PROTECTIVE APPARATUS FOR TURBO-GENERATORS.

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SUMMARY.

The paper deals briefly with the causes of breakdowns in turbo-alternators, particularly in the stator winding, and discusses means for limiting damage in case breakdowns do occur.

Some of the systems of alternator protection which are at present in use are dealt with briefly and their advantages and disadvantages pointed out, particularly as regards protection for faults between turns of the same phase winding. A new system of protection is proposed which has the advantage of protection against faults between turns. The system has been tried out in the factory, but the author recommends that it be tested under actual operating conditions.

An investigation has been made of the phenomena occurring when the field circuit is opened. and it is shown that it is permissible to open the main field circuit without any discharge resistance. Different methods at present in use of opening the main or exciter field are discussed, and it is shown that they unnecessarily prolong the discharge of the field and the destructive effect of the fault currents. It is therefore recommended that a simple circuit breaker without discharge resistance and operated directly by the fault-current relays be provided in the main field circuit.

INTRODUCTION.

The increase in size of distribution systems, power plants and generating units has brought forward many new problems in the protection of supply systems and plant in the case of faults. Many improvements have been made in oil switches, automatic tripping devices and in the arrangement of protective reactances to control and limit the large amounts of power which have to be dealt with in the case of faults on modern large stations. Recent papers* on this subject indicate that, so far as the distribution system is concerned, satisfactory protection can now be obtained. Until recently it has not been possible to secure the same degree of protection on turbo-generators as on feeders and supply apparatus, but during the past year or two great advances have been made in generator protection, and it is the object of this paper to indicate the troubles which may arise and to describe the methods taken to avoid them and so minimize the damage in those cases where troubles do occur. It is an unfortunate fact that too frequently electrical breakdowns have occurred on large turbo-generators where the resulting arc has ignited the combustible material on the end windings or, if in the slot portion, has burnt the laminations, with the result that a complete rewinding and in some cases core rebuilding has been necessary. This results in a prolonged interruption of the supply, with the attendant loss of revenue in addition to the heavy cost of repairs.

It is impossible to stop a turbo-generator set quickly even when the steam is cut off and the vacuum broken, so that if the insulation of the stator end-connections takes fire, the fans supplying air at a high pressure convert the machine into a furnace, with the result that the temperature may be sufficient to crack the yoke casting which supports the laminations.

In some cases flames reaching to the roof of the power house have been observed. In such cases the insulation on one end of the stator windings is completely destroyed. A breakdown in the slot portion, while not so spectacular, may seriously damage the core and necessitate its rebuilding and rewinding. In these cases, if the machine could have been made "dead" *immediately* after the electrical trouble developed, and before the insulation became ignited or the laminations were seriously burnt, the damage could have been quickly and cheaply repaired. The cost of rewinding a 5 000-kW stator is of the order of £1 500, and the loss due to an interruption of several months in the supply may be many times this amount. The cost of complete protective gear as outlined in this paper, including an automatic field switch, is of the order of a few hundred pounds and therefore insignificant compared with its value as an insurance against loss.

The causes of electrical breakdowns, and recommendations for reducing the damage therefrom, are thus worthy of serious consideration by all engineers responsible for the operation of modern generating stations.

ELECTRICAL BREAKDOWNS IN ALTERNATORS.

The great majority of breakdowns in turbo-alternators are due to the following causes:—

(1) Faults between turns in the stator end-connections, or between conductors in the slot.
(2) Faults between phases on the stator end-connections.
(3) Faults to earth on the stator end-connections.
(4) Faults to earth in the stator slot conductors.
(5) Short-circuits or earths in the rotor winding.

The majority of serious breakdowns in turbo stators occur on the end connections. The following are some of the possible reasons:—

(*a*) The end connections are exposed to a number of deteriorating influences from the cooling air. Even if the air is cleaned by means of the wet air-washing apparatus at present in common use, an appreciable amount of dirt is often deposited in the course of time. In some cases free moisture has been carried over into

* See, for instance, A. E. McCOLL: "Automatic Protective Devices for Alternating-current Systems," *Journal I.E.E.*, 1920, vol. 58, p. 525; also E. B. WEDMORE: "Automatic Protective Switchgear for A.C. Systems," *ibid.*, 1915, vol. 53, p. 157.

the machine, due to defective operation or the freezing up of air washers.

Another cause of trouble is the condensation on the machine of moisture from the atmosphere, due to the windings having a lower temperature than the air itself. This condition sometimes occurs when the generator has been shut down during the week-end and the atmospheric temperature has increased during this time. If no dampers are installed in the air ducts, air from the outside atmosphere may be drawn into the machine owing to the natural draught in the building, and deposit its moisture on the cooler generator surfaces. Large amounts of water have been found dripping from the winding or the core, and breakdowns have been traced to this cause.

(*b*) Due to their complicated shape, it is not possible to use the same high-grade insulation (i.e. moulded mica) on the end connections as on the slot conductors.

(*c*) In the bar and connector type winding, before the end windings are placed in position it is usual to apply between the different conductors in the same slot a high flash-test of 50 or 100 times the operating voltage between turns in order to eliminate faulty conductors. It is not possible to apply such a test between the stator end-connections when the machine is completely wound and all the series turns form a complete circuit. The only practical way to test between turns on the finished stator is to run the machine at the maximum overspeed and field current, when a voltage of approximately $1\frac{1}{2}$ times the normal value (or, say, 200 volts per conductor for an average size of machine) is obtainable. This voltage may not indicate weak parts in the insulation due to defective material or workmanship. Earths inside the slots due to the use of non-fireproof material which deteriorated under the high operating temperature have occurred on machines of older design. These faults have practically disappeared in modern machines where mica wrapping is used.

In some cases, however, the stator conductors have not been sufficiently braced at the point immediately where they leave the slots, and an earth has developed. This difficulty is practically overcome by the modern methods of bracing the winding.

In one case a machine of older design broke down due to the deterioration of the slot insulation owing to vibration. The clearance between the conductor and the laminations was in this case excessive and on no machine of modern design has this trouble been observed. In general it can be said that earths in the slot conductors have practically disappeared in modern machines.

Faults in the rotor windings are usually due to broken connections, to displacement of end windings caused by centrifugal force, or to the use of combustible insulating materials in the slots. As faults in rotor windings do not jeopardize the whole machine they will not be further considered in this paper.

Precautions for preventing stator breakdowns can be grouped as follows :—

(1) Care in design and manufacture.
(2) Installation of suitable air-cleaning apparatus.
(3) Care in operation.
(4) Protective reactances.

Generator Design.

Insulation.—The insulation should be able to withstand continuously the temperature, the dielectric stresses, and the mechanical stresses to which it is to be subjected.

As regards temperature, modern turbo-alternators are now insulated with materials which meet the requirements. The stator conductors are, as a rule, insulated by means of mica backed with a small amount of paper and moulded tightly on the bars (Haefely process). This insulation is of a permanent nature and will withstand temperatures of at least 150° C. The rotor is insulated by means of fireproof material only, e.g. mica, asbestos or similar materials. Excessive temperature-rise is therefore rarely the cause of breakdowns (in machines of modern design) as the new methods of insulation have appreciably increased the factor of safety, notwithstanding the fact that operating temperatures have been increased. Practically none of the breakdowns which have come to the author's knowledge had any relation to the temperature-rise. An examination of the winding after a failure showed as a rule that the insulation was in good condition and had not deteriorated due to excessive temperature.*

Bracing of the stator winding.—This is of the greatest importance. The end connections should be braced to prevent short-circuits between turns or phases. The stator slot conductors should be braced at the point where they leave the core, as a deformation at this point will cause the mica insulation to crack and result in a fault to earth. The insulation of the stator end connections is one of the most difficult problems. On account of the complicated shape of the connectors moulded-mica insulation as used for the slot conductors cannot be adopted and the insulation is invariably applied in the form of tape. It is difficult to fill the interstices between the layers of tape in order to guard entirely against atmospheric influences. Thus the end connectors which, as previously mentioned, are the most vulnerable portion of the winding, can be made reasonably safe by the liberal and careful use of tape and varnish. In all large machines the stator conductors are of such heavy cross-section that a solid conductor would cause excessive heating due to eddy currents, and generally the conductor must be divided into parallel laminations. In some types of winding the lamination is carried further than necessary to reduce the eddy currents to a reasonable value ; this is undesirable, as the conductor is weakened and less able to withstand bending in case of short-circuits. A mechanically very strong winding is obtained by laminating the slot conductors and using solid copper bars for the end connections where no lamination is required. The slot conductors must in this case be twisted or transposed in the slot.

It is important that faulty slot conductors and end connections be removable with the minimum disturbance to the remaining parts of the winding. Specifications for turbo plant sometimes require interchangeability of individual coils, but it has not been sufficiently realized that this feature is of no avail unless protective

* Newbury, *Electrical World*, 1920, vol. 76, p. 58.
G. A. Juhlin: "Temperature Limits of Large Turbo-Alternators," *Journal I.E.E.*, 1921, vol. 59, p. 281.

gear is provided which will localize the damage and prevent the insulation of the whole winding being destroyed by fire.

Air-cleaning apparatus.—Various forms of apparatus have been devised for air cleaning. These may be divided broadly into two classes, i.e. dry filters and wet filters, the former being very costly in maintenance and presenting a considerable fire risk. The wet filter does not remove all the dirt and, unless carefully adjusted, may allow free moisture to pass into the machine. To avoid the serious objection to wet- and dry-air filters the air-cooling system has been developed. In this arrangement the air-circulating system is completely closed on itself. The air passes through the generator, where it is heated, then through a cooler where it is cooled, then again through the generator, and so on. By this means the only dirt that can be deposited in the machine is that contained in the original volume of air which fills the air-circulating system, and this amount is entirely negligible. Fig. 1 shows a sectional arrangement of generator and air cooler.

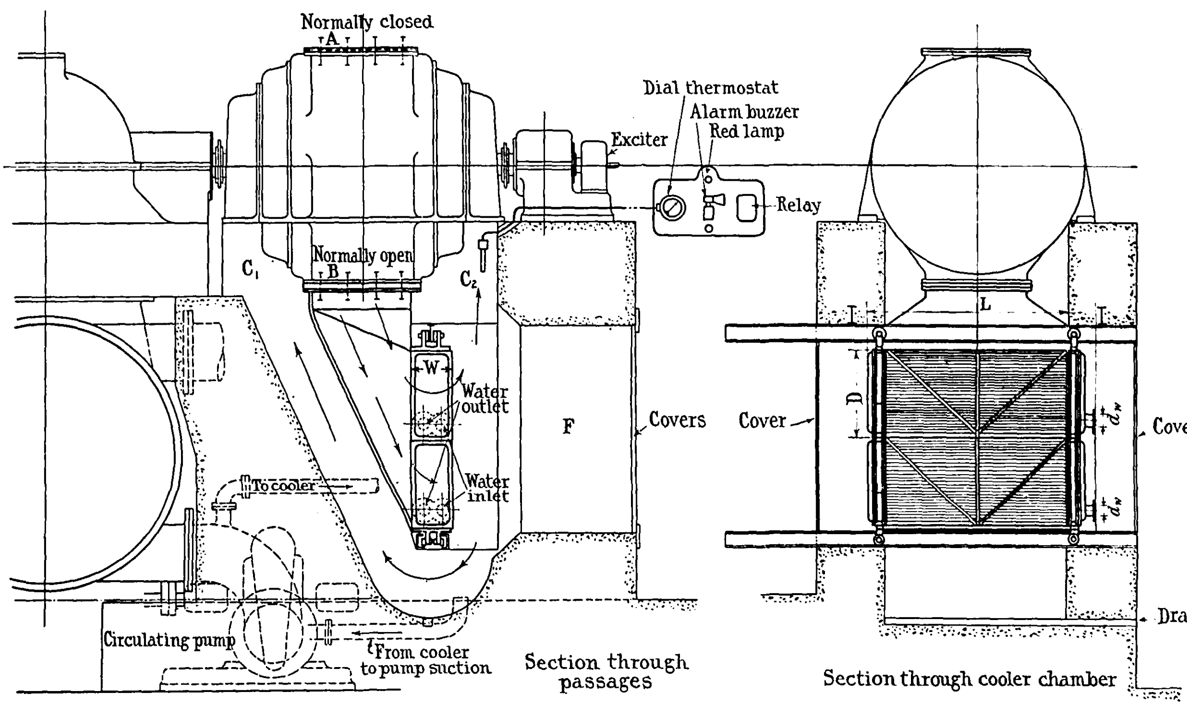

FIG. 1.

Care in operation.—Generators should be examined from time to time. Clamping bolts should be tightened and the windings thoroughly cleaned and re-varnished. Each manufacturer will supply detailed instructions for the care and maintenance of his machines.

Protective reactances.—The use of internal and external reactances for protective purposes is a big subject, and one which cannot be covered in this paper. It is sufficient to say that by their proper use the shocks on the generators may be greatly reduced.

In spite of every precaution which can be taken in the design and manufacture of turbo-generators, breakdowns will occur occasionally, and in such cases the best that can be done is to isolate the machine and to " kill " its field in the shortest possible time in order to limit the extent of the damage. If the protective apparatus supplied for this purpose does not function sufficiently rapidly to prevent the insulation on the end windings from catching fire, then means must be provided for extinguishing the fire.

ALTERNATOR PROTECTIVE DEVICES.

The development of protective devices for alternators has probably been somewhat as follows :—

(1) Fuses, operating on overload only.
(2) Circuit breakers, operating on overload only.
(3) Circuit breakers, operating on overload and reverse power.
(4) Circuit breakers, operating on generator fault only and not on overload (balanced protection).
(5) Circuit breakers, and field switch operating on generator fault only and not on overload (balanced protection).

The last-named is the only protective system in which the generator field has been " killed " wherever the main circuit breaker has opened automatically, and marks a great advance, especially in the case of enclosed machines.

The following are the main requirements of modern electrical generator protective gear. The gear should operate on all possible faults in the generator or in the cables between generators and busbars, but should be inoperative for faults and short-circuits external to generator and cables. The gear should operate the main circuit breaker, interrupt the field current and reduce the generator voltage to a small value in the shortest possible time. Further, it should not introduce in the system new weak points which are likely to increase the risk of breakdowns or cause unnecessary shut-downs.

The system most commonly used is the Merz-Price

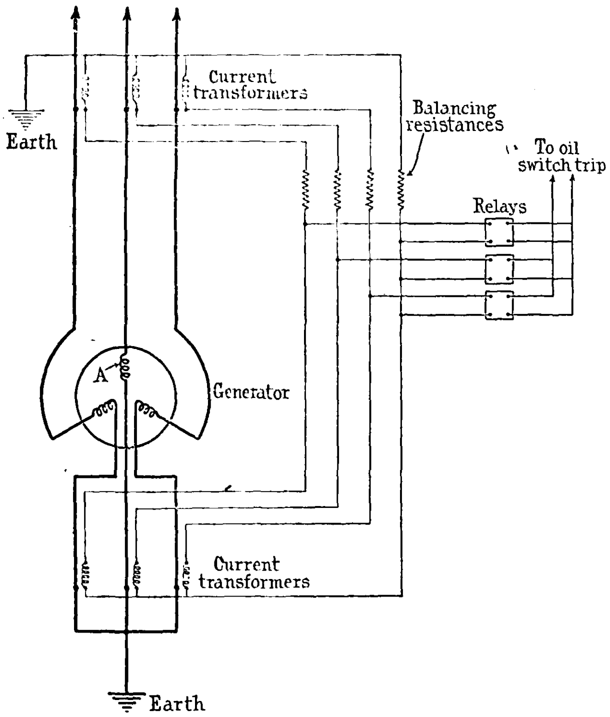

FIG. 2.—Protection of three-phase generator by Merz-Price (balanced current) system.

balanced protective gear. In this system (Fig. 2) two current transformers are inserted in each of the phase windings, one transformer being located at the terminals or the switchboard and the other at the star point. The transformer secondaries belonging to each phase are interconnected by means of pilot wires, and the tripping relay is connected between the pilot wires. The relay closes the tripping circuit for the main breaker and the field switch. The star point of the system must be earthed. It will be seen that the gear will trip for a fault to earth in the generator leads, or a fault between phases.

In the case of a fault between different turns of the same phase winding the fault currents are purely internal and will not cause unbalancing of the currents in the phase terminals. No protection is therefore obtained for such faults until they develop into an earth or into a short-circuit between phases. This constitutes the most serious defect in the Merz-Price system.

Another limitation of the Merz-Price gear is in connection with the current transformers and the earthing resistance. Two current transformers seldom have identical magnetic characteristics, and perfect balance is therefore seldom obtained ; also a heavy magnetization due to a short-circuit on the system may upset the magnetic balance. This defect is evident on heavy overloads, and trouble has been observed due to the gear tripping the machine in the case of short-circuits on the system. To overcome this difficulty the setting of the relay must be made very coarse, and in some installations it has been found that a setting of 100 per cent of the full-load current is necessary. Improvements have recently been made in the relays, and the relay setting can now be reduced to 15 per cent or less. The disadvantage of coarse relay settings is that the earthing resistance must have a very low value, or the star point must be directly connected to earth, so that in case of a fault to earth the fault current will be sufficiently large to trip the gear. Cases have been known where the generator developed an earth not far distant from the star point and the Merz-Price gear failed to operate, resulting in the destruction of the winding. Assume for example that the relay is set at 15 per cent and that an earthing resistance is used which will pass 30 per cent of normal load current in the case of an earth on the terminals; if now an earth develops at a point A (Fig. 2) located 40 per cent distant from the star point, the fault current will be 12 per cent, or less than the current required to operate the relay. Consequently, all parts of the winding between the star point and point A, or one half of the winding, will be unprotected in the case of faults to earth.

If the star point is earthed directly without an earthing resistance full protection can be obtained for the stator winding. In general, however, it is desirable to limit the fault current by a resistance, as even in the short period required to operate the gear (see Fig. 3) appreciable damage might be done if the full current were allowed to flow. The unprotected part of the winding is the part nearest the star point which has normally a low potential to earth and for this reason should be the least likely to fail. In practice, however, breakdowns near the star point have been observed and these require protection. Earths on the feeders

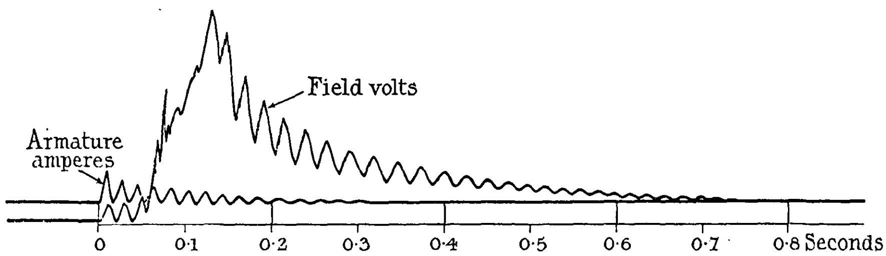

FIG. 3.—Oscillogram showing operation of relay-operated field switch.

may explain similar failures. If these occur the star point assumes a potential equal to the phase voltage, and an earth may occur at a weak point of the insulation near the neutral point.

It is therefore desirable that the unprotected part of the winding shall be as small as possible, say 5 per cent of the total winding. This can be effected by making the earthing resistance of sufficiently low value. For example, if the minimum setting of the relays is 15 per cent, and 5 per cent of the winding is allowed to be unprotected, the earthing resistance should be of such value as to pass 15/5, or 3 times full-load current for an earth on one of the terminals.

Self-Balancing System.

This system has recently been proposed by Mr. J. R. Beard to overcome some of the above-mentioned defects

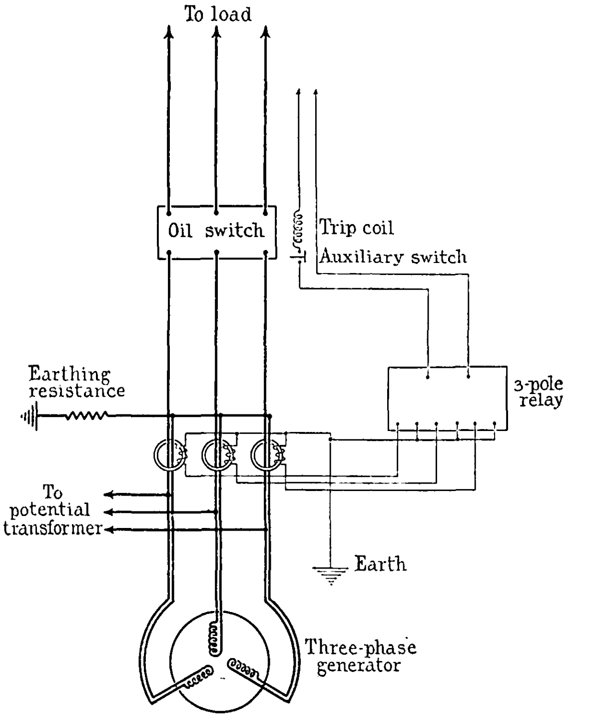

Fig. 4.—Self-balancing protective gear for a three-phase generator.

in the Merz-Price system and has been adopted in several power stations. Fig. 4 shows the arrangement. The two ends of the phase windings are carried through the same core, and a secondary winding on this core is connected to the relay. The advantage of this arrangement is that the current balance is obtained by means of a single current transformer, thus eliminating the difficulties in obtaining a perfect balance mentioned above in connection with the Merz-Price system.

The relays can be set to operate at their minimum current, and even if a relatively high earthing resistance is used the gear will operate on faults to earth although they may occur near the star point of the generator. The limitation to this device is the fact that in order to prevent complication of the gear a busbar-type current transformer is used to obtain the balance. With such a transformer the sensitivity is limited unless the out-of-balance current exceeds approximately 20 amperes. The self-balancing gear has some minor disadvantages compared with the Merz-Price gear from the switchgear point of view, but it gives better protection and is for this reason to be preferred for turbo-alternator work.

As regards faults between turns, the conditions are the same as in the Merz-Price gear and no protection for such faults is therefore obtained.

Mid-Point Protective Gear.

The author has devised a protective gear which will operate for all possible faults including faults between turns. Mr. J. R. Beard and Mr. A. Collins have been working on similar lines and have co-operated with the author in the development of the scheme. The general arrangement is shown in Fig. 5, from which it will be seen that the protected generator A, B, C, D is provided with tappings E, F, G from the mid-point of each phase. Reactance coils (or potential transformers) are connected in parallel with each phase and also provided with mid-point tappings M, N, O. The mid-point of the generator and that of the reactance coils are connected together. Current transformers are inserted in the mid-point connections and the secondaries of these transformers are connected to the relays.

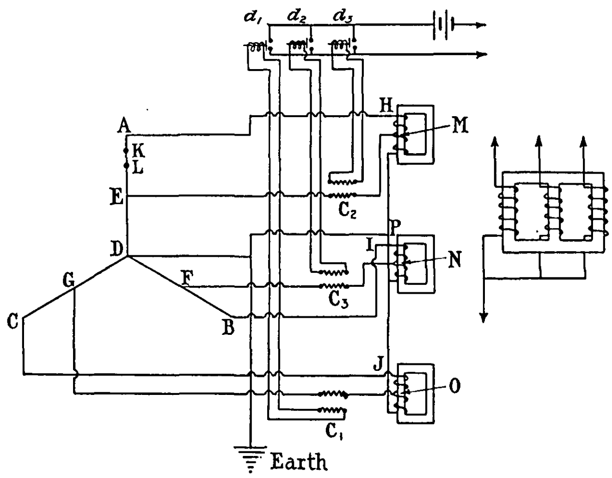

Fig. 5.—Mid-point protective gear.

When the machine is in normal operation the interconnected points of generator and resistance are at the same potential and no current will flow in the mid-point connections. If a fault occurs between turns, for example between points K and L (Fig. 5), the number of active turns between points A and E will be reduced and at the same time the flux will be weakened by the demagnetizing action of the fault currents. Both actions will reduce the voltage between A and E and, to a smaller extent, the voltage in ED. The voltages in AE and DE will therefore be different, whereas the voltage of HM and MP will remain equal, being generated by the same flux. A current will therefore flow in the mid-point connection EM. The voltage and current induced in the mid-point connection is used to operate a tripping relay (by means of a transformer).

The unbalancing of the voltages in the phase halves or the shifting of the mid-point in the generator phase winding occurs not only on a fault between turns but also when a fault occurs to earth or between phases. For example, a fault to earth at K (Fig. 5) will circulate a large current in KD which will reduce the voltage of DE to a greater extent than the voltage of AE. The same will be the case for a fault from K to any point of the other two phases.

The system will therefore deal with any fault in the generator winding, including faults between turns, and will give more complete protection than has hitherto been obtainable.

It will be seen that a fault outside the generator, for instance in the cables leading from the generator, will not cause unbalancing, and the generator leads would therefore not be protected. To include the leads in the protection, the cables can be provided with a conducting shield surrounding the central core and insulated for half the phase voltage from the core and from the armour. This shield is connected to the mid-point at the generator end. The reactance coils in this case are located at the switchboard and their mid-points connected to the shield. It will be seen that a fault from one of the cores to earth must be preceded by a fault from the core to the shield which forms the mid-point connection, and such a fault will operate the gear.

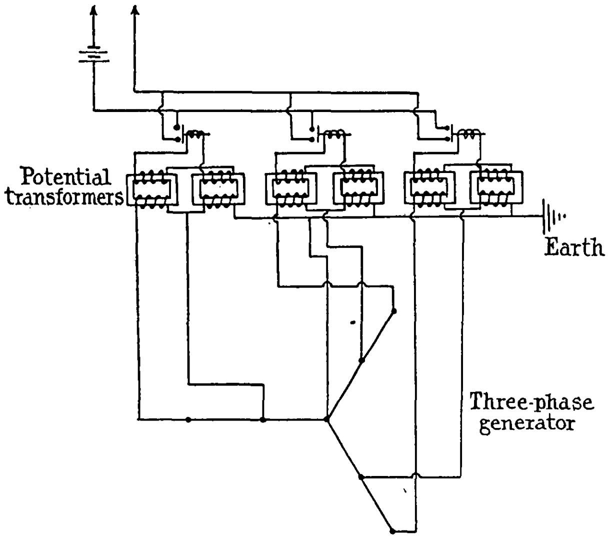

FIG. 6.—Method of connecting potential transformers in mid-point protective gear.

The generator winding has in this system to be provided with three tappings insulated for 50 per cent of the generator voltage, and three terminals for the mid-point connections, which carry normally no current and can be of very small section. It is not necessary to bring out the 6 phase leads as in other systems; the star point can be made in the stator winding and the generator therefore requires only 4 main leads and 3 small pilot leads.

Instead of installing separate reactance coils the potential transformers which are usually required in connection with the voltmeters and wattmeters can be provided with tappings and used for the protective gear. A convenient arrangement is shown in Fig. 6. In this arrangement two potential transformers are required per phase, the secondaries of which transformers are connected in opposition in series with the relay. Special secondary windings are provided for the instruments. As regards the sensitivity and the operation for faults to earth near the star point, this gear is similar to the self-balancing gear in so far as no operation is to be feared for heavy overloads and the relays can be set to their maximum sensitivity. The limitation for dealing with these faults is therefore determined only by the sensitivity of the relays, the impedance of the reactance coils, and the amount of resistance between the neutral point and earth. This will be understood from the following explanation. If a fault to earth occurs at point E (Fig. 5), it will short-circuit E and D, and also that part of the reactance coil lying between M and P through the relay. The other part of the reactance coil HM is still supplied with voltage from AE. The reactance coil operates therefore as a short-circuited transformer, HM being the primary and MP the secondary, and the current in the relay will depend upon the reactance between the two halves of the winding HM and MP and upon the impedance of the relay circuit. The leakage in the reactance coil can, if desired, be made very small at slight extra expense by special arrangement of the windings, and this method is therefore to be recommended if high earthing resistances are used. As an alternative, the size of the reactance coil can be somewhat larger than that of an ordinary potential transformer to obtain a small impedance.

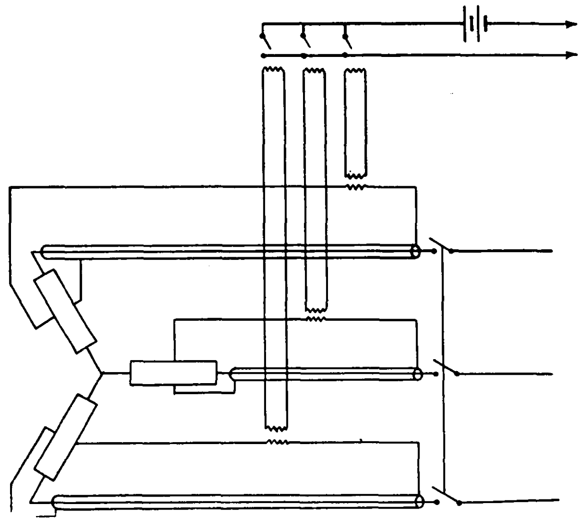

FIG. 7.—System of internal protection for alternating-current apparatus connected in two parallel circuits.

A simplification of the described arrangement can be made in the case of a generator where the phases are wound in two parallel circuits (Fig. 7). In this case the mid-points of the two parallel windings can be interconnected over the transformer which operates the relay. This system is very limited in its application, as few generators are wound in two parallel circuits, this being desirable only for extremely large currents. Further, it would be limited to 4-pole and 2-pole machines wound with concentric winding, as in 2-pole machines wound with involute or basket-type winding (similar to a d.c. armature) the mid-points in the windings of each pole are not equipotential. In some cases, however, the active conductors are divided in two parallel conductors lightly insulated from each other, and the parallel circuits are continued throughout the winding and twisted in the centre of the winding to avoid eddy currents. In such case equipotential mid-points can be created without great difficulty by omitting the twist in the centre of the winding and substituting two other twists, located half way between the mid-point and the extremities of the winding.

Fig. 8 shows an application of the mid-point protective gear for two a.c. generators running in parallel. This arrangement has the disadvantage that two machines are tripped out when a fault occurs. The sound machine would, however, be immediately ready for synchronizing. This disadvantage would perhaps not be important in a station where a large number of machines run in parallel. The great advantage of the arrangement is that extremely little gear is required, i.e. only three current transformers and relays for each pair of generators.

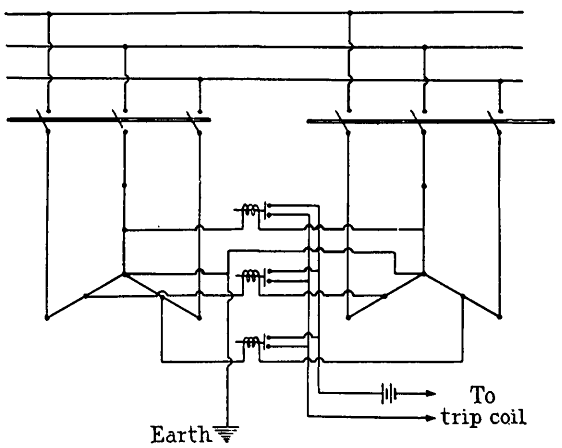

FIG. 8.—Mid-point protective gear for two alternators in parallel.

Automatic Field Switches.

As previously mentioned, a complete generator protective equipment should include an automatic field switch to interrupt the field circuit immediately the fault occurs. This field switch, so far as the protection of the generator is concerned, is as important as, if not more important than, the main switch.

The automatic field switch can be located in different parts of the field circuit and can take the form of :—

(1) A switch in the exciter field circuit.
(2) A reversing switch in the exciter field circuit.
(3) A circuit breaker in the main field circuit.
(4) A switch to short-circuit the slip-rings and exciter.

Hitherto, in order to limit the voltage-rise on breaking the induction circuit, it has been standard practice to provide a non-inductive field-discharge resistance or " kicking coil " where a field circuit was to be opened. The normal operation of the field-discharge switch is to connect the field winding in parallel with the discharge resistance and to open subsequently the current supply from the exciter armature. Thus, after the switching operation the field circuit is not interrupted, but the current circulating through the winding and the resistance is allowed to die out gradually. The ohmic value of the discharge resistance is, as a rule, roughly equal to the field resistance.

It is of great interest to study the phenomenon of field discharge in detail. The general formula which applies in the case is

$$E = -L\frac{dI}{dt} = -n\frac{d\phi}{dt}10^{-8} \quad . \quad . \quad . \quad (1)$$

therefore

$$L = n\frac{d\phi}{dI}10^{-8} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where I = current in amperes,
R = total resistance in circuit,
L = self-induction coefficient in henrys,
t = time in seconds, and
n = effective total number of turns in the rotor.

As regards the self-induction coefficient L, it is perhaps worth while to point out that a misleading definition is often given in literature and text-books, namely:—The self-induction coefficient is equal to the number of line linkages per unit of current; a qualifying statement usually being added to the effect that this applies only to circuits having no iron. This definition has frequently led to error when applied to problems similar to the present example, the mistake being made that L was determined as a variable by taking corresponding values of ϕ and I, which method gives absolutely incorrect results. It is proposed to replace this definition by the following, in accordance with expression (2) :—The self-induction coefficient of a circuit at a given current is equal to the rate of change of the number of line linkages with respect to the current. This definition is applicable to all circuits, and L can be introduced as a variable quantity in the case of circuits containing iron.

For our problem we can determine $d\phi/dI = \tan\alpha$ (curve 2 of Fig. 9) by drawing tangents at different points of the saturation curve and determining for each point $(d\phi/dI)$, $L = (d\phi/dI)10^{-8}n$ and L/R. After having determined the curve for L/R it will be possible to construct the discharge curve from the following consideration.

For any point of the curve we obtain :—

$$IR = L\frac{dI}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$\frac{L}{R} = -I\frac{dt}{dI} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Expression (4) represents the length of the subtangent at the point in consideration. The subtangent at any point of the I curve is therefore equal to the momentary

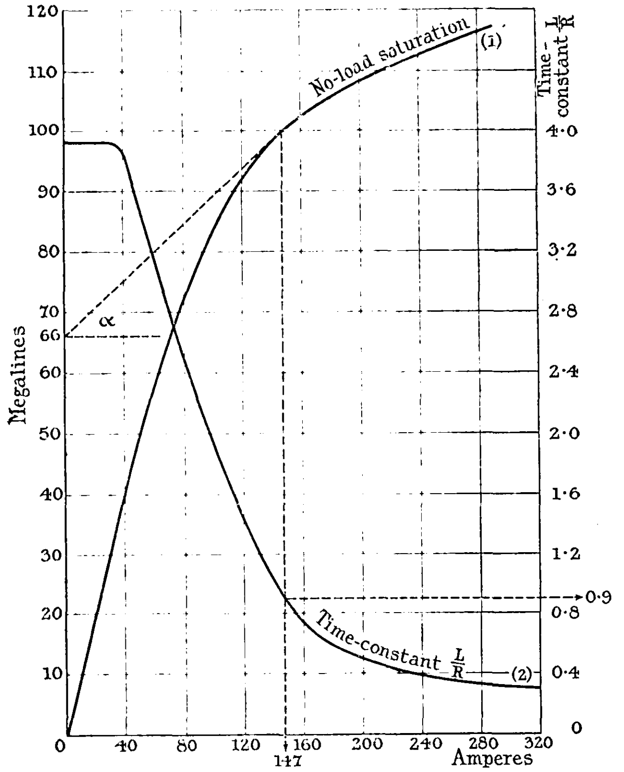

FIG. 9.—Characteristic curves of turbo-alternator.

value of the time-constant L/R. We can therefore determine the tangent on the I curve for the moment of switching off by setting off the subtangent L/R

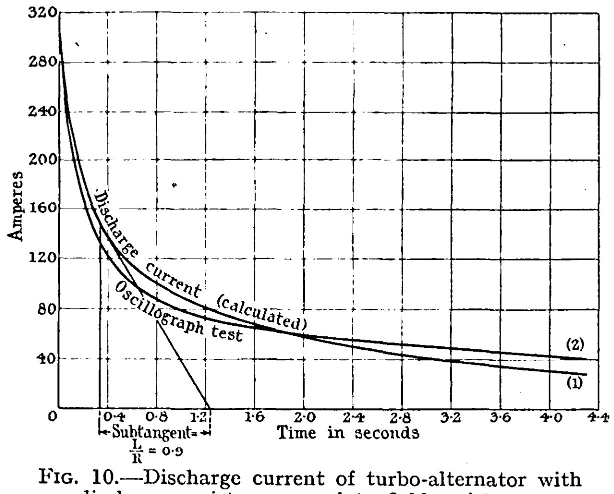

FIG. 10.—Discharge current of turbo-alternator with discharge resistance equal to field resistance.

corresponding to the initial maximum current. Identifying a small part of the tangent and the curve we can find a second point of the I curve, from which a new tangent can be drawn, using the new value for L/R. Continuing in the same way the whole curve can be determined point by point.

As an example we may take a 7 500-kVA, 3 000-r.p.m. turbo-alternator. Curve 1 in Fig. 9 shows the no-load saturation curve. The stator has 40 series turns per phase. The rotor has 324 turns (total). The field resistance is 0·44 ohm, and the discharge resistance 0·38 ohm.

Curve 1 (Fig. 10) has been determined from these data and checks sufficiently closely with the oscillograph test (see Fig. 11) which is replotted to a different scale in curve 2 of Fig. 10. As will be seen from this curve, the self-induction coefficient L varies in the ratio of 0 to 3·25 approximately, for different values of the current, and this explains the rapid drop in current for the initial part of the curve.

Some factors have not been taken into consideration in this method—for instance, the damping currents in the rotor body, the distribution factor of the rotor winding, and the field leakage. The influence of the damping in the rotor will be considered later, whereas the other factors can be taken into account by adding or subtracting a percentage to ϕ as calculated from the saturation curve.

TIME REQUIRED FOR THE FIELD DISCHARGE.

Oscillograms taken on turbo rotors, and calculated curves show that an appreciable time elapses before the field current has decreased to a reasonably small value. From Fig. 12, which refers to an 8 900-kVA, 25-period, 2-pole machine, we find that the time taken to reach a field current of 10 per cent of the no-load value is approximately 11 seconds. In this test the main field circuit was interrupted and a discharge resistance equal to the rotor resistance was used. For a 23 500-kVA, 25-period, 2-pole generator of recent design, the time to reach 10 per cent of the normal field current would be approximately 30 seconds, or 1 minute if the exciter field instead of the main field circuit were opened.

It is evidently necessary in the case of a stator breakdown that the voltage shall disappear as quickly as possible, and the present arrangements therefore appear to be unsatisfactory. The discharge is too slow and the voltage is maintained for a sufficient period to cause appreciable damage. This is confirmed by experience. The first remedy for this sluggishness suggested by the previous considerations is to use a high discharge resistance. It is obvious from the formula that the discharge time is inversely proportional to the total resistance in the discharge circuit. If, for example, a resistance of 19 times the rotor resistance is used, the total resistance will be increased in the ratio of 1 : 10, compared with the usual arrangement of a resistance equal to the rotor resistance, and the rapidity of the discharge will be increased in the same proportion.

A danger to be feared from the use of such high discharge resistances is the high voltage-rise on the rotor winding during the switching, and this, therefore, requires investigation. After the discharge switch in the main field circuit has opened, the field current does not disappear immediately but is maintained at its full value for a short period, and this, circulating through the discharge resistance, will cause a reversed slip-ring voltage equal to the ohmic drop in the resistance. If, as is usual, the discharge resistance is equal to the field resistance, the voltage-rise is equal to the excitation voltage, but if a high discharge resistance of, say, 19 times the field resistance is used, the voltage-rise would be theoretically 19 times the excitation voltage.

rise if a high discharge resistance is used, and, secondly, to retain to a certain extent the sluggishness of the discharge. The damping circuit may be represented by a separate field winding short-circuited on itself, having the same number of turns as the field winding and lying in the same slots. If the resistance of the main field is equal to R_f, the ohmic value of the discharge resistance to R_r, and the equivalent resistance

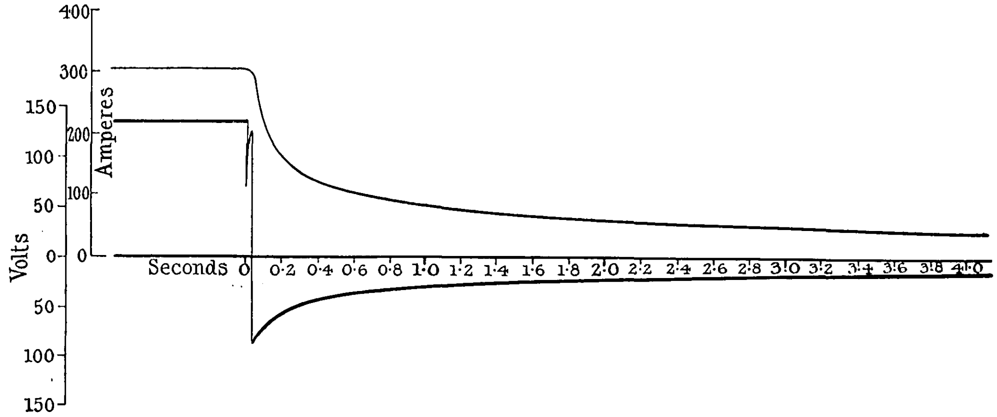

FIG. 11.—Oscillogram of discharge current on a 7 500-kVA, 3 000-r.p.m. turbo-alternator with discharge resistance equal to rotor resistance.

For a generator having an excitation voltage of 50 at no load the voltage-rise at no load when opening the switch would be $19 \times 50 = 950$ volts. If the machine is loaded the field current and the excitation voltage are appreciably increased; the flux and the stored magnetic energy will, however, be only slightly increased and the voltage-rise on full load would therefore not be appreciably greater than at no load. For

of the damping circuit to R_d, then the equivalent resistance of the two circuits combined will fulfil the conditions

$$\frac{1}{R_e} = \frac{1}{R_f + R_r} + \frac{1}{R_d}$$

The equivalent resistance R_e determines the discharge current and voltage. R_d can be determined experi-

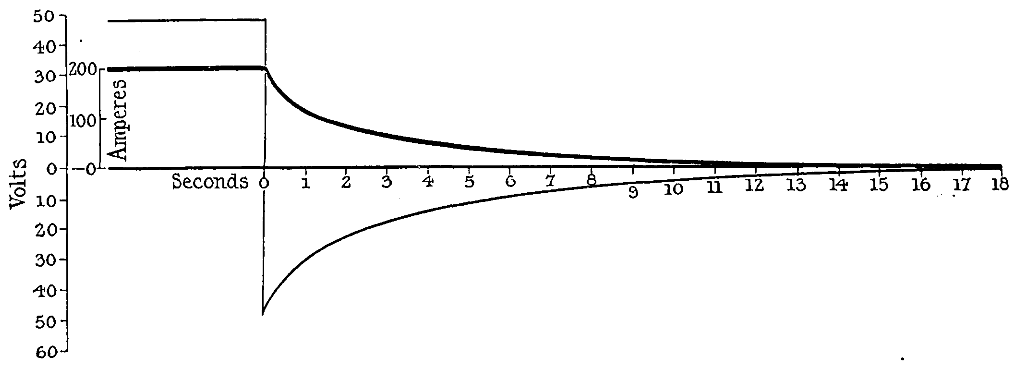

FIG. 12.—Oscillogram of discharge current on an 8 900-kVA, 1 500-r.p.m. turbo-alternator with discharge resistance approximately equal to rotor resistance.

the purpose of the investigation the excitation voltage is therefore always understood to refer to no load on the generator.

INFLUENCE OF DAMPING CURRENTS IN ROTOR BODY.

The next factor to be taken into consideration is the damping action of the closed circuits formed by the rotor slot-wedges and the rotor body. The effect of the damping currents is, first, to reduce the high voltage-

mentally by making two discharges for different values of R_r and recording the current/time or voltage/time curves. The oscillogram shown in Fig. 13 was taken on the same rotor as was used for Fig. 12, the discharge resistance being 30 times the rotor resistance, or $R_r = 30R_f$, whereas, in Fig. 11, $R_r = R_f$. Comparing the two tests we find that the time to reach a certain percentage of the maximum voltage is in the ratio of 9 : 1, the rapidity of the discharge being increased

9 times. The resistances R_e will therefore be in the same ratio, i.e.

$$9\left\{\frac{1}{31R_f}+\frac{1}{R_d}\right\}=\frac{1}{2R_f}+\frac{1}{R_d}$$

or $R_d = 38R_f$ approximately.

The damping circuit of this rotor has therefore an effect equivalent to a discharge resistance of 38 times the rotor resistance. If the rotor were open-circuited without a discharge resistance a voltage-rise of 38 times the excitation voltage would therefore be expected. The oscillogram reproduced in Fig. 14 was taken under this condition, i.e. the rotor circuit was directly open-circuited by means of an ordinary circuit breaker without any discharge resistance, while the normal field current was flowing. The observed voltage-rise was 25 times the excitation voltage. This voltage is lower than would be expected from the previous comparison of time-constants, due to the fact that the circuit is not interrupted instantaneously, the arc persisting for a fraction of a second, and the flux is already somewhat reduced when the arc finally breaks. The reduction in the voltage-rise due to this reason may be taken as roughly 25 per cent.

It will be observed from Fig. 14 that after the rotor circuit has been open-circuited without discharge resistance, the voltage across the slip-rings does not disappear, but a voltage of opposite polarity to the normal excitation voltage appears and dies out rapidly. This voltage indicates that after the current has been broken a rotor flux still exists, and is being maintained by the currents circulating in the damping circuit. The time required for this flux and the remanent voltage to disappear depends on the value of the resistance R_d in the damping circuit. By noting the time required for the remanent slip-ring voltage to disappear, we can obtain a value for R_d. A comparison of Figs. 12 and 14 on this basis gives $R_d = 35R_f$, which is roughly in agreement with the figure previously found.

It should be noted that the rotor of this machine was built up of 2-inch plates shrunk on a shaft, spaces being left between the plates. This explains the high resistance of the rotor body.

Similar tests were made on the previously mentioned 7 500-kVA, 3 000-r.p.m. turbo-alternator having a rotor of the solid forged type provided with radial ventilating ducts. The tests reproduced in Figs. 11, 15 and 16 were taken for $R = R_f$, $R = 20R_f$ and $R = \infty$ respectively. The value of the damping circuit resistance

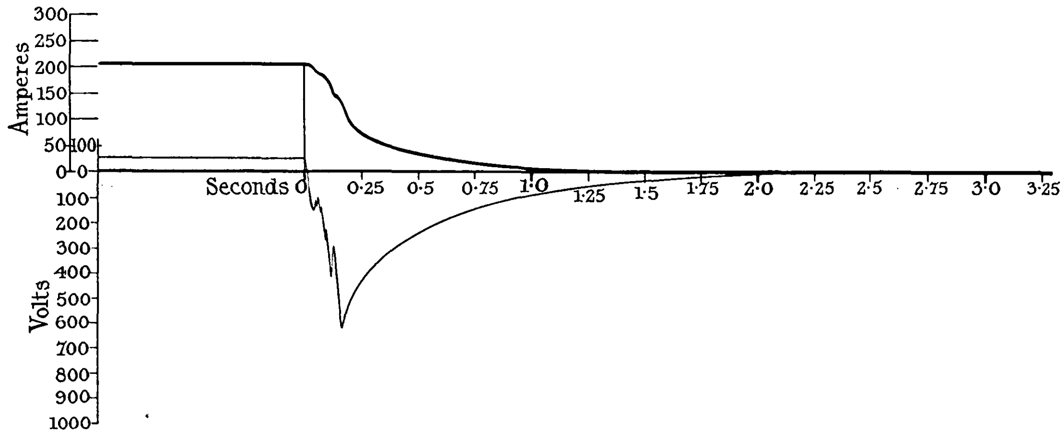

FIG. 13.—Oscillogram of discharge current on an 8 900-kVA, 1 500-r.p.m., 25-period turbo-alternator with discharge resistance equal to 30 times the rotor resistance.

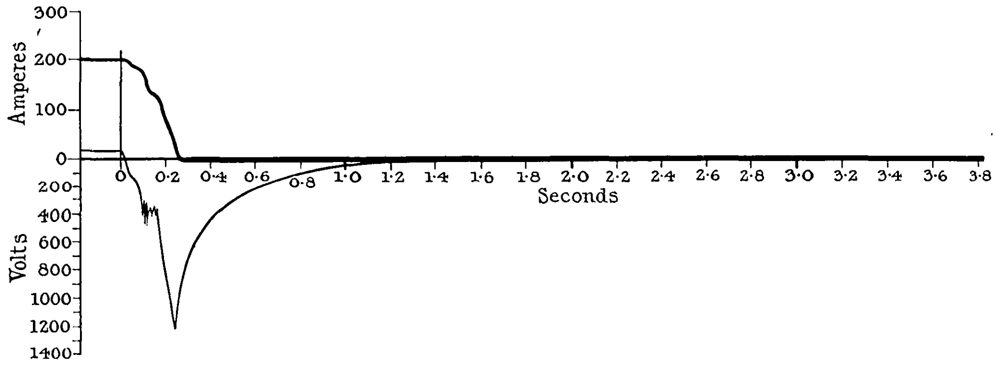

FIG. 14.—Oscillogram of discharge current on an 8 900-kVA, 1 500-r.p.m. turbo-alternator with no discharge resistance, i.e. rotor open-circuited.

determined from these tests is roughly 5 times the rotor resistance, indicating that the rotor built up of plates has a resistance roughly 7 times greater than that of a solid rotor.

No tests have been carried out on rotors built up of thin laminations. These rotors will probably, as regards the resistance of the damping circuit, be fairly similar to a plate rotor. In both types the damping currents will to a large extent circulate in the squirrel cage formed by the metallic slot-wedges, and the coil-retaining rings.

For rotors of the solid type we may assume $R_d = 5R_f$ (approx.) and if the rotor is wound for 125-volt excitation at full load and 60 volts at no load, the voltage-rise between the slip-rings would be roughly 250 volts, or 500 volts if the rotor were wound for 250-volt full-load excitation.

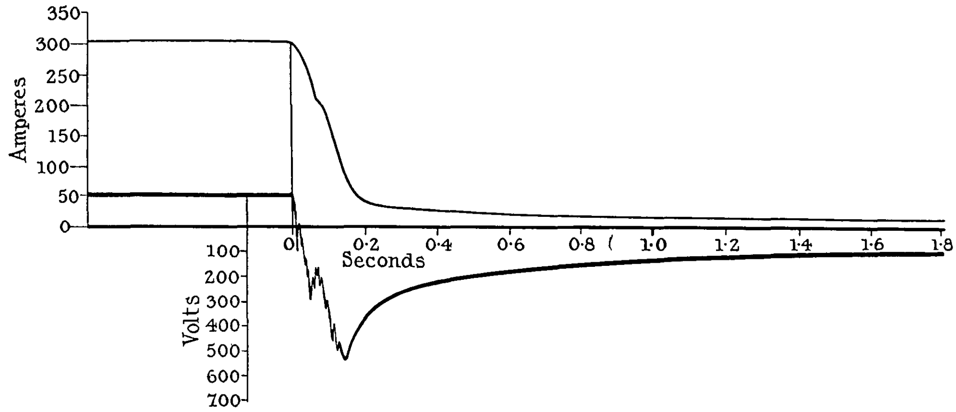

FIG. 15.—Oscillogram of discharge current on a 7 500-kVA, 3 000-r.p.m. turbo-alternator with discharge resistance equal to 20 times the rotor resistance.

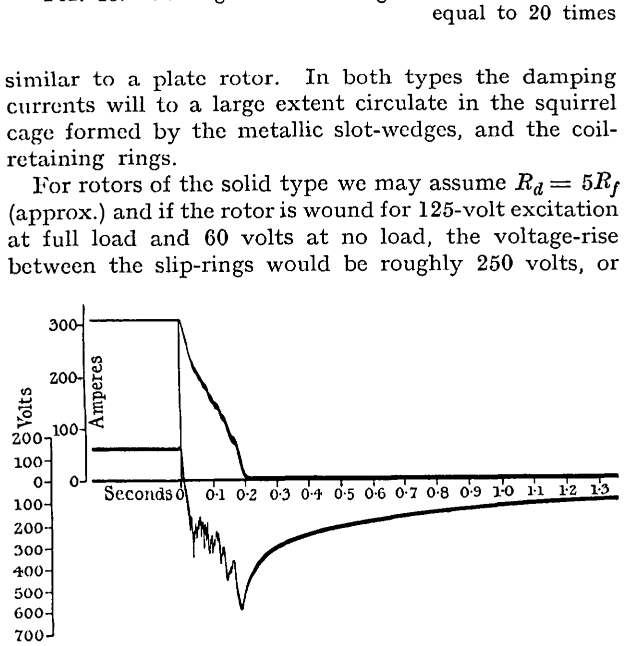

FIG. 16.—Oscillogram of discharge current on a 7 500-kVA, 3 000-r.p.m. turbo-alternator with discharge resistance equal to infinity, i.e. rotor open-circuited without discharge resistance.

The 7 500-kVA, 3 000-r.p.m. solid rotor gave a maximum voltage of 600 volts for a field current considerably in excess of the normal value.

The test illustrated in Fig. 14 was taken on an 8 900-kVA rotor built up of plates, and shows the highest voltage-rise observed on any of the tests. The actual peak observed was 1 200 volts measured between the two slip-rings, and the maximum voltage to earth would be one-half this value, or 600 volts, neglecting asymmetric capacity and insulation resistance. For a solid rotor of average output or size the figure would be 150 to 250 volts. This is an unexpectedly low value in view of the opinion generally held, i.e. that a break in the main field circuit would cause such an excessive voltage-rise as to lead to a certain breakdown. It is usual to test the field winding and the exciter circuit at 2 500 or 3 000 volts (R.M.S.) a.c., equivalent to a d.c. voltage to earth of 3 500 or 4 200 volts, and this test will therefore give a large margin of safety for any voltage-rise which would occur during operation of the protective gear. The discharge resistance which has hitherto been used in conjunction with automatic field switches is therefore unnecessary, there being no danger of an insulation breakdown if the main field is opened by means of an ordinary circuit breaker. It has been shown earlier in the paper that the discharge resistance has the undesirable property of preventing the rapid discharge of the field in case of a fault, and these resistances may therefore be omitted altogether for new installations; also those resistances which are already installed may be disconnected. This applies to machines having rotors of the solid cylindrical type. No investigations have been carried out on laminated rotors, but it will no doubt be permissible to follow the same course with these. As a precaution it may in these cases be desirable to make a trial during which a needle spark-gap is connected across the slip-rings. The needle gap should be set to operate at about 1 500 volts or over, according to the voltage at which the rotor has been tested. If no discharge takes place across the needles when the field is opened, the discharge resistance may be taken out of circuit. If a discharge takes place, indicating that there is practically no damping effect in the rotor, a discharge resistance is necessary to reduce the voltage-rise to a safe value. The voltage-rise between the slip-rings for a rotor without any damping effect may be estimated as being approximately equal to 0·8 (no-load field current) × (discharge resistance). A slip-ring voltage of 1 000 or more would generally be permissible.

The elimination of the discharge resistance will greatly increase the value of the protection obtained, save the unnecessary expense of resistance units and special switches, and reduce the number of moving parts, thus increasing the reliability of the switch.

AUTOMATIC FIELD SWITCH IN EXCITER FIELD CIRCUIT.

In the previous considerations the field switch has been assumed to be located in the main field circuit. Another method which is frequently used is to provide a small automatic switch in the exciter field circuit.

If the exciter field is opened, the exciter voltage disappears fairly rapidly even if a discharge resistance is used, as the stored energy in the exciter field is small compared with the copper loss in the exciter field winding. After the disappearance of the excitation voltage the main field current continues to circulate until the large amount of magnetic energy in the alternator field has been dissipated. The field winding during this time is practically short-circuited on itself, and the resistance in the discharge path would be one-half the amount which would be in circuit in the case of a main field switch and a 1 : 1 discharge resistance. The time of the discharge being inversely proportional to the total resistance, the discharge would therefore be twice as long.

It is generally advisable to provide direct-connected exciters with a series winding supplying a small percentage of the total ampere-turns. This winding has the effect of making the exciter more stable in the case of rapid variations of the exciter field rheostat, and prevents loss of field and reversals of polarity on the exciter. If such compound-wound exciters are used in connection with an exciter field switch the series winding has an additional retarding influence on the field discharge, which will therefore be extremely slow. In one case where this arrangement was adopted on a large unit, severe damage resulted to the stator winding and core during a stator breakdown.

Another minor disadvantage of locating the field switch in the exciter field circuit is that, due to the remanence of the exciter field, the main current is not quite interrupted and the alternator voltage cannot be reduced below approximately 5 per cent.

The oscillogram (Fig. 17) shows a field discharge on the previously mentioned 7 500-kVA rotor, the exciter field being opened. The discharge time to reach 20 per cent of the normal voltage is approximately 10 seconds, which is roughly twice as long as on the oscillogram (Fig. 11) taken with a main switch and a 1 : 1 discharge resistance. For a 23 500-kVA, 25-period alternator of recent design the discharge time to reach 10 per cent of the normal voltage would be roughly 60 seconds.

AUTOMATIC REVERSING SWITCH IN EXCITER FIELD CIRCUIT (SUICIDE CONNECTION).

In this method the field circuit of the exciter is opened and subsequently reversed. The reversal of the field has the advantage over the previous method that the remanence of the exciter is destroyed, and the remanent voltage on the a.c. terminals reduced. The discharge time depends only upon the total resistance in the discharge path, and in this respect there is no advantage compared with the simple exciter field switch. An oscillogram was taken with this connection, the other conditions being the same as in the oscillogram (Fig. 17). The discharge curve was found to be identical with the latter oscillogram and is therefore not reproduced.

An advantage could be obtained from the use of a reversing switch, by exciting the exciter field coils separately from an independent source and allowing the exciter to generate reversed voltage. The maximum reversed voltage obtainable would be approximately $1\frac{1}{2}$ times the full-load excitation voltage, or 4 times the no-load excitation voltage. We have seen that the opening of the main field circuit produces an instantaneous reversed slip-ring voltage. This reversed voltage is, at the moment of interruption, usually greater than $1\frac{1}{2}$ times the full-load excitation voltage but decreases gradually towards the end of the discharge.

The main field switch therefore produces a more rapid reduction of the current during the first period of the discharge, whereas the separately-excited reversed exciter would give a more rapid reduction for the final part of the discharge. The most rapid discharge could therefore be obtained by the following sequence of operations :—

(1) Open-circuit the main field.
(2) Simultaneously reverse the separate excitation of exciter.
(3) Close the main field again as soon as the reversed slip-ring voltage has dropped to a somewhat lower value than the reversed exciter voltage.
(4) Open the main field as soon as the a.c. voltage or the a.c. fault currents (not slip-ring voltages) have dropped to zero, to prevent building up the main field in the reversed direction.

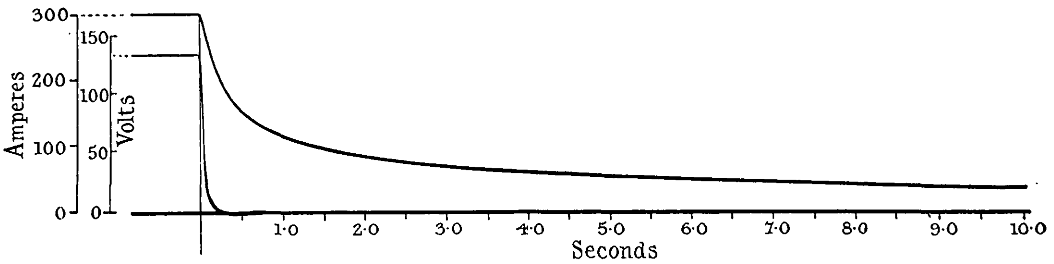

FIG. 17.—Oscillogram of discharge current on an 7 500-kVA, 3 000-r.p.m. turbo-alternator when exciter field is open-circuited.

A system of quick-acting relays could be arranged to obtain this result, but it is not likely that the advantage obtained would warrant the use of such complicated gear.

SLIP-RING SHORT-CIRCUITING SWITCH.

Another method of interrupting the field current is to establish a dead short-circuit between the two slip-rings. This will short-circuit the exciter armature, and some sparking will therefore occur on the exciter commutator unless a preventive resistance is used. This sparking is, however, not very severe and is of short duration, as the exciter immediately loses its field. From this point of view the method is quite practicable. The disadvantage lies rather in the fact that the resistance in the discharge path is smaller than in any other method, and the discharge time correspondingly lengthened.

The slip-ring short-circuiting switch has been used in practice in the method illustrated in Fig. 18. The automatic switch consists of a single-pole double-throw switch in the main field circuit. Normally the exciter armature is connected directly to the slip-rings, and the resistance R is short-circuited. In the operating position the slip-rings are short-circuited and the resistance is connected in series with the exciter armature. The exciter field is also short-circuited, and the exciter therefore is de-energized. The " loading resistance " eliminates sparking on the exciter commutator.

A disadvantage of this method, as previously explained, is the sluggishness of the field discharge. Due to the fact that no external resistance is inserted in the main field circuit during the discharge, the discharge time is practically the same as for a switch in the exciter field circuit.

The following table of data in regard to the previously mentioned 7 500-kVA, 3 000-r.p.m. turbo-alternator gives roughly the relative time of the field discharge for the different methods of connecting the switch :—

Method	Relative Time	Pressure between Slip-rings
		volts
Main field broken..	1	− 300
Ditto, but discharge resistance equal to field resistance ..	4	− 50
Exciter field opened or reversed	8	0
Slip-rings short-circuited.. ..	8	0

METHOD OF TRIPPING AUTO-FIELD SWITCH.

The field switch can be tripped in different ways, the following being those more usually adopted :—

(1) Direct from the fault-current relays.
(2) By means of an auxiliary switch on the main a.c. circuit breaker.
(3) By means of a combination of methods (1) and (2).
(4) A time-lag may be introduced after the tripping of the main switch.

If all apparatus belonging to the protective system could be absolutely depended upon, there is no doubt that method (1) would be preferable, on account of the more rapid action. It happens sometimes, however, that the relays operate for a fault outside the generator, due to faulty adjustment, or, if reverse-power relays are used, these may operate for a failure in the motive power. In these cases the field switch would be tripped and, if we assume further that the main breaker fails to operate due to a defect in the tripping mechanism, the sound machine will remain connected to the system with the field out of circuit. It is often assumed that such an operation contributes a grave danger. As a matter of fact, nothing serious happens if the field circuit of one of several parallel-running alternators is interrupted for a short time. The alternator if of the cylindrical type will operate as an induction generator, and increase its speed slightly, thus losing part of its watt load. The current drawn from the system will be mainly a wattless magnetizing current and this will cause a voltage-drop on the system. This voltage-drop will be severe only if the affected machines constitute a large percentage of the total plant capacity. The increase in speed can immediately be detected by the ear, due to the beats produced by the interference of the machines running at slightly different speeds.

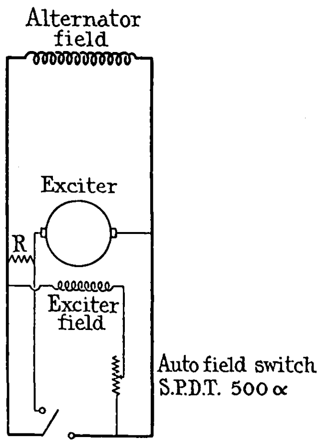

FIG. 18.—Automatic field-suppression. Slip-ring short-circuiting system with exciter protection.

NOTE.—R is a loading resistance, not to be less than about 50 per cent of the main field resistance for momentary service.

A case has recently come to the author's knowledge where the field of a 23 500-kVA alternator was interrupted due to an accidental opening by hand of the exciter field circuit. The machine was at the time operating in parallel with other plant of a capacity roughly equal to its own capacity. The current drawn from the line was observed to be approximately 60 per cent of the full-load current, which corresponds to the magnetizing current operating as an induction generator ; no other serious disturbance occurred. Other similar cases have occurred on sets of smaller capacity. It might be worth while to mention here that neither reverse-power relays of the usual type, nor balanced-current relays, will operate in the case of loss of field, as has sometimes been stated in literature and patents on this subject.

The next possibility is that in the case of faults occurring in the machine the main a.c. breaker fails to open. If the field is not interrupted the system will feed into the fault, as will also the defective generator itself. If the field is interrupted the faulty machine will not contribute to the fault currents. The energy flowing into the fault, and the damage, will therefore be appreciably reduced, particularly if the faulty machine is large compared with the other plant in parallel with it.

The object of method (4) is to prevent large voltages being induced in the rotor due to the inductive effect of the fault currents in the stator. For the same reason it has also been proposed to connect over-tension devices between the rotor slip-rings. Experiments carried out by the author on a machine with a solid rotor have shown that the voltages induced in the rotor in the case of a stator fault are of even smaller magnitude than those observed for a direct opening of the main field circuit under no-load conditions, and therefore not of a dangerous nature.

The conclusion is, therefore, that operation directly from the fault-current relays (method 1, see Fig. 19) is the most satisfactory method, although there would not be much to choose between methods (1), (2) or (3) if the main breaker is very quick-acting and is periodically tested to eliminate all possibility of "sticking."

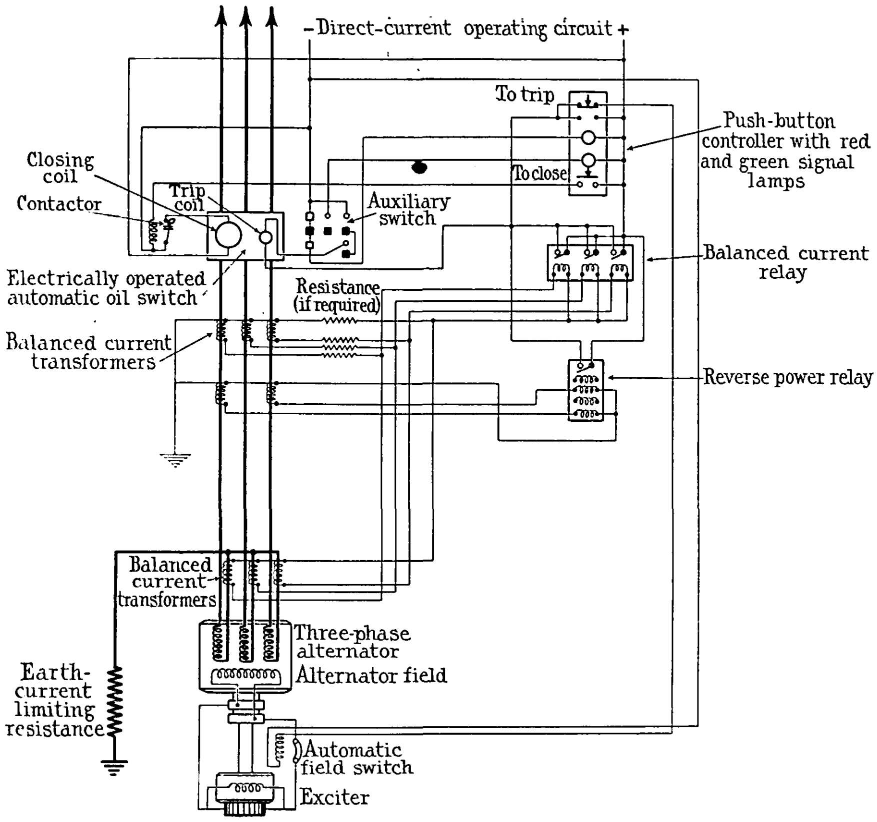

FIG. 19.

EXTINGUISHING OF FIRE.

Although the installation of electrical protective devices greatly reduces the possibility of fire in the windings, it is still advisable to provide means for extinguishing a fire in the extreme case of the protective gear failing and the winding becoming ignited. The usual method of extinguishing is to apply a hose or a fire extinguisher through the inspection covers in the stator end guards. This is a very drastic method and should be used only as a last resort; also there is usually so long a delay in applying the extinguisher that the winding is ruined. If serious damage is to be prevented extinguishing must be done *immediately* after the accident and preferably automatically by the action of the fault-current relays, and an extinguisher must be used which will not ruin the insulation. It is sound practice to provide air dampers in the air inlet and outlet, which are automatically closed by means of solenoids energized from the protective relays.

Fig. 20 shows the arrangement adopted for a 15 000-kW set. A point which requires attention on these dampers is the leakage, as the volume of air normally circulating is so large that even a small part of it is sufficient to sustain a fire which has been well started. As soon as the dampers are closed the air pressure generated by the fans rises considerably, as shown in Fig. 21. It will be seen that the pressure rises from a normal value of 7 inches to a maximum of 15 inches if the damper is completely closed. The dampers must therefore be made to fit well; also the generator casing and end guards should be designed for as small clearances as possible. It is highly probable that many air dampers, particularly in the case of large machines, would fail to extinguish a fire on account of excessive leakage.

Another advantage of dampers in the air ducts is that the air circulation can be positively stopped while the generator is not in operation, thus preventing condensation of humidity due to the natural draught in the building. Such condensation may also take place when a cold machine is started up and the air temperature is above the temperature of the machine. When this condition occurs it is therefore advisable not to open the dampers before starting up, but to leave the dampers closed until the generator has attained a temperature above that of the cooling air.

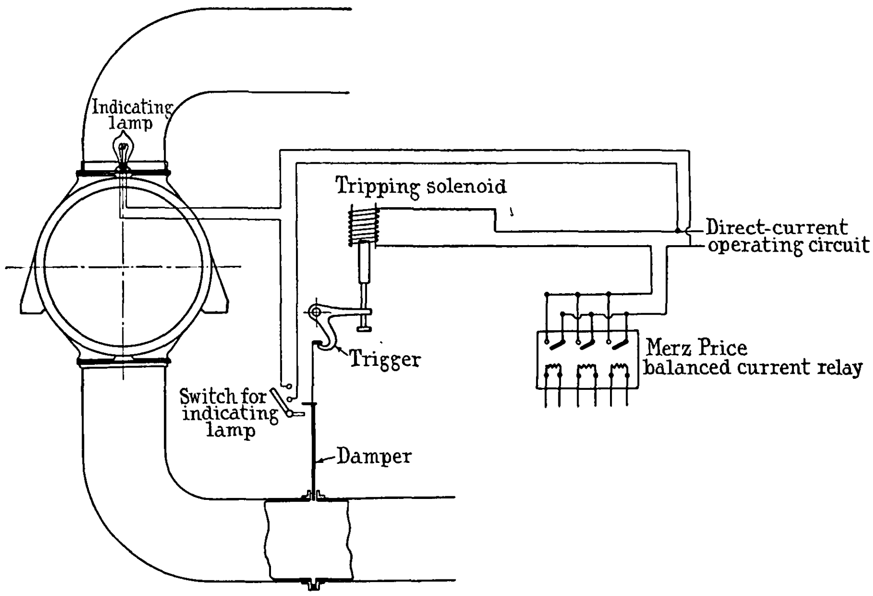

FIG. 20.

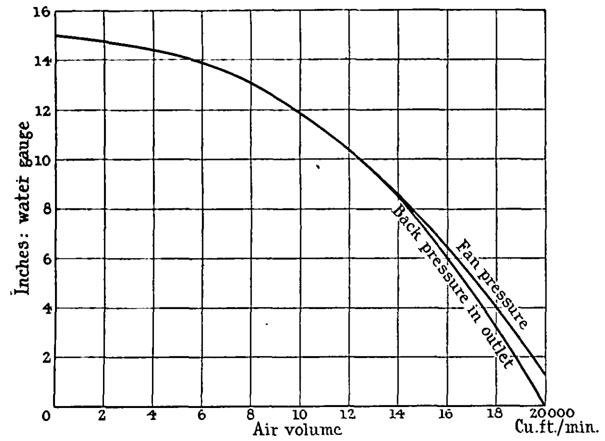

FIG. 21.—(Air pressure)/(air volume) curve for a 5 000-kVA, 3 600-r.p.m. turbo-alternator.

In addition to the use of air dampers some engineers strongly recommend the provision of pipes inside the end bells, through which steam may be turned upon the windings. This method is being employed by several power-station engineers, more particularly on the Continent and in the United States, and seems to give good results. Interesting data on this subject are given by M. A. Savage in the *General Electric Review*, Jan. 1918. In this article tests made to investigate the effectiveness of extinguishing by steam are described. The general conclusions reached are that steam will extinguish any fire due to burning insulation, providing the following recommendations are followed :—The leakage of the air dampers should be less than 10 to 20 per cent. A sufficient volume of steam should be admitted to displace the volume of air contained in the machine. Outlet dampers are more effective than inlet dampers. The insulation when properly dried out will not be materially damaged.

The method is also being used by the Duquesne Light Co., Pittsburgh, U.S.A., on some 18 000-kVA, 12 000-volt machines. This company reports that during a peak on the system it has been possible to put a machine back on the line after a fire without shutting down the steam end or examining the winding. This method of procedure would, however, not be recommended generally, even by the strongest advocates of the system.

The author is of opinion that such a system of steam pipes can be recommended. The only doubtful point is the influence of the hot steam on the insulation. It is not likely that the condensed steam can penetrate very far into the interior of the insulated windings, and a thorough drying-out after the application should remove all moisture. The temperature of the steam cannot rise above 100° C. after expansion through the nozzles, and this temperature cannot harm the insulation. Arrangements should be made to prevent any steam leaking past the inlet valve during normal operation. This can be effected by providing two interlocked valves in series and a water drain between the two valves. A tell-tale hole should be provided between the valves to detect any leakage of the first valve. It is not advisable to operate the steam valves automatically from the Merz-Price relays, as only in case of actual fire is their operation required. It would, however, be possible to install thermo-electric relays in the generator and operate the valves from these. In this case, however, there is still a possibility that the steam jets may be operated by an accidental closing of the relays.

Instead of using steam it is, of course, possible to use water, and some engineers prefer this. The author believes, however, that the steam is likely to do less damage to the generator than is the water.

The difficulties of extinguishing fire are practically eliminated when the circulating system is used, as the amount of air available for sustaining the combustion is limited. For a 12 000-kW generator the total volume of air in the circulating system would be approximately 1 500 cubic feet. The total weight of combustible material on one end of a generator of this size would be approximately 400 lb. To burn completely this weight of material would require approximately 30 000 cubic feet of air, i.e. approximately 20 times the volume actually present. Thus it would appear that if there is no great leakage of air into the system, the burning cannot be very extensive. Damage due to the electric arc would, however, continue until the field was "killed," and the generator disconnected from other running machines.

Conclusions.

(1) In spite of every precaution which can reasonably be expected, breakdowns will sometimes occur in the insulation of a.c. generators.

(2) A comparatively small electric arc may set fire to the combustible material on the end windings. This fire being fanned by the blowers will speedily develop into a general conflagration of the end windings, totally destroying the insulation and often doing other damage. If the fault occurs inside the core serious burning of the laminations may result, necessitating a complete rebuilding of the core.

(3) If the generator can be disconnected from the busbars and its field "killed" immediately after the fault occurs, ignition of the insulation and burning of the core laminations can usually be prevented. In such cases the damage is ordinarily of a comparatively insignificant nature, and can be rapidly and cheaply repaired.

(4) The balanced-current protection system is the simplest and most satisfactory one yet devised for operating the protective gear in the event of faults to earth, or between phases on a generator. Its weakness lies in the fact that it does not operate on faults between turns of the same phase. Such faults, if they do occur, will develop into an earth or fault between phases.

(5) The protective system proposed by the author and Mr. J. R. Beard operates under all fault conditions, but it introduces certain complications in the auxiliary apparatus. The system has not yet been tried on a scale sufficient to recommend its general adoption at the present time. It is recommended that the system be installed on a few sets to obtain experience of its behaviour under actual operating conditions.

(6) The possibility of preventing extensive damage in the event of a fault occurring in a generator winding depends largely upon the speed with which the main circuit breaker can be opened, and the voltage reduced on the generator terminals. This necessitates opening the main field circuit of the generator.

(7) Calculations and tests show that there is little risk in opening the main field circuit even in the case of large generators. Currents set up in the field-circuit core body and in the slot wedges retard the collapse of the field to such an extent as to limit the induced pressure to a safe value. The various schemes proposed for opening or reversing the exciter field circuit or short-circuiting the main field give results many times slower than opening the main field circuit.

(8) There is no gain in interlocking the field switch with the main circuit breaker so that the former will not open if the latter fails to operate, for in the event of a fault less damage is likely to be done with the circuit breaker closed and the field switch open than if both remain closed.

(9) Inlet and outlet dampers should be provided in the air ducts. These may be arranged to close automatically in the event of a breakdown in the generator winding, and should be kept closed at all times when the generator is not in operation.

(10) It is sound practice to install steam pipes inside the end bells of generators, so that steam may be turned into the generator in case of fire. This operation should not be automatic, on account of possible damage to the insulation of the machine, and would be used only if a fire actually started.

(11) With the closed air-circulating system serious burning is not likely to occur, but protective gear should be installed to limit the extent of the electrical burning.

(12) A complete protective system for a turbo-generator set would consist of the following :—

- Balanced protective gear.
- Inlet and outlet air dampers.
- Automatic cut-off valve on turbine, and vacuum breaker on condenser.
- Main circuit breaker and field switch.
- Steam pipes inside the end bells.

All the above safety devices, with the exception of the steam supply to the end bells, could, without risk to the plant, be made to operate automatically upon the occurrence of a fault in the generator.

It is questionable whether the complete protective system outlined above is necessary, as a fire can usually be prevented if the main field is "killed" instantaneously.

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