Presented at the 299th meeting of the American Institute of Electrical Engineers, New York, October 9, 1914.

USE OF REACTANCE WITH SYNCHRONOUS CONVERTERS
AN INSURANCE TO CONTINUITY OF SERVICE AND A PROTECTION TO APPARATUS

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ABSTRACT OF PAPER

The paper presents the results of overload and short-circuit tests made several years ago upon some synchronous converters in circuit with auxiliary reactors.

Two entirely separate sets of tests upon two synchronous converters of widely different operating characteristics are described. In the one case the reactor is in the a-c. circuit and in the other in the d-c. circuit; yet in each it may be called, and in fact is, a protective reactor.

In presenting this original information the author, with a view to indicating its commercial application and hoping to provoke discussion, has endeavored to divide synchronous converter installations in a general way into classes with respect to the need or desirability of employing protective reactance, and also with respect to the general design or type of the reactor to be employed. In order to do this, synchronous converter installations are divided into a few general classes with respect to the character and exactions of the service conditions under which they are required to operate.

The paper was written shortly after the tests were made, but although much has been learned or written about protective reactors since that date, the author believes nothing has transpired to affect the value of these tests or to make it necessary to change the form in which it was originally intended to present them.

SYNCHRONOUS converter installations considered with regard to the relative importance of service and apparatus may be divided into three classes:

1. Installations where it is of prime importance to keep voltage on the lines at all times.

2. Installations where heavy overloads are frequent but where, to protect apparatus and accordingly maintain service, the voltage may be allowed to drop off during the overload.

3. Installations where high momentary overloads are frequent, unattended by appreciable voltage drop, but where brief even though comparatively frequent interruptions to service are not objectionable in order to protect apparatus.

Installations of the first class are found feeding the network of circuits forming the distribution system of a metropolitan lighting and power company. Here the aggregate of power handled is the largest found in any power systems. The generating, transforming and converting stations are of the largest and most highly concentrated. The customers are the most numerous and the most widely distributed. The service required is the most varied in quality and quantity.

In such a system, handling an enormous aggregate of power, there is a large demand for service every hour of the twenty-four, every day in the year. Any failure, of however brief duration, to supply this demand means a great aggregate loss to the customer in money and convenience. In such a system, where immense quantities of power are generated in a concentrated generating station or group of stations, passed out through diverging feeders, transformed and converted in a plurality of substations and finally delivered 24 hours per day through a multiplicity of circuits to the ultimate consumer, the secret of satisfactory service lies in the smooth and orderly working of the various parts of the system. The difficulties in the way of securing uniform operation of such a quantity and variety of apparatus have been overcome only through great engineering skill. The method of operation is carefully prearranged and the various pieces of apparatus are started and stopped according to a schedule so as to make the service continuous. It is a tremendous undertaking to start and place in normal operating condition all the apparatus on the system when once it has been shut down. The utmost perfection of cooperation between men is required. A very severe strain is placed upon the power company's apparatus, while the delay and loss to the consumer incident to interruption is absolutely prohibitive. It becomes, therefore, a matter of necessity to maintain voltage on the customers' circuits at all times.

The direct-current feeders are interconnected at many points. A short circuit or ground on one feeder would trip out the overload breakers at a number of stations and thereby completely remove voltage from a comparatively large section of network. It is, therefore, considered preferable to omit automatic tripping features in the d-c. feeders. A short circuit or ground must, therefore, burn itself free or be eliminated only by some of the a-c. circuit breakers or apparatus letting go. In some of the very largest systems, the current-carrying capacity of the largest feeder is so small compared to the momentary overload capacity of the feeders to which it is tied, and of the apparatus supplying them, that the trouble almost immediately clears itself. The total voltage is available at the scene of trouble. An arc of such magnitude is formed in consuming this voltage that the trouble shortly burns through. The voltage being consumed in the feeder having the fault, the remaining feeders continue supplied with scarcely reduced voltage and the apparatus running from them is scarcely affected. In these systems the trouble clears itself without seriously overloading the substation apparatus. In case the trouble should exist in the immediate vicinity of a substation so that substation would tend to carry the entire trouble, that substation would be saved from damage by the tripping out at the generating station of the a-c. supply feeders. The trouble would then, if it lasted long enough, be thrown on the remaining substations, which would more or less equalize it, and on account of their great capacity would be able to carry it until it cleared itself. There is, accordingly, no need of protective reactance in a substation of this character.

In systems of this general character but of somewhat smaller dimensions the current capacity of the largest feeder bears a less desirable ratio to the overload capacity of the feeders and apparatus supplying it. There are three immediate results:

(a) The trouble does not clear so quickly, as the current at the reduced voltage available at the trouble is not so great.

(b) The voltage on the other feeders falls off appreciably from the normal condition. Lights dim and motors slow down, but, in general, all apparatus continues to operate and a general shutdown does not result. The apparatus on the particular feeder in trouble probably stops owing to the greatly reduced voltage.

(c) Greater momentary overloads are thrown on all the supply apparatus. It is important, therefore, to give the apparatus characteristics such as to enable it to withstand these overloads satisfactorily.

The converting apparatus is usually a synchronous converter, though in some installations motor-generator sets are employed. These motor-generator sets have not the momentary overload kilowatt capacity of the converter. Usually the motor will pull out of step before the generator is dangerously overloaded. The synchronous converter will, in general, carry several times more kilowatt load than the motor-generator set before dropping out of step. It will carry so much overload before failing in this respect that the effect upon commutation must be considered. In the case of a shunt-wound motor-generator set, owing to the poor voltage regulation of the generator, the current which can be commutated before the motor pulls out approaches more nearly the value of current which can be commutated by the converter. Some tests which will be given later on show that it is possible to throw six times normal full load current on some converters before they will flash over. It is obvious, however, that the actual possible limit of the converter is not the limit which must be observed in a commercial case. Assuming, therefore, that the converter will carry 400 per cent normal load current for a time comparable to that required for d-c. line trouble to burn itself free, it remains to equip the converter with auxiliaries which will enable it to escape all load in excess of this amount. There are several ways in which this may be accomplished when it is first known how much the voltage must be reduced.

1. In the case of a booster or split pole converter the voltage can be lowered to the full buck value at any desired overload by means of relays in the d-c. circuit actuating the voltage controlling element of the converter. On account of the time element of the relays and rheostat and the magnetic lag in the iron circuit of the converter this method is probably not quick enough.

2. A resistance short-circuited by a circuit breaker may be placed in the d-c. lead. The breaker would be tripped at some fixed value of current and the resistance placed directly in circuit. Owing to the time element of the ordinary overload circuit breaker this method is probably not quick enough.

3. With reactance placed in the a-c. circuit, a series field can be added to the main poles acting in opposition to the shunt winding, so that the power factor becomes badly lagging on overloads and the reactance produces a drop in voltage. This involves a series field on the converter, and the overload capacity of the converter is further limited by the wattless armature currents caused by the overload current in the series field.

4. A larger amount of permanent reactance may be placed in the a-c. circuit so that, even with a shunt-wound converter and approximately constant power factor, a great drop in voltage will occur at large overloads.

The fundamental objection which has been raised to apply to this last method as well as to the other methods suggested is that, owing to the inertia of the rotating part, the synchronous converter, in common with the direct-current generator, delivers an instantaneous direct current when the resistance of the external d-c. circuit is suddenly reduced, which can not be reduced

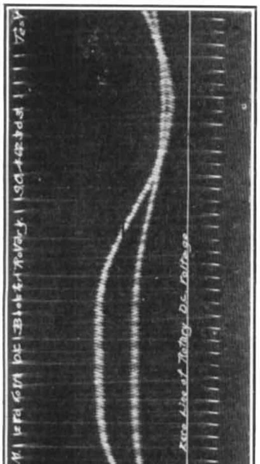

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FIG. 2

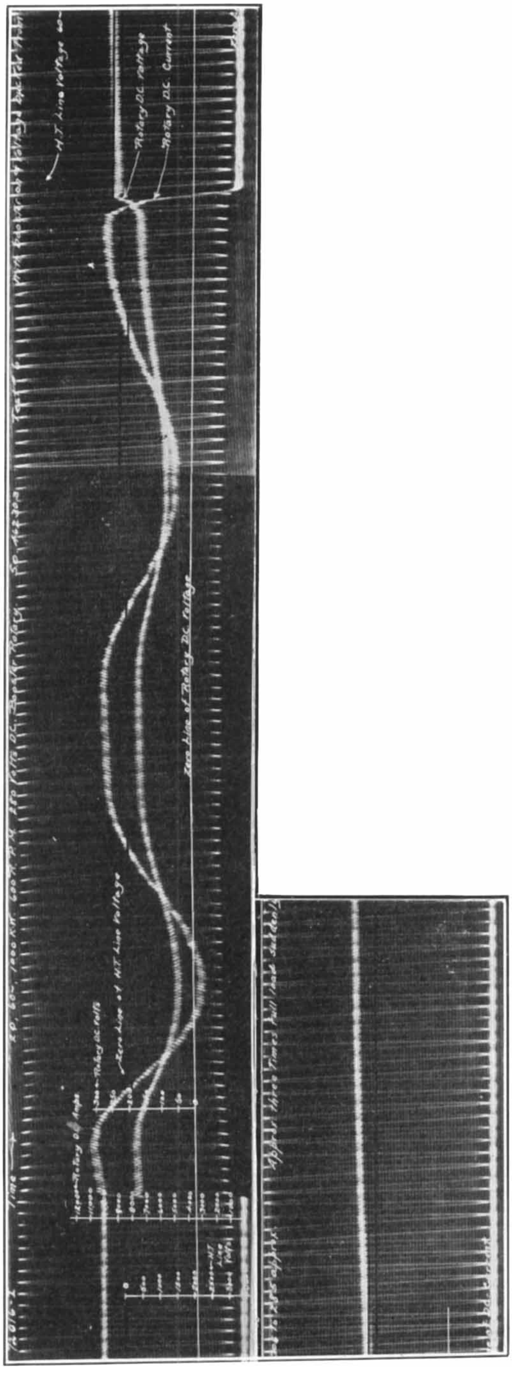

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FIG. 3

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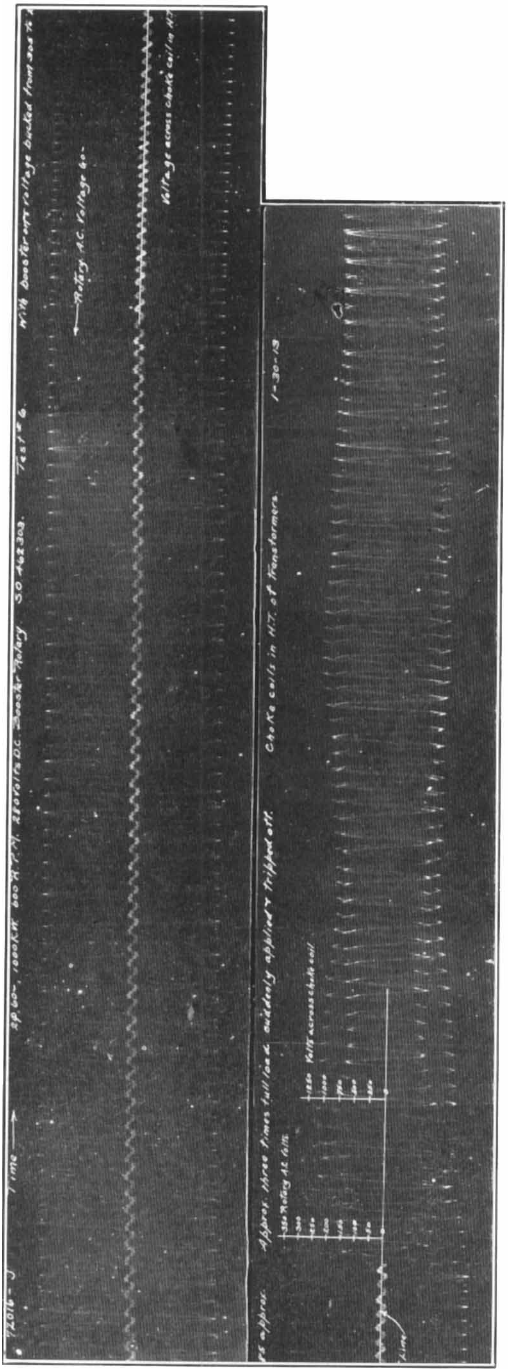

FIG. 4

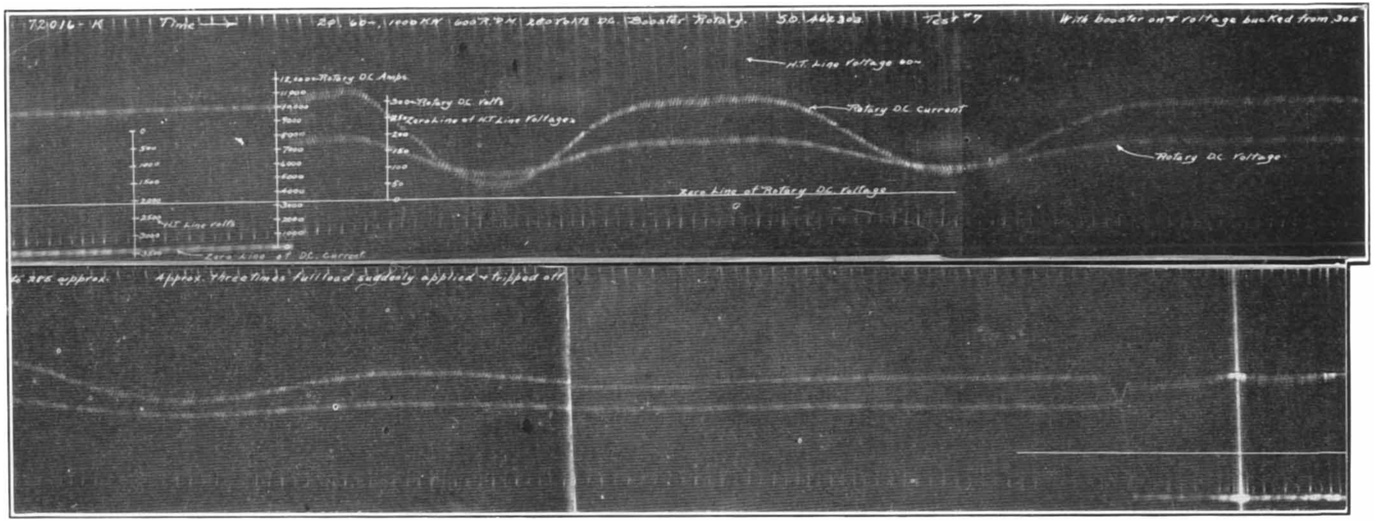

FIG. 5

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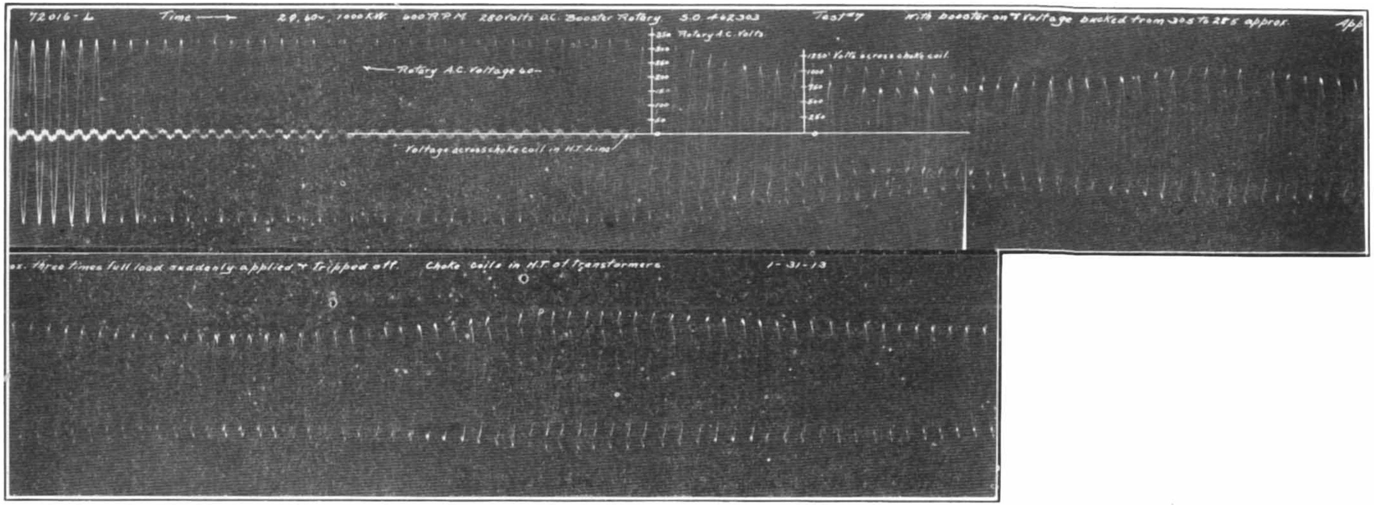

FIG. 6

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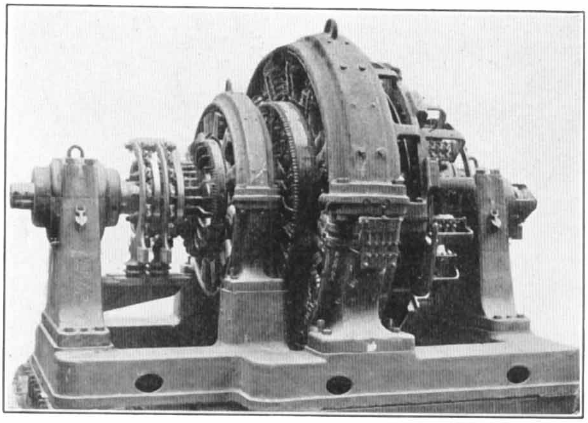

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FIG. 7—280-VOLT, 1000-KW., 60-CYCLE COMMUTATING-POLE SYNCHRONOUS CONVERTER

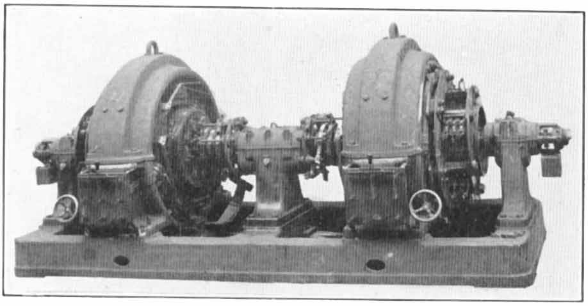

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FIG. 10—TWO 750-VOLT, 60-CYCLE SYNCHRONOUS CONVERTERS CONNECTED IN SERIES

by any of the means suggested and which, particularly in the case of the converter, is likely seriously to affect the commutation.

Without debating this question, it is proposed to state that with a reactor of the air-core or unsaturated type in the a-c. circuit, there is no question but that the voltage drop across the reactor will follow instantaneously and exactly the alternating current variations. It follows that, if the alternating current is at all times approximately proportioned to the direct current, a reactor may be employed in the a-c. circuit to limit the overload current which the converter can deliver.

Assuming a reactor of 30 per cent, the voltage impressed at the collector rings under several conditions of load is shown by the side A in the triangles of Fig. 1. The effect of the varying reactive drop B is to vary the phase angle of the voltage impressed at the collector rings. The converter must therefore be well equipped with dampers so as to follow closely these phase variations. The line voltage is the constant vertical line C.

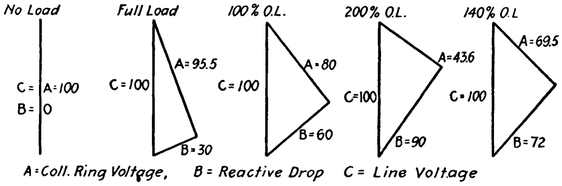

FIG. 1—SYNCHRONOUS CONVERTER—EFFECT OF 3 PER CENT REACTANCE IN THE A-C. SUPPLY CIRCUIT

With these factors in mind, it is proposed to describe some tests which were made to determine the suitability of reactors for such service in connection with a converter under a certain set of known conditions.

A certain 250-volt three-wire Edison system enjoying the enviable record of having maintained voltage on the bus over a long period of years was the subject of this study. Ordinary feeder troubles have drawn the substation bus voltage down to 180 volts or 200 volts. In one or two cases of very severe trouble the bus voltage has been drawn down to approximately 160 volts, that is, to 64 per cent of normal, before the trouble cleared itself without a general shut-down. The amount of reactance required, therefore, for a converter on this system is such as will draw down converter voltage to 64 per cent of normal before the overload exceeds the limits of the converter.

A 250-volt converter was not available, but a 280-volt, 1000-kw., two-phase, 60-cycle, 600-rev. per min. commutating-pole booster converter with voltage range of from 240 to 320 d-c. was available. This converter was wired up to a bank of three-phase-two-phase transformers, in the circuit to which were placed three air-core reactors. The converter was loaded on rack resistors. The load was thrown on by closing a knife switch and was tripped off by means of a d-c. circuit breaker. One element of the oscillograph was arranged to show the voltage of the a-c. supply circuit outside of the reactance coils, for the purpose of showing that to a large degree the reduction of the d-c. voltage came about independently of any reduction in the voltage of the supply circuit. The other two elements of the oscillograph were arranged to show the direct current and voltage, which are the quantities of particular interest in determining the effect of the reactance. There was approximately 30 per cent reactance in the circuit in coils and transformer. There was a drop of not more than 5 per cent in the line voltage; but, due to the reactance and a large resistance drop in the converter, transformers and leads, the converter direct voltage at 8600 amperes output—that is at 2.4 normal load—was reduced 50 per cent, to 140 volts. See Figs. 2, 3 and 5. Figs. 4 and 6 show the record of a second oscillograph. Fig. 4 was taken simultaneously with Fig. 3, and Fig. 6 with Fig. 5. They show the low-tension voltage at the collector rings and the voltage across the reactance coil in the high-tension circuit. Fig. 5 was taken to see if the hunting would dampen out, and the load was held a total of 8 4/5 seconds, which is much longer than the average line trouble takes to clear itself.

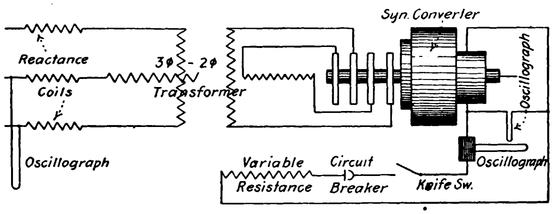

FIG. 8—CONNECTIONS FOR CURRENT-LIMITING REACTANCE

The synchronous converter employed was provided with relatively inefficient dampers, and there was marked hunting at approximately 80 alternations per minute when load was first thrown on, owing to the shift in phase angle of the voltage impressed at the collector rings. There was severe sparking at intervals corresponding to the period of hunting, which practically died out as the hunting ceased. The sparking was not so severe but that the load might very probably have been further increased or the reactance reduced, without exceeding the flashing limitations of the converter even with its ineffective dampers. This hunting and sparking would have been greatly reduced and possibly entirely eliminated if the converter had been provided with a damping winding of better design. There was no appreciable instantaneous d-c. generator effect, as the circuit was closed, which could be separated from the hunting action and the tests were considered by a large number of engineers who witnessed them to show very conclusively the value of reactance used in such an application.

2. The substations on large or medium size interurban railway systems are in the class of installations which are subject to heavy overloads, where it is, in general, satisfactory that the voltage on the lines shall drop off and vary considerably during the overloads in order that the supply apparatus may be protected from injury. The size of the individual piece of converting apparatus is small compared to the capacity of the transmission system of trolley wires and feeders, though it is still large compared to the maximum momentary overload likely to be thrown on it. This is owing to the number of converter substations which will be in parallel and will divide any abnormal overload. In the case of a short circuit or ground on a d-c. feeder, there is great likelihood that the trouble will burn itself free as in the first class of systems, the capacity of a single feeder or trolley wire being small, relative to the size of the whole system.

These systems are large enough to have carefully worked out train schedules and to require close adherence thereto. Uniformity of trolley voltage is therefore an important requisite and the supply apparatus is given a voltage characteristic which continues to rise for all moderate overloads. In many cases compound-wound converters with suitably chosen series field and reactance are employed.

With a shunt-wound converter considerable voltage variation would be experienced unless the a-c. and d-c. reactance and resistance drops should happen to be quite small. With considerable series field and unsaturated reactor, a converter would continue to take on load owing to its approximate straight-line rising voltage characteristics, and some means must be supplied to prevent this load from reaching a value under abnormal conditions which would be injurious to the converter. There are disadvantages in having this protection in the form of a circuit breaker, since such a form of relief simply throws a greater over-load upon the remaining converters on the system when one trips, and a general shut-down may result. It is much preferable to have the converters in each substation protected in such a manner that, in case a short circuit, grounded feeder, or abnormal load due to the bunching of cars occurs at any point of the system, the converters in the immediate vicinity will continue on the line carrying all the overload they are able to carry. By providing a voltage characteristic which will droop before the critical safe overload is reached, the excess load is automatically distributed among the converters elsewhere on the system without actual interruption of service or drop in trolley voltage such as need affect the time schedule. The drooping characteristic on overload is obtained by employing a saturating iron-core reactor. Iron-core reactors have been installed in some of the largest substations in the country to equalize the load between transformer synchronous converter units having different inherent regulation characteristics. The use of them to divide the load between the different substations of a system, and by the voltage drop they produce thus protect the individual substation apparatus from injury, thereby tending to secure continuity of service, is therefore but a wider application of the well-known functions of a well-known piece of apparatus.

3. The substations on small and medium size interurban railway systems are in the third class of installations. One converter supplies a comparatively long section of trolley line on which there are a comparatively small number of cars running at relatively long intervals. The drop in trolley line and feeder to points distant from a substation is considerable. Additional drop in reactance would be objectionable under normal operating conditions. The converter should have a rising voltage characteristic, therefore, to take care of the normal operating conditions. It must, however, have some protection from d-c. short circuits and abnormal overloads, particularly when these occur close to a substation. The overloads have a maximum so much greater than the average load and are, relatively, so infrequent that neither of the two previous methods of protection is best adapted. In this case it is necessary actually to get the converter off the line to prevent damage. The bigger the momentary

overload which can be carried before tripping off, the better, but momentary interruptions are not serious (particularly as in such a system the feeders and trolley wires are usually sectionalized so that a trip out at one substation does not mean an interruption on the whole system) and the converter *must* be protected, at a temporary expense to service if necessary.

There is a limit to the current which any commutating machine will commutate without flashing over. This limit of instantaneous commutating capacity is usually way above the permissible capacity for any appreciable time limited by armature heating. The breaker may then be set considerably above any guaranteed overload value on such a system as we are now discussing, where the overloads, though very great, are very brief. A converter will also usually carry a much greater load momentarily than it will permit to be tripped off without flashing. Now there are certain auxiliaries which will greatly increase the severity of the short circuit to which the converter may be subjected without feeling it. If it is possible to throw overloads of five to six times normal on a converter before it will flash, the auxiliaries must prevent any excess beyond that amount. These auxiliaries consist of a reactor to introduce a time element in the rise of current when the short circuit is established, and a quick-acting circuit breaker. These two must be proportioned so that the trouble will be cleared before the current has reached a value which the converter can not safely commutate nor stand being tripped off. The reactance must be of the air core or unsaturated type and the breaker must necessarily be quite different from the ordinary d-c. carbon circuit breaker which has a very appreciable time element.

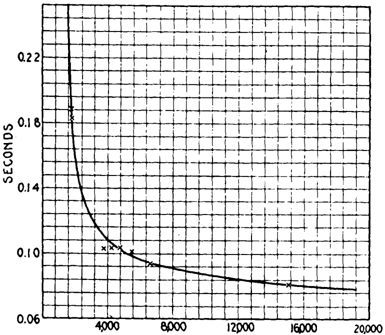

FIG. 9—TIME OF OPENING OF 1600-AMPERE, 600-VOLT CIRCUIT BREAKER

The ordinary carbon type d-c. circuit breaker has a time element which would require a prohibitive amount of reactance. Curve Fig. 9 gives the time element of an ordinary circuit breaker of 1600 amperes capacity. This gives the time for the mechanical operation only. Figs. 12-15 show the time taken by such a breaker to open the circuit.

The high-speed circuit interrupter as developed by Messrs. Fortescue and Mahoney consists essentially of an ordinary single-pole breaker, the parts of which are accelerated by means of a heavy steel spring. After the spring has ceased accelerating the momentum of the moving parts is gradually absorbed by means of a dash pot, so that the mechanism is not injured by sudden stopping. The breaker is provided with magnetic blowouts and a special condenser-operated tripping device, the moving parts of which are designed to have a minimum of friction and moment of inertia.

The operation of the tripping device depends upon well known characteristics of a direct-current circuit, as follows: Under steady conditions of load the only resistance offered to the flow of current is the ohmic resistance of the conductor. If the circuit were absolutely non-inductive, current changes due to change of resistance would take place at an infinite rate, but due to the fact that inductance is always present in any circuit, the current takes an appreciable time to reach a definite value. This is due to the e.m.f. set up by the inductance which is proportional to the rate of change of the current, and is in opposition to the impressed e.m.f. of the circuit. Thus if I_0 be the current in a circuit whose resistance is R_0, if the resistance of the circuit be suddenly changed to R_1, the e.m.f. of self-induction must be equal at the instant of change to $I_0 (R_0 - R_1)$. The back e.m.f. of self-induction is therefore in a measure proportional to the severity of the short circuit. If a condenser connected in series with an electromagnet be shunted across the circuit, when the sudden overload or short circuit takes place there will be a drop in the e. m. f. across the condenser due to the inductance of the lines between the source of e. m. f. and the point at which the condenser and magnet are connected, proportional to $I_0 (R_0 - R_1)$, and the condenser will discharge through the magnet. By using a proper value of capacity the magnet may be made to operate at any required value of this back e. m. f. provided that R_1 be not greater than a certain value which depends on the line constants of the circuit and the periodicity of the condenser and magnet. Should R_1 be greater than this value the trip will not operate because it requires an appreciable time for the energy set free from the condenser to be transformed into mechanical energy in the magnet, and when R_1 is large the back e.m.f. lasts for a very short period. The tripping action is thus not only dependent upon the rate of change of the current but also on the final value of the resistance. It may therefore be depended on to open the circuit only when the final value of the current would be such as to endanger the circuit.

For slowly varying currents, such as those due to the ordinary overloads, the regular overload tripping arrangement must be included in the breaker, as the condenser trip fails to operate under these conditions.

In case the current increases at such a rate that the ultimate value when the circuit breaker opens will be such as to endanger the circuit, additional inductance may be introduced in the circuit between the source of e.m.f. and the point at which the tripping gear is connected.

A series of tests was made to determine how severe a short circuit a synchronous converter would stand without flashing when protected by this quick-acting breaker and suitable operating reactance. The converter shown in Fig. 10 was used. This is a 1500-volt, 60-cycle set consisting of two 750-volt converters mounted on a common bed plate and connected electrically in series. The armatures are mechanically separate, though a single bearing housing is used between them. The set is rated at 600 kw., 1500 volts, or 500 kw., 1250 volts, that is, it has a full-load current of 400 amperes. It is three-phase, with a speed of 1200 rev. per min. The oscillograms are marked 400 kw. though the machine will meet the higher ratings without exceeding standard temperature guarantees. The connections for test were made as per Fig. 11.

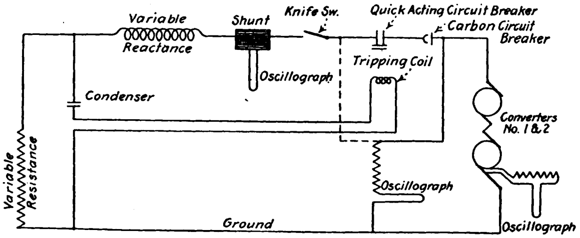

FIG. 11—SYNCHRONOUS CONVERTER WITH QUICK-ACTING BREAKER AND REACTANCE

The oscillograms are shown in Figs. 12 to 22, Fig. 22 simply giving the time for Figs. 12 to 21. It shows a 25-cycle wave taken with the film run at the same speed, and is of no other value. The d-c. circuit of the converter was closed by means of a knife switch as shown in Fig. 11, the load consisting of resistance which could be varied in amount. The reactor, of air-core type, was so constructed that its reactance could be varied by placing the sections in series or parallel.

In the first tests, as shown by Figs. 12 to 15, the quick-acting circuit breaker was omitted and the circuit was opened non-automatically by means of the carbon circuit breaker after a period long enough to determine whether the load itself would immediately result in flashing. For Figs. 12 to 14 one element of the oscillograph was connected as indicated by dotted lines, to show the voltage across the resistor and choke coil. It will be observed from Fig. 12 that approximately 2100 amperes or 525 per cent normal load current was thrown on and tripped off this converter without flash-over. Figs. 13 and 14 show duplicate tests under heavier short-circuit conditions. The direct current rose to a steady value of 2600 amperes and the converter flashed when the circuit was tripped. Fig. 15 shows test under the same conditions except that the voltage element of the oscillograph was changed to the full line position in Fig. 11 so as to give the machine voltage. In these tests the final direct current was, of course, limited only by the total resistance in the d-c. circuit, although the effect of the reactor in retarding the rise and fall of the current is very noticeable from the films.

For the tests shown by Figs. 16 to 21, the quick-acting breaker was in circuit. The object of the reactor in connection with this breaker was to so affect the rate of increase of current that the breaker would be able to trip out before the current reached such a value as to cause flashing. Fig. 16 shows a test under the same short-circuit conditions as Fig. 15. Figs. 17 and 18 are with reduced resistance in the short-circuit path. As shown by Fig. 19, the resistance was then reduced to approximately 0.1 ohm. The quick-acting circuit breaker started to open the circuit and then arced across the terminals and short-circuited, so that the current—3500 amperes—was practically the same as though the quick-acting breaker had not opened at all. The quick-acting breaker was simply an experimental breaker and did not have the proper insulating clearances which would be given a commercial breaker to meet such conditions. The converter of course flashed over, as would be expected, when the circuit was finally tripped by hand. The next test, as shown by Fig. 20, was made with no resistance except that of the cables and the reactance coil, which later amounted to 0.23 ohm, in the external circuit. The impedance was increased to 13 ohms. The

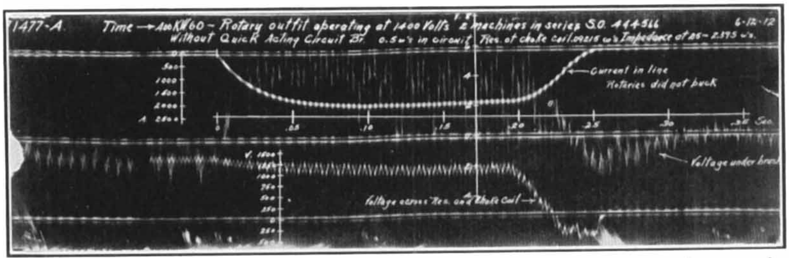

FIG. 12 [YARDLEY]

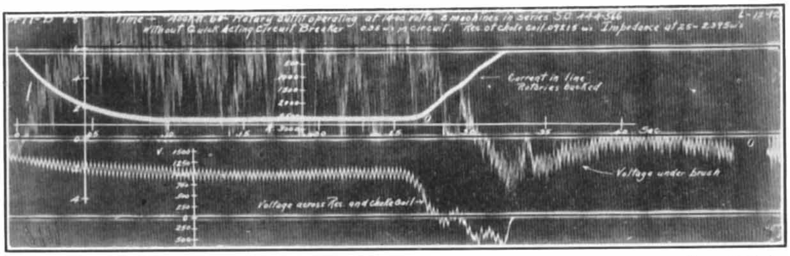

FIG. 13 [YARDLEY]

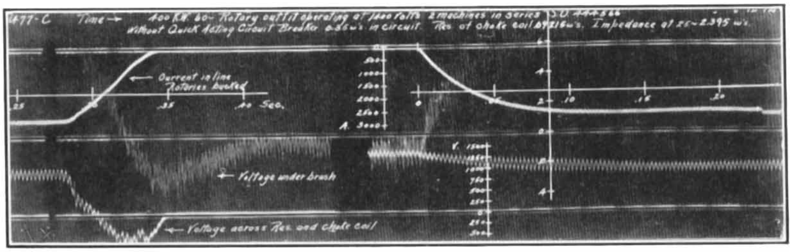

FIG. 14 [YARDLEY]

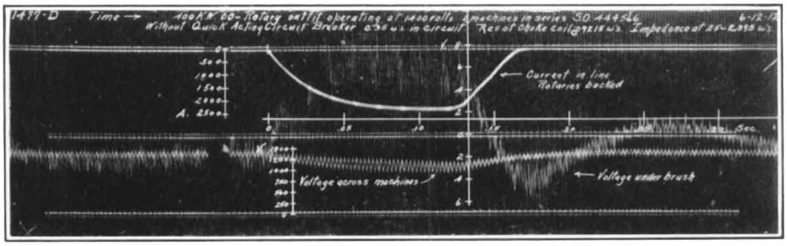

FIG. 15 [YARDLEY]

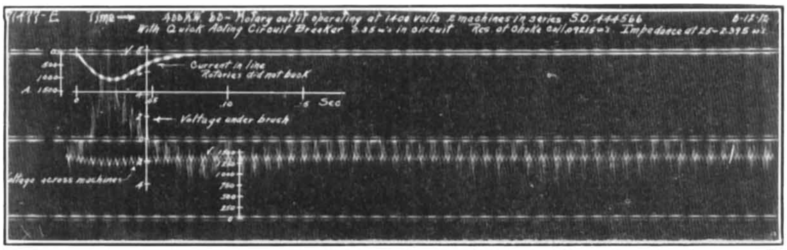

FIG. 16 [YARDLEY]

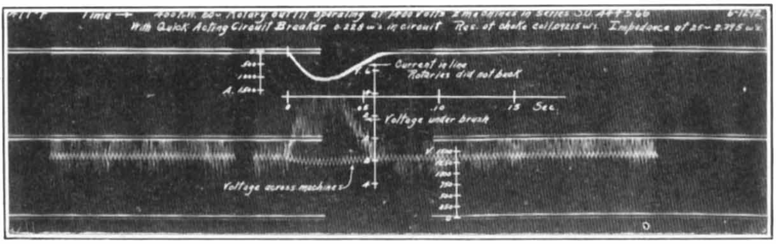

FIG. 17 [YARDLEY]

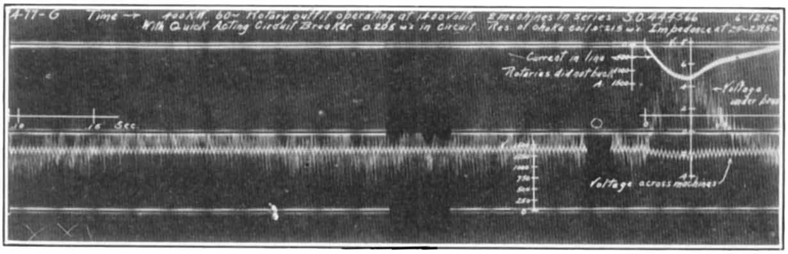

FIG. 18 [YARDLEY]

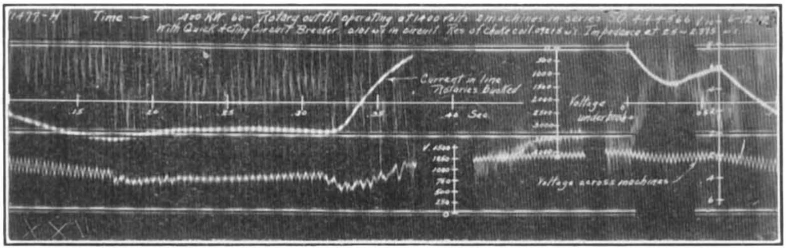

FIG. 19 [YARDLEY]

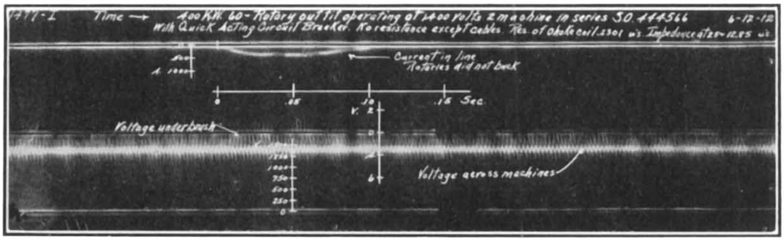

FIG. 20 [YARDLEY]

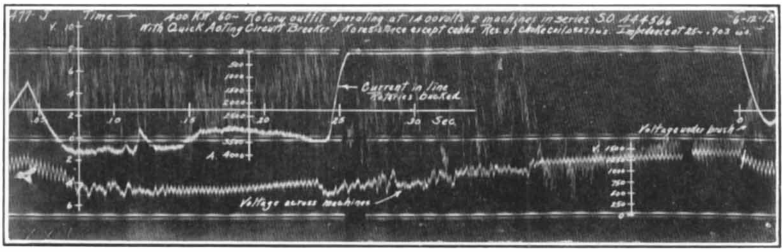

FIG. 21 [YARDLEY]

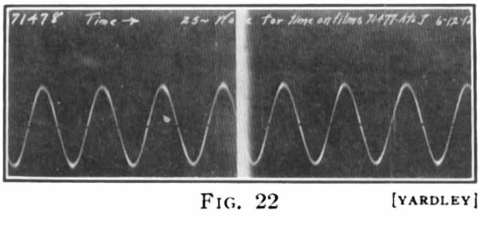

FIG. 22 [YARDLEY]

last test, as shown by Fig. 21, was made with the choke coil resistance of 0.05473 ohm and the cable resistance only in the external circuit and the impedance reduced to 0.903 ohm. This test was made for the purpose of showing how quickly the current would rise under such a short-circuit condition. The breaker opened as in Fig. 19 but arced across terminals and short-circuited, causing a final flow of current of 3900 amperes. It is interesting to note that the converter carried this 975 per cent current load at approximately 700 volts without flash-over, although it of course at once flashed over when the load was tripped off.

These tests are described to establish the fact that, if a properly designed quick-acting circuit breaker be used, and the proper amount of reactance be placed in the d-c. circuit, it is impossible to flash a converter over, as the circuit breaker will trip out the circuit before the current approaches the tripping out flash-over value. As shown by Figs. 12 and 13, this flash-over value for this particular converter is somewhere between 2100 and 2600 amperes. It is interesting to mention that as far as this particular converter is concerned there is scarcely need of such protection under the particular test conditions. The tests were made one right after the other and whenever the converter flashed over the commutator and brushes were so slightly burned that it was unnecessary to do any work on them between tests.