Protection from Flashing for Direct-current Apparatus

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The equipment developed for the protection of direct-current apparatus as described in this article is applicable to all direct-current apparatus and all methods of operation. Special means of protection for use only with particular apparatus or conditions of operation have not been mentioned. The principal steps in the experimental development of high-speed circuit breakers and flash barriers are briefly given. The protection afforded by the high-speed breaker or barriers is sufficient for most apparatus and service, but *complete* protection for *any* direct-current apparatus and service requires both the high-speed breaker and flash barriers. Attention is directed to the importance of arranging the connections to the brush rigging so that the magnetic action on the arc will be a minimum and properly directed, so the flash will do the least damage. This article was presented as a paper at the Thirty-fourth Annual Convention of the A.I.E.E., Atlantic City, N.J., June 28, 1918.—Editor.

The problem of protection from flashing has for many years confronted engineers who build and operate direct-current machines. Numerous schemes and suggestions have been put forward which it was hoped would overcome the tendency to flashover on extra heavy overloads or short circuits. Some time ago it was felt that the subject of prevention and protection from flashing had not received the study and investigation justified by the trouble experienced, and it was decided to make a comprehensive study of the entire subject.

Some form of barrier has been the most common protection suggested, and different forms have been tried with a slight degree of success on some machines and absolute failure on others. It was the opinion of many engineers that barriers could not be designed to take care of a short circuit and that their value was doubtful. However, a special form of barrier, which gives the required protection, will be described later.

It was realized that the means for prevention of flashing at the commutator and brushes of direct-current machines must operate to remove the cause very quickly. The use of some form of high-speed device, which would open the circuit or insert resistance before the short-circuit current could reach a value which would cause flashing, seemed the most logical way to solve the problem, although it was appreciated that the action of the device must be much more rapid than any commercial circuit-opening device previously produced. An investigation was conducted along these lines and two distinct types of high-speed breakers developed, which will be described separately.

A flash at the commutator starts from excessive sparking. Sparking is produced by the breaking of current in the coils short-circuited by the brush as each segment of the commutator passes from under the brush. As the coil is inductive, the spark or arc tends to hold and, if the arc is of sufficient volume,

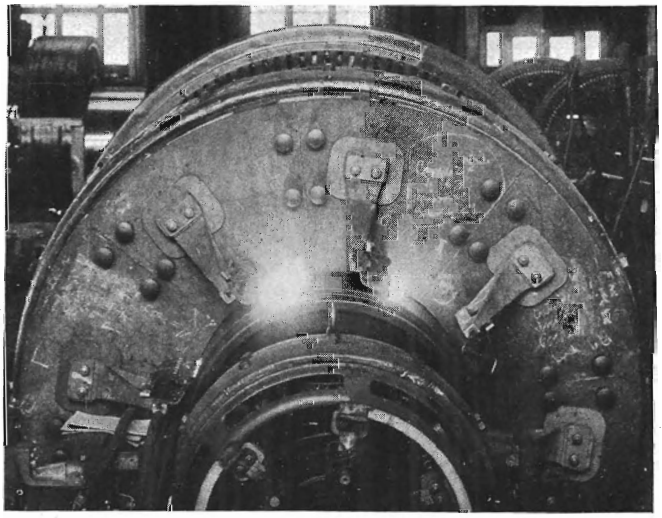

Fig. 1. Flashing at Brushes on 1000-kw., 1500-volt Generator Forming Part of 2000-kw., 3000-volt Motor-generator Set at Five Times Load, Showing Different Stages of Arc Formation

the vapor produced thereby forms a low resistance path between segments and from brush to brush or to frame, through which a large current may pass. See Figs. 1 and 2.

Sparking may be prevented by providing a magnetic field of proper strength and distribution to influence the coils during reversal of their current as they pass through short circuit by the brushes. To provide the correct commutating field for all conditions

Fig. 2. High-speed Photograph of Flashing on 300-kw., 600-volt, 25-cycle Synchronous Converter with Short Circuit on 0.015 Ohms Additional in the External Circuit and Standard Circuit Breaker

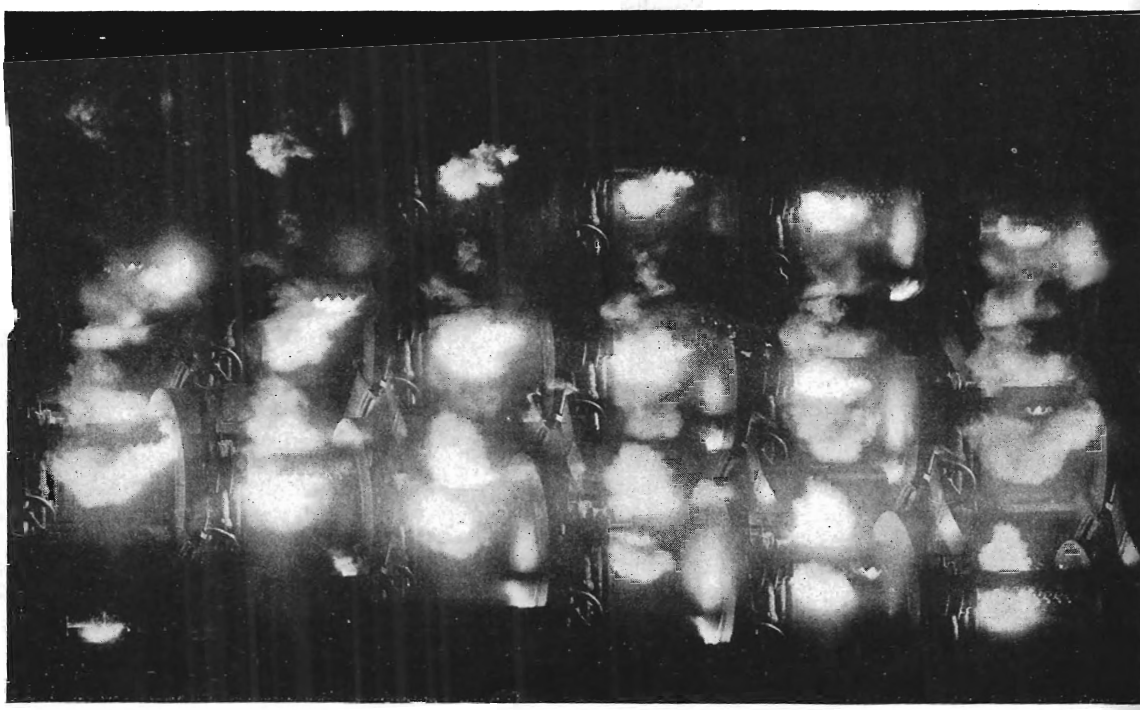

Fig. 3. High-speed Photograph of Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter with Standard Circuit Breaker

of load has been the object of designers but success has been only partial. At high loads, saturation of magnetic circuits and distorting influence prevent attainment of the desired field, and for sudden changes in load the changes in field cannot be properly synchronized. It is more difficult to avoid sparking with rapidly varying loads than with gradually changing or steady load, but if a sudden load which would cause flashing is of short enough duration, the arcing at brushes may not produce enough conducting vapor to establish an arc supported by the main voltage. *The value of load that causes flashing when applied suddenly (short circuit) is a function of the time required to throw it off.* The quicker the circuit is opened the higher the value of current that will not cause arcing.

With the ordinary circuit breaker which begins to open in about 0.15 second, there is a certain maximum load which cannot be exceeded for each commutating machine without causing flashing. If feeders have sufficient resistance to limit the short-circuit current to this critical value, flashing will occur only on the rare occasion of a short circuit in a feeder itself. See Fig. 3. It has been the standard practice of nearly all manufacturers to recommend tapping the feeders, especially railway feeders, at a sufficient distance from the substation to insure enough resistance in the circuit to limit current in case of short circuit near the station.

Inductance may be added to the circuit to retard the rate of increase of current on short circuit to such an extent that the ordinary breaker will have time to trip before the current in the machine reaches a value that would cause flashing. The amount of inductance required to delay the rise in current sufficiently, however, introduces other disadvantages which make its use undesirable. When the current is interrupted, the increase in voltage from inductive "kick" is difficult for circuit breakers to handle and introduces the possibility of applying dangerous voltage stresses to the apparatus.

Reactors have been tried in a few instances with some success, but it has always been a mooted question whether the resistance of the reactor did not give as much or more protection than the inductance of the coil, and if this is the case resistance only would be much cheaper to install. A coil to give the delay required is usually very large and expensive and occupies much valuable space, giving a total cost out of proportion to the cost of the machines protected or the protection obtained.

With special high-speed circuit-opening devices operating in about 0.005 second, the more sensitive machines, such as 60-cycle synchronous converters for railway voltages, may be short-circuited without flashing over, even though the maximum current is of higher value than would cause flashing with suddenly applied load and ordinary circuit-breaker protection.

The speed at which a circuit breaker must operate to prevent flashing depends on the amount of load thrown on the machine but, under worst conditions, our tests seem to confirm that it must be *quicker* than one half cycle of the machine to be protected. The time of operation of the breaker would be measured between the time that the current reaches the flashing value to the time that the current is again reduced to the same value after the breaker opens. If the arc formed between two segments is not blown out as they pass from one set of brushes to the next, and all following segments have similar arcs formed between them, the arc would completely bridge between positive and negative brushes in one-half cycle, which would complete the flashover. Complete flashover might also occur from gases being blown by windage, magnetically, or by expansion, to increase or decrease the half cycle time.

The time of operation of circuit breakers as given herein is measured from the beginning of short circuit to the instant the breaker begins to reduce the current rise.

Investigation covering these several schemes of protection was made, which it is believed will be of interest and will be described briefly with oscillograms, reproductions from photographs, etc., showing behavior under different loads and short-circuit conditions.

All short-circuit tests were made by connecting positive and negative terminals with a 500,000 circular mil cable; the only equipment in the circuit being the necessary current shunt for the oscillograph, a contactor to close the circuit, and a circuit breaker for overload protection, in addition to the protective device being investigated. Power for the 300-kilowatt, 25-cycle, and 500-kilowatt, 60-cycle, 600-volt synchronous converters, used in fuse, barrier, reactor, and high-speed circuit breaker tests, was supplied from a 6000-kilowatt frequency changer set only a few feet from the test, so that there was very little drop in the voltage of the

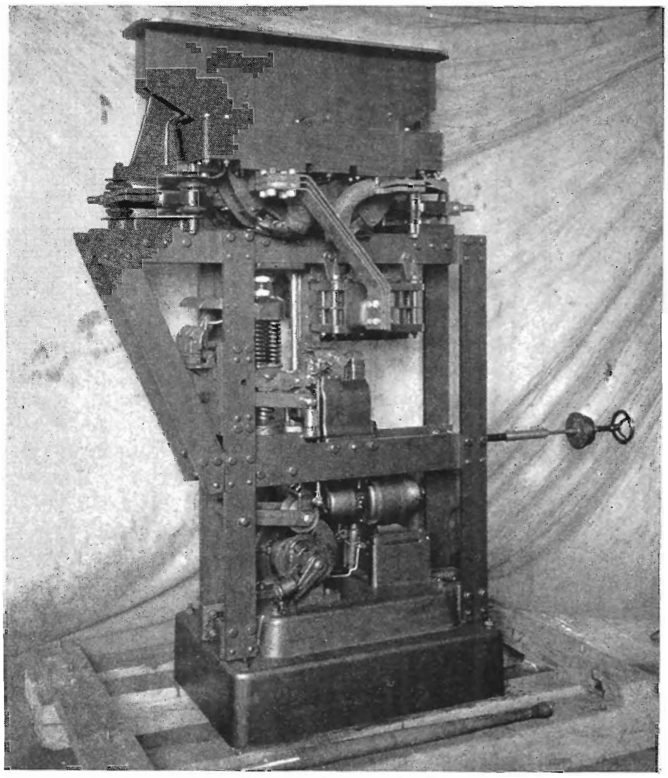

Fig. 4. 3000-ampere, 3600-volt, Direct-current, High-speed Circuit Breaker

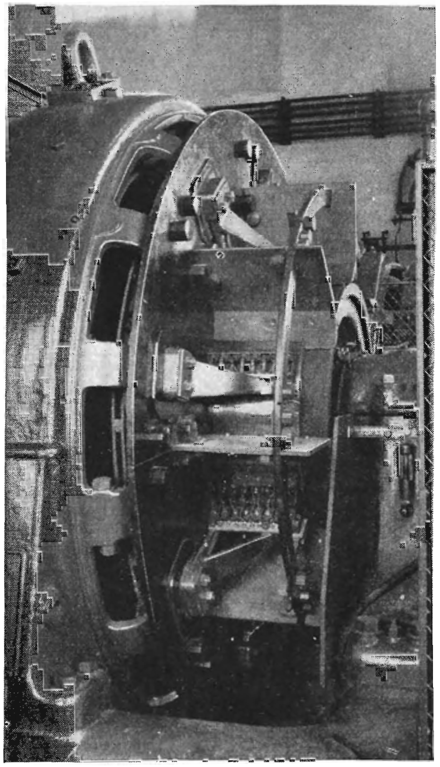

Fig. 5. Type of Flash Barrier Installed on 2000-kw., 3000-volt Synchronous Motor-generator Set Used in Connection with High-speed Circuit Breaker

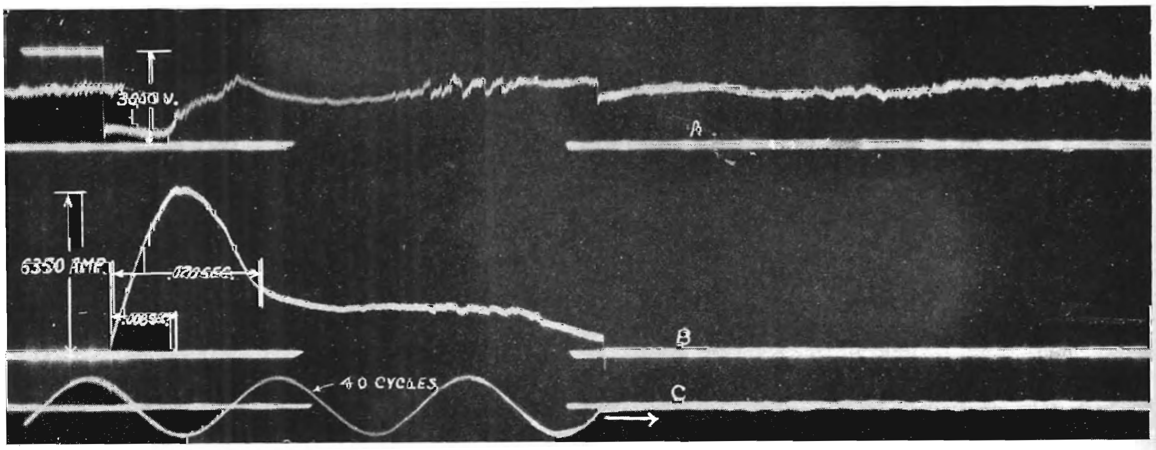

Fig. 6. Direct-current Short Circuit on 2000-kw., 3000-volt, Motor-generator Set with High-speed Circuit Breaker and Standard 3000-volt Switchboard Type Circuit Breaker

generator or from resistance, and the oil switch was set so that it did not trip out.

High-speed Circuit Breaker

At the time this development was started it was felt that if a circuit breaker could be designed to operate *within* the time required for a commutator bar to pass from one brush to another; that is, within one half cycle, protection would be afforded against practically any short circuit. Designs were therefore begun on a circuit breaker which would open within 0.007 second, which would cover most commercial machines, i.e., for 60 cycles and lower fequency.

High-speed breakers had been suggested and attempts made to produce such devices previous to this time but, as far as the writers know, had never been made to obtain as high speed as the discussion shows would be necessary.

Different types of construction were studied and samples of several preliminary models constructed without obtaining the speed desired. One of the most promising types of construction considered consisted of a knurled flywheel operating continuously with a knurled cam, so designed and located that a current relay would insert a wedge between the wheel and the cam and trip a breaker attached to the cam by suitable toggle mechanism. This preliminary sample indicated that 0.035 second was the best speed that could be attained.

It was then decided to concentrate all energies on a circuit breaker using the well-known principle of a latch, heavy spring and series tripping coil, and the high-speed breaker shown in Fig. 4 was finally built.

The problem was to obtain very quick tripping, rapid acceleration of contacts and a sufficient number of ampere turns in the magnetic blowout to insure rapid breaking of the arc. Previous ideas of design had to be abandoned when working for such high speed, when a loss of 0.001 second meant a very serious increase in time of operation.

It was found that a series blowout coil had to be used, as sufficient time could not be allowed for the building up of a field after the contacts opened as is ordinarily done in circuit-breaker design, and the strength of this coil must be many times that usually used to rupture the circuit by giving the quick start and acceleration to the arc necessary for the speed desired. The breaker in question has a total of about 150,000 ampere turns at the maximum current obtained.

The moving parts must all be as light as possible, consistent with the great strength required, so that they can be started, accelerated, and stopped in a very short space of time and distance. Even with this type of construction, it was found necessary to use somewhat high spring pressure; the spring being compressed to about 8000 pounds when the breaker was closed and ready for tripping.

A very special latch with very small tripping movement was designed somewhat similar to the hair trigger on a rifle, in connection with a special high-speed tripping coil so that about 0.001-inch movement of the plunger would trip the breaker. It will assist in appreciating the speed attained when it is noted that the breaker must be arranged so that it will not trip under ordinary load condition and must be set above the tripping point of the regular substation breaker so that it will act while the current is increasing from say three and one half times load to eight times load; current rising at the rate of about 1,000,000 amperes per second. Fig. 6 gives a very good idea of speed and limiting of current, from which it will be seen that the breaker starts to insert resistance in about 0.008 second and the load on the machine is reduced well below the flashing value in 0.02 second after the short circuit was applied.

A breaker was tested very exhaustively in connection with a 2000-kilowatt, 3000-volt, direct-current synchronous motor-generator set shown in Fig. 9, built for the Chicago, Milwaukee & St. Paul electrification, and found to give complete protection from damage or burning on short circuit when equipped with barriers shown in Fig. 5.

In connection with the test, it was found that even the speed of 0.008 second obtained would not completely protect machines from flashing on the most severe short circuit, and barriers shown were designed and installed. Tests referred to with high-speed breakers were taken with these barriers, which will be described later.

It is evident that it is preferable in case of short circuit to insert resistance by a high-speed breaker to quickly limit the current to some conservative value and then open the circuit. This type of protection has been adopted as standard. All tests, investigations, etc., were based on this theory, although some tests were taken by opening the circuit. It was found that there was a greater tendency for machine to flash if the circuit was opened completely at one time or if too high resist-

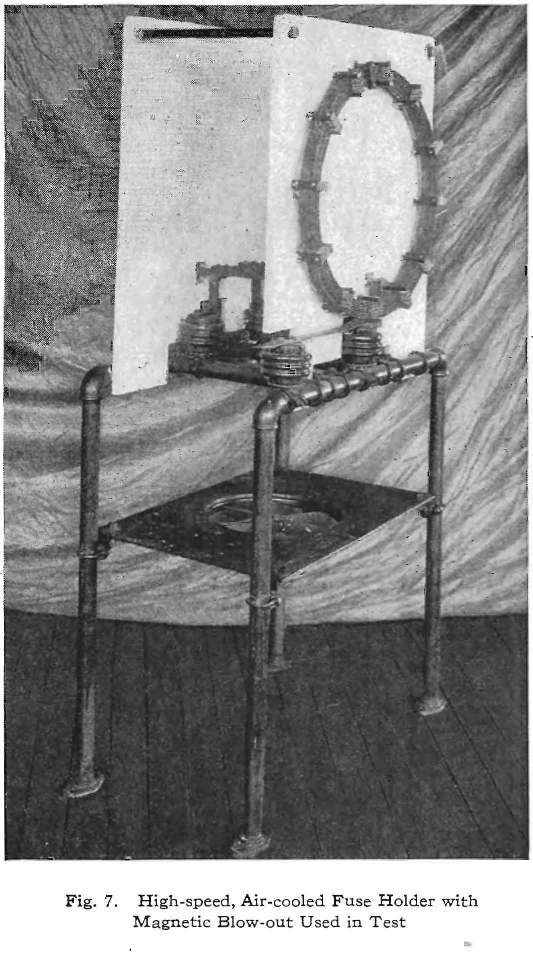

Fig. 7. High-speed, Air-cooled Fuse Holder with Magnetic Blow-out Used in Test

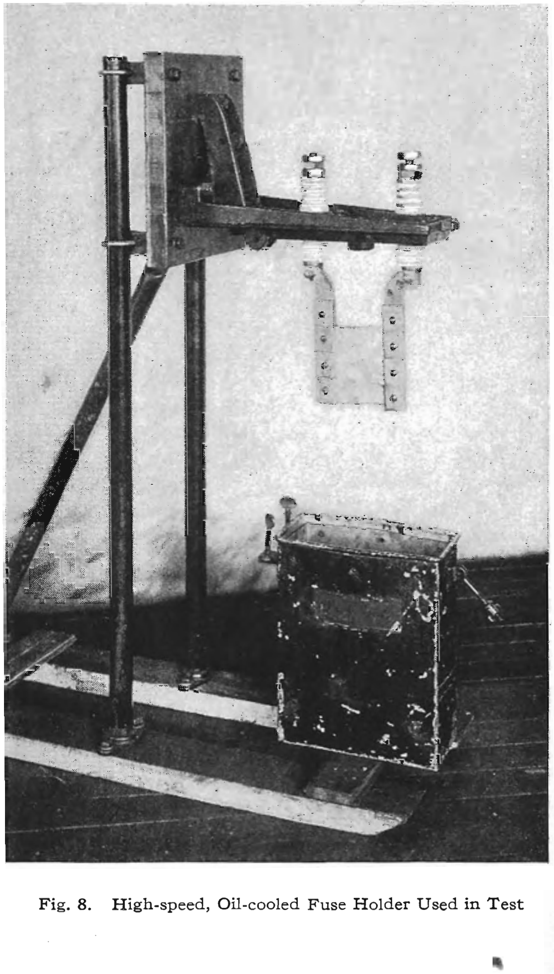

Fig. 8. High-speed, Oil-cooled Fuse Holder Used in Test

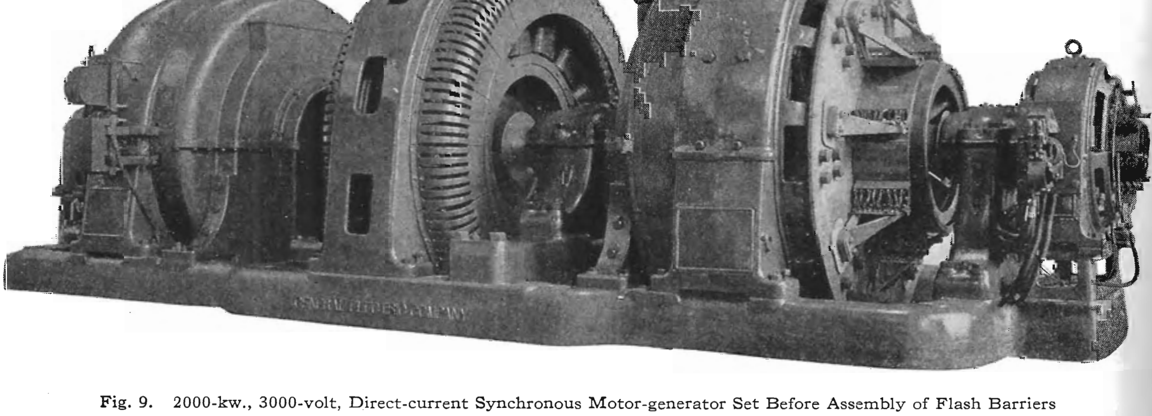

Fig. 9. 2000-kw., 3000-volt, Direct-current Synchronous Motor-generator Set Before Assembly of Flash Barriers

ance was inserted, reducing the load to too low a value. For the sake of convenience and comparison, all tests were made throwing short circuit on the machine without load.

Some of these breakers have been in service since early in 1917 in the substations of the Chicago, Milwaukee & St. Paul Railroad and have amply justified the faith of the railroad company and the designers, as they protect the apparatus from all short circuits experienced, although all feeders are tapped directly to the overhead trolley system immediately at the substation.

One of these breakers is installed in each of the substations connected between the negative bus of the station and the ground or return circuit, as this location gives maximum protection, and one breaker can be used for each machine or one for the entire substation, as shown in Fig. 10.

High-speed Fuse

It is evident that if a fuse could be developed that would melt at a very small increment of current above normal rating, it might be possible to obtain a speed which would limit the current on a short circuit along the same line as the high-speed circuit breaker just described.

A careful study of all available metals was made by Mr. P. E. Hosegood, who suggested using a silver fuse, and a number of silver fuses of different shapes were tried in the special fuse holders shown in Figs. 7 and 8. The oscillograph record, taken with air brake fuse and magnetic blow-out, shown in Fig. 11, indicates that a very high speed is obtained, giving excellent protection and duplicating almost exactly the speed of the high-speed circuit breaker. It was found that a short circuit could be thrown on the 300-kilowatt, 25-cycle, 600-volt synchronous converter without flashing over and with very little sparking at the brushes. The oil-immersed fuse holder without magnetic blow-out gave practically the same result, Fig. 12, the operation being slightly better as far as speed was concerned but the mechanical difficulties of replacing the fuse, etc., being greater.

Reactors

Oscillograph records of short circuit on the 300-kilowatt, 25-cycle, 600-volt synchronous converter show an average initial current rise of about 1,300,000 amperes per second. To protect by reactance, the amount required would depend on the rate of circuit-breaker action. With coils made of 1000 feet of 500,000 circular mil cable, wound on cable reels having an inductance of approximately 0.02 henry in circuit, this particular machine could be short-circuited without flashing when protected by a breaker opening in about 0.15 second.

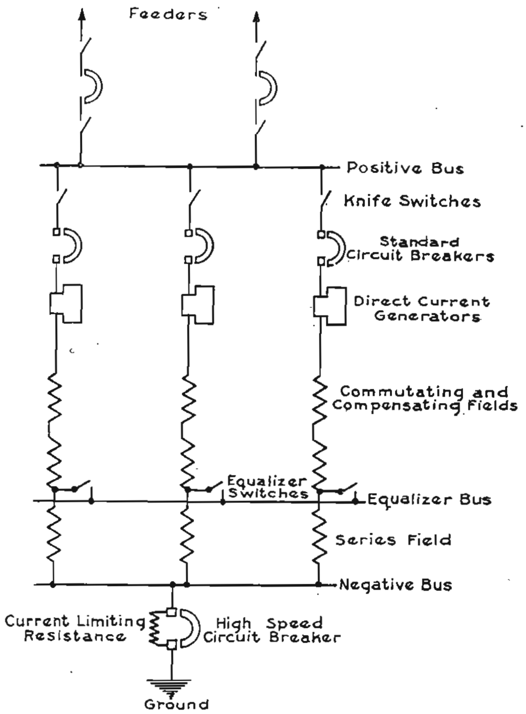

Fig. 10. Diagram of Direct-current Connections for Substation Equipped with Three Motor-generator Sets Protected by One High-speed Circuit Breaker Connected Across Limiting Resistance

An examination of records, Figs. 13 and 14, will show the severe duty on the circuit breaker and increase in voltage on the apparatus.

It was suggested that shunting the reactor by resistance might reduce duty on the circuit breaker. The coils were shunted by 14 and by 100 ohms and it was impossible to determine from either observation or oscillograph any effect due to the resistance.

The effect of an iron core in a reactor having an inductance of 0.00105 henry is shown in Fig. 15, from which it will be noted that the iron saturated at about 1000 amperes in about 0.007 seconds, after which the current rises abruptly, being limited only by the inductance of the coil as if there were no iron in its magnetic circuit. The delay of about 0.007 second, due to the presence of iron in the coil, is far less than the time required for the usual breakers, now in use, to open. The

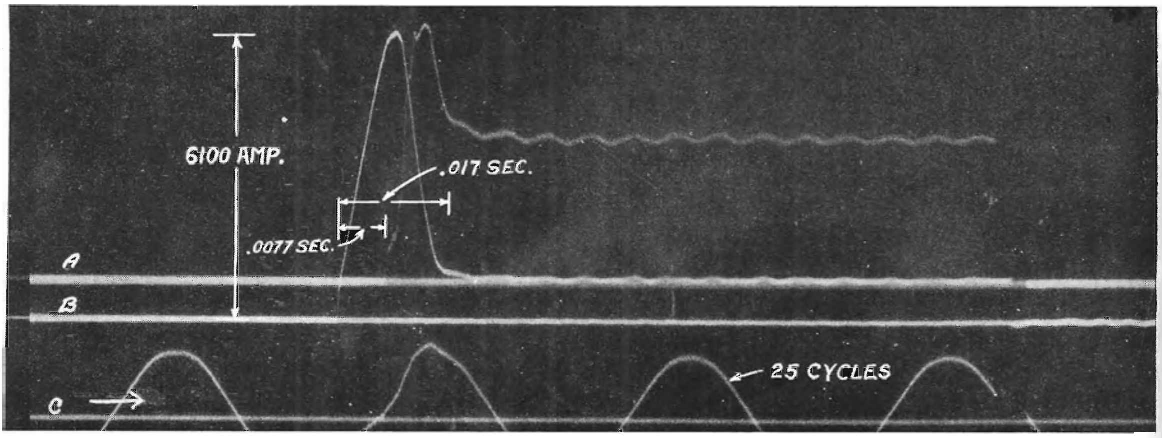

Fig. 11. Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Protected by Air-cooled, High-speed Fuse. Curve *A*, voltage across fuse; Curve *B*, line current; Curve *C*, collector-ring voltage

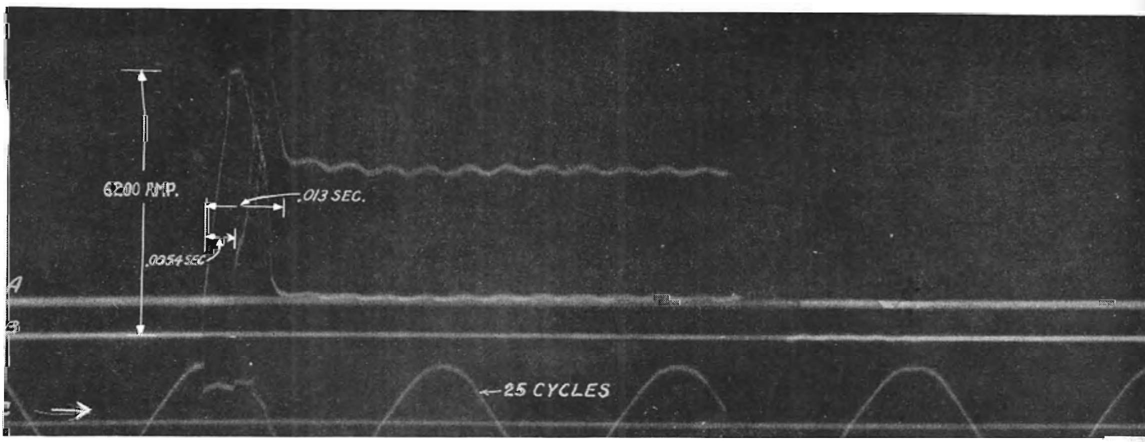

Fig. 12. Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Protected by Oil-cooled, High-speed Fuse. Curve *A*, voltage across fuse; Curve *B*, line current; Curve *C*, collector-ring voltage

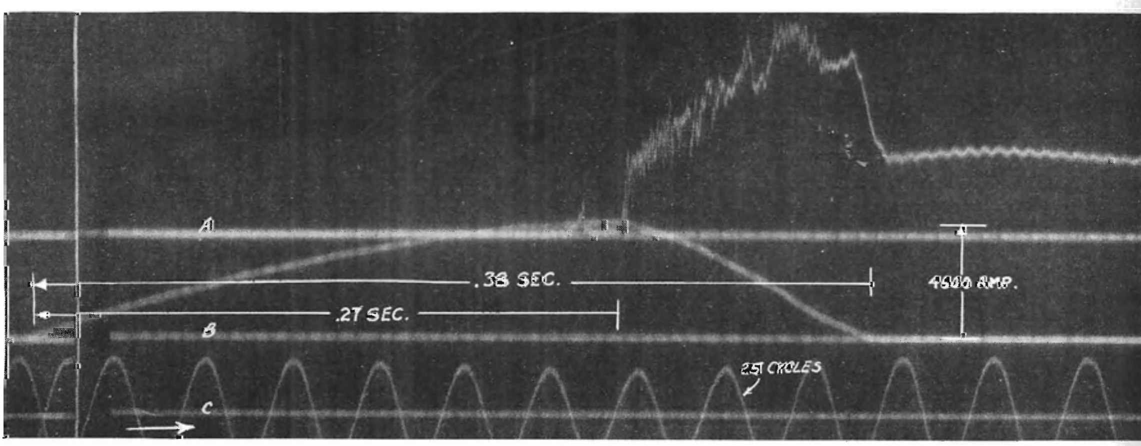

Fig. 13. Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Protected by Air-core Reactor in Direct-current Circuit and Standard Circuit Breaker. Curve *A*, voltage across circuit breaker; Curve *B*, line current; Curve *C*, collector-ring voltage

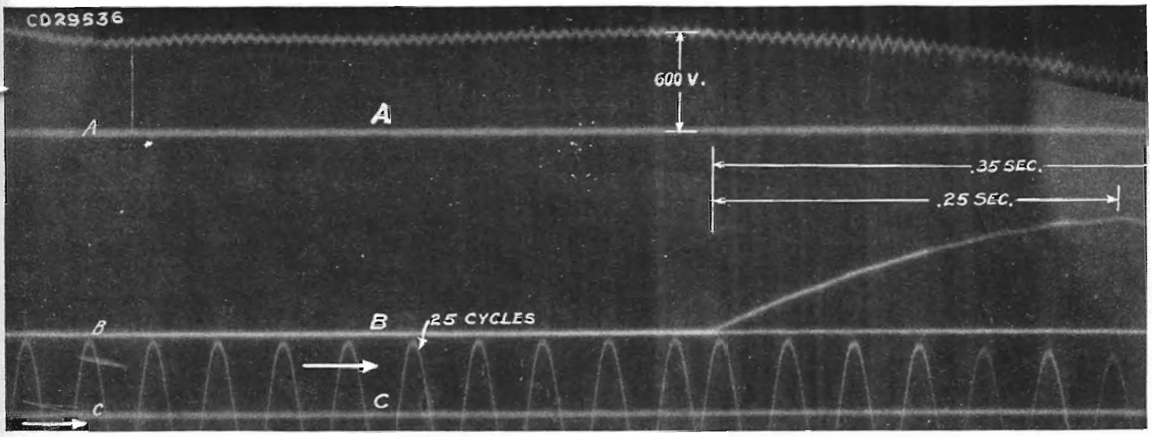

Fig. 14. Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Protected by Air-core Reactor in Direct-current Circuit and Standard Circuit Breaker; Curve *A*, voltage across armature; Curve *B*, line current; Curve *C*, collector-ring voltage

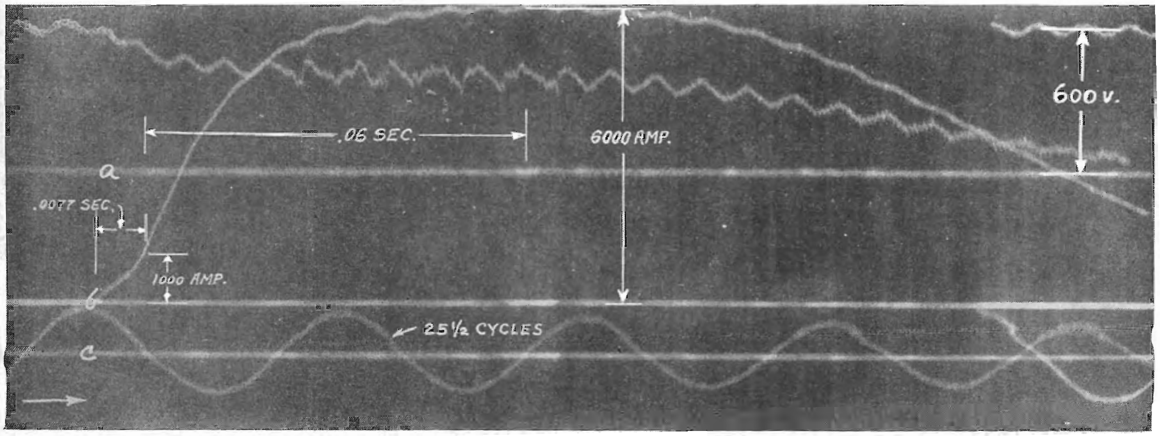

Fig. 15. Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter, Protected by Iron-core Reactor in Direct-current Circuit and Standard Circuit Breaker. Curve *A*, voltage across the armature, Curve *B*, line current; Curve *C*, collector-ring voltage

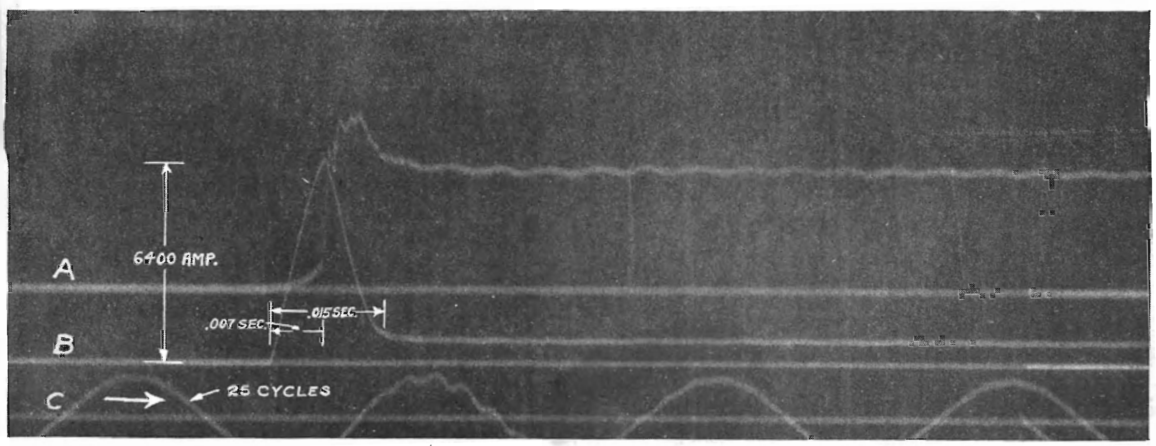

Fig. 16. Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Protected by Second Form of High-speed Circuit Breaker. Curve *A*, voltage across circuit breaker; Curve *B*, line current; Curve *C*, collector-ring voltage

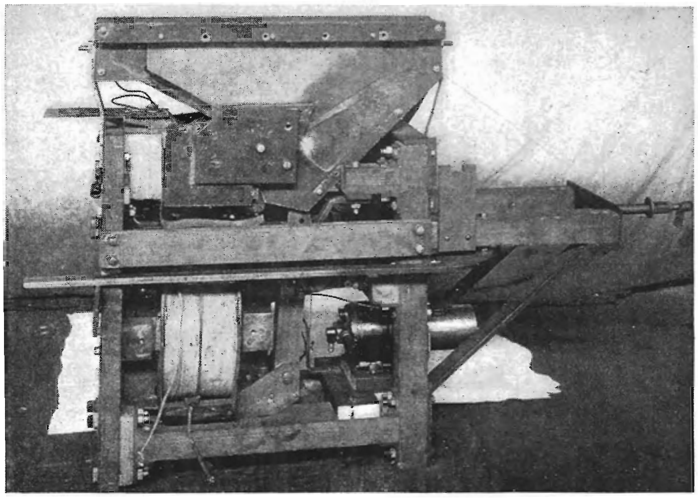

Fig. 17. Second Form of High-speed Circuit Breaker, Capacity 1500 Amperes, 600 Volts

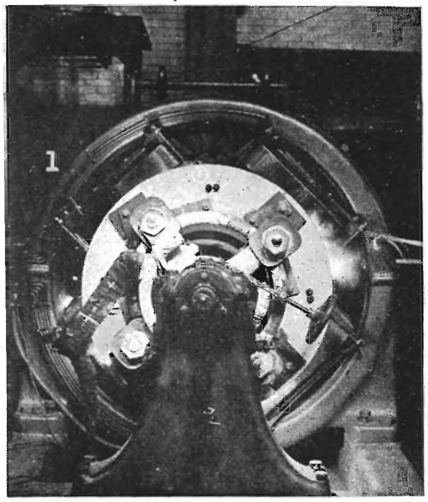

Fig. 18. Short Circuit on 300-kw., 25-cycle, 600-volt Synchronous Converter Protected by Flash Barriers and Standard Circuit Breaker

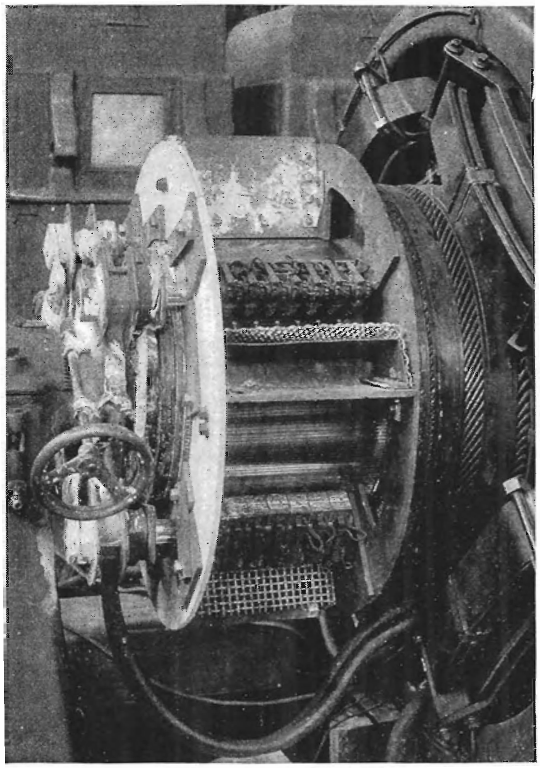

Fig. 19. Final Development of Flash Barriers on 300-kw., 25-cycle, 600-volt Synchronous Converter

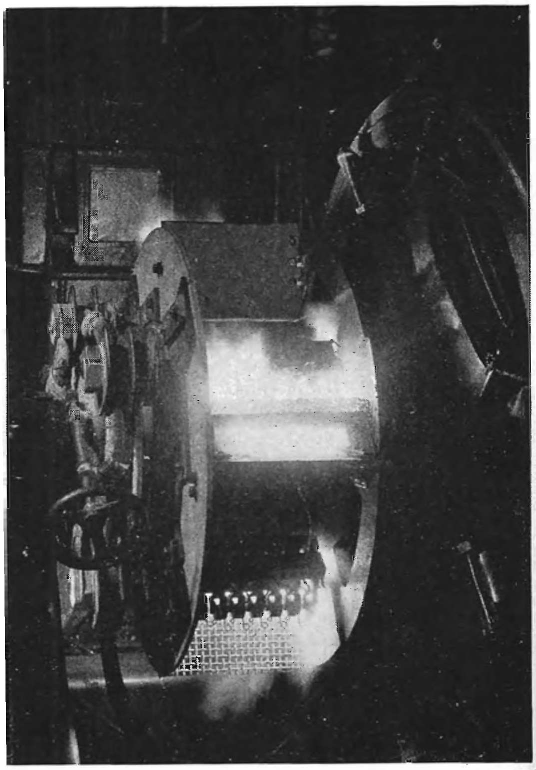

Fig. 20. Short Circuit on 300-kw., 25-cycle, 600-volt Synchronous Converter Protected by Flash Barriers and Standard Circuit Breaker

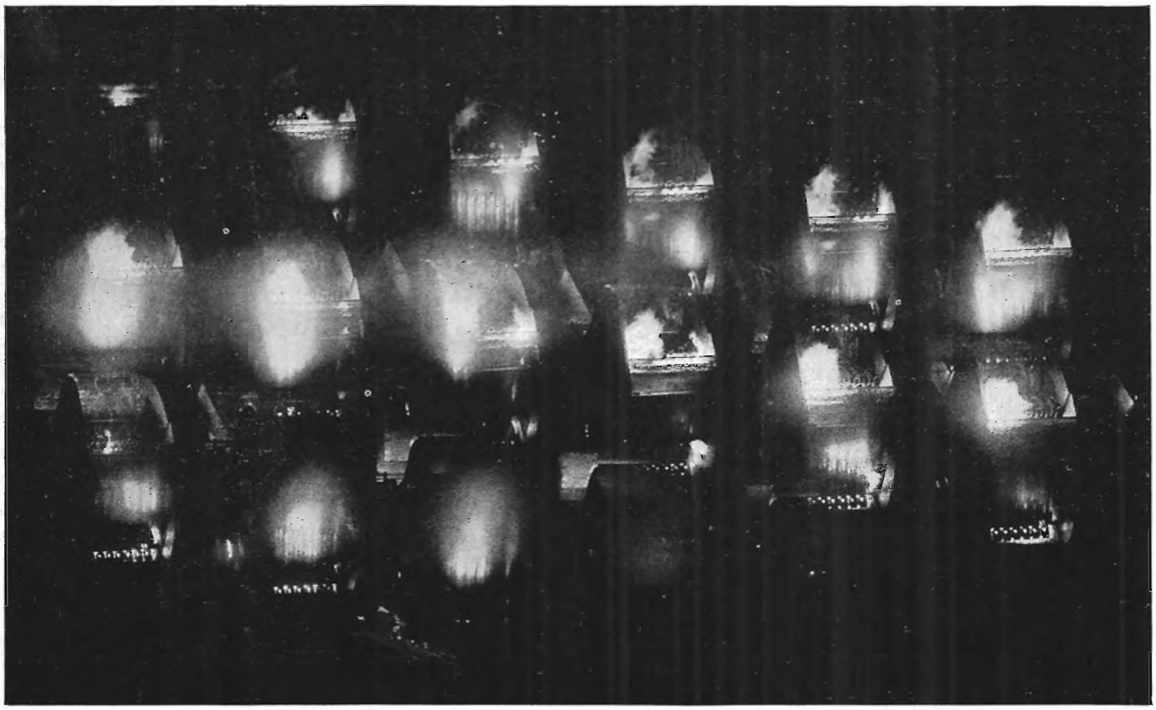

Fig. 21. High-speed Photograph of Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Protected by Flash Barriers and Standard Breaker

Fig. 22. High-speed Photograph of Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Protected by Flash Barriers and Standard Circuit Breakers

weight of this reactor was 7 per cent of the weight of the synchronous converter, and would have to be many times larger to give protection with an ordinary breaker.

Second Form of High-speed Circuit Breaker

Mr. J. F. Tritle has more recently suggested a design for a high-speed circuit breaker which is simple and substantial in construction. This device was built as shown in Fig. 17 and test indicated that the speed was even faster than the large breaker previously described, as will be seen by comparing oscillograms, Fig. 6, on the large breaker, and Fig. 16 taken with the later breaker. This device is essentially a contactor having a laminated structure with electric holding coil and series bucking coil so that it opens when the load current reaches a value sufficient to offset the ampere turns of the holding coil. Tests on the 300-kilowatt, 25-cycle synchronous converter with this device show that a short circuit could be thrown on the machine without any tendency of the machine to flash over, and the only sparking obtained extended not over one-half inch from the brushes. Similar tests, Fig. 23, on the 60-cycle, 500-kilowatt synchronous converter showed more sparking and, although it protected the machine at times on short circuit, there were other times when the machine flashed over. When the machine was equipped with barriers, dead short circuit could be thrown on with impunity, there being no tendency to flash over and scarcely sufficient sparking to be noticeable.

This later type of high-speed breaker is a part of the more recent equipment being furnished the Chicago, Milwaukee & St. Paul Railway.

Barriers

The barriers shown in Fig. 5 in connection with the description of the high-speed circuit breaker were developed to delay time of flashover, so that the breaker would give complete protection. Such satisfactory and promising results were obtained without the breaker that it was decided to continue investigation to ascertain if it would be possible to devise barriers that would take care of all short circuits experienced in actual service.

Under certain conditions it might be desirable to supplement rather than replace appliances already installed or to protect from disturbances other than direct-current load which cause flashing. For instance, a synchronous converter could not be protected by a high-speed, direct-current circuit breaker if flashing is caused by alternating-current phase displacement. For this reason additional protection, such as barriers, to dissipate the arc when started was also needed.

Many different forms of barriers were tried on the 300-kilowatt, 25-cycle, 600-volt synchronous converter, previously mentioned. With increasing success as improvements were made to meet failures, the barriers shown in Fig. 19 were evolved. These barriers gave complete protection from flashover or damage on short circuit. Fig. 20 shows machine on short circuit giving a good idea of flashing and protection afforded, while Fig. 21 shows clearly the small amount of flash which extends beyond the barrier.

About 65 short circuits were thrown on the 300-kilowatt, 600-volt, 25-cycle machine without burning of brushes, brush connections or rigging, or damages of any kind to commutator or machine. Oscillogram, Fig. 26, shows a record of current reaching 34 times full load and gives a good idea of the protection afforded. Many of these short circuits were applied at very short intervals, even as close as one minute apart, without failure to hold and extinguish the arc when the breaker opened the circuit.

Figs. 21 and 22 are very interesting high-speed pictures of the same short circuit analyzed by means of a special high-speed camera devised by Lieut. Chester Lichtenberg, and the successful high-speed pictures we are able to show in this paper are mainly due to his efforts. This camera made it possible to obtain as high as 24 complete pictures of one short circuit, while the best results it was possible to obtain with a motion-picture camera were two under-exposed and therefore indistinct pictures.

A little explanation is necessary to read these photographs as, due to the construction of the camera, the lower right-hand picture is the first picture of the short circuit; the next picture being the one immediately to the left, and so on to the end of the plate; the first picture at the right of the next row being the next picture in the same order and until the end of the plate and the number of rows of pictures. These pictures show very clearly the growth of the arc, disposition on commutator, and dissipation of the arc as the regular breaker opens. These permanent records eliminated the personal factors of memory and observation and showed the way for changes to give improvements in barriers. Fig. 29 illustrates very clearly what happens if the machine is short-circuited without protection.

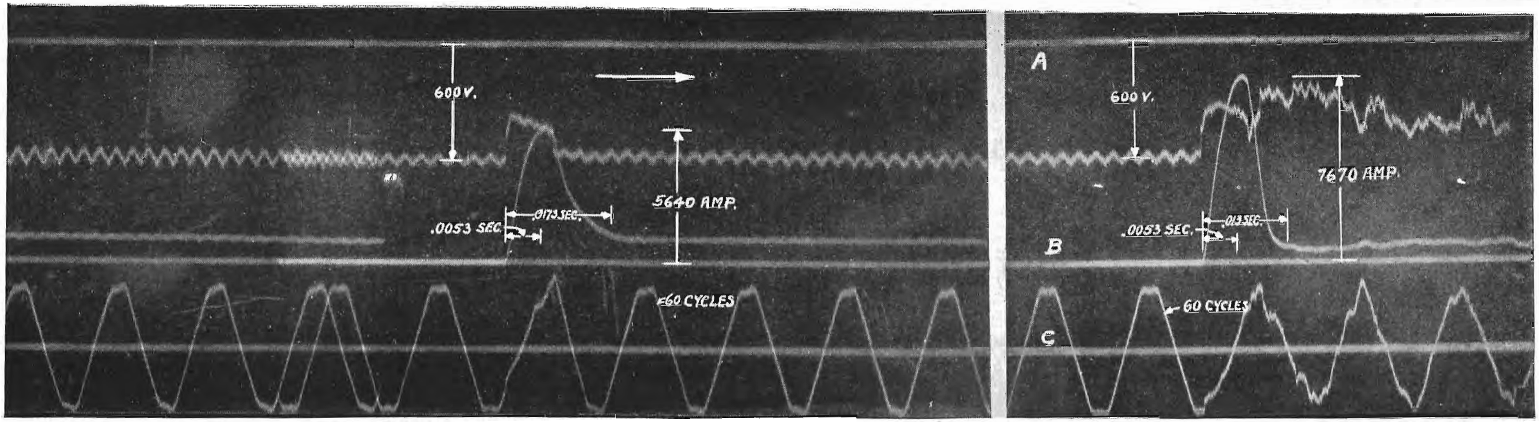

Fig. 23. Short Circuit on 500-kw., 600-volt, 60-cycle Synchronous Converter Protected by Second Form of High-speed Circuit Breaker

Left-hand curves
Load of 0.03 ohms

Right-hand curves
Short circuit

Curve *A*, armature volts   Curve *B*, line current   Curve *C*, collector-ring voltage

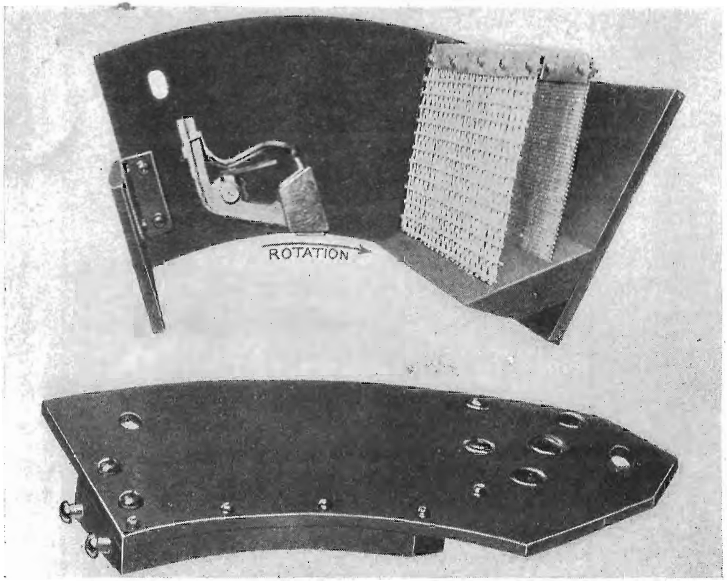

Fig. 24. Flash Barrier with Front Removed to Show Location and Construction of Arc Scoop and Wire-mesh Arc Coolers

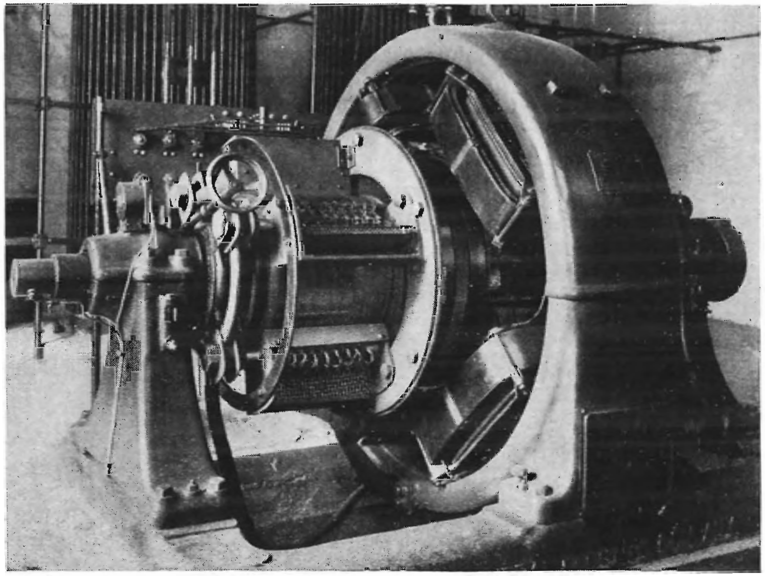

Fig. 25. 500-kw., 25-cycle, 600-volt Synchronous Converter, Installed in Automatic Substation, Equipped with Commercial Form of Flash Barrier

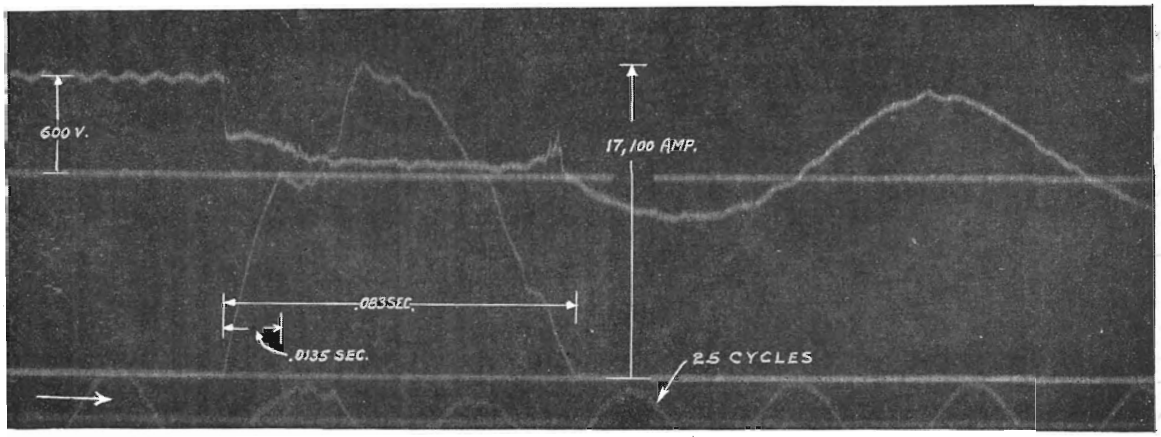

Fig. 26. Short Circuit on 300-kw., 600-volt, 25-cycle Synchronous Converter Equipped with Flash Barriers and Standard Circuit Breaker. Curve *A*, armature volts; Curve *B*, line current; Curve *C*, collector-ring voltage

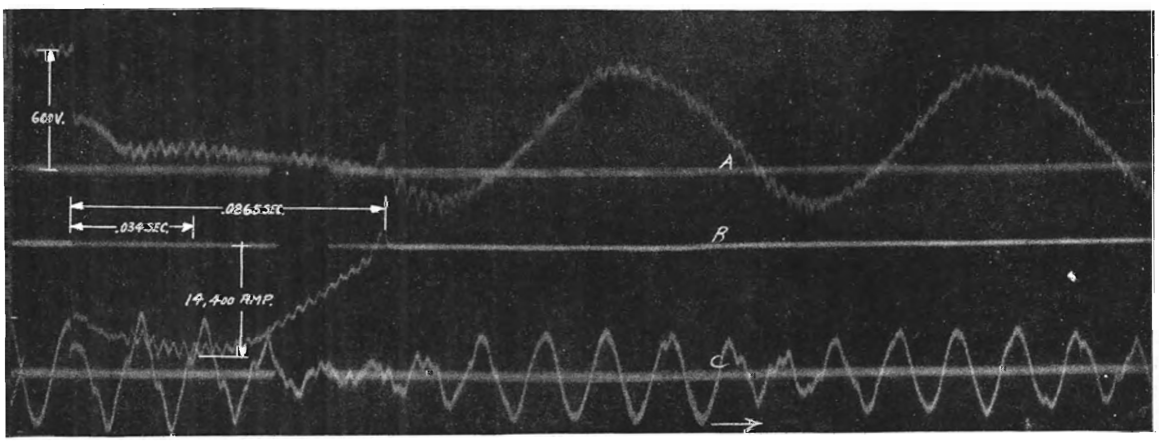

Fig. 27. Short Circuit on 500-kw., 600-volt, 60-cycle Synchronous Converter Protected by Flash Barriers and Standard Circuit Breaker after Arrangement of Brush Rigging had been Changed

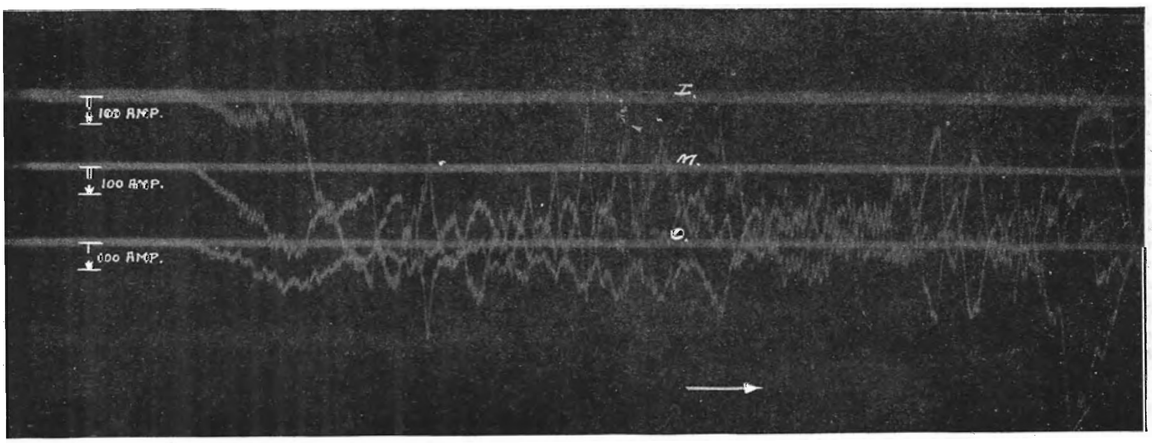

Fig. 28. Short Circuit on 50-kw., 600-volt Generator. Curve *O*, current in outside brush; Curve *M* current in middle brush; Curve *I*, current in inside brush

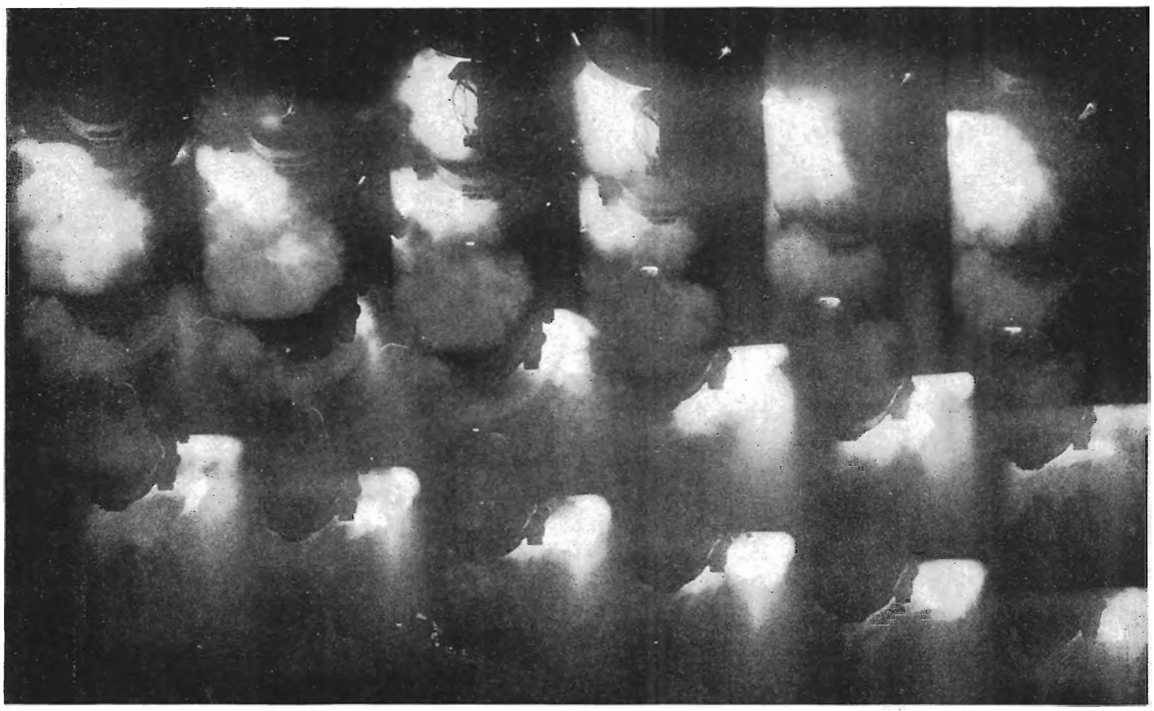

Fig. 29. High-speed Photograph of Short Circuit on 500-kw., 600-volt, 60-cycle Synchronous Converter Without Protection

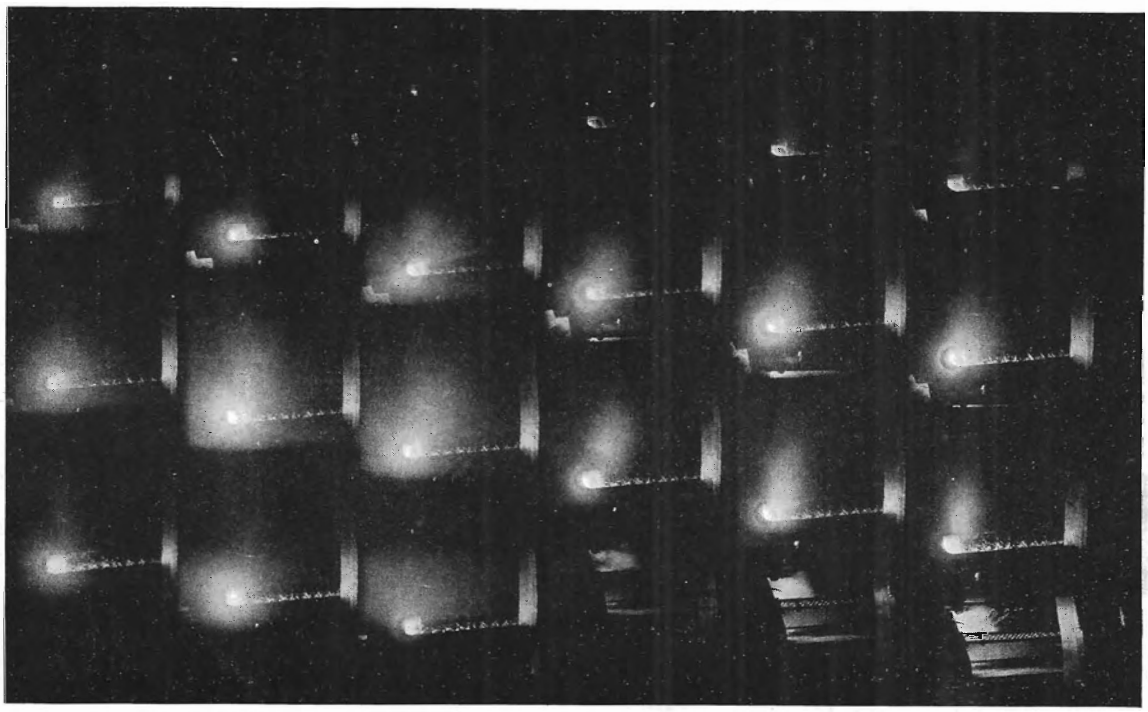

Fig. 30. High-speed Photograph of Short Circuit on 500-kw., 600-volt, 60-cycle Synchronous Converter with Flash Barriers and Standard Circuit Breaker with Preliminary Arrangement of Brush Rigging. Arc at outer end of commutator

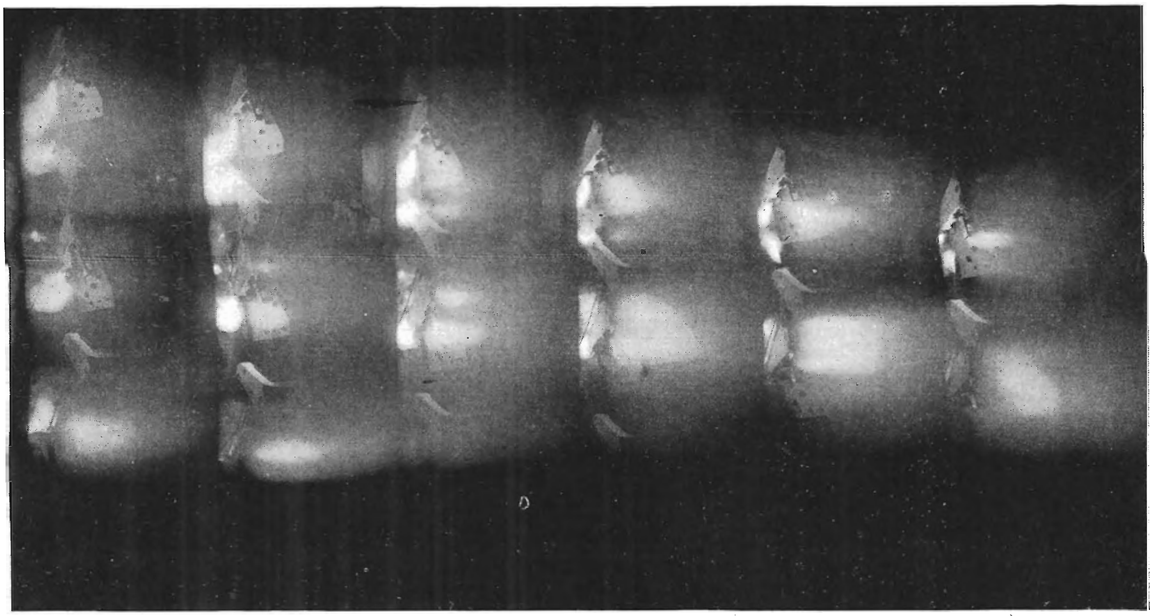

Fig. 31. High-speed Photograph of Short Circuit on 500-kw., 600-volt, 60-cycle Synchronous Converter with Flash Barriers and Standard Circuit Breaker with Preliminary Arrangement of Brush Rigging. Arc at outer end of Brush Rigging

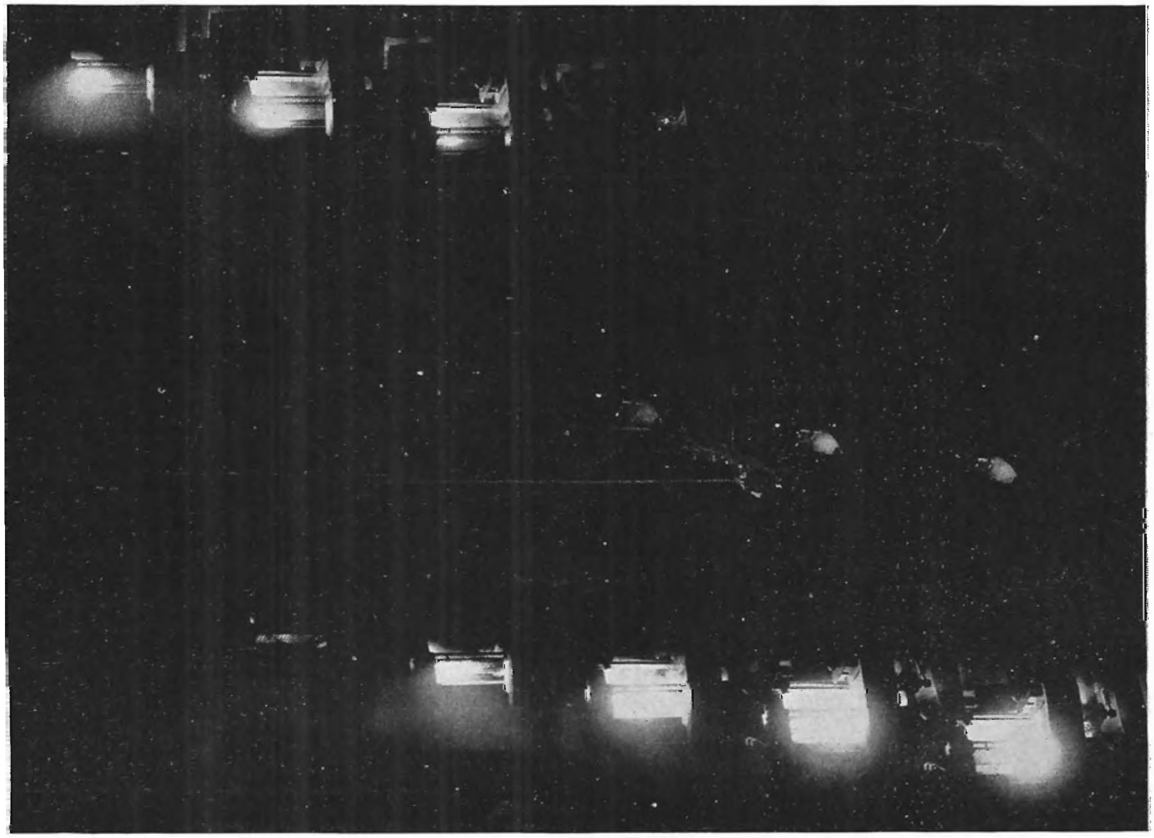

Fig. 32. High-speed Photograph of Short Circuit on 500-kw., 600-volt, 60-cycle Synchronous Converter Protected by Flash Barriers and Standard Circuit Breaker after Arrangement of Brush Rigging has been Changed. Uniform distribution of flashing

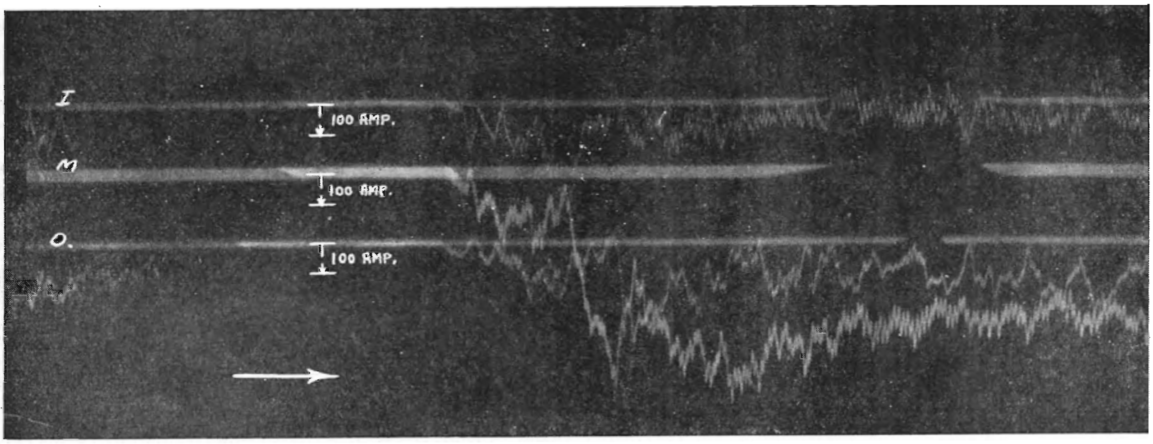

Fig. 33. Short Circuit on 50-kw., 600-volt Generator. Curve *O*, current in outside brush; Curve *M*, current in middle brush; Curve *I*, current in inside brush

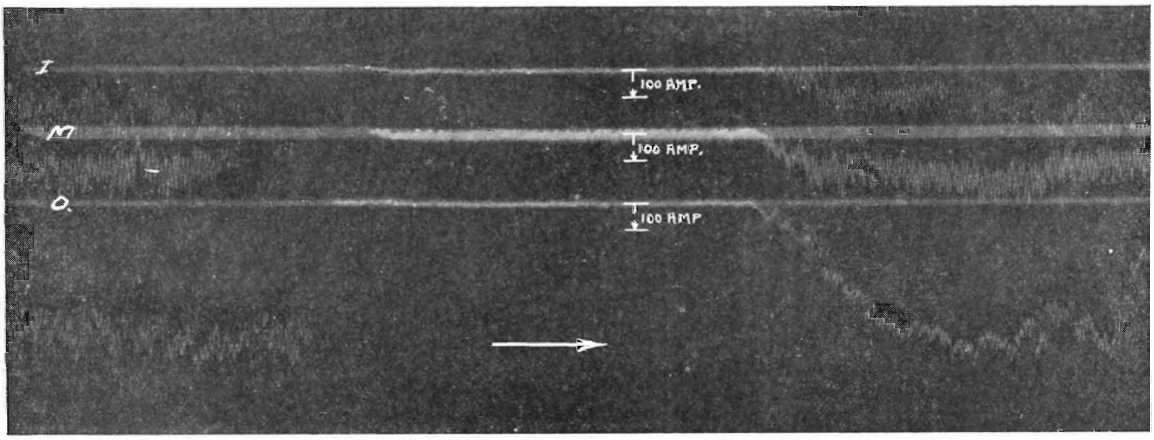

Fig. 34. Short Circuit on 50-kw., 600-volt Generator. Curve *O*, current in outside brush; Curve *M*, current in middle brush; Curve *I*, current in inside brush.

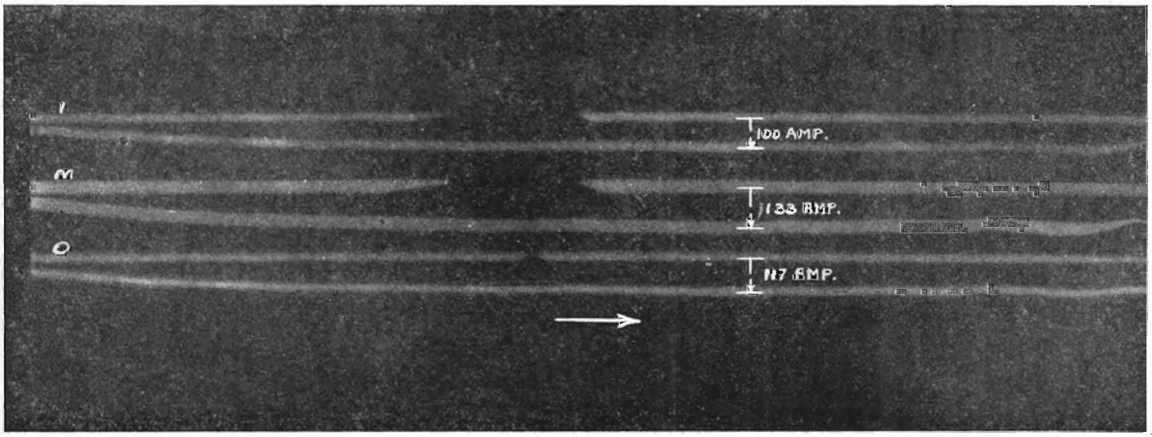

Fig. 35. Current Passed Through 50-kw., 600-volt Generator from an External Source

The general arrangement of a successful barrier, Fig. 25, is shown herewith.

A close-fitting box of fire-proof insulating material surrounds each set of brushes and is located so as to give a small clearance between the box and the commutator.

On the side of the box towards which the commutator rotates after leaving the brush is fastened a V-shaped "scoop," Fig. 24, of fire-proof insulating material, preferably having good heat conductivity, pointing toward the brush and having small running clearance from the commutator.

Radially above the scoop, about one inch apart, are two metal screens, one coarse and one fine mesh, through which the arc is successively forced and cooled.

It was found that a moderate amount of material is required to give the necessary thermal capacity to prevent an arc from passing beyond a screen of this kind. The scoop running very close to the commutator with narrow edge and small clearance picks up the arc from the commutator and deflects it into the arc coolers which, from their construction, allow free passage of all gases generated by the arc. The cooling and condensing of the arc reduces the gas pressure so that shields at the end of the commutator, to prevent the arc being thrown from the end of the commutator and communicated to pillow block and frame, are permissible. It will be noted from the illustrations that the commutators extend beyond the end of the barrier as it was found that the arc must be prevented from being communicated to the end of the bars.

Investigation was then transferred to a 500-kilowatt, 60-cycle, 600-volt synchronous converter, and barriers of similar type, but without continuous end shields, were tried.

Tests showed that these barriers did not give protection on short circuit although they prevented machine from flashing over on very high overload. The high-speed camera record indicated that the arc was being thrown to the outer end of the commutator for some reason causing such high gas pressure at the outer end of the commutator that the arc was blown under the barrier and the machine flashed over. Figs. 30 and 31.

The differences in performance were ascribed to differences of magnetic fields acting on the arc.

To demonstrate the effect of the magnetic field, various arrangements of connections of brush rigging were made, each to produce a different field where the arcing occurs. The results indicate that it is possible to arrange the brush rigging and connection to make a barrier, as described above, effective on practically all commutating machines and to prevent complete flashover. Figs. 32 and 27 show the effects of change in connection on arc distribution, giving the uniform distribution most favorable to good barrier performance.

Other tests were made to record the simultaneous short-circuit current in the outer, middle, and inner brushes by the oscillograph. The records in Figs. 28, 33 and 34 show typical variations of current distribution produced by different connections to brushes. The distribution of current is principally dependent on the magnetic field surrounding the brushes where the arc is formed. To show that differences of impedance have very little influence, record Fig. 35 was taken with current supplied from an exterior source with no flashing. It will be seen that current is practically the same in all brushes. With some connections the deflection of the arc can be plainly seen to follow the well-known relation of current, flux, and force, but with the more complicated connections the difficulty of determining resultant field from many sources makes it difficult to determine the direction of deflection of the arc except by experiment.

Direct-current machines for use in* automatic substations are being equipped with these barriers and short-circuit tests at the substations have been taken, indicating that they will take care of any short circuit experienced in actual service. These barriers are in operation and short-circuit tests were taken on a 500-kilowatt, 600-volt, 25-cycle synchronous converter of the Des Moines Electric Railway, Des Moines, Iowa, a 500 kilowatt, 600-volt, 60-cycle synchronous converter of the Columbus Electric Railway & Light Company, Columbus, Ohio, and a 500-kilowatt, 30-cycle, 1200-volt synchronous converter at Monteith Junction, Michigan; and other installations are now in service.

The investigations and tests indicate that if any commutating machine is equipped with barriers and the last high-speed circuit breaker described, complete protection will be given against external short circuits of all kinds so that interruption to service will not be of any greater duration than necessary for closing the circuit breaker as in ordinary overload operation.

* See paper by Taylor and Allen, A.I.E.E., "Transactions," vol. xxxiv, 1915, page 1801.