fuse in position, was about 0.13 ohms, which represented a reasonably small per cent. loss for commercial circuits, especially for the smaller circuits, although possibly a little greater loss than is to be found in actual practice on the larger circuits. In some of the tests the resistance was 0.24 ohms, although no appreciable difference was noticed in the results, showing that *within limits* the resistance can probably be varied somewhat without seriously affecting the results.

In some of the tests, however, it was noted that fuses that were reasonably satisfactory under severe short-circuit conditions were liable to fail if the current flow was limited by a resistance, even to a fairly large amount; for example, 1 500 amperes when testing 100- and 200-ampere fuses, and vice versa; fuses that apparently were successful under the limited load conditions would fail in the heavier short circuit tests. This result was evidently dependent upon the special interior construction of the several fuses used. While this point was interesting and suggestive, it was not investigated sufficiently by the committee having the tests in charge to warrant them in drawing any definite conclusions or recommending modifications of the present requirements for tests.

The failures noted during tests might be divided into two classes: first, failures in which the circuit was opened but the fuse tubes were burst or the end caps or ferrules blown off; and secondly, failures in which the arc held either through or around the fuse. While both classes of failures were rated "poor," the second class is, of course, by far the more dangerous. In one of the worst failures the arc held inside the tube until the emergency switch was opened; in the meantime flame and melted metal were thrown in a continual stream from both ends of the fuse a distance of, say, 20 ft. and a volume of flame and gas or smoke was discharged upward through the side of the tube at least 25 or 30 ft. Lest it might be thought that these failures were frequent, it should be stated that the reverse was true. Such failures clearly indicated defects, which in later tests of improved samples under practically the same conditions were found to have been removed.

In contrast with a comparatively few bad failures were a large number of successful tests of fuses of the different sizes and makes, which operated quietly and with but little or no flash outside the fuse tube. This was especially true of the last two series of tests. It is, therefore, believed that the enclosed fuses that have been approved and included in the List of Approved Electrical Fittings, published by the National Board of Fire Underwriters and the Associated Factory Mutual Fire Insurance Companies, are safe for general use. Accidents will occur; and so also will defective fuses be found now and then, but in view of the care being used by the manufacturers in constructing them the danger from this cause should be small.

It should be noted that with but few exceptions the fuses tested were provided with indicators, and while these are not required by the specifications, it has been found necessary to furnish them in practice, due to the demands of the users. The indicator is, therefore, considered in the trade as an essential part of a commercially successful enclosed fuse. This question of indicator has been rather difficult to solve, not so much because they could not be made to work, but because they tended to interfere with the safe operation of the fuse. This feature has been found to be of such importance that in making the tests for approval it has been required that if an indicator was to be used in the commercial product, it also be provided on the fuse submitted for test. Although, as stated, the indicators are not mentioned in the specifications, a record of their performance was kept throughout the tests, and it may be of interest to know that while the majority operated as intended, they frequently failed to give the proper indication.

A considerable number of fuses have also been tested for rating in line with the specifications. Some of these tests were made at the Underwriters' Laboratories, Chicago. The other tests were carried on at the Mass. Institute of Technology. In the latter tests, to economize time and increase the accuracy of comparison, several fuses were connected in series (at times as many as 20) and the rated current was passed through them until the maximum temperature had been reached, as noted by frequent readings of thermometers placed on the fuse tubes, with small bits of cotton waste over the bulbs to shield them. The temperatures thus recorded may not have properly indicated the actual temperature of the fuse casing, although probably the results were not greatly in error. They did show, however, when the conditions were approximately constant, which was the information specially desired. The maximum temperature was reached in about four hours; the current was then raised to 10 per cent. overload, and thence by steps of about 2.5 to 5 per cent. overload, until all of the fuses had melted. The current was held at each step until all the fuses had reached the maximum temperature or had melted, and the instant a fuse melted, which was indicated on the ammeter, a dummy fuse, provided for the purpose, was put in its place in order to interrupt the continuity of the test as little as possible.

In the last series of tests a few 200-ampere fuses were tested, but otherwise the rating tests were limited to 30, 60 and 100 amperes, due to the lack of time and proper facilities for continuing the tests on the larger sizes. From 2 to 4 fuses of each size and make were tested, and in addition two of each were subjected to 50 per cent. overload, and the time required to melt them, starting cold, was noted.

Direct current was used in most of the tests, although for some of them alternating current was more convenient and was, therefore, used. Regarding the use of alternating current for this work, the point has been raised that the temperature of the terminals is liable to be increased, due to the eddy currents set up in the caps, especially in those of the larger fuses. This matter has not been investigated, although it seems probable that any such action can have but little effect on the final results. Nevertheless, tests with alternating current would not be out of order, for enclosed fuses are frequently used on alternating current systems.

As a rule, it has been found that if the fuses meet the specifications regarding the 10 per cent. and 25 per cent. overloads, they require a somewhat longer time to melt than given in the specifications. Manufacturers are still confident that the "blowing" time can be brought within the limits specified and are at work on this feature, which was not considered of sufficient importance, however, to prevent approval of the fuses at the present time.

APPENDIX.

SPECIFICATIONS FOR NATIONAL ELECTRICAL CODE STANDARD ENCLOSED FUSES AND CUT-OUTS.

CUT-OUTS.

These requirements do not apply to rosettes, attachment plugs, car lighting, cut-outs and protective devices for signaling systems.

GENERAL RULES.

Must be supported on bases of non-combustible, non-absorptive insulating material.

Cut-outs must be of plug or cartridge type, when not arranged in *approved* cabinets, so as to obviate any danger of the melted fuse metal coming in contact with any substance which might be ignited thereby.

Cut-outs must operate successfully on short-circuits, under the most severe conditions with which they are liable to meet in practice, at twenty-five per cent. above their rated voltage, and with the largest fuses for which the cut-out is designed.

The most severe service which can be required of a cut-out in practice is to open a "dead short-circuit" with only one fuse blowing, and it is with these conditions that all tests should be made.

Must be plainly marked where it will always be visible, with the name of the maker, and current and voltage for which the device is designed.

ENCLOSED-FUSE CUT-OUTS—PLUG AND CARTRIDGE TYPE.

Base.—Must be made of non-combustible, non-absorptive insulating material. Blocks with an area of over twenty-five square inches must have at least four supporting screws. Holes for supporting screws must be so located or countersunk that there will be at least one half of an inch space, measured over the surface, between the screw-head or washer and the nearest live metal part, and in all cases when between parts of opposite polarity must be countersunk.

Mounting.—Nuts or screw-heads on the under side of the base must be countersunk at least one eighth of an inch and covered with a waterproof compound which will not melt below 150 degrees Fahrenheit.

Terminals.—Terminals must be of either the Edison plug, spring clip, or knife blade type, of *approved* design, to take the corresponding standard enclosed fuses. They must be secured to the base by two screws or the equivalent, so as to prevent them from turning, and must be so made as to secure a thoroughly good contact with the fuse. End

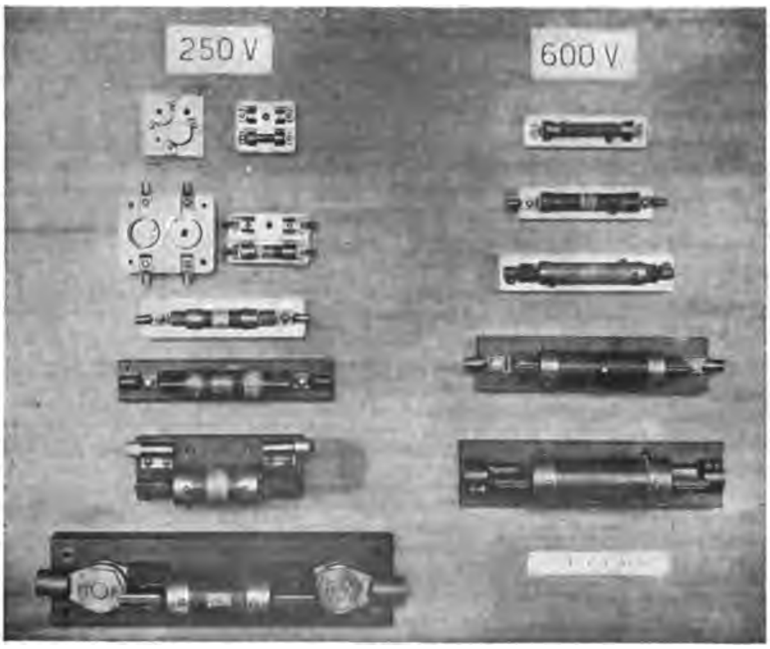


FIG. 1.

Showing maximum sizes in the several classifications of the National Electrical Code Standard Enclosed Fuses and Cut-outs.

NOTE.—The 30-ampere 250-volt plug cut-out is shown equipped with a plug casing for a Standard cartridge fuse and also an Edison plug fuse; the 60-ampere plug cut-out is equipped with a plug casing.

Samples of all the approved makes of Standard Enclosed Fuses are shown in this Fig. generally inserted in cut-outs of a different make to illustrate the interchangeable feature.

stops must be provided to insure the proper location of the cartridge fuse in the cut-out.

Connections.—Clamps for connecting wires to the terminals must be of a design which will ensure a thoroughly good connection, and must be sufficiently strong and heavy to withstand considerable hard usage. For fuses rated to carry over thirty amperes, lugs firmly screwed or bolted to the terminals and into which the connecting wires shall be soldered must be used.

Classification.—Must be classified as regards both current and voltage as given in the following table, and must be so designed that the bases of one class cannot be used with fuses of another class rated for a higher current or voltage.

0–250 Volts.	251–600 Volts.
0– 30 amperes.	0– 30 amperes.
31– 60 "	31– 60 "
61–100 "	61–100 "
101–200 "	101–200 "
201–400 "	201–400 "
401–600 "	

Design.—Must be of such a design that it will not be easy to form accidental short-circuits across live metal parts of opposite polarity on the block or on the fuses in the block.

Marking.—Must be marked, where it will be plainly visible when the block is installed, with the name of the maker and the voltage and range of current for which it is designed.

ENCLOSED FUSES,—PLUG AND CARTRIDGE TYPE.

These requirements do not apply to fuses for rosettes, attachment plugs, car lighting, cut-outs and protective devices for signaling systems.

Construction.—The fuse plug or cartridge must be sufficiently dust-tight so that lint and dust cannot collect around the fusible wire and become ignited when the fuse is blown.

The fusible wire must be attached to the plug or cartridge terminals in such a way as to secure a thoroughly good connection and to make it difficult for it to be replaced when melted.

Classification.—Must be classified to correspond with the different classes of cut-out blocks, and must be so designed that it will be impossible to put any fuse of a given class into a cut-out block which is designed for a current or voltage lower than that of the class to which the fuse belongs.

Terminals.—The fuse terminals must be sufficiently heavy to ensure mechanical strength and rigidity. The styles of terminals must be as follows:

0–250 Volts.

0– 30 "	*A*	Cartridge fuse (ferrule contact)	to fit	*a*, spring clip terminals. *b*, Edison plug casings
	B	Approved plugs for Edison cut-outs		

TABLE OF DIMENSIONS OF THE NATIONAL ELECTRICAL CODE STANDARD CARTRIDGE ENCLOSED FUSE.

Voltage.	Rated Capacity. Amperes.	A Length over Terminals. Inches.	B Distance between Contact Clips. Inches.	C Width of Contact Clips. Inches.	D Diameter of Ferrules or Thickness of Terminal Blades. Inches.	E Min. Length of Ferrules or of Terminal Blades outside of Tube. Inches.	F Diam. of Tube. Inches.	G Width of Terminal Blades. Inches.	Rated Capacity. Amperes.
		Form 1						Form 1	
0–250	0– 30	2	1	1/2	9/16	1/2	1/2		0– 30
	31– 60	3	1 3/4	5/8	13/16	5/8	3/4		31– 60
		Form 2						Form 2	
	61–100	5 7/8	4	7/8	1/8	1	1	3/4	61–100
	101–200	7 1/8	4 1/2	1 1/4	3/16	1 3/8	1 1/2	1 1/8	101–200
	201–400	8 5/8	5	1 3/4	1/4	1 7/8	2	1 5/8	201–400
	401–600	10 3/8	6	2 1/8	1/4	2 1/4	2 1/2	2	401–600
		Form 1						Form 1	
251–600	0– 30	5	4	1/2	13/16	1/2	3/4		0– 30
	31– 60	5 1/2	4 1/4	5/8	1 1/16	5/8	1		31– 60
		Form 2						Form 2	
	61–100	7 7/8	6	7/8	1/8	1	1 1/4	3/4	61–100
	101–200	9 5/8	7	1 1/4	3/16	1 3/8	1 3/4	1 1/8	101–200
	201–400	11 5/8	8	1 3/4	1/4	1 7/8	2 1/2	1 5/8	201–400

31– 60 "	Cartridge fuse (ferrule contact) to fit	*a*, spring clip terminals. *b*, Edison plug casings.
61–100 "	Cartridge fuse (knife blade contact).	
101–200 "		
201–400 "		
401–600 "		

251–600 Volts.

0– 30 amps.	Cartridge fuse (ferrule contact).
31– 60 "	
61–100 "	Cartridge fuse (knife blade contact).
101–200 "	
201–400 "	

Dimensions.—Cartridge enclosed fuses and corresponding cut-out blocks must conform to the dimensions given in the table attached.

Rating.—Fuses must be so constructed that with the surrounding atmosphere at a temperature of 75 degrees Fahrenheit they will carry indefinitely a current 10 per cent. greater than that at which they are rated, and at a current 25 per cent. greater than the rating, they will open the circuit without reaching a temperature which will injure the fuse tube or terminals of the fuse block. With a current 50 per cent. greater than the rating and at room temperature of 75 degrees Fahrenheit, the fuses, starting cold, must blow within the time specified.

0– 30 amperes,	30 seconds.
31– 60 "	1 minute.
61–100 "	2 minutes.
101–200 "	4 "
201–400 "	8 "
401–600 "	10 "

Marking.—Must be marked, where it will be plainly visible, with the name or trade mark of the maker, the voltage and current for which the fuse is designed, and the words " National Electrical Code Standard." Each fuse must have a label, the color of which must be green for 250-volt fuses and red for 600-volt fuses.

It will be satisfactory to abbreviate the above designation to " N. E. Code St'd " where space is necessarily limited.

Temperature Rise.—The temperature of the exterior of the fuse enclosure must not rise more than 125 degrees Fahrenheit above that of the surrounding air when the fuse is carrying the current for which it is rated.

Test.—Must not hold an arc or throw out melted metal or sufficient flame to ignite easily inflammable material on or near the cut-out, when only one fuse is blown at a time on a short-circuit, on a system having a capacity of 300 kw. or over, at the voltage for which the fuse is rated.

The above requirement that the testing circuit must have a capacity of at least 300 kw. is to guard against making the test on a system of so small capacity that the conditions would be sufficiently favorable to allow really poor fuses to stand the test acceptably. On the other hand, it must be remembered that if the test is made on a system of very large capacity, and especially if there is but little resistance between the generators and fuse, the conditions may be more severe than are liable to be met with in practice outside of the large power stations, the result being that fuses entirely safe for general use may be rejected if such test is insisted upon. A more definite rule regarding the conditions of this test is desirable, and the matter is under consideration. In any case the test should be arranged to best represent the severer conditions of actual practice, not, however, including central station equipments where specially designed and stronger fuses are undoubtedly necessary.

DISCUSSION ON "STANDARDIZATION OF ENCLOSED FUSES," AT NEW YORK, SEPT., 22, 1905.

H. O. Lacount: Here on the table is a complete line of the standard enclosed fuses adopted by the Underwriters National Electric Association. The collection shows clearly what has been accomplished in regard to interchangeable features. Instead of this one table half covered with fuses, it would have required at least five such tables to hold all the enclosed fuses of these exact capacities which were in the market a year ago. Thus the number of fuses has been reduced about nine-tenths. To make all enclosed fuses of any given capacity interchangeable in the cut-outs, regardless of the make or date or place of purchase, was the object constantly in view, so that they might be as interchangeable, for example, as ordinary standard pipe-fittings. In order to make the cartridge type of enclosed fuse as interchangeable as possible in the Edison plug cut-out, which was adopted as part of the standard, fuse casings have been made which will receive the cartridge fuses, and can then be screwed into the plug cut-out. With these cut-outs thus equipped with casings, it is certain that the standard cartridge fuse, up to 60 amperes, at 250 volts, will go into either of the standard cut-out bases.

President Wheeler: I might add to what Mr. Lacount has said about this cut-out, that Mr. E. H. Johnson and Mr. C. S. Bradley discovered about 23 years ago that it was necessary in practice to have a fuse on both sides of a circuit; otherwise one side being grounded in one place and the other side in another place, there might be established a circuit with no fuse in action at all. This array of samples reminds me vividly of the fact that at that time I was going over the ground described to-night—the standardization of fuses—though of course they were fuses of a type different from these. I am much interested in the paper, because of my interest in standardization and in the increase of interchangeability. I hope to see the INSTITUTE do something further this year in the way of standardization.

L. W. Downes: If I am not very much mistaken, the tests that Mr. Lacount refers to as having taken place in 1896, were conducted in the presence of Mr. Lacount, Professor Puffer, and Mr. E. V. French, in my laboratory at Providence. That was at the beginning of the enclosed fuse industry.

Although quite a large number of the National Electrical Code fuses, made by the D. & W. Fuse Company, with which I am connected, have been used for several months, no complaints have been received. There are certain objections to the form of contact, but this holds true of any form of fuse that can be devised. I believe that the best results will be obtained by such a fuse as is represented in the type A, or screw-clamp contact, where the fuse terminals are firmly bolted to the cut-out.

It is difficult to make fuses interchangeable according to the new National Code standard; and it has been found impossible to have the width of the blade always the same. A variation of two or three thousandths of an inch in thickness is practically unavoidable, and is sufficient to spread the jaws of the terminals and thereby materially reduce the area of the contact. It is to be hoped, however, and I believe it to be a fact, that the area of the standard fuse terminals will be found amply large enough to allow for this necessary variation.

In his paper Mr. Lacount refers to tests, and recommends that the available generator capacity back of the fuse be, say, 10 times that at which the fuse is rated. If kilowatt capacity is meant it seems low to me. Take, for example, a 600-ampere, 600-volt fuse; the required kilowatt capacity for testing this will be 3 600 kw. I believe that Mr. Lacount is too conservative. I should say that as the ampere capacity of the fuse increases the relative generator capacity for testing it should be even greater than that given by him. A 600-ampere fuse that will operate perfectly when tested on a 1 000-kw. generator may go to pieces when tested on a 5 000-kw. circuit.

H. O. Lacount: My recommendation was intended to emphasize the point that the available capacity on the testing circuit should not be too small. For example, it would require that when testing a 600-ampere fuse of a given voltage, the source of current should be capable of delivering to the testing circuit 6 000 amperes at that voltage; with 100-ampere fuses, for example, 1 000 amperes should be available.

L. W. Downes: You referred, then, to the ampere capacity, and not to the kilowatt capacity?

H. O. Lacount: Yes.

L. W. Downes: The D. & W. Fuse Company was given an unusual opportunity to investigate the effect of large generator capacity back of the fuse by the Interborough Rapid Transit Company of New York. An exhaustive series of tests was conducted. A generator capacity of not less than 5 000 kw. was available, with a measured current on short-circuit as high as 18 000 amperes. The tests were conducted at several points on the line of the Manhattan Railway Division, the majority of them being made at the 99th Street station, where the potential drop between that point and the generating station was extremely small. There was practically no drop in leads connected with the fuses between the third-rail and the elevated iron structure, which acted as the ground or return circuit. In the earlier tests elaborate arrangements were perfected for measuring the current, and rise in potential, and for taking instantaneous photographs of the fuses at the instant of disruption. It was found that a very slight resistance in the circuit materially affected the operation of the fuse; therefore I think it desirable to test fuses with a much larger relative generator capacity than Mr. Lacount has suggested, as otherwise the conditions that accurately tell how the fuse is going to operate in service will not be obtained. I believe that for the security of the property a fuse should be tested under the severest conditions that it is likely to be called upon commercially to withstand.

President Wheeler: When the fuse melts, what causes the potential to rise beyond the potential that the fuse is intended to stand?

L. W. Downes: The potential rise, as measured on the Manhattan Division when short circuiting these fuses, was approximately 100%, the normal potential being 625 volts. The first evidence of the potential rise was in the flashing-over of the motors on passing trains. The test took place between 11 and 1 o'clock at night when the load was light; several trains were stalled at different times by the flashing-over of the motors immediately after the fuses under test had been short circuited. This great rise in potential I attribute to the large mass of iron in the elevated structure becoming magnetically charged, so to speak, and thus raising the potential as in a transformer action. In a large number of tests conducted on other circuits, where great masses of iron were not present, no such extraordinary rise in potential was noticed.

President Wheeler: I am surprised that fuses are used for service of that kind. I did not suppose these conditions would arise in ordinary service.

L. W. Downes: These fuses are placed on what is termed the "shoe-beam," to which the shoe is attached.

President Wheeler: But is not that rather a special use, and does it not show that, for the majority of purposes, fuses do not need this extra large generator capacity in testing? It seems to me that nine-tenths of the fuses used are not for service where the potential will rise 100%.

L. W. Downes: I do not think the potential rise affected in any way the operation of the fuse, as this rise occurred after the fuse had opened the circuit.

President Wheeler: What is the necessity of having very large dynamo capacity when testing fuses, except to keep on supplying the current that will continue to flow when the fuse arcs under the higher potential?

L. W. Downes: With limited dynamo capacity, the rush of current through the fuse on short circuit is materially cut down. The operation of the fuse, good or bad, is dependent entirely on the rapidity with which the metal of the fuse-link enclosed in the tube is converted into vapor, since this governs the resulting pressure developed within the fuse-casing. It is estimated that the instantaneous pressure developed within the casing of the 400-ampere fuse, such as is employed on the Manhattan Division of the Interborough Rapid Transit Company, may rise as high as 900 to 1 100 lb. per square inch. Now if the generator capacity is small the period occupied in converting the fuse-metal into vapor is materially lengthened, and as this vapor escapes and condenses very rapidly the pressure produced is consequently less, so that the fuse will operate satisfactorily, which it would not do if the period of operation were materially cut down.

President Wheeler: I do not think this condition applies to ordinary fuses in ordinary service.

L. W. Downes: I feel that it does, and for this reason: throughout the country the capacity of generators in central stations is constantly growing greater. Formerly it was held that a 300-kw. generator was a big machine; now there are 1 000-, 1 500-, 2 000-, or 3 000-kw. generators in central stations supplying light and power. It is on such circuits that fuses may be installed, some of them within the station or very close to it, and on lines with a very small drop.

A. H. Pikler: In reviewing this paper I find no mention made of the material or substance used for enclosing the fuse. As this is quite important in view of the danger of fire, the maintaining of the arc, etc., it would be well to consider that point in future standardizing of enclosed fuses.

W. L. Puffer: In regard to the rise of potential noted by Mr. Downes, if the generator is so large that the electromotive force remains at its primary value, the current obtained on short circuit follows the usual law. The flow of such an enormous current in any kind of circuit will give rise to a large magnetic field, which will produce the same results when the circuit opens as does a spark-coil in an automobile or in a gas-lighting system—there is a kick or discharge which makes a terrific spark through which the current keeps flowing.

I have in mind some short-circuit tests of 50-ampere fuses during which the bus-bar voltage of a 480-kw. compound generator went down 75% at the time the switch closed, and when the fuse opened the circuit the bus-bar voltage went up 100 per cent. The current that went through that 50-ampere fuse was somewhere between 5 000 and 10 000 amperes; nevertheless the operation was over so quickly that had the lamps in this hall been on the circuit no flicker in the light would have been perceived. I think the enormous increase of voltage coming across that gap produced the effect which Mr. Downes spoke of as necessitating the use of a larger fuse in railroad work.

As far as the amount of current to be used on testing a fuse is concerned, it seems to me that a fuse is put in as a protection to a circuit delivering a certain amount of current. The circuit is designed for a certain per cent. of drop, and therefore the maximum possible current will be, roughly speaking, the increase obtained when the circuit is closed; in other words, if the average drop is 5% the current would increase about 20 times. This is in line with what the last speaker said, and he is correct; but I think it hardly just to expect all small users to buy a fuse that is sufficiently good to be used on Interborough work, for example. I think that in such places they should have a specially made apparatus It does not seem to me that the insurance people and the engineering people are especially interested in that type of fuse for general distribution.

As far as the heating of the knife-blade terminals is concerned, experiments that I have seen seem to suggest that the knife-blade itself is not a source of heat, but that the heat which appears there at times comes from another place. This has been suggested to me by the fact that when the fuse is removed and a dummy fuse put in its place there is no heat, which would seem to indicate that the blade had nothing to do with it.

H. G. Stott: Perhaps I can throw a little light on the fuse tests on the Interborough lines. Mr. Downes has referred to the rise of potential when a fuse breaks. The reason for this rise of potential is, of course, very simple. There is a 100-lb. iron rail carrying between 20 000 and 30 000 amperes at the moment of short circuit; when this current is suddenly interrupted the enormous magnetic flux surrounding the iron conductor induces counter electromotive force of self-induction in the rail causing, as has been stated, a rise of potential of about 100 per cent. It is quite obvious also that the moment the short circuit takes place the same self-inductive electromotive force is generated, but in the opposite direction to that in which it is broken, so that it tends to reduce the potential on the circuit almost to zero. This, of course, is in accordance with Lenz's law, that the electromotive force of self-induction is always opposed to the electromotive force giving rise to it.

Experience shows that though a certain fuse might be perfectly satisfactory on a given system, it might fail absolutely on another system with a greater kilowatt capacity. A note of warning should be attached to all standard specifications for fuses, calling the purchaser's attention to the well-known fact that fuses must be designed to meet the special conditions under which they are to work, and that because a fuse is labeled 600 volts it does not follow that this fuse will safely open such a circuit.

Reference has been made in the discussion to switchboard fuses on the supposition that they are in use in the Interborough system; I wish to say that that supposition is wrong, as nothing but circuit-breakers are used on any Interborough switchboard.

A paper presented at the 199th Meeting of the American Institute of Electrical Engineers, New York, September 22, 1905.

AIR-GAP FLUX IN INDUCTION MOTORS.

BY A. S. LANGSDORF.

In determining the variation of the value of the flux in polyphase induction motors, and its progression around the air-gap, it is customary to assume that the current in each phase follows a sine law. In this way it has been shown that the flux rotates synchronously around the air-gap and that its magnitude varies between a maximum and a minimum; but it does not appear that the law of this variation in magnitude has been investigated. It is common practice in determining its mean value to consider the flux a maximum (in the case of three-phase motors) when the three currents are, respectively, $I, -\frac{1}{2} I, -\frac{1}{2} I$, where I is the maximum current per phase; and a minimum when the currents are $\frac{\sqrt{3}}{2} I$, 0, and $-\frac{\sqrt{3}}{2} I$; the mean of these two values being then considered as the average for the cycle.* This method is, of course, only approximate; but it will be shown in what follows that the actual average is not only greater than the value obtained as above, but it may even exceed the above assumed maximum.

The object of this investigation was to study the effect upon the flux distribution of varying numbers of teeth in the stator. It was found that the law of this variation could be conveniently expressed in the form of relatively simple equations, which are derived in the manner shown below. Four

*The Induction Motor, De la Tour (Mailloux) pp. 5–8.

distinct cases are considered: (1) Three-phase motors having an *even* number (t) of slots per pole per phase; (2) three-phase motors, t odd; (3) two-phase motors, t even; and (4) two-phase motors, t odd. In each case, for convenience, a unit length of core parallel to the shaft is assumed.

Let t = number of slots per pole per phase.
a = pitch of slots.
n = number of conductors per slot.
d = radial length of air-gap.
l = developed length of pole-pitch.
I = maximum current per phase.

I. Three-phase Motors, t Even.

$i_1 = I \sin \theta$ = current in phase 1.
$i_2 = I \sin (\theta - 120)$ = current in phase 2.
$i_3 = I \sin (\theta - 240)$ = current in phase 3.

$$l = 3\,a\,t$$

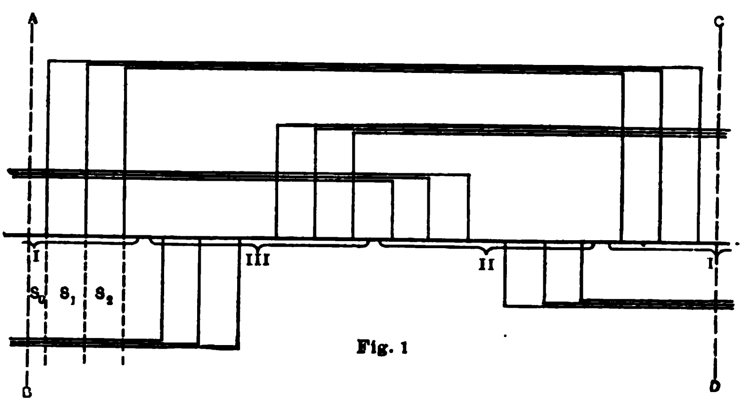


Fig. 1

Let Fig. 1 represent the instantaneous distribution of magnetomotive forces for a general phase angle θ, the rectangles corresponding to any particular phase being drawn with slightly different ordinates for greater clearness. The ordinates have a length equal to $\frac{4\pi}{10} n\,i$, and if we assume that the reluctance of the teeth and core is negligible in comparison with that of the air-gap, the flux per unit area will be $\frac{4\pi}{10} \frac{n\,i}{d}$.

The flux included between the lines $A\,B$ and $C\,D$; that is, included in a space equal to that of the pole-pitch, is the summation of all the rectangular areas between these lines, provided the ordinates are read in terms of $\frac{4\pi}{10}\frac{n\,i}{d}$. The flux is also equal to the area under a stepped " curve " (Fig. 2) whose ordinate at any point is the algebraic sum of those of the several rectangles at that point. This curve will, in general, consist of two parts; one above the horizontal axis, or positive; the other below the axis, or negative. The expression for the net area obtained by adding all the rectangular areas is, therefore, not the flux per pole; to obtain the latter there

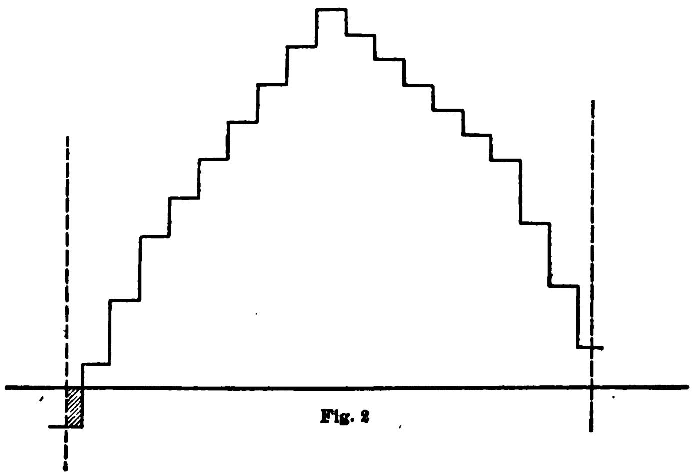


Fig. 2

must be added to the net value an amount equal to twice the area of the negative loop of the stepped curve.

The net value, ϕ_0, may be found by considering each phase separately, thus·

Phase 1.

$$\phi_1 = \frac{4\pi}{10}\frac{n\,i_1}{d}a\left[(3\,t-1) + \left\{(3\,t-1)-2\right\} + \dots + \left\{(3\,t-1)-2\left(\frac{t}{2}-1\right)\right\}\right]$$

$$= \frac{4\pi}{10}\frac{n\,a\,t^2}{d}\cdot\frac{5}{4}i_1$$

Phase 2.

$$\phi_2 = \phi_2' + \phi_2''$$

$$\phi'_2 = -\frac{4\pi}{10}\frac{n\,i_2}{d}\,a\left[\left(\frac{1}{2}+\frac{3\,t}{2}\right)+\left\{(\quad)+1\right\}+\ldots\right.$$

$$\left.+\left\{(\quad)+\left(\frac{t}{2}-1\right)\right\}\right]$$

$$= -\frac{4\pi}{10}\;\frac{n\,a\,t^2}{d}\;\frac{7}{8}\,i_2$$

$$\phi_2'' = \frac{4\pi}{10}\frac{n\,i_2}{d}\,a\left[\left(\frac{1}{2}+\frac{t}{2}\right)+\left\{(\quad)+1\right\}+\ldots\right.$$

$$\left.+\left\{(\quad)+\left(\frac{t}{2}-1\right)\right\}\right]$$

$$= \frac{4\pi}{10}\;\frac{n\,a\,t^2}{d}\cdot\frac{3}{8}\,i_2$$

$$\phi_2 = \phi_2''+\phi_2'' = -\frac{4\pi}{10}\;\frac{n\,a\,t^2}{d}\cdot\frac{1}{2}\,i_2$$

Phase 3.
By analogy with phase 2,

$$\phi_3 = -\frac{4\pi}{10}\;\frac{n\,a\,t^2}{d}\cdot\frac{1}{2}\,i_3$$

$$\therefore \phi_0 = \frac{4\pi}{10}\;\frac{n\,a\,t^2}{d}\;\left(\frac{5}{4}\,i_1-\frac{1}{2}\,i_2-\frac{1}{2}\,i_3\right)$$

At the moment when $\theta = \frac{\pi}{2}$, the stepped curve referred to above is entirely positive between the limits $A\,B$ and $C\,D$, but immediately thereafter a negative loop appears in the space s_0 (Fig. 1), due to the progression of the field. This loop has an area

$$\phi_{s0} = \frac{a}{2}\left(\frac{4\pi}{10}\;\frac{n\,i_2}{d}\;\frac{t}{2}-\frac{4\pi}{10}\;\frac{n\,i_3}{d}\;\frac{t}{2}\right) = \frac{4\pi}{10}\;\frac{n\,a\,t}{4\,d}\;\left(i_2-i_3\right).$$

and it remains the only negative area until the ordinate in space s_1 becomes zero. If this ordinate is b_1, we have

$$b_1 = \frac{4\,\pi}{10}\,\frac{n\,i_1}{d} + \frac{4\,\pi}{10}\,\frac{n\,i_2}{d}\,\frac{t}{2} - \frac{4\,\pi}{10}\,\frac{n\,i_3}{d}\,\frac{t}{2}$$

$$= \frac{4\,\pi}{10}\,\frac{n\,I}{d}\left(\sin\theta + \frac{\sqrt{3}\,t}{2}\cos\theta\right),$$

$$\text{which vanishes when } \theta = \tan^{-1}\left(-\frac{\sqrt{3}\,t}{2}\right).$$

We have, therefore, that between

$$\theta = \frac{\pi}{2} = \tan^{-1}\left(-\frac{1}{0}\,\frac{\sqrt{3}\,t}{2}\right)$$

and

$$\theta = \tan^{-1}\left(-\frac{1}{1}\,\frac{\sqrt{3}\,t}{2}\right),$$

the flux per pole is

$$\phi = \phi_0 + 2\,\phi_{s0} = \frac{4\,\pi}{10}\,\frac{n\,a\,t^2}{d}\left(\frac{5}{4}\,i_1 - \frac{1}{2}\,i_2 - \frac{1}{2}\,i_3\right)$$

$$+ 2\,\frac{4\,\pi}{10}\,\frac{n\,a\,t}{4\,d}\,(i_2 - i_3)$$

Proceeding in this manner from slot to slot, letting the ordinates in spaces s_2, s_3, etc., successively vanish, the following expressions result:

$$\text{From } \theta = \tan^{-1}\left(-\frac{1}{1}\,\frac{\sqrt{3}\,t}{2}\right) \text{ to } \theta = \tan^{-1}\left(-\frac{1}{2}\,\frac{\sqrt{3}\,t}{2}\right),$$

$$\phi = \phi_0 + 2\left[\frac{4\,\pi}{10}\,3\,\frac{n\,a\,t}{4\,d}\,(i_2 - i_3) - \frac{4\,\pi}{10}\,\frac{n\,a}{d}\,i_1\right].$$

$$\text{From } \theta = \tan^{-1}\left(-\frac{1}{2}\,\frac{\sqrt{3}\,t}{2}\right) \text{ to } \theta = \tan^{-1}\left(-\frac{1}{3}\,\frac{\sqrt{3}\,t}{2}\right),$$

$$\phi = \phi_0 + 2\left[\frac{4\pi}{10}\, 5\, \frac{n\,a\,t}{4\,d}\,(i_2 - i_3) - 3\,\frac{4\pi}{10}\,\frac{n\,a}{d}\,i_1\right]$$

In general, we have that between

$$\theta = \tan^{-1}\left(-\frac{1}{p}\,\frac{\sqrt{3}\,t}{2}\right) \text{and } \theta = \tan^{-1}\left(-\frac{1}{p+1}\,\frac{\sqrt{3}\,t}{2}\right)$$

$$\phi = \phi_0 + 2\left[\frac{4\pi}{10}\,(2p+1)\,\frac{n\,a\,t}{4\,d}\,(i_2 - i_3) - \frac{p(p+1)}{2}\,\frac{4\pi}{10}\,\frac{n\,a}{d}\,i_1\right]$$

where p is an integer that takes all values from zero to $\left(\frac{t}{2} - 1\right)$ inclusive. When p has the latter value, the superior limit of θ becomes 120°; i_3 then becomes zero, and thereafter the cycle of changes is repeated in inverse order. To obtain the average value of ϕ it will, therefore, be sufficient to integrate the function between the limits θ = 90° and θ = 120°, dividing then by $\frac{\pi}{6}$.

The ϕ function being a discontinuous one, we have

$$\phi_{aver.} = \frac{6}{\pi} \sum_{p=0}^{p=\frac{t}{2}-1} \int_{\theta=\tan^{-1}\left(-\frac{1}{p}\,\frac{\sqrt{3}\,t}{2}\right)}^{\theta=\tan^{-1}\left(-\frac{1}{p+1}\,\frac{\sqrt{3}\,t}{2}\right)} \phi\, d\,\theta$$

The expression for ϕ may be written

$$\int_{\theta=\tan^{-1}\left(-\frac{1}{p}\,\frac{\sqrt{3}\,t}{2}\right)}^{\theta=\tan^{-1}\left(-\frac{1}{p+1}\,\frac{\sqrt{3}\,t}{2}\right)} \phi = \frac{4\pi}{10}\,\frac{n\,a\,I}{d}\left[\left\{\frac{7}{4}\,t^2 - p\,(p+1)\right\}\sin\theta - \frac{2p+1}{2}\,\sqrt{3}\,t\cos\theta\right]$$

whence

$$\phi_{aver.} = \frac{6}{5}\frac{n\,a\,I}{d}\sum_{p=0}^{p=\frac{t}{2}-1}\left[\frac{p\,t^2 + 4\,t^2 - 4\,p\,(p+1)^2}{\sqrt{4\,(p+1)^2 + 3\,t^2}} + \frac{3\,t^2 - p\,t^2 + 4\,p^2\,(p+1)}{\sqrt{4\,p^2 + 3\,t^2}}\right]$$

II. Three-phase Motors, t Odd.

Constructing the magnetomotive force rectangles (Fig. 3) and proceeding as in (1), we find that between $\theta = \frac{\pi}{2}$ and $\theta = \tan^{-1}(-\sqrt{3}\,t)$

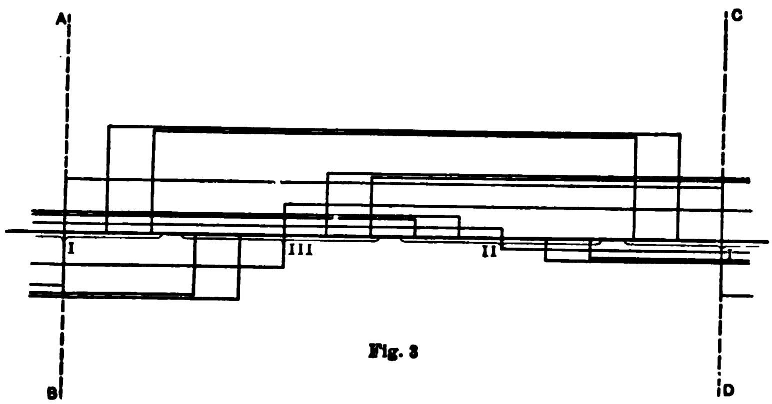


Fig. 3

$$\phi = \phi_0 - \frac{4\,\pi}{10}\frac{n\,a\,i_1}{d}\left(\frac{5}{4}\,t^2 + \frac{1}{4}\right) - \frac{4\,\pi}{10}\frac{n\,a\,t^2}{d}\frac{1}{2}\,(i_2 + i_3)$$

$$= \frac{4\,\pi}{10}\frac{n\,a\,I}{d}\frac{7\,t^2 + 1}{4}\sin\theta$$

In general, after $\theta = \tan^{-1}(-\sqrt{3\,t})$ and between

$$\theta = \tan^{-1}\left(-\frac{\sqrt{3}\,t}{2\,p-1}\right) \text{ and } \theta = \tan^{-1}\left(-\frac{\sqrt{3}\,t}{2\,p+1}\right),$$

$$\phi = \phi_0 + 2\,\frac{4\,\pi}{10}\,\frac{n\,a}{d}\left[p\,\frac{t}{2}\,(i_2 - i_3) - \frac{p^2}{2}\,i_1\right]$$

where p takes all integral values from *unity* to $\left(\frac{t-1}{2}\right)$ inclusive. This general value may be written

$$\phi = \frac{4\,\pi}{10}\,\frac{n\,a\,I}{d}\left[\left(\frac{7\,t^2+1}{4} - p^2\right)\sin\theta - \sqrt{3}\;p\,t\cos\theta\right]$$

To obtain the average value of the flux we have

$$\phi_{aver.} = \frac{6}{\pi}\left[\int_{\theta=\frac{\pi}{2}}^{\theta=\tan^{-1}(-\sqrt{3}\,t)} \phi_0\,d\,\theta + \sum_{p=1}^{p=\frac{t-1}{2}} \int_{\theta=\tan^{-1}\left(-\frac{\sqrt{3}\,t}{2\,p-1}\right)}^{\theta=\tan^{-1}\left(-\frac{\sqrt{3}\,t}{2\,p+1}\right)} \phi\,d\,\theta\right]$$

which reduces to

$$\phi_{aver.} = \frac{6}{10}\,\frac{n\,a\,I}{d}\left[\frac{7\,t^2+1}{\sqrt{3\,t^2+1}} + \sum_{p=1}^{p=\frac{t-1}{2}}\left\{\frac{7t^2+2pt^2+2p+1-8p^3-4p^2}{\sqrt{(2\,p+1)^2+3\,t^2}}\right.\right.$$

$$\left.\left. + \frac{7\,t^2+8\,p^3+1-2\,p\,t^2-4\,p^2-2\,p}{\sqrt{(2\,p-1)^2+3\,t^2}}\right\}\right]$$

III. Two-phase Motors, t Even.

Using similar methods, and remembering that

$$i_1 = I\sin\theta$$
$$i_2 = I\sin(\theta - 90)$$
$$l = 2\,a\,t$$

we have that between

$$\theta = \tan^{-1}\left(-\frac{1}{p}\,\frac{t}{2}\right) \text{ and } \theta = \tan^{-1}\left(-\frac{1}{p+1}\,\frac{t}{2}\right)$$

$$\phi = \frac{4\pi}{10}\frac{n\,a\,I}{d}\left[\left\{\frac{3\,t^2}{4} - p\,(p+1)\right\}\sin\theta - \frac{2\,p+1}{2}\,t\cos\theta\right],$$

where p takes all integral values from zero to $\left(\frac{t}{2} - 1\right)$, inclusive. The extreme limits of θ are, therefore, 90° and 135°; thus

$$\phi_{aver.} = \frac{4}{\pi}\sum_{p=0}^{p=\frac{t}{2}-1}\int_{\tan^{-1}\left(-\frac{1}{p}\frac{t}{2}\right)}^{\tan^{-1}\left(-\frac{1}{p+1}\frac{t}{2}\right)} \phi\,d\,\theta$$

Reducing this expression,

$$\phi_{aver.} = \frac{8}{10}\frac{n\,a\,I}{d}\sum_{p=0}^{p=\frac{t}{2}-1}\left[\frac{2\,t^2 + p\,t^2 - 4\,p\,(p+1)^2}{\sqrt{4\,(p+1)^2 + t^2}} + \frac{t^2 - p\,t^2 + 4\,p^2\,(p+1)}{\sqrt{4\,p^2 + t^2}}\right]$$

IV. Two-phase Motors, t Odd.

Between $\theta = \frac{\pi}{2}$ and $\theta = \tan^{-1}(-t)$

$$\phi = \phi_0 = \frac{4\,\pi}{10}\frac{n\,a\,I}{d}\left(\frac{3\,t^2+1}{4}\right)\sin\theta;$$

after $\theta = \tan^{-1}(-t)$, and between the limits

$$\theta = \tan^{-1}\left(-\frac{1}{2\,p-1}\,t\right) \text{ and } \theta = \tan^{-1}\left(-\frac{1}{2\,p+1}\,t\right)$$

$$\phi = \frac{4\pi}{10}\frac{n\,a\,I}{d}\left[\frac{3\,t^2+1-4\,p^2}{4}\sin\theta - p\,t\cos\theta\right],$$

where p takes all integral values from unity to $\left(\frac{t-1}{2}\right)$, inclusive.

$$\phi_{aver.} = \frac{4}{\pi}\left[\int_{\theta=\frac{\pi}{2}}^{\theta=\tan^{-1}(-t)} \phi_0\, d\,\theta + \sum_{p=1}^{p=\frac{t-1}{2}} \int_{\theta=\tan^{-1}\left(-\frac{t}{2p-1}\right)}^{\theta=\tan^{-1}\left(-\frac{t}{2\,p+1}\right)} \phi\, d\,\theta\right]$$

$$= \frac{4}{10}\frac{n\,a\,I}{d}\left[\frac{3\,t^2+1}{\sqrt{t^2+1}} + \sum_{p=1}^{p=\frac{t-1}{2}}\left\{\frac{3\,t^2+2\,p\,t^2+2\,p+1-8\,p^3-4\,p^2}{\sqrt{(2\,p+1)^2+t^2}} + \frac{3\,t^2+8\,p^3+1-2\,p\,t^2-4\,p^2-2\,p}{\sqrt{(2\,p-1)^2+t^2}}\right\}\right]$$

The results of the above four sets of equations are represented graphically in Figs. 4 and 5. It is interesting to note the marked reduction of extremes of values in going from $t = 2$ to $t = 3$, and the comparatively small change produced by a further increase in the number of slots. These curves have been drawn by reducing all the equations to the basis of equal pole-pitch and equal number (N) of conductors per pole per phase. Thus,

$$n = \frac{N}{t}$$

$$a = \frac{l}{3\,t} \text{ for three-phase motors}$$

$$a = \frac{l}{2\,t} \text{ for two-phase motors,}$$

whence

$$\frac{4\,\pi}{10}\frac{n\,a\,I}{d} = \frac{4\,\pi}{10}\frac{N\,l\,I}{d}\,\frac{1}{3\,t^2} \text{ for three-phase motors}$$

and

$$\frac{4\,\pi}{10}\,\frac{n\,a\,I}{d} = \frac{4\,\pi}{10}\,\frac{N\,l\,I}{d}\,\frac{1}{2\,t^2} \text{ for two-phase motors.}$$

Therefore,.

$$\phi = \frac{4\,\pi}{10}\,\frac{N\,l\,I}{d}\,\frac{1}{3\,t^2}\left[\qquad\right]$$

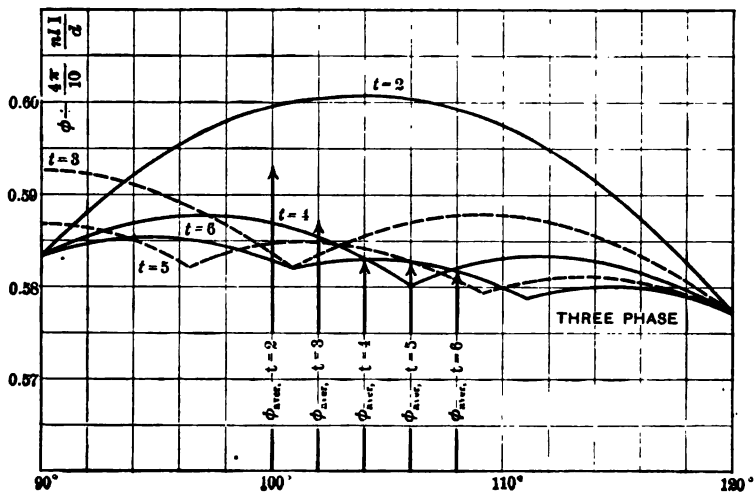


FIG. 4.

and

$$\phi = \frac{4\,\pi}{10}\,\frac{N\,l\,I}{d}\,\frac{1}{2\,t_2}\left[\qquad\right]$$

for the corresponding cases. The ordinates of the curves of Figs. 4 and 5 are, respectively, the expressions

$$\frac{1}{3\,t^2}\left[\qquad\right]$$

and

$$\frac{1}{2\,t^2}\left[\qquad\right]$$

It would appear from an examination of Figs. 4 and 5 that the actual flux is made up of two components; one, a flux of uniform value, ϕ aver., rotating synchronously; and the other, a flux consisting mainly of one of sextuple frequency in the case of three-phase motors, and of quadruple frequency in the case of two-phase motors.

It was at first thought that this tendency to produce a superposed flux of higher frequency would account for the load losses of induction motors; but since the quantity I in the expression for ϕ is the maximum value of the nearly constant magnetizing current, the changes in the high-frequency flux

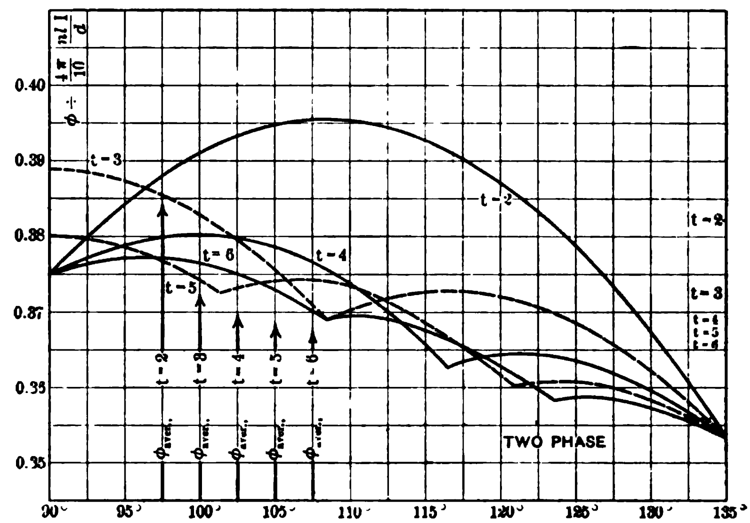


Fig. 5.

with increased load on the motor would be in the wrong direction to account for the increased losses. Moreover, these changes of flux do not really take place; with a sinusoidal impressed electromotive force, the flux will also be sinusoidal, and will be approximately constant if the electromotive force is constant. The object of this investigation, as stated in the introductory paragraphs, was to obtain expressions for the *average* flux per pole by a consideration of the changes that would take place throughout a cycle were it not for the damping action of the secondary current. This value, averaged for a cycle, is plainly more rational than one derived from one or two arbitrarily selected points in that cycle. It seems probable that the source of the load losses must be looked for in the vernier action of the teeth and slots of stator and rotor, which gives rise to periodic disturbances in the flux distribution; these disturbances increasing with the slip, and hence with the load.

Discussion on "Air-Gap Flux in Induction Motors," at New York, Sept. 22, 1905.

B. A. Behrend: Mr. Langsdorf assumes, in Fig. 1, that the magnetic flux produced by one of the coils lodged in the slots can be represented by a straight line parallel with the abscissa. This assumption is erroneous and, therefore, vitiates the conclusions that are drawn from his mathematical arguments.

Now, as to the practical application of the author's theory. To use his formula, would require, in my opinion, a great deal more time than is at the disposal of engineers, and the results of such calculations would be more than problematical on account of the incorrect and incomplete premises. Designing engineers cannot afford to make use of complex mathematical argument about the accuracy of which there is a shadow of doubt when important work, involving the expenditure of much time and possibly hundreds of thousands of dollars, is at stake.

Fitzhugh Townsend: This paper is of interest in that it is an additional step in the theory of the induction motor. The assumption that the magnetomotive forces are sinusoidal removes it, however, from the conditions of practice. In the induction motor it is more correct to assume that the impressed electromotive force is a sine wave, and if the resistance reaction is small the curve of magnetic flux which cuts the primary turns will be the same in form as the electromotive-force wave. This refers to the curve of total magnetic flux enclosed by the coil, taking time as the abscissa. Of course if the curve of flux density is plotted with respect to distance around the circumference, it will not be a smooth curve, because of the concentration of the winding in slots.

In the induction motor the magnetic reluctance varies just as it does in the static-transformer, owing to the change in permeability which accompanies the flux variation, and it also varies with the slip, on account of the venier action of the teeth. The magnetomotive-force curve, therefore, differs from the sine form by the amount necessary to maintain a sinusoidal magnetic flux, in spite of variations in magnetic reluctance.

A. H. Pikler: The equations given in the paper are quite simple and permit of easy interpretation. They are based on the assumption of sinusoidal exciting current, while in reality the current is always distorted, on account of the cyclic change in permeability of the magnetic material. The practical application of the author's conclusions to machines in use would, therefore, not be attended with satisfactory results.

A. S. Langsdorf (by letter): In reply to the remarks of Mr. Behrend I would call attention to the following passage from his book on "The Induction Motor" (chap. II., p. 11), as follows:

"The magnetic field in a three-phase current motor is produced by three windings, I., II., and III., Fig. 7. If the current in III. is a maximum, and if the currents vary according to a simple sine curve, then the currents in I. and II. are each equal to half the current in III. The magnetomotive forces of each phase are represented by the ordinates of the curves I., II., and III., respectively. * * *"

The curves referred to in the quotation are straight lines, and from these assumptions, which are identical with those adopted by the writer, Mr. Behrend obtained a value for the flux per pole. The difference between the two methods followed in arriving at a result is that Mr. Behrend determined only one point on the curve of flux variation, while I have obtained the average of all possible values.

I do not attach much importance to the peculiar form of the curves deduced from his equations. The point that deserves emphasis is that it is possible to write an equation which gives an *average* value of the flux; from this average value the flux density, assuming a sinusoidal distribution, can be calculated, and from this the effective value of the equivalent sinusoidal magnetizing current can be found.

A paper presented at the 200th Meeting of the American Institute of Electrical Engineers New York, October 27, 1905.

SOME EXPERIENCES WITH LIGHTNING PROTECTIVE APPARATUS.

BY JULIAN C. SMITH.

This paper will deal with some experiences with lightning protective apparatus which the operating department of the Shawinigan Water & Power Company has had during the years 1903, 1904, and 1905.

The generating station at Shawinigan Falls has three generators each of 3 750-kw. capacity, 2 200-volt, 30-cycle, two-phase, and one generator of 6 600-kw. capacity, 2 200-volt, 30-cycle, two-phase. Each of these generators is direct-connected to a water-wheel operating under a head of 130 ft.

Referring now only to the long-distance lines, it is sufficient to note that the energy is delivered through a double set of bus-bars to the low-tension side of the step-up transformers. These transformers are T-connected for transforming from two-phase to three-phase. The ratio of voltage transformation is 2 200:50 000. The neutral point of these transformer banks is grounded, giving about 29 000 volts between each wire and earth.

In 1903, only the No. 1 Montreal line was operating. This line connected the generating station at Shawinigan Falls, P. Q., with the Montreal terminal station, situated just outside the city of Montreal. The distance from the generating station to the terminal station is 85 miles. The transmission line consists of three 7-strand aluminum cables, each of 185 000 cir. mils cross-sectional area, spaced 60 in. apart and arranged in the form of an equilateral triangle with the apex upward. These cables are supported on 35-ft. poles, with cross-arms

6 ft. long fastened with through bolts. The top of every pole is bored to receive a pin. All pins are 18 in. long, and were boiled in stearine.

The voltage at Shawinigan is normally about 50 000; at the Montreal terminal station it is 44 000.

In the spring of 1904, a sub-station was built in Joliette, distant about 45 miles from the generating station, and from this sub-station a branch line was built to the city of Sorel. This line is about 20 miles long and is operated at 12 500 volts. The only special point of interest is a submarine cable about 5 000 ft. long by means of which the line crosses the St. Lawrence River.

In the Montreal terminal station, the voltage is reduced to 2 400 and supplied to a set of 30-cycle bus-bars. From these bus-bars the frequency-changers are operated. Each frequency-changer consists of a 30-cycle synchronous motor connected to a 60-cycle generator. There are at present installed in this station five of these motor-generators each of 1 000-kw. capacity and one of 5 000-kw. capacity. In addition to these machines there are two synchronous converters, each of 1 000-kw. capacity, operating street railway circuits. It is interesting to note that the whole load of the long-distance line consists of synchronous apparatus, and that by properly regulating the fields of this apparatus the power-factor can be kept at unity.

In the fall of 1904 the No. 2 Montreal line was completed. The No. 2 line is parallel to the No. 1 line for nearly the entire distance, and in most places is not more than 100 ft. distant. The second line is similar to the first except for the size of the conductor and for the fact that a ground-wire is strung along the line at the neutral point of the triangle. This ground-wire is connected to the earth at each pole by a wire running down the pole.

When the No. 1 line was put into service the lightning apparatus installed was as follows: at each end of the line was a bank of Westinghouse lightning-arresters of the low-equivalent type and a bank of static-interrupters. The number of gaps in these arresters was decided upon only after a series of tests had been made to determine the lowest practicable break-down voltage. These arresters were set to discharge at about 65 000 volts. In 1904, a bank of General Electric arresters was placed on the 50 000-volt line in the Joliette sub-station. This bank was also adjusted to discharge at about 65 000 volts.

In 1904 three banks of horn-arresters were put on the No. 1 Montreal line. These arresters consist of bent copper rods. The horns were spaced 6.25 in. apart at the gap, this distance corresponding to a break-down voltage of 90 000. See Fig. 1. In 1905, when the No. 2 line was equipped with lightning-arresters, three banks of low-equivalent arresters were put in, one at each end and one at Joliette. In addition to these arresters three banks of the 1905 type of horn-arresters were put in. Some changes were made in the setting of these arresters as will be noted farther on.

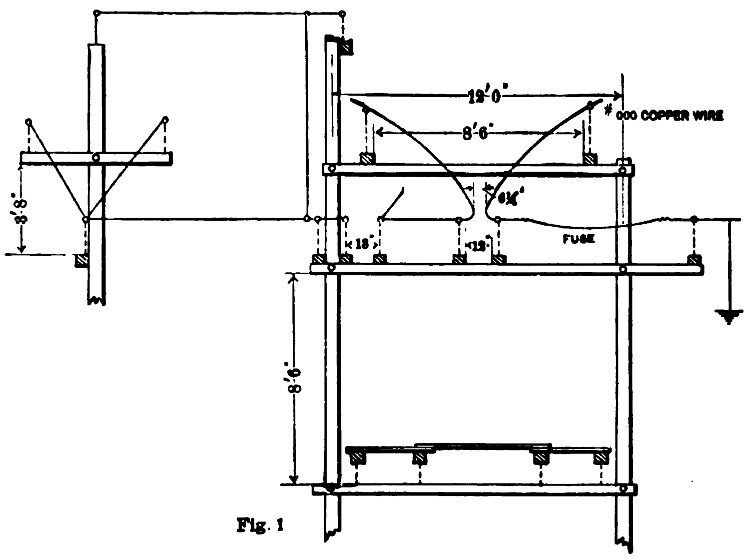


Fig. 1

Horn Lightning-Arrester, Joliette.

The Montreal lines run in a general northeasterly south-westerly direction, parallel to the St. Lawrence river and about 20 miles distant from it. The elevation of the power-house is about 200 ft. above sea-level, that of the sub-station being nearly the same. Some 10 miles farther north and parallel to the transmission lines, the Laurentian mountains bound the north side of the St. Lawrence Valley. In general, the country over which the lines pass is a flat farmland, but near the power-station the country is very rough.

The prevailing winds are westerly, and the general course of the electrical storms is parallel to the lines. The storm period extends from March to October. Nearly all the storms occur during the latter part of June, and in July, August, and early in September. The storms are most severe during July and August. In the territory covered by the lines of the Shawinigan company there occurs during each year about fifteen thunder storms. As these storms move along in an easterly direction and sometimes take days to cover the 100 miles, we have found that from June 25 to September 10, a storm is reported nearly every day from some part of the line. In general, however, there are not more than four or five severe storms during each year, and these storms are most severe in well-defined localities. The discussion of our experiences with lightning will be simplified if these experiences during 1903, 1904, and 1905 are considered separately, year by year.

As stated above, the only line in operation in 1903 was the No. 1 Montreal line. That line was protected by low-equivalent arresters at each end. During the summer of 1903, several disturbances occurred which may be summarized as follows:

1. Poles splintered by heavy discharges.
2. Insulators broken, in a few instances.
3. Flashes across the static-interrupter terminals.
4. Arcs on the transformer terminals.
5. Arcs inside the transformer cases at the top between adjacent leads.
6. Damage to apparatus caused by 3, 4, and 5.
7. Interruption to service, due usually to excessive voltage-drop, causing synchronous apparatus to fall out of step.

1. On several occasions poles were splintered. In most cases two or three poles were torn to pieces; the adjacent poles on both sides were less damaged, the damage decreasing as the distance increased from the point of disturbance. One of the worst cases recorded by us shows that 5 poles were torn to pieces while 10 poles on each side were somewhat splintered. This disturbance extended over a distance represented by 25 poles, or about 2 500 feet. This case, however, is exceptional, usually not more than one pole is badly damaged, and a few of the nearby poles slightly splintered.

2. In only one or two instances were insulators broken; in each instance it was the top insulator. In these cases the breakage seemed due to the flashing over and consequent heating, as the insulator was not in any case punctured. In no

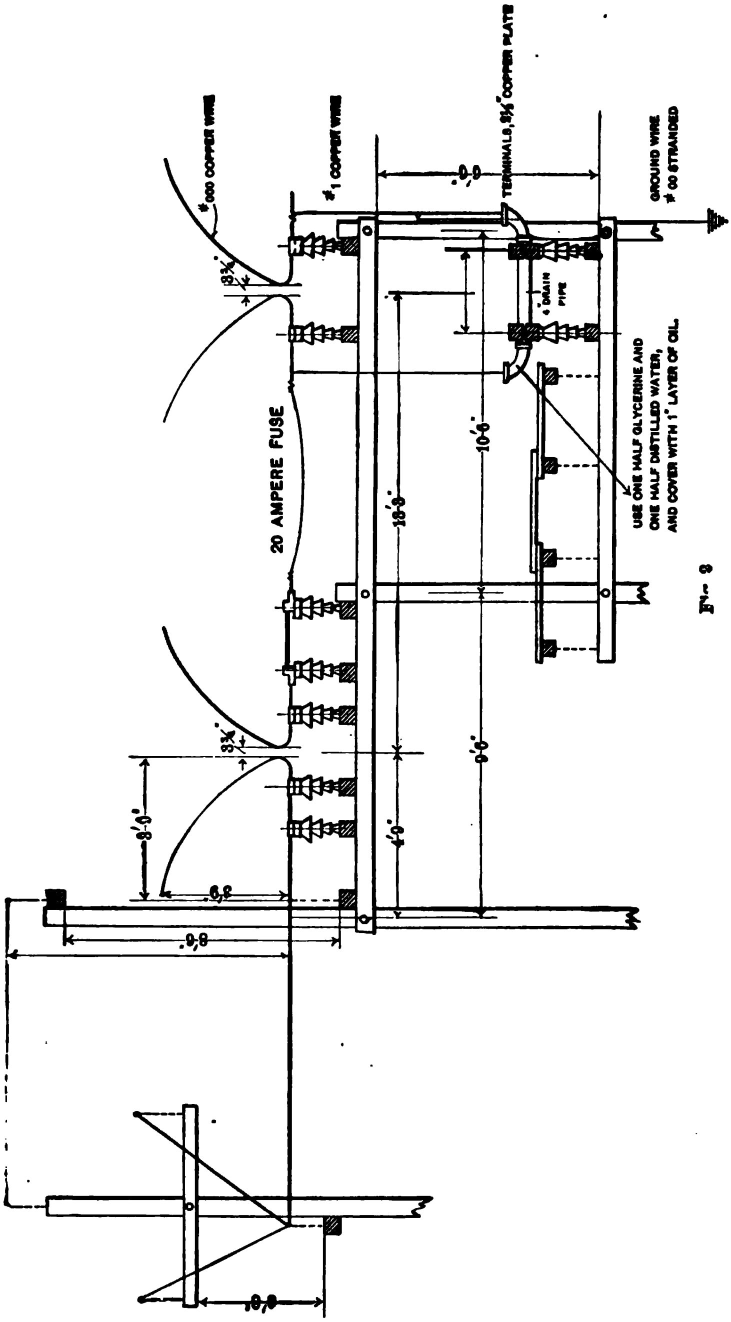


FIG. 2

Horn Lightning-Arrester and Resistance. 1905 Type.

case was an insulator so badly damaged as to need immediate replacing.

3. At the same time that the pole were splintered on the line there would be evidences of excessive potential in the stations. The most frequent occurrence was an arcing over on the terminals of the static-interrupters. In some cases this flash would reach across to an adjacent static-interrupter

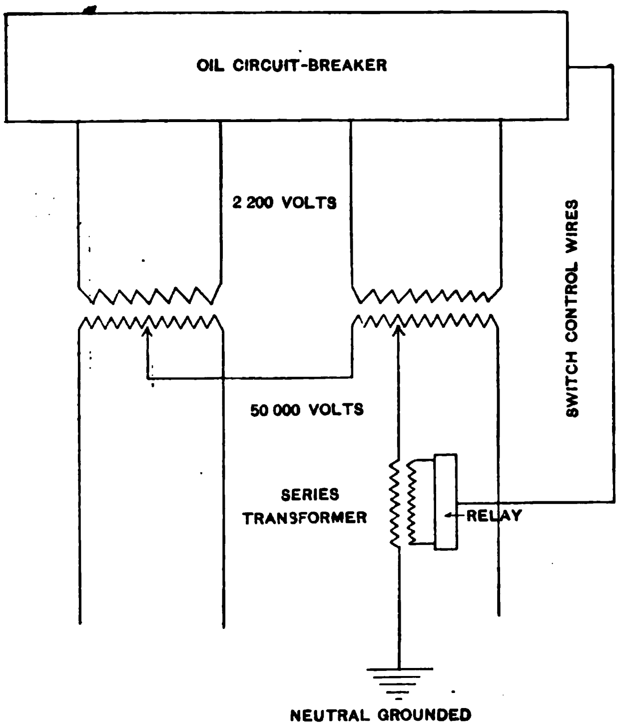


Fig. 3

Transformer Connections.

Note: Neutral point grounded through a series transformer and relay Current in ground-wire trips oil circuit-breakers.

and establish a short circuit between the lines. In most cases, however, it was simply a flashing from the ends of the terminal to the case, or between the incoming and outgoing wires of a single static-interrupter, thereby short circuiting the reactance coil.

4. The arcs on the transformer terminals were more rare,

only occurring when the static-interrupters were put out of service by the flashing over mentioned above.

In view of the above disturbances and damage it was decided to put in a type of horn lightning-arrester affording a low resistance path to ground, to depend on a fuse for the interruption of the short circuit which would occur if the horns did not break the arc, and to set these horns so that only the heavier discharges would break them down. The horns were consequently adjusted to discharge at about 90 000 volts.

At the end of 1903, it was determined that the arresters installed were sufficient to meet the conditions caused by ordinary storms. They protected the line from abnormal rises of potential due to switching or short circuits; but in those cases when the lightning-stroke damaged poles on the line the rise of potential was so high and took place so rapidly that the arresters could not carry enough current to keep the potential of the line within safe limits. The horns installed were especially designed to meet only the conditions which were not met by the standard arresters.

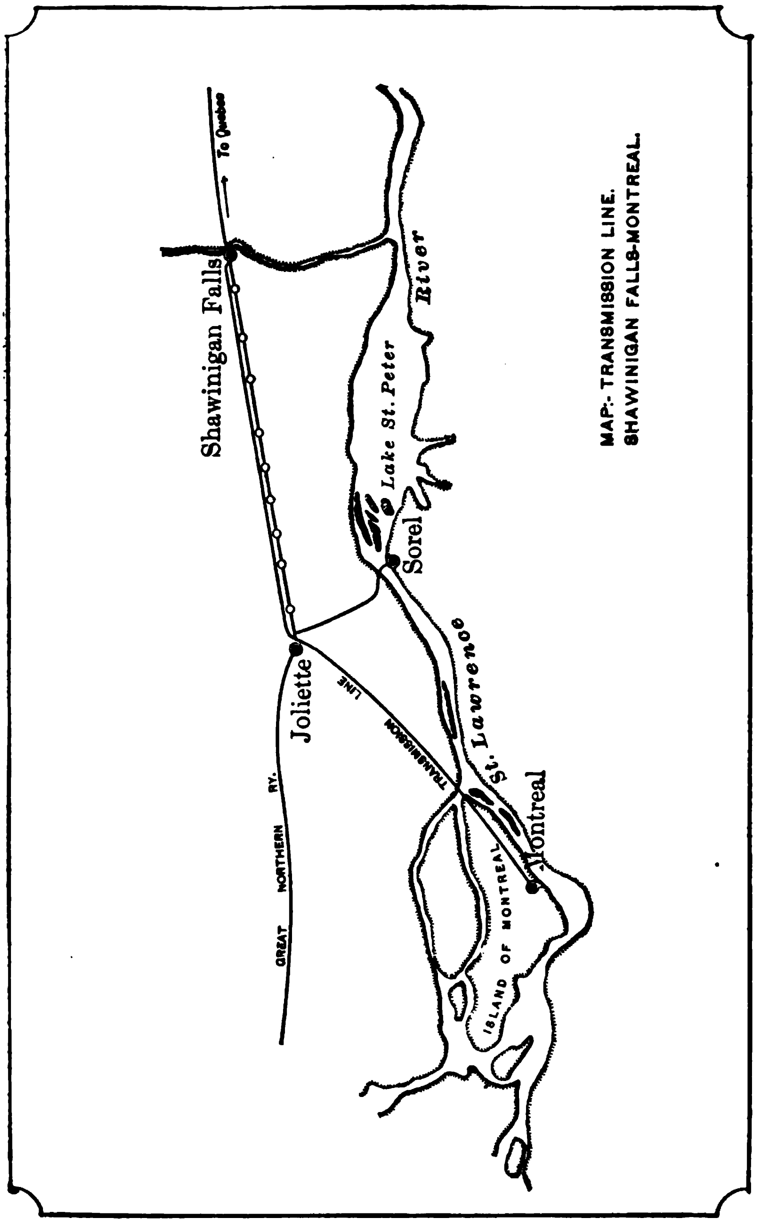
In 1904 there were more than the usual number of storms. On the following dates the horns discharged:

Date.	Shawinigan.	Joliette.	Montreal.
July 11.......	3 horns	1 horn	None
Aug. 5.......	2 "	3 horns	"
Sept. 20.......	2 "	2 "	"

One or two storms did not cause any disturbance.

The storm of July 11 was central near the power-station, and one pole about five miles distant was splintered. The Joliette horns discharged about an hour before the discharges took place at Shawinigan.

On August 5, the storm was central at Joliette. Both the horn arresters and the standard arresters discharged violently. the horns at Shawinigan discharging at the same time. There was evidently a rise of potential in the Joliette station, as one of the glass windows through which the wire enters the building was cracked, due to the flashing over which must have occurred, At the same time that this disturbance occurred in the station, some 25 poles about five miles away were splintered, a few of them very badly. No disturbance other than the discharge of the arresters occurred in the other stations. The service was not interrupted, a rather severe blow being felt, lasting only about a second.



MAP:- TRANSMISSION LINE.
SHAWINIGAN FALLS-MONTREAL.

On September 20, the storm was central about midway between Shawinigan and Joliette. Fifteen poles were struck. No excessive potentials were noticed in the stations, nor was the service interrupted.

During 1905, the number of storms was less than usual, but there were two very violent storms, both near Shawinigan. Poles on the No. 1 line were damaged. At various times during the summer the horns of both lines discharged, but it is noteworthy that the horns of the two lines did not discharge at the same time; that is, the two lines only about 100 ft. apart would not be equally affected by lightning discharges.

The horn arresters on the No. 2 line were designed to take less current than those on the No. 1, as a resistance consisting of a mixture of glycerine and water was put in the ground connection; in parallel with this resistance was a horn-gap. During the first storms it was noticed that the resistance had "an equivalent spark-gap" greater than the horn, although the resistance was about 10 000 ohms and the gap about three inches. The resistance was greatly decreased early in the summer by pushing the terminals closer together, and the gap was slightly increased. After this was done the lightning discharge went through the resistance.

Another factor came into play in 1905. The two long-distance lines are operated in parallel on the low-tension sides at both ends. As stated previously the neutral point of the transformer banks is grounded at Shawinigan. A series transformer was placed in the ground-wire leading from each bank of transformers, and an overload relay connected to this series transformer so that if any considerable amount of current flowed into the neutral the relay would open the low-tension side of all of the transformers connected to that line. The operators in the Montreal terminal station were depended upon to separate the two lines in cases of trouble. By this means a ground or heavy disturbance on one line would cut that line out of service. Our experience during the past year shows that this scheme works satisfactorily. To some extent, however, it masks the action of the lightning-arresters, as in case of heavy discharges over the horns the relay would cut off the line.

Summing up our experience with reference to the horns, I would say that we consider them a valuable addition to the standard equipment. Since the installation of the horn arresters we have had no arcs in our station. No damage has been caused to our apparatus. No interruptions to the service have been caused directly by lightning. On the other hand, each time the horns discharged a more or less severe short circuit occurred, in no case, however, being severe enough to cause trouble or to cause our synchronous apparatus to fall out of step.

A paper presented at the 200th Meeting of the American Institute of Electrical Engineers, New York, October 27, 1905.

NOTE ON LIGHTNING-ARRESTERS ON ITALIAN HIGH-TENSION TRANSMISSION LINES.

BY PHILIP TORCHIO.

During a recent trip abroad the writer inspected several high-tension transmission lines in Italy, and found that American lightning-arresters with choke-coils are quite generally used at the ends of the lines. In addition, Siemens horn-arresters are sometimes installed at the ends of the line and at intervals on poles along the line.

The protection furnished by these devices, however, is not considered sufficient, on account of their inability to protect the line and the machines under all conditions of lightning discharges and surges, or even static disturbances caused by load fluctuations in the ordinary operation of the system. Transmission engineers have found it necessary to supplement the ordinary lightning-arresters with some other protection, and to that end a variety of devices has been developed on different installations. Among these the so-called "Series Lightning-Arrester" of Gola, and the "Water-Resistance Static-Discharger" call for special attention. The series lightning-arrester has been described in the technical papers (see *Transactions* of the Associazione Elettrotecnica Italiana, January and February, 1905, in which are also cited earlier publications relating to this form of arrester).

It is claimed by Gola that the shortcomings of the ordinary commercial lightning-arresters are due to some deficiency in the choke-coils employed and not to any deficiency in the lightning-arresters themselves, their function being only to discharge the line. To overcome the shortcomings of such choke-coils, Gola devised an apparatus in the shape of a large shell, consisting of a choke-coil and a number of large cast-iron diaphragms and shells connected in series by means of small copper conductors, the whole being placed in series on the line to perform the functions of a choke-coil, and also to introduce an abrupt and great change in the section, material, and shape of the line conductors leading to the station apparatus. The device is illustrated in Fig. 1. In proximity to the sharp-edged ends of the shell are located corresponding air-gap, horn-shaped lightning-dischargers which are connected, through a resistance to ground, either directly here, or in series with ordinary lightning-arresters, according to the requirements demanded by the line voltage. The function of the supplementary lightning-arresters is to assist the main air-gap in

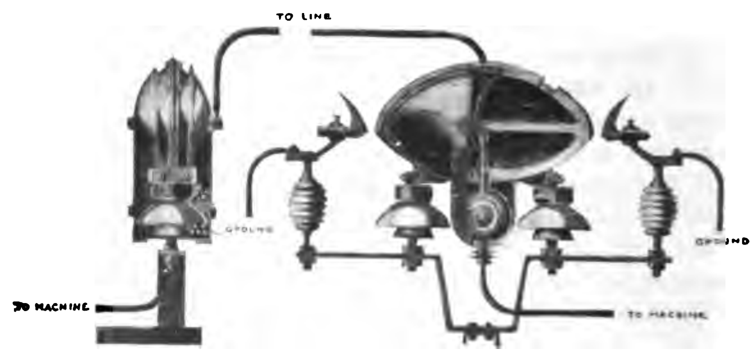


FIG. 1.

rupturing the arc after the lightning discharge has taken place. It is claimed that while this device will allow the main line current to pass undisturbed, it will so obstruct the passage of lightning or static-discharge currents as to cause them to be reflected at this point and pass to ground via the dischargers above mentioned. This obstruction is claimed to be due to several effects of discontinuity of the circuit, in so far as the

" homogeneous circuit of the line conductors of approximately constant section and of the same material (generally copper), always in a diamagnetic medium (air or insulating material), is suddenly interrupted by the introduction of several lengths of conductors of magnetic material of section and surface enormously greater, joined one to another by lengths of copper conductors again of small section, but placed in a magnetic medium, the whole with sudden changes of direction and section."

Gola, in the publication above referred to, makes several interesting comparisons between hydraulic and electrical laws, and by analogy attempts to explain the operation of the series arrester. The device has been used in many places in Italy for the last two or three years. In many cases it has proved to be most effective, while in other cases the results have been indifferent.

The "Water-Resistance Static-Discharger" of Friese and others is connected at each end of the line, one discharger between each conductor and ground, thereby forming a per-

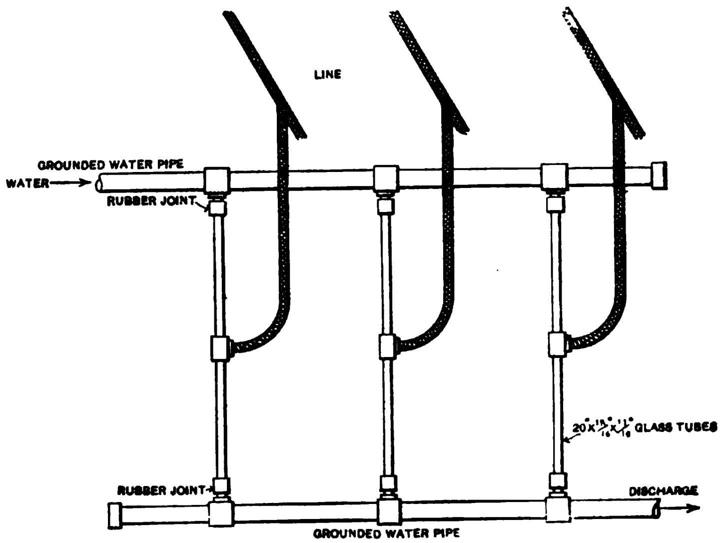


FIG. 2.—Water-Resistance Static-Discharger.

manent continuous path to ground for a small fraction of the main-line current. A general feeling prevails that this grounding will eliminate a great many troubles from lightning and surges on the line. Several ways of grounding the line are in use in Italy, but the one at the Morbegno station of the Valtellina three-phase railway may be considered as representative of the water-resistance type of grounding device. The device, which is shown in Fig. 2, is mounted on an iron frame outside the station. It consists of grounded feed and discharge water-pipes supplying the necessary water to three pairs of glass tubes, each pair being joined at the middle by a metallic union to which are brought the grounding connections from the line conductor; the grounding is made through the two water tubes in parallel. The current to ground in this system, operating at 20 000 volts (11 000 volts to ground) is 0.2 ampere from each line wire to ground. The superintendent of the station was hopeful of the success of the device.

At the Paderno station of the Milan Edison Company a different arrangement of water-resistance static-discharger was being installed at the time of the writer's visit. It consisted of

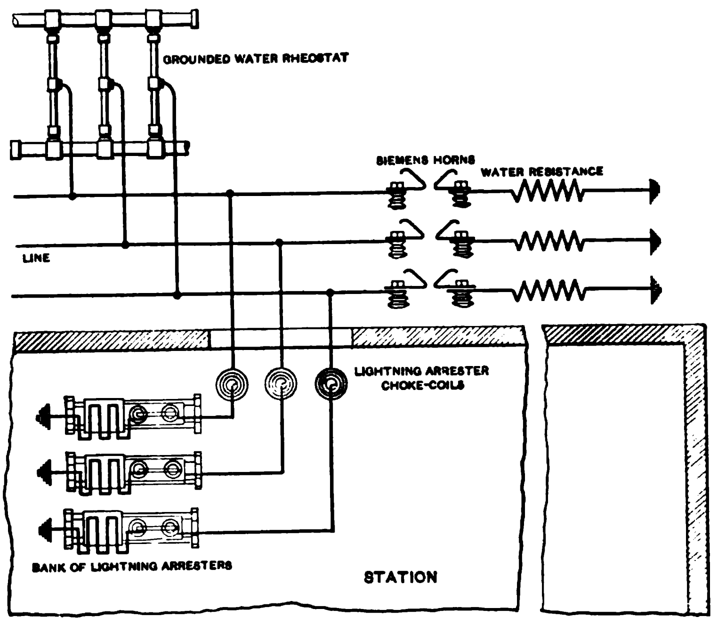


FIG. 3.—Scheme of Station Protection.

only three large glass water-tubes, but of greater diameter and length than those used in the Morbegno station. In this case it was also expected that the device would give satisfactory results.

Summarizing the observations made by the writer, the best practice of to-day for the protection of Italian transmission lines indicates that the plan illustrated in Fig. 3 should be adopted. The plan shows that:

1. The terminals of the transmission lines should be extended in a direct line some distance away from their entrance

into the station, and the ends should be equipped with Siemens' horn-arresters grounded through water resistances.

2. On the line side of the branch entering the station a water-resistance static-discharger should be installed.

3. Choke-coils and ordinary lightning-arresters should be installed inside the station. Possibly, choke-coils of the series lightning-arrester type should also be added.

4. Siemens horn-arresters should be used on the poles along the line only after careful study of the installation. Series lightning-arresters, with Siemens horn-arresters, or ordinary lightning-arresters may, however, be installed at particular points; as, for instance, where a line divides into branches, or at special points of a line installed in a mountainous country.

A paper presented at the 200th Meeting of the American Institute of Electrical Engineers, New York, October 27, 1905.

PERFORMANCE OF LIGHTNING-ARRESTERS ON TRANSMISSION LINES.

BY N. J. NEALL.

This paper describes a method of obtaining, by means of test-papers, records of the operation of lightning-arresters in service; it gives some results obtained by the use of this method on several transmission lines.

A method for registering lightning-arrester operation should have the following characteristics: (1), it should be applicable to all types of arresters; (2), simple to install; (3), not interfere with the operation of the arresters; and (4), it should be positive in its information.

These requirements were met in the test-papers[1] furnished by the Westinghouse Electric and Manufacturing Company to a number of operating companies about one and one-half years ago, who agreed to investigate this matter under its auspices. Instructions were issued relatively to these tests, from which the following extracts are taken:

"A method of keeping a record of the operation of lightning-arresters by inserting special papers between the gaps. These papers to be carefully marked; to contain all necessary information as to events during their service in gaps; * * *.

(1) *Form of Record Papers.* (See Fig. 1, sketches 1 to 3.) Aside from the shape necessary to completely cover the gap, nothing special is required except that the paper be of uniform texture in order that any punctures may be clearly marked. For this purpose a light bond paper has been found satisfactory. The peculiar shape of the papers for the low equivalent lightning arrester is due to the overhang of the porcelain support for the non-arcing metal cylinders used in this type. There is a simple arrangement for drawing the paper into place by a sort of spring action

1. Originals of these papers. as well as of Figs. 13, 14, 16, 18, 19, 21, are on file with the Secretary of A. I. E. E. for reference and comparison. If requested, the writer will gladly lend any special papers for reference.

due to the folding. *No discharge must pass over the gaps without passing through the paper.* For method of installation see Figs. 1, 2, 3.

(2) *Marking of Record Papers.* In order to avoid confusion all lightning arresters on the same phase or leg of the system should be given the same distinctive letter or identifying mark. By marking the record papers accordingly the relation of all parts of the system to be shown by the papers would be greatly simplified.

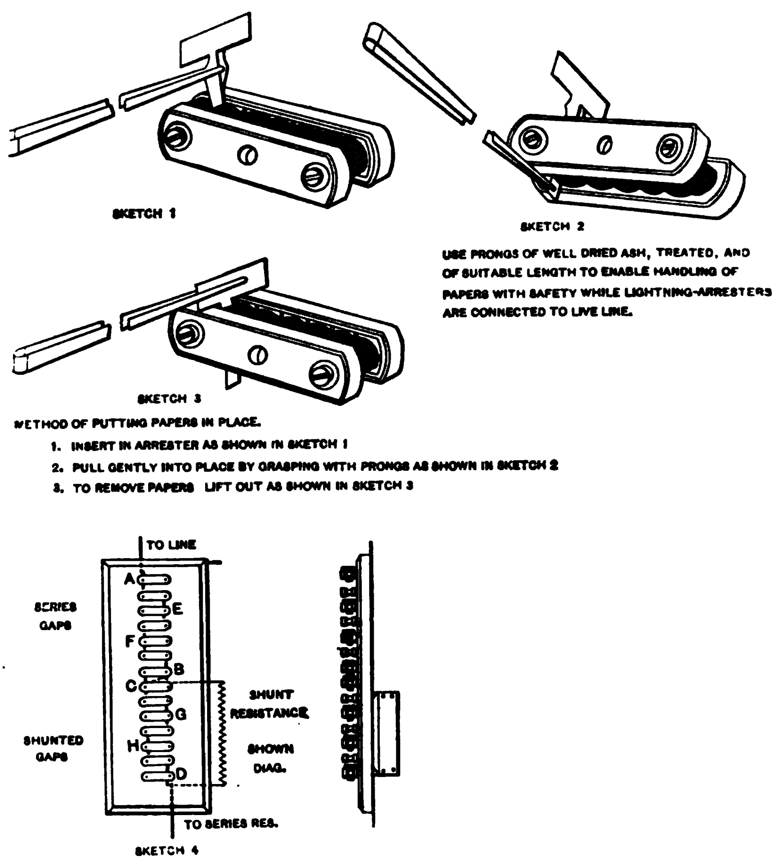


Fig. 1.

Shows form of test papers and method of placing them in low-equivalent lightning-arresters (Westinghouse Electric & Manufacturing Company).

(3) *Handling of Record Papers.* In order that a complete knowledge may be obtained as to the behavior of the system as a whole, it is necessary that these record papers be placed in all lightning arresters connected thereto. It therefore becomes necessary to watch all points with equal care in the matter of records, and this fact should be kept

strongly in mind during the investigation. Be careful that the proper papers are placed in the various gaps; that is, a low equivalent lightning arrester should have two kinds of papers—one color for series gaps and the other for shunted gaps; * * *.

(4) *Distribution of Record Papers.* (See Figs. 1 and 4, sketch 4.) *Low-Equivalent Lightning-Arresters.* One paper should be placed in the first and one in the last series gap units; one paper in the first and one in the last shunted gap units.

A gap unit consists of seven non-arcing metal cylinders in porcelain holder (See Fig. 1.) A gap, however, is the air-space between two adjacent cylinders.

Fig. 2.

Test papers being inserted in a low-equivalent lightning-arrester.

The same general recommendations given above apply to the inspection of other types of lightning-arresters.

"Any special arresters on your system should be equally well studied, and submitting a sketch of connections, we shall be glad to suggest such an arrangement of papers as will give fullest data of their operation.

(5) *Inspection.* During fair weather or uneventful periods, inspect these papers once a week, replacing with fresh papers and completing to this effect the record papers thus removed.

After any disturbances, such as lightning storms or discharges due to switching, etc., remove the papers as soon as possible, replacing with fresh papers and note on the test papers for record the attending circumstances.

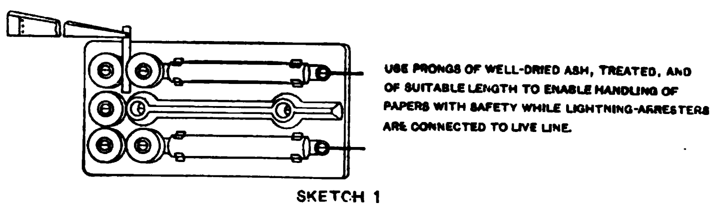


Fig. 3.

Method of inserting test papers in simple multi gap type lightning-arrester with resistance pencils in series (General Electric Company).

(6) *Dates*. Papers should be, above all else, carefully marked before insertion with dates and location data; and upon removing from gaps, necessary information should be immediately completed.

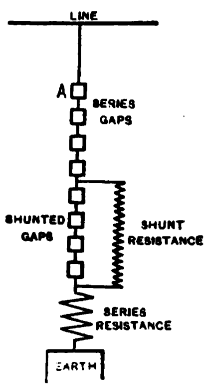


Fig. 4.

Arrangement of gaps and resistances in the low-equivalent lightning-arrester (Westinghouse Electric & Manufacturing Company).

(7) *Returns*. In filing papers do not use pins as they may cause confusion with static puncture holes. In case a record paper is destroyed by a hold-over in the gaps, a statement should be enclosed fully describing the circumstances.

(8) *Precautions*. Should the ground connections be impaired or the resistances become open-circuited, these records would have no value and might only be misleading. For this reason, not to speak of best service of the protective apparatus, resistances and ground connections should be inspected from time to time for open circuit. This can be done by a magneto or by "lighting out."

(9) *Duplicate Records*. If it is desired to keep a duplicate record, then in addition to the above instructions, please note, etc. * * *."

The general idea in the distribution of test-papers in accord with the foregoing instructions was so to cover the country that the same apparatus at different localities would come under comparison; there was no endeavor to make a thorough comparison of all types of arresters used, chiefly because the selection rested with plants in operation, and the main investigation was to be of the effectiveness of the arrangement of gaps and resistances in the low-equivalent lightning-arrester. Incidentally, however, some interesting results were obtained on other types at what happened to be comparable voltages of transmission, and they will be referred to in detail later. Incomplete reports were obtained from other plants, with occasional records of special interest.

The range in voltage of the high-tension plants under discussion extends from 6 600 to 55 000, particular interest attaching to returns at 25 000 and 30 000 volts. The tests covered territory extending from Maine to California, the following companies taking active part in the investigation:

Boise-Payette River Electric Power Co., Boise, Idaho;

Cascade Water, Power & Light Co., Ltd., Nelson, British Columbia;

Indiana Union Traction Co., Anderson, Ind.;

Missouri River Power Co., Helena, Montana;

New Richmond (Wis.) Roller Mills Co.;

Northern California Power Co;

Shawinigan Water & Power Co., Montreal, Canada.

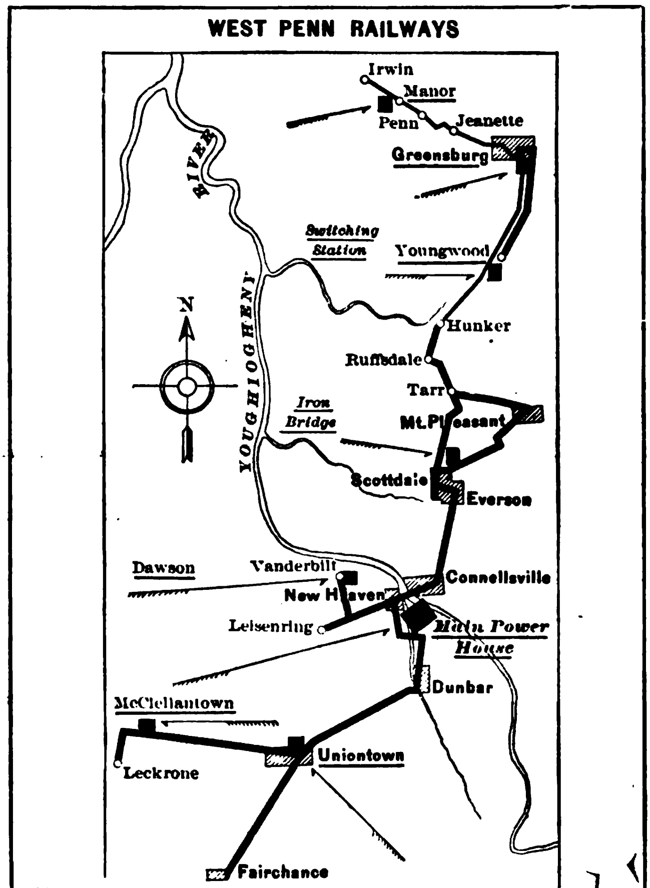
St. Paul Gas Light Co., St. Paul, Minn.;

Trade Dollar Consolidated Mining Co., Dewey, Idaho;

Westbrook Electric Light and Power Co., Westbrook, Me. (through S. D. Warren & Co., Boston, Mass.);

West Penn Railways Co., Connellsville, Pa.;

The records from the following plants are particularly complete and will be taken up for special consideration: West Penn Railways Co.; St. Paul Gas Light Company; Indiana Union Traction Company



MILES FROM POWER HOUSE			
Connellsville	1.5	Youngwood	20
Uniontown	12.	Greensburg	25
McClellantown	21.	Manor	29
Iron Bridge	10.	Dawson	8

FIG. 5.

Map of lines of the West Penn Railways Company. This company operates a lighting and railway (synchronous converter) service transmitting from Connellsville—the power-house—at 22 000 volts, to the various sub-stations. The transformers for this purpose are protected throughout by low-equivalent lightning-ar esters and static-interrupters. There is no special line prctection.

West Penn. Rwys. Co.[1]—This system is located in Western Pennsylvania in the foothills of the Alleghenies, along the head waters of the Monongahela, and is particularly subject to lightning disturbances. As will be seen from the map, the

FIG. 6.

A group of low-equivalent lightning-arresters tested on the lines of the West Penn Railways Company, Manor substation. Test-papers can be seen in place.

line is extensive, operating both a railway (synchronous converter) and lighting system, with a large number of substations. The line is approximately 50 miles in length, and some 54 low-equivalent arresters were under test. Figs. 5 and 6.

1. *Street Railway Review*, Apr. 15, 1905.

St. Paul Gas Light Company.[2]—The chief interest of this plant lies in the use of the high-tension cable for conveying power at 25 000 volts underground several miles from the city limits of St. Paul to a sub-station in the city. The overhead line is approximately 25 miles in length and runs through a part of the country (upper Mississippi valley) where lightning disturbances are known to be frequent and severe. This plant

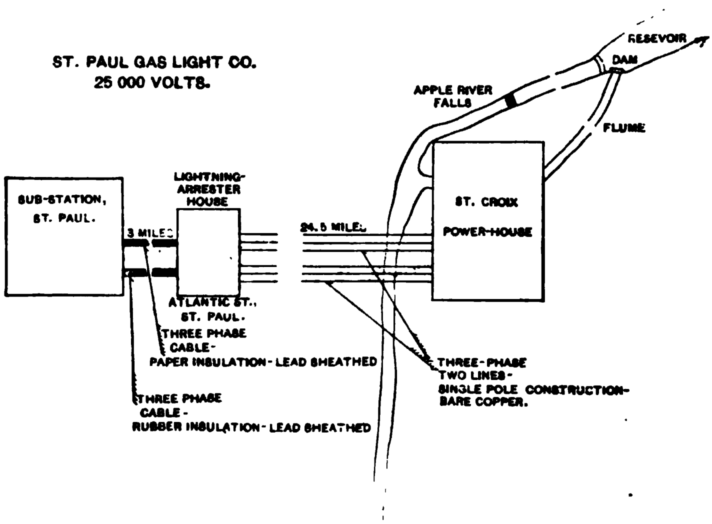


FIG. 7.

Map of lines of the St. Croix Power Company (St. Paul Gas Light Company). This company supplies power at high tension—25 000 volts—for the purpose of furnishing light to the city of St. Paul. Air-blast transformers are used at the power-house and oil transformers at sub-stations, and the standard protection of the General Electric Company lightning-arresters and air-insulated choke-coils, as well as special arrangement of the same are used throughout. A copper overhead grounded wire runs from the power-house for 2 000 ft.

s doubly interesting in the present instance because of the special arrangement of lightning-arresters of the multi-gap carbon-pencil type (G. E. Co.) under test. There were: a regular G. E. arrester between line and ground, an arrangement of G. E. units on the W. E. & M. Co. low-equivalent lightning-arrester principle, see Figs. 7, 7a, 7b, 8, 9, the Pearson-Cutcheon ar-

2. TRANSACTIONS A. I. E. E., 1900, vol. 17, page 635.

rangement[3] for protecting transformer windings at the power-house, and the St. Paul end is protected by G. E. units between line and ground at the point of connection of the overhead lines to the underground and between legs at the sub-station end of cables. There were choke-coils and special multiplex connections (between phases) of arresters at both ends of the overhead lines.

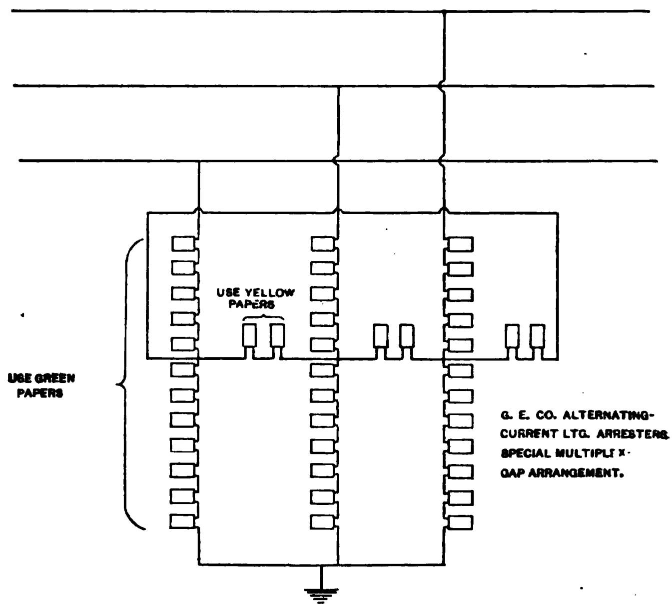


FIG. 7a.

Method of connection suggested to St. Paul Gas Light Co. for a study of the effectiveness of the multiplex connection of lightning-arresters. In Febuary, 1905, connections were changed to those shown in Fig. 7b.

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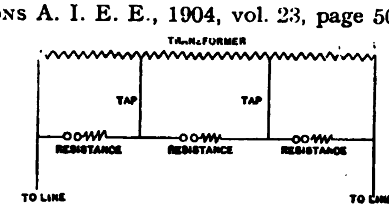
3. TRANSACTIONS A. I. E. E., 1904, vol. 23, page 568.



The Pearson-Cutcheon arrangement of gaps and resistances for the protection of generating apparatus is shown diagrammatically by abovesketch.

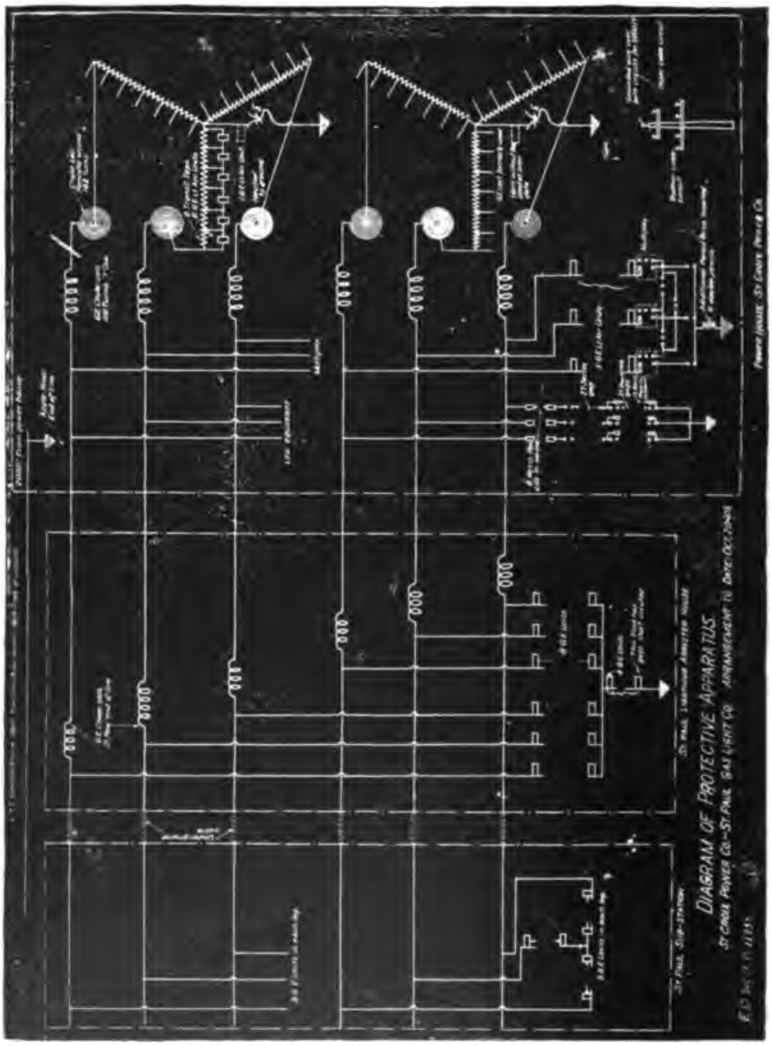


FIG. 7b.

Indiana Union Traction Company.[4]—This is an extensive interurban line as will be seen by reference to map. There are some 24 equipments of protective apparatus at 30 000 volts, and 36 at 15 000 volts—the original layout. Figs. 10, 11, 12.

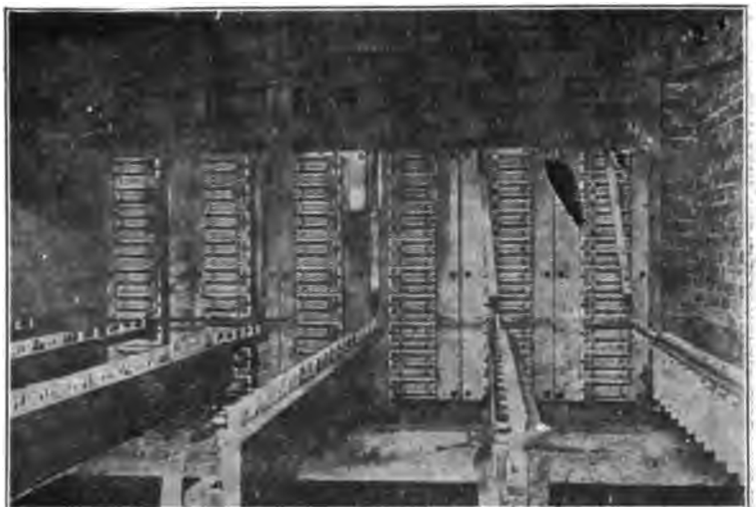


FIG. 8.

View of the lightning-arrester house of the St. Croix Power Company (St. Paul Gas Light Company) showing in the background the standard arresters of the General Electric Company with a special multiplex arrangement (locally made); and in the foreground special arrangement of units on the same manner as for a low-equivalent lightning-arrester. (The arrangement of General Electric arresters shown in background above was modified Feb. 12, 1905, (see Fig. 7b) the gaps to ground being reduced to 25, with 11 resistance pencils; the multiplex arrangement being retained, with 48 gaps between line and line with 22 resistance pencils.)

DISCUSSION OF DATA.

By referring to the file of records and the corresponding summaries note can be made of the following:

All arresters operate more frequently than has been hitherto supposed to be the case.

4. *Street Railway Journal*, Dec. 17, '04, p. 1064.

Fig. 9.

View of the Pearson-Cutcheon arrangement of General Electric Company arrester units applied to the transformers at power-house of the St. Croix Power Company (St. Paul Gas Light Company).

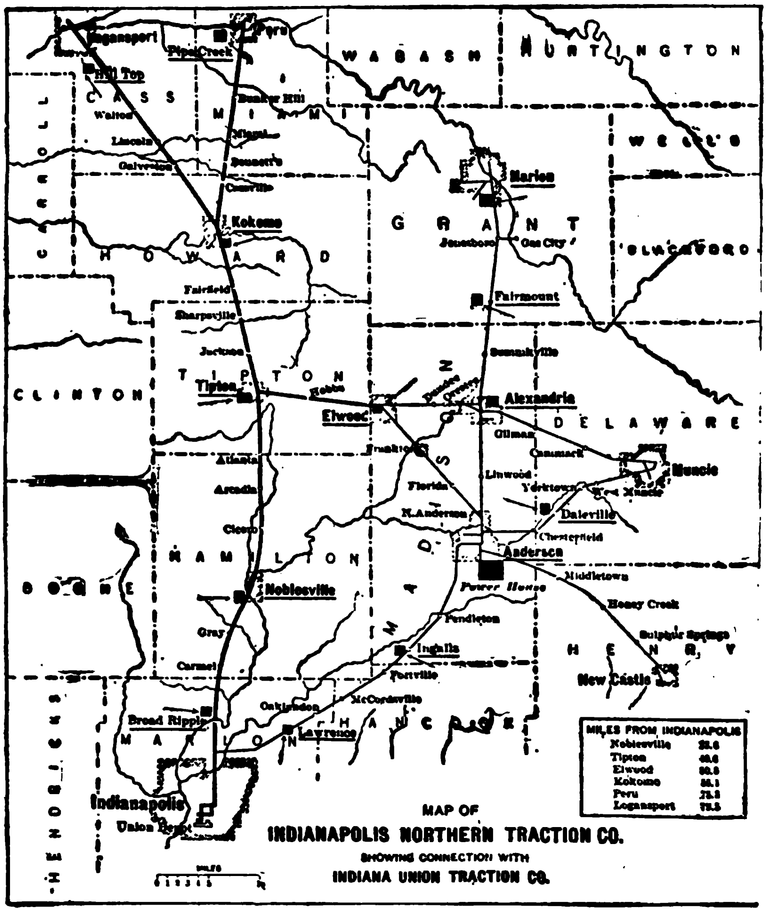


Fig. 10.

Map of Lines of Indiana Union Traction Company.
Points from which records were received.

30 000-volt Lines		15 000-volt Lines.		
		Power-House—Anderson—Power-House.		
Broad Ripple.	Tipton.	Lawrence.	Daleville.	Elwood
Peru.	Noblesville.	Fairmount.	Ingalls.	Muncie
Kokomo.	Logansport.	Alexandria.	Marion.	

By comparing the holes made by the discharges through the older forms of arrester which have no series resistance, with those made by discharges through the low-equivalent arrester for the same voltage (Indiana Union Traction Co., Fig. 14), it will be seen that no greater difficulty in discharge is encountered, as evidenced by the ragged edges or torn appearance of the holes in the low-equivalent arrester papers. These blister-like holes seem characteristic of free severe static discharges. If a paper is placed in the path of discharge of a high-tension condenser used in the equivalent spark-gap method[1] a blistered hole invariably results, see Fig. 16. If an element having a high static resistance[2] is inserted in the circuit, this hole is reduced to a fine one with smooth edges, see Fig. 17. If current continues to pass, the hole will be enlarged and badly smoked, but will still have smooth edges. By comparison it is found that the typical static discharge through a carbon-pencil type of resistance is of this smooth-bore character, while free gaps give the blister.

A curious effect observed in the plain-gap papers shows that the original puncture may be very fine, and yet the current once having held over will completely burn it away. On the other hand, the low-equivalent lightning-arrester gives evidence of a quicker suppression of the short-circuit arc after the discharge has passed. The action of the shunted gap is shown clearly and aids, by means of the summaries, in locating the center of disturbance.

In the case of the Indiana Union Traction Company the summaries will show not only the point of original discharge but the reflection on the line due to these causes. It is possible that a few of the discharges over series gaps at distant points may be due to lightning, but I think it safer to consider them due to reflection. Figs. 13 and 14, Tables 1 and 2.

St. Paul Gas Light Company.—By comparing the West Penn Railways Co. records with the records from the St. Paul Gas Light Co. it will be found that the evidences of freer operation are most pronounced. Figs. 18 and 19, Tables 3, 4, 5.

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1. *Electric Club Journal*, April, 1905.

2. By "high static resistance" is meant high resistance or "skin effect" due to very high frequency (by bridge or at commercial frequencies the "ohmic" resistance may be negligible).

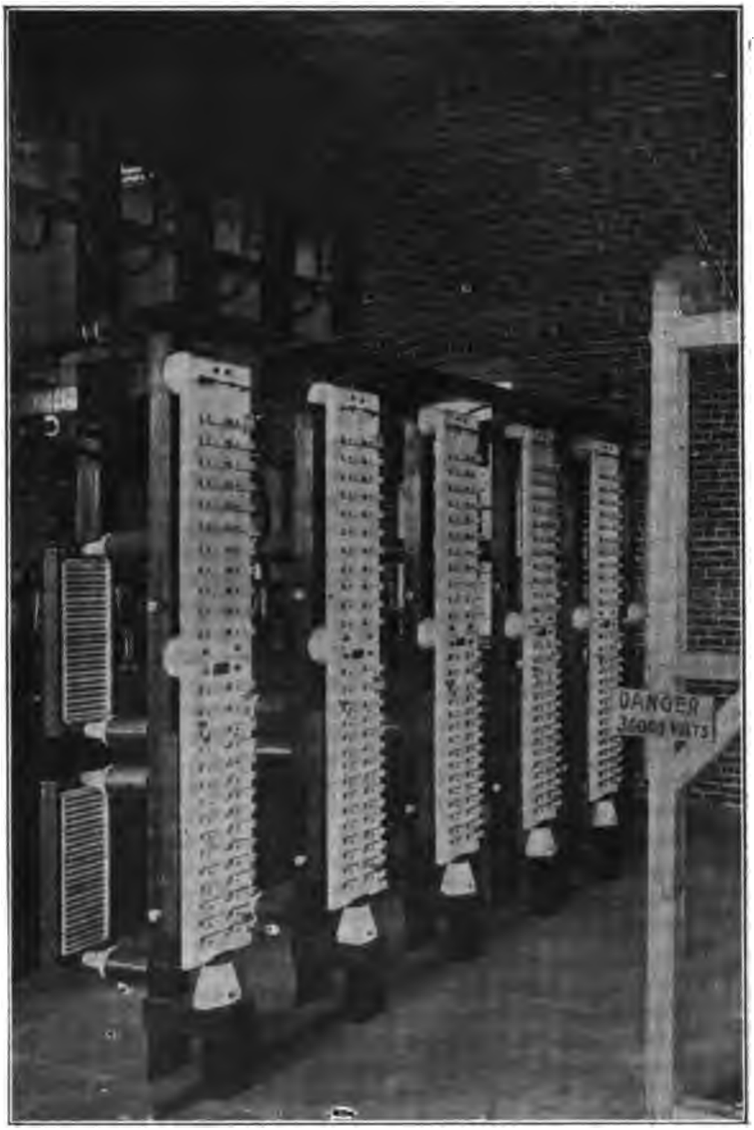


FIG. 11.

A group of low-equivalent lightning-arresters tested on the 30 000-volt lines. at power-house, Indiana Union Traction Co. Test papers can be seen in place.

There seems to be enough for two arrester groups to care for in this plant, and nothing to show any superiority of the low-equivalent arrester arrangement of G. E. units in the present case. This can perhaps be explained by the fact that the resistances for this purpose were not properly proportioned, and that in general it was easier for the initial breakdown to happen elsewhere.

FIG. 12.

A group of low-equivalent lightning-arresters tested on the 15 000-volt lines at power-house, Indiana Union Traction Company. Test papers can be seen in place.

The special multiplex arrangements have not had a satisfactory test, owing to the general arrangement of lightning-arresters.

Test-Papers from Idle Lines.—In order that a fair basis of comparison may be obtained for the foregoing it is desirable to know how severe the induced disturbances on a line may be.

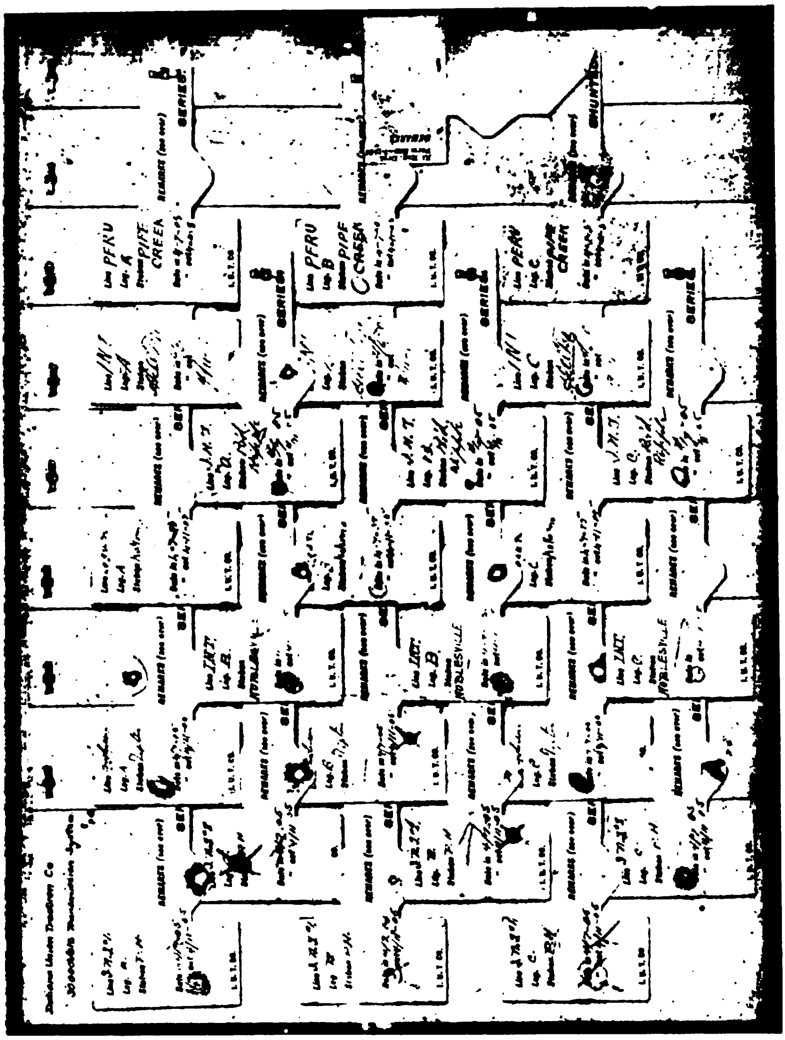


FIG. 13.

A page from the file of returns from the Indiana Union Traction Company 30 000-volt lines showing the general arrangement adopted throughout this investigation. The test papers (in duplicate) are first carefully inspected for punctures and those selected for final mounting which are thought to be most typical. It will be seen that the papers, reading up and down, are arranged according to the phases, *a*, *b*, *c*, etc.; and from left to right show the relation of events to lightning-arresters on the same wire from power-house to sub-stations in a given order. In this and in Figs. 14, 18, 19, papers are turned back to show typical discharges. The papers differ in color—this scheme being used entirely to avoid confusion in testing where a large number of arresters of different kinds or special gaps in a given arrester are concerned. It often happens that owing to rises of voltage which affect only the gaps nearest line, test papers in those gaps will show punctures when the remaining papers do not. Since no special note is made of papers placed near lines, it is necessary to examine all papers to check this. Again, the paper may imperfectly cover a gap, and were papers not in duplicate we should find it difficult to determine the presence and volume of a discharge.

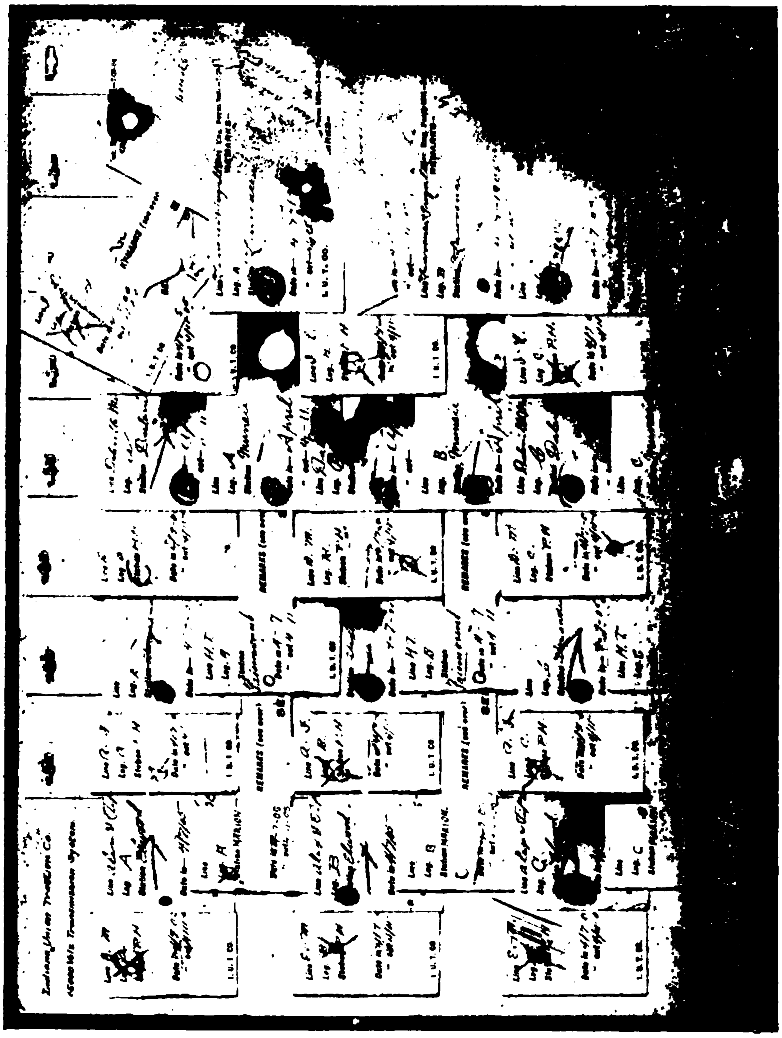


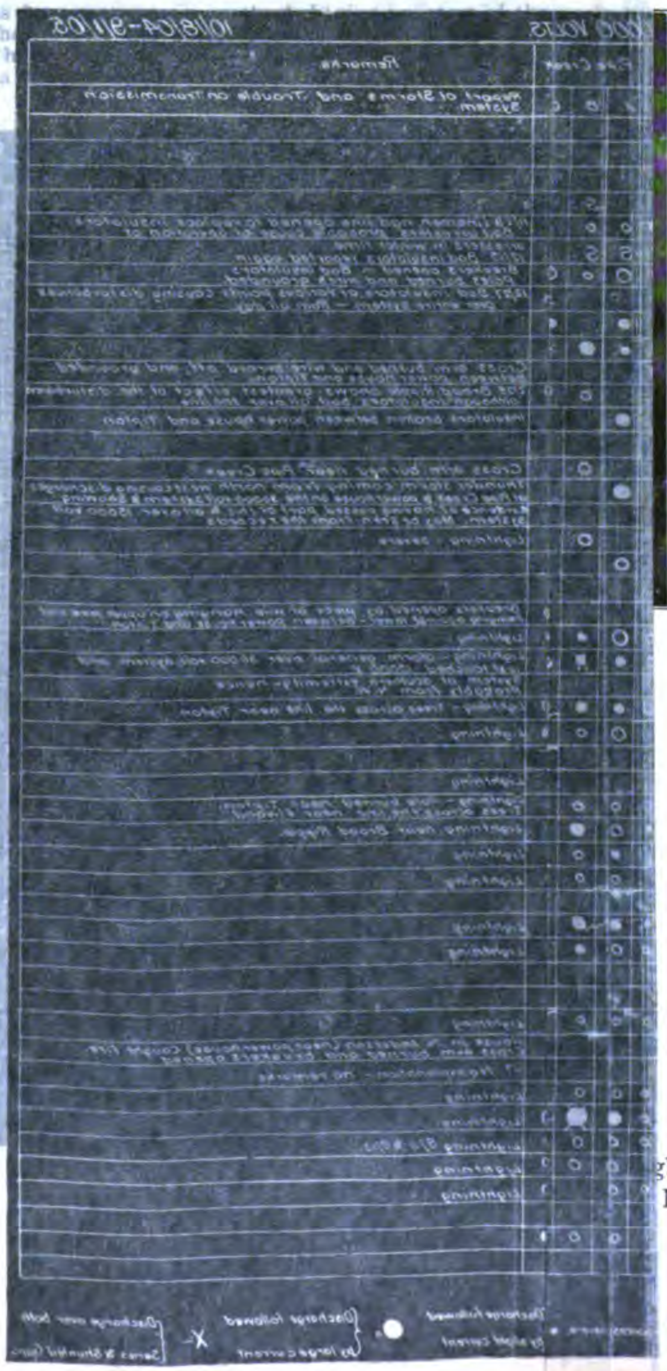
FIG. 14.

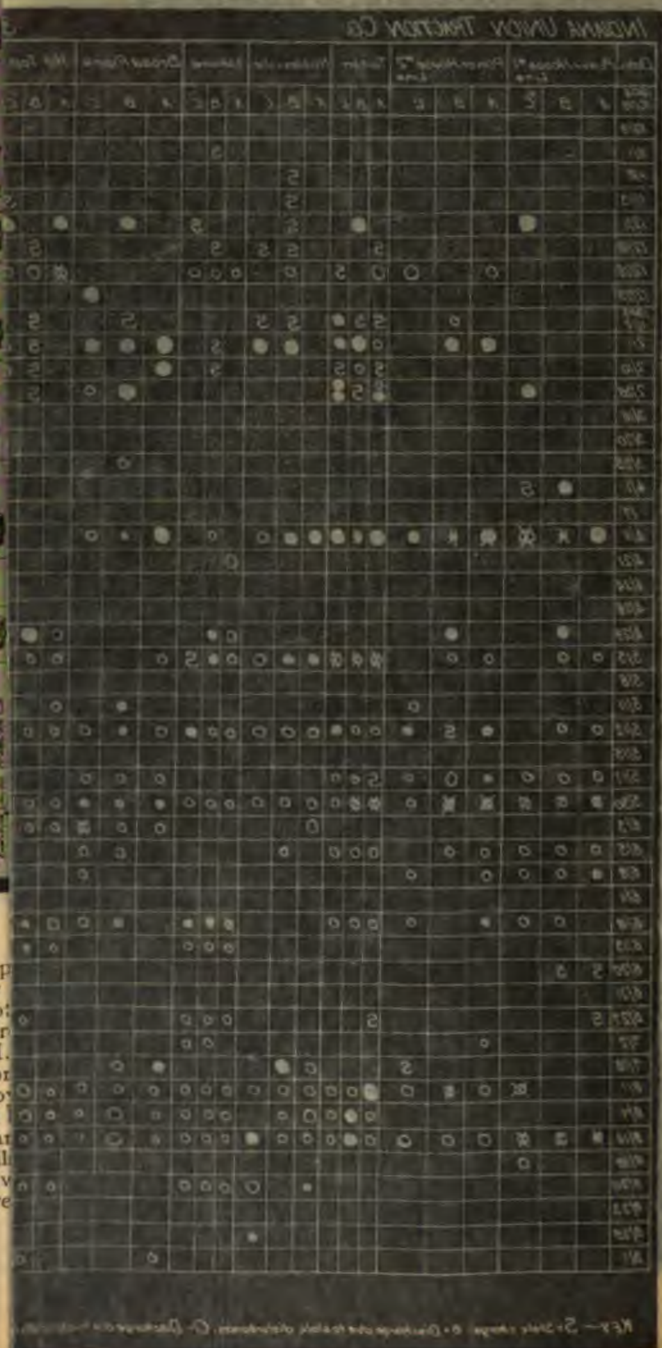
A page from the file of returns from the Indiana Union Traction Company 15000-volt lines.

Note in the upper right-hand corner (or upper left-hand corner of this page) the free discharge over the series and shunted gaps of lightning arrester, line I. & L., leg *a*, station power-house, on 4/7–4/11/05, and the corresponding puncture on the plain gaps, leg *b*, station Ingalls, getting hereby a good comparison of the old and new types of arresters. The large holes are due to the large amount of current which can pass over the arresters at the time of discharge. By comparing them with the Ingalls & Lawrence papers, leg *b*, same date it will be seen that the new type without impairing freedom of discharge, suppresses the short-circuit arc very quickly.

...ion Traction Company. 30 000 volts.

...ume of discharge over the 30 000-volt arresters is not so great ...bly arises from several causes, chief of which is the geographical ...ell on one line and not on the other; again, the operation of ...nsmission, and, therefore, the higher the voltage, the less the ...Note particularly the operation in the winter months of 1904- ...new and stronger ones. By placing in parallel to the Remarks ...direct means of measuring the amount of protection secured. ...rison of data and synopsis for 4/7–4/11/05.





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independently of the stored energy which endeavors to readjust itself at the time of a lightning-arrester action.

For this purpose we may refer to two sets of papers, Figs. 20, 21.

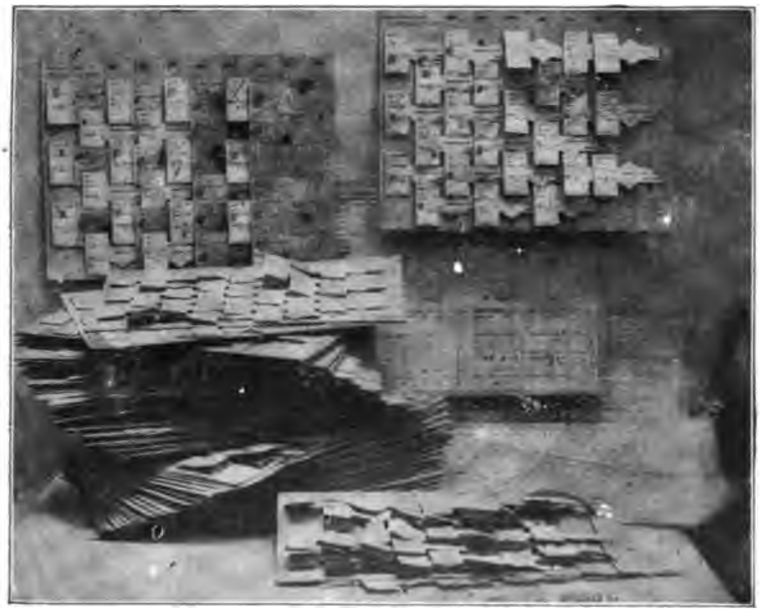


FIG. 15.

View of files of returns from Indiana Union Traction Company. Each page (11¼ in. by 8½ in.—approximately letter size) contains a complete set of records for any given period. In this case two pages—one of 30 000 volts test-papers and one of 15 000 volts, respectively—complete the record. The summary sheets (see above) are then filled out, and the whole filed by the vertical system.

Approximately 10 000 test papers (in duplicate) were received from this company, of which 5 000 were selected for filing.

26 000 papers (approximately) have been received in all from the companies mentioned; of these approximately one-half were kept for record. This work has taken only a part of one man's time. A complete set of returns from the above company, for example, could be assorted, inspected, mounted, and summarized in 2.5 hours.

The one from a line in the Salt Lake Valley of the Utah Light & Railway Co. called the Sandy Creek line, taken by Mr. P. H

Thomas[1], and the other from the Missouri River Power Co.'s lines, in Montana. The former coming from simple gaps, the latter from arresters of the G. E. type (with resistances short circuited). A curious indication of these discharges is the

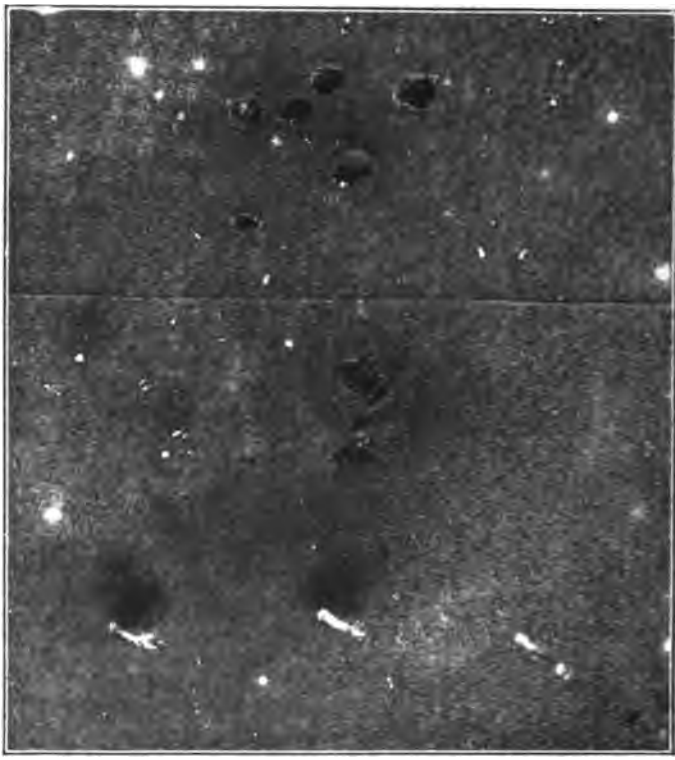


FIG. 16.

Test papers from the laboratory, showing typical punctures. 1. Free static discharges (note blistering) magnified two diameters.

Values of test: Condenser (oil immersed) charged to 30 000 volts, 0.10 microfarad approximately. The effect of this discharge should not be confused with ordinary static machine sparks. The latter may look formidable, but will bend around rather than pass through paper.

smooth-bore hole which does not at first seem to fit in with the facts of the blistering action reported for the free condenser discharge. I think that the difference can be readily explained as follows:

1. *Electric Club Journal*, March, 1905.

The charge may be induced at a particular part of the line which is remote from the discharge path. The intervening impedance reduces the abruptness of the discharge at the ar-

Fig. 17.

Test papers from the laboratory showing typical punctures, full size.

2. Free static discharge and current. (Note burning.)

3. Static discharge through a gap and high static (400 ohms) resistance. (Note reduction in freedom of discharge.)

4. Static discharge with current simultaneously impressed over a gap and high static resistance. (Note burning away of holes by current which has been also greatly reduced by high resistance.)

rester. In practice this induced disturbance is the one that first breaks down the gaps between line and ground, and following closely on this comes the stored capacity of the system

FIG. 18.

A page from the file of returns from the West Penn Railways Company, 22 000 volts. For comments on method of filing see Fig. 13.

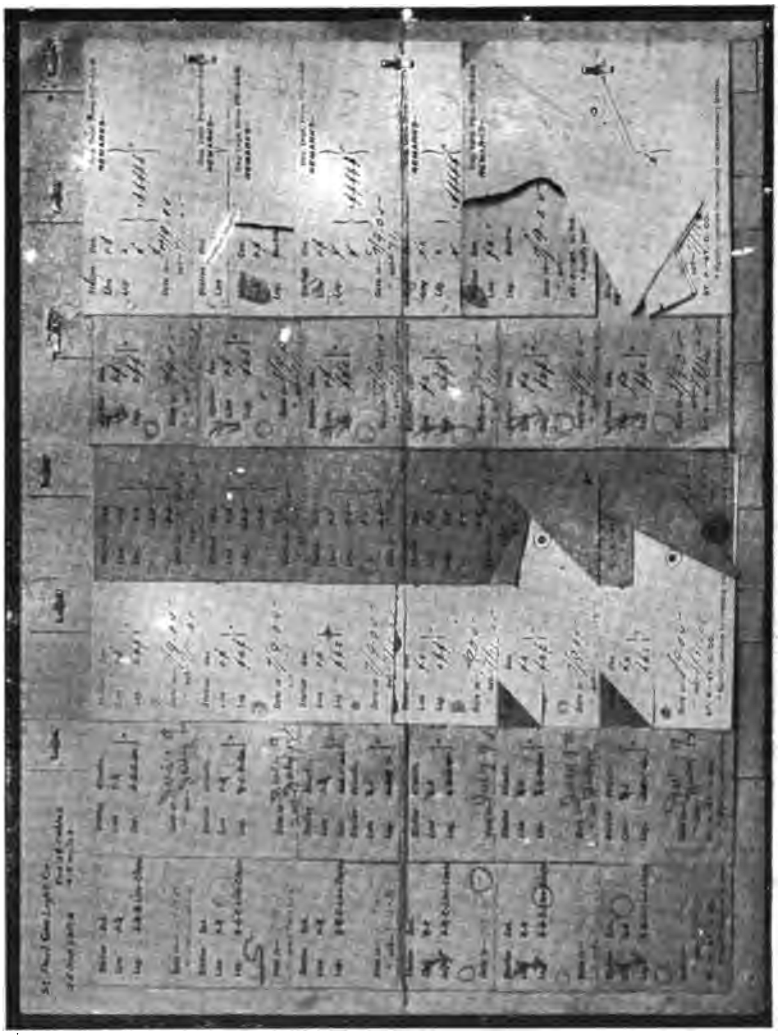


FIG. 19.

A page from the file of returns from the St. Paul Gas Light Company —St. Croix Power Company—25 000 volts. (See Fig. 13 for comments on method of filing.)

trying to readjust itself to the new conditions. Lastly, but most serious of all, the generator current endeavors to establish a short circuit following the discharge. It is possible for only the first two effects to occur, generally all three come into action.

The most important information given by these papers is that the lightning disturbances on a line are not of the magnitude generally supposed. It is impressive that the small

Magnified and photographed by Charles Edward Skinner.

FIG. 20.

Paper and its magnification showing a discharge over a gap of 1.63 in. on idle line. Magnified 19 times.

(Courtesy of The Electric Journal.)

Test-papers punctured by lightning disturbances on an idle line in Utah. Taken by Mr. Percy H. Thomas in 1902 from Sandy Line, Utah Light and Railway Company, Salt Lake City Valley.

holes made in paper are substantially the same as those made in insulation, and yet these small holes pave the way for very serious breakdowns of apparatus, due to normal current following.

A comparison of lightning-arrester papers punctured in practice with the papers taken from the idle lines, leads to the belief that the low-equivalent arrester is discharging these disturbances almost as freely as if the resistances were omitted.

Table I (for comments)

"Paper" line. This table should be directly compared with Table 6 comparison of data and synopsis for 7/9-7/11/06.

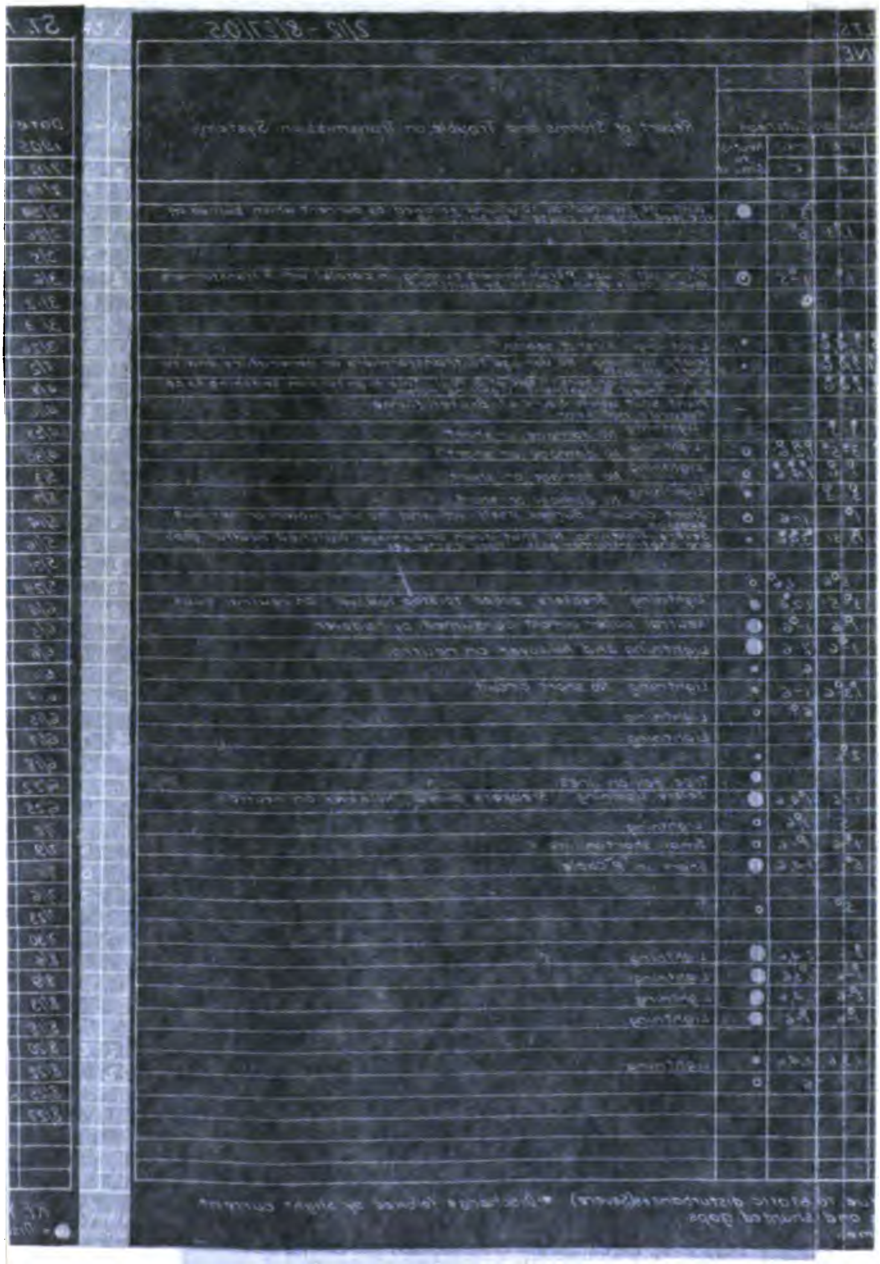
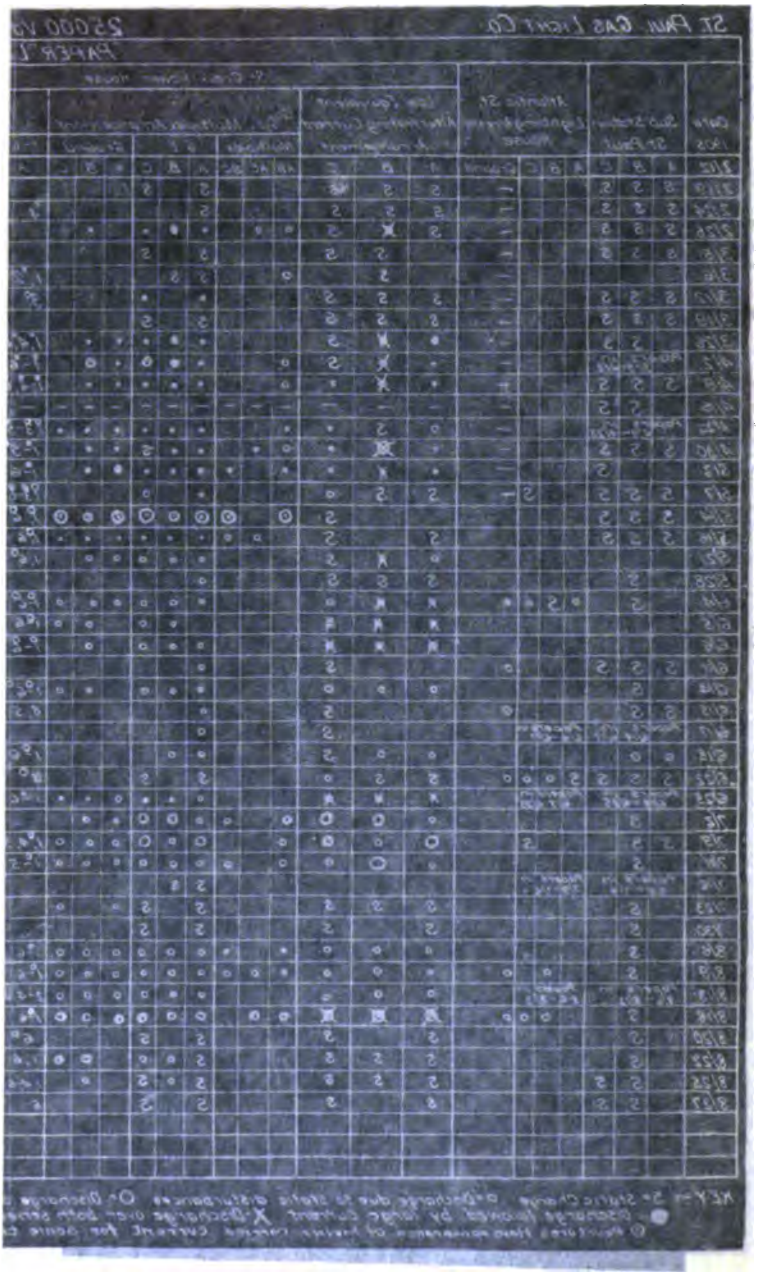


TABLE 4. (See

Synopsis of returns from the St. Paul Gas Light Company—
Fig. 19 and Table 4 enable a direct com



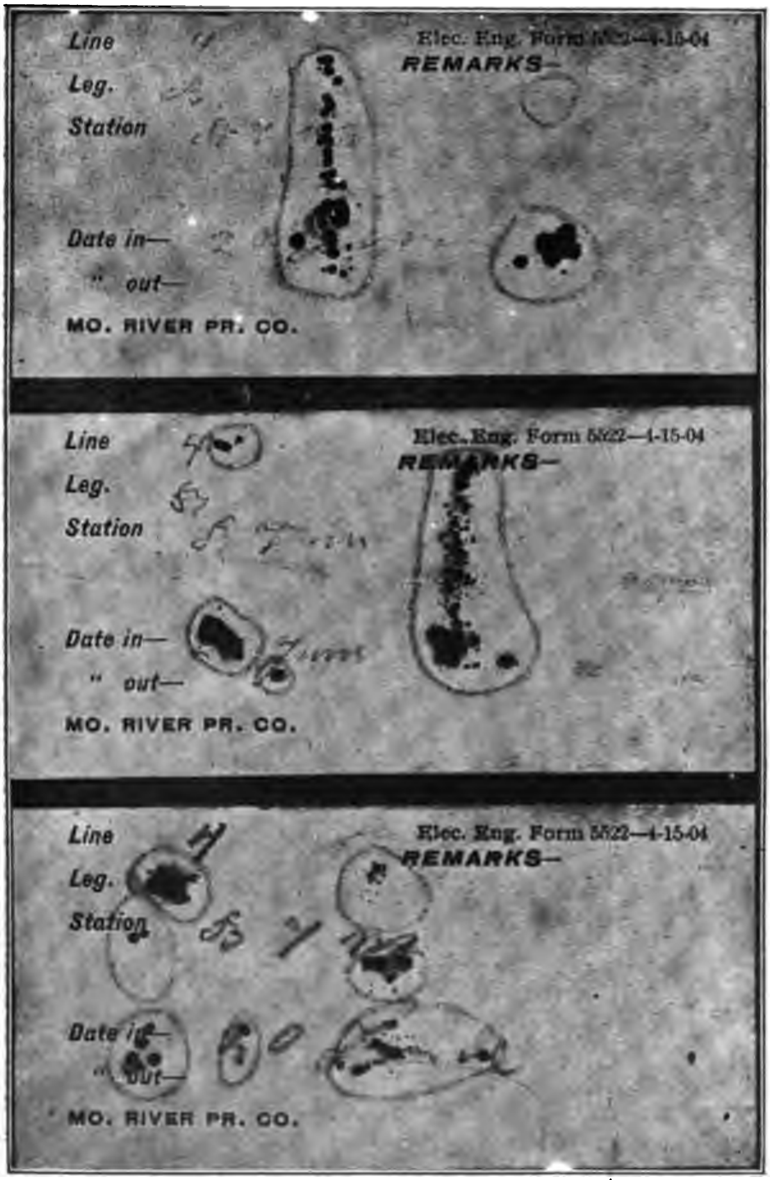


FIG. 21.

Test-papers punctured by lightning disturbances on an idle line in Montana, slightly magnified. Line, 5 miles, 10 000 volts, idle. Arrester, 20 General Electric gaps, with resistances short circuited, in series to ground. Date in and out, one month, June–July 5, 1905.

RESULTS OBTAINED.

A comparison of results shows clearly that for freedom of discharge the arresters which are built like the low equivalent with low resistance have freer discharge than the straight gaps and high resistance.

The action takes place through the series gaps and both of the resistances; and nothing occurs in the shunted gaps unless

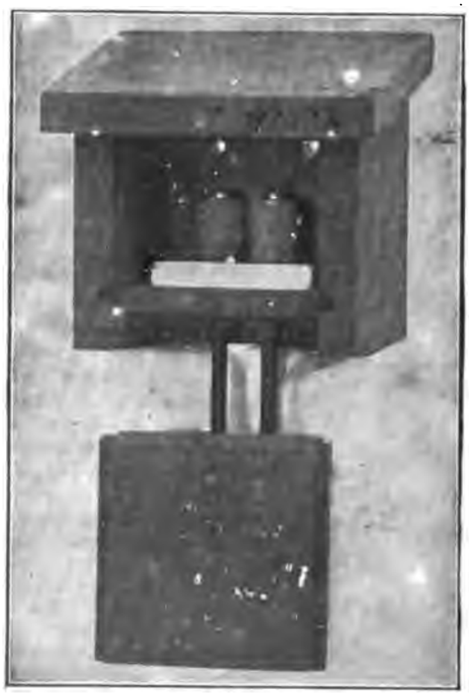


FIG. 22.
"Tell-tale" gap for investigation of special protective apparatus.

discharges are of high frequency and above a certain severity. When discharges are found in the shunted gaps the papers usually show a clean puncture, indicating that the discharge is chiefly static. It seems that the time-element of the disturbances, together with the throttling action of the non-arcing metal multi-gaps, enables the static disturbance to pass before the line current can follow.

Arresters with gaps and resistance capable of carrying considerable current for a short space of time act like high-potential regulators, relieving the line of surges promoted by many causes other than lightning.

The papers show the ability of arresters to discharge automatically and repeatedly without attention. At 55 000 volts the papers in hand show as free discharges as are obtained at lower voltages.

Multi-gaps without Resistance.—The returns from the Indiana Union Traction Co. show that arresters of non-arcing metal multi-gaps without resistance, when used on plants having very large generating capacity, cannot be depended upon to operate successfully, but are liable to short circuit or burn; but this difficulty is obviated by the introduction of resistances on the low-equivalent arrester principle. In fact the large burned holes indicate that a large amount of current has followed the discharge, and I have been told that the circuit-breakers are thrown out nearly every time these arresters discharge, whereas the low-equivalent arresters for the same voltage discharge freely without this breaker action. In other words, the old type of arrester under these conditions takes the discharge but fails to interrupt the short circuit which causes the breakers to open. In a synchronous converter system this involves the starting and synchronizing of apparatus. By avoiding any necessity for starting again, the newer type of arrester has greatly improved the normal operating conditions of the plant.

Multi-gap Type with Resistance Pencils, G. E. Co.—The returns from St. Paul indicate that two groups of these arresters will share the discharge, although in this case they are not symmetrically arranged. This may arise from the inability of either arrester to discharge the line completely, because neither discharges freely, and seems to show that several arresters in multiple which are not free dischargers are better than a single arrester.

In a freely discharging arrester with disturbances of the order noted above, a good free discharger should take all the discharges; and of two arresters thus placed in multiple the one with the freer path to ground would carry off the disturbances. This is a point which can only be determined by a test of this kind and is yet to be proved conclusively.

Judging by the character of the puncture the multi-gap arrester with carbon pencil appears not to discharge very freely.

The multiplex arrangement acts occasionally, but with the exception of the data given, Tables 4 and 5, on May 7—May 14, 1905, St.Paul Gas Light Co., no action of primary importance seems to have taken place.

No information of any moment has been obtained as to the value of the apparatus for cable protection, as the performance in this regard has been practically uneventful.

Pearson-Cutcheon Arrangement.—This method of protection has given evidence of its ability to carry off certain rises of potential at the terminals of transformer windings. It is curious to observe the erratic way in which this takes place, often skipping some coils and taking others. In many cases this action may be considered as representing the amount of the disturbances which ordinarily reaches apparatus protected by lightning-arresters and choke-coils; if the protective apparatus be properly proportioned, certainly nothing would be thought of the small amount of disturbances which the apparatus simultaneously shares. The ability of the device to operate satisfactorily seems to be established by these tests. Further tests, however, should be made with transformers in delta connection, and with generators.

Points on Operation of Transmission Lines.

Indiana Union Traction Company.—Reference to the returns for the winter months 1904–1905, Table 3, will show the disturbances raised on a line due to the action of grounding, etc., by reason of insulators breaking down. The fact that no shunted gaps operated throughout this period shows the whole trouble to have been one of potential disturbance within the system rather than from lightning. It is interesting to know that the operation of this line has been uniformly successful from the standpoint of lightning or other static disturbances.

St. Paul Gas Light Company.—The experience with cables on this plant seems to indicate that in general they are free from disturbances from lightning.

As is indicated in the *Remarks*, Tables 4 and 5, it was found inadvisable to switch high-tension single-pole because of the disturbances thereby created.

The absence of cable disturbances is particularly noticeable, although there is full evidence of high potential by reason of the "S," seen frequently in the synopses, as well as the action of the Pearson-Cutcheon arrangement without any attendant

Of the other plants contributing to this record little of novelty can be said. Each in its way gives some information bearing on its local situation. For example, lightning in certain parts of British Columbia is very rare, and for more than a year several storms of this kind were reported, and, judged by their effect on the papers, they were of a relatively light nature.

Conclusions Concerning Records.

Records to be effective should run along regularly in the same way that any other part of the plant is metered. There is a natural variation from year to year in the severity of lightning storms over any given locality.

The first purpose of this test was to demonstrate its applicability, which is now sufficiently indicated by the facts presented. It is reasonable to expect that the advance in the design and installation of apparatus from now on will in general be such as to reduce to a minimum the inherent disturbances in a plant, limiting these to what might be called uncontrolled forces, such as lightning, wind, etc., the effect of which, however, can be largely cared for by properly installed protective apparatus.

In proposing this method for general investigation of all protective apparatus certain of its features are not lost sight of, these are: first, it requires frequent handling; secondly, the time-interval between the placing and removing of papers covers more than one discharge—refinement on this would call for complicated apparatus; thirdly, the method will not succeed unless pursued by constant determination to obtain results; fourthly, lines must be carefully marked and all incidents directly or indirectly related to the operation of arresters in any given case must be carefully traced out; fifthly, records require careful filing and summarizing. Fig. 15.

The method is applicable, however, for all apparatus giving protection to a line by carrying disturbances from line to ground over an air-gap or its equivalent. Where there are a number of gaps in series, like the multi-gap arresters, the papers can easily be installed without impairing the action of the arresters.

In special cases such as the investigation of an overhead grounded wire, horn lightning-arresters, etc., use can be made of a special tell-tale gap placed in the path to ground at some part of the device. This gap is shown in Fig. 22 and consists of two non-arcing metal knurled cylinders between which a test paper can just be placed. By insulating the leads in such a way that any discharge passing to ground must go through this gap, a record can be obtained of the operation of the apparatus in question. Figs. 23, 24. An overhead grounded wire by reason of its great length and frequent grounding could have a special section cut out for investigation and provided with gaps. The application to the horn lightning-arrester is obvious.

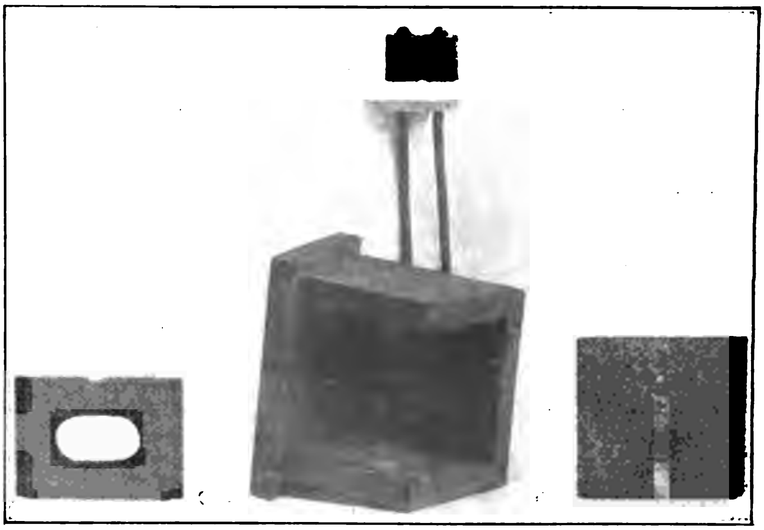


FIG. 23.

Detail of " Tell-tale" gap for investigating the performance of special protective devices.

VALUE TO ENGINEERING.

The novelty of this method of testing does not lie in the apparatus but rather in its present comprehensive application. It follows that by a concerted effort engineers have at their disposal a means of establishing beyond dispute within a comparatively short time, say two years, the many questions of protection still under study. The problem naturally divides itself into three classes:

1. Observations on the occurrence and magnitude of lightning discharges.

2. A determination of the value of standard protective apparatus at all voltages.

3. A study of the value of protective apparatus located along a line.

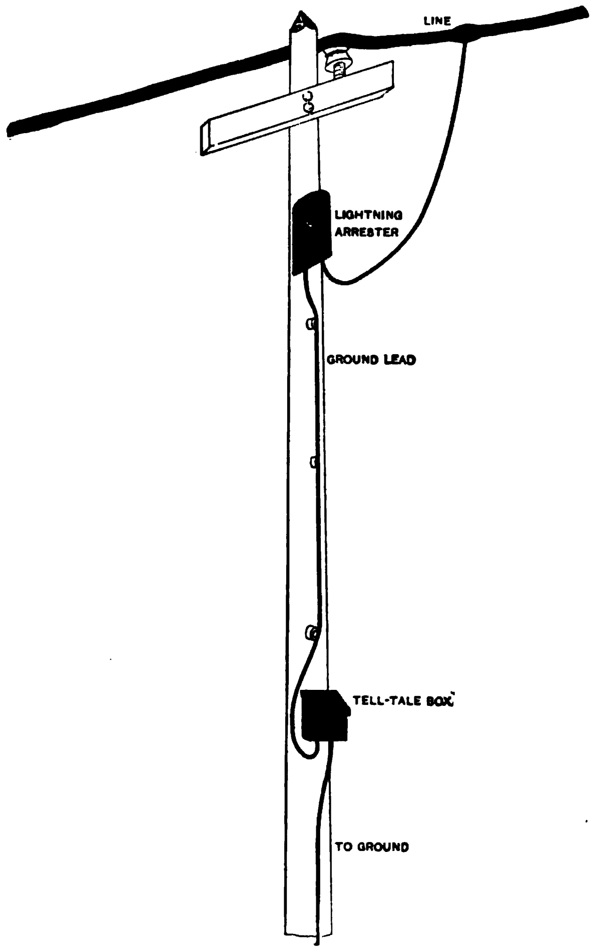


FIG. 24.
Shows application of "tell-tale" gap.

No endeavor has been made to mention all the facts given by the reports shown by these records. It is hoped that what is given will be of sufficient importance to receive the attention of those concerned in this subject.

DISCUSSION ON LIGHTNING AND LIGHTNING PROTECTIVE APPARATUS.

President Wheeler: The subject of lightning and lightning protective apparatus, though of extreme importance, has unfortunately not received the attention it deserves. Most of us do not appreciate the amount of damage to property and the number of injuries and deaths caused by lightning discharges. We need more reliable information as to the nature of lightning and lightning discharges and the most effective method of protecting apparatus from these discharges. I regret that none of the papers takes up the subject of lightning striking things that are not electrical, such as buildings. I mention this because I think the public is usually misguided in the matter, many lightning rods that are worse than useless being sold to the credulous public. Engineers should at all times try to prevent the public from being imposed upon.

P. H. Thomas: Progress is being made nowadays with lightning protective apparatus. I do not believe that the behavior of lightning arresters is going to be one of our great mysteries much longer.

It is interesting to learn that European engineers are advising the use of American lightning arresters; but it is also significant that they seem to find it wise to install special additional lightning protective apparatus. This would indicate that European engineers have not full confidence in American apparatus.

There are only one or two really fundamental features in a lightning arrester; an air-gap for discharging the static charge, and some means for interrupting the arc that may be established by the discharge. However ingenious the arrangement of any arrester, these are the basic features of all—except one special type of arrester not including a spark-gap, viz., a high resistance path between line and ground, which will undoubtedly carry off slow accumulations of static charge; how serious this sort of accumulation is, I do not know, but I do not believe it very serious. It is hard to believe that a high resistance, like a water-resistance, will offer a different character of opposition to the flow of current at the 100 000 volts of a static discharge than it offers at the 50 000 volts of a step-up transformer. For ordinary discharges then, it would seem that a high water-resistance really cannot give protection.

As stated above, the basic features of all lightning arresters are air-gaps and arc-interrupting devices. The commonest form of gap is the multi-gap arrangement, which is to a great extent self-interrupting. Other interrupting devices are the extension of the arc, as in the horn arrester, by the heat generated or by magnetic force; and the interruption of the circuit by fuses. The efficacy of most of these methods is usually and must in general be increased by the use of a certain amount of resistance in series with the arrester. These are the only devices that commercial designers have to work with at the present time.

What needs to be known in regard to lightning arresters may be summarized as follows:

First, are present series resistances too great for free discharge?

Secondly, is it possible to use less resistance and still have non-arcing arresters?

Thirdly, is it possible to use less series resistance in the horn type of arrester than in the multi-gap type?

Fourthly, can any system be arranged by which it is feasible to protect lines by the use of fuses for interrupting the discharge, the difficulty being to protect the line after one discharge has occurred before replacing the fuse, and to prevent the dropping out of synchronous apparatus?

These questions are of greatest importance in the protection of commercial installations. If all our attention is concentrated upon these features, I believe the solution of this problem will be arrived at more quickly than by the effort to devise new combinations or forms of the old elements.

Taken in connection with a great deal of corroborative evidence, Mr. Neall's paper pretty nearly enables us to answer satisfactorily the first of the four questions asked above. In a majority of cases, both of lightning and static discharge—practically in all cases of static discharge—as far as the speaker's experience goes, the series resistance or the total resistance contained in the arrester, seems sufficiently small not to impede the discharge of actual accumulated electric charge without injury to the apparatus. On the other hand, there were a number of cases where Mr. Neall found discharges in the shunted gaps, showing that they perform a useful function; but as far as his evidence goes, there seems to be no reason to suppose that the series resistance in connection with the shunted gaps is not sufficient in practice in all cases where there is first-class insulation strength in the apparatus and wiring. Of course more evidence is always needed on this point.

Mr. Neall's paper does not throw much light on the second, third and fourth questions—is it possible to use less resistance? does the horn type of arrester require less? and is it feasible to use a fuse arrester?

To get the most satisfactory lightning protection, only the best types of insulated electric apparatus should be used, and the line insulation should be made as good as possible. That has not been the case until very recently. Not until recent times does the speaker believe, has the standard of insulation strength been brought sufficiently high for the best results. More attention to the insulation means, other things being equal, less trouble from lightning discharges.

Mr. Neall's efforts to obtain data from commercial operation on this important branch of engineering work should be encouraged by all operating engineers. In the first place, close attention to these details is in itself an education; it gives the operating engineers an opportunity to study the action of the protective apparatus and to judge whether it is sufficient or not. It determines, too, what are the sensitive parts of the system, where the worst discharges are to be expected, which knowledge should lead to the addition of protective apparatus; weak methods of insulation will be detected, etc. This information gathered from different parts of the country for a number of years will materially aid manufacturers in their efforts to perfect the lightning protective apparatus. A protective system like other systems should be to some extent an evolution.

Mr. Smith's paper is interesting and important, though it deals with a different kind of data. He confines his observations to one plant, while Mr. Neall gives data from plants that are operating under many different conditions of voltages and locations. Mr. Smith says that since 1903, when he installed horn arresters, he has had no difficulty from lightning so far as interruptions of circuits or damage to apparatus is concerned. If I am not mistaken, there was at that time a substantial increase in the insulation strength in the wiring and apparatus of the plant he describes, which will undoubtedly do much to help eliminate trouble and leaves us rather uncertain as to whether the horn arrester or the increase in insulation was the essential protective feature; at any rate, with the increased insulation and the adopting of the horn arrester, he has secured substantially the protection. This is a most hopeful sign, as the very high voltage plants are the ones that are the most difficult to protect. There are of course many ways in which lightning can affect the line—electromagnetic induction, electrostatic induction, the accumulation of a charge on the wire from a charged cloud, the gradual accumulation of charge from the atmosphere, and finally, the direct stroke on the line. However, all things considered, it appears that the most dangerous kind of lightning is that in which a direct stroke (usually comparatively small) actually reaches the line. In Mr. Smith's plant in all cases in which the horn arrester has acted, some poles have been damaged; in one case, 15 poles were totally destroyed. This is very significant, and the conclusion is suggested — it is supported also by much evidence from different plants—that these severe strokes do not pass very far on the line, but that in the first few hundred feet their greatest severity is overcome by the discharges that pass down the pole. Of course a certain amount of the charge passes to the nearest station where it encounters the arresters which should be able to relieve the system, as the severity of the wave is limited to the insulation strength of the line. The obvious conclusion is that it will be very helpful in high-tension plants where the lines are very long if arresters can be placed one, two, or three miles from the station. At such places the arrester gets a chance at the static wave initiated by a direct stroke or otherwise before it reaches the apparatus. The drawback to doing this sort of thing is the necessity of leaving the arrester unattended, and the likelihood that it will cause more trouble than it will prevent.

The desirability of placing the arresters on the line near the stations brings forward a discussion on the fuse type, on account of the certainty of its freeing the line after a discharge. I believe that there is a great deal to be said in favor of using fuse arresters in plants like that of the Shawinigan Water and Power Company; but if the fuse type is to be used, there is perhaps no need of making a horn of it. It should be made as simple as possible—a plain gap, a fuse of non-corrodible wires of the *smallest practicable diameter and highest resistance* enclosed in a tube, which will open the circuit quickly. Unfortunately, when one fuse is blown the plant is unprotected until another fuse is put in; but it is only occasionally that one of these very severe discharges occurs. A direct stroke on the line is not likely to occur more than once in two or three days. Another method is to provide a number of fuses connected in parallel, in which case and if a separate series gap is provided for each fuse, the chances are that any lightning discharge will pick out one fuse and leave the others. If this sort of protection be used, there can be two or three discharges without replenishing the fuses.

In the light of present experience the natural conclusion seems to be that the type of arresters found to give best service should be placed in all modern stations; if then there is any trouble in any particular locality, the arrester already installed can often be supplemented by a fuse arrester or another arrester placed on the line some distance from the station. A trial of many variations of arrangement of protective apparatus will often determine an arrangement that will protect the whole line. There may be many plants in which the horn arrester, without series resistance and without fuses, may operate without throwing out synchronous apparatus or circuit breakers, but in most cases, I think this an unlikely condition, and furthermore additions to the size of the plant may change such a condition. It will in general be necessary to have a series resistance in which case the multi-gap arrester may just as well be relied upon to protect the apparatus.

Charles F. Scott: Many of the papers that are read and much of the discussion which takes place in regard to lightning, particularly among practical station men, seem to treat lightning as if it were definite and uniform in its action. Perhaps the most characteristic features of lightning are the varied conditions under which it occurs and the equally varied phenomena arising from it. The practical question is, what lightning arrester will answer not only for a given specific condition, or for all the conditions which may arise? Some of these varying conditions are: the character of the discharges, as pointed out by Mr Thomas; the difference in the tendency of an arc to follow a discharge, *e.g.*, the dynamo current which may follow the discharge depends upon the voltage of the line and the kilowatt capacity of the station; the location of the arresters, whether at the power house or at a distant point on the line, as the line resistance between generator and arrester may be a considerable factor in determining the readiness with which the subsequent current may be extinguished. With a very high voltage the current which may follow a short circuit is less in volume; consequently, it is less apt to burn the arrester, and is in someways, therefore, less liable to damage the spark-gaps than a current at a lower voltage.

Mr. Neall's paper is valuable in that it tends to bring together many isolated cases of lightning discharges. The paper summarizes an experience of some years in the development of a system of records of lightning protective apparatus. I have visited some plants where tell-tale papers of the kind described by Mr. Neall have been in use, and found the operating engineers interested in watching the effects of lightning discharges on the tell-tale papers. The papers were classified, and after a storm, they have shown the positions at which discharges have occurred In this way some idea is reached as to the effectiveness of the protective apparatus.

No mention has been made this evening of the practice of grounding the neutral point of the system. As is well known, those who use a grounded neutral are usually of the opinion that it is the only safe way to operate a plant; on the other hand, there are others who regard the insulated system as the only safe way to operate. The practice of the Shawinigan Water and Power Company is, I believe, to ground the neutral; at the Missouri River Power Company plant the practice is to keep the system entirely insulated. The latter plant has run continuously for service 24 hours a day and seven days a week, carrying a fairly uniform load all the time. As motors are used in connection with mining operations and smelters, the interruption of the power would be a very serious matter. During the past year they have had only three or four disturbances on the high-tension system; one of these was in the station and was simply a discharge across a new terminal that had recently been put in and was not properly insulated. The arc following the discharge went out of its own accord without interrupting the circuit. Out on the line there had been several discharges resulting in short-circuits; these short-circuits were interrupted by opening the switches at the power station, and as these switches were closed immediately the only inconvenience was that of starting such motors as had stopped. I have been told that the Missouri River Power Company has had more interruption from lightning on 2 000-volt distribution lines than on the 55 000-volt transmission line. The service of this line has been so satisfactory that an extension to the plant is being made, and the whole system will operate at 70 000 volts. This is higher, I believe, than is employed anywhere at present.

The operating engineers at this plant say that by listening at the telephone, at times a slight crackling noise may be heard every little while, due probably to a discharge on the line. The phenomena of lightning on the line manifests itself in different ways. When a storm—such as a winter wind storm with a light driving snow—first strikes the line, there is a slight clicking in the telephone; when the storm is leaving the line the telephone clicks in a different way.

The matter of protecting the poles on the line seems to me to be one of the most serious questions in lightning protection. Mr. Smith reports that great disturbances occur on the line, such as the splintering of poles, with no concurrent disturbances to the generating and transforming apparatus within the station. I believe that no transformer in service has been damaged by lightning during the several years that his plant has been in operation. It is rather remarkable that in a country where storms splinter so many poles, the apparatus in the station has been so well protected.

W. S. Franklin: The problems that confront us at present in connection with lightning-arresters can, probably, be solved only by experiments on long-distance high-voltage transmission lines. It seems to me that the important thing to know about a lightning arrester is not that it operates successfully a great many times, but the number of times it fails to operate, the number of failures that result in damage to the apparatus in the station or to the pole lines. Mr. Neall's paper, though interesting, seems to me to be faulty in this respect.

The series lightning arrester described by Mr. Torchio—Gola's series arrester—is, I think, a very fanciful arrangement. It is well known that iron is not magnetic at the excessively high frequencies which correspond to the frequency of lightning discharges; therefore, the iron diaphragm is no longer iron so far as the lightning discharge is concerned. The only thing that constitutes a sufficient change in the condition of the line effectually to reflect a pulse of discharge is change in capacity or in inductance. Changes in resistance are extremely ineffective in producing reflection unless the resistance is suddenly made very large indeed over a considerable length of line.

The kind of resistance that is needed not only for line discharges but also for use in series with a spark-gap, is that which offers a comparatively low resistance to quick discharges and a comparatively high resistance to slow discharges—in short, a skin resistance. The use of resistances in series with spark-gaps has been by no means pushed to the extent it should be in the development of lightning arresters. My idea is to use a series of three-foot terra-cotta pipes painted before the final firing with about two cents' worth of platinum chlorid spread out on a surface about six feet broad. This arrangement presents an enormously high resistance to a slow discharge, corresponding to low frequency machines, and at the same time a resistance nearly as low as a solid conductor to the extremely rapid discharge induced by lightning. In the protection of pole lines something similar should be done to prevent a flow of current down a pole when the pole acts as a lightning arrester; that is, to prevent it from flowing through the fairly high resistance material of the wood, for a high resistance substance conducts not only on the surface but through the material. If the pole were made of copper, it would conduct only on the surface; being of wood, even the extremely quick pulses of current which constitute lightning discharges are able to penetrate into the very heart of the pole. Perhaps the problem could be solved by applying to the pole some kind of conducting paint offering a comparatively high resistance, but not so high resistance as that of the pole itself.

In regard to the freedom of spark discharge, as affected by resistance in series with gaps, I think the question of the influence of a series resistance cannot be answered by the character of the spark in the gap. An ordinary thread two or three feet long connected in series with a Leyden jar will discharge across the spark-gap, and instead of giving a large brilliant spark will give the weakest kind of a pale-violet spark. In this case the noise produced by the spark is a snap, as clearly defined as the snap of the brilliant spark produced when there is no resistance in series. The sharpness of this snap is the real indication of freedom of discharge, and to judge of the freedom of discharge by the brilliancy of the spark or by the amount of the visible puncture produced in the bit of paper placed in the spark-gap, would be misleading. I think that the retardation of discharge by series resistance, provided that the resistance is of the right kind, has been greatly overestimated.

The practical way to judge of the influence of series resistance upon the freedom of the discharge is, it seems to me, to have an auxiliary spark-gap in parallel with the lightning-arrester, and then to have that auxiliary spark-gap protected by a small amount of inductance and then to see, when the rush of current comes in over the line whether the time that elapses during the building up of sufficient voltage to break through the lightning-arrester is enough to allow the current to force its way through the choke-coil and to jump across the auxiliary gap. In judging of the freedom of discharge in the lightning-arrester, this time element is very important.

The enumeration of the important features of lightning protective apparatus by Mr. Thomas is very interesting. I think that a vitally important feature is the provision for the dissipation of the energy of the discharge (*e.g.*, in a series resistance) so as to prevent oscillation and thus greatly lessen the time during which the spark-gap remains a fairly good conductor and thereby reduce to a minimum the likelihood of the formation of an arc

Mr. Scott expresses the opinion that the most important problem facing us at the present time in the matter of lightning protection, is to protect against these extremely violent lightning discharges. It is precisely in these cases where it is necessary to provide for the dissipation of the energy. Ordinary "static discharges" so called, represent but little energy, and special means for dissipating this energy is unnecessary.

J. H. Hallberg: I wish to relate an experience with a modern well-known lightning arrester. It was installed on a

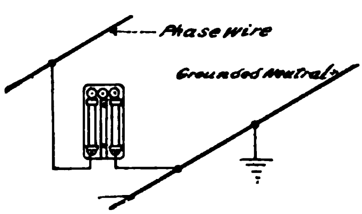


Fig 1.

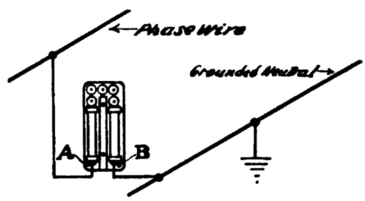


Fig 2.

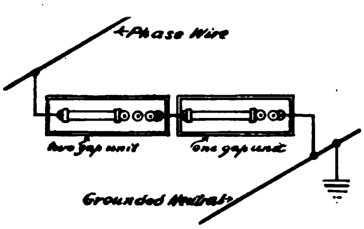


Fig 3.

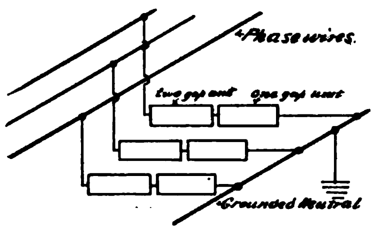


Fig 4.

three-phase four-wire 4 000-volt system, with a grounded neutral. There were about 2 400 volts between the neutral and each phase-wire, and about 4 000 volts between the phase-wires.

Fig. 1 shows a standard 2 400-volt lightning arrester which would be entirely destroyed during a lightning discharge, due to the main current following the discharge. Fig. 2 shows a 3 600-volt arrester, which in several cases permitted the lightning discharge to jump and the current to follow from *A* to *B*. instead of over the air-gaps as it normally should. Fig. 3 shows the same type of lightning arrester differently assembled; this was installed later on and successfully overcame all troubles under the most severe conditions. Fig. 4 shows the lightning arrester equipment which was finally adopted as a standard for the system referred to.

I have experimented considerably with several arresters, and find that, in the form of arrester here referred to, if the resistance is maintained it produces a straight path, and effectually prevents the main current from following the lightning discharge.

It would be interesting to know if the graphite resistance used in the General Electric lightning arrester deteriorates to any appreciable extent with repeated discharges.

H. C. Wirt: I believe there will be no appreciable increase of resistance in any of the General Electric arresters made within the last three years where the resistance amounts to 450 ohms with a six-inch stick. That resistance is now made almost wholly of carborundum, whereas in the first form of arresters graphite resistances were used. The carborundum is much more satisfactory than the graphite.

My experience is that all types of lightning arresters give more or less trouble. There is real need for reliable data on the operation of lightning protective apparatus, and I think it unwise to attempt to draw conclusions from investigations extending over a short period of time. Though the puncturing of paper may occur frequently, still it may not be a true representation of the operation of the arrester. Before any reasonable conclusion can be drawn from them, these punctures should be carefully examined by one who has had considerable experience with lightning protective apparatus. An experience of this kind is remarkably uncommon.

What is wanted is improvement in all makes of lightning arresters. I have reports on all makes of arresters in operation except some of recent construction, and experience prompts me to say that these arresters, too, will give more or less trouble. For the last year and a half, I have been observing carefully the operation of lightning arresters in a modern power house; up to two months ago, I felt safe in predicting the successful operation of a particular form of arrester; now I am tempted to qualify such predictions because within the last month three transformers have burned out during storms.

Personal observation leads me to believe that more can be learned from high-tension than from low-tension plants. There are disturbances going on in such systems which are not shown on any instruments now in use. I think we should not be hasty in forming an opinion regarding the possibilities of an arrester without any resistance. Very little has been written regarding the form, size, and number of gaps, size of cylinders, static capacity of these cylinders, though all these things have been under investigation. There is also considerable difference in respect to non-arcing metals. I think it is possible to reduce the number of gaps by using better non-arcing metals.

The lightning arrester on the line may not be under observation at the critical moment, and an entire season might pass without a discharge that would cause an injury to the apparatus. I think it may be possible—it seems so from recent tests—to get a condition at the factory that approximates the conditions on the outside. The article by Dr. Steinmetz on the Manhattan trouble is worth careful study. I think it is possible for arresters to take care of many of the conditions that cause surging.

H. A. Pikler: It seems to me that in most of the cases where the rising potential is due, not to the direct effect of the stroke of lightning, but to magnetic or static induction, surges, and short-circuit, that the protective apparatus does protect the line. In cases where the lightning strikes the line directly, the insulators are broken down and the poles damaged. I believe that in cases like this, the resulting damage is due to the enormous skin effect on the line. Short portions of line offer so good a resistance to the very high oscillatory discharge of the lightning that it naturally seeks a path of lower resistance; this breaks down the insulation and goes to ground through the pole. A remedy for this would be to install lightning-arresters at such distances and on such portions of the line that the resistance from the arrester to the ground is lower than that of the insulator. If this were done perhaps the discharges would go along the lightning-arrester and not through the insulator to the pole.

H. G. Stott: Lightning phenomena may be divided into two classes; the first corresponding in degree to the surges which are the result of switching in and switching out cables, short-circuits on the lines, mistakes in synchronizing, etc., which may amount to a net rise of three or four hundred per cent. This class of phenomena can undoubtedly be taken care of in several ways with the apparatus at present in use. The second class, however, corresponds to the effect produced by the explosion of a ton of dynamite, and at present there is apparently absolutely no way of safeguarding apparatus from a direct lightning stroke of this kind. In the case of the first class the present type of lightning arrester is probably an element of safety to the insulation of the entire system and will safeguard against any ordinary surge, or induced lightning discharge. When purchasing apparatus, a small additional investment will frequently be sufficient to give an insurance of safety to the insulation of four or five times the working voltage, and would seem to be the best kind of an investment in lightning protection. In the second class of lightning discharge we are brought face to face with two absolutely contradictory conditions: the first condition is that in order to take care of the lightning discharge the best possible path to earth must be provided; the second condition is that the worst possible path to earth ought to be provided in order to prevent the line current from following the discharge to earth. These two conditions it seems practically impossible to harmonize; for whatever is done to improve the one must at the same time work against the other, so that any apparatus designed to meet both requirements must necessarily be a compromise and, therefore, inefficient under both extreme conditions.

A plan I should like to see tried would be to put in a single air-gap in series with an oil-switch in the connection to the ground. A current transformer would operate the oil-switch through a relay, in case of a severe discharge to ground followed by the line current, after a predetermined interval. This oil-switch after tripping out would then automatically close itself again after an interval of, let us say, three or four seconds, and so be ready for the next discharge. The generator relay being set, of course, for a longer time than the time-interval, would not operate.

Philip Torchio: A word further in regard to the protective devices I have seen in Italy. The opinion abroad is that the present lightning arresters safeguard the ordinary operation of a station; for even if a generator is struck by lightning it would be disconnected from the bus-bars before causing a shutdown. But the real troubles are short-circuits along the line caused by a flashing between the wires; these short-circuits cannot be stopped without opening the line, resulting, of course, in an interruption to the service.

The Milan Edison Company has put in double insulators of the type described by Mr. Semenza in a paper presented before the INSTITUTE a short time ago.* Since then—it was three years ago—no trouble has been caused by the breaking down of insulators, though there have been a great many storms.

It seems to me that at present the question of lightning protection of the station apparatus is not so important as the protection of the line itself. What really needs to be known is how to protect the whole line, say, at 20 miles from the station, as well as just outside the station.

The water-resistance dischargers used abroad are in a way similar to the arresters mentioned by Professor Franklin. They expose large surfaces to lightning discharges. Mr. Thomas has said that these discharges—on account of their high resistance—would not act to discharge the line potential more than any other type of resistance under ordinary operating conditions. But will not these oscillatory discharges, involving a relatively small amount of energy, be made harmless in a short time by even a high resistance discharger acting as a safety valve?

N. J. Neall: I think, considering all the difficulties in getting the performance of lightning-arresters during storms, that the method described in the paper is the most effective yet proposed for getting the needed information from operating en-

*TRANSACTIONS, A. I. E. E., 1904, Vol. 23, p. 147.

gineers. I should be very glad to hear of any other method that can be used to get the same information. One year of trial is certainly not sufficient to establish a case; three or five years would be better, because that is the only way in which to get a record of all the storms which might affect a given line.

As far as the bad performance of arresters is concerned, the tests now placed before you are complete; had there been any bad performances they should have been included in this record. As a matter of fact I do not know of any cases of serious failure of the low-equivalent arrester in and of itself. In some instances extraordinary conditions affected the operation of the arresters, and for this reason I have not endeavored to give the impression that the arresters are capable of taking care of very high discharges.

The value of the standard protective apparatus as manufactured to-day is not for extraordinary disturbances but for everyday conditions. A few years ago nothing was heard about line protection; but now that lines are operated from 60 to 200 miles in length the protection of the line itself has become an important matter.

The remaining point is, that the papers placed in the discharge-path of the condenser were in the path of a 30 000-volt condenser. The character of that discharge is different from the discharges obtained by Mr. Wurts from a static machine and Leyden jars. The energy of the discharge is different. There is no novelty as far as the skin effect is concerned, in the tests made by us; we have however gone a little further and used larger quantities than have been previously employed.

Charles P. Steinmetz: The successful operation of long distance transmission systems depends to a large extent upon their protection from lightning. Unfortunately, the same absolute confidence can not yet be placed upon the proper performance of that part of the electric circuit constituting the lightning protective apparatus that is had in respect to almost every other part of the system, notwithstanding all that enthusiastic engineers and designers of lightning arresters may assert. The reason is obvious: Under the term "lightning" are included a large number of phenomena, not all of which are fully understood or have been investigated.

In its broad definition, "lightning" in electric circuits comprises all the effects of voltages different from and usually higher than the normal operating voltage of a system. Such abnormal voltages may enter a system from the outside, as in overhead lines, or originate in a system. Hence the terms "external" and "internal" lightning may be used. The nature of both types of disturbance is the same, but they frequently differ quantitively, as in frequency, amplitude and duration.

Common causes of internal disturbances are: spark discharges over faults in the insulation, sudden changes of circuit conditions, etc. Some of these disturbances have already been discussed before the INSTITUTE. Other disturbances such as high-frequency oscillation resulting from a ground on a high-voltage three-phase system; the interesting effects observed at the junction of overhead lines with underground cables; and the complex set of phenomena resulting in a three-phase system from the coincidence of the 3d, 9th, 15th, etc.; harmonic, may well form the subject of a paper. As is well known, the 3d, 9th and 15th harmonics in a three-phase system are in phase, and therefore rise and fall simultaneously; which may result in cross-currents flowing between the different parts of the system through the ground, and occasionally high-frequency oscillations or low-frequency high-power surges of the whole system against ground—in the latter case, mainly of triple frequency.

The discussion on the paper deals only with those high-voltage disturbances that enter the system from the outside, that is, from the atmosphere. The designing of lightning protective apparatus is seriously limited by the fact that such apparatus must not only promptly and effectually discharge atmospheric disturbances entering the line, but must do so without producing internal surges. The charge and discharge of electric transmission systems by atmospheric disturbances is sudden and liable to be oscillatory. It is, therefore, a sudden change of ci cuit conditions; and it is changes of this character that produce internal surges. If lightning were a very high-frequency oscillation, like the discharge from a Leyden jar, the system could be protected by interposing reactive coils between the station and line, and shunting the discharge through multiple spark-gaps to ground; if it were a steady gradual charge of the line, it could be discharged to ground by a high-resistance shunt, with or without a spark-gap: again, if it were a low-frequency high-power surge, an effort could be made to take care of it.

But lightning is not limited to any one of these phenomena; it may include two or all of them at the same time, as for instance, a gradual static charge of the line, followed, as soon as the voltage has risen sufficiently high, by a discharge in the form of a high-frequency oscillation, which in short-circuiting the line, gives rise to a low-frequency high-power surge. And even still other, and practically unknown forms of lightning may exist; for instance, globular lightning has occasionally been observed, so that no question can be raised regarding the fact of its existence; practically nothing is known about it however, excepting that it is extremely destructive; it seems to be rather a discharge centre than a simple discharge. Obviously, then, since our knowledge of lightning is incomplete, the results of efforts to construct lightning protective apparatus cannot yet be perfect.

In the interior of a body of perfect conductivity, no electrical disturbances can be produced by external causes. Hence if a transmission system is enclosed by a grounded conducting shell—put underground—atmospheric disturbances cannot enter it. Since a transmission line cannot be put underground, the best available protection is to put the ground above the transmission line. That is, a grounded system of wires above the transmission line is the most perfect protection from lightning, and the more perfect the nearer it approaches the character of a grounded enclosing shell of perfect conductivity. A single grounded wire over the transmission line offers considerable protection from atmospheric disturbances; but two such wires are better than one; and, naturally, the greater the number of wires the more perfect is the protection afforded.

To protect a transmission line by overhead ground wires, however, it is essential that the line be within the protective zone of the wires, that is, within the space enclosed by an angle of 45 degrees, or preferably 60 degrees from the ground wires downward.

Barbed wire, by reason of its more rapid action, is more effective than ordinary wire against some kinds of atmospheric disturbances; for example, electrostatic charges picked up from drifting rain or fog; while with other disturbances it offers no superiority over plain wire.

The conductivity of the ground wire is of considerable importance. For the purpose of bringing ground, or zero, potential up to a point above the transmission line, and thereby lowering the electrostatic potential of the space in which the transmission line is located, the size of the ground wire obviously is immaterial; but high conductivity of the ground wire is of importance in protecting the transmission line from the inductive effects (electromagnetic or electrostatic) of oscillating, or sudden, atmospheric discharges, such as lightning flashes; and also in protecting the stations in case a direct stroke of lightning reaches the line, by its damping effect as a grounded secondary conductor.

Inasmuch, however, as a system of overhead ground wires cannot be a complete enclosing shell of perfect conductivity, its protective effect, however great, cannot be quite complete; therefore protective devices have to be installed at the stations as safeguards against the entrance of lightning from the line.

The elements available for the construction of station protective apparatus are mainly spark-gaps, resistances, and reactive-coils. The purpose of the spark-gap is to isolate the line from the ground when normal voltage prevails, and to connect it to ground in case of abnormal voltages, but to connect it in such a manner that the connection is disrupted again when the voltage returns to normal; that is, the gap must let a spark pass at abnormal voltage, but must not hold an arc at normal voltage. *n* sparks in series require about the same voltage as (in some cases very much less voltage than) one spark *n* times the length; *n* arcs in series, however, require nearly *n* times the voltage of a single arc of *n* times the length. Hence the greater the number of the spark-gaps, and the shorter, therefore, their length, the more favorable is the relation of arc voltage to spark voltage. This relation of spark to arc has led to the almost universal introduction of the multiple-gap arrester.

In addition to spark-gaps, arc-interrupting devices, as for instance shunted resistances, are used; which, due to the particular character of the arc, are caused, by the increase of arc voltage with decrease of current, to make the arc unstable and so extinguish it.

The purpose of the series resistance is to make the discharge non-oscillatory. A discharge from line to ground or from line to line will be oscillatory if no series resistance or other oscillation-preventing device is in circuit, and may cause a low-frequency surge in the system, which may be more destructive than the lightning itself.

In its effect upon the discharging capacity of the arrester, the series resistance is unqualifiedly bad; the greater the series resistance interposed, the less discharge ability the arrester has. Considered solely from the standpoint of the discharge of lightning, the best lightning-arrester is therefore the one that has no series resistance. If an arrester could be made without series resistance and depended upon to discharge non-oscillatory it would be the preferable type.

The reactive-coil protects the station against a high-frequency oscillation, but offers no protection whatsoever against static charges of low-frequency surges, because the amount of reactance which can be introduced is limited: The reactance employed must be less than would be appreciable at the normal frequency of the system; and therefore less than would exert an appreciable effect on low-frequency surges. Its purpose is to obstruct a high-frequency oscillation, like that of a Leyden jar discharge, but it is not a general protective device any more than is the series resistance.

The important feature of very high-power discharges is their extreme suddenness, which causes destruction at the point of entrance, usually in the middle of the transmission line, without transmitting sufficient energy to the terminal stations to be very serious at those points. Very high-power discharges destroy transmission-line poles, but do not menace a station unless the discharge occurs very close to the station.

J. B. Taylor (by letter): Professor Franklin referred to the suddenness and sharpness of the sounds caused by atmospheric disturbances on telephone lines indicating rapidity with which charges may collect on a conductor under different atmospheric conditions. Tests on telephone lines have led me to the conclusion that these sharp crackling sounds are due to the sudden discharge of a line to ground, on account of its potential having gradually increased to a breaking-down point. On several occasions I have observed discharges of this nature in the middle of winter during snow storms. A line approximately 40 miles long would charge and discharge with such rapidity that the disturbance in the telephone line was, on several occasions, mistaken for a cross with a telegraph line.

The action in this case was apparently as follows: each flake of snow carries a charge, and sufficient of these strike the wires to charge the whole line. On account of the protectors used—carbon blocks separated by thin sheets of mica—as soon as the line reached a potential of about 400 or 500 volts one of the discharge gaps would be bridged, and the line discharged with the accompanying sharp click, these discharges occurring so rapidly that the result was the same as though the line had become crossed with a telegraph circuit. A Weston voltmeter connected between telephone line and ground would give a steady deflection, in one case the deflection corresponding to a current of, roughly, 3 to 4 milliamperes. These disturbances would sometimes continue without interruption for several hours, and the service was seriously interfered with. The obvious remedy was to ground the neutral, thus causing the charge to be dissipated as fast as it accumulated. This neutral point was readily obtained from a tap taken from the middle point of an impedance coil bridged across the line. The line to which I have referred was at Burlington, Vermont, and the observations made some years ago, when I had no facilities for getting more complete data as to the polarity and potential of the snow-flakes. Snow-storms causing this trouble would occur perhaps on an average of three or four times in a year.

After devising the grounded neutral for removing the trouble, I learned that in Montreal this same charging of lines during snow-storms was of more frequent occurrence, and the same remedy—the grounded neutral—used to remove such disturbances.

W. S. Franklin (by letter): The practically important thing nowadays in making up one's mind what to try in the way of improved lightning protection is *elimination*. Let us not entertain the distracting idea that everything ever imagined is to be considered in this important practical problem; in fact I think that many aspects of the lightning discharge may be legitimately and definitely set aside.

First as to globular lightning. There is no doubt in my mind that this is a wholly subjective phenomenon. A fixed impression on the retina of a particularly vivid end-on lightning flash follows the eye when, at the crash of thunder, the attention of the observer is upset and at the same time the eyes jump and the slowly-moving globe of fire seems to have vanished in a crash of simultaneous thunder.

Secondly, as to sudden versus sluggish lightning discharges. I believe that the sudden variety is the only variety that need be considered. Even the slow accumulation of charge on a line which engineers call the "static charge" is a series of spits, if one can trust the evidence of the telephone. A very sluggish lightning discharge of moderate intensity can be taken care of by the grounding of a point in the system; for example, the neutral point in a three-phase system, and a very sluggish discharge of high intensity would on the other hand represent an immense amount of energy and it would have to be taken care of by the same means that are used to guard against short-circuits in the system; that is, by fuses and circuit breakers.

Thirdly, as to the use of a guard wire. A complete metal shell would be absolutely effective as a screen for purely static effects, and at the time of discharge a complete metal shell would allow a disturbance to pass through it too small to be of any consequence. The incomplete metal shell, the guard wire, approximates in its degree of shielding to a complete metal shell. For purely static and very sluggish dynamic effects this degree of approximation is fairly great. For extremely abrupt dynamic effects, however, the guard wire becomes more and more nearly ineffective. Sunlight, for example, is an extremely abrupt type of electrodynamic disturbance, and of course in this case the guard wire screens only its shadow.

I am inclined to think that the value of the guard wire lies mostly in its affording what one might call a spark-guard to prevent a spark from above from actually reaching the transmission wires. Of course when analyzed this spark-guard effect partakes in part of the nature of the ideal screening effect of which Dr. Steinmetz speaks, but it is by no means simply that. The behavior of a system at the instant of a breakdown cannot be described in terms which apply to the system in a quiescent or steadily varying state; the ideas of static screening and of the reflection of an orderly electromagnetic wave by the guard wire cannot be applied to what takes place at the instant of a terrific collapse or breakdown of the dielectric (the air) near the line.

Fourthly, it may be of importance so to design a transmission line as to realize the condition of the "distortionless" circuit; for example, by providing high-resistance leakage paths to earth from the line, so that any wave starting out from the place of a lightning discharge would retain its abruptness unimpaired, and thus be of a character to be arrested by a choke-coil and deflected to earth through a spark-gap.

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THE NATIONAL BUREAU OF STANDARDS.

BY S. W. STRATTON AND E. B. ROSA.

Early in the history of our Government an office of weights and measures was established in connection with the Coast & Geodetic Survey for the purpose of providing suitable standards of length in connection with its work. At about the same time it became necessary for the Secretary of the Treasury to adopt standards of mass and capacity, and to provide copies of the same for use at the various custom-houses, thus increasing its functions to include mass and capacity. Later he was directed by the Congress to provide copies of these standards of length, mass, and capacity to the various states. This work was necessarily delegated to the office of weights and measures. Precision measurements of length necessitated the adoption and comparison of thermometic standards through the ordinary range of temperature. During the last years of the office of weights and measures it had begun in a very small way the testing of standards of electrical resistance and electromotive force, but owing to the limited facilities of the office its work was practically confined to the bare necessities arising in connection with the work of the Treasury Department. In urgent and important cases comparisons were made for other departments of the Government and for the public, although no provision was made directly for that purpose. In the meantime the scientific, manufacturing, and commercial interests of the country had assumed gigantic proportions. Accurate measurements were employed where before guesswork and rules of thumb were considered quite sufficient. Scientific work, and the introduction of scientific methods of manufacturing necessitated accurate methods of measurement. The dissemination of scientific knowledge and the adoption of the interchangeable method in manufacturing made the use of uniform working standards imperative, a result to be obtained only through primary standards of the highest type, and a central institution provided with the facilities for their comparison with secondary or working standards.

It was not until 1901 that our Government provided suitable standardizing facilities, although the necessity for such work had been recognized for many years previously. In fact the demand for it had become so great that for some time previous to the establishment of the National Bureau of Standards we were compelled to avail ourselves of the facilities of foreign governments; principally those of the Physikalisch-Technische Reichsanstalt of Germany, an institution to which too much credit cannot be given for having demonstrated the value of such institutions founded on broad scientific principles, and independent of commercial considerations. The work of that institution is too well known for further comment, but it may be safely stated that were it not for its magnificent example the Bureau of Standards would probably not be in existence to-day. At that time the United States held a creditable position in physical science and had some of the best laboratories in the world; it was leading in the manufacture of electrical and other machinery, and in some kinds of scientific instruments. To be compelled to ask foreign laboratories for standards and standardizing facilities was clearly a situation that ought to be corrected. The Congress acted promptly when the matter was brought to its attention.

Funds were appropriated for the construction and equipment of laboratories and for a small scientific force, with a view to increasing the latter as soon as the laboratories were completed. Since it would require at least two to three years for the planning and building of the laboratories, temporary quarters were at once secured in connection with the quarters formerly occupied by the office of weights and measures.

Immediately after the passage of the Act establishing the Bureau of Standards, March 3, 1901, the planning of the laboratories was begun, as well as the selection of the scientific staff, and the development of some of the more important methods of testing. The first and one of the most important problems which presented itself was the selection of a site. After a careful examination of all the sites available in that section of the city of Washington, in which it was desired to locate the bureau, one was found which was sufficiently near the city and lines of transportation to be reasonably easy of access, and which possessed the desired physical qualifications. The site secured is about 7.5 acres in extent and is situated in the northwest section of the District of Columbia, about 3.5 miles from the White House on Connecticut Avenue extended. The location has proved by experience to be a most excellent one, and while it is sufficiently large for immediate purposes, steps have been taken towards securing sufficient adjacent property to protect the bureau from mechanical and electrical disturbances that may arise with the future development of the city.

The selection of the site was naturally followed by the designing and constructing of the buildings. It was decided to erect two buildings, one of which should contain the mechanical plant, instrument shop, and other work requiring heavy apparatus; the other, a physical laboratory, situated at some distance from the first, and as far as possible free from machinery or mechanical disturbances. The amount appropriated for the buildings, exclusive of the equipment, $325 000, would not permit of ornamental or expensive construction; nevertheless it was sufficient to erect two strong, substantial, fireproof buildings, of dark-red brick, trimmed with buff Bedford limestone; and of a style well suited for laboratories. They were designed by the Supervising Architect of the Treasury Department according to general specifications drawn up by the experts of the bureau. At all times these experts exercised direct supervision as to both design and construction. Both buildings were planned with reference to future extensions on the east and west. A third building to accommodate machinery for the liquidification of gases is nearly completed; it is practically an extension of the mechanical laboratory to the west.

It is proposed to erect a similar but larger building at the east of the mechanical laboratory for the testing of engineering instruments, the strength and other properties of materials. At the east and west ends of the physical laboratory it is proposed to erect in the future two buildings, each about the size of the present physical laboratory, one to be devoted to electrical work, the other as a chemical and metallurgical laboratory. The entire group of buildings will be connected by tunnels through which heat, power, light, and other facilities will be distributed from the mechanical laboratory. In designing the buildings and their equipment special attention has been paid to the production and distribution of general laboratory facilities, the details of which will be described later. The work of many physical laboratories is seriously handicapped by the lack of these facilities, such as a sufficient range of temperature, pressure, and electrical current. Often the provision of some special facility necessitates a greater expenditure of labor and time than the solution of the problem in hand. The testing work of the bureau also requires a complete variety and range of these facilities.

One of the first principles laid down in the general specifications of the laboratory was that it should be possible to install at any time pipes or wires leading from the mechanical plant to the various laboratory rooms, or from one room to another. This principle has been rigorously carried out and will be adhered to in all future buildings. Another feature incorporated as far as possible is that all laboratory rooms shall be general in character, that is to say, all are provided with the same facilities, temperature regulation, and conveniences, varying only in the special equipment installed, so that any room in the physical laboratory would serve almost equally well for investigations or testing in optics, electricity, heat, or for precision measurements of length, mass, and capacity. The space beneath the first floor of the physical laboratory is unexcavated, thus obviating all fixed piers of masonry, but which may be installed when and where necessary or removed in case they are not needed. The heavy wall brackets are attached to the wall in such a manner that they may, also, be removed in case the wall space is required for other purposes. The physical building has now been occupied for about a year and has been found to be exceedingly well adapted to the purpose for which it was designed.

The entire personnel of the bureau, numbering 14 the first year, was increased to 24 the second year, 58 the third year, 71 the fourth year, and 87 for the present fiscal year beginning July 1, 1905, the fifth year in the history of the bureau. Over 75% of the personnel consists of scientific and technical men, the selection of which presented a difficult problem owing to the high standard that must be maintained by the bureau, and the great demand for the same classes of men by educational institutions and the engineering professions. Nevertheless, the bureau from the beginning has insisted on filling its positions with none but the best material, often allowing them to remain vacant rather than appoint undesirable or even fairly good men. The selections have always been made by competitive civil service examinations; this is not always the quickest or most advantageous way of selecting professional men, especially when the demand is greater than the supply, but it guards successfully against political influence or favoritism. The Civil Service Commission has coöperated with the bureau in maintaining a high standard in the scientific qualifications of its personnel. With the exceptions of the leaders in the principal lines of the bureau's work, the policy has been to appoint graduates of first-class scientific or technical colleges to the lower grades of assistantships, advancing them to the higher grades as they become proficient and vacancies occur. At entrance they are allowed to select the line of work in which they desire to specialize, and every opportunity is given them for development. The leaders of several important sections of the bureau are men who entered it as minor assistants, but who were equipped with a thorough scientific training which enabled them to take advantage of the splendid opportunities the bureau offers in certain fields of scientific research.

The grades, or ranks, in the scientific corps are: laboratory assistant, assistant physicist or chemist, associate physicist or chemist, and physicist or chemist, with two or three different salaries in each grade. With a few of the higher positions yet to be provided, they constitute a series of positions with a uniform gradient of salaries from the lowest to the highest. Whenever possible vacancies or new positions are filled by promotion, new men being appointed to the lower places, but always selected with the educational qualifications that will permit of the advancement of meritorious men through all of the grades above. Promotion in all cases depends upon the success with which the work of the previous grade has been performed. This principal is not only adhered to in the scientific corps, but in the clerical and engineering positions of the bureau.

To provide the minor assistants in the routine testing and experimental work, a system of apprentices and aids has been established. Graduates of first-class manual training and technical high schools are appointed to the position of apprentice and advanced to the position of aid at end of two years, or as soon thereafter as a vacancy may occur. All aids are eligible for promotion to the lowest grade of laboratory assistant, if during the period of minor service they have acquired the requisite mathematics and theoretical scientific training, provision for which is made in the evening classes of the George Washington University of Washington. While the work of the younger members of the bureau's staff is carefully supervised by its experts, independent thought and originality are encouraged, due credit being given them in the publications of the bureau, when merited.

Manufacturing concerns and engineers solve great problems by the association of experts. In like manner the different sections of the bureau coöperate and assist one another in their work. For example, the specialist engaged in the development of the fundamental electrical standards has at his hands the best facilities for the measurement of length, mass, time, and temperature, and can readily consult with the corresponding experts, as well as with the chemist. The advantages to be gained by this association of specialists can only be appreciated by those who have wasted valuable time calibrating or testing instruments which were only incidental to the problem in hand.

The entire scientific staff of the bureau meets once a week in a room set aside for this purpose. This room is equipped with all the facilities of a first-class physical lecture room where papers intended for publication are presented and discussed. Current literature pertaining to the work of the bureau is reviewed, and reports made as to work contemplated or in progress.

The leaders of the various sections of the bureau's work constitute a Council which meets from time to time with the Director for the discussion of matters pertaining to the policy, or administration, of the bureau. The results of all scientific work intended for publication are submitted to the Council for approval. The Council has been of great assistance in the administration of the affairs of the bureau; great credit is due its members, and especially the editorial committee, for the care and supervision they have exercised as to the bureau's publications.

The working unit of the bureau's force is the section based upon a definite class of work and headed by an expert. For purposes of administration, these sections are grouped into three divisions; the first under the immediate charge of the Director comprises six sections, as follows:

1. Weights and Measures.
2. Heat and Thermometry.
3. Light and Optical Instruments.
4. Engineering Instruments.
5. The Office.
6. The Instrument Shop.

The second division, in charge of the physicist, also comprises six sections, as follows:

1. Resistance and Electromotive Force.
2. Inductance and Capacity and Absolute Measurements.
3. Electrical Measuring Instruments.
4. Magnetism.
5. Photometry.
6. The Engineering Plants.

The third division comprises the chemical work of the bureau and is in charge of the chemist, but has not as yet been subdivided into sections. As the work and personnel of the bureau grows, the more important sections will become divisions.

The scientific staff for the present year consists of 1 physicist, 1 chemist, 4 associate physicists, 1 associate chemist, 9 assistant physicists, 2 assistant chemists, 17 laboratory assistants, 4 aids, 4 laboratory apprentices; total 43.

The office and clerical force consists of 1 secretary, 1 librarian, 6 clerks, 1 storekeeper, 1 draftsman, 6 messengers; total 16.

The engineering and mechanical personnel for the present year consists of 1 engineer, 3 assistant engineers, 1 electrician, 6 mechanicians, 2 woodworkers, 2 shop apprentices, 3 firemen, 6 laborers, 2 watchmen, 1 janitor; total 27.

The Act establishing the Bureau of Standards provides for a Board of Visitors, to be composed of scientific or technical men who shall visit the bureau at least once a year and report on the work of the bureau, its equipment, and personnel. It was thought by those interested in the establishment of the bureau that a board of this kind would serve to guard the character of its work, and advise as to the policy of the institution, especially as to its relations to the public. The Board of Visitors consists of five members, each appointed for a period of five years; the original appointments being made for one, two, three, four, and five years respectively. Thus far the members appointed originally for a period of less than 5 years have been reappointed. At present the members are: President Ira Remsen of Johns Hopkins University, representing the chemical interests of the country; President Henry S. Pritchett, of the Massachusetts Institute of Technology, representing technical educational institutions; Professor Elihu Thomson, representing the electrical interests of the country, and whose selection was made at the suggestion of the members of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS; Professor Edward L. Nichols, representing physical interests; and Mr. Albert Ladd Colby, Secretary of the American Association of Steel Manufacturers and representing a wide range of manufacturing to which the bureau's work is also very closely related. These gentlemen have all been connected with the bureau from the beginning and have been of great assistance in its development.

The Director of the bureau renders an annual report to the Secretary of Commerce and Labor, covering a financial statement and the principal needs of the bureau in the exercise of its functions. An estimate of the expenses for the next fiscal year is also submitted, which is transmitted to the Congress as a basis for making appropriations. For the present year the appropriations were as follows:

Salaries	$99 660 00
Apparatus and Equipment	40 000 00
Fuel and Miscellaneous Expenses	12 500 00
Improvement and Care of Grounds and Buildings	2 500 00

The functions of the bureau as defined by law include the custody and construction of primary standards, the construction of secondary standards, their multiples and subdivisions, and the comparison of these standards with the secondary or working standards used by the public. The bureau is also authorized to determine physical constants and the properties of materials. The importance of such problems is too well recognized for comment, but the character of the work involved and the apparatus employed can hardly be appreciated by those who have not been brought in touch with it. Consider, for example, the construction of a copy of the standard metre, and the work involved in subdividing it to the ultimate division of a micrometer, or the construction of its multiples as used in base measuring apparatus, steel tapes, and other engineering standards, also the testing of the various instruments for measuring temperatures from that of solid hydrogen to the highest temperatures that it is possible to produce. And yet, these are but examples that have their counterpart in every section of the bureau's work.

The relation of the bureau's work to the manufacture of scientific instruments and apparatus is very close and important. The bureau is coöperating with the makers of such apparatus in every way possible; they visit the bureau from time to time for suggestions and advice, and are regularly submitting apparatus to the bureau for testing and investigation. The time is not far distant when our makers of scientific apparatus will be supplying not only the home demand but also the foreign markets. The benefit to be derived from the bureau to this industry would alone justify its maintenance.

The laboratories of the bureau are always open to manufacturers, scientists, and others who desire information or instruction as to methods of measurements, physical constants, or the properties of materials. The bureau receives daily many requests for information of this character, and it is rapidly becoming one of the most important parts of the bureau's work.

The Mechanical Equipment.

The mechanical building contains the mechanical and electrical plant, the instrument shop, about one-half of the electrical work, photometry, and engineering testing. It stands on ground sloping towards the north so that the north part of the basement story is wholly above ground, but projects only a few feet above it on the south. The accompanying views of the building were taken before the grading of the grounds was completed. The building is 135 ft. long east and west, 48 ft. wide at the ends and 58 ft. wide in the center. An extension of the basement wholly below the ground level on the south is 20 ft. wide and projects 25 ft. east and west beyond the main portion of the building, Figs. 1 & 2. This increases the floor area of the basement by 50 per cent., affording ample accommodation for the mechanical and electrical plant on this floor.

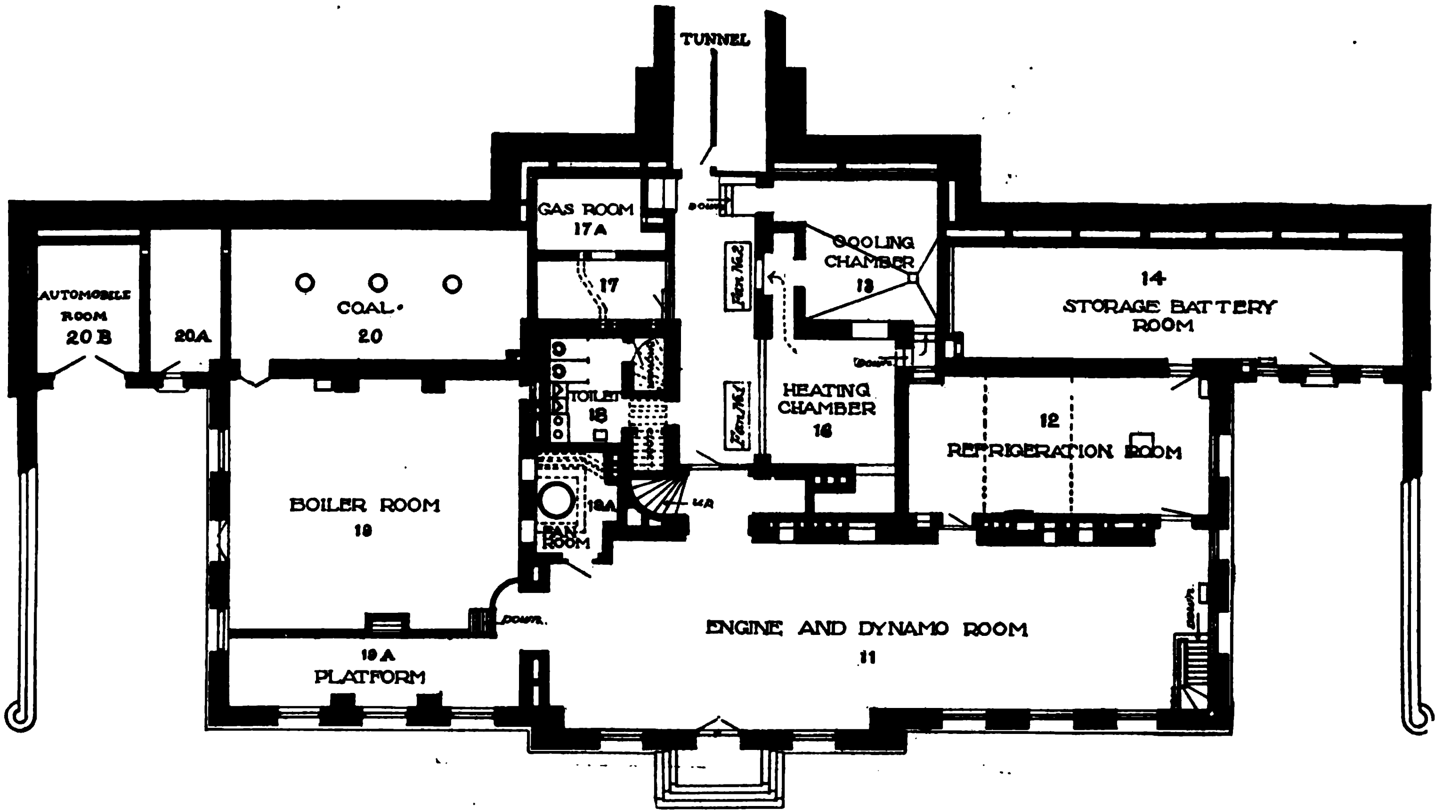
The boiler room is 42 ft. square and 19 ft. high, the floor being 5 ft. below the engine room floor, and like the engine and dynamo room it is lined with white-enameled brick. Two water-tube boilers of 125 h.p. each have been installed together with an economizer and forced draft. Space is reserved for additional boilers, with a final capacity of 500 h.p. The platform along the north side of the boiler room accommodates the filters, electric and steam high-pressure water-pumps, boiler-feed pumps, feed-water heater, and other auxiliary machines. Under the platform are located the heater for the hot-water service, pressure tanks for the cold water service, storage-tank, etc.

The engine and dynamo room is 87 ft. long and has an average width of 24 ft. The larger of the two engines is a tandem

FIG. 1—Mechanical Building (from the South).

compound of 120 h.p., driving two direct-current 37.5 kw. generators, each giving 300 amperes at 120 volts connected in a three-wire system. The smaller engine, shown at the right in Fig. 3, has a capacity of 40 h.p. and, like the larger engine drives two direct-current generators. Beyond the engines there are the following machines some of which have been installed since the accompanying picture was taken.

1. A double motor-driven booster for charging storage-cells, having a capacity on each side of 200 amperes at 30 volts



MECHANICAL LABORATORY—BASEMENT FLOOR PLAN.

and which is also used alone to charge storage batteries of relatively low voltage and large current capacity.

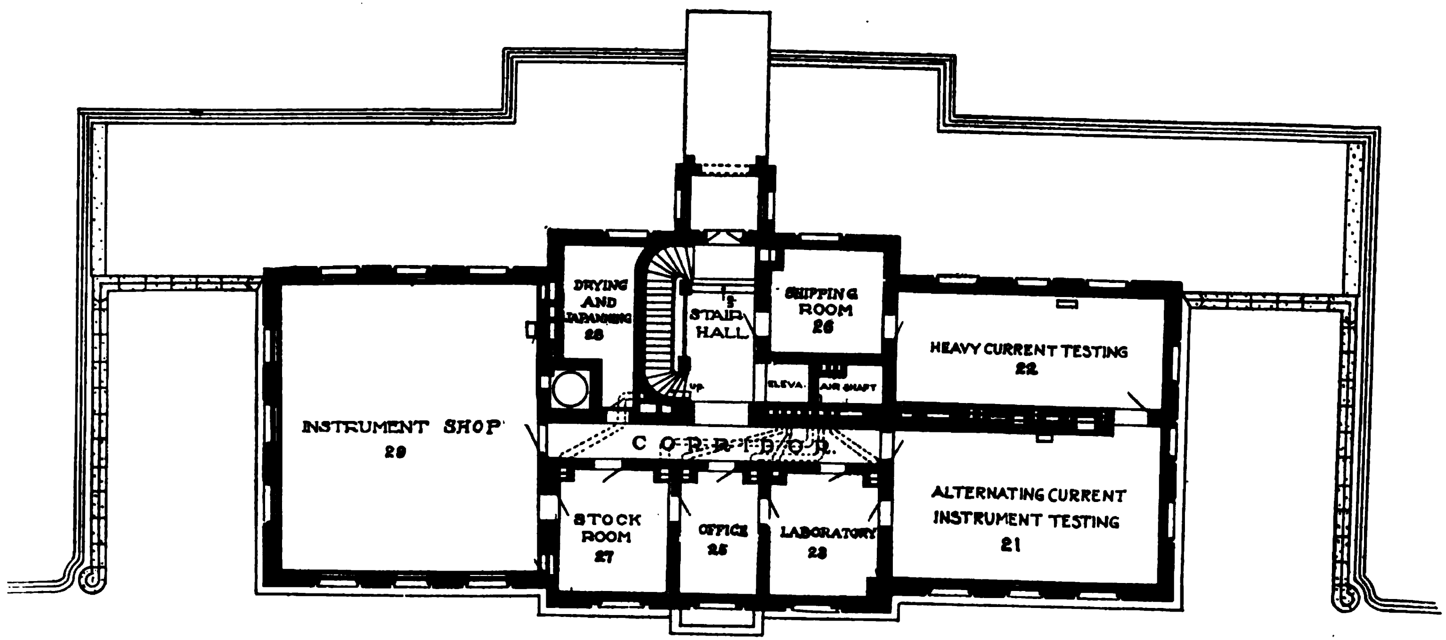
2. A pair of two-phase alternators, surface wound, and giving an electromotive force of nearly sine wave form, direct connected to a driving motor. One machine gives 60 cycles and the other 180; the two may be placed in series and the wave form varied through wide limits by varying the relative amplitudes and phases of the two waves. By using them separately and varying the speed, considerable ranges in frequency may be obtained.

Fig. 2—Mechanical Building (from the North).

3. Another three-machine set contains two 60-cycle, three-phase alternators, the relative phases of which may be varied by shifting the field of one of them. Thus, connecting one to the current coil and the other to the voltage coil of any instrument, any required power-factor may be obtained.

4. A second smaller set of a similar kind gives two 60-cycle currents of adjustable phase relation. This is useful in calibrating phase indicators as well as testing power measuring instruments.

5. A three-phase 120-cycle alternator, driven by an inverted



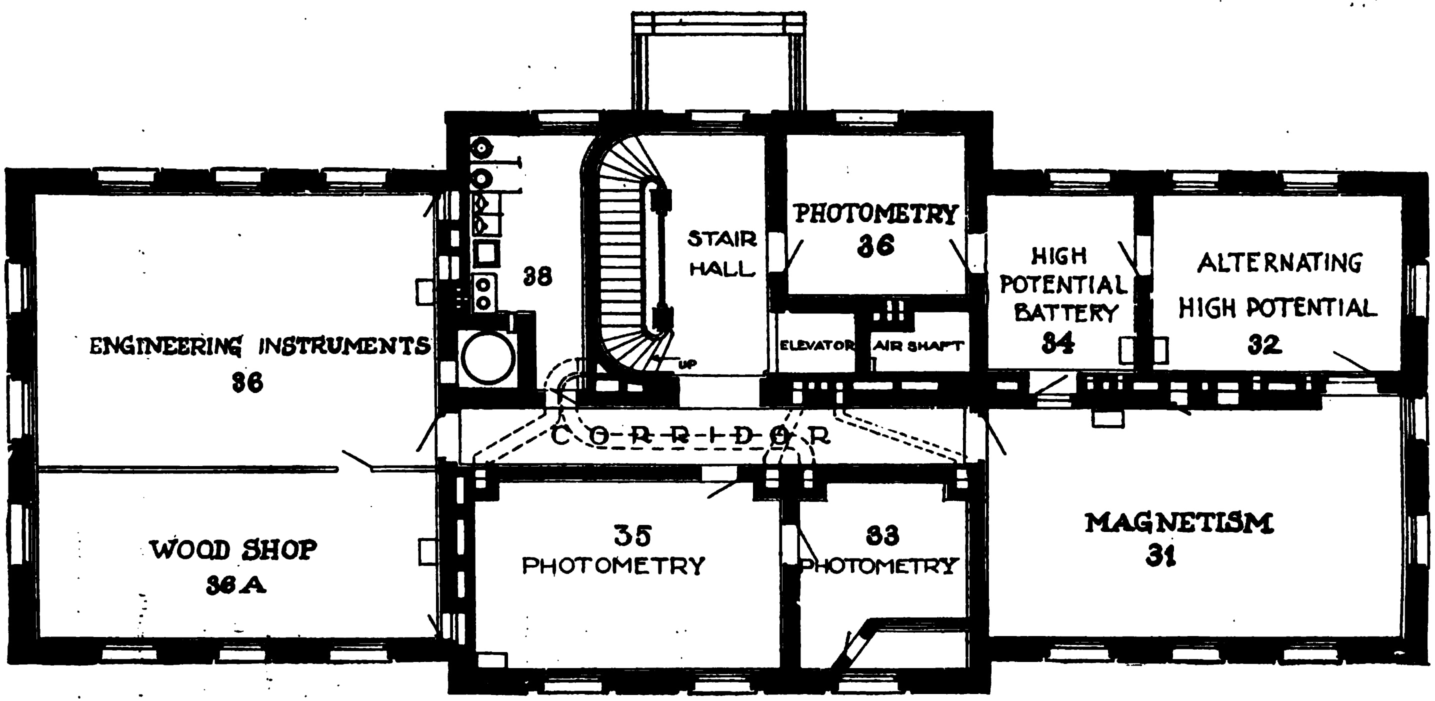
MECHANICAL LABORATORY—FIRST FLOOR PLAN.

synchronous converter used as a motor, the latter also giving alternating current at 60 cycles.

6. A ten-machine set has been built and is soon to be installed. This set contains eight alternators and two driving motors all direct connected, but capable of being uncoupled in the middle and operated as two independent sets. One set has, besides the driving motor, three alternators of 6, 18, and 30 poles respectively, giving 60, 180, and 300 cycles, sine-wave form, and capable of being joined in series, so varying the wave form. The second set has a driving motor and five alternators

FIG. 3—Engine Room.

giving 420, 540, 660, 780, and 900 cycles respectively. All the machines may be joined in series, as they have the same current capacity, namely, 20 amperes. The voltages, however, decrease gradually from 250 for the largest to 10 for the smallest. When joined in series all the odd harmonics to the 15th will be present in the electromotive force, or any may be quickly cut out. The wave form can be varied indefinitely by varying the number of harmonics employed and their relative intensities and phases. This machine will be very useful in testing and research, not only for varying wave form, but for obtaining a great variety



MECHANICAL LABORATORY—SECOND FLOOR PLAN.

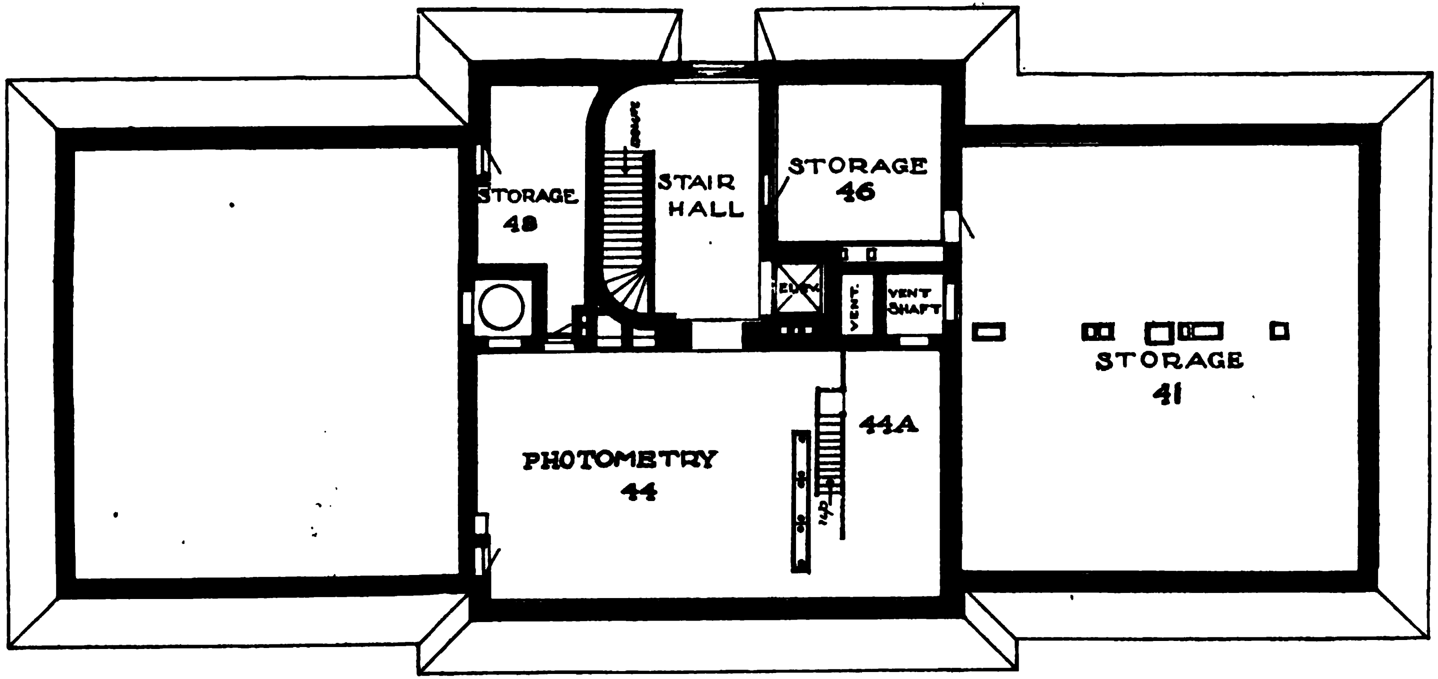
of frequencies. The switchboard, which is now building, will be equipped with hot-wire instruments arranged to show what components enter into the resultant electromotive force. The operating switches give quick and complete control over the various possible combinations.

The switchboard shown in Fig. 3 not only controls the various direct- and alternating-current generators, but also six storage-batteries arranged in groups of two on the three-wire system, for use in operating the motors when great steadiness of speed is desired, for lighting and power when the engines are not running, and for experimental purposes. There are also several plug-panels which enable the current from any generator or battery to be sent to any laboratory room in either building.

In the foreground at the left is shown part of a motor-driven exhaust-fan for withdrawing fumes from the battery rooms and other rooms of both buildings.

In the sub-basement under the engine-room floor are located the high-pressure steam-mains, exhaust-steam pipes, air-ducts, water, gas, and other piping, and the wiring. This gives an engine room practically free from piping, affording free travel for the crane and giving a very pleasing appearance.

The refrigeration room is 41 by 18 ft. and contains a 30-ton ammonia refrigerating machine of the absorption type. Its capacity is equivalent to the melting of 10 tons of ice in 8 hours. This is used to furnish low temperatures in small rooms for experimental purposes, to remove moisture from the air of laboratory rooms in order to obtain a dry atmosphere in hot or wet weather, and for making ice. The machine is indispensable, and greatly increases the efficiency of the laboratory work, more especially of course in the summer; but it is found necessary to use it for some kinds of work part of the time during at least 9 months of the year. The cold brine is pumped from the machine through a system of piping around both buildings, so that it may be used in almost any of the laboratory rooms. Flowing through a coil of pipe in any room, it condenses moisture out of the atmosphere and reduces the humidity from 100 or 90 or 80 per cent. to perhaps 70 or 60 or 50 per cent. according to the surface exposed. Thus electrical surface leakage may be so far reduced that precision measurements may be made in the hottest and dampest summer weather. Moreover, the temperature of the laboratory may be controlled



MECHANICAL LABORATORY—ATTIC FLOOR PLAN.

at the same time, the gradual rise of temperature during the day being prevented. The rate of absorption of heat may be regulated by varying the speed of the fan which blows air against this cold brine coil.

A large tank of calcium chloride brine in the sub-basement under the refrigerating room gives a considerable storage capacity for "cold," and avoids the necessity of running the machine every day except in summer.

The storage-battery room is 61 ft. long and contains the following chloride cells:

4 batteries of 66 cells each, 200 ampere-hour capacity.
2 " " 66 " " 400 " " "

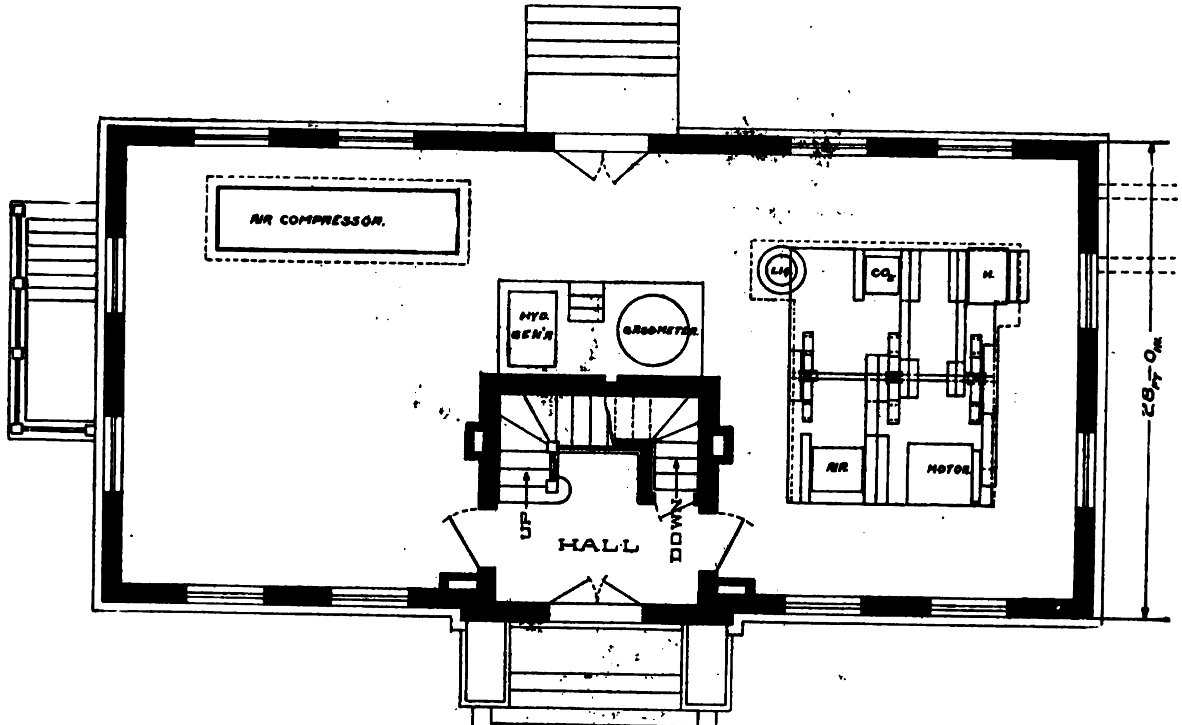
Two additional batteries of the 400-ampere size will probably be installed next year.

The heating and ventilating plant is located near the engine room, as shown in the basement floor plan.

The forced draft, double-duct system is used, with thermostatic dampers to control the proportion of hot and tempered air in each room so as to secure constant temperature. This is effective in cool weather; in hot weather the temperature of the laboratory rooms may be controlled by means of the brine coils. Two large motor-driven blowers stand in the basement hall, at the entrance to the tunnel, one handling the hot air and the other the tempered air. The second may receive cooled air (in hot weather) from the cooling chamber, which contains a large number of brine coils. The hot and tempered air for the physical building passes through ducts in the upper part of the tunnel to the basement of the physical building, and is there distributed through the flues shown in the floor plans to the various rooms. The air is heated by passing through stacks of steam-coils, the steam being for the most part the exhaust from the engines.

The Low-Temperature Building.

The low-temperature building is being erected to accommodate the machinery and apparatus necessary for the liquefaction of air, hydrogen, and other gases, and to provide space and facilities for low-temperature experiments. The building is about 28 by 58 ft. and two stories high, being built of dark red brick, trimmed with limestone to correspond with the main buildings. It is connected with the sub-basement of the mechanical laboratory by means of a tunnel, through



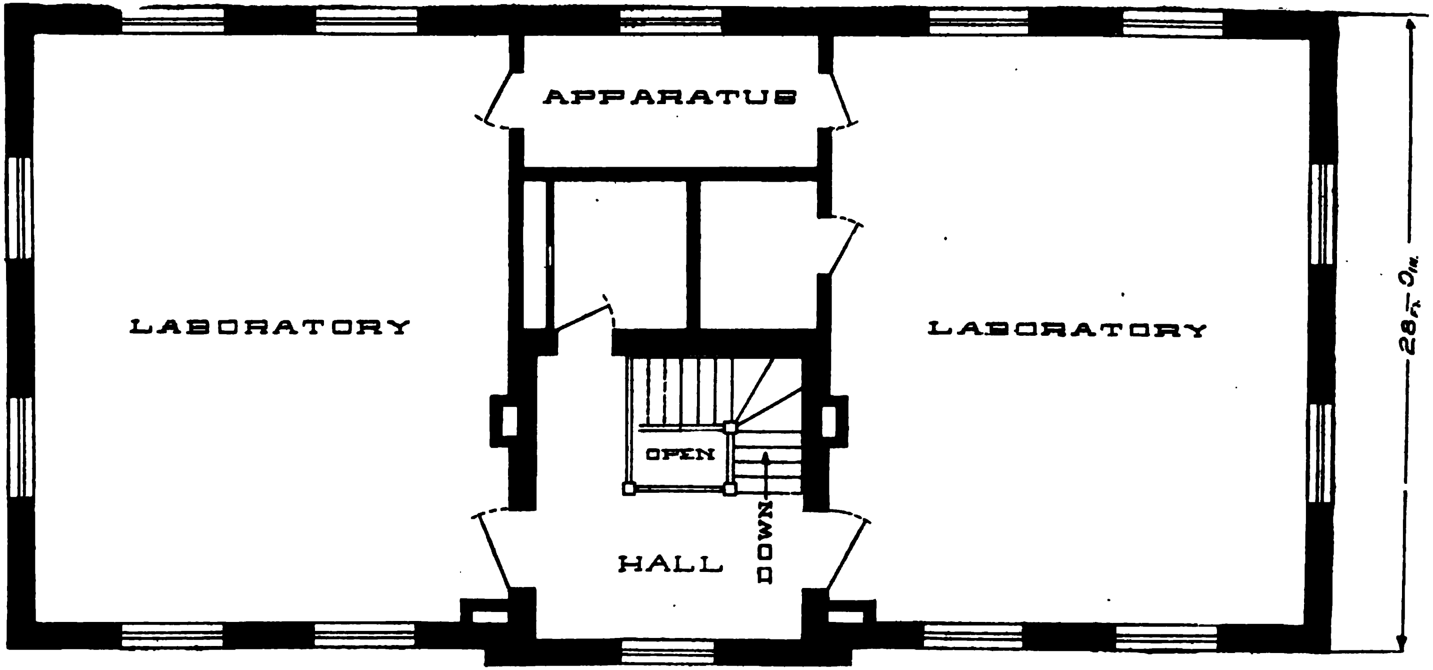
LOW TEMPERATURE LABORATORY—FIRST FLOOR PLAN.

which water, gas, steam, and waste pipes and wires are carried. The bureau purchased from the British government a complete plant for the liquefaction of air and hydrogen; this was built in London and exhibited last year at the St. Louis exposition. The apparatus consists of a hydrogen generator and gasometer for storing the gas; power pumps for compressing air and hydrogen to 3 000 pounds per square inch, and heavy cylinders for storing hydrogen at this pressure; a combined air and hydrogen liquefier; and a machine for liquifying carbon dioxide

Fig. 4.—Low-Temperature Building (under construction).

which is used as an auxiliary refrigerant in the process of liquifying air. In liquifying hydrogen, both liquid CO_2 and liquid air are employed as auxiliary refrigerants, the compressed hydrogen being thus cooled to the temperature of liquid air and then suddenly expanded, thereby suffering a reduction of temperature sufficient to liquify a portion of the gas. The liquified hydrogen may be frozen in a separate apparatus, its temperature being reduced to about 16° absolute.

This is the only apparatus in America for liquifying hydrogen, and we believe the only one outside the Royal Institution

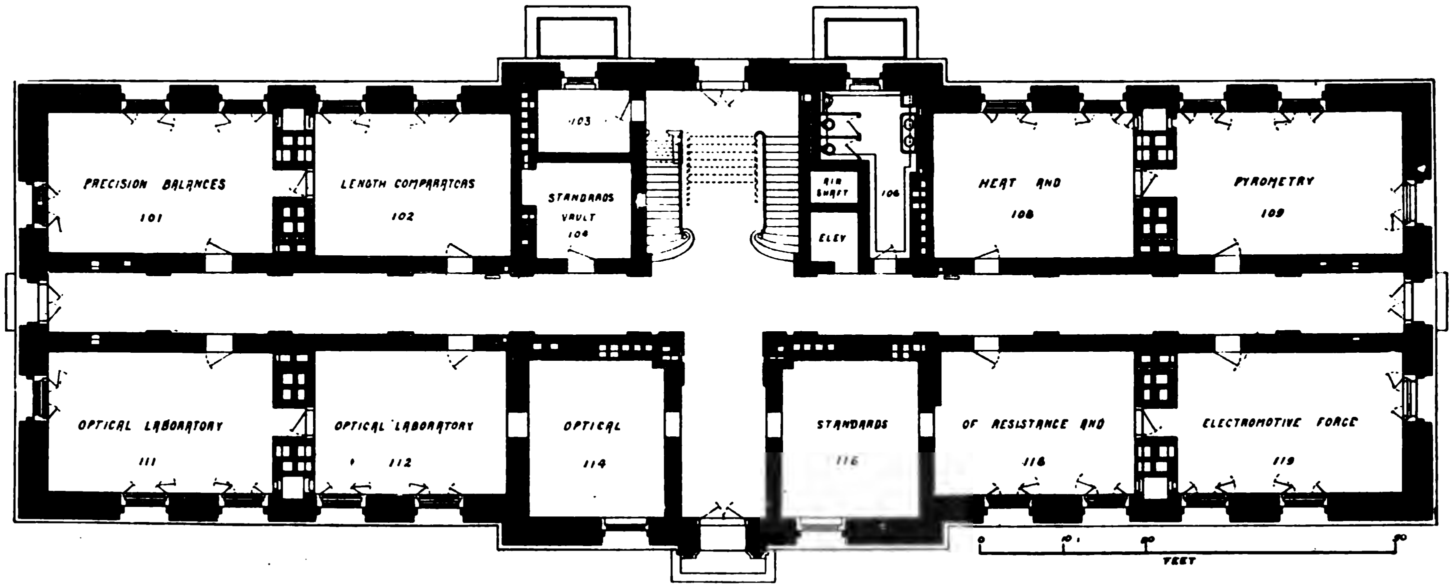


LOW TEMPERATURE LABORATORY—SECOND FLOOR PLAN of Great Britain for producing liquid hydrogen in considerable quantities; that is, by the liter. It will be of great service to the bureau in research work and also in the testing of low-temperature thermometers. In the near future a second air compressor of larger capacity will be installed and a second liquefier for air will be added.

Piping and Wiring of the Physical Building. The physical building is 172 ft. long, 55 ft. wide, and four stories high, besides a spacious attic. It faces the south overlooking the city of Washington.

FIG. 5—Physical Building (from the North).

The corridor extends the entire length of the first floor. The exterior of the building is so designed that the two additional buildings which may in the future be placed one on the east and the other on the west of this building may be connected with it by means of an arcade opening into the corridor of the first floor. A basement is excavated only under the central portion of the building and under the corridor; the four rooms at either end of the ground floor have concrete floors resting on the ground, covered by a substantial



PHYSICAL LABORATORY—FIRST FLOOR PLAN.

flooring of oak blocks. This gives a firm support for tables, apparatus or even temporary piers if necessary.

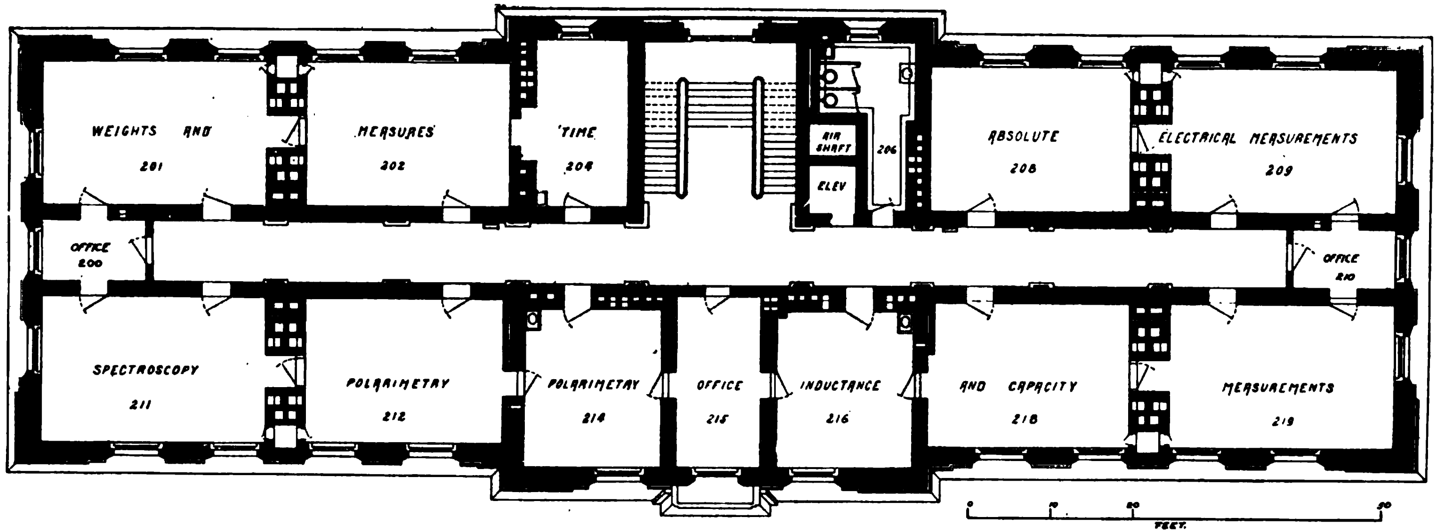
Instead of building up permanent piers through the floor as is often done, the entire building is so substantial and free from vibration that the most delicate apparatus can be mounted on brackets or shelves attached to the walls of the building.

In one of the basement rooms a subdivided storage-battery has been installed for use in this building. Six other rooms of the basement will be used as constant temperature rooms as they may be needed.

FIG. 6—Physical Building (from the Northeast).

The entire first and second floors are given up to laboratory work. And in order that the changes in temperature may be a minimum double windows have been provided, and automatic temperature control secured by means of thermostatic dampers, controlling the supply of hot and tempered air. This of course regulates the temperature only in winter, or in cool weather; in summer the temperature is controlled in some rooms when necessary by means of brine coils as explained above.

Between rooms 101 and 102, next to the outer wall, is a vertical shaft three feet square, extending from the basement



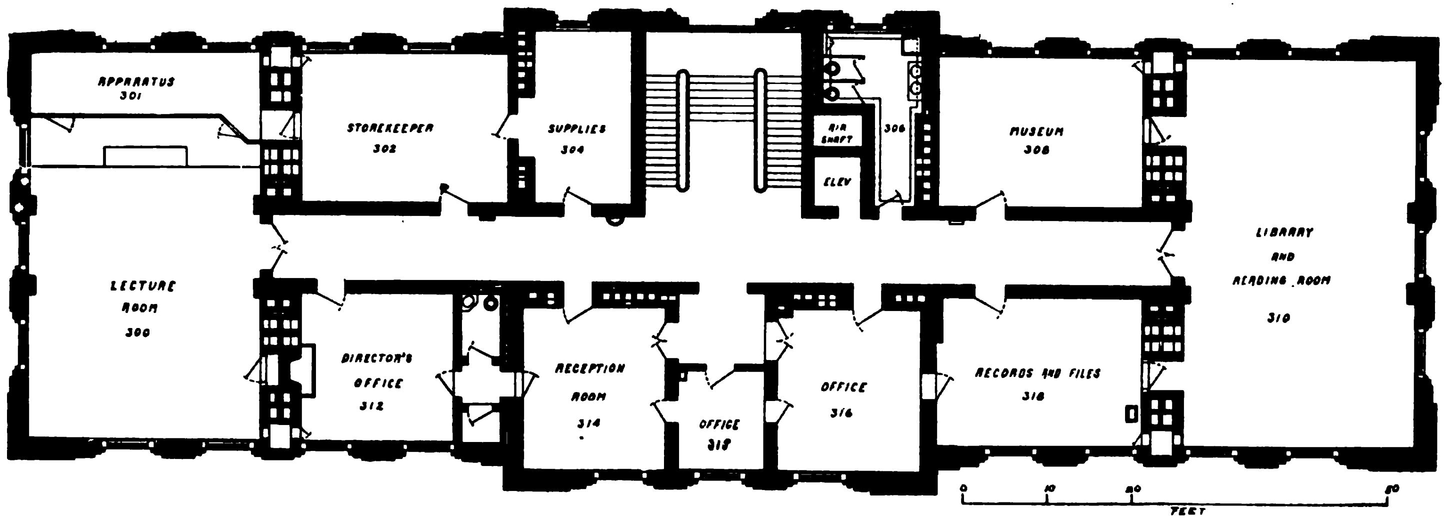
PHYSICAL LABORATORY—SECOND FLOOR PLAN.

to the attic, and in corresponding positions there are three similar shafts in the other three quarters of the building. All the pipes for distributing hot and cold water, ice water, cold brine, gas, compressed air, vacuum, and all electric wiring for lighting and experimental purposes are carried up through these shafts. A door opens into each shaft on each floor, making all main pipes and wires accessible without having them exposed in the laboratories. On each floor branches are brought out from the water and waste pipes to the sinks, from the air and gas pipes to the work tables, from the brine pipes to any cold boxes or other apparatus requiring it and from the distributing wires in the shafts, to the small local switchboards, of which there is one for each suite of laboratory rooms in the building. The wires connected to these small switchboards run to a main switchboard near the north door of the first floor, and thence trunk lines run through the tunnel connecting the two buildings to the main distributing switchboard of the dynamo room. Thus through these two main switchboards and a local laboratory board any circuit in any laboratory room may be joined to any circuit of any other laboratory room or to any battery or generator in the mechanical building. By means of a subdivided battery wired to the switchboard and an auto-transformer at the switchboard any direct or alternating voltage less than the regular line voltages (120 and 240) can at any time be obtained.

Great pains have been taken to equip every laboratory with the conveniences necessary for the most efficient work.

The General Division.

Section 1. *Weights and Measures.* The duties of the section of weights and measures include the comparison of standards of length, mass, and volume with the official standards of the United States, all of which are in the custody of the bureau. These measures are submitted by the government departments, by state and city inspectors of weights and measures, by manufacturers, and by scientific and technical institutions, and individuals. In cases where there are no local inspectors the bureau tests and seals commercial weights and measures, provided they conform with certain essential requirements as to construction. This section also gathers information as to the laws and usage of local and foreign weights and measures, and when such information is sufficiently important it is pub-



PHYSICAL LABORATORY—THIRD FLOOR PLAN.

lished by the bureau. In addition to the verification of weights and measures this section tests hydrometers and aneroid barometers, and it is preparing to take up the testing of watches and other time-measuring apparatus. To illustrate more fully the nature of the work of this section, it might be well to mention a few examples, and also to describe briefly the more important equipment.

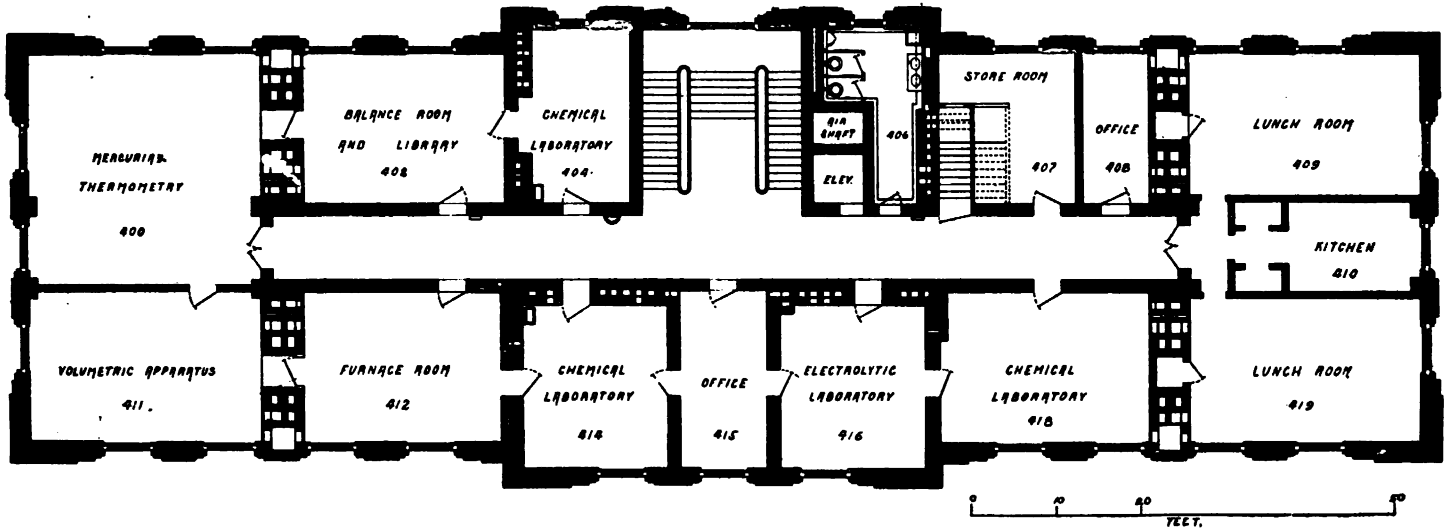
The construction in the shops of the bureau of a special comparator for directly comparing end standards and gauges with a line standard has just been completed. There is no problem in the field of precise measurements more difficult than to determine the absolute value of an end standard in terms of a line standard. It is comparatively easy to compare two end standards or gauges with one another to the one hundred thousandth part of an inch, but to determine their absolute values is an entirely different thing. Thus far all measurements made with this comparator have been made with contact pieces, between which the end standard or gauge is placed, and the contact pieces have been pressed together with a constant known pressure. This corresponds with the use of such gauges in practice, but on account of the possibility of wear on the gauges it is proposed to provide means for making the contacts by both optical and electrical means.

The bureau is well equipped to test-bars of one meter or less, and is rapidly completing a 50 meter comparator for testing tapes and geodetic base apparatus. When these comparators are finished it will be possible to measure 50 metres or yards with a probable error not exceeding the one five millionth part of the total length.

The bureau possesses two platinum-iridium copies of the international metre to which all length measurements, both customary and metric, are reduced.

For the comparison of masses, the bureau possesses a complete series of the very best balances, duplicates of which will only be found in the standardizing laboratories of a few of the first-class countries. All mass comparisons are referred to the international kilogram, two copies of which are in the possession of the bureau. Like the metres, they are made of platinum-iridium.

Last January a meeting of the state sealers of weights and measures was held at the bureau for the purpose of discussing the means for securing uniform laws and inspection of com-



PHYSICAL LABORATORY—FOURTH FLOOR PLAN.

mercial weights and measures throughout the United States. A compilation of the various state laws on the subject showed the greatest diversity. The efforts of the bureau will be toward uniform laws and practices in matters pertaining to weights and measures.

Section 2. *Thermometry, Pyrometry, and Heat Measurements.* The work carried on by this section includes the testing of thermometers of all kinds and of the various forms of pyrometers for the measurement of high temperatures, the determination of calorific values of fuels, and investigations bearing on the establishment and control of the temperature standards of the bureau. Information is furnished, upon request, to departments of the government, and to cities, manufacturing interests, technical schools, and individuals, as to methods of measurement, thermal constants, specifications for thermometers, etc.

The intercomparison of the primary standard mercurial thermometers of the bureau in the interval 0°–100° cent., in a specially designed comparator is now nearing completion. A number of platinum resistance thermometers, together with the necessary apparatus for their use, have been designed and constructed, to be used in connection with the establishment of the standard scale of temperature.

An investigation of the methods of measurement of high temperatures by means of the light and heat emitted by incandescent bodies, with a view to their application in the laboratory and in the industries, has been completed.

The demands of electrochemical processes make it necessary to control and measure temperatures far beyond the range of any pyrometer requiring contact with the heated substance. With the establishment of a satisfactory scale of extreme temperatures in view, an investigation has been carried on in which the several methods of estimating such temperatures by optical and radiation pyrometers were compared at the extreme temperature of the electric arc. The results of this investigation showed the several methods to be in satisfactory agreement.

The construction and study of a standard gas thermometer, which is the ultimate standard in all thermometric work, is of fundamental importance in its bearing on the standards of the bureau. Progress has been made in assembling the apparatus necessary for this investigation.

The low-temperature liquid air and hydrogen plant recently acquired by the bureau makes available the equipment necessary for the extension of the temperature scale and the study of the standards at the lowest attainable temperatures.

The great importance in many industrial processes of an accurate knowledge and control of the temperatures at which the operations are carried out is just beginning to be realized in this country. The representatives of many manufacturing plants have visited the bureau during the year, with a view to studying the pyrometers in use in its laboratories, and consulting its experts concerning the methods of temperature measurement. No inconsiderable part of the work of this section has been the furnishing of information of this kind to the public.

Section 3. *Optics*. While the work of this section is chiefly related to the determination of physical laws and constants, considerable testing has been done, especially in connection with polariscopic apparatus and standards. The spectroscopic work has been confined to the determination of the laws and conditions governing the production of pure spectra, with a view to their application in spectroscopic methods, the determination of standard wave lengths, and their use in optical methods of measurement. It has involved investigations in connection with the spectra of mixed gases and multiple spectra, and the spark and arc spectra of alloys. It is proposed further to examine the individual lines by means of the echelon spectroscope. For this purpose a 30-step echelon grating has been purchased and a special mounting constructed.

The work of polarimetry includes the examination of methods and apparatus used in polariscope analysis of sugar. Polarizing apparatus for especially accurate measurements and a thermostat for use in connection with this apparatus have been designed and built in the bureau shops. An accurate quartz compensation polariscope has been assembled, and a number of quartz control plates to be used as primary standards have been obtained. One of the greatest obstacles to accurate polariscopic measurements is the lack of sources of monochlomatic right of sufficient intensity. Sodium light, the accepted standard, is far from monochromatic. One of the spectral lines emitted by a quartz mercury lamp has been found to answer every requirement. Accordingly a determination of the rotation of quartz for light of this particular wave length has been undertaken. The measurement of the absolute rotation of quartz control plates for primary standards is well under way.

Section 4. *Engineering Instruments and Materials.* It has been impossible to assign to this section laboratory space and assistance commensurate with the importance of the work and the demand for testing. The bureau is in a position to study and test water meters not larger than 2 inches, gas meters, speed indicators, and pressure gauges. Designs have been completed for an anemometer testing machine, which is now in process of construction.

An investigation in connection with fire-hose couplings has been taken up with a view to the selection of a national standard in this direction. The more important tests of materials include the test of the tensile strength of the new cable for the elevator in the Washington Monument, the cement used in the construction of the new office building for the House of Representatives, and the adhesive power of a large number of mucilages, with a view to determining the proper specification to be used in government purchases of this article.

It is planned to increase the facilities for this work in the near future, to include the testing of engineering and building materials, not the mere physical tests of individual specimens which is now well done by private testing laboratories but their behavior under varying conditions.

Section 5. *The Office.* The clerical assistants of the bureau are organized as the office in charge of editorial work, the files, records, and accounts, the purchase and disbursement of supplies, printing, and the library. The office also furnishes the stenographic assistance to the various sections, attends to the mailing of publications, and other clerical work.

Section 6. *Instrument Shop.* An instrument shop equipped with suitable machinery and provided with expert mechanicians is an essential feature of any laboratory; this is especially true in institutions where precise measurements and original investigation constitute the greater part of the work. The shop of the bureau is equipped with modern machinery, each machine separately driven by an electric motor. It is both an instrument shop and a machine shop, capable of handling a wide range of work. A supply of metal sheet, rod, tube, and wires, as well as a great variety of other materials used in the construction of apparatus, is kept in stock. The mechanicians have been carefully selected, both as to personal and technical qualifications; they have been trained in the best American and foreign instrument shops.

A system of apprenticeship has been established. The apprentices are graduates of manual training and technical high schools, thus assuring the fundamental education necessary in this class of assistants, and so often lacking in men who have been trained in commercial shops.

FIG. 7—Instrument Shop.

THE ELECTRICAL DIVISION.

Section 1. *Resistance and Electromotive Force.* The work of this section consists in the construction and verification of resistance standards and standards of electromotive force, the calibration of precision rheostats, Wheatstone bridges, potentiometers, and other resistance apparatus, the verification of resistance standards for current measurement, and the determination of the electrical properties of materials.

The permanent equipment for this work, the installation of which has recently been practically completed, has been planned with the view of facilitating the routine testing work by the application wherever possible of direct reading methods and the use of specially designed apparatus; so that several fundamental investigations relating to the mercurial resistance standard and the standard cell can now be seriously taken up.

One of the rooms has been fitted up for the verification of resistance standards of precision, the results of which are, at present, based on the mean value of a number of coils as determined through one-ohm standards re-verified from time to time at the Reichsanstalt. The results are thus based upon the primary mercurial standards of that institution pending the construction of similar standards by the bureau, which work is now under way. A considerable number of standards, including the master standards of the leading American manufacturers of electrical apparatus have already been verified.

By the aid of the new Weston high sensibility D'Arsonval galvanometers, resistance standards as low as 0.0001 ohm are readily compared, by the Kelvin Double Bridge method, to one part in a million.

The comparison of coils without potential terminals is greatly facilitated by the aid of a direct-reading substitution method involving the use of a shunt compensation ratio set, one arm of which consists of four sections having a total resistance of one ohm, and provided with a separate ten-step shunt dial. The resistances are so proportioned that the dials correspond to 0.001, 0.0001, 0.00001, and 0.000001 ohm per step. Suitable comparing stands have been designed to adapt the method to the comparison of precision standards with potential terminals.

Special importance has been attached to the accurate establishment of the ratios 1:10, 1:100, etc., upon which the multiples and submultiples of the unit depend. Such measurements are quickly made to an accuracy of one part in a million by the aid of a mercury contact rheostat of the Anthony pattern by means of which one arm of a bridge may be altered in the ratio of 1:10:100 by parallel, series-parallel, and series combinations of ten approximately equal coils.

The equipment includes also a Carey-Foster Bridge built by the Weston Electrical Instrument Co., on plans elaborated from a bureau design.

For the calibration of resistance boxes, bridges, potentiometers, etc., a direct-reading apparatus has been designed based on the proportionality of the resistances included between two points in a circuit and two points having the same potential in a parallel circuit. By this method all errors due to plug-contact resistances are obviated and much time is saved. A direct-reading substitution method has also been employed with entire satisfaction.

In the calibration of resistance standards for current measurement the Kelvin double-bridge method is employed. Recently measurements were made to determine the change of resistance due to the Joule and Peltier effects, as the load and rate of stirring are varied.

Investigations pertaining to the standard cell, interrupted by the work incident to the equipment of the new laboratories, have been resumed in coöperation with the chemical division. An electrolytic method of preparing mercurous sulphate has been devised and efforts are now being made to obtain large and perfect crystals of that material by another method, on account of the alleged influence of the size of grain. The methods of preparation and purification of the remaining constituents and the influence of impurities are also under investigation.

Section 2. *Inductance and Capacity and Absolute Measurements.* This work includes the investigation of methods of measurement of inductance and capacity, the construction and testing of the bureau's standards of inductance and capacity, the testing of capacities and inductances for the public and the measurement of the inductances and capacities of instruments. The bureau possesses a series of standards of inductance and capacity, the values of which have been fixed with high precision using several different methods of measurement.

The testing of condensers includes: (1), the measurement of the capacity of the condenser; (2), the variations of this capacity with the frequency of charge or the duration of the charge; (3), the temperature coefficient; (4), the insulation or leakage resistance; (5), the phase angle of the charging current; that is, the power-factor of the current, which is very small in a good condenser. There are considerable differences even among good mica condensers, and very great differences when good and poor condensers are compared. The bureau possesses a series of mica condensers which represent the best makers of Germany, England, France and America. After testing a considerable number of condensers the performance of a good one has been determined. A good condenser after it has been investigated and its constants ascertained is a very valuable piece of laboratory apparatus, and is an instrument of precision. Without such investigation it is an unknown quantity. Every well equipped laboratory ought to have at least one such condenser, and it ought to be retested occasionally to guard against change.

Very few standard condensers are provided with thermometer holes, the idea being that the temperature coefficient is too small to be taken into account. This is a serious error. Provision should be made for inserting the bulb of the thermometer, not simply into the box containing the condenser, but into the mass of paraffine in which the condenser is imbedded, or at least in contact with the condenser. The temperature lag is considerable, but a thermometer used in this manner gives the mean temperature of the condenser very nearly and if the capacity is known at different temperatures it is not necessary to bring the condenser to a particular temperature.

Inductance standards are susceptible of very exact measurement, and if properly made are very permanent. Many of the methods of measuring inductances require the use of a standard, and some of these methods are convenient and very sensitive. If accurate standards are employed the measurement of inductance becomes a matter of precision. Very few laboratories possess such accurately calibrated inductance standards, and few people seem to realize that inductance measurements can be made with accuracy, or that there is any need of attempting to make them accurate. The bureau certifies well made standards of inductance (of suitable value) to 1/50 of one per cent. They are subject to much smaller changes arising from changes of temperature or of frequency of the test current than standard condensers, and are destined to play a much more important part in electrical measurements in the near future than in the past. The bureau will be glad to furnish information to anyone interested regarding the subject of standards of inductance or of capacity.

A standard of mutual inductance is very useful in calibrating ballistic galvanometers, and by having more than one value it may be applied to galvanometers of quite different sensibilities. Inductance standards (either variable or of fixed values) may be so arranged as to be used either as mutual or self inductances.

The equipment of the bureau for measurements of inductance and capacities is very complete. Much use is made of tuned galvanometers, which are very sensitive and which do not respond to the harmonics contained in the test current. This gives results free from error due to such harmonics, which error is present in some of the best known methods and is often serious. A very thorough study has been made of the sources of error in inductance measurements, particularly the errors due to residual inductances and capacities of the wire resistances employed, and methods have been developed for eliminating these errors. The bureau is prepared to measure these residual

FIG. 8.—Laboratory for Inductance and Capacity Measurements.

inductances and capacities in the "non-inductive" coils of resistance boxes or resistance standards, so as to permit their use with alternating currents in inductance measurements. This important source of error has been too generally ignored.

In this section extended investigations are being carried out in absolute measurements of the fundamental electrical units, namely, the ohm, the volt, and the ampere. The equipment of the bureau for this work is very complete.

The following are some of the more important researches completed or in progress in the line of absolute measurement:

1. An extended research on the ratio of the electromagnetic and electrostatic units, employing three different types of standard condensers; namely, spherical, cylindrical, and parallel planes. This has involved the design and construction of an absolute cylindrical condenser and an absolute plane condenser. Each of the three types of condensers has more than one value and each is being measured by two different methods, at different frequencies and under many different conditions. The results so far are very gratifying.

2. Development of plans for an absolute electrometer, for the purpose of determining the absolute value of the standard cell, by measuring a high voltage by the electrometer and multiplying the result by v, the ratio of the units. The parallel plate condenser is so constructed as to be made into an absolute electrometer, when the work on the determination of v is ended.

3. The bureau has a carefully constructed absolute standard of inductance the value of which is accurately known by calculation. We shall measure its value very accurately (1) by our improved methods using alternating current and (2) by means of a ballistic galvanometer. This will give two new determinations of the ohm in absolute measure, the first by a method never before used and the second by Kirchhoff's method. We have also made a careful study of the various methods of determining resistance in absolute measure, and are designing apparatus to be used in that connection.

4. One of the instruments recently designed and constructed is a new type of chronograph, which gives the speed of the driving motor or frequency of current employed with great accuracy and very quickly. One can see by mere inspection a change of speed as small as one part in 5 000, and for a run of a few minutes the mean speed (when the speed is steady) can be quickly determined to within one part in 100 000. Several other new instruments have been devised.

5. Study of the silver coulometer (voltameter) and comparison of different forms of the coulometer to determine the uniformity of results obtained with each different type and the differences among the several types. (Results published in Bulletin.)

6. The absolute measurement of current by means of an electrodynamometer, involving a careful study of various types of suspension. (Results soon to be published.)

The last two investigations have been made in connection with the magnetic work.

Section 3. *Electrical Measuring Instruments*. The work of this section includes the investigation and testing of instruments of precision for measuring electric current, voltage, and power (both direct and alternating) and the testing of laboratory and commercial instruments designed for such measurements, such as ammeters, voltmeters, wattmeters and watt-hour meters for direct and alternating currents, and special alternating-current instruments such as frequency meters, phase meters, curve tracers, etc. A considerable amount of work of investigation of instruments and methods of measurement has been done as well as some testing of instruments. The facilities required for handling and measuring alternating currents up to 1 000 amperes and direct currents of several thousand amperes are of course much more difficult to provide than those required for smaller currents. A battery of four large storage cells has been installed and so connected that by means of switches the cells may be used in series or in parallel, furnishing current up to 10 000 amperes at 2 volts, 5 000 amperes at 4 volts, or 2 500 amperes at 8 volts. At present we are testing current shunts up to 5 000 amperes capacity; but a new controlling rheostat and current standard have recently been designed and when completed will increase the capacity to 10 000 amperes, the resistances of the conductors, switches, rheostat, and standards being low enough to give a current of 10 000 amperes with an electromotive force of 2 volts.

Ammeters and current shunts for all ranges are tested for error of reading on short load or continuous load as desired, and errors due to temperature coefficients and to thermoelectric effects are investigated.

Alternating-current ammeters and current transformers are tested up to 1 000 amperes capacity, and effects of change of load, of frequency, and of wave form ascertained.

Direct-current voltmeters and millivoltmeters and portable galvanometers are tested, and errors due to orientation, load, temperature, etc., ascertained.

Alternating-current voltmeters are tested, their inductances measured, and the errors due to change of frequency or of temperature ascertained.

Potential transformers are accurately calibrated, showing their ratio of transformation with different loads on the secondary, so that they may be depended upon as closely as the voltmeters employed in connection with them.

Phase meters and frequency indicators can also be accurately calibrated, using sine wave form or distorted waves.

The special alternating-current generators, mentioned in connection with the engine room, and a number of storage-batteries of different capacities furnish the necessary testing currents, and permit the best conditions for a test to be secured.

A considerable number of instruments have been designed and built in the instrument shop of the bureau for use in this work.

Section 4. *Magnetism.* The work in magnetism has not been developed so far as the work of the other electrical sections. A considerable number of instruments for testing the permeability and hysteresis of specimens of iron have been secured and comparisons made by testing the same sample with different apparatus. Koepsel's apparatus, the Picou permeameter, the Ewing apparatus, and apparatus built in the instrument shop of the bureau have been used, and plans are under way for an equipment for magnetic testing by means of alternating current. It is expected that this work will be largely developed during the coming year.

Section 5. *Photometry.* The photometric work of the bureau comprises the testing of incandescent lamp standards for candle-power and distribution of light, the commercial testing of lamps as to life, candle-power, and efficiency for various departments of the government, and the study of special problems in photometry.

The equipment includes a precision photometer with a Lummer-Brodhum contrast screen, a horizontal rotator with four mercury cups giving separate potential leads to the lamp, and a potentiometer, standard cells, current standards, etc., for the accurate measurement of current and electromotive force. An extended research on the use of a rotating sectored disc for reducing the intensity of light from a source has been made on this photometer and will shortly be published.

An integrating photometer (modified Matthews form) has been designed and built for measuring mean spherical and mean hemispherical candle-powers. It is larger than the Matthews instrument, has 20 pairs of mirrors and their positions have been calculated so as to give the greatest possible accuracy of both mean spherical and mean hemispherical candle-power. This instrument will shortly be applied to study the effect of the frosting of lamps on the mean candle-power and on the distribution of the light.

A commercial photometer has been designed and constructed, for the rapid testing of incandescent lamps. This includes a horizontal and an end-on rotator, Bunsen screen with Leeson disc, variable sectored disc by the use of which lamps ranging from 4 to 100 candle-power can be read without readjustment of the comparison lamp. An efficiency meter, by means of which efficiencies or watts per candle can be read directly, has recently been designed and built and added to this photometer.

An equipment for life tests is being installed, for use in the testing of lamps for the departments of the government and for seasoning standards.

The equipment of the laboratory also includes a Brace spectrophotometer, a flicker photometer, standard Hefner lamps, etc.

Section 6. *The Engineering Force.* The engineers, firemen, electricians, janitors, and laborers are organized into a section under the charge of the chief engineer, who acts also in the capacity of superintendent of grounds and buildings. The entire mechanical and electrical equipment constitutes a somewhat complicated system, and it requires a considerable force to operate and care for it.

THE CHEMICAL DIVISION.

The chemical laboratory is located on the fourth floor of the physical building, occupying nine rooms and possessing an excellent equipment. The working staff consists of a chemist, an associate chemist, and three assistant chemists. This work was not begun as early as the work in the other divisions for lack of suitable quarters, but was taken up shortly before the physical building was completed.

In addition to the planning and installing of the permanent equipment and apparatus of the chemical laboratories, a number of investigations have been undertaken which were considered important from a commercial or scientific standpoint, or have been necessary in connection with the work of this and other government bureaus.

The bureau has undertaken to standardize some of the more important chemical reagents, and considerable work has been done in this direction. Samples of a few important materials, including limestone and steel, have been carefully analyzed with a view to their distribution when necessary for the purpose of checking the accuracy of methods of analysis used in scientific work and the industries. Questions relating to the purity of reagents and analytical methods are of the greatest importance to scientific and commercial interests. It is hoped that the bureau may considerably extend this work during the coming year. A number of substances have been examined physically and chemically for the Department of Commerce and Labor and other departments of the government

FIG. 9.—High-Temperature Laboratory.

with a view to determining standards and standard specifications to be employed in the purchase of government supplies. The relation of the chemical work to that of other sections of the bureau is exceedingly important. Scarcely a problem can be taken up concerning the construction of standards, or properties of materials, that does not involve chemical preparations, chemical analysis, or the coöperation and advice of expert chemists. The entire work of the bureau has been greatly strengthened and its efficiency increased by the organization of the work in chemistry.

TESTS MADE FROM JULY 1, 1904, TO JULY 1, 1905.

Standards of Length, and Length Measuring Instruments:		
Engineers' and surveyors' steel tapes	163	
Standard Rules, etc	11	
Geodetic level rods	30	
Polariscope tubes	40	244
Standards of Mass:		
Standards of mass from 0.1 mg. to 10 kg	571	
Balances	10	581
Standards of volume and measuring apparatus:		
Pipettes	181	
Flasks	559	
Bottles, etc	15	
Graduates	43	
Hydrometers	25	823
Barometers:		
Aneroid barometers	99	
Standard barometers	2	101
Heat and Temperature Measuring Instruments:		
Standard thermometers	333	
Clinical thermometers	12340	
Thermocouples	2	
Calorimeters	6	
Pyrometers	6	
Miscellaneous	4	12 691
Optical:		
Polariscope	1	
Quartz plates	11	
Samples of sugar	527	539
Engineering:		
Water meters	4	
Tensile strength tests	13	
Samples of cement	37	
Pressure gauge	1	
Paper tester	1	56
Forward		15 035

Brought forward		15 035
Electrical Standards and Measuring Instruments:		
Resistance standards, precision	34	
" " for current measurement 1 000 amperes and less	19	
Same for 5 000 amperes	1	
Wheatstone bridges	5	
Potentiometers	5	
Samples of wire for conductivity test	7	
" " iron rail and weld	1	
Direct-current voltmeters	40	
Alternating-current voltmeters	17	
Direct-current ammeters	27	
Alternating-current ammeters	21	
Indicating wattmeters	20	
Curve-drawing wattmeters	2	
Watt-hour meters	48	
Current transformers	4	
Potential transformers	3	
Portable galvanometers	14	
Standard cells (Weston)	10	
" inductances	8	
" condensers, mica	8	
Air condensers, adjustable	1	
Inspection of measuring apparatus	1	
Electric motors	5	
Samples of alloy for special test	6	
Electromagnet	1	
Arc lamps, current test	212	520
Photometry:		
Incandescent lamps, c.p. of standards	38	
" " " " commercial	1 011	
" " " " "	34	
Oil tests	4	1087
Chemical tests	38	38
Total		16 680

Publications of the Bureau.

1. The *Bulletin* contains the more important investigations carried out in the various sections of the bureau. Three numbers of the *Bulletin*, so far, have been published, together constituting Volume I. The following is a list of the papers contained in this volume.

No. 1.

[Issued November 1, 1904.]

No. 2

[Issued February 1, 1905.]

No. 3.

[Issued November 1, 1905.]

Each of the above articles is reprinted as a separate paper bearing the number given above.

2. *Circulars* which give information regarding the testing of apparatus, fees, etc. The following circulars have been issued:

Before July 1, 1903. (Treasury Department.)

1. Announcement of Organization.
2. The Verification of Tapes.
3. The Verification of Standards and Standard Measuring Instruments.
4. Table of Equivalents of Customary and Metric Weights and Measures.

After July 1, 1903. (Commerce and Labor.)

1. Verification of Standards and Measuring Instruments.
2. Verification of Metal Tapes.
3. Verification of Standards of Mass.
4. Verification of Standards of Capacity.
5. Testing of Clinical Thermometers.
6. Verification of Electrical Standards and Measuring Instruments.
7. Pyrometer Testing and Heat Measurements.
8. Testing of Thermometers.
9. Testing of Glass Volumetric Apparatus.
10. Legal Weights (in pounds) per bushel of various commodities.

3. Annual report of the Director, which is addressed to the Secretary of Commerce and Labor and by him transmitted to the Congress and distributed with the other department reports.

4. Special publications, of which the following have been issued:

1. Laws Concerning the Weights and Measures of the United States.
2. Table of Equivalents of the Customary and Metric Weights and Measures.
3. Conference on the Weights and Measures of the U. S.
4. The International Metric System. (A chart intended especially for schools.)

Any of the above publications will be sent free upon request to any person interested in the subject treated.

THE EXPOSITION LABORATORY.

In addition to the exhibit which the National Bureau of Standards made in the government building at the Louisiana Purchase Exposition, it undertook, at the request of the authorities of the exposition, the installation and operation of an electrical testing laboratory in the Palace of Electricity. The work which was undertaken in this laboratory was as follows:

1. The exhibition in actual operation of a complete collection of instruments and apparatus for electrical measurements of the highest precision.

2. The verification of electrical measuring instruments for the Jury of Awards, The Electrical Railway Test Commission, exhibitors and others, and the investigation to some extent of instruments and standards.

The laboratory was located on the east side of the Electricity Building, in Space 29, being about 175 feet in length and occupying a floor space of about 4 000 square feet. The building was divided into six rooms, all of which, except the office, were used for the apparatus and equipment of the laboratory.

The laboratory building was erected by the bureau at an expense to the government of about $4 000.00. The exposition furnished water, gas, and electricity free of charge, and made an appropriation of $1 000.00 to pay for extra assistants during the period of installation and during the session of the electrical jury.

The laboratory building was a substantial frame structure, erected on the floor of the Electricity Building, and against, but not supported by, its east wall. Within it was lathed and plastered, with a pine wainscot finished in the natural wood, and a hard pine floor laid upon the floor of the main building. The east wall was substantial and steady enough to support galvanometers and other wall instruments, while some of the most delicate apparatus was mounted on massive concrete piers which extended through the floors from the solid ground. Substantial benches and tables were erected, and the laboratory possessed many of the appointments of a permanent installation. It was on the opposite side of the Eleotricity Building from the heavier machinery, and the only machine which caused appreciable vibration was in an adjacent exhibit, the manager of which kindly shut down the machine at certain times when the vibration caused serious disturbances to the more delicate galvanometers. The latter were all of the moving-coil type, and hence not easily disturbed magnetically.

The most serious difficulty in carrying on precision electrical measurements under such circumstances is due, not to the magnetic disturbances or mechanical vibrations, but to the humidity of the atmosphere in midsummer. The bureau could not have undertaken to install precision apparatus or to make exact measurements, had it not been possible to cool and dry the atmosphere of the laboratory artificially. Fortunately a 10-ton refrigerating machine was installed in a space immediately adjacent to the laboratory of the bureau; the owners operating it as an exhibit and furnishing refrigeration to the bureau without charge, in consideration of which the exposition furnished the gas used by the refrigerating machine free of charge to the exhibitors. This machine was of the absorption type, not requiring a mechanical compressor, and hence operating very quietly and not disturbing the work carried on in the adjacent laboratory.

The several rooms of the laboratory were ventilated by means of a large blower, driven by an electric motor, which forced air into the rooms through a system of ducts. Between the blower and the main duct was a chamber containing iron pipe through which cold brine was pumped from the refrigeration machine. The air passing through this chamber was cooled and its surplus moisture was condensed, so that as it entered the laboratory rooms it was cool and dry, ready to absorb moisture due to respiration and evaporation without becoming saturated. Thus the atmosphere was kept dry enough to maintain good insulation in wiring and instruments, and make it possible to conduct electrical measurements with no errors due to surface leakage. That would have been impossible under the normal conditions in midsummer.

By means of a system of automatic temperature control, installed as an exhibit, the temperature of the laboratory was maintained quite steady. This cool and relatively dry atmosphere made the laboratory a very comfortable place in which to work, and the cool office of the bureau was a favorite retreat for the electrical jury in some of the hottest days of the jury period.

The amount of money available for the installation of the laboratory was limited, and owing to the unusually high cost of labor and materials, the building absorbed the greater portion of the fund. For this reason the work of installation could not be pushed as rapidly as was desired and the equipment was not entirely completed until midsummer. It was, however, in full working order during the time of the congresses and the jury period, and until the end of the exposition, although the laboratory force, amounting to about 20 in September, was gradually reduced in October and November. The laboratory was heated only by gas stoves, so that late in the season it became uncomfortably cool.

Although the laboratory was designed primarily as an exhibit, and the continuity of the work was considerably interrupted by visitors, still considerable testing was done, and not a little research.

The work of the laboratory was separated into two principal divisions The first was for the testing of standards of resistance, standard cells, resistance boxes, potentiometers, Wheatstone bridges and other resistance apparatus, and the determination of specific resistances, temperature coefficients, etc.

The second division of the work was the testing of electrical measuring instruments, including direct- and alternating-current ammeters, voltmeters, wattmeters, watt-hour meters, frequency and phase meters, inductances, capacities, etc. The dynamo room contained direct- and alternating-current generators for producing current for experimental purposes, and the battery room contained several storage-batteries kindly loaned by an exhibitor.

Laboratory for Resistance and Electromotive Force Measurement. The north room of the laboratory building, about 22 by 30 ft. in size, was fully equipped with apparatus for the first division of the work the most of which was brought from Washington. This work can be conveniently specified under four separate heads as follows:

1. *The comparison of resistance standards* with one another and the verification of precision resistance boxes, potentiometers, and other apparatus requiring the accurate measurement of resistance. The apparatus included sensitive galvanometers, Kelvin and Carey-Foster bridges, ratio coils, a large number of manganin wire standards and other apparatus required in this kind of testing.

2. *The verification of low resistances* for use in measuring current, especially accurately adjusted manganin resistances of 0.01, 0.001, 0.0001, and 0.00001 ohm intended to be used as standards in the calibration of current measuring instruments. This equipment included a storage-battery for giving relatively large currents, with heavy bus-bars and reversing switches for

conducting the current to the Kelvin bridge used in measuring resistances, and other apparatus incident to the measurements.

3. *The measurement of the electromotive force of standard cells* by comparison with the standards of the bureau. This equipment included a potentiometer, with its galvanometer and auxiliary apparatus and suitable baths for containing the standard cells and the cells to be tested.

4. *Miscellaneous tests*, such as electrical conductivity, thermoelectromotive forces, temperature coefficients, etc.

Laboratory for the Testing of Electrical Measuring Instruments. The large middle room of the laboratory, about 22 by 65 ft., was fully equipped with apparatus, most of which was brought from Washington, although a considerable number of pieces were loaned by the makers. The testing done in this division of the work may be conveniently specified as follows:

1. *Inductance and capacity.* This work included the verification of standards of inductance (both fixed and variable) the determination of the inductance of measuring instruments, particularly of alternating-current instruments and of high resistances intended for use in alternating current circuits; the measurement of the capacity of condensers and the testing of the quality of condensers.

The equipment included a full collection of standards of inductance and capacity, resistances, direct-and alternating-current galvanometers, rotating commutators, alternating-current generators and other apparatus required for absolute and relative measurements.

2. *Direct- and alternating-current voltmeters.* The equipment for this work included potentiometers, standard cells, rheostats, multipliers, and batteries of small storage cells for use in calibrating direct-current voltmeters and such alternating-current voltmeters as could be calibrated by a potentiometer and direct current; the latter were employed to test other alternating current voltmeters.

A special Weston testing set was also used. This consisted of a combination of a potentiometer and a laboratory standard voltmeter, with accurate resistance coils and switches, so that a voltmeter could be quickly and accurately tested for any multiple of 5 volts up to 550.

3. *Direct- and alternating-current ammeters, wattmeters and watt-hour meters.* The equipment for this work included a very complete collection of measuring instruments, such as

potentiometers and standard cells, accurate resistances, standard alternating current ammeters and wattmeters that could be calibrated by direct current, and then used to measure alternating current and power, electrical generators and a variety of auxiliary apparatus needed to provide the necessary range of current and voltage, frequency and wave form.

Instruments were tested, not only for accuracy under normal conditions, but also with varying loads, frequency, power-factor, wave form and temperature.

To control the frequency the alternating-current generators which furnished the testing current were driven by motors which received their current from storage-batteries installed in one of the rooms of the laboratory adjacent to the dynamo room. Thus the speed of the motor was not subject to variations due to fluctuations of voltage on the supply lines of the Electricity building, and the speed and hence the frequency of the current could be maintained accurately constant for any period desired. By changing the voltage or introducing resistance any desired variation of frequency could be secured.

To vary the wave form two alternating-current generators were direct connected to a single driving motor, one generator giving an electromotive force at 60 cycles and the other an electromotive force at 180 cycles. Either of these could be used alone or both in series. In the latter case the 60-cycle electromotive force was the fundamental and the 180 cycle was the harmonic; the latter could be increased or decreased in amplitude by varying the exciting current of the generator and thus the resultant wave form could be varied throughout a wide range.

Variations in the temperature of instruments under test were made by placing them in a specially constructed testing room which was cooled by means of cold brine circulated through coils of pipe, or heated by means of electric current. Thus any temperature between 0° cent. and 40° cent. (32° fahr. and 104° fahr.) could be maintained and the variation in the readings of instruments ascertained; that is, their temperature coefficients determined.

4. *Miscellaneous tests.* These include tests of frequency meters, phase indicators, wave form apparatus, primary and secondary batteries and other direct and alternating current instruments and machines.

A small instrument shop was equipped in one of the rooms, and one of the machinists of the bureau was in attendance during a part of the season.

The laboratory was conducted by ten of the members of the electrical division of the Bureau of Standards, assisted by a number of scientific assistants temporarily employed.

A paper presented at the 201st Meeting of the American Institute of Electrical Engineers, New York, Nov 24, 1905.

A TESTING LABORATORY IN PRACTICAL OPERATION.

BY CLAYTON H. SHARP.

The writer has been asked by the INSTITUTE to prepare a paper describing the results attained in the establishment and maintenance of a laboratory for commercial electrical testing.

The importance of laboratory work to the progress of electrical engineering does not need to be emphasized. Electrical engineers fully realize that their science originated in the laboratory, and that improvement and progress result very largely from laboratory researches and tests. The laboratory is the basis for all work of exact measurement, without which scientific engineering disappears and rule of thumb methods become the fundament of practice.

The laboratories with which the electrical engineer concerns himself can be divided into three classes: first, those having to do with the conservation of units and primary standards, and with the certification to the accuracy of secondary standards which are to be used in general practice; secondly, those engaged in making experiments, researches, and tests having an immediate commercial end in view; thirdly, those used primarily for purposes of instruction.

Under the first class come the great national laboratories. One of the best of this class we are now so fortunate as to have in our own country, in the laboratory of the National Bureau of Standards. Laboratories of this character are invaluable, not only to electrical engineering but to other constructive arts and sciences. Apart from their primary usefulness in connection with the fundamental standards of measurement, laboratories of this class are enabled, through their unique position in enjoying governmental support, to enter into experimental investigations of questions too extensive, too abstruse, or too expensive to be undertaken by an individual or by an industrial corporation, but which, at the same time, are of such great practical importance that the use of public funds in prosecuting them is justifiable, even though there may be no prospect of immediate commercial returns.

Of laboratories of the second class many are in existence. The large and progressive manufacturing and operating companies maintain well-equipped laboratories for the research and testing work so vital to them.

We realize, however, that in spite of the existence of these laboratories, many electrical workers are practically without laboratory resources. The cost of proper laboratory equipment is by no means small, and the salaries of laboratory experts is of considerable moment if the product submitted to test is of only moderate value. Consequently, manufacturers of smaller output, purchasers of electrical supplies in moderate quantities, inventors, users of electrical instruments, and many consulting engineers have found it impracticable to provide themselves with laboratory facilities. To such parties a desideratum would be the establishment of a completely equipped electrical laboratory, as a quasi-public institution, where all desired tests and experiments would be made at a reasonable expense, exactly as they would be made in a private laboratory, and, if desired, under conditions insuring privacy.

Recognizing this fact, the Electrical Testing Laboratories has been formed as a business enterprise. This organization has equipped and put into operation an extensive plant for testing purposes. The writer recognizes the very proper custom not to exploit any business enterprise at a meeting of this INSTITUTE, and to eliminate commercialism as far as possible from the papers here presented. It has been his object to follow this tradition as far as practicable, but it is manifestly impossible to eliminate some general reference to the business of the laboratories, for it is in this very feature that the interest of this paper to the members largely consists; and without this it would be a mere description of the routine of laboratory work.

He believes, moreover, that, organized as the laboratory is for public service of a nature in which the INSTITUTE is particularly interested, no further apology is needed for presenting certain facts as to the nature and scope of the work done by a laboratory of this character. It may be mentioned in this connection that the Société Internationale des Electriciens in its corporate capacity stands sponsor for a similar laboratory in Paris, the Laboratoire Centrale d'Electricité. This laboratory while receiving a subvention from the City of Paris, and from the French Government, by which it is recognized as a public utility, is chiefly supported and directed by the Société Internationale des Electriciens. The Electrical Testing Laboratories in this city has a plant which is by no means inferior to that of the Laboratoire Centrale, and is, it is believed, in position to render services to the electrical profession and industry similar to those which the Paris laboratory has rendered to its supporters. It cannot be out of place, therefore, to make a brief report of its activities to the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

The Electrical Testing Laboratories has now been permanently established and in practical operation for nearly two years in a large and substantial building in East Eightieth Street, New York City. The building and equipment have been described at length,[1] it is, therefore, unnecessary at this time to discuss these details. It is sufficient to say that the building is of adequate size, unusually substantial, and well adapted to laboratory purposes, while the equipment of apparatus is most generous as to quantity, quality, and range. The arrangements for obtaining large quantities of electrical power are also excellent. In other words, an earnest effort has been made to obtain as perfect an electrical laboratory equipment as is practicable.

As has been indicated in the foregoing, the purpose of these laboratories is to fill a hitherto existing lack in the electrical field. The Electrical Testing Laboratories is not engaged in producing any manufactured product. It does not attempt or expect to supplant the testing laboratories organized by operating and manufacturing companies, but rather to supplement them. By abstaining from giving advice or rendering opinions it does not encroach upon the particular province of the consulting engineer, while it places at his disposal facilities for obtaining such experimental data as he may need in his practice. It will thus be seen that the purposes of this enterprise are not in the least antagonistic to any other industry or established interests, but the establishment is in a position to be of im-

1. *Electrical World and Engineer* for January, 7, 14, and 21, 1905.

partial service to all. The National Bureau of Standards maintains the primary standards; the Electrical Testing Laboratories devotes itself to commercial electrical measurements for the promotion of electrical industries: thus these two laboratories are mutually supplementary, the one undertaking a work which is essentially a function of government, and the other applying the results of such work to productive industries.

It is pertinent to inquire to what extent, by whom, and for what purposes, the testing facilities thus offered have been made use of in commercial undertakings. As an answer to this question tabulations have been prepared classifying the tests which the Electrical Testing Laboratories has been called upon to make in two ways; namely, with respect to the kind of tests requested and with respect to the parties ordering the tests. In this classification each order is considered as a unit, no account being taken of the number of articles to be tested under it. Thus an order for a check of a voltmeter counts the same as one for the complete study of a set of integrating watt-hour meters or for the determination of the conductivity, insulation resistance, capacity, and dielectric strength of several lengths of wire or cable. A partial examination of the records shows, for instance, that 310 orders covered a total of 581 individual instruments; 148 orders a total of 484 reflectors.

In these classifications certain large tests performed under general contracts are not included. These contracts cover tests of incandescent lamps bought in large quantities. The tests are made to determine the acceptability of the lamps under the specifications which are agreed to by the manufacturer and the purchaser, or to fix the value of the lamps, the laboratories in this case acting as the intermediary between the producer and the consumer.

The Electrical Testing Laboratories was engaged in this class of work previously to entering into the field of general testing. The volume of lamp testing is very large, the total number of lamps submitted for inspection and test during the year ending April 30, 1905, was 13 000 000. The existence of this well-established line of testing has made it financially possible for the laboratories to engage in the larger work upon which it had entered, and still constitutes the real backbone and substantial income of the business, without which the maintenance of the general laboratories would be impracticable. The results achieved through this systematic testing of incandescent lamps have been of very great significance to electrical science and industry. Under this stimulus, the quality of the lamps manufactured in this country has steadily risen, and the practice of electric lighting has reached a high degree of excellence. The initiative in this practice of lamp testing came from large lighting companies, and large purchasers of lamps.

TABLE I.

ANALYSIS OF ORDERS.

Instruments.	*Number of Orders.*
Indicating	219
Instrument transformers	9
Integrating and recording	93
Precision instruments	20
Loans	19
Total	360
Materials, Supplies, and Machines.	
Conductivity	34
Insulating materials and insulators	70
Wires and cables	30
Dynamos, motors, and batteries	11
Fuses, circuit-breakers, and mechanical joints	28
Magnetic properties of iron and steel	7
Miscellaneous	2
Total	182
Photometry.	
Arc lamps	20
Gas lamps	10
Incandescent lamps, inspection and candle-power	140
" " life	51
Meridian, Nernst, osmium, and tantalum	22
Reflectors	129
Standards of light (including standard lamp sales)	153
Miscellaneous	13
Total	538
Miscellaneous.	
General	53
Private laboratories	3
Tctal	56
Grand total	1 136

An examination of the above table shows that the aggregate number of tests which have been carried out is by no means inconsiderable. The number of photometrical tests of all sorts is substantially equal to the number of instrument tests and materials tests combined. While this indicates that there is an extensive field for photometrical testing, it is not a good indication that this field of testing is as large as that of all other electrical tests. At the beginning of the period covered by Table I. the laboratories had already an established reputation for photometrical tests and in consequence there was a large preponderance of such orders. This preponderance has been steadily diminishing with the increase of business in the more general line of electrical testing.

Similarly, the number of instrument tests is twice as large as the number of materials tests. This may be interpreted as indicating that the importance of accuracy in electrical measurements and metering is more definitely appreciated than the importance of testing materials and machines. In forming such a conclusion, however, it should not be lost sight of that many tests of instruments have been made for parties intending to conduct their own tests of materials or machines. For example, the instruments and instrumental transformers which have been used as sub-standards in efficiency tests of some of the largest generators ever constructed have been checked by the Laboratories.

The following table classifies the orders received with respect to the occupation or position of the clients from whom such orders have come. This classification is approximate only, since, for instance, it frequently happens that a manufacturer requires a test of materials which he is purchasing, and hence for purposes of classification would properly be placed under the head of consumer. These cases cannot be distinguished from those in which the manufacturer has a test made of his own product.

TABLE II.

Manufacturers	Consumers	Electrical Engineers	Dealers	Colleges and other Laboratories	Other Parties
56%	29%	8%	4%	2%	1%

It is seen that more than one half of all orders came from manufacturers, and that consumers' orders number only about one half of the manufacturers' orders. There is, however, a well marked tendency for the relative number of orders from consumers, electrical engineers, and dealers, to increase more rapidly than orders from manufacturers. Consumers and dealers will undoubtedly realize more and more with increasing competition and increasing demands upon them, the importance of testing materials and supplies.

As indicating the increasing use made of the facilities thus provided, and illustrating the fact that the laboratory is in practical operation, a diagram is given showing the number of orders received every month. A moderately steady increase can be seen, and a considerable volume of work. Each summer the volume decreases considerably, but increases rapidly during the fall when the vacation season is past.

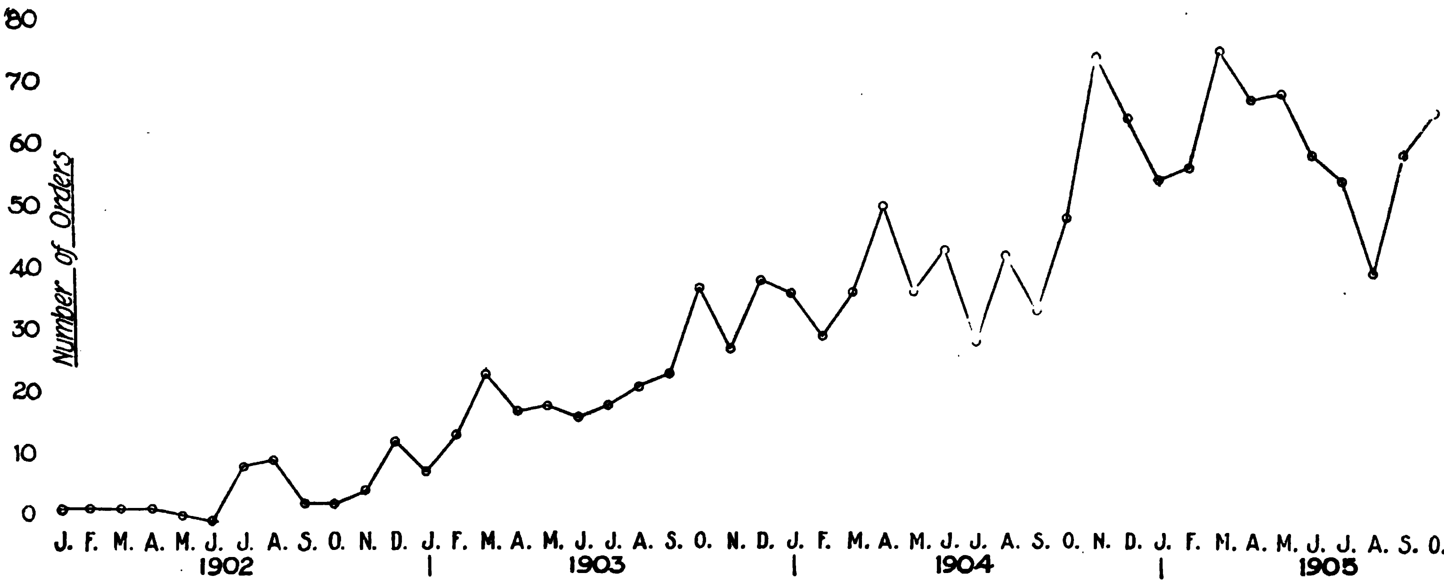
Certain further approximate analyses of the work done by the laboratories can be made which indicate some of its fields of usefulness. For example, a large number of orders from manufacturers have covered tests and experiments required in developing new or improved products and in getting exact data on their existing product. Some manufacturers submit samples of their output systematically and periodically to the Electrical Testing Laboratories for test, and use the data thus obtained for their own information. This is sometimes done when the manufacturer is supplied with his own testing department, and it serves as a check on his own results. Sometimes the results are used for advertising purposes. A catalogue of a certain line of appliances of interest to the illumination engineer has recently been issued in which the characteristics of each article are shown by curves obtained by the laboratories. Manufacturers, consumers, and others frequently submit samples of different makes of an article for competitive tests. These are all subjected to similar tests and a separate report is written covering the behavior of each. A comparison of such reports is sufficient to give a clear idea of the relative merits of the articles tested. It will be noticed that the method of returning separate and independent reports on competitive articles precludes the possibility of the laboratories making any direct comparison between them or drawing conclusions as to their relative merits. This is in accord with the fixed policy of the laboratories. An exception is made in case samples are designated in such a way as not to reveal their true identity. Thus a comparative report will be returned on samples of cable marked *A*, *B*, and *C*, but separate and independent reports if they are designated as Smith's make, Jones's make, and Brown's make. In no case is an opinion rendered as to the relative merits of articles as disclosed by the data obtained.

A number of tests have been made which are noteworthy either for their unusual nature or for their magnitude and comprehensiveness. Among these may be mentioned a study of the heat-dissipating qualities of various insulating varnishes; an efficiency test by electrical means of a variable-speed gearing; a study of the relation between voltage and sparking distance in air on the high-tension transformer set installed in the laboratory; complete studies of nearly every kind of integrating watt-hour meter which is, or might be, a commercial possibility in this country; spectro-photometric tests of most of the usual light sources; stroboscopic tests to determine the amount of variation of the light from incandescent lamps during each half cycle of alternating currents of various frequencies; complete tests of Nernst, osmium, tantalum, and flaming-arc lamps; comparative life-tests of incandescent lamps on direct-current and alternating-current circuits; determination of the influence of frosting the bulb of incandescent lamps, or enclosing them in globes, on their life and efficiency; international comparison of standards of light by the exchange of standard lamps with the principal European laboratories.

Thus it will be seen that while the laboratory equipment is intended primarily for routine testing of the every-day useful sort, it has been made use of for tests which are out of the ordinary and which would usually be carried on in a physical laboratory.

To sum up, it may be noted that systematic and constant testing and experimenting are of the greatest importance in promoting electrical science and industry. By testing, the manufacturer is able to determine the quality and properties of the raw material entering into his product; and he is able to detect faults, to make improvements, and to blaze a trail into unexplored fields. By testing, the purchaser may assure himself that he is getting the quality that he has specified, and can protect himself against carelessness and fraud. By testing, the electrical engineer is enabled to collect the data needed for his plans and recommendations. The attainment of accuracy in practical electrical measurements is also of great importance and can be obtained only by reference to accurate laboratory standards.

It is, therefore, a matter of congratulation that the electrical industry has attained to the stage in its development where it


Number of Orders
0
10
20
30
40
50
60
70
80
J. F. M. A. M. J. J. A. S. O. N. D. J. F. M. A. M. J. J. A. S. O. N. D. J. F. M. A. M. J. J. A. S. O. N. D. J. F. M. A. M. J. J. A. S. O.
1902
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feels the need of such facilities as are afforded by the laboratory of the National Bureau of Standards and of the Electrical Testing Laboratories, and that it is showing its appreciation of the availability of such facilities by making practical use of them in the conduct of commercial operations.

Discussion on "The National Bureau of Standards," and "A Testing Laboratory in Practical Operation," at New York, November 24, 1905.

F. B. Crocker: The Institute has done much commendable work in encouraging standardization, but it has remained for the Government to do something even more important by giving to the public the standards of weights and measures needed in the industries.

The matter of international standardization is very important. As a profession, I think we have reason for congratulating ourselves that it is much more advanced in the electrical industries than in other engineering industries, or, for that matter, in any other branch of human interest. This is so because the electrical units are international, and have been so since the Chicago Congress of 1893.

The matter of standardizing electrical machinery, while fairly well established in this country, is in some respects unsettled even here. There is very little international standardization of electrical machinery, but I think the time has come when even that will be attempted. At St. Louis the International Electrical Congress passed resolutions favorable to international standardization of electrical apparatus.

I think that uniform practice is an excellent phrase by which to designate all of the efforts to bring about uniformity in all branches of applied science. The mechanical engineers, for example, are responsible for uniformity in steam-engine practice; electrical engineers for electrical-generator practice; and in the matter of direct-connected units the responsibilities for standardizing are shared alike by both professions. Such standardization is actually accepted to-day, and I think that it will reach even further.

As a representative of the Committee on Standardization of the Institute, I heartily endorse the work that has been described here to-night; work by the government, powerful in its influence, which can accomplish a great deal; and work by the various standardization interests—all of which are producing such excellent results.

W. E. Goldsborough: Several years ago, when the matter of the formation of a National Bureau of Standards was being agitated, I felt that laboratories throughout the country, and also manufacturing plants, were in great need of a proper standardizing bureau to which to refer instruments needing adjustment and accurate calibration, and to which could also be referred matters in doubt relating to important scientific or engineering constants and other data. Since the appropriations for establishing the Bureau of Standards were passed by Congress a great deal of work has been done to meet all of the demands I have enumerated, and many more.

I visited the site of the new laboratories of the National

Bureau about a year and a half ago; and was much impressed with its possibilities as a permanent home for an institution of this character.

To my mind it is essential that there should be in the United States a court of last resort to determine and regulate units and standards of measurement. Heretofore such work has been restricted to a few educational, or commercial, laboratories, which have, to a large extent, been obliged to develop their own methods and make their own standards; and none of them possessing a corps of men devoting their time exclusively to refined work of the character now carried on by the Bureau of Standards.

Undoubtedly, with the aid given to electrical engineers by the bureau, much more rapid progress can be made in all branches of commercial electrical development than has hitherto been possible.

I have been in many finely equipped laboratories, and have seen many enthusiastic men working with refined instruments; but I do not know of any place in which will be found more ideal conditions for scientific work or a more enthusiastic body of men at work than in the National Bureau of Standards.

C. O. Mailloux: I visited, last year, the laboratories of the Reichsanstalt, at Charlottenburg, and also, very soon after, those of the National Bureau of Standards, at Washington. The laboratories at Washington were far from being in completed form; but I felt, even then, that the Bureau of Standards was already ahead of the best establishments of the same character in Germany or elsewhere.

George F. Sever: Some years ago Professor Crocker read a paper before the Harvard Engineering Society, on the accuracy of electrical engineering. In that paper was embodied practically all the ideas that the National Bureau of Standards and the Electrical Testing Laboratories have evolved; that is to say, the electrical engineering profession is so exact in every detail that it can, by means of these standardization laboratories, obtain results that are practically a dead lift with other professions.

The Electrical Testing Laboratories are extremely beneficial to the electrical testing laboratories of the universities. In the old days the electrical and physical laboratories of the various universities did the work that is now done by the two institutions represented here to-night, much less satisfactorily than they conduct it. In those days one university had a certain set of standards; other universities had, in turn, other sets of standards. There was no means whatsoever of standardizing the standards; for the professors of electrical engineering and the professors of physics in the various universities were unable to coöperate at that time.

University teachers most heartily welcome the establishment of the Bureau af Standards and the Electrical Testing Laboratories. The latter have relieved Columbia University of a lot of commercial work that often completely disorganized and impaired the success of teaching, by taking time and equipment and interfering with the training of students under a purely academic standard. In university electrical laboratories, apparatus must be adapted for many different kinds of tests; it cannot be maintained for some one particular line of work, requiring the same process over and over again, as the financial facilities and the personnel are limited as compared with the conditions in a commercial testing company. The charges for similar work are usually larger than those made by a commercial laboratory.

All things considered, then, the establishment of the Electrical Testing Laboratories in this city is of great advantage not only to the universities, but to the engineering profession as well.

C. A. Doremus: To the chemist, the knowledge that his volumetric apparatus is of standard type is of the greatest importance. Accurate measures are needed as much as accurate weights. If I am correctly informed, the Act which legalized the U. S. gallon does not mention the temperature at which the volume of water shall be measured, This spells confusion.

Heretofore we have had to depend on the German government for our standard volumetric apparatus. We now may go directly to the Bureau of Standards.

Dr. Stratton confirms the importance of this bureau to the chemist when he says: "Scarcely a problem can be taken up concerning the construction of standards, or properties of materials, that does not involve chemical preparations, chemical analysis, or the coöperation and advice of expert chemists." This statement, together with the fact that one of the heads of department is a chemist, shows how intimate a relation exists between the bureau and chemistry.

One of the most important functions of the bureau is the standardization of polariscopic apparatus. This apparatus is used in assessing the duty on sugar, one of the chief sources of revenue of the government. The government must know that the polariscopes at New York, Boston, and New Orleans, all indicate the same percentage of sugar in the same sample.

Pure chemicals are essential in the testing of materials such as steel, copper, etc. The chemical manufacturer is beginning to recognize the value of producing chemicals of standard quality. They need not always be absolutely pure. Indeed, impurity may be acquired from a container; but it is necessary for the chemist to know whether a particular chemical is contaminated, and to what extent. It is this ideal condition which the chemical manufacturer is trying to bring about, and the bureau will greatly facilitate his efforts.

The electrochemist will also look to the bureau for important information. If it has been found available to enter the field of research of low temperatures, it will not be long before experimental work at high temperatures will become a matter of routine in the bureau.

William McClellan: A comparison of old foreign catalogues of instruments with catalogues of American instruments shows a great difference in the kinds of instruments listed. The makers across the water, even now, are producing instruments which enable the physicist to start his most advanced work at first principles. The American maker has ceased to do this, or rather never began making this sort of instrument, but is willing to leave standardizing to the proper bureau. Measuring-instruments of all kinds can now be standardized at Washington, and with more despatch and accuracy than in an ordinary laboratory, and much of the drudgery and inaccuracy of former methods of experimental work avoided. One recalls the difficulties Professor Rowland had with his preliminary work in connection with the mechanical equivalent of heat, in order to be sure of his thermometers. Most of us would now avoid such troubles by applying to the Bureau of Standards. Few physicists have the time or the ability to make their own ohms and volts, and would rather leave it to the bureau.

The standardization of machinery referred to by Professor Crocker, should enlist the interest of every engineer. But to insist too much on this would stifle proper experimenting and improvement. The exploiting of apparatus modified for commercial reasons is responsible for much of the variety existing, but this has not prevented the manufacturers from standardizing in some particulars. A more common cause of trouble is the whim of an engineer which introduces a slight change with little or no compensating advantage. This can only be prevented by rational conservatism.

These two papers suggest the question as to where the activities of the two organizations should be divided. At this point it would be interesting to hear from the Director of the National Bureau as to just how far the bureau can go in the matter of making commercial tests—where the government does or would prevent anything further in this line. It would be interesting, too, to know what classes of people have patronized the bureau at Washington.

S. W. Stratton: This question arises in connection with nearly every phase of work done by the bureau. For example, in the matter of weights and measures the line drawn between fundamental standards and local standards is sharp; however, we hope to bring about relations between the state and city sealers of weights and measures which will give the bureau control of their working standards. By associating ourselves with the sealers they will be instructed in the various methods, without interfering with the routine testing of commercial weights and measures. There is hardly a section of the bureau's activities which can be separated from routine testing.

In photometry the policy of the bureau has been to do commercial testing for the departments of the government, and for the public in cases where an authoritative test is required.

It is absolutely necessary for those who are solving problems in connection with photometric standards to keep in touch with commercial testing. In fact, the bureau is frequently called upon to instruct individuals and officials in the methods of such testing, just as it offers to city officials and others every opportunity for instruction in matters pertaining to the testing of commercial weights and measures. Here again, in order that the experts of the bureau may be thoroughly familiar with the practical side of the problem, a certain amount of this commercial testing is done for the departments of the government, and for the public when no local facilities are provided. Work was done by the bureau last year for many educational institutions of importance, for instrument makers, and many commercial firms.

John W. Lieb, Jr.: We Americans are apt to be taken to task for our utilitarian spirit, but this institution affords good evidence that the nation has arrived at a point where it appreciates the importance of experimental research, scientific investigation, and correct standards of weights and measures. I believe that the National Bureau of Standards at Washington is likely to play a very important part in enlisting the sympathy and coöperation of the manufacturing industries in this country toward bringing about that great desideratum, the universal adoption of the metric system.

E. B. Rosa: The National Bureau of Standards is not completely developed, not by a good deal, but it is well started. Recalling that the Reichanstalt has cost more than $1 000 000 for the grounds, building, and equipment, and that there is an institution for the testing of weights and measures quite distinct from the Reichanstalt, called the Normal Aichungs Kommission, and that there is still another institution for the testing of engineering instruments and materials, it will be appreciated that the government has not made such a very bad beginning. The three German institutions represent an equipment cost of $1 500 000; taking into account the greater cost of labor and material in this country, the plants could not be duplicated here for less than $2 000 000. The total cost of the equipment of the National Bureau of Standards is, to date, not more than $600 000. This expenditure represents about one-third of the amount expended by the Germans for this kind of work, and therefore allowance should be made if in the matter of equipment the National Bureau of Standards does not contain all that is found in the German institutions.

A paper presented at a Meeting of the Chicago Branch of the American Institute of Electrical Engineers, Chicago, May 2?, 1905.

LIGHT ELECTRIC RAILWAYS.

BY JAMES R. CRAVATH.

Although the building of interurban electric railways has been carried on very actively in the Central States during the last six years, a general survey of the situation shows that the territory served by such roads is rather limited, especially in states west of Indiana. The typical interurban electric railway of the Central States costs from \$20 000 to \$25 000 per mile of single track. The building of such roads has therefore been generally confined to such places as in the opinion of the builders have sufficient population and resources to yield an annual gross revenue which will leave from \$1 200 to \$1 500 per track mile to pay interest on the investment after paying operating expenses, maintenance, and depreciation. Without going into details, it can be said in a general way that a gross revenue of \$3 000 to \$4 000 per track mile per year must be earned at the start on a most economically constructed interurban road of the ordinary type, if it is to be a financial success.

It has for some time been apparent to engineers that have had to advise regarding numerous proposed interurban electric roads in certain states (of which Illinois and Iowa are the most notable examples) that there is need for a class of electric railway that does not require the heavy investment needed to build the typical interurban road of to-day. In other words, there are scores of places that would not yield an interurban road a gross revenue of \$3 000 per track mile per year, and there is little prospect that they ever will; yet half or two-thirds that income would be certain and continuous. On account of the numerous opportunities for roads of a cheaper class in our rich agricultural states, which have comparatively few large manufacturing towns, many engineers have looked forward with much hope to the single-phase alternating-current railway motor as making possible a considerable saving in the cost of construction and operation of these roads. A careful review of recent estimates on cost of construction made by various engineers does not reveal any great possible reduction in first cost by the use of the single-phase electric motor as long as present standards of heavy track construction, heavy rolling stock, and high speeds are adhered to.

It is the purpose of this paper to consider whether it is not feasible to work out a new type of light electric railway construction which will involve only about one-third the cost of the typical high-speed interurban road with which we are familiar, which can prosper on a much smaller revenue, and yet fulfil all the transportation requirements of many rural communities. The advent of the single-phase railway motor at least makes such an undertaking appear more promising of success now than in the past.

The first thing to be done in planning such a road is to dismiss the idea of using cars of the weight and operated at the speed required in interurban service, for it would be useless to figure on any material cheapening of the cost of construction, as compared with that of interurban roads, if cars weighing 25 to 30 tons are to be run at speeds of 40 to 50 miles per hour. Of course, first-class, substantial, heavy construction is absolutely essential for interurban service where such construction is to be the basis for operation of cars of the weight and at speeds just mentioned. But the question naturally arises: is it necessary to adhere to such high standards of service and construction for serving all kinds of communities? Why should hamlets and farming townships in Illinois and Iowa, with populations of 100 to 1 000, be entirely denied electric railway transportation facilities because they cannot support first-class, high-speed, electric railway service, such as now connect the closely situated manufacturing towns of Indiana and Ohio? In other words, is there any reason for establishing a kind of engineering dead-line, and saying no electric railway outside the cities is worth considering unless it is up to the present interurban standards?

As the character of a road should depend entirely on the character of its rolling stock, consideration will be first given to that feature. It is suggested that on a light electric rural and interurban railway, small double-truck cars for a track of about 28-inch gauge might be adopted. Narrow-gauge railways have fallen into disrepute among railway engineers, and with good reason, because the ordinary narrow-gauge road does not differ sufficiently in cost from a standard-gauge road to make the saving worth while in most cases, and also because of the inability to take standard-gauge cars from connecting roads. If we go into the narrow-gauge business we must go far enough to gain some substantial advantage. It is therefore suggested that a road of about 28-inch gauge, although at a disadvantage in not being able to take standard steam-road cars, nevertheless has the decided advantage of a greatly reduced cost of construction.

OUTLINE OF CAR SUGGESTED FOR LIGHT RURAL ELECTRIC RAILWAY, 28″ GAGE.

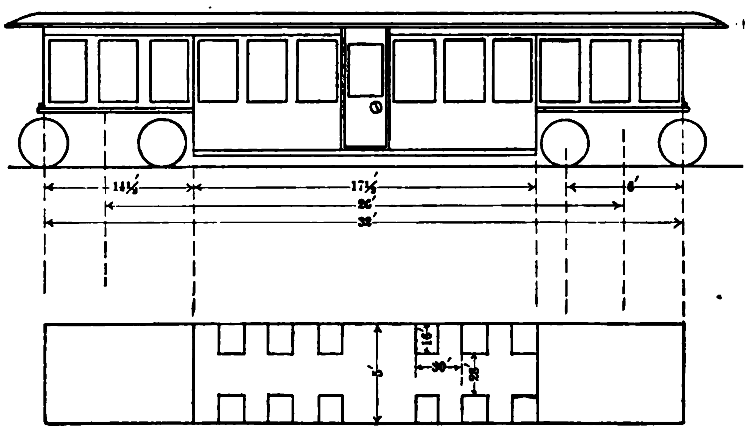


FIG. 1.

On a road of the character proposed, maximum speeds of 15 to 20 miles per hour will answer all practical requirements. This speed should be feasible on a roadway of 28-inch gauge, with light double-truck cars of 8- to 10-tons' weight. A suggestion as to a suitable form of car construction for such a road, with dimensions, is presented in the accompanying outline drawing, Fig. 1. As 28 inches is about one-half standard gauge, no doubt cars of one-half the width of standard-gauge cars could be used with safety. This would permit a passenger car of 5-ft. width. Such a car, if equipped with cross-seats, would be of sufficient width for a single seat of 16- to 18-in. width on each side of an aisle 24 to 28 inches wide. Longitudinal seats could be used if preferred. It would not be possible to use the regular plan of placing motor-trucks under the car, because, in order to keep the center of gravity of the car low enough for safety on the narrow gauge, wheels of 16- to 18-inch diameter would have to be used, and it would be impossible to place motors of sufficient capacity on trucks equipped with such wheels. The motor-trucks in this case should therefore be equipped with 30- to 33-in. wheels, which would give abundant room for motors of sufficient capacity to propel the light cars proposed. The car floor is made higher at the ends over the motor-trucks than under the balance of the car. If a motor-truck were placed only under one end of the car the trail-truck could have small wheels and be arranged in the common manner. By the arrangement shown the center of gravity will be low, and it leaves a compartment at one or both ends of the car above the motor-trucks, in which can be installed the various electrical appliances that are usually under the car but which cannot be so placed when the car-body is hung as low as it is in this case. These compartments can also be occupied by the motorman and used for baggage. The car body can be supported by I-beams or channels in the sides of the car just below the windows, and these beams can also support the side-sills of the passenger compartment by means of tie-rods and struts. The length of the car may vary considerably, but for very light traffic a car 18 feet long is suggested. This will seat comfortably 12 passengers. Equipped with a motor-truck at one end only, it will probably weigh not more than 10 tons, and with a motor truck on both ends, 12 tons.

It is assumed that single-phase motors are to be used, which would cause the electrical equipment to weigh more than a direct-current equipment. No such narrow-gauge, single-phase motors have been produced yet, as far as the writer knows, but undoubtedly could be produced were there need for them. Motor-cars, such as suggested, could haul one or two light freight-cars on roads without heavy grades. For a road of this kind trailers would probably best serve to carry freight; and they should be designed so as to allow the freight to be readily transferred to grain elevators or steam-road freight cars.

With double-truck motor-cars of the type suggested, a maximum speed of 15 or 20 miles per hour should be safely possible on a 28-in. gauge track with standard T-rails of about

30 pounds per yard. It costs much less to build a 28-in. gauge road laid with 30-lb. rails than a road of standard gauge. The tonnage of steel required is half that of a road equipped with 60-lb. rails, these being the lightest that it is now considered good practice to use in interurban electric railway work. The cost per ton of light rails is also about 25% less than that of rails weighing more than 40 lb. The ties used can be half the standard 8-ft. length and less than the usual 6-in. by 8-in. cross-section.

The cost of grading would be reduced from standard-gauge construction for the two following reasons: first, the reduction of the cross-section of cuts and fills by the narrowing of the embankment; secondly, with a road of this kind operating at slow speeds on a narrow gauge it would be good engineering to avoid many of the cuts and fills that would be necessary on a high-speed road, and to pick a location which goes round hills rather than through them. The rolling prairie country of the Central States would almost invariably permit the location of the route of such a light railway so as to be almost free from all heavy grading work. What would be considered a very crooked route for a standard-gauge steam-road would be unobjectionable on a light railway of this kind. By laying out the road so as to avoid heavy grading work, the expense of bridges and trestles would also be reduced to a minimum. In crossing large streams of course approaches and bridges must be built which are out of the way of floods, but large streams are the exception and probably the majority of light railways of this class would not cross any large streams unless on a highway.

The next question is that of ballast. Since many branch steam lines and some interurban electric lines are still operating without ballast it would hardly seem wise to invest much money in ballast for a light railway of this kind. Ballast is desirable, to be sure, but in this case the expense would hardly be justified.

The overhead trolley construction should be simple in character, since it will have but light traffic passing under it. By using single-phase, alternating-current motors with a trolley pressure of 3000 to 4000 volts, feeders will not be needed to supplement the trolley on a rural road 20 miles long with power supply from one end. The trolley-wire itself can be No. 0 wire. The poles will therefore need to be heavy enough to support the trolley-wire bracket only. It is assumed that the catenary construction would be used with the trolley-wire, supported at frequent intervals by a steel catenary, the catenary resting in turn upon center-bearing, high-pressure insulators. Instead of a costly iron bracket for supporting the trolley, a bracket consisting of a 5-ft. wooden cross-arm, supported from above by a tie-rod and bolted to the pole at one end, would answer the purpose.

In most cases power could be purchased from a light and power company at the principal terminus of a line, thus keeping the cost of power within reasonable limits, as the amount of power required would not justify a separate power-house. It is assumed that the railway company would furnish a generator, this generator to be placed in the lighting company's station. The balance of the power investment to be made by the lighting company.

The following estimates are on the cost per mile of a railway built according to the foregoing ideas; these estimates are of course conjectural, as no such road has ever been built. The figures are based on cost of present railway construction, assuming all the supplies and rolling stock to be standard.

COST OF ROAD AND EQUIPMENT PER MILE.

TRACK AND GRADING.

Right of way donated.	
Grading averaging 7000 cubic yards per mile at 18 cents per cubic yard	$1 260
30-lb. T-rail at $33 per ton, 52.8 tons, 30-ft. lengths	1 742
352 rail-joints at 75 cents each	264
2 640 ties, 4 in. by 6 in. by 4 ft., at 20 cents each	528
30 kegs spikes at $3	90
360 bonds at 30 cents each, in place	108
Labor, laying track	300
Highway crossings	25
Fencing (20 miles)	150
Track total	$4 467

GENERAL ROADWAY ITEMS FOR 15-MILE ROAD.

Culverts, etc.	$1 500
Bridges	1 000
Special work	2 000
	$4 500
Per mile	300

OVERHEAD LINE PER MILE.

48 poles (25-ft.) at $4	$192
Wood brackets (cross-arm size) 3.5 in. by 4.5 in. by 60 in., at 50 cts.	24
48 high-pressure insulators at 15 cents	8
5 280 feet No. 0 trolley wire at 15 cents per lb	253
5 280 feet 0.25-in. steel stranded catenary at 65 cents per foot	34
528 clips and catenary attachments at 20 cents	106
Miscellaneous overhead supplies	50
Labor on trolley and catenary	150
48 cross-arm tie-supports at 15 cents	7
Telephone wire, 2 miles, No. 8	30
Telephone insulators and brackets	10
Labor on telephone line	25
	$889

ROLLING STOCK, BUILDINGS, ETC., FOR 15-MILE LINE.

3 passenger motor-cars at $2 500	$7 500
2 passenger trailers at $750	1 500
1 freight motor car	2 200
15 miscellaneous freight cars at $300	4 500
Car-house and repair-shop	2 000
100-kw. generator capacity in lighting station	2 000
Miscellaneous engineering and superintendence	15 000
Total for 15 miles	$34 700
Per track mile	$ 2 313

RECAPITULATION COST PER TRACK MILE.

Track and roadbed	$4 467
General roadway items	300
Overhead work	889
Rolling stock, buildings, and miscellaneous	2 313
Total per mile of track	$7 969

The estimates are believed to be fairly liberal for the class of construction proposed. The total amounts to about $7 900 per mile of track, or a little over one-third of the cost of a standard-gauge high-speed road.

The next question to determine is whether a road of this kind is capable of earning enough to pay interest on the investment. Assume the road to be 15 miles long. A good passenger and freight service for a rural community could be given by a daily schedule calling for the equivalent of 15 round-trips of trains consisting of motor-cars, hauling freight cars whenever necessary. On a 15-mile road this would mean 450 train-miles per day, or say 135 000 train-miles per year, allowing for some reduction from foregoing schedule during the winter.

The following is believed to be a fair estimate of the ordinary operating expenses per train-mile of such a road:

Power per train mile, one kw-hr. at 3 cents (purchased)	$0.03
Motormen's wages	0.025
Repairs and maintenance on rolling stock	0.005
Repairs and maintenance on track and overhead line	0.01
General expenses	0.015
	$0.085

135 000 train miles per year at $0.085	$11 475
Cost of operation per track mile ($11 475 ÷ 15 miles)	765
Interest at 6 per cent. on $7 900 per mile cost construction	474
Interest and operating expenses per track mile	$1 239

Obviously, there are plenty of locations where a road could easily earn this, and in addition enough to cover depreciation. In these locations standard-gauge high-speed roads would be prohibited by financial considerations.

Without doubt difficulties stand in the way of the construction of the first roads of this class that may be built. One of the most serious obstacles is that no cars, motors, trucks, or overhead work suitable for such a road are now being manufactured; and before such roads can be built these must be developed, either by the manufacturers or by the prospective user. It is not to be expected that the manufacture of light electric railway apparatus will be attempted until there is a wide enough interest in and demand for railways of this kind to induce manufacturing companies to develop and market suitable equipments.

Rural Passenger and Freight Traffic.

Supplementary to the engineering and construction matters considered in the foregoing part of this paper, tentative estimates have been compiled by the author on the traffic possibilities of a strictly rural territory. Light railways of this class need not necessarily be confined to strictly rural business, as doubtless most of them would serve small towns as well as the intervening country. However, in a rich agricultural state where the chief industry is farming the revenue from the farmers is the first thing to be considered.

In the United States census of 1900 the annual value of farm products in three of our richest agricultural states is given as follows:

Iowa	$6 600 per square mile
Illinois	6 180 per square mile
Indiana	5 700 per square mile

In Iowa 40 bushels per acre is considered the average corn crop. If this brought 35 cents per bushel, the yield per square mile would have a value of $8 960, but of course this amount would not be shipped. If $7 000 worth were shipped, it is fair to assume that the local rural railway would be able to get a price equal to one per cent. of the value of the shipment, or $70 per square mile.

Rough estimates obtained from the owners of six ordinary farms located in central Iowa result in the following average estimates of the amount of farm products shipped. The total area of these farms was 1 513 acres and the amount of live-stock shipped 470 000 lb. or 295 lb. per acre. The grain hauled to town from these farms amounted to only 7 095 bushels, or 4.7 bushels per acre, as that part of the country has practically abandoned grain shipment and gone into the stock-raising business. The tonnage of coal hauled from town to these farms averaged 8.1 tons per square mile.

Take as a basis the figures from the six farms before mentioned, and suppose that the live-stock is worth four cents per lb. With 295 lb. per acre the value of live stock would be $11.80 per acre. Assuming the 4.7 bushels of grain per acre to be oats (as most of it was) at 25 cents per bushel, the value would be $1.17 per acre, which added to the live-stock makes a total of $12.96 per acre or $8 300 per square mile for the value of products shipped. If one per cent. of this could be obtained for the local freight rate, it would give the road a revenue of $83 per square mile of tributary territory. Estimating on a tonnage basis, the revenue from hauling the same products would be as follows:

94 tons live stock at 50 cents per ton	$47
8.1 tons coal at 50 cents per ton	4
3 000 bushels of grain at 1 cent per bushel	30
Total freight revenue per square mile	$81

It will be seen that all these estimates correspond in ultimate results: this leads one to believe that they are not unreasonable.

Now consider these estimates in the light of the probable earnings of a strictly rural electric railway.

For this purpose assume that a road is to extend from a good-sized county seat 15 miles into a country which has no railroad stations nearer than said county seat. The tributary territory to such a road may be estimated to be 106 square miles by the following process of reasoning: for the first three miles out of the terminal no tributary territory is considered, although of course there should be considerable passenger and light freight business from this portion of the road. For the remaining 12 miles of the road the tributary territory is estimated as follows:

4th mile of track, 1 mile on each side	2 square miles
5th mile of track, 3 miles on each side	6 square miles
6th mile of track, 4 miles on each side	8 square miles
7th to 15th miles inclusive, 5 miles on each side	90 square miles
Total tributary territory	106 square miles

While a territory extending five miles each side of the track may not seem a conservative estimate at first, it must be remembered that traffic will naturally seek the nearest railroad; and in this case it is assumed that there are no other railroad stations as near to the territory served.

The possible gross revenue from freight has already been estimated to be between \$70 and \$83 per square mile. Taking the lowest figure, \$70, the revenue from 106 square miles would be \$7 420 or \$494 per track mile.

Assume that a prosperous rural community yields \$10 per year per capita in passenger revenue—not an unreasonable assumption when one considers that the estimated earnings of interurban lines between large towns include a large population which does not ride and is not dependent on the interurban road. Assume a rural population of 10 per square mile. A territory of 106 square miles, with 10 persons per square mile, makes a total of 1 060 population and \$10 per capita per year for this population is \$10 600, or \$706 per mile of track for the rural population.

Suppose that the road has at about 10 miles from its terminus a town of 1 000 inhabitants. These should yield a revenue of \$5 per capita per annum or a total of \$5 000. This is equivalent to \$333 per mile of track.

Earnings and Operating Expenses per Track Mile: Summarized.

Passenger earnings (rural)	$706
Village passenger earnings	333
Freight earnings, lowest estimate	494
Mail and light express	100
Total gross earnings	$1 633
Operating expenses	765
Net	$868
Interest on investment	474
Surplus	$394

Considering better railway transportation as one solution of the good-roads problem in the middle West, and the number of places demanding light electric railways, it is important that the attention of the public, of electric railway engineers, and of the manufacturers of electric railway apparatus, be centered on the light electric railway problem. From the manufacturing standpoint it opens an immense field for this kind of railway equipment, while from the farmer's standpoint the increase in the value of farms served by such a road would ultimately pay for its construction.

It is with the object of creating interest in the subject of light electric railways that this paper has been written; the details attending the building of such railways may properly be taken up later. If the suggestions offered in this paper result in the establishment of the light electric railway as a recognized and important part of the transportation industry in this country, the author's object will have been accomplished.

A paper presented at the 202d Meeting of the American Institute of Electrical Engineers, New York, December 15, 1905.

THE RELATION OF RAILWAY SUB-STATION DESIGN TO ITS OPERATION.

BY SYDNEY W. ASHE.

This paper is limited to a consideration of sub-stations in which high-tension alternating current is received and converted into low-tension direct current. In the operation of a modern railway converter sub-station, reliability of service is of paramount importance, being more important than considerations of first cost, of depreciation, and of maintenance; and in turn the reliability of service is affected to a marked degree by the length of time required to manipulate the various combinations of sub-station apparatus. The following factors will be noticed in this connection:

1. The best method of starting converters.
2. The protection of converters;
3. The use of oil-switches when synchronizing;
4. The regulation of load;
5. The best arrangement of switch-gear;
6. The operation of reverse-current relays;
7. The adjustment of load between the sub-stations which feed the same circuit;
8. The noiseless operation of synchronous converters.

1. *The best method of starting converters.* In considering the various methods for starting converters, it should be noted that the prime requisite of every method is ability to start and synchronize a converter in the shortest time without affecting the system generally. The first rule that a sub-station operator must learn is to be ready at all times to carry upon the converters whatever load may come upon the sub-station, this load being limited only by the maximum carrying

capacity of the feeder oil-switches. Occasionally, as a result of congestion of traffic, excessive overloads come upon a station. In this case another converter must be started immediately, synchronized, and placed on the bus-bar. This calls for a convenient arrangement of switch-gear, a rapid, reliable method for starting and synchronizing converters, and a quick and steady operator.

Three methods are usually employed for starting converters; namely,

A. From the direct-current side.

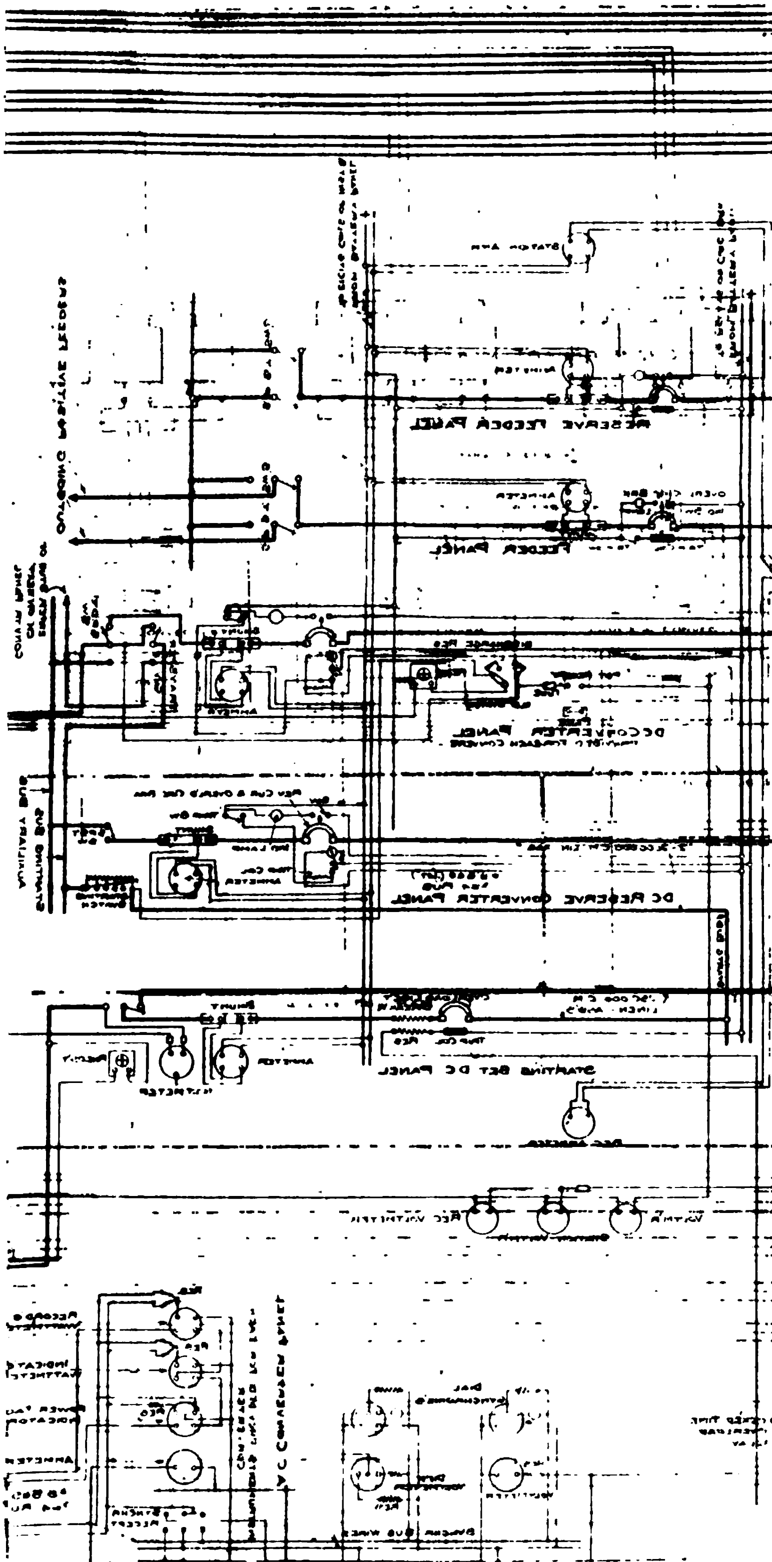
B. By means of a small direct-connected induction motor.

C. From the alternating-current side.

Method A. The converter is started as an ordinary shunt motor, receiving its current either from a shunt-wound generator or from the direct-current bus-bar. A double-throw switch is usually provided so that the converter may receive current from either source. Ordinarily, when started by current from a shunt-wound generator about two minutes are required to start, synchronize, and connect a 1 500-kw. converter to the bus-bar. In emergency cases the machine is started by current from the direct-current bus-bar, and only a minute and a half are required to place it in service. The advantages of method "A" are the smallness of first cost, and the rapidity of starting, since it requires but one starting set for all the converters, and the expense of maintenance is slight.

The disadvantages of the method consist in a small factor of reliability, and the possibility of a heavy surging of current during the process of synchronizing. The latter disadvantage may, however, be obviated by the use of a simple modification of the switch-gear, devised by Mr. H. G. Stott. This device is now used in connection with the Interborough Rapid Transit Company's equipments. It consists in closing a local storage-battery through tripping coil of the circuit-breaker of the starting bus-bar a fraction of a second before the converter oil-switch closes. The converter then runs practically free from the direct-current side, and self-excited at the instant the oil-switch closes. The oil-switch motor and the tripping-coil of the circuit-breaker are in multiple with the battery when the control-switch on the bench-board has been closed. The oil-switch requires only 0.4 of a second for complete connection, whereas the circuit-breaker operates almost instantly.

When the converter is rotating slightly under or above its



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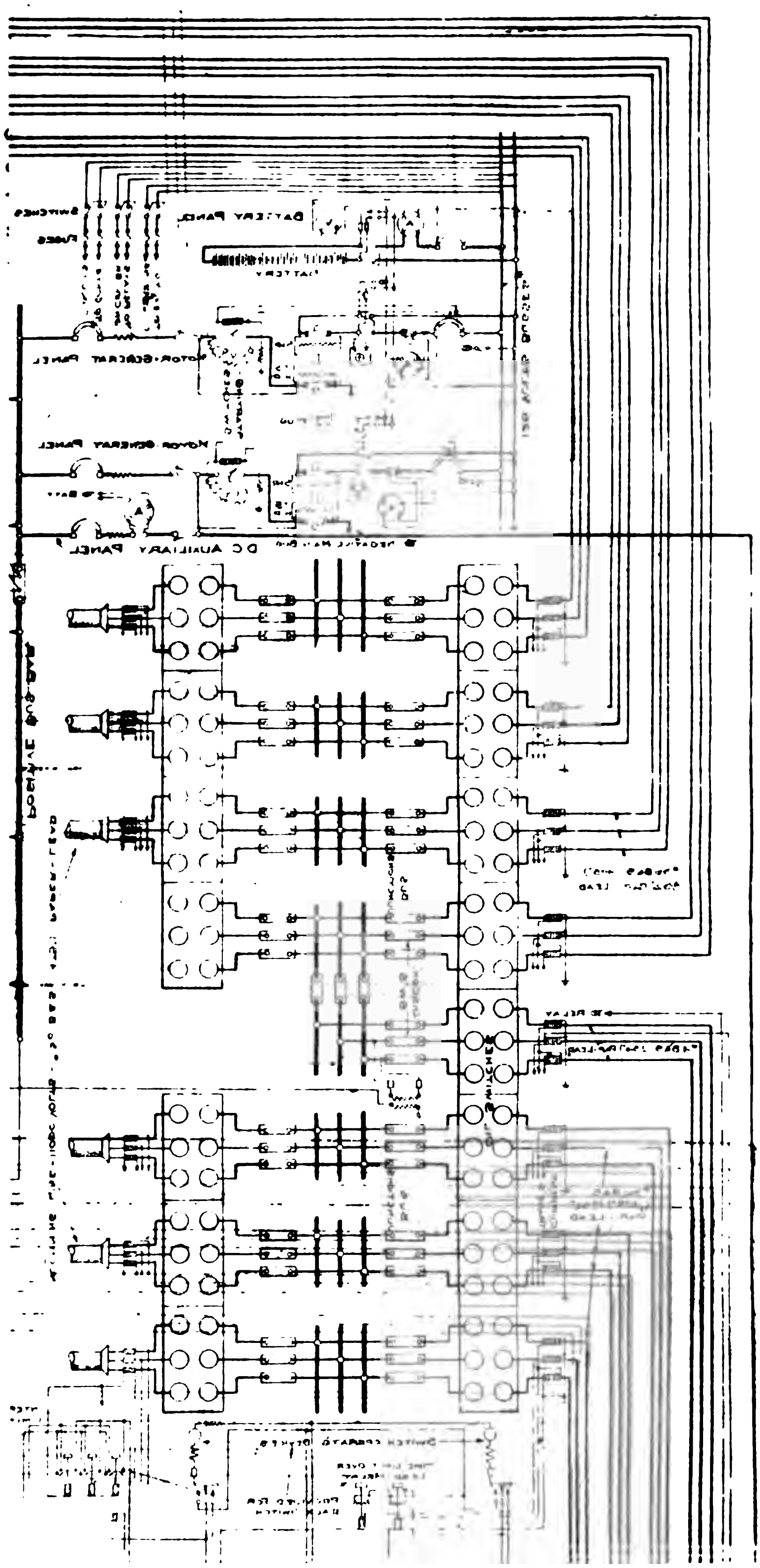

synchronous speed, and the pointer of the synchronism indicator is moving slowly round the dial, if the local storage-battery switch be closed just as the pointer is approaching zero it is possible to connect the converter through the transformer to the alternating-current bus-bar without the operator being conscious of the fact except from the noise made when the oil-switch closes. A complete wiring diagram of a sub-station in which this method of starting converters is employed is shown in Fig. 1.

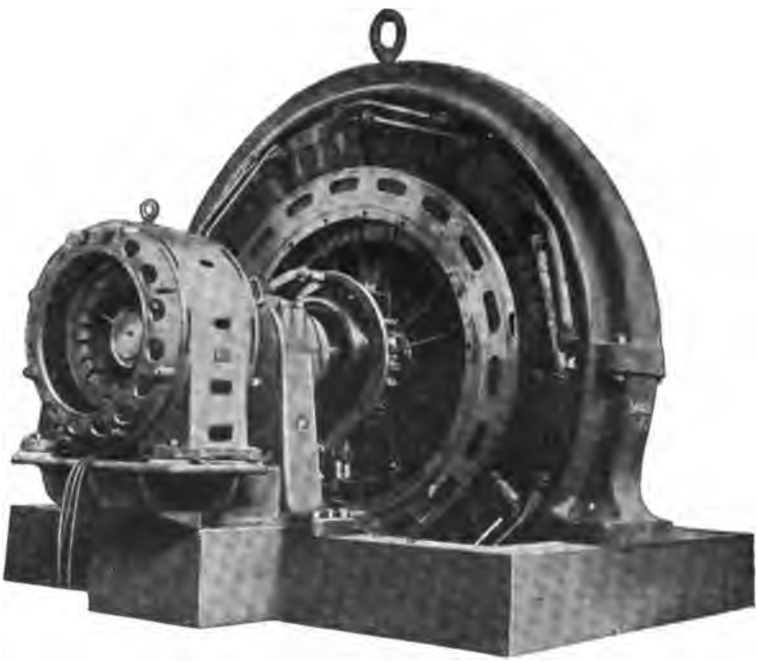

FIG 2.

Method B. With this method, by means of a small induction motor mounted upon the main shaft of the converter, the converter is brought up to synchronous speed (Fig. 2). The starting motor has fewer poles than the converter and therefore a higher normal speed. A variation in speed may be obtained by placing a slight load upon the converter through the medium of a resistance shunted across the brushes, the converter being self-excited. Varying the resistance in series with the converter field-coils will also cause a slight variation of load upon the induction motor. This is the means usually employed, the electrical connections for which are shown in Fig. 3.

The main advantage of this method is the increased factor of reliability, since each converter has its individual starting motor. For mechanically starting the converter armature it is common practice to install a motor somewhat smaller than

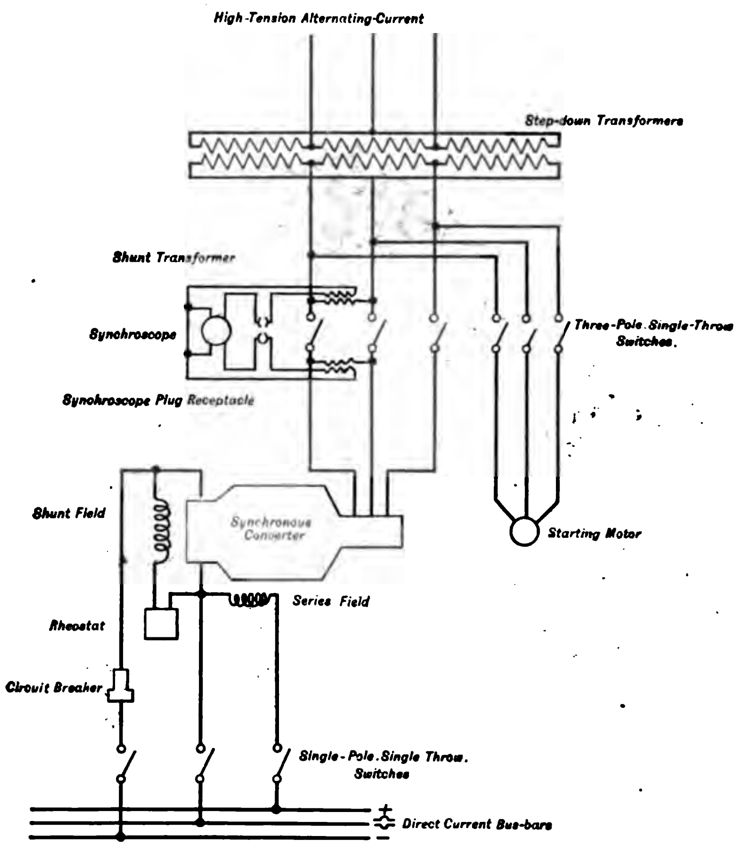

FIG. 3.

the motor used for driving the exciter generator in method "A." As a result, a converter does not accelerate so quickly with this method as when started from the direct-current busbar. One of the disadvantages of this method is the fact that owing to the torque of the induction motor varying with the square of the impressed voltage, a very small drop of voltage will keep the motor from starting at all. For instance, if only 80 per cent. voltage were received, as is sometimes the case after a bad shutdown at the power house, or on the system, due to a variety of causes, it is highly improbable that the converter will start. Another bad feature is, in case of a burn-out on a starting motor the converter is crippled. Other disadvantages are the greater first cost and increased cost of maintenance.

Method C. In this method, the ordinary connections for which are shown in Fig. 4, two sets of taps on the low-tension side of the step-down transformers are commonly used. These taps are connected to a two-way switch, the middle terminals of which are connected to the converter slip-rings. To prevent an excessive starting current, reactance is inserted between the converter slip-rings and the low-tension windings of the transformer.

The converter is started as an induction motor by throwing the two-way switch so that the low-potential taps are connected. When the current has fallen sufficiently low—the converter speed increasing—the two-way switch is thrown in the opposite direction, connecting the converter directly to the normal-voltage taps.

It is usual with this method to start converters of 300 kw. or less, from starting taps giving one-half normal voltage. Converters varying from 300 kw. to 1 500 kw. are started by voltages of one-third and two-thirds the normal voltage. On the one-third voltage taps, with 25-cycle converters, the current at starting is generally a little less than that at full load.

Owing to the large ratio of the field-turns to those of the armature, high electromotive forces are liable to be induced in the field windings when making use of this method of starting. It is common practice to provide a field-switch which disconnects the windings at several points, as represented by Fig. 5.

With this method no time is lost in adjusting the speed as the converter builds up into synchronism, but an objection to this method is the large current drawn at starting. This, however, is generally at a power-factor that yields a correspondingly increased starting torque, and brings the converter up to synchronous speed in a shorter space of time. Another important advantage is the large factor of safety due to the entire absence of starting sets and starting motors. The additional field-switches consume, however, additional time for their manipulation.

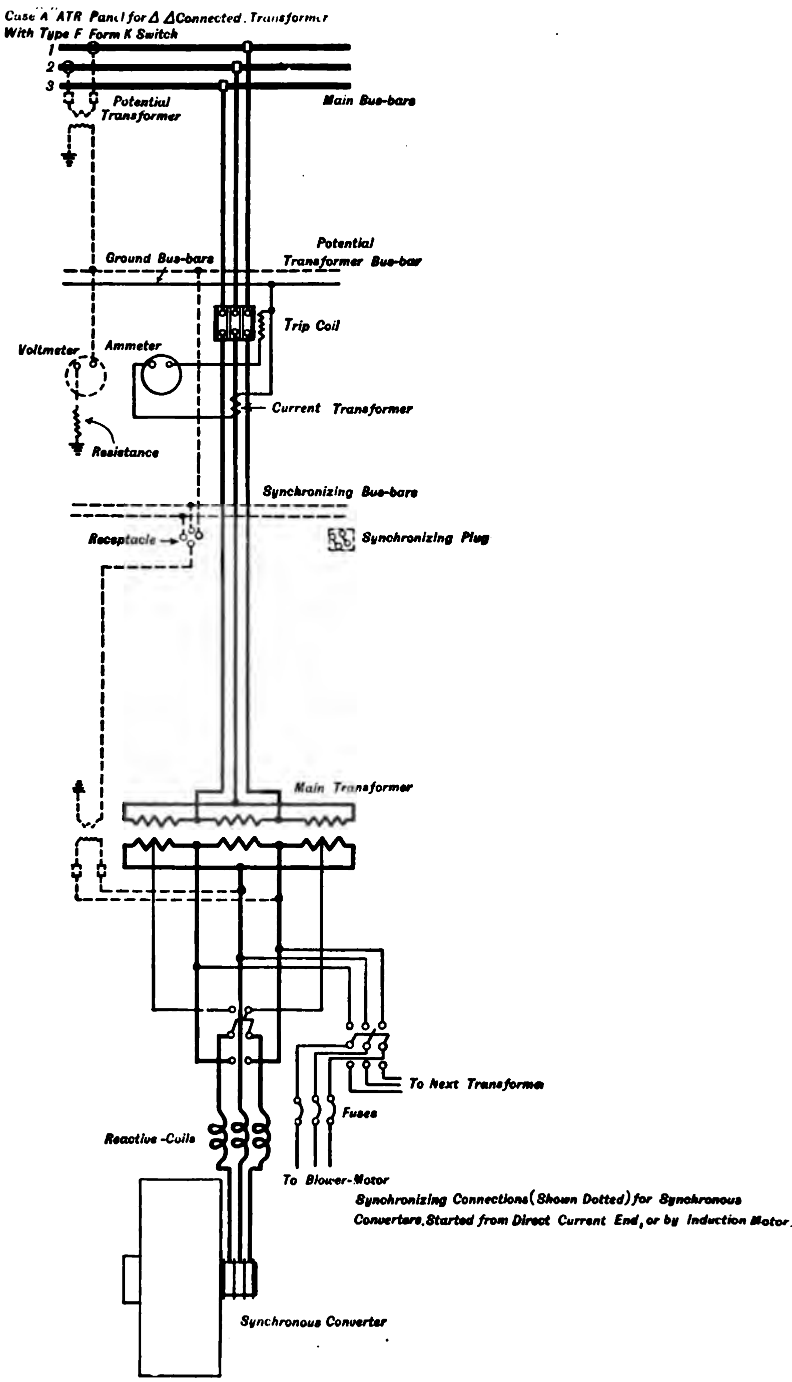
Case A "ATR Panel for Δ Δ Connected. Transformer
With Type F Form K Switch
1
2
3
Potential Transformer
Main Bus-bars
Potential Transformer Bus-bar
Ground Bus-bars
Trip Coil
Voltmeter
Ammeter
Current Transformer
Resistance
Synchronizing Bus-bars
Receptacle
Synchronizing Plug
Main Transformer
To Next Transformer
Fuses
Reactive-Coils
To Blower-Motor
Synchronizing Connections (Shown Dotted) for Synchronous Converters, Started from Direct Current End, or by Induction Motor.
Synchronous Converter

FIG. 4.

The time ordinarily required to put converters in service when using this method is approximately as follows:

300 kw......................... 45 seconds;
1 000 kw......................... 75 seconds;
1 500 kw.........................120 seconds;

It is possible to start these converters more quickly. The following times have been recorded, though they do not represent the minimum:

300 kw..........................16 seconds;
1 000 kw..........................40 seconds;
1 500 kw..........................65 seconds;

This includes the time necessary to close the high-tension alternating-current switch of the converter transformer, the time of starting by means of air-brake lever-switches, and the time included in closing the field-switches, the direct-current circuit-breakers, and the line-switch.

Considering the best starting conditions, the chief disadvantages of this method are the high potential generated in the field windings, the large starting current which may affect the regulation of the system, and the necessity for a change in design. The two former disadvantages are minimized by the arrangements previously mentioned. The latter disadvantage, however, necessitates the elimination of the circular dampers embracing the entire pole-piece. A converter constructed in this manner is liable to "hunt" on the slightest provocation, and ultimately trip itself out of the circuit. For instance, a short-circuit on some other part of the system, throwing a lagging current on the line, or some slight trouble in the governor of one of the engines supplying it, or anything which may happen to vary the angular velocity of the prime mover, is sufficient to start hunting in a synchronous converter. It may be noted, however, that to the writer's knowledge, converters of large capacity have been started from the alternating-current side, even when protected by the most efficient form of pole-dampers, but as the self-induction of the converter armature were small in these cases, the starting current was excessive. The pole-dampers act as the closed secondary of a transformer, tending to neutralize the self-induction of the armature. When starting without pole-dampers, the starting current is approximately four times that used with methods "A" or "B" for the same capacity machine.

It should be noted when considering the time necessary to start converters, that this time depends to a great extent upon the personal peculiarities of the operator. Moreover, the interval of starting for all methods has been so far reduced as to be adequate to the demands of railway operation. When an excessively steady overload comes upon a station, the operator

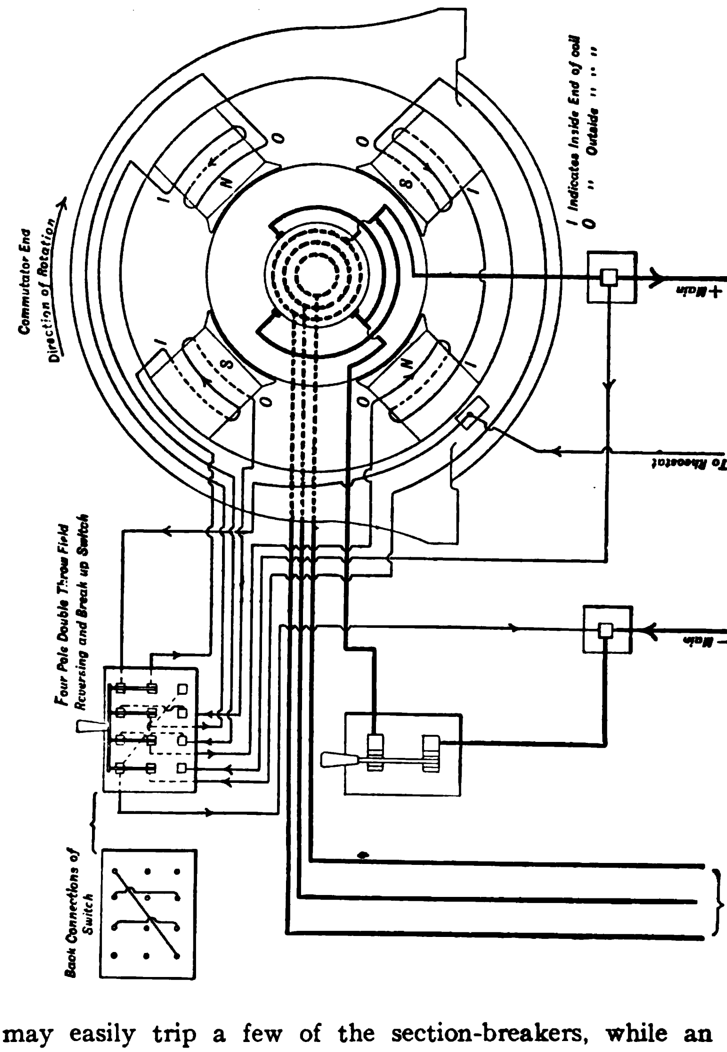

FIG. 5.

may easily trip a few of the section-breakers, while an additional machine is accelerating. The cars on the rail-sections fed by this sub-station will receive slight power from adjoining rail-sections as the I R drop will be excessive. The cars will consequently slow down. When the power has been off the circuit for about 20 seconds and the speed of the converter is approaching synchronism, the circuit-breakers formerly opened may be closed, and the other section-breakers and switches opened. In this way trains may be kept moving during the time required to start, synchronize, and place on the bus-bars this additional machine. Passengers in the cars will hardly be conscious of what has occurred.

The Protection of Converters. In the design and installation of circuit-breakers, the inductance of the system is usually relied on to prevent an excessive rise of current during the interval of time elapsing between a short-circuit and the opening of the circuit-breaker. This, however, is not sufficient protection; for an excessive short-circuit in the system, say during light load when only one machine is operating, will often cause a flash, accompanied by a shrill sound, around the commutator of the converter. At first one might think that a reactance-coil of low ohmic resistance could be placed in series with the breaker to minimize this effect; but a coil of constant reactance, resistance, or self-inductance, could not entirely meet the conditions, owing to the variability of the time-constant of the circuit. For instance, the self-inductance and resistance would vary with the distance from the sub-station in which the short-circuit occurred. Proper conditions, however, might be approximated and a coil designed which would partly protect the converter.

Where sub-stations are equipped with storage-batteries which float on the system, there is a tendency for the storage-batteries to bear the brunt of the load, in case of short-circuit, permitting the converter circuit-breaker to open, followed shortly by the opening of the battery circuit-breaker. This, however, does not always prevent the converter from flashing over, owing to the fact that the velocity of chemical action at the electrodes of the battery, and the limitations of the velocity of migration of the ions of the electrolyte are insufficient to prevent this action. Theoretically, the converter bus-bar voltage would drop, the battery carrying the peak of the load. As a matter of fact, the battery does not always perform this function.

The Use of Oil-Switches when Synchronizing. Much has been written of the superiority of oil-switches over air-switches for opening and closing alternating-current circuits. This superiority is due to several causes; namely, the smothering action upon the arc by the oil, the rupturing of the circuit at the zero point of the current wave, the absence of leakage between contact points, and the small dimensions of the switch. Electrically operated oil-switches, however, have a few disadvantages which, while not vital, are worth mentioning. It is not the intention of the writer in mentioning these disadvantages to criticise the use of oil-switches over air-switches, as the former are far superior to the latter for heavy traction work.

With an oil-switch, the time required to close the circuit varies with the voltage of the local storage-batteries. When this voltage falls below a certain point, the switch fails to operate. Such switches are guaranteed to operate over a considerable range of voltage, something like 125 volts to 70 volts, but several instances have been brought to the attention of the writer in which switches have not operated when the voltage has fallen below 95 volts. This characteristic is extremely objectionable; for it obliges the operator to re-synchronize, inasmuch as the general sub-station rule requires the starting over again of all auxiliary apparatus when an oil-switch fails to operate. Another objectionable feature is that sometimes oil-switches fail to lock when closed by the switch-motor, opening again and closing subsequently when the converter is perhaps as much as 60° out of synchronism. This performance is characterized by operators as "looping the loop." One can readily imagine what happens when a converter that is considerably out of synchronism is closed upon the circuit, making what is termed "a bad shot." This may do considerable damage. These troubles, however, are not of frequent occurrence and an operator who is familiar with the "individuality" of each switch soon learns to test it frequently, as well as to keep his storage-batteries well charged, and thus to minimize these disagreeable characteristics.

The Regulation of Load. Railway operation does not call for as close a voltage regulation as is requisite for electric lighting circuits. Economic operation, however, demands that converters be run on as constant a load as possible. The general use of storage-batteries for load-regulating in railway work seems to have been retarded owing to their objectionable features; for instance, their acid fumes, the necessity for special wiring, and their heavy depreciation. In addition their enormous first cost has placed them actually out of competition with synchronous converters and generating apparatus. The usefulness of storage-batteries in railway work is being more and more appreciated, as evidenced by their recent applications. An interesting development in connection with storage-batteries is a carbon regulator put to use during the last year. It consists of a variable carbon resistance which is used in connection with pilot-cells and an exciter, to vary the excitation of the field-coils of a booster.

Referring to Fig. 6, *H* is a solenoid carrying the total generator load, which acts on a soft-iron plunger suspended from the lever *A-B* of the carbon regulator. At the other end of the lever is a spring *S*, whose tension is adjustable. *K* and *L* are piles of carbon discs on the opposite sides of the fulcrum, *C*, of the lever. The resistance of these piles is altered by slight

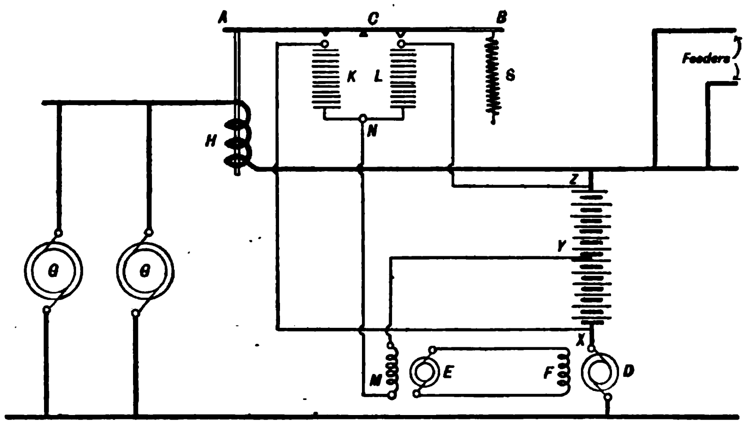

FIG. 6.

variation in mechanical pressure, produced by slight fluctuations of current in the coil *H*. The details of the electrical connections are self-explanatory. The battery booster is represented by *D*; *F* being its field-coils. *E* is a small exciter, whose field-coils, *M*, are connected to the carbon regulator as shown.

Consider the operation of this regulator, a perspective view of which is shown in Fig. 7. As the lever-arm is raised or lowered, the resistance increases in one arm and decreases in the other, causing wide variations in voltage across the exciter field-coils, the direction and intensity of the current in the coils varying accordingly. The action is somewhat analogous to that of Wheatstone's bridge.

With the polarity of the booster changing and its field excitation varying in intensity, it is possible automatically to charge the main battery or to raise the battery voltage so as to carry part of the load of the bus-bar. By limiting the motion of the lever-arm it is possible to limit the load which the battery will carry under extreme conditions. With this system, close regulation of the load on the converter is obtained, as evidenced by the load-diagram, Fig. 8. This diagram was

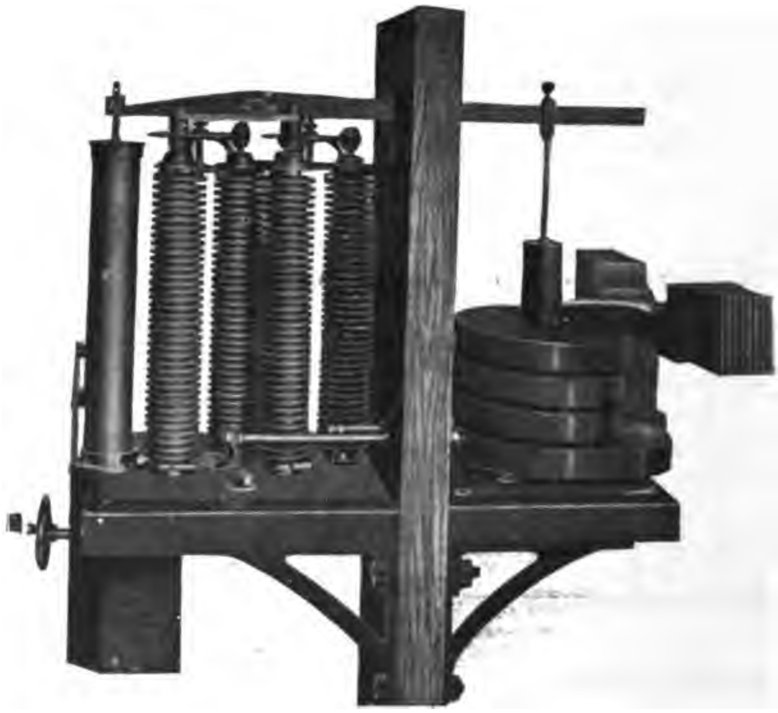

FIG. 7.

taken in the sub-station of the Lewiston & Auburn Electric Railway on October 7, 1905.

The Best Arrangement of Switch-Gear. The most suitable arrangement of switch-gear is obviously that which best facilitates the manipulation of sub-station apparatus with a minimum outlay.

There are two distinct arrangements of switch-gear, their adoption depending upon the capacity of the sub-station. With one arrangement, which is especially applicable to small

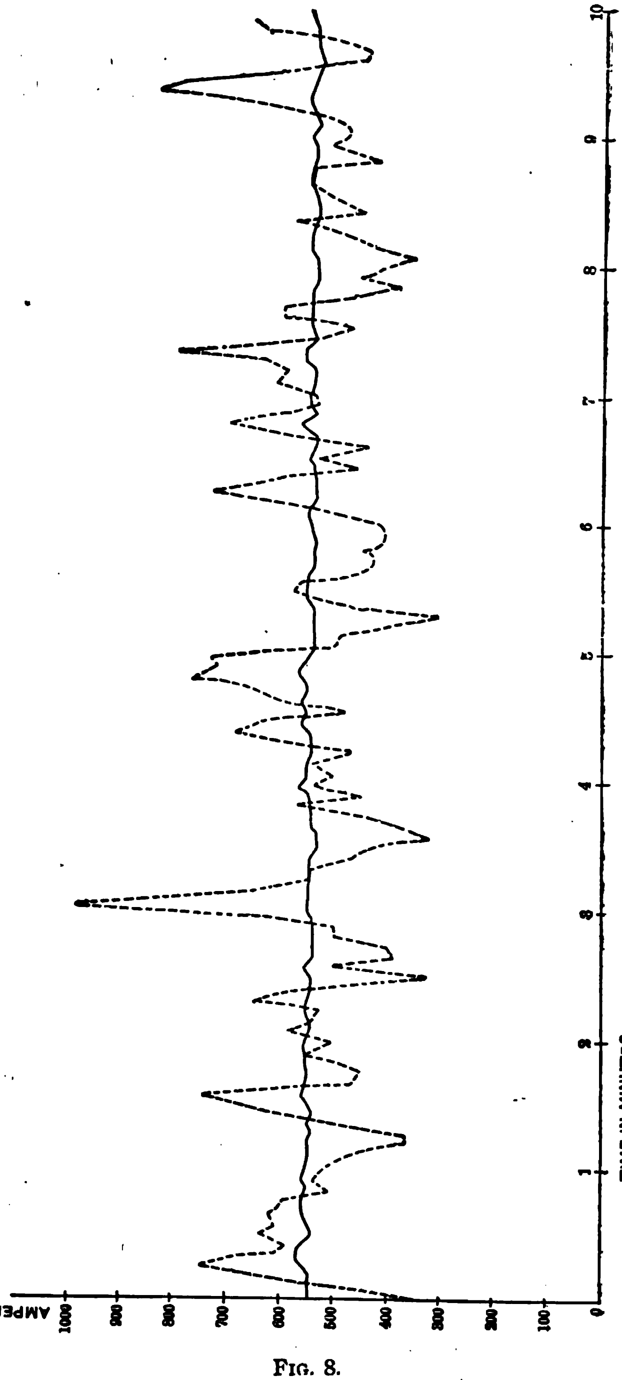
AMPERES
0
100
200
300
400
500
600
700
800
900
1000
TIME IN MINUTES
1
2
3
4
5
6
7
8
9
10

FIG. 8.

sub-stations, all of the switch-gear is located upon the main floor with the converters and with the transformers. The other method, which is usually employed in stations of large capacity, consists in locating all the manually operated switches, except the negative switches, in a switchboard gallery.

It is worth noting that in the first case, where all the switching apparatus is located on the same floor with the transforming apparatus, as in Fig. 9, the station attendance is minimized; for the operator may also perform part of the duties of station foreman, and the converter tender may also perform the duties of janitor, thus dispensing with two men. But this system is not wholly advantageous. In the first place, it is

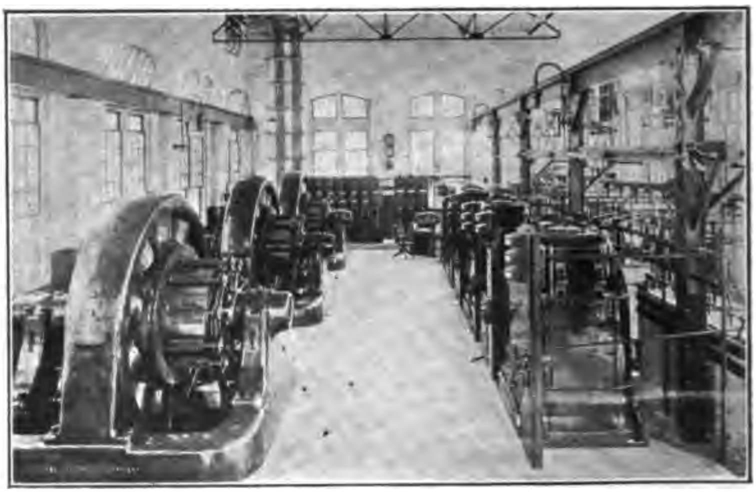

Fig. 9

difficult to keep the switch-gear clean; and in case of trouble the operator is too near the converters to act with unconcern. On the other hand, this system reduces the expense of wiring to a minimum, allows excellent ventilation, and results in a very compact station.

Where a switchboard gallery is employed, as in Fig. 10, the operator is able at a glance to scan the whole station, a great advantage in case of trouble. He is relieved of the fear of personal injury; he is less hampered, and more comfortable, and can better perform his duties. But the expense of wiring is greater and the ventilation inferior.

It is becoming the standard practice to construct the switchboard in three distinct sections; namely, a controller-board from which the oil-switches are operated, as in Fig. 11; a set of machine-panels; and a set of distributing-panels. The positive direct-current bus-bar forms a connecting link between the machine-panels and the distributing-panels. This system is sometimes modified in small stations.

Various arrangements of circuit-breakers are employed; in some cases they are mounted directly upon the switchboard-panels; in others distinct and separate compartments are used.

FIG. 10

The latter is preferable if the expense be justified; for it disconcerts an operator to see the flash of an opening circuit-breaker.

It has become quite common to separate the negative switches from the positive switches, the reasons for which are obvious.

A feature worth mentioning is the arrangement of a circuit of lamps on the switchboard, and their feeding from the local battery circuit, so that in cases of failure of power at the power house there may be sufficient illumination in the evenings for the operator to manipulate the board. Upon the same circuit a complete set of signal-lamps should be installed to indicate whether switches and circuit-breakers are open or closed.

The Operation of Continuous Reverse-Current Relays. Much criticism has been directed against continuous reverse-current relays, owing to their sensitiveness, the amount of adjustment they require, and their inability to perform their service at all times. While these criticisms are partly warranted, the fact remains that such relays are better than no protection at all.

Fig. 11.

An operator is supposed to try the relay controlling the machine circuit-breaker each time a converter is disconnected from the bus-bar. The field rheostat of the converter is cut in entirely, the converter dropping its load. The positive bus-bar voltage being slightly higher than the machine voltage, the reverse-current relay is energized, closing the local-battery circuit through the tripping-coil of the circuit-breaker which should open instantly.

Sometimes when a converter is being placed on the bus-bar its voltage is slightly lower than that of the bus-bar and consequently it "backs out," the circuit-breaker being tripped by the action of the reverse-current relay. This feature is disagreeable but it tends to make the operator more careful.

If reverse-current relays were not sensitive they would be practically worthless. Hence the features which appear to make the instrument objectionable are necessary elements of its successful application.

The Adjustment of Load between Sub-stations that Feed the Same Circuit. Where all sub-stations are equipped with converters of the same capacity, it is desirable to have a definite rule governing the adjustment of power-factor of converters, in order that the rail load may automatically distribute itself to the proper sub-stations. Such a rule requires the adjustment of the power-factor of all converters so as to be unity at full load; but it fails where applied broadly, owing to the practical impossibility of finding any two converters of the same capacity—although manufactured by the same company—with identical characteristics, and equal brush contact resistances. This rule is, however, usually observed with discretion by sub-station operators, and its observance yields good results. But if the rule be adhered to rigidly, the results are not altogether satisfactory.

For instance, assume two converters operating in multiple between a common alternating-current bus-bar and a common direct-current bus-bar. Assume also that the field resistances of the converters are adjusted for unity power-factor at full load. When the load upon both machines is greater than the combined full load capacity of each machine, one converter may draw more than half the load. Also when the total load is less than the combined normal load of both machines, the other converter may absorb the greater proportion of the load. This condition is aggravated by the resistance of the converter field-coils changing with the temperature, and also by the maintenance of the converter direct-current brushes.

When an individual converter in a sub-station is disconnected from the direct-current bus-bar, it does not follow that the original station load will distribute itself over the remaining converters operating in multiple. Moreover, when an additional machine is connected to the circuit, the sub-station will draw more of the load from the adjoining sub-stations. The energy in this way surges back and forth with each operation. It is obvious, therefore, that it is practically impossible to frame a rule of this character which may be adhered to rigidly. If storage-batteries are employed as a method of regulation, keeping the individual load upon the converters practically constant, this rule would apply more generally; but where the energy fluctuation upon the converters varies from quarter load to 50 per cent. overload and sometimes 100 per cent. overload, it is obvious that the previous rule will not apply. The same reasoning holds good in the case of a sub-station equipped with machines of different capacities.

Noiseless Operation of Converters. The operation of converters is usually accompanied by a shrill and disagreeable sound. It is not caused by the commutator, by the slip-rings, or by air passing through the crevices of the armature as is usually supposed, but is purely an electromagnetic phenomenon. It is probably the result of vibrations set up in the armature-core teeth by the varying electromagnetic conditions of the circuit.

That this tone is caused by magnetic action may be illustrated by the following simple experiment performed by the writer. A converter was driven by a separate belt-connected shunt motor, and the speed was adjusted to 1 800 revolutions per minute. The converter was a four-pole machine, so that this corresponded to a frequency of 60 cycles. The converter field-coils were unexcited and the machine operated practically without noise. Upon exciting the field-coils, this shrill tone became audible, and then increased in intensity until upon over-excitation it became very loud. This would seem to indicate that the phenomenon is purely magnetic, and that it might be obviated or at least modified by proper design. The desirability of such modification must be evident in the case of sub-stations located in residential sections.

A paper presented at the 202d Meeting of the American Institute of Electrical Engineers, New York, December 15. 1905.

SOME CONSIDERATIONS DETERMINING THE LOCATION OF ELECTRIC RAILWAY SUB-STATIONS.

BY C. W. RICKER.

No attempt will be made in this paper to define the conditions under which indirect distribution, through the medium of transformer sub-stations, is more economical than direct distribution from one or more generating stations containing prime movers. It is assumed that because of the size of the railways to be considered, and the local conditions determining the cost of generating power, the indirect method of distribution has been selected as offering the best economy in commercial operation; and an attempt will be made to outline a general method for determining the number and location of sub-stations.

In many cases, perhaps the majority of cases, a general solution of this problem is quite impossible. Most of the large electric railway systems now in existence are the result of development not foreseen by their projectors; and there is little reason to believe that future systems will be very widely different in this respect, but probably they will continue to grow by extensions and consolidations depending upon the distribution and development of local centres of industry and population.

For convenience of discussion, electric railways large enough to require indirect distribution may be classified as follows:

1. Large simple networks, serving a single community.
2. Long single lines or groups of such lines, connecting separate communities or different parts of one very large community.

3. Complex networks, with connecting lines, serving a large city and its suburbs.

4. Several networks with long connecting lines, serving separated communities.

Railways of the last named class are usually consolidations of the local systems of neighboring cities or towns, and interurban lines, which frequently furnish power for lighting and general uses in the towns served. There are usually well-marked centres of load which, together with local business conditions, determine the position and equipment of sub-stations.

Railways of class 3, those serving a large city and its suburbs, are also most often the result of the consolidation of separate lines and networks. While the large central network belongs in class 1, the outlying districts present a difficult problem to the engineer, for he must anticipate the direction, character, and sequence of growth so as to provide for them. This requires an intimate knowledge of local conditions, both industrial and social, and, in addition, he has need to be something of a prophet to foresee the changes which the building of new lines and the starting up of new works may produce. The problem is a local and particular one, and must depend mainly upon individual judgment for its solution.

Classes 1 and 2 can be treated more generally. Take first the case in which a large network, or long line or group of lines, is contained wholly within a large city, so that a fairly uniform schedule can be operated over the whole system, and the mean load upon each mile of road is approximately uniform throughout the system, at any given time.

It is required to adjust the cost of losses in the primary distribution, the secondary distribution including the track, and in the sub-stations, the fixed charges upon each of these three divisions and the cost of sub-station attendance, so that their sum shall be a minimum, with due regard to the conditions of regulation and continuity of service.

As the density of the load in such a system is very great, the unit of sub-station equipment may be made large enough, so that at the time of least load one unit per sub-station can be operated at or near its best efficiency. Hence the sub-station losses per kilowatt-hour may be considered constant.

The aggregate capacity of the sub-stations will equal the capacity of the generating station plus the sub-station reserve capacity, if any is necessary, which will not exceed one unit per sub-station. The greater the distance between sub-stations, the larger the sub-station unit will be; hence the cost of sub-station apparatus will decrease as the number of sub-stations decreases, until the largest practicable unit is reached. The same is true of sub-station land and buildings.

The cost of sub-station attendance will depend only upon the number of sub-stations, as the same number of attendants is required in a small as in a large sub-station, unless the cost of land makes it necessary to double-deck the sub-stations, which will cause a sharp rise in the cost of attendance when the number of units becomes greater than can be placed on one floor.

Assuming that direct-current motors are to be used, the voltage of the secondary conductors will be determined by the conditions of standard practice; and the weight of the secondary conductors may be determined by Kelvin's law, subject to the limiting condition that the maximum drop shall not be so great as to prevent the required acceleration of train units. With a fixed secondary voltage, the cost of the secondary conductors decreases rapidly as the number of sub-stations increases, much more rapidly than the distances between sub-stations while the energy losses in the secondary conductors decrease if the conductors are proportioned by Kelvin's law, and remain constant at the limiting conditions of fixed maximum drop.

In this case the primary distribution would be underground, and the primary voltage would be determined by the relative cost of copper and insulation, and should be as high as is consistent with safety; hence the losses in the primary conductors may be considered constant, and the total cost of the primary conductors will be independent of the number of sub-stations, but will depend upon the mean distance and the total energy to be transmitted, and may be determined by Kelvin's law.

To obtain the greatest reliability of service, each sub-station should be fed directly from the generating station by at least three cables. In the case of a great difference in the number of sub-stations considered, the total cost of cables and conduits would be somewhat greater with the larger number of sub-stations as more and smaller cables would be required. Otherwise the cost of the high-tension distribution, and the losses in it, may be considered constant.

Neglecting those quantities that are constant, the fixed charges on sub-station land, buildings, and apparatus, and the cost of sub-station attendance increase as the number of sub-stations increases; the fixed charges on the secondary distributions decrease and the losses in the secondary distribution decrease or remain constant.

The various losses and charges upon which the solution of the problem depends may then be considered as constants or variables dependent directly upon the number of sub-stations and inversely upon the distance between sub-stations. These quantities may be reduced to a common base of annual kilowatt-hours; curves representing them may be drawn with respect to the number of sub-stations as one coördinate, and a summational curve may be drawn which, if the premises are rightly chosen, will indicate the number of sub-stations at which the sum of the various charges is a minimum.

In a far greater number of railways the load is not uniform throughout the system. This is true especially of the long interurban railways using a comparatively small number of heavy train units. The load at any given time is concentrated upon parts of the system, or travels from end to end of the long lines. In such a system, the aggregate capacity of the sub-station apparatus in operation at any given time, is greater than that of the generators; hence the load-factor of the sub-stations is unfavorable, and in most cases the power-factor of the system is low.

In a solution by the method outlined in this paper, several curves must be drawn in addition to those named: One showing the all-day losses in the sub-station apparatus, which will increase with the number of sub-stations; a second showing the losses in the primary transmission lines, which will also increase with the number of sub-stations, due to the greater length of lines and to the lower power-factor; and a third showing the fixed charges on the primary transmission lines.

The last two curves are relatively much less important than the first. It is possible by compounding or automatic adjustment of fields, to keep the power-factor of the synchronous converters very near unity, making the transmission losses more nearly constant, and independent of the number of sub-stations. In such systems it is not usual, and seldom practicable, to use separate feeders from the generating station to each sub-station; and the primary distribution is usually by overhead lines, generally supported on poles which are used for other conductors as well. But with all the sub-stations along a single line of railway, or a group of such lines connected to one transmission line, the additional cost of extending the same for a greater number of sub-stations will usually be but a small part of the whole expense. So, for at least a preliminary consideration of the problem, the last two curves may be omitted and the same quantities used that are considered in the solution for a road having a uniform distribution of load, with the addition of one containing the all-day losses of the sub-station apparatus.

In systems consisting of long lines with infrequent train service, the cost of attendance and all-day losses in converter sub-stations often become so great that the regulation in secondary conductors economically proportioned for standard direct-current voltage will not permit the operation of the required schedule. The usual remedy is to set the sub-stations nearer together, though at the cost of operating economy.

If other conditions still make the use of standard direct-current equipment desirable, it would seem that better economy could be obtained by lengthening the sub-station sections and using boosters, a plan that has been found profitable in the supply of such lines of less length from direct-current generating stations. The fixed charges on, and losses in the boosters should then be included in the curves of sub-station apparatus.

In the discussion of the method of treating the problem of sub-station location herein suggested, the usual type of converter sub-station, with direct current. secondary distribution has been kept in mind; but the method is no less applicable to a complete alternating-current system with static sub-stations, in which case the curves of sub-station losses, attendance, and fixed charges, all become flatter, while the higher trolley voltage available permits a wider spacing of sub-stations without exceeding the limiting conditions of regulation—all of which indicate a better efficiency of sub-station apparatus and secondary distribution, in roads of low and non-uniform load density.

To show this method of treatment more clearly, a simple problem will be discussed by means of it. A typical interurban railway consisting of one long line has been selected, because it suffices to exhibit the method without an excessive amount of labor. No attempt has been made to determine exactly the quantities used, but only to make them consistent, as in any problem they must be determined for the particular conditions encountered.

Assuming the following data, there is required the number of sub-stations to obtain the best operating economy.

Distribution..........Alternating-current–direct-current.
Length of line........60 miles.
Service..........Hourly in both directions, 20 hours per day.
Schedule speed.......30 miles per hr.
Stops per single trip.....10
Cars on the line......4 for 18 hours, 2 for 2 hours.
Car-hours per day........76
Weight per car (approximate).....30 tons.
Mean amperes per car.....135
Mean square amperes per car.......35 000
Running current, multiple, per car....200 amperes
Starting current, multiple, per car.....400 amperes.
Track...................single, 80 rails.
Track resistance per mile............0.0313 ohm.
Sub-station power-factor..............1.
Resistance of copper per mil-mile.....54 750 ohms.
Weight of copper per mil-mile.......0.016 lb.
Price of copper per lb.................$.15
Rate of interest.....................5%
Annual fixed charges on sub-station buildings and land.................7%
Annual fixed charges on sub-station equipment 15%
Cost of energy at sub-station alternating-current. bus-bar........................$.0125

The secondary copper is assumed continuous and of uniform section from end to end of the line.

The sub-stations are arranged so that the drop in the secondary copper and track is the same at points midway between sub-stations and at the ends of the line, the end-sections being three-fourths the length of the intermediate sections.

Assuming this line fed through different numbers of sub-stations, it is desired to draw the following curves, with the number of sub-stations as abcissas and the total annual cost in dollars as ordinates.

Annual charges on sub-station buildings and land
Annual charges on sub-station equipments
Annual charges on secondary conductors
Annual cost of sub-station attendance
Annual cost of sub-station losses
Annual cost of losses in secondary conductors and track.

The cost of and loss in the primary distribution are assumed to be nearly enough constant, so that they may be neglected in a preliminary discussion; but if desired, curves representing them may be added to those enumerated. These quantities have been computed, and the curves drawn, for the number and arrangement of sub-stations shown in the following table.

Sub-station Capacity.—With the service outlined, the maximum load of any sub-station will be that due to the starting of two cars at once, 800 amperes, lasting for a few seconds.

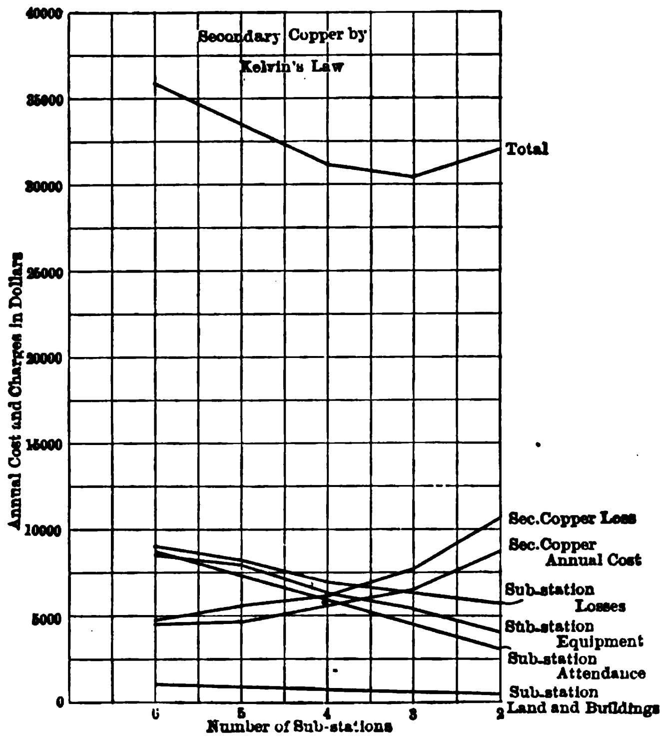

FIG. 1.

With the largest number of sub-stations, the capacity of each has been made equal to one half of this, allowing a momentary overload of 100% in case the whole load falls upon one sub-station. With the smallest number of sub-stations, the capacity of each has been made equal to the maximum load. In the intermediate arrangements, the capacity of each sub-station is graded between these limits in the proportion of the combined line and track resistance between adjacent sub-stations; this is very nearly proportional to the distance between the sub-stations.

TABLE I.—SECONDARY COPPER BY KELVIN'S LAW.

Sub-Stations.					Daily Total Input Kw-hr.	All Day Eff.	Cost Kw-hr. Direct-current Bus-bar.	Annual Charges on			Annual Cost of			Totals.
No.	Dist.	Cap.	Com. Cap.	Total Cap.				Real Estate	Sub-Sta. Equip'ts	Second'y Copper	Sub-Sta. Attend.	Sub-Sta. Losses.	Second'y Copper Loss.	
6	10.9	260	250	1 560	8 500	77.6	1.61	840	8 550	4 480	8 640	8 730	4 530	35 770
5	13.3	281	300	1 400	8 410	79.3	1.58	700	7 780	4 550	7 200	7 960	5 450	33 640
4	17.1	315	300	1 260	8 185	81.7	1.53	560	6 225	5 480	5 760	6 920	6 110	31 055
3	24.	377	400	1 131	8 070	82.7	1.51	420	5 220	6 450	4 320	6 400	7 625	30 435
2	40.	520	500	1 040	7 926	84.3	1.48	280	3 900	8 690	2 880	5 750	10 420	31 920

TABLE II.—SECONDARY COPPER BY LIMITING DROP.

No. of Sub-Station.	Annual Charges Secondary Copper.	Annual Cost of Secondary Copper Loss.	Totals.
6	4 460	4 560	35 780
5	5 850	4 560	34 050
4	8 380	4 560	32 405
3	15 120	4 560	36 040
2	76 400	4 560	93 770

Sub-station Losses and Secondary Copper.—The mean all-day efficiency of the sub-stations of each arrangement was obtained by dividing the total output of the sub-stations by the total input. The total output was assumed constant at 6 669 kw-hr. The efficiency of each sub-station at the mean load of one car and at the mean load of two cars was computed from typical

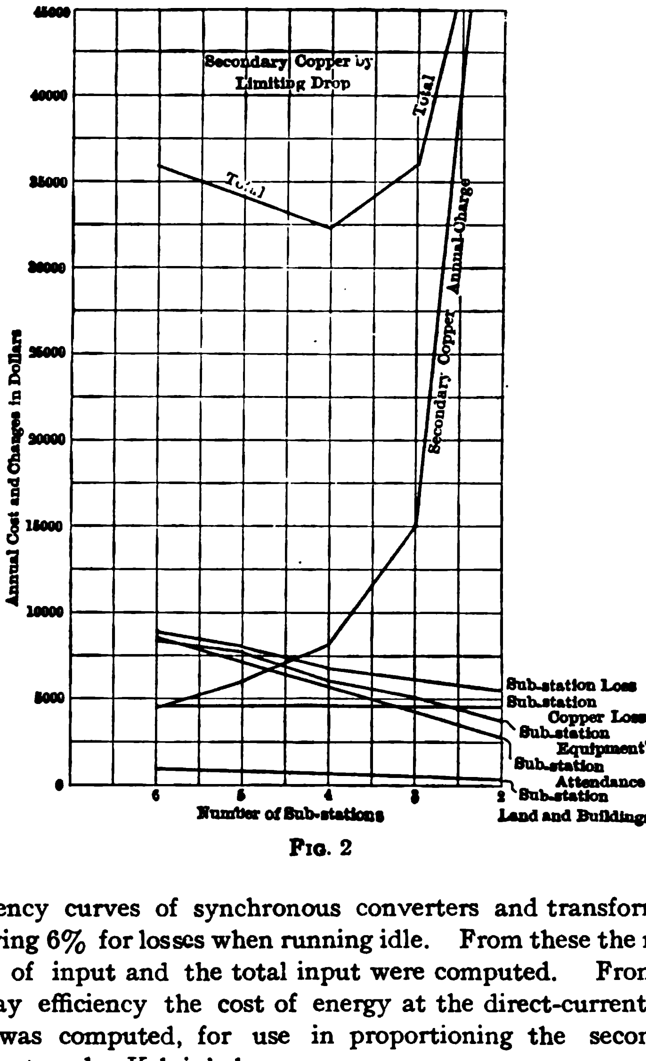

FIG. 2

efficiency curves of synchronous converters and transformers, allowing 6% for losses when running idle. From these the mean rates of input and the total input were computed. From the all-day efficiency the cost of energy at the direct-current busbar was computed, for use in proportioning the secondary conductors by Kelvin's law.

The exact computation of the losses in the secondary con ductors is very laborious; to approximate these losses the load was assumed to be fixed at its mean distance from the sub-station, one-quarter section, and the resistance of the secondary copper multiplied by the car-hours per section, and the mean square current per car. The annual cost of the secondary copper was taken at 6% to cover interest and cost of reclaiming. The secondary copper was proportioned by Kelvin's law, for each arrangement of sub-stations as follows:

$$\frac{35\,000 \times \text{car-hr. per year} \times \text{res. per mile copper} \times \text{length section} \times \text{cost kw-hr.}}{4\,000}$$

$$= \frac{\text{wgt. mil-mile} \times \text{res. mil-mile} \times \text{length section} \times 15 \times 6}{\text{Res. per mile copper} \times 10\,000}$$

$$\text{Res. per mile copper} = \frac{0.95}{\sqrt{\text{car-hr. per year} \times \text{cost kw-hr.}}}$$

The annual loss in the secondary conductors and tracks was computed in the same way. The annual loss in the sub-station apparatus is the difference between the total input and output. In computing the cost of these losses the cost of power at the sub-station alternating-current bus-bar should be used.

Cost of Sub-stations.—The cost of sub-station buildings and land was taken at $2 000 each. Switchboards and wiring were estimated at $2 500 per sub-station. The nearest commercial sizes of synchronous converters and transformers were used in estimating the cost of sub-station equipments, at prices varying from $21 per kw. for 500 kw. to $38 per kw. for 250 kw.

Table I. and Fig. I. show the results of this computation, with a minimum operating expense at three sub-stations, spaced 24 miles apart and secondary copper, 746 000 cir. mils., which is evidently impossible to operate without the use of boosters in the sub-stations.

Table II. and Fig. II. show the results of recomputing the same problem with the secondary copper proportioned to permit a maximum drop of 300 volts in line and track, about the worst condition in which operation is practicable.

It is apparent, then, that economy of operation is usually sacrificed to regulation.

DISCUSSION ON "THE RELATION OF RAILWAY SUB-STATION DESIGN TO ITS OPERATION," AND "SOME CONSIDERATIONS DETERMINING THE LOCATION OF ELECTRIC RAILWAY SUB-STATIONS," AT NEW YORK, DECEMBER 15, 1905.

H. A. Lardner: Among the disadvantages of the method of starting synchronous converters from the direct-current side not noted by Mr. Ashe may be included the fact that direct current is not always available. For instance, the converter sub-stations of the majority of interurban railways are shut down at night; and unless storage-batteries are included in their equipment direct current is not available for starting the converters in the morning. Therefore, it becomes necessary to include another method of starting them.

The author suggests that one disadvantage of the method of starting from the direct-current side is the small factor of reliability; but I think this difficulty can practically be obviated by the installation of two resistance boxes so connected that either one may be utilized. They would be in circuit such a short time that they could be comparatively small and inexpensive, and would constitute about the only special apparatus necessary for utilizing this method.

The starting of converters on the direct-current side strongly appeals to me because of its certainty of action; and with the addition of Mr. Stott's method of synchronizing referred to, it is applicable in a great many cases. I personally know of many installations among the smaller sub-stations where satisfactory results are obtained from direct-current starting, even without the modification of the switch-gear referred to.

I should like to know why the direct current for operating the circuit-breaker in Mr. Stott's device can not be taken from the bus-bars, or from the direct-current side of other operating converters, as well as from a storage-battery. It seems a unique and a useful method; and that it would be applicable to even the smallest stations if it does not require the introduction of an auxiliary storage-battery. It must be remembered that the small sub-stations of the majority of interurban railroads do not contain such desirable, but rather expensive, pieces of apparatus as motor-operated oil-switches and other devices requiring an auxiliary storage-battery.

In the discussion which the author gives of the method of starting converters by means of a small induction motor mounted upon the converter shaft, he does not call attention to the fact that many converters, at least of the smaller sizes, do not include such convenient methods of assisting the synchronizing of the machines as a resistance across the brushes or in series with the field coils.

A more common method of synchronizing by means of the small induction motor is to allow it to run the converter above synchronous speed, and then open the motor switch and catch the converter as the speed falls past the point of synchronism. I am not prepared to say that the refinement of a resistance in connection with this method is an expense that is prohibitive; but it is not usually found in stations with converters of under 500 kw. I should like to ask whether the author has made any tests showing the time required to start converters by this method?

While breakdowns of the starting motors have undoubtedly been rare, it seems a rather bad feature of this system that trouble with the starting motor, or with any of its switches and connections, is sufficient to cripple the converter itself until these are corrected. The speaker feels, therefore, that at least one other method should be provided if the method of starting by a motor is used.

The method of starting converters from the alternating-current side, as described by method C, has, in the speaker's opinion, many advantages; among them are great simplicity and the omission of special apparatus. The introduction of taps running from the middle points of the transformers is a slight modification, and the double-throw switch required is also. Furthermore the division of the fields is not seriously objectionable.

The author presents, as the chief disadvantage to this method, the necessity of eliminating dampers and other devices, introduced for the correction of hunting. It would be interesting to hear from designers of this class of apparatus on this subject. Personally I have observed many installations in which the converters were of 500 kw. and under, operating at 25 cycles, where this method of starting was satisfactorily used, and where hunting practically did not occur. For many cases, especially where the size of the converter is 500 kw. and under, I am rather in favor of the use of method A and method C—method C to be used principally for starting the sub-station apparatus in the morning when direct current is not available; and method A for the addition of other units at any time during the period of operation.

The disadvantage of method C, in that it draws a large starting current from the line is not serious under the above conditions; and even though it becomes necessary to employ this method in an emergency when many cars are depending on the sub-station, it is always possible to trip feeder circuits and otherwise lighten the load on the sub-station until the converter can be started. As shown by the author, the time required under this method is very short, especially with the smaller sizes of machines.

Referring to the paper by Mr. C. W. Ricker, I note his suggestion that in the case of interurban railway sub-stations he believes it possible to secure better economy by lengthening the sub-station sections and using boosters. I question whether this method will be practicable in many cases. The entire capacity of a sub-station may momentarily be required for starting cars at the extreme ends of the section fed thereby; and schedules frequently work out in exactly this way. If it were attempted to install boosters to handle the loads at the extreme ends of the section they would have to be of considerable size, especially as to commutator capacity even though under severe load for only short periods. I think that after taking into consideration the added cost of these machines, and of their switching apparatus, their maintenance, and the space required, their use would not be considered desirable, nor justified by other savings made in first cost and in operation.

Referring again to the last paragraph of Mr. Ricker's paper, in which he says that in alternating-current systems with static sub-stations, the trolley voltage available permits a wider spacing of sub-stations, I would call attention to the fact that while this is undoubtedly true, it must be remembered that owing to the characteristics of the alternating current, the usual saving by increase of pressure cannot be applied, owing to the fact that the drop in both rail and overhead conductor due to the alternating current is, per ampere, considerably in excess of the drop for direct current.

W. I. Slichter: In connection with that part of Mr. Ashe's paper describing a method of starting synchronous converters by means of an auxiliary induction motor and devices for regulating its speed, it is interesting to note that there is another method of indirect starting by the use of the single-phase commutator motor. The alternating electromotive force of a converter is approximately the voltage that is suitable for the single-phase commutator motor, and by putting a reactance in series with such a motor an easy means can be obtained for regulating the voltage and the speed. By this method it would be easy to secure the proper speed for throwing the converter into synchronism.

John B. Taylor: I was somewhat misled by the title of Mr. Ashe's paper, which I think should be "The Relation of Converter Sub-station Equipment to its Operation." Since the matter of alternating-current starting of converters has been brought into such prominence, regret that I did not bring to the meeting some oscillograph records, showing the induced voltage in the field, the manner in which the current falls with increasing speed, and various other factors involved in starting synchronous converters from the alternating-current end.

Under method C, Mr. Ashe states, "To prevent an excessive starting current, reactance is inserted between the converter slip rings and the low-tension windings of transformer." There seems to be a general impression that the purpose of the reactive coil is to permit starting from the alternating-current side. How this impression came about I do not know, but as a matter of fact the reactive coil is used for several reasons: to permit automatic compounding, to compensate partly or wholly for drop in the transmission line, transformer, and in the converter itself; it also allows the converter to run under variable load with comparatively slight changes in power-factor, and makes it almost unnecessary for a station attendant to change the adjustment of field rheostat; it likewise readily permits the desired division of load between converters.

All such factors as brush resistance and field resistance become of small importance when reactive coils are used, as there is no more difficulty in securing adjustment of load between converters than with any class of direct-current machinery.

Reactive coils permit the running in parallel of machines of different manufacture, or of different rating of the same manufacture. For example, I call to mind a case where the secondary voltage on one bank of transformers in a sub-station is 370 volts, and on another bank in the same sub-station the pressure is 380 volts, and there is no difficulty in dividing the load between two converters connected respectively to each of the two banks of transformers.

Evidently a mistake has been made in copying the diagram of connections which Mr. Ashe has shown on the blackboard. This diagram is evidently intended to show the diametrical connection of a six-phase converter with transformer taps and switches arranged to start the machine from the alternating-current end, the mistake in connections being such as to apply the full secondary voltage of the transformer to adjacent collector rings instead of to collector rings which connect to points on the armature windings diametrically opposed to each other. Consideration of a vector diagram will make it evident that if connected in this manner the converter will run at double voltage.

Mr. Ashe states that the current required for starting a 25-cycle converter is a little less than current at full load. For the converters which are started from taps giving one-third of the full secondary voltage, possibly two-thirds or three-fourths of full-load current would be a fairer value. The standard practice, when starting converters from the alternating-current side is, for the larger machines, to apply to the collector rings, first, one-third of the secondary voltage, and, after the machine has reached synchronous speed and the field excited, to transfer to taps giving two thirds of full secondary voltage, and finally transfer again to the main leads of the secondary winding of transformer. The tap giving one third of full voltage is used in all cases, so as to make the practice uniform and ensure the starting of the converter under all conditions. This starting should not fail in case the alternating current for any reason drops to 80 or 90% of the normal value. As a matter of fact, most of the General Electric Company's converters will start at one-fourth voltage, and some of them, if the armature happens to stand in a favorable position, will start at as low as 17 or 18% of full voltage.

When converters are started from transformer taps the effect of the compensator action should be noted. The current in the high-tension line falls very rapidly as we reduce the voltage applied to the converter collector rings; that is, the current in the high-tension line when starting a converter from one-fourth voltage taps compared with the current in the line when starting from one-third voltage taps would be in the ratio of 9 to 16, or but little more than one-half as much on the one-fourth voltage tap as on the one-third voltage tap.

I might mention one test I have in mind, made with a 1 000-kw. converter at Buffalo, which was supplied with power from Niagara Falls. Starting this machine at one-third voltage disturbed the high-tension voltage of the system at the substation less than two per cent.

The matter of disturbance in voltage, due to starting converters from the alternating-current side may, I think, be summed up as follows: in a railway system the greatest disturbance that can occur will not be sufficient to cause trouble; in a lighting system, in which synchronous converters are also used for feeding the lighting circuits, the disturbance in voltage becomes an important factor. There are comparatively few such systems in this country, and as a rule, they are so large and have so many converters in service that the tendency to disturb the voltage is thereby reduced to a minimum. On systems of this character I doubt if it would be a serious matter to start the converters from the alternating-current side. As stated above, where it is desired to reduce the starting current to the lowest possible value, a tap giving less than one-third voltage might be employed.

The breakdown of field winding of converters is a matter that has been given more prominence by Mr. Ashe than it deserves. While it is true that some fields have broken down, due to the induced voltage when starting from the alternating-current end, in most of these cases the field wiring was not in accordance with present practice. In some cases a two-pole field breakup switch was installed, and the wiring arranged so that one terminal of the field winding was permanently connected to ground, which arrangement caused an increase in potential strain at the other end of this section of the winding. The present arrangement of wiring breaks up the field winding into three sections, and both terminals of each section are isolated when the field breakup switch is opened. The induced voltage in the field winding is not over 2 000 volts to each group, and there is no more reason why this winding should break down on a synchronous converter than on an engine-driven railway generator, which must have its field constructed to withstand the heavy "kicks" due to opening the field circuit.

The times required for putting converters in service, as given by Mr. Ashe, are quite fair for the alternating-current method of starting. The time, 16 seconds for a 300-kw. machine, however, I should say is rather small. It is possible to make this record with a machine of this size if started from half-voltage taps with no reactive coil in circuit, in which case it would take about 8 seconds for the machine to reach full speed; but it is my impression that the 300-kw. machine started at half voltage with a reactive coil in circuit—the standard connection for 25-cycle converter of this capacity—would take more than 16 seconds to attain full speed, and a few seconds more will be required for the manipulation of switches to make the transfer to full voltage.

As far as the use of bridges on the pole pieces is concerned, there are a number of synchronous converters in service having bridges, or damping coils, which start satisfactorily from the alternating-current end, and there is no practical reason for leaving off these bridges to accommodate this method of starting. There are also in use numerous converters without these bridges, and Mr. Ashe's statement that such machines are liable to hunt is not borne out in practice. The previous speaker, Mr. Lardner, I believe corroborates my statement in this respect.

The drawing of a dividing line between machines which should start at one-half voltage and those which should start at one-third voltage is more or less arbitrary. As a matter of fact, the General Electric Company have a definite dividing line, not exactly that indicated by Mr. Ashe, which is drawn, however, more for the sake of uniformity in practice than for any other reason.

H. G. Stott: One important point to which no reference has been made in either paper presented to-night, is that in operating synchronous converters we are limited to a maximum drop of 12% between the power house and the converter. If we assume that the line is fairly well loaded, giving a maximum drop under normal conditions of 8 to 10%, then a sudden additional drop of, say, 5%, due to a momentary overload or short circuit, will cause the converter to flash over. This, then, becomes one of the limiting conditions in the location of substations.

E. M. Hewlett: Mr. Ashe refers to the possibility of the motor-operated switch operating accidentally; also of the care that attendants give to the switch. I think that if the necessity of taking care of switches was appreciated more by operating men, occasion for complaint would be eliminated. It is my experience that as operators become familiar with these switches, complaint ceases.

In order, however, fully to provide against accident, switches are now constructed with a positive stop, and a trip-coil which automatically moves the stop out of the way when it is desired to operate the switch.

D. B. Rushmore: The form of damping device mentioned in the paper by Mr. Ashe is used because of its efficient operation and not because this form is necessary; a converter starts as well with damping devices as without them. The use of such devices may, however, slightly change the power-factor at starting.

Reactive coils may be adjusted for an even division of load at any one output, and unequal division of load should be small at other outputs.

It is understood that most of the large converters in New York City are operating with the series coils cut out. In small sub-stations where much drop in the line exists, compound coils are universally used.

The advisability of installing power-factor indicators in small stations is open to question; experience having shown that use is seldom made of them.

At present one seldom hears of trouble from the heating of converters; and with the use of steam turbines instead of reciprocating engines this evil should entirely disappear. It is now well understood that while variation in angular velocity may enter as a disturbing factor, it has but little effect upon the parallel operation of alternators.

Mr. Ricker's paper illustrates the fact that regulation is more important than other commercial consideration in determining the allowable voltage drop in power transmissions.

R. B. Owens: The main consideration in connection with the location of electric railway sub-stations, namely, voltage, seems to me to have been omitted from Mr. Ricker's paper.

We have to-day two distinctly different systems of operating railways for heavy traffic; the alternating-current system, and the direct-current system with sub-stations, the latter system using alternating-current generators and synchronous converters operating at, say, 650 volts.

Without going into the question as to whether direct-current generators of large size can be successfully designed for a pressure of 1 000 to 2 000 volts, I believe it is true that makers are prepared to furnish converters of 1 000 volts, and perhaps more, and also motors, at least of the bi-polar type, that will operate successfully at such voltages. If this is true, it materially affects the whole question of sub-station location, and also materially narrows the field which some have supposed belonged to the alternating current.

The relative merits of high-voltage converters and high-voltage motors as compared with single-phase-current systems for heavy traction will bear discussion. The question seems to be: how far can the direct-current voltage be carried; can converters be made that will operate successfully at 1 000 to 2 000 volts; can motors be made that will operate at such voltages? The whole nature of the problem is changed; instead of sub-stations with a load-factor of a few per cent. it may be possible to get load-factors of a decent percentage. It is of great interest to hear from some of the designers as to whether such apparatus can be afforded. I think it is a question of voltage. The question lies in the design of direct current machinery, in large units, to operate successfully under conditions met in traction work at high voltages.

William McClellan: It is a question if this method offers much help in connection with most of the cases of sub-station location. It has always seemed necessary to divide a line into load sections rather than distance sections, and consequently it is difficult to arrange any general method of solution. As a rule, sub-stations on any one system are alike only in general arrangement, but differ in size of apparatus and cost of construction, which still further operates to prevent the use of a general rule.

A factor which is sometimes neglected in considering the location of sub-stations, is the possibility of congestion at certain points. The problem is rendered all the more difficult when these are ordinarily points of light load. This condition is of frequent occurrence in steam railroad work, but is easily overcome by concentrating locomotives at the point for the time being, and thus relieving the congestion. In heavy electric railroading this finally becomes a question of feeders, for the portable sub-station may be used in the same way as the extra locomotives, if the high-tension feeders are sufficient to transmit the power. It is obvious that no general method can cover this point, which is of increasing importance in heavier railroading.

C. P. Steinmetz: The papers presented deal fully with one phase of the complicated problem of electric railroading. They deal with the electric railway sub-station, so far as it is a *converter* sub-station, and converter sub-stations seem destined to remain for a long time to come. It is proper, therefore, that a large part of the paper should be devoted to the synchronous converter.

Railway converter sub-stations can be divided into two typical classes: first, the sub-stations in a large, high-power distribution system, as in those of the Manhattan, the Interborough, and the New York City Railway systems, all in New York City; and secondly, the sub-stations of systems of comparatively low power and extended distribution, as in interurban systems.

In systems of the first class the loss of voltage between generating station and sub-station, and between sub-stations, is very small. The sub-stations contain at all times a large number of high-power units in operation, which run practically at steady full load; so that individual momentary variations of load are not perceptible in the sub-station to any great extent; the daily changes of load are taken care of by varying the number of converters in use. In sub-stations of this class the possible variation of voltage due to line drop is insignificant; therefore automatic control of voltage for variations of load on the converters is not necessary; and means for controlling the voltage, such as series fields on the converters for compounding, and reactive coils are not only not needed, but also are undesirable, because, if present, they are a source of possible danger of racing in case the direct-current system feeds back into the sub-station; this danger, due to the small resistance between sub-stations, is greater than it is in the case of sub-stations of the second class, that is, sub-stations of interurban systems.

In interurban systems, sub-stations of moderate power, with two or three converter units of, say, 500-kw. or less, are fed from long-distance high-potential transmission lines, with considerable drop of voltage in the transmission lines and comparatively high resistance between the sub-stations. In these systems the variation of load would be so large as to make it impracticable to use for any ordinary methods of voltage control; therefore the so-called methods of phase-control, by means of powerful series fields and reactive coils, becomes necessary.

In the operation of a converter sub-station, the most important factor is starting the converters. In early days, converters were started from the alternating-current side by throwing full voltage on a machine and letting it run up to synchronism as a synchronous motor. To-day a different method is employed. Starting from the alternating-current side causes the severest disturbance in the system, especially when starting under full load.

At present, converters are started either by means of a starting induction motor, or from the direct-current side or synchronism.

The method of starting may be subdivided, then, into two general methods: those that require synchronism, and those that do not require synchronism. There may be some difference in the two methods as to the time required to start; the second method may take a little longer time to synchronize but in either case the maximum time is sufficiently short for all practical purposes.

The method of starting or synchronism when started from the direct-current side, is the least severe on the system. By this method, moreover, a converter can be put into the system without any trace of disturbance. The method was introduced to a large extent to avoid shock on the system, but recently the tendency has been strongly away from that; and at least in interurban systems it may almost be said that the method of starting by synchronism has failed. It has failed because employed under just those conditions where the utmost rapidity of starting is essential. If there is trouble in the system, such as heavy overloads, or if the direct-current voltage cannot be held up and begins to disappears altogether, and the voltage on the alternating-current side of the system fluctuates up and down, synchronizing cannot be undertaken with safety, because even after the converter is started, its speed, as obtained from the starting motor, rapidly changes up and down, and may cause the alternating frequency to vary; the station attendant watching the phase-lamp, sees it flicker rapidly, then slowly, and then rapidly again, without ever becoming steady, however, and finally throws the switch; and all this occurs in those cases where the greatest rapidity of starting is essential.

Some disastrous experiences in this direction were had on the suburban line running from Schenectady to Albany, which made it necessary to abandon direct-current starting and adopt alternating-current starting. The converter sub-station was in use, but due to the rapid growth of local traffic, the load was heavier than had been expected, and the voltage control on the alternating supply system was possibly not so good as had been anticipated; consequently when the attempt was made to synchronize converters, it was almost impossible, with average, or even more than average, skill, to get them in step without throwing them in when out of phase with different speeds and disabling the whole sub-station. These are the main reasons for returning to the alternating-current starting.

It is true that a specially skilled operator might be able to get the converter in circuit in this manner without throwing the whole sub-station out of service by throwing the switch, not at equality of frequency, but when the two frequencies are approaching each other. It is practically impossible to succeed by attempting to close the switch while the frequencies are together, because they cross each other so rapidly that there is danger of so doing just after the frequencies coincide and while they are again going apart. And that is the most dangerous point at which to connect the converter in circuit; it fails to catch short-circuits and throws the other converters on the system out of service when they are most needed.

In general, the proper moment of synchronism is not when the machines are in step and in synchronism, but just a moment before they are in synchronism. For that reason direct-current starting is of exceptionable usefulness in interurban systems.

In large metropolitan sub-stations the difficulty is largely reduced, because the voltage has steadied on the alternating-current side as well as on the direct-current side, and synchronism can be effected. Nevertheless, if the switch is thrown when the converter is out of synchronism the result is much more disastrous, because there is almost no resistance between the generating station and the sub-station, or between sub-stations; and the electromagnetic momentum of the whole system feeds back into the converter, thus reversing the converter at full velocity. This result may occasionally happen even when the machine is manipulated by the most skilful operator. Assuming the efficiency of the operator as very high, that his liability to error is only one-tenth of one per cent. and that he makes a mistake only once in 10 000 times, then in a city like New York, where more than 100 converters of 1 000 kw. or more have to be thrown into the system daily, three times a year he would throw some big converter in wrong, out of step, and tear down the station, with the usual disastrous results. On this showing it is preferable to start from the alternating side by means of low voltage.

At least two compromise arrangements, methods of so connecting a converter in circuit as to reduce the disturbance on the system, have been developed. In one method the converter is started from the direct-current side and brought up approximately to synchronous speed, possibly a little above synchronism; it is then disconnected absolutely from the direct-current side and the alternating-current switch immediately closed. The converter drops in step almost instantly, with hardly an appreciable disturbance on the system. This method is not quite so simple as starting from the alternating-current side from rest; but it is sufficiently simple for a large system, where the risk is considerable.

Referring to the employment of anti-hunting devices with alternating-current starting: one of the most effective devices of this character is a squirrel-cage induction-motor winding. which is extensively used in synchronous motors intended for very severe conditions, such as operating heavy fluctuating loads at the end of a long transmission line in which there are resistance losses. It is obvious that a squirrel-cage winding is of great advantage in starting converters.

Two other anti-hunting devices are short circuits consisting of heavy closed copper bands around the field poles, or between them, both of which devices operate on the reduction of the magnetic flux; when hunting, the magnetic flux shoots across the field pole, and cuts through the copper bands in which a heavy short-circuit current is set up by the electromotive force produced thereby.

The short circuit between the field poles obviously cannot interfere with starting, but are motors and start up giving a quarter phase winding to the normal pole and gives effect to the quarter-phase motors secondary as a field.

The other arrangement of short-circuiting *around* the field poles is used to a considerable extent in synchronous motors; and I know it gives no trouble. I have not used it in connection with converters, but see no reason why it would not prove satisfactory in that connection.

In regard to the noise made by converters, I have always observed that comparatively they are as noiseless as any other machines. In engines and other apparatus some part will always be noisy; and no satisfactory explanation of the cause can be given. All theories in this direction, when compared with experience, have fallen down. So far, the prevention of noise in machinery has been a case of elimination rather than of cure.

Lastly, in regard to the use of the storage-battery in electric railway systems, it is a very useful and desirable element. The only and main objection to a storage-battery which has prevented its introduction in most railway systems, especially in interurban systems, is its cost, which, as a rule, is prohibitive.

APPENDIX

REPORTS OF

BOARD OF DIRECTORS, COMMITTEES, ETC.

For the Fiscal Year, ending April 30, 1905.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

ANNUAL REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1905.

The Board of Directors presents herewith for the information of the Institute a report of its work during the past year, also of the financial standing of the organization.

The Annual Convention was held at St. Louis, September 14, 1904, occupying but one day, and taking the form of a joint meeting with the Institution of Electrical Engineers, according to the program outlined in the Annual Report one year ago. This Convention was fixed during the holding of the International Electrical Congress. At this Convention President Arnold delivered his annual address, and the joint discussion was upon the topic " Different Methods and Systems of Using Alternating Current in Electric Railway Motors."

The growth in membership during the year has not equalled that of either of the previous two years, which could hardly be expected to be maintained. The total membership is now 3460. There are also 617 students enrolled. Among the four national engineering societies the Institute now stands second in numerical strength, being exceeded only by the American Institute of Mining Engineers with a membership of 3680 on December 31, 1904.

The Board of Directors has held during the year twelve regular and three special meetings. At these meetings the various standing and special committees have reported, and brief abstracts of their reports for the year are included herewith.

Through the courtesy of the Association of Edison Illuminating Companies, the Institute was provided with a spacious booth suitably furnished at the St. Louis Exposition, with an attendant in charge, for the accommodation of visitors. This arrangement proved entirely satisfactory and was maintained through the entire period of the Exposition without expense to the Institute.

Among the Italian exhibits at the Exposition was a bronze bust of the late Professor Galileo Ferraris, also a reproduction of his historical apparatus. At the close of the Exposition this exhibit was presented to the Institute by the Board of Directors of the Royal Italian Industrial Museum.

On September 17, 1904, at the New York State Building, Universal

Exposition, St. Louis, President Robert Kaye Gray, in behalf of the Institution of Electrical Engineers, presented to the American Institute of Electrical Engineers, a magnificent painting representing Dr. William Gilbert of Colchester before Queen Elizabeth.

Through the courtesy of the Engineers' Club these gifts have been placed in the clubhouse, 374 Fifth Avenue, New York, pending the erection of the Union Engineering Building, where ample space will be available for historical, technical and decorative exhibits.

Committee on Papers.—Eight monthly meetings have been arranged for upon the following subjects: Transmission of Intelligence, Heavy Electric Traction, High Tension Electric Railways, Instruments and Measurements, Safety Devices. For these meetings 16 papers have been prepared. Of these but two were volunteered, 14 being written at the request of the Committee, the authors and titles being suggested by specialists. Arrangements have been also made for the presentation of 20 papers at the Annual Convention, June, 19–23. The manuscripts of seven of these are already on hand.

The Editing Committee.—The experience of the present Editing Committee has covered but one month of the past year, but it realizes the increase in the number of original papers presented at branch meetings, and the volume of the reported discussions. Of this mass of material, provision is made in the By-Laws for the printing of such matters as may be of permanent value. It has in view the suggestion of a plan by which the local Executive Committees may be authorized to select for publication either in the Transactions or the technical press such portions of this material as they deem worthy of bringing to the attention of the Editing Committee for approval.

Board of Examiners.—During the year, ten regular and four special or adjourned meetings have been held. At these meetings 527 applicants were recommended for election to the grade of Associate. The applications of 332 persons for enrolment as students were considered, and of these 331 were recommended for enrolment. Fifty-four applications for transfer to full membership were acted upon. Of these 28 were recommended and 26 not recommended for transfer.

Committee on Increase of Membership.—During the past year 595 Associates were elected, a decrease of 203 from the previous year. The total membership at the close of each fiscal year since 1899 is given in the following table:

Year.	Honorary Members.	Members.	Associates.	Total.	Increase.
1900	2	374	807	1183	50
1901	2	387	871	1260	77
1902	2	405	1142	1549	289
1903	2	417	1810	2229	680
1904	2	459	2566	3027	798
1905	2	482	2976	3460	433

Committee on Finance.—The plan outlined a year ago by which certain funds were established for specified purposes has been continued, all of which including the daily balances are drawing interest. No change has been made in the items of $8000 in U. S. bonds, and the Mailloux Fund of $1000 in a certificate of deposit; the income of the latter being devoted to continuing the files of certain periodicals in the library contributed by the founder of the fund.

The ordinary receipts during the fiscal year ending April 30, 1905, were $43 130.95. This amount was made up of $33 822.19 from members, including entrance fees from Associates and transfer fees from Members; $1660 in students' dues, $5765.40 from advertising sales and subscriptions, $743.89 interest and exchange, $977.75 badges, and $161.72 miscellaneous. The ordinary operating expenses of the Institute were $37 529.25, leaving a balance of ordinary receipts over expenses of $5601.70.

The bank balance available for current expenditures on April 30, 1905, was $11 054.31. Adding this sum to $8875.63, the market value of the United States bonds owned by the Institute makes a total of $19 929.94 in cash or its equivalent. Subtracting from this amount $4400, as due to the Life Membership Fund, gives a net balance of $15 529.94 in cash or its equivalent immediately available for any ordinary or extraordinary expenditure of the Institute.

The total amount of bills payable by the Institute, April 30, 1905, was $368.82. During the year the property of the Institute was increased by purchase of furniture, etc., to the amount of $667.40, and the stock of Transactions to the value of $3413.00, all of which was paid from current revenue.

Local Organization Committee.—During the year additional Branch organizations have been authorized by the Board of Directors as follows: Baltimore Branch, December 16, 1904; San Francisco Branch, December 23, 1904; Syracuse University Branch, February 24, 1905; University of Colorado, Student meetings, December 16, 1904. 185 Branch meetings have been held during the year (Sept. 1 to May 1—others will be held before the summer) at which 156 original papers were presented. The average attendance at these meetings was 1097, a slight falling off from last year. This was due no doubt to the fact that there was an abnormal attendance at the initial meetings of the Branches, most of which were organized in 1902-3. The increase of membership in the immediate vicinity of Branches has been 193. No meetings have been reported at Cincinnati and Denver. A special committee has been appointed to recommend a plan for the selection for publication of original papers presented at the Branches.

Union Engineering Building.—Plans and specifications for the Union Engineering Building to be erected under the gift of Mr. Andrew Carnegie have been approved by the Joint Committee, and bids invited. The United Engineering Society has been incorporated and an agreement entered into between it and the Founder Societies, the American Institute of Electrical Engineers, American Society of Mechanical Engineers and the American Institute of Mining Engineers. The nine trustees of the United Engineering Society are appointed by the Founder Societies.

The United Engineering Society will own and its trustees will administer the Engineering Building and the Founder Societies will pay to the United Engineering Society funds for the purchase of the land and will receive Treasurer's receipts therefor. The United Engineering Society now holds title to the land purchased for the Institute two years ago by Mr. Carnegie, on the north side of 39th Street, half way between 5th and 6th Avenues.

Building Fund Committee.—This committee sent to the membership early in May, 1904, its fourth announcement embodying a full statement of the progress of the work at that time, and the amounts subscribed to March 31, 1904. An appeal was made to the members for subscriptions, and their valuable personal aid in obtaining subscriptions. On May 26, 1904, the committee reported subscriptions to the amount of $60 000. The committee then canvassed the Local Branches and was assured by their officers of their hearty desire to coöperate. In July, 1904, the committee published its fifth announcement, containing a list of subscriptions amounting to $62 752 from over 500 members. This has since been increased to $66 534.50, of which $19 301.25 has been deposited to the credit of the Land, Building and Endowment Fund. The committee contemplates a vigorous prosecution of its work as soon as the plans of the Union Engineering Building are issued.

Standardization Committee.—The existing committee having been appointed in March, 1905, has not been able to do more than outline its proposed work. It contemplates reviewing the last report of the committee, adopted June 20, 1902, making such modifications as seem desirable, and also completing the work of the committee during the past two years under the chairmanship of Professor Ryan, which has not been finally formulated. The committee proposes to coöperate with foreign societies, notably the Institution of Electrical Engineers and the British Standards Committee. It will be glad to receive general or specific suggestions from the membership which may be addressed to the Secretary.

National Electric Code.—This committee met, December 6, 1904, in conference with code committees of the National Electric Light Association and the Association of Edison Illuminating Companies, followed by attendance, December 7, 1904, at the New York meeting of the Underwriters' Electrical Association. In April, 1905, at the instance of the American Institute of Electrical Engineers, a meeting of the National Conference was called by its secretary, at Boston, April 21, 1905. In advance of this meeting a circular was issued by our committee inviting criticisms, from the membership, of the existing code. Fifteen replies were received, but it was decided by the committee, in conference with the other code committees, to defer action upon them to a more favorable opportunity. At the meeting of the National Conference, April 21, the chairman of this committee was present as an official delegate. The existing situation is about as follows:

1. The relations of the Institute, and other bodies in the Conference, to the code, as appearing on the fly-leaf of the same, have, it is believed, been materially improved and corrected by the amended phraseology to appear on the fly-leaf of the forthcoming edition of 1905.

2. With the exception of a few details submitted in the replies men-

tioned, the Institute membership appears to be generally satisfied with the code.

3. Measures have been secured for entertaining appeals to the Board of Insurance Underwriters from the rulings of individual insurance inspectors alleged to have misapplied the code.

John Fritz Medal.—The first award of the John Fritz medal has been made to Lord Kelvin for Cable Telegraphy and other General Scientific Achievements. This medal was established by the professional associates and friends of Mr. John Fritz of Bethlehem, Pa., on his 80th birthday, August 21, 1902. The board of award is composed of 16 representatives of national engineering societies, four being past-presidents of the Institute, viz. Carl Hering, Charles P. Steinmetz, Charles F. Scott, and Bion J. Arnold. The medal is of gold, its intrinsic value being about $100, and is accompanied by a certificate.

Edison Medal Committee.—This committee organized May 20, 1904, under the Deed of Gift, and resolutions of the Board of Directors adopted April 22, 1904. The by-laws prepared for the government of this committee were submitted to the Board of Directors and approved December 23, 1904. It was found impracticable to award the medal for the year 1904. A letter accompanied with a copy of the by-laws was sent by the committee to each of 86 institutes of learning in the United States considered eligible. Replies have been received from only five of these institutions.

Committee on By-Laws.—During the year this committee has considered certain by-laws referred to it by the Board of Directors, also several amendments deemed necessary in the administration of Institute affairs. Such of these as were acceptable to the Board were adopted February 24 and March 24 and were printed in the April, 1905, issue of the PROCEEDINGS. Complete copies of the Constitution and amended by-laws will be furnished upon application to the secretary.

Membership.—The total membership at the close of last year's report was 3027, classified as follows:

Honorary Members		2
Members		459
Associates		2566
Total May 1, 1905		3027
Elected prior to May 1, 1904, and since qualified		65
Elected May 1, 1904, to April 30, 1905, and qualified		450
Restored to Membership		1
		3543
Deduct—		
Total Deaths	17	
Total Resignations	23	
Dropped as delinquents	43	
		83
Total membership, April 30, 1905		3460

The membership April 30, 1905, is classified as follows:

Honorary Members	2
Members	482
Associates	2976
Total	3460

The net gain in membership during the year was 433, an increase of 14 per cent. As there are now applications pending and associates elected, but not yet qualified, to the number of 267, there is an immediate prospective total of about 3700 members.

Associates Elected.—The Associates elected during the year, May 1, 1904, to April 30, 1905, and their present status is as follows:

Qualified and now Associates	450
Elections cancelled	3
Not qualified on April 30	142
Total elections	595

Resignations.—The following Members and Associates have resigned in good standing during the year:

Members.—G. W. Blodgett.

Associates.—G. L. Bayley, Chas. Brandeis, R. G. Brown, Mario Capucio, O. T. Crosby, A. G. Compton, F. N. Drane, Keith Donaldson C. B. Graves, P. F. Gaehr, DeForest Hicks, C. H. Hurd, David Halstead, H. F. Hitner, Wm. Hallock, R. A. Joslyn, C. G. Y. King, G. L. Knight, C. W. Naylor, C. T. Penton, S. C. Shaffner, E. E. Flitchner. Total, 23.

Deaths.—There have been during the year the following deaths:

Members.—Max Osterberg.

Associates.—Adolpho Aschoff, E. K. Adams, B. B. Abry, H. C. Brown, Geo. A. Cooke, Geo. W. Frank, M. R. Gutieriez, B. S. Lanphear, E. H. Mullin, A. Meuschel, E. F. Phillips, C. E. Stephens, R. B. Strong, A. W. Underwood, C. E. Webber, C. W. Wilkes.. Total, 17.

FINANCIAL STATEMENT FOR APRIL 30, 1905.

GENERAL BALANCE SHEET.

ASSETS.

CASH:		
General library fund	$339.11	
Carnegie fund (library)	4,160.19	
Land Building and Endowment fund	22,747.54	
Mailloux fund	1,000.00	
Mercantile Trust Co. (on deposit)	11,054.31	
		$39,301.15
U. S. bonds market value		8,875.63
Secretary's petty cash		500.00
Library volumes and fixtures		22,705.04
Transactions		7,622.50
Office Furniture and fittings		799.45
Badges		103.00
Congress books		201.00
Accounts receivable		10,514.12
Suspense account		1,775.00
		$92,396.80

LIABILITIES.

General library fund	$339.11
Carnegie fund (library)	4,084.17
Land, Building and Endowment fund	22,747.54
Mailloux fund	1,008.20
Life Membership fund	4,400.00
Surplus (cash and bonds)	15,597.76
Surplus (property)	44,220.11
	$92,396.89

RECEIPTS AND DISBURSEMENTS.

Ordinary Receipts.

Entrance Fees	$2,657.00
Current Dues	29,256.90
Past Dues	1,318.34
Students' Dues	1,660.00
Advance Dues	319.95
Transactions Sales	1,038.36
Transactions Subs.	787.52
Binding	158.72
Advertising	3,939.52
Electros and Cuts	3.00
Badges	977.75
Transfer Fees	270.00
Interest on Bank Balances	480.59
Income from Investments	240.00
Exchange	23.30
	$43,130.95

Ordinary Disbursements.

Stenography & Typewriting	403.52
Stationery & Printing	2,476.03
Postage	2,327.66
Express	829.14
Badges	893.88
General Expenses	1,648.49
Certificates	11.25
Office Fittings	266.25
Salaries (excepting librarian)	6,214.35
Cuts and Electros	1,739.92
Publishing Transactions	10,104.71
Rent	2,642.54
Advertising Com's'ns	543.14
Binding Volumes	2,032.82
Binding Pamphlets	115.26
Meeting Expenses	380.39
Branch Meetings	1,057.77
Library Rent	1,475.04
Library Salaries	834.00
Library Insurance	106.35
Library Miscel.	460.81
Students' Expenses	3.75
Congress Reception	781.76
St. Louis Expenses	105.35
Reception	75.06
Balance	5,601.70
	$43,130.95

SPECIAL RECEIPTS AND DONATIONS AND SPECIAL EXPENDITURES

Special Receipts and Donations.

Land, Building and Endowment Fund, Donations and Interest	$18,150.20
General Library Fund, Interest	10.28
Mailloux Fund, Interest	30.00
Carnegie Fund (Library), Interest	123.76
Carnegie Fund, Cash Return	6.75
	$18,320.99

Special Expenditures.

Land, Building and Endowment Fund, paid United Engineering Society	$1,000.00
Land, Building and Endowment Fund, Collection Expenses	2,012.59
General Library Fund	40.84
Mailloux Fund	22.10
Carnegie Fund (Library)	478.72
Balance to credit of Special Funds	14,766.74
	$18,320.99

The total receipts for 1905, exclusive of donations, were in excess of 1904	$2,144.1.
The total Disbursements for 1905 were in excess of 1904	1,135.05
Due from Members account of entrance fees and dues	9,230.00
Due on miscellaneous accounts	1,284.12
Unpaid bills, May 1, 1905, amount to	368.82

Total Cash Receipts from ordinary sources	43,130.95	
Total Cash Disbursements, account ordinary expenses	37,529.25	
		$5,601.70
Property on hand according to inventory, May 1, 1905:		
Office Furniture and Fittings	$799.45	
Badges	103.00	
Transactions	7,622.50	
Congress Books	201.00	
Library Volumes and Fixtures	22,705.04	
		31,430.99

TOTAL NET ASSETS.

Cash:		
Mercantile Trust Co., deposit	$11,054.31	
Farmers Loan & Trust Co., Library Fund	339.11	
Farmers Loan & Trust Co., Building Fund	22,747.54	
Farmers Loan & Trust Co., Carnegie Fund	4,160.19	
Certificate of Deposit, Mailloux Fund	1,000.00	
	$39,301.15	
Secretary's Petty Cash	500.00	
U. S. Bonds, market value	8,875.63	
Inventory as above	31,430.99	
		80,107.77
Total Net Assets last year		57,853.36
Increase		$22,254.41

PROPERTY ACQUIRED DURING THE YEAR.

(Reported as directed by the Constitution.)

Office Furniture and Fixtures	$256.50
Transactions	3,413.00
Library Books and Binding	405.96
Library Table	5.00
	$4,080.46

Respectfully submitted for the Board of Directors,

RALPH W. POPE,

Secretary.

TREASURER'S REPORT.

FOR THE YEAR MAY 1, 1904, TO AND INCLUDING APRIL 30, 1905.

GEORGE A. HAMILTON, *Treasurer*, in account with the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

On account of General Fund	Dr.	Cr.
Balance from April 30, 1904	$7,861.44	
Received from Secretary during year	45,180.29	
Payments on Warrants:		
No. 2144 to No. 2513 inclusive		$41,987.42
Balance to new account, May 1, 1905		11,054.31
	$53,041.73	$53,041.73

GENERAL LIBRARY FUND.

Balance from April 30, 1904	$369.67	
Received from the Secretary	10.28	
Payments on Secretary's warrants		$40.84
Balance to new account, May 1, 1905		339.11
	$379.95	$379.95

CARNEGIE FUND (LIBRARY).

Balance from April 30, 1904	$4,303.43	
Received from the Secretary during the year	259.46	
Payments on Secretary's warrants		$402.70
Balance to new account, May 1, 1905		4,160.19
	$4,562.89	$4,562.89

LAND, BUILDING AND ENDOWMENT FUND.

Balance from April 30, 1904	$7,609.93	
Received from the Secretary during the year	18,150.20	
Payments on warrants by special authorization of Board of Directors		$3,012.59
Balance to new account, May 1, 1905		22,747.54
	$25,760.13	$25,760.13

MAILLOUX FUND.

Balance from previous year	$1,000.00	
Balance to new account		$1,000.00
	$1,000.00	$1,000.00

Respectfully submitted,

GEO. A. HAMILTON,

Treasurer.

May 11, 1905.

MR. JOHN W. LIEB, JR., PRESIDENT AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, NEW YORK CITY.

Sir: Pursuant to the provisions of the Constitution, the Committee on Finance has during the year exercised supervision over the financial affairs of the Institute. It has considered all bills and approved for payment such as constituted a proper charge against the Institute.

It has considered and reported upon specific appropriations, and has made special reports upon various matters referred to it by the Board of Directors.

As provided by the Constitution, it has employed an expert accountant to audit the accounts of the Institute; and this report, made by Mr. William H. Macnabb, has been approved by the Finance Committee, and is transmitted herewith.

Very truly yours,

J. J. CARTY, ***Chairman Committee on Finance.***

May 11, 1905.

MR. J. J. CARTY, CHAIRMAN FINANCE COMMITTEE, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, NEW YORK CITY.

Dear Sir: In accordance with your instructions I have carefully examined all the books of account, records, bills rendered and bill-book entries, cash receipts and cash-book entries, ledger entries from all sources, and ledger balances, cash payments, checks, check stubs, and cancelled checks, warrants, vouchers, and receipts of the American Institute of Electrical Engineers, for the year ending April 30, 1905.

I have verified all additions, and compared receipts of cash by the Secretary, with the amounts turned over by him to the Treasurer, and find same correct.

The amounts of cash on hand, May 1, 1905, as shown by the balances in the books of account, have been verified by me, and I have personally inspected the United States Bonds on hand, as well as a Certificate of Deposit for $1,000.

The books and accounts are correct; all special funds are in correct form, and all trust funds intact.

The statement of assets and liabilities, receipts, and disbursements, etc., as submitted by the Secretary, and the report of the Treasurer, have been verified by me, and are correct, and in accordance with the books and records of the Institute; and the assets as shown are held in fact in the manner and condition as shown on the said books and statements.

Yours respectfully,

WM. H. MACNABB,

Accountant.

REPORT OF GENERAL RECEPTION COMMITTEE OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS IN CONNECTION WITH THE INTERNATIONAL ELECTRICAL CONGRESS AND CIRCULAR TOUR.

To the Board of Directors of the American Institute of Electrical Engineers:

One of the important events of the fiscal year just closing was the International Electrical Congress held at St. Louis, September 12–17, 1904. At the last International Congress held in Paris in 1900, the Institute was represented by official delegates and visiting members, and they were splendidly entertained in London *en route* to Paris by the Institution of Electrical Engineers. The American Institute of Electrical Engineers had been desirous of reciprocating the courtesies received at the hands of the sister society, and the International Electrical Congress at the St. Louis Exposition afforded a welcome opportunity to again extend a cordial invitation to the Institution to visit America. The invitation was accepted and it was arranged to hold a joint meeting in St. Louis during the sessions of the Congress.

In order to facilitate the visits of our guests to some of the principal cities and important centers of electrical industry, a circular tour was organized under the auspices of the Institute, embracing visits to Boston, New York, Schenectady, Montreal, Niagara Falls, Chicago, St. Louis, Pittsburg, Washington and Philadelphia. A general invitation was also extended to visiting members from European Electrical Engineering Societies, and in addition to our official guests the Institution of Electrical Engineers, a large delegation from the Associazione Elettrotecnica Italiana joined in the tour, together with a number of official delegates to the Congress, and Electrical engineers from many European countries. President Arnold placed the arrangements for the reception and entertainment of our guests in the hands of a General Reception Committee, with Mr. J. W. Lieb, Jr., as Chairman, with the coöperation of a Committee on Transportation and Arrangements, of which the late Mr. E. H. Mullin was Chairman. In the several cities visited, prominent members of the INSTITUTE assumed the chairmanship of the Local Committees and with the coöperation of efficient Local Committees they provided splendid programmes of entertainment, and assured everywhere a cordial welcome to the visitors. When it is considered that this lavish entertainment was provided through the Local Committees without expense to the membership at large of the INSTITUTE, a deep debt of gratitude is due the Chairmen of the Local Committees, through whose efforts the INSTITUTE was able to accord a dignified and worthy reception to its visitors and guests from abroad. About 150 joined in the circular tour, of whom 74 were representatives from the Institution, 42 of the Associazione Elettrotecnica Italiana, 16 visiting electrical engineers from other foreign countries, and 18 members of the INSTITUTE, who acted as hosts and guides to the visitors; in all 16 ladies accompanied the party and contributed notably to the gayety and enjoyment of the trip.

The representatives of the Associazione Elettrotecnica Italiana arrived in New York August 24–25, and spent the interval until September 2 visiting New York and vicinity under the guidance of a committee of American members.

The representatives of the Institution, our official guests, arrived in Boston September 2, where they were joined by the A. E. I. and other visitors, and here began the official round of entertainments and visits. The official welcome of our INSTITUTE to the Institution and all foreign visitors and guests took place Monday, September 5, at the Waldorf-Astoria, with addresses by President B. J. Arnold; President Robert Kaye Gray of the Institution; President Moisé Ascoli of the A. E. I.; Dr. Wilhelm von Siemens; Professor Elihu Thomson; Professor John Perry, F. R. S.; Charles A. Coffin, Esq., President of the General Electric Company, and President-elect J. W. Lieb, Jr.

The week spent in St. Louis was marked by notable receptions and banquets, culminating September 17 in a luncheon tendered by the Institution to the INSTITUTE in the New York State Building, at the conclusion of which President Gray of the Institution presented to us a magnificent oil painting representing Dr. William Gilbert of Colchester before Queen Elizabeth, as a mark of appreciation from the Institution to its sister society.

Through the courtesy of the Engineers' Club of New York City, this gift temporarily adorns one of its walls, pending the construction of the United Engineering Building, in which it will find a permanent home in the headquarters of the INSTITUTE. A committee of three, consisting of Messrs. Arnold, Rice, and Weaver, was appointed by the Council to prepare a resolution of thanks, of which the following is a copy:

TO THE INSTITUTION OF ELECTRICAL ENGINEERS OF GREAT BRITAIN.

GREETING:

"Having in mind the many evidences of friendship and good will from the officers and members of your body during their recent visit, as our official guests, to the International Electrical Congress of St. Louis, 1904, and which culminated in the presentation through your distinguished President, Robert Kaye Gray, on September 17, 1904, of the magnificent painting representing Dr. William Gilbert of Colchester before Queen Elizabeth:

"The President, Board of Directors and Members of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS desire to express formally by these presents, their grateful appreciation for the generous and thoughtful gift, and their recognition of the kindly spirit which prompted it.

"This masterly representation of a historic scene will always be cherished by us as a testimonial of the warm friendship which, no less than professional ties, binds our INSTITUTE with the elder Institution of the mother country. The painting will be displayed in a prominent position in our new headquarters in the United Engineering Building, in honor of the esteemed donor and of its great subject, your illustrious countryman, who gave the world not only the first clear conception of the principles of the magnet, but also the first treatise in which, according to the light of to-day, true scientific method was employed.

"We beg of you to accept this official expression of our appreciation of your generosity as a slight token of the high esteem in which your society is held by our INSTITUTE."

Attest: RALPH W. POPE, *Secretary.*

Signed: J. W. LIEB, JR., *President.*

These resolutions were formally presented by Mr. T. C. Martin at a meeting of the Council of the Institution, and a copy was also presented to President Gray, its esteemed Past-President, who was at the head of the delegation visiting America.

In each of the important cities visited on the tour the Local Committee published an Electrical Handbook containing a description of the important electrical industries and constituting a valuable library of ten volumes, or 11, including a volume of "Edisonia" contributed by the Association of Edison Illuminating Companies.

The Committee of Organization of the International Electrical Congress, the Advisory Committee, and the Chairmen and

Secretaries of the eight sections were almost without exception members of the INSTITUTE. An extensive programme of papers and discussions, many by foreign electrical engineers, was presented at the Congress, covering the whole range of electrical science and its practical applications.

Through the courtesy of the Association of Edison Illuminating Companies, a handsomely furnished booth was placed at the disposal of the INSTITUTE for use as head-quarters in the Electricity Building at the St. Louis Exposition, and many members availed themselves of its facilities.

Attached to this report and filed with it in the archives of the INSTITUTE, are copies of the circular letter issued by the INSTITUTE giving the general arrangements for the reception of visiting electrical engineers, and inviting participation in the circular tour; a list of the Local Chairmen and Local Committees; a list of the visiting members of the Institution of Electrical Engineers and of the A. E. I.; the names of those who took part in the circular tour; the programme of the trip prepared by the Institution and the programme for the entertainment in New York of the A. E. I. in advance of the beginning of the circular tour; and a copy of the Souvenir Number of the Electrical Magazine, containing an account of the trip from the visitors' point of view.

Respectfully submitted,

CALVIN W. RICE, *Vice-chairman.*

J. W. LIEB, JR., *Chairman.*

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

ANNUAL REPORT OF LIBRARY COMMITTEE.

We beg to submit herewith a report of the present state of the Library of the INSTITUTE, and the state of the several funds under the cognizance of this Committee.

Progress in upbuilding the Library has been halted during the past as during the preceding year, owing to the undesirability of pressing upon the membership the claims of the Library to their support, in view of the large sum of money the INSTITUTE is endeavoring to obtain by donation in order to meet the obligations assumed in connection with the United Engineering Building.

The compilation of the Wheeler Bibliography is now complete and the manuscript will soon be placed in the hands of the printer. The volume should be printed and be in the hands of members during the present year.

Through the kindness of Mr. W. J. Johnston, the Library has come into possession of a complete set of the *Operator*, 1874–1883. This is undoubtedly the only complete set of this pioneer periodical in existence. Mr. Edward D. Adams has very kindly entered a subscription for the Library covering a period of five years, for the "International Catalogue of Scientific Literature." This catalogue is a continuation of the "Catalogue of Scientific Papers" formerly issued by the Royal Society of London, a complete set of which was presented to the Library by Mr. Adams. Mr. Adams has also brought up to date, by the purchase of recently issued volumes, the complete sets of the *Transactions* and of the *Proceedings* of the Royal Society, which he presented to the Library. From the New York Public Library, through the kindness of Dr. John S. Billings, the Library has received many copies of periodicals, Transactions, etc., which were lacking from our sets. The

Smithsonian Institution has presented to the Library a complete set of its miscellaneous publications on subjects relating to electricity and physics.

During the year a catalogue of the periodical publications in the Library was printed, the entries including the Transactions of professional and scientific bodies. A copy of this will soon be sent to each member of the INSTITUTE, together with a circular asking their aid in filling out certain departments in the Library.

During the year gifts of books and pamphlets were received from the following:

ADAMS, EDWARD D.
AHEARN, T.
ARMY WAR COLLEGE.
AMERICAN PHYSICAL SOCIETY
BEHREND, B. A.
BREWER, A. R.
BOSTON PUBLIC LIBRARY.
BRADLEY, C. S.
BRITISH PATENT OFFICE.
BRIDGE, J. H.
CROCKER, F. B.
CARNEGIE LIBRARY.
COLUMBIA UNIVERSITY.
DUNLAP, J. R.
DOHERTY, H. L.
ECLAIRAGE ELECTRIQUE.
GAUTHIER-VILLARS.
GODDARD, C. M.
HERING, CARL.
HOBART, H. M.
HAMILTON, G. A.
JOHN CRERAR LIBRARY.
JOHNSTON, W. J.
LAIRD & LEE.
LAMB, F. J.
LIBRARY OF CONGRESS.
LOW, G. P.
MAVER, W.
MASSACHUSETTS BOARD OF GAS & ELECTRIC LIGHT COMMISSIONERS.
McGRAW PUBLISHING COMPANY.
NEW YORK PUBLIC LIBRARY.
NEW YORK STATE LIBRARY.
NEW YORK ELECTRICAL SOCIETY.
PETTY, W. M.
PLAINFIELD PUBLIC LIBRARY.
SPANG, H. W.
SAGER, J. C.
SMITHSONIAN INSTITUTION.
U. S. NAVAL BUREAU OF EQUIPMENT.
VAN NOSTRAND COMPANY, D.
WARDLAW, G. A.

Following are the statistics of the Library, brought up to May 1, 1905:

STATISTICS OF LIBRARY.

Source.	Titles.	Volumes.	Pamphlets	Valuation.
Report of May 1, 1904	6924	9420	114	$20,136.68
PURCHASES:				
Carnegie Fund	8	214	2	263.30
Donation Fund	20	38	7	64.64
Mailloux Fund	3	10		22.10
Institute Appropriation	1	1		.90
Periodical Volumes	64	116		232.00
GIFTS:				
Edward D. Adams	3	24		187.34
B. A. Behrend	36	41	24	58.00
C. S. Bradley	1	118		120.00
McGraw Publishing Company	77	106	157	42.50
Miscellaneous Gifts (35 donors)	82	116	88	116.85
Total, May 1, 1905	7219	10204	392	$21,244.31
Duplicates	217	593		144.72
	7002	9611	392	21,099.59
Duplicate Periodical Titles	122			
	6880	9611	392	$21,099.59

Following is the total valuation of the Library, May 1, 1905, including permanent Library fixtures:

TOTAL VALUATION.

Books	$21,099.59
Book Stacks	1,470.25
Furniture, Catalogue Cases, etc.	135.20
	$22,705.04

Following are tabulations giving the present state of the several funds of which the Library Committee has cognizance:

DONATIONS (GENERAL LIBRARY FUND).

Dr.		Cr.	
Balance May 1, 1904	$369.67	Purchase of books	$64.64
Interest to May 1, 1905	10.28	Unexpended	315.31
	$379.95		$379.95

CARNEGIE FUND.

Dr.		Cr.	
Balance May 1, 1904	$4,432.38	Books	$339.32
Interest to May 1, 1905	123.76	Wheeler Bibliography	134.45
		Unexpended	4,082.37
	$4,556.14		$4,556.14

MAILLOUX ENDOWMENT FUND. ($1,000.)

Dr.		Cr.	
Balance May 1, 1904	$.30	Book	$1.00
Interest Accrued	30.00	Subscriptions	21.10
		Unexpended	8.20
	$30.30		$30.30

The table below gives an account of funds appropriated by the INSTITUTE for library purposes during the past year:

INSTITUTE APPROPRIATIONS.

Appropriation for Maintenance	$3,000.00	Rent	$1,475.04
Special Appropriation for Periodical Catalogue	250.00	Insurance	106.35
		Salary, Librarian	780.00
		Extra Assistance	54.00
		Binding	277.75
		Library Supplies	16.51
		Subscriptions	32.00
		Express and Postage	14.60
		Catalogue of periodicals	101.25
		Miscellaneous	8.10
		Unexpended	384.40
	$3,250.00		$3,250.00

Following is a comparative statement of disbursements from the annual appropriations of the past two years:

	1903–1904	1904–1905
Rent	$1,505.04	$1,475.04
Insurance	54.77	106.35
Salary Librarian	780.33	780.00
Extra Assistance	50.00	54.00
Binding, Periodicals and Books	254.20	277.75
Library Supplies	65.36	16.51
Subscriptions	20.00	32.00
Express and Postage	11.35	14.60
Miscellaneous	7.70	*109.35
Unexpended	251.25	334.40
Appropriation	3,000 00	3,250.00

*Including $101.25 for printing Catalogue of Periodicals, for which an extra appropriation of $250.00 was made.

Annual Appropriation, 1905–1906.

The annual appropriation asked of the Institute for Library purposes is limited to the sum required for routine expenses, and it includes no provision for the purchase of books or Library fixtures. The estimated requirements for the fiscal year May 1, 1905, to May 1, 1906, are as follows:

Rent	$1,475.04
Insurance	115.00
Salary Librarian	780.00
Extra Assistance	50.00
Binding	300.00
Library Supplies	75.00
Subscriptions	40.00
Express and Postage	25.00
Miscellaneous	139.96
	$3,000.00

Gano S. Dunn.
W. J. Jenks.
F. A. Pattison.
F. W. Roller.
W. D. Weaver, Chairman.

ANNUAL REPORT OF BOARD OF EXAMINERS.

To the Board of Directors, American Institute Electrical Engineers:

Dear Sirs: In compliance with your request, the following report is submitted of the work of the Board of Examiners for the fiscal year ending April 30, 1905.

During the year, ten regular meetings were held; also four special or adjourned meetings. At these meetings, 527 applications for Assoicate membership were recommended for election to that grade. The applications of 332 persons for enrollment as Students of the Institute were considered, and of these, 331 were recommended for enrollment. The Board of Examiners acted upon 54 applications for transfer to the grade of Full Membership; and of these 28 were recommended for transfer, and 26 were not recommended for transfer.

The following remarks are suggested by matters that at times engage the attention of the Board of Examiners:

It is to be assumed that any Board, having charge of work similar to that with which the Board of Examiners has to do, would naturally strive to follow carefully the rules laid down for its guidance. But apart from this, the By-Laws of the Institute, Section 40, specifically requires the Board of Examiners to do so, in the following language:

> "It shall be the duty of the Board of Examiners to carry out strictly the provisions of the Constitution respecting the election of Associates, and the transfer of Associates to full membership."

It has been observed that many full members of the Institute appear not to make themselves conversant with the qualifications required by the Constitution for transfer to full membership, prior to endorsing the applications of their friends and acquaintances for transfer. It appears also, not to be fully recognized by some members that the Constitution lays down hard and fast rules as to the professional qualifications which Members must possess, and as to the time during which applicants shall have been in the active practice of the profession of electrical engineering, during a certain portion of which time they shall have been in responsible charge of work.

An important point that seems to be frequently lost sight of, both by endorsers and by applicants for transfer, is that membership in the Institute should signify that the Member by his work in some branch or another of the electrical engineering profession, has attained a prominent position in the profession. It may be assumed that it is not a function *per se* of the Institute to give an Associate a reputation.

There should be, it would seem, a differentiation between that class of men who by their ability and energy have attained to prominence in the electrical engineering profession, and another class who, for one reason or another, make no mark in the profession. (Consider that both classes have been regularly graduated electrical engineers.) Yet there appear to be members of the INSTITUTE who fail to appreciate this distinction. It is obviously no fault of the INSTITUTE if a man after graduation as an E. E. elects to become, for example, an author, or to adopt any other occupation where in the nature of things he cannot practise electrical engineering.

Another matter that occasionally arises for consideration is as to what time after graduation a young man may be said to have become fitted to practice electrical engineering as a profession. On this point, Mr. H. W. Buck, in an article on "Electrical Engineering," *Encyclopedia Americana*, aptly says:

> "A man makes a mistake to consider himself a qualified electrical engineer after he has been graduated by a college, for he is not one—his mind has been trained into a condition where he can readily absorb the principles of the electrical profession, but that is all; and the subsequent apprentice training is as important as the college course in order to acquire a broad view point from which to make a correct start in the direction for which the man is best fitted."

This time will doubtless vary in nearly every instance; and perhaps the decision in such case or cases, must be, as heretofore, left to the judgment of the Board of Examiners, or Board of Directors, as the case may be.

There seems to be some difference of opinion as to the merits or general fitness of the existing constitutional qualifications for transfer. Some associates and members appear to consider them too rigid. Others intimate that judging by alleged, but not specified, poor examples of members already transferred, the standard is too low.

It is the opinion of the Chairman that the present standard of qualifications for transfer to membership is not too high. If any change should be contemplated in this direction, it would, he thinks, perhaps be advisable to increase the time of actual practice of the profession of electrical engineer, and the time of actual charge of work. This change might temporarily conduce to limiting the full membership list, owing to the great number of young men who have entered the electrical engineering profession within the past few years, but every passing year would add large numbers to the eligible list for transfer, so far as the time limit of practice is concerned.

While holding the views just expressed as to the maintenance of the present standard of qualifications for transfer to full membership it should be added that in common with his colleagues on the Board of Examiners, the Chairman has long felt that there might with advantage be made a distinction between members in the Associate class who are in line for transfer to full membership, and those who are simply associated with the electrical profession for commercial reasons. It would seem, also, that a satisfactory method might be adopted by which men of prominence in other engineering professions, or who are prominent in the electrical engineering profession in a semi-technical way, might be admitted to some grade of membership in the INSTITUTE above that of Associate.

The Board of Examiners has had this last mentioned matter under informal consideration in the past, and in fact had prepared a set of suggested amendments to the Constitution to cover the points noted; but it was understood when these proposed amendments were submitted to the Board of Directors for its consideration, that the time was not then thought to be opportune. The Chairman would respectfully suggest that perhaps the time is now ripe for some action on this question.

Very truly yours,
(Signed) WM. MAVER, JR.,
Chairman Board of Examiners.

REPORT OF THE COMMITTEE ON PAPERS.

TO THE BOARD OF DIRECTORS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, New York City:

DEAR SIRS: Your Committee on Papers begs leave to submit the following report of its work during the past year.

Arrangements have been made for eight regular monthly meetings on the following subjects: Transmission of Intelligence, Heavy Electric Traction, High Tension Transmission, Central Station Practice, Light Electric Traction, High Tension Electric Railways, Instruments and Measurements, and Safety Devices. For these meetings 16 papers have been prepared. Of these but two were volunteered, the remaining 14 being written at the solicitation of the Committee. The names of the writers and their subjects were suggested to the Committee by specialists.

The work of the Committee has been again somewhat hampered by the non-delivery of promised papers. In connection with the preparation for five different meetings, eminent engineers have given notice to the Committee, within only a few days of the time when their manuscript should have been in the hands of the printer, that it would be impossible for them to prepare these manuscripts.

Arrangements have been also made for the presentation of 20 papers at the Annual Convention. The manuscripts of seven of these are already on hand.

Very respectfully submitted,
Committee on Papers by
SAMUEL SHELDON,
Chairman.

ANNUAL REPORT OF THE EDISON MEDAL COMMITTEE.

To the Board of Directors, American Institute Electrical Engineers:

Dear Sirs: The Edison Medal Committee met on the 20th of May, 1904, and organized under deed of gift and under the resolutions passed by the Directors of the American Institute of Electrical Engineers, April 22, 1904. At this meeting Mr. Gherardi was elected to act as Secretary of the Committee. In accordance with the resolution of the Directors the members of the Committee were, at this meeting, divided by lot into groups as follows:

To serve 1 year: Messrs. Clarke, Martin, and Browne.
" " 2 years: " Howell, Scott, and Reber.
" " 3 " " Bradley, Kelly, and Wolcott.
" " 4 " " Edgar, Sprague, and Gherardi.
" " 5 " " Doherty, Stott, and Hamilton.

At this meeting a sub-committee was appointed by the Chairman to prepare By-Laws to govern the work of the Committee. This Committee was composed of Messrs. Clarke, Hamilton, and Gherardi.

Since that time the Sub-Committee on By-Laws has drawn up a set of By-Laws in accordance with deed of gift, and after various meetings of the Committee, these By-Laws were finally accepted by the Board of Directors on the 23d of December, 1904.

The first question of importance which called for consideration was the award of the medal for the year 1904. At the many discussions of this subject it was decided, in view of the very great difficulty involved, due to the lateness of time at which the Committee was organized and the By-Laws accepted, that it was impracticable to award the medal for the year of 1904.

The matter was finally referred to the Board of Directors of the Institute and our recommendation to them that the medal be not awarded for 1904, was adopted and approved by them.

A Committee on Institutions of Learning composed of Messrs. Browne, Wolcott, and Stott was appointed to carry on such correspondence with the various institutions of learning as was necessary, and to pass upon the eligibility of all such institutions of learning as wished to compete for the medal.

The Committee sent a letter and copy of the By-Laws to each institution of learning in the United States and Canada which they considered eligible, to the number of 137.

From these we have received reply of only five institutions, which are as follows:

University of Arkansas, Fayetteville, Ark.
Thos. S. Clarkson Memorial School of Technology, Potsdam, N. Y.
University of Missouri, Columbia, Mo.
New York University, New York City.
School of Mining, Kingston, Ont.

I am very sorry indeed that so few of the institutions have responded and am at a loss to understand why so many of them have apparently taken no notice of our letter, unless it be that they considered it unnecessary to make reply until such time as they may have a student whom they wish to enter for competition.

I certainly hope that as the end of the college year draws near we may have a good many theses presented to us for the competition this year.

Yours very truly,

JOHN W. HOWELL,
Chairman, Edison Medal Committee.

May 9, 1905.

ANNUAL REPORT OF THE COMMITTEE ON NATIONAL ELECTRICAL CODE.

TO THE BOARD OF DIRECTORS, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS:

GENTLEMEN: I beg to submit the following report on behalf of the Committee on National Electrical Code.

The Committee met in New York on December 6, 1904, and also met at that time in conference with code committees of the N. E. L. A., and the Assn. Ed. Illg. Cos. The committee also attended the annual New York meeting, on December 7, of the Underwriters' Electrical Association. A report was submitted to the President and Board of Directors on December 20 upon the actions at those meetings.

At the instance of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, through its Secretary, a meeting of the National Conference was requested. In order to ascertain the views of the membership of the INSTITUTE as to the rules in the National Electrical Code, the Board of Directors directed the Secretary of the INSTITUTE to issue early in April, 1905, a circular letter of enquiry to the membership. A copy of this circular is appended herewith. Fifteen replies to this circular were received by the Committee. The corporations whose officers' replies are included in this list are the Bishop Gutta-Percha Co., the Crocker-Wheeler Co., the Pennsylvania R.R. Co., and the United Gas Improvement Co. The remaining replies were from individuals not representing corporations. The rules of the 1903 code specifically criticised in the replies were 20 in number, viz., 1c, 1d, 8a, 12a, 12m, 12n, 13a, 21d, 22c, 24a, 33e, 34a, 36c, 41d, 41e, 41f, 47, 51, 54b, 81. Of these, three rules were criticised by two persons, viz., 1c, 21d, and 36c. No rule was criticised by more than two persons. It is considered that most of the criticisms are good, and should receive careful attention in detail; but that none of them are of sweeping importance.

The committee met in New York on the 20th of April last to consider these criticisms, and also to confer with the code committees of the National Electric Light Association and of the Assn. of Ed. Illg. Co. In view of the greater importance of the matters coming before the conference, it was voted to defer action upon the criticisms until a more favorable opportunity.

The Conference met in Boston on the 21st of April, 1905. An official report will no doubt be forwarded to the INSTITUTE, and to all the other conferring bodies, by the Conference Secretary. As the delegate of the

INSTITUTE to the conference, I submitted an interim report to the President of the INSTITUTE on April 24 last.

Summing up the situation,

(1) The relations of the INSTITUTE, and other bodies in the conference, to the Code, as appearing on the flyleaf of the same, have, we believe, been materially improved and corrected by the amended phraseology due to appear on the flyleaf of the forthcoming edition of the Code (1905).

(2) With the exception of a few details, mentioned above, the membership of the INSTITUTE appears to be generally satisfied with the rules in the Code.

(3) Measures have been secured for obtaining appeals to the Board of Insurance Underwriters from the rulings of individual insurance inspectors alleged to misapply the Code.

Respectfully submitted,

A. E. KENNELLY,
Chairman.

May 5, 1905.

(Copy of circular referred to in above report.)

NEW YORK, April 3, 1905.

TO THE MEMBERSHIP OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS:

A meeting of the National Conference on Standard Electrical Rules will be held at 10 o'clock a.m., Friday, April 21, 1905, at No. 55 Kilby Street, Boston, Mass.

The INSTITUTE will send an official delegate, to be appointed by the President, and will also be represented at the sessions of the Conference by its Committee on National Electrical Code.

The Code Committee will be glad to receive suggestions which any member or associate member may desire to offer recommending any important substantial change in the National Code, such as modification, addition to, or elimination of, any rule or requirement which may be shown to be necessary as a result of experience in the practical operation of the Code or owing to the progress in the state of the art.

If no criticisms are received by the Chairman of the Code Committee prior to April 14, it will be assumed that no special action amending the Code is called for by the membership.

Communications, preferably typewritten, should be sent to the Chairman of the Code Committee not later than April 14, 1905, so that they may be considered by the Committee in advance of the meeting of the National Conference.

Yours very truly,

A. E. KENNELLY, *Chairman.*
L. A. FERGUSON,
P. G. GOSSLER,
F. A. C. PERRINE,
H. A. SINCLAIR,
ARTHUR WILLIAMS,
C. J. H. WOODBURY.

Address all communications to
A. E. KENNELLY,
Chairman A. I. E. E. Code Committee,
Pierce Hall, Harvard University,
Cambridge, Mass.

ANNUAL REPORT OF REPRESENTATIVES ON JOINT COMMITTEE ENGINEERING BUILDING.

To the Board of Directors, American Institute of Electrical Engineers:

Plans and specifications for the Engineering Building to be erected under the gift of Mr. Andrew Carnegie have been approved by the Committee and bids have been called for.

The United Engineering Society has been incorporated and an agreement entered into between it and the " Founder Societies " the American Institute of Electrical Engineers, American Society of Mechanical Engineers, and the American Institute of Mining Engineers. The nine trustees of United Engineering Society are appointed by the Founder Societies. The United Engineering Society will own and its Trustees will administer the Engineering Building and the Founder Societies will pay to the United Engineering Society funds for the purchase of the land and will receive Treasurer's receipts therefor. The United Engineering Society now holds title to the land purchased for us two years ago by Mr. Carnegie on the north side of 39th Street half way between 5th and 6th Avenues.

Such in brief are the results of the work of the past year.

The architectural competition referred to in the report to the Board of Directors in 1904 resulted in 26 sets of plans. After careful examination by the Committee plans were selected and were found to be those submitted by Herbert D. Hale, Architect, and Henry G. Morse, Associate. These plans were elaborated by the architect and were carefully studied by the Committee. They were submitted to the governing boards of the three Societies for suggestion and approval.

In order that proper provision might be made for a great engineering library the Committee suggested to the governing boards of the Founder Societies that a conference committee on library be appointed. Such a committee was appointed, there being three members from each of the three Societies. A comprehensive scheme for bringing together the libraries of the Societies and making them the nucleus of a great engineering library was recommended to the governing boards of the Societies and accepted by them. The Conference Committee on Library has made a study of the plans and recommended the arrangement of the library and stack room floor of the Building.

The Building will provide a reception room on the first floor, a mezzanine coat room, and a large auditorium on the second floor. Over this will be assembly and small lecture rooms. Above the meeting rooms will be office floors for the three Founder Societies and other engineering and scientific bodies, termed Associate Societies. The library will occupy the upper floor.

The Committee has had a double problem: first, to determine the probable future needs of the growing Engineering Societies and second, to design the Building so as to accommodate these needs.

The details of the plans are not given in this report as it would be anticipating a report which the Committee has in preparation for distribution through the Secretaries of the several Societies, which will contain the plans with descriptive matter.

The Joint Committee is constituted as follows: AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, Charles F. Scott, Bion J. Arnold, Schuyler Skaats Wheeler; American Society of Mechanical Engineers, Charles Wallace Hunt, James M. Dodge, Frederick R. Hutton; American Institute of Mining Engineers, Albert R. Ledoux, Theodore Dwight, Charles Kirchhoff; The Engineers' Club, John C. Kafer, William H. Fletcher, Thomas C. Martin. Of this Committee Mr. Scott is chairman, and Professor Hutton is secretary.

This Joint Committee represents the four organizations named in the letter of Mr. Carnegie, in which he devoted one and one-half million dollars "for the erection of a suitable home for you all."

Soon after its organization two sub-committees were appointed on behalf of the Engineering Societies, one on organization consisting of Messrs. Wheeler, Ledoux, and Hunt; and one on building plans consisting of Messrs. Scott, Hutton, and Kirchhoff (the latter has been succeeded by Mr. Dwight).

A statement regarding the plan of permanent organization by Dr. Wheeler, who has been instrumental in its evolution and who is treasurer of United Engineering Society, is appended to this report.

The Engineering Building faces on 39th Street and the Club building faces on 40th Street abut in the rear and there will be convenient means of access between the buildings. The titles to the two properties and the administration of the buildings will be independent, being vested in the United Engineering Society on the one hand and The Engineers' Club on the other.

The contract for the Engineers' Club, Whitfield & King, Architects, has been let and work is just beginning. The buildings which formerly occupied the five lots which will be occuiped by the Engineering Building have been removed and all is in readiness to proceed when the contracts are let.

Respectfully submitted,

CHAS. F. SCOTT,
BION J. ARNOLD,
SCHUYLER SKAATS WHEELER.

STATEMENT REGARDING UNITED ENGINEERING SOCIETY.

On behalf of the representatives of the INSTITUTE on the Joint Committee for erecting the building for the United Engineering Society, and particularly with reference to the sub-committee on organization of which I was lately made chairman, I report as follows:

The original Joint Committee consisted of fifteen members, three each from five bodies, but the Civil Engineers withdrew and the Committee thereupon became one of twelve members.

The original Sub-Committee on Organization, Dr. Ledoux Chairman, quickly decided that the fund should be handled as two funds, one belonging to the Club and the other to the Engineering Societies, and that tenancy in common and other arrangements being undesirable for the sister engineering societies, a separate corporation should be organized for holding their property, authorized if possible by a special Act of the Legislature.

Such an Act was obtained, but through error it provided that the Society's property should be exempt from taxation, in violation of a very recent amendment of the State Constitution. This, however, did not nullify the Act in general and the Act is useful in providing simple and satisfactory machinery for the administration of the affairs of the Society for the three beneficiaries in such a way that its property shall be exempt from taxation. The property of a membership corporation may be kept exempt from taxation if it is used exclusively for library, educational, and similar purposes, and no profit is made out of it. United Engineering Society had to be a "holding" corporation for membership corporations, a legal relation without precedent, and the special charter obtained as above, being Chapter 703 of the Laws of the State of New York signed May 11, 1904, gives authorization for this arrangement.

The settlement of the question of the division of the fund of $1 500 000 was long delayed, but was finally made $1 050 000 for the engineering societies and $450 000 for the Club.

The question of placing a bond between the properties of the Club and the United Society so that neither could be alienated from the other, was taken up, but was not carried out further than by the Club's placing upon its minute book a declaration of intention to stay with the societies.

It had been understood the donor of the fund was to purchase the four-story 25-ft. residence to the east of the Engineering Society site in 39th Street, and was to resell it in the market after restricting it to its present height for the benefit of the United Engineering building.

A misunderstanding in regard to the above proposition developed and the arrangement was not made. The Club purchased the property, after obtaining Mr. Carnegie's offer to carry the mortgage for them for twenty years at four per cent., and the Club placed the restriction on it as to its height in favor of the United Society. The ultimate object of the Club is to hold the property available for an addition. For the present it has been leased by them for ten years.

Organization.

The special charter granted to United Engineering Society by the State of New York, confers upon certain individuals (being the individuals appointed by the several societies to represent them in the United Society) the right to organize as a corporation and leaves the character of that corporation to be determined almost exclusively by such by-laws as the men above referred to may adopt. In consequence great attention was given to the preparation of these by-laws, since upon them depends the whole complexion of the holding company. After much discussion and seven revisions in print, a set of by-laws was approved by each of the founder societies and adopted by the United Society. The organization so formed provides a corporation to be managed absolutely by nine men, and these men are to be appointed, removed, etc., absolutely by the Founder Societies, three men each. These trustees are to allot space in the building to the various societies, both founder and associates, and each is to pay a share of the total cost of maintaining the property proportionate to the space each occupies. Carried on in this way the property is not taxable.

For further detail of the organization see the printed by-laws of United Engineering Society adopted December 16, 1904.

Expenses.

All of the expenses of the Joint Committee so far that are not directly chargeable respectively to each of the two interests, are divided between them in the same ratio as the original fund.

Plans and specifications for the complete building of the United Engineering Society are about ready to be issued for bidding, the contract for the erection of the Club having been let some weeks ago.

Schuyler Skaats Wheeler.
Treasurer United Engineering Society.

ANNUAL REPORT OF LOCAL ORGANIZATION COMMITTEE.

To the Board of Directors, American Institute of Electrical Engineers:

The local work of the Institute has shown a healthy development during the past year. Four additions have been made to the list as follows:

Baltimore Branch, December 16, 1904, J. B. Whitehead, Chairman; C. G. Edwards, Secretary.

San Francisco Branch, December 23, 1904, G. O. Squier, Chairman; A. H. Babcock, Secretary.

Syracuse University Branch, February 24, 1905, W. P. Graham, Chairman and Secretary.

University of Colorado, Student Meetings, December 16, 1904, H. B. Dates, Chairman; A. J. Forbess, Secretary.

The original object of the local organization work was three-fold. First, to afford the means by which members geographically scattered might participate in the work of the Institute by contributing to the discussion of papers read at the general meetings and in contributing new material; secondly, to awaken local interest and activity among electrical men, not only among those belonging to the Institute but outsiders as well; thirdly, to bring the up-to-date engineering papers before the students in technical schools and universities in order to bring them into sympathetic relations with the Institute and its work.

The formation of over 30 centers of local Institute activity in two years and a half, followed in nearly all cases by sustained interest and in many cases by the presentation of original papers, indicates the comprehensive activity of the electrical men of our country; it, moreover, indicates the response given by our membership at large to the opportunities afforded through the action of the Board of Directors.

Latitude has been given in the method of organization and conducting of branches in order to enable each to meet in the best manner the local conditions by which it is surrounded. The results which are being secured are due in a large measure to the intelligent direction of the

STATISTICS OF BRANCHES, MAY, 1905.

Branch	Membership		In-crease	A.I.E.E. Students	No. of Meetings Since Sept. 1 1904	Average Attend-ance.	Original Papers Since Sept. 1 1904
	Apr. 20 1904	May 1 1905					
Chicago	152	176	24		6	80	6
Minnesota	12	15	3		9	22	2
Pittsburg	128	157	29		6	60	5
Denver	32	32	0				
Cincinnati	47	56	9		1	60	
St. Louis	60	65	5		4	20	1
Schenectady	113	121	8		7	90	2
Philadelphia	92	114	22		6	45	4
Boston	195	187	—8		6	85	5
Washington, D. C.	44	51	7		6	40	16
Toronto	24	26	2		11	19	6
Columbus	33	42	9		10	16	6
Seattle	17	24	7		1	12	2
Atlanta	19	37	18		5	12	5
Pittsfield	27	31	4		14	35	22
Baltimore	21	34	13		4	23	
San Francisco	36	57	21		5	42	
Cornell University	14	13	—1	102	5	75	
Lehigh University	4	5	1	0	7	40	20
Univ. of Wisconsin	19	19	0	8	16	18	17
Univ. of Illinois	5	4	—1	15	7	22	3
Purdue University	5	7	2	46	5	26	2
Iowa State College	5	10	5	34	8	32	11
Worcester Polytechnic Institute	10	14	4	13	8	45	5
Syracuse University	8	12	4	15	7	16	2
Ohio State Univ.	1	3	2	9	10	30	2
Penn. State College	1	2	1		12	40	8
Univ. of Missouri	1	2	1	15	7	15	
Armour Institute	1	3	2	46	5	32	3
Washington Univ.	1	1	0	19	3	12	1
Univ. of Michigan	3	3	1	15	10	25	12
Univ. of Arkansas	2	2	0	11	9	12	1
Univ. of Colorado	2	2	0	15	9	20	7

officers in charge. The secret of success lies largely in the management of the Branch, as the selection of topics and the conduct of meetings in such a way as to present live and important subjects in an interesting and profitable manner is sure to meet with the coöperation of the members and to attract others. In some Branches the arrangements for each meeting are assigned to one of the members of the executive committee; each member then has a definite thing to do and he takes an interest in doing it successfully.

One of the elements in Branch meetings is the benefit resulting from bringing together electrical men from the various interests in which they are engaged for social acquaintance as well as technical discussion. In several cases the members are invited to dine together at a restauran' on the evening of the meeting. This is an especially pleasant oppor-tunity for out-of-town members who may chance to be in the city, as the chairman has found from his own experience.

The INSTITUTE has at present 617 Students. These young men rep-sent over 50 institutions. They pay a nominal fee, which is approximately equal to the cost of the PROCEEDINGS which they receive. The INSTITUTE may congratulate itself in gaining a substantial hold upon these young men and in contributing a substantial influence toward rendering them acceptable members at a later time. The institutions from which the larger enrollment comes are Cornell University, Purdue University, Armour Institute, Iowa State College, Washington University (St. Louis), University of Colorado, University of Missouri, Syracuse University, University of Michigan, Worcester Polytechnic Institute, Pennsylvania State College, University of Arkansas, McGill University, each of which numbers from 102 to 10 students. Schenectady and Pittsburg, the seats of large manufacturing companies, enroll about 30 each.

The appended statistics show the work of the year. The increase in membership is about 18%. The number of meetings does not represent a full year, as some meetings will be held after this report is closed. With few exceptions there have been monthly meetings and in some places meetings are more frequent. The aggregate attendance averages between 1100 and 1200. There is considerable activity in the preparation of new papers.

CHAS. F. SCOTT.
Chairman Local Organization Committee.

ANNUAL REPORT OF STANDARDIZATION COMMITTEE.

TO THE BOARD OF DIRECTORS, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS:

GENTLEMEN: As this Committee was not appointed until the March meeting of the Board of Directors, it is not in a position to make a report upon work done.

It is recognized by the Committee that the previous reports have been very useful and important in crystallizing and standardizing electrical practice. And as electrical progress is not fixed and completed, neither is the possibility for useful work through the Standardization Committee of the INSTITUTE, terminated.

It is the purpose of the present Committee to review the last Report of the Committee, adopted by the INSTITUTE June 20, 1902, making such modifications as may be found desirable; also to complete the work of the Committee during the past two years under the Chairmanship of Professor Ryan, which has not been finally formulated and adopted. It is the purpose, also, to coöperate with the work of similar societies in other countries, notably the Institution of Electrical Engineers and the British Standards Committee. The move toward international standardization received a decided impetus at the International Electrical Congress held in St. Louis in September last; both through the paper of Col. Crompton, reporting the work of the British Standards Committee, and also the action of the Board of Delegates, recommending international coöperation.

The Committee will be glad to receive suggestions either general or specific from the members of the INSTITUTE, which may be addressed to the Secretary.

CHAS. F. SCOTT,
Chairman

ANNUAL REPORT OF THE LAND AND BUILDING FUND COMMITTEE.

TO THE BOARD OF DIRECTORS, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS:

DEAR SIRS: I have the honor to submit the Annual Report of the A.I.E.E. Land and Building Fund Committee.

In the report of the Committee to President B. J. Arnold, dated May 5, 1904, it was shown that the contributions to the Fund to that date were $45 000.

Early in May the Committee sent out its Fourth Announcement, embodying the report of Mr. Chas. F. Scott, Chairman of the Joint Committee of the Union Engineering Building, to the Board of Directors of the INSTITUTE, a full statement of the progress of the work, the character and plans of the Engineering Building, a full list of subscribers, and the amounts subscribed to March 31, 1904. At the same time, an appeal was made by circular to INSTITUTE members asking not only for subscriptions, but also for the valuable aid of their personal offices in securing subscribers.

On May 26, the Committee reported contributions to the amount of $60 000, among the recent subscriptions being $5000 from Thos. A. Edison, and $5000 from Dr. M. I. Pupin, the latter being promised on condition that nine other contributions of like amount were to be made to the Fund.

The Committee then took in hand the careful canvass of the Local Branches of the INSTITUTE with regard to the possibility of arousing local interest in, and securing subscriptions for, the Fund. The officers of the Branches responded enthusiastically, expressing their desire to coöperate actively with the plans of the Committee; and a large number of subscriptions were due to their efforts. In the month of December a regular list of the members of the Local Branches was prepared, and much care was expended on the making of this list. During this month, the Committee wrote special letters to such members of the various Branches as seemed likely to be contributors.

In July, the Committee published its Fifth Announcement, giving the text of the Act for Incorporating the United Engineering Society, the report of the Library of the Union Engineering Building, a statement of the work of the Joint Committee, and a list of subscriptions to June 30, 1904, amounting to $62 752, showing that over 500 members had subscribed, and urging still wider and more effective support.

In July and August, the Committee wrote to every subscriber from whom an instalment was due, and in December similar applications were made, other letters being addressed in the meantime as the respective promises of subscriptions matured. The Committee has also prepared a special list covering over 15 000 of the leading firms and organizations in the electrical field.

The subscription list has now reached $66 534.50, of which $19 301.25 has been placed in the treasury of the INSTITUTE.

The Committee is now looking forward to a vigorous prosecution of its work as soon as the plans of the United Engineering Building are issued and it has reason for the belief that much of the careful labor which has been expended in preparation for a wider range of activity, and in the enthusing of those whose eventual support is hoped for, is now about to bear abundant fruit.

Very truly yours,

CALVIN W. RICE,
Chairman.

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