flow in opposite directions through R, so that there is no current when $I_1 = I_2$ and $i_1 = i_2$. This method is called the *circulating current* method.

Fig. 208 shows an alternative method, known as the *opposed voltage* method. The relay is in series with the two secondaries, which are connected so that their e.m.f.'s oppose.

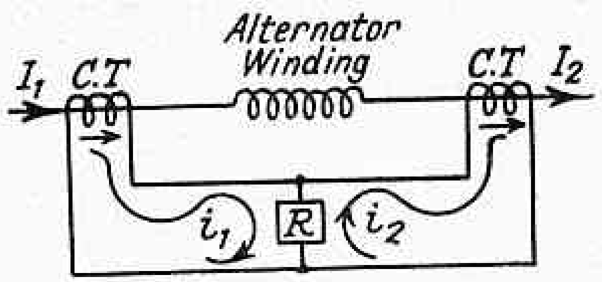

FIG. 207. CIRCULATING CURRENT METHOD OF TESTING BALANCE

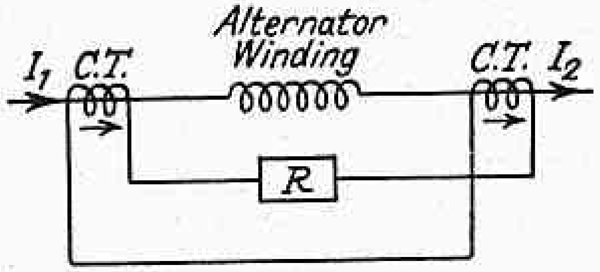

FIG. 208. OPPOSED VOLTAGE METHOD OF TESTING BALANCE

A very important disadvantage in simple balance systems is due to the inequalities of current transformers. Thus an external fault may lead to a large current; then, although the currents in the

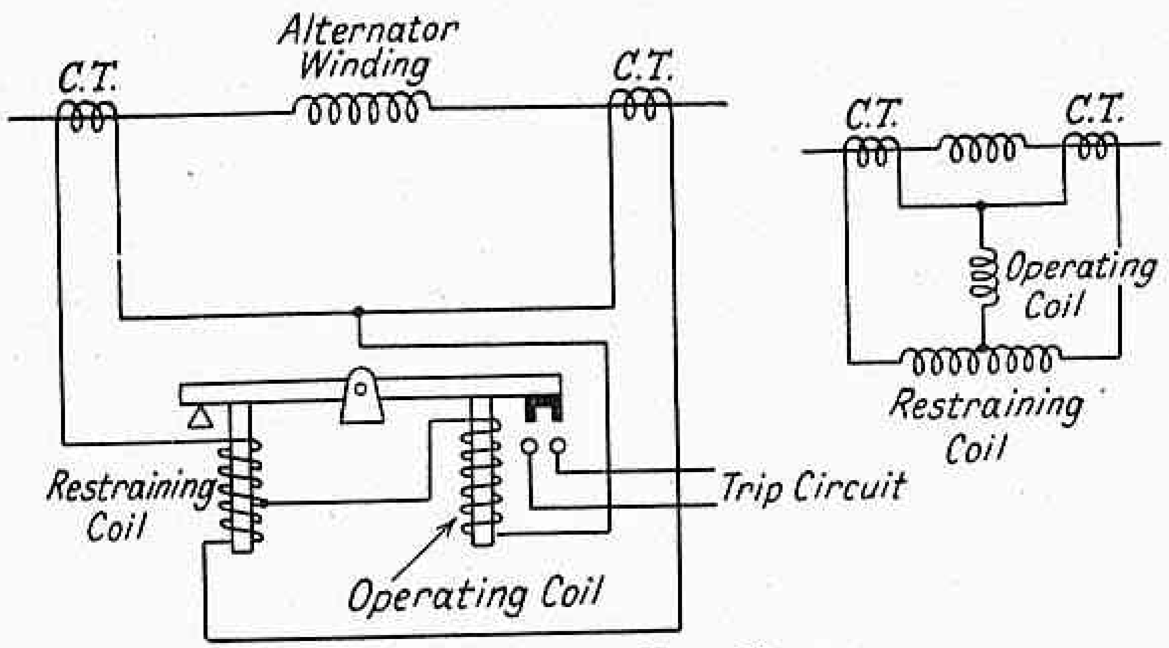

FIG. 209. BIASED BEAM RELAY

primaries of the current transformers are equal, they may produce e.m.f.'s which vary by more than the permissible difference if they are ten or twenty times the normal current.

This disadvantage is overcome by the use of *bias*. Fig. 209 shows a *biased beam* relay. The system is still the circulating current system of Fig. 207, but there is in addition a restraining coil which carries both circulating currents. Thus if the currents are large, there is a comparatively large restraining force which cannot be overcome by an error in the current transformers. It can be seen that the relay operates when the ratio I_1/I_2 differs from unity by

more than a certain amount, which is adjustable by varying the number of turns of the restraining coil.

A similar result can be achieved by biasing the relay mechanically by moving the fulcrum nearer to one side, or magnetically by having two operating coils each of a different number of turns.

Protection of Alternators and Transformers. It is not considered advisable to have overload protection for alternators, which are now designed to withstand their complete short-circuit current without danger. They are disconnected by hand.

If the steam supply is cut off, there is no occasion to disconnect the alternator, as it will run as a motor and take a small current.

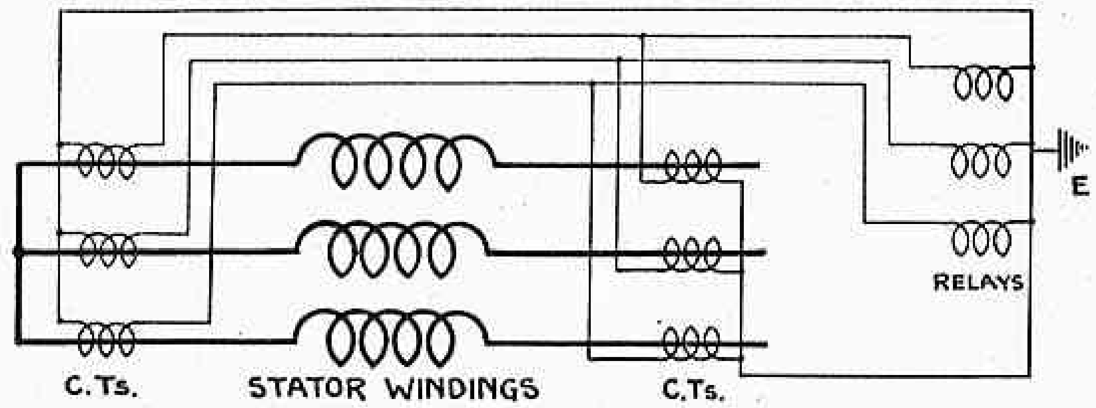

FIG. 210. MERZ-PRICE SYSTEM FOR ALTERNATOR
(*Automatic Protective Gear* (Henderson))

It will keep in synchronism, and operate when the steam supply is restored.

The result of a failure of the field of an alternator is very uncertain and depends upon the load and the condition of the machine. The machine can be switched out by means of an under-current relay in the field circuit. The occurrence of a field failure is, however, rare, and automatic protection is not often provided.

The most dangerous fault in an alternator is a failure of the insulation, for then the machine will feed current into its fault and destroy itself.

If an earth fault occurs on the stator windings whose star point is earthed, power will flow through the fault to earth. If this power is greater than the load supplied, the machine will receive power from other generators and reverse power protection will suffice. The reverse power relay can contain two wattmeter elements, as used in measuring three-phase power, or three single-phase wattmeter elements. As the reverse power relay will not act unless the power sent into the fault is greater than the output of the machine, the method is not satisfactory and is obsolescent.

Self-balance protection is the most useful method for alternators and transformers. Fig. 210 shows the Merz-Price system, in which three pairs of current transformers are connected to relays. When the currents at both ends of each winding are equal, equal e.m.f.'s

CHAPTER X

VOLTAGE TRANSIENTS AND LINE SURGES

Introduction. There are various ways in which a transmission line may experience voltages greater than the working value, and it is necessary to provide protective apparatus to prevent or minimize the destruction of the plant. Internal causes producing a voltage rise are (1) resonance, (2) switching operations, (3) insulation failure, and (4) arcing earths: a very important external cause is lightning.

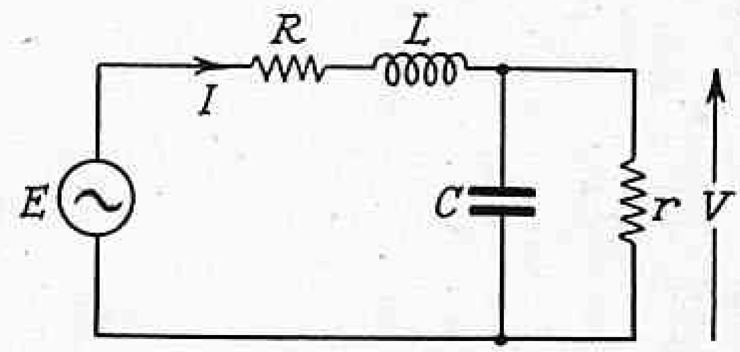

FIG. 237. RESONANCE

Resonance. The effect of resonance is most easily understood by considering the voltage at the end of a lightly loaded cable of short length. The alternator and transformers may be represented by their leakage inductance L, and the cable by a capacitance C. The system is then as shown in Fig. 237, where R represents the resistance of the alternator winding, transformers and cable, and r the resistive load. The total impedance of the circuit is

$$Z = R + j\omega L + \frac{(1/j\omega C)r}{1/j\omega C + r} = R + j\omega L + \frac{r}{1 + j\omega Cr},$$

the current is

$$I = E/Z,$$

and the voltage on the cable is

$$V = I \times r/(1 + j\omega Cr),$$

since the latter expression represents the impedance of the parallel combination of C and r. Substituting for I in terms of E we get

$$V/E = \left(\frac{r}{1 + j\omega Cr}\right) \div \left(R + j\omega L + \frac{r}{1 + j\omega Cr}\right)$$

$$= \frac{1}{1 + (R + j\omega L)(1/r + j\omega C)}$$

$$= \frac{1}{(1 - \omega^2 LC + R/r) + j\omega(L/r + CR)}$$

The magnitude of (V/E) is

$$|V/E| = [(1 - \omega^2 LC + R/r)^2 + \omega^2(L/r + CR)^2]^{-\frac{1}{2}} \quad . \quad (112)$$

The voltage at the termination is thus

$$E_T = E + E' = \frac{2R/(1 + pCR)}{Z + R/(1 + pCR)}\,E$$
$$= \frac{2R}{Z(1 + pCR) + R}\,E.$$

It must be remembered that $p = d/dt$ and E is a voltage which is zero until $t = 0$ and E after $t = 0$. E_T may be found in the following way.

$$E = \frac{Z(1 + pCR) + R}{2R}E_T$$
$$= \tfrac{1}{2}(pCZ + Z/R + 1)E_T$$
$$= \tfrac{1}{2}CZ(dE_T/dt) + \tfrac{1}{2}(Z/R + 1)E_T.$$

This is a linear differential equation for E_T of which the solution is

$$E_T = \frac{2E}{Z/R + 1} + A\varepsilon^{-[(Z + R)/CZR]t},$$

where A is an arbitrary constant and is determined by the fact that E_T can rise at a finite rate from its zero value. This gives

$$A = -\,2E/(Z/R + 1)$$

so that
$$E_T = \frac{2E}{Z/R + 1}\,[1 - \varepsilon^{-[(Z + R)/CZR]t}]$$
$$= E_{T0}\,[1 - \varepsilon^{-[(Z + R)/CZR]t}],$$

where E_{T0} is the voltage at the end when there is no capacitance. Fig. 251 shows the graph of E_T. The effect of the capacitance is to cause the voltage at the end to rise to the full value gradually instead of abruptly, i.e. it flattens the wave front. It is usual to specify the condition of the wave-front by stating the time the wave takes to increase from 10 to 90 per cent of its value and multiplying by 1·25. If the wave reaches x of its value in time t

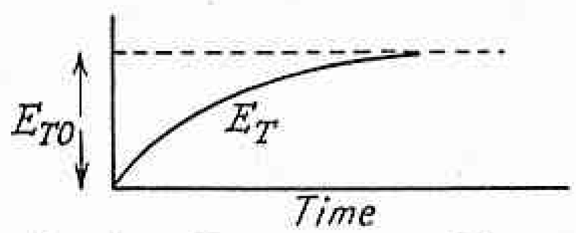

FIG. 251. FLATTENING OF WAVE DUE TO SHUNT CAPACITANCE

$$1 - \varepsilon^{-[(Z + R)/CZR]t} = x,$$

so that
$$t = \frac{CZR}{Z + R}\,\text{logh}\left(\frac{1}{1 - x}\right).$$

The specifying time in this case is therefore

$$1{\cdot}25\,.\,[CZR/(Z + R)]\,[\text{logh } 10 - \text{logh } 1{\cdot}11]\text{ sec.}$$
$$= 2{\cdot}75\,CZR/(Z + R)\text{ sec.}$$

In the case of a capacitance at a point of a line which stretches in both directions away from it, $Z = R$ and the time is

$$1{\cdot}37CZ\text{ sec.}$$

Thus a 10 000 $\mu\mu$F. capacitance in a line of surge impedance 500 ohms flattens the wave so that the time of the wave-front becomes

$$1{\cdot}37 \times 10^{-8} \times 500\text{ sec.} = 6{\cdot}9\ \mu\text{sec.}$$

Flattening the wave-front has a very beneficial effect, as it reduces the stress on the line-end windings of a transformer connected to the line.

Lightning. With the increase of high-voltage overhead lines the problem of lightning is assuming greater importance, and much

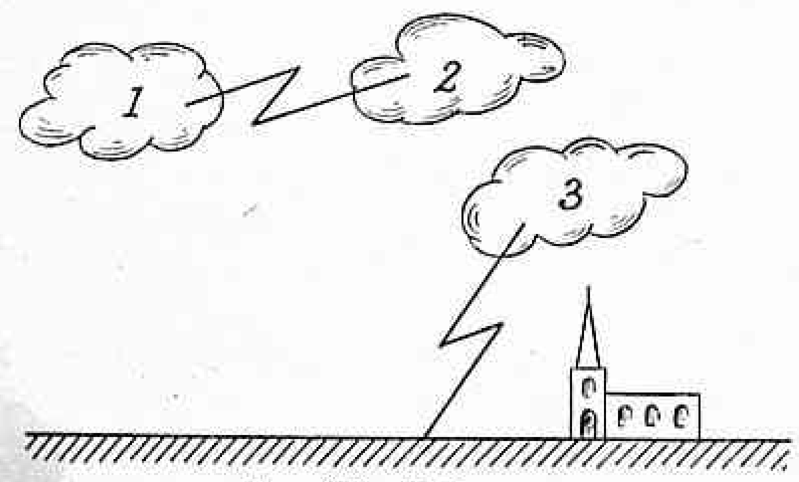

FIG. 252. B STROKE

damage is done yearly by lightning. There are two main ways in which lightning affects a line: by a direct stroke, and by electrostatic induction. The way in which thunderclouds get charged up to very high potentials is complicated and not known precisely.

A direct stroke can take place in several ways. In one way the charged cloud induces a charge of opposite sign on tall objects, such as tall masts, church spires, etc. The electric stress at the top points of these objects causes ionization of the air, and eventually a direct stroke takes place between the cloud and the object. Such a stroke is known as the *A stroke*, and is characterized by the comparatively long time taken to produce it and the fact that it strikes the highest point, usually a lightning conductor. Another way results in a much more sudden stroke, which is produced in the manner shown in Fig. 252. Three clouds are involved, and the potential of cloud 3 is decreased by the presence of the charged cloud 2. When cloud 1 flashes over to cloud 2, both these clouds are discharged rapidly; then cloud 3 assumes a much higher potential and flashes to earth very rapidly. This is the *B stroke*, and is characterized by its rapidity and the fact that it ignores tall jects and reaches earth in a random manner. A direct stroke may cause a potential of 10 million volts, and shatter insulators and towers in its vicinity. The most that can be hoped from protective devices is that they will limit the damage and prevent the resulting travelling waves from affecting the plant. Fortunately direct strokes are rare.

The majority of surges in a transmission system are due to lightning, and are caused by electrostatic induction in the manner

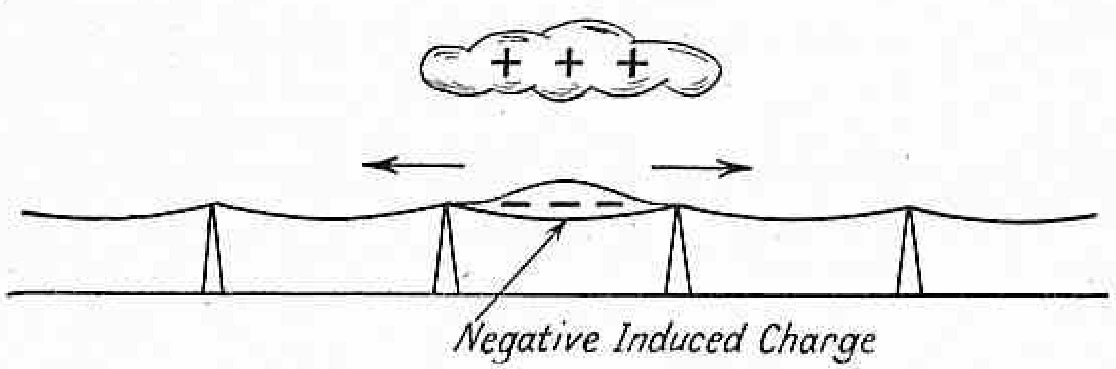

FIG. 253. SURGE DUE TO ELECTROSTATIC INDUCTION

indicated in Fig. 253. A positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction. The induced positive charge leaks slowly to earth via the insulators. When the cloud discharges to earth or to another cloud, the negative charge on the line is isolated as it cannot flow quickly to earth over the insulators. The line thus acquires a high negative potential, which is a maximum at the place nearest the cloud and falls slowly

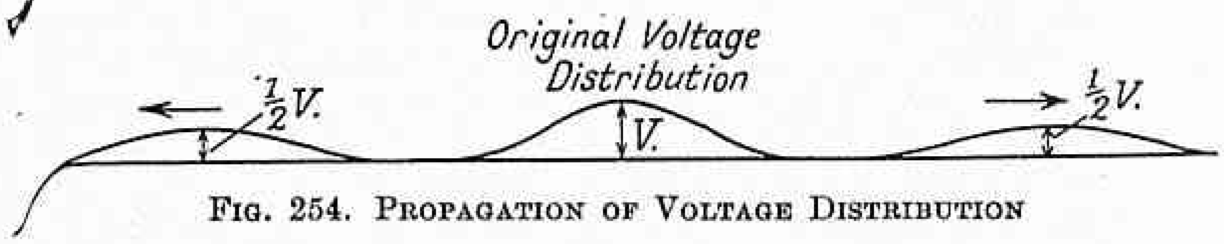

FIG. 254. PROPAGATION OF VOLTAGE DISTRIBUTION

to a small value at a distance. The charge will flow from a higher to a lower potential and the result is travelling waves in both directions. The two waves will be equal and thus each will have half the potential of the charge at the time of the discharge of the cloud; they will also have the space-voltage distribution of the original charge, as shown in Fig. 254. The waves travel in exactly the same way as the waves due to switching, so that the current at any point of the line is the voltage divided by the surge impedance. In a line without resistance or leakage the waves travel without change of shape, but the effect of resistance and leakage is to attenuate the wave and to flatten the wave-front.

The steepness of the wave-front depends upon the space-voltage distribution. If the wave reaches its maximum in 1 000 ft., the time

that it takes for the wave to reach the maximum when it passes a point is

$$\frac{1\ 000}{186\ 000 \times 5\ 280}\ \text{sec.} = 1{\cdot}02\ \mu\text{sec.}$$

Waves have been recorded with wave-fronts of 1 to 80 μsec. and wave-tails of 3 to 200 μsec. A very steep wave-front may be obtained when a thundercloud is near a building which the line enters. The building screens the line inside from the cloud, so that the induced charge stops abruptly at the building. Extra precautions are therefore necessary where an overhead line enters a building.

Arcing Earths. In the early days of transmission it was the practice to insulate the neutral point of three-phase lines, for then

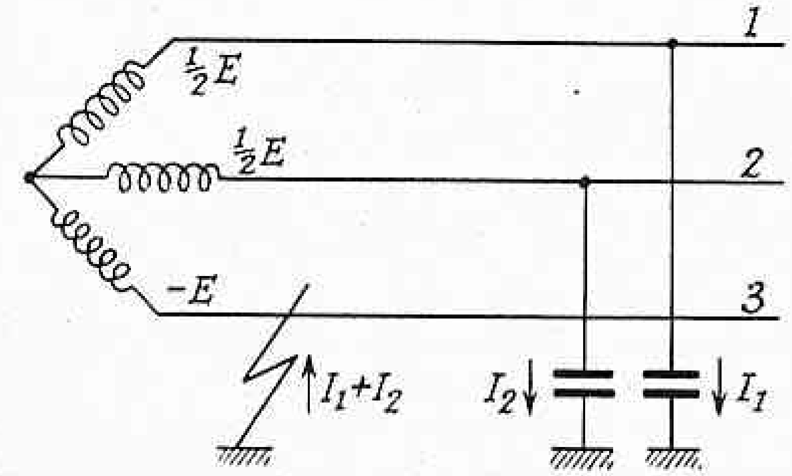

FIG. 255. ARCING GROUND IN THREE-PHASE LINE

an earth on one phase would not put the line out of action; this also eliminated the longitudinal (or zero phase-sequence) current and resulted in a decrease of interference with communication lines. Insulated neutrals gave no trouble with short lines and comparatively low voltages, but it was found that when the lines became long and the voltages high a serious trouble was caused by *arcing earths*, which produced severe voltage oscillations of three to four times the normal voltage. These oscillations were cumulative, and hence very destructive. Arcing earths are eliminated in this country and in America by solid earthing of the neutral, whilst in Germany the neutral is earthed through an inductance (a *Petersen coil*).

There are two accepted theories of arcing earths, in one of which the arc is extinguished at the normal frequency, and in the other at the frequency of oscillation of the line. Let us consider the *normal-frequency arc-extinction theory* for a three-phase line.

Fig. 255 shows a three-phase line. Suppose that line 3 arcs to earth when its voltage to neutral is a maximum $-E$. At this instant lines 1 and 2 have voltage $+\frac{1}{2}E$. Before the arcing earth objects and reaches earth in a random manner. A direct stroke may cause a potential of 10 million volts, and shatter insulators and towers in its vicinity. The most that can be hoped from protective devices is that they will limit the damage and prevent the resulting travelling waves from affecting the plant. Fortunately direct strokes are rare.

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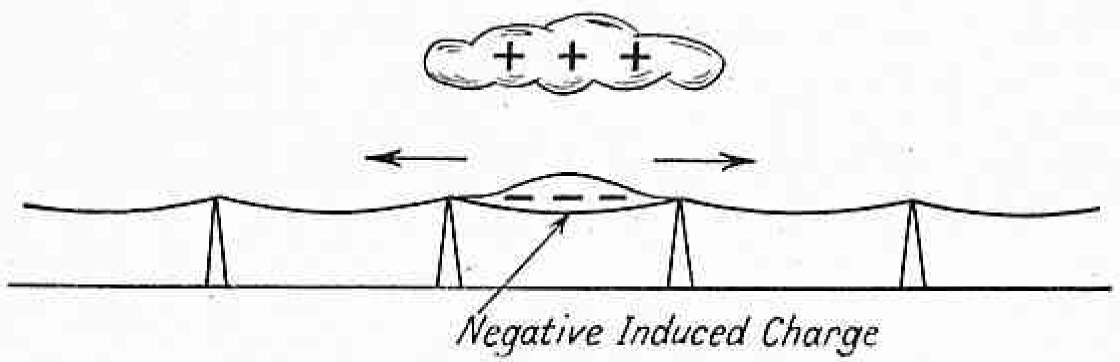

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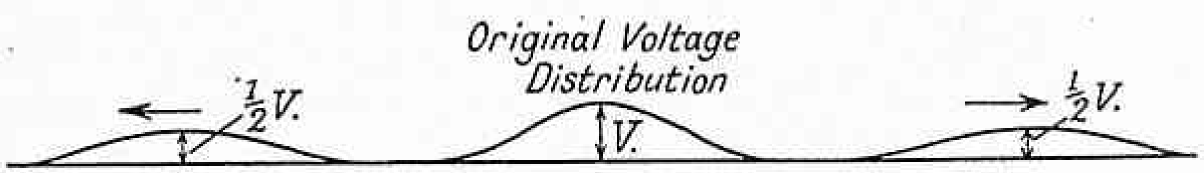

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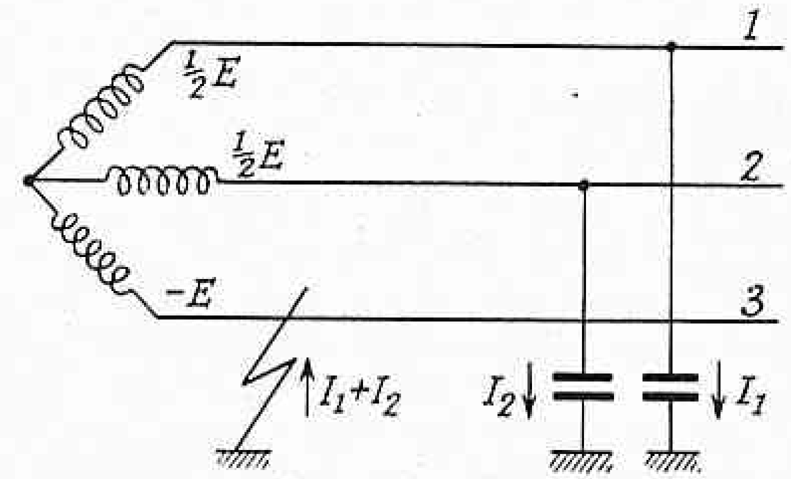

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Fig. 255 shows a three-phase line. Suppose that line 3 arcs to earth when its voltage to neutral is a maximum $-E$. At this instant lines 1 and 2 have voltage $+\frac{1}{2}E$. Before the arcing earth occurs the capacitances of the lines cause the neutral to be at or near the earth potential, so that the earthing of line 3 causes a sudden voltage of $+E$ to be applied to lines 1 and 2. The ultimate steady state would then be for the lines 1 and 2 to be at potential $\frac{3}{2}E$. But we have shown that when an e.m.f. E is suddenly switched into a circuit of low resistance, the voltage in the circuit oscillates between 0 and $2E$ with a frequency $1/2\pi\sqrt{(LC)}$ (see equations (115*a*) *et seq.*), where L and C are the inductance and capacitance in the circuit. The voltage of lines 1 and 2 will therefore oscillate rapidly between the original value of $\frac{1}{2}E$ and $\frac{1}{2}E + 2E = \frac{5}{2}E$. The high frequency oscillation dies out rapidly. The arc is fed through the capacitances of the lines, as shown in Fig. 255, and will go out when the sum of the capacitance currents passes through zero. The capacitance currents lead the voltages by 90°, so that when their sum $I_1 + I_2$ is zero the line voltages are $E_1 = -\frac{3}{2}E$, $E_2 = -\frac{3}{2}E$, and $E_3 = 0$. If the arc were to remain extinct, the voltages would have to be these values plus E, viz. $E_1 = -\frac{1}{2}E$, $E_2 = -\frac{1}{2}E$, and $E_3 = +E$. Thus the faulty line 3 would have a maximum voltage again, and so arc to earth again. In other words, when line 3 arcs to earth the capacitance currents of lines 1 and 2 maintain the arc until the voltage of line 3 attains its opposite maximum voltage with respect to the neutral; then at the instant when the capacitance currents would allow the arc to go out, line 3 arcs again to ground. We saw that at the instant that the arc is extinct the lines are at potentials $-\frac{3}{2}E$, $-\frac{3}{2}E$, and 0. The charges due to these potentials diffuse rapidly through the system in an oscillatory manner, with the average voltage $\frac{1}{3}(-\frac{3}{2}E - \frac{3}{2}E + 0) = -E$ as the mean position. This is equivalent to an insertion of an e.m.f. of $\frac{1}{2}E$ in lines 1 and 2, so that an added voltage E is applied to these lines. When the arc restrikes, lines 1 and 2 acquire potentials of $-\frac{5}{2}E$ plus this new value $-E$, so that the maximum voltage is $\frac{7}{2}E$. We see therefore that the healthy lines are subjected to a voltage of $3\frac{1}{2}$ times the normal value. As this state can be maintained for a considerable length of time, in a known case 30 min., by the continued arcing, it is very dangerous.

Petersen Coil. We have seen that the capacitance currents I_1 and I_2 maintain the arc even when the voltage of the faulty line 3 is too low to restrike it. In fact these currents have the particularly harmful effect of maintaining the arc until the very moment when the voltage of line 3 is sufficiently high to restrike it. If the neutral is earthed through an inductance L of such a value that the current it passes neutralizes $I_1 + I_2$, the normal frequency follow current through the arc is

$$I_L + I_1 + I_2 = 0.$$

The arc is then extinguished except for the brief moments when the voltage of line 3 passes through its maximum value and can restrike it.

It has been found that the Petersen coil is completely effective in preventing any damage by an arcing earth, and is therefore used extensively on the Continent. The coil is usually provided with tappings, so that its value can be adjusted to suit the capacitances of the system. It is found that effective operation is secured when the inductance is 90 to 110 per cent of the theoretical value for exact neutralization of the capacitance currents.

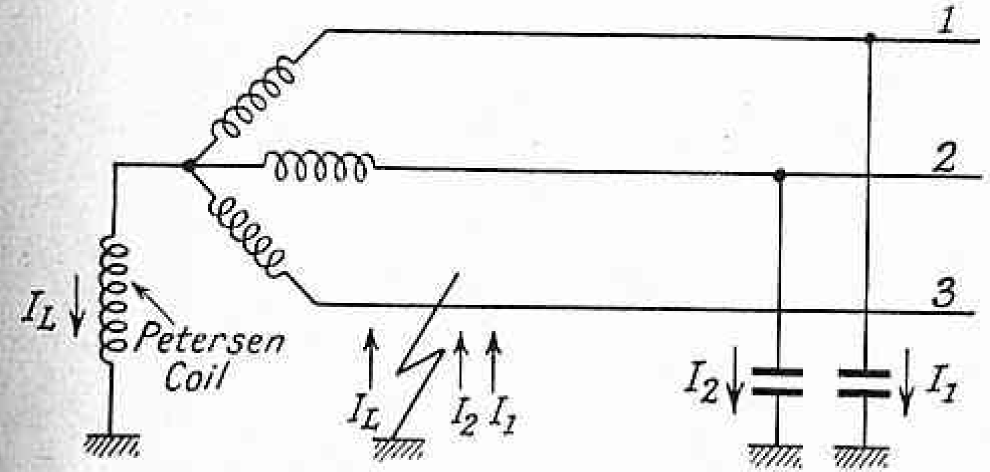

FIG. 256. PETERSEN COIL

Lightning and Over-voltage Protection. The insulation of a transmission system is always designed to withstand voltages of twice the normal value for a reasonable length of time, as switching surges often produce voltages of this magnitude. It is clearly uneconomical to design the system so that the insulation can withstand the very high voltages that may be encountered from extraneous or fault conditions, and recourse is had to protective devices which are adjusted to break down before the insulation, or otherwise prevent a dangerous voltage from damaging the insulation.

Dangerous voltage rises are found to be due to the following: (1) surges due to direct lightning strokes or induced voltages, (2) arcing earths, (3) comparatively low-voltage high-frequency oscillations, (4) static overvoltage. The protective apparatus for these classes are: (1) ground wire and lightning arresters, (2) earthing of neutral solidly or through a Petersen coil, (3) surge absorber or capacitance, (4) water-jet earthing resistance, earthing inductance, or solid earthing of the neutral point.

It is true to say that with the advent of high-voltage overhead lines, such as the Grid, the main cause of damage is lightning. We have seen that most travelling waves due to lightning are caused by electrostatic induction. The latter can be reduced considerably by the use of earth wires running above the transmission line and earthed at every pole or tower. If C_1 is the capacitance of the cloud to the line and C_2 the capacitance of the line to ground, the induced voltage on the line is $C_1/(C_1 + C_2)$ times the cloud voltage. The presence of the earth wire *above* the line causes a considerable increase in C_2 and reduction of the line voltage. The induced voltage could be very much reduced by an array of earth wires above the line, but this is too expensive to install in practice.

The earth wire also provides considerable protection against direct strokes (of the A type), provided the earth resistance of the earth wire is kept low. If the current in the stroke is I and the earth resistance is R, the voltage of the earth wire is IR, and unless R is low this voltage may be sufficient to cause a flash-over from the earth wire to the lines. The earth resistance should be of the order of 10 to 20 ohms.

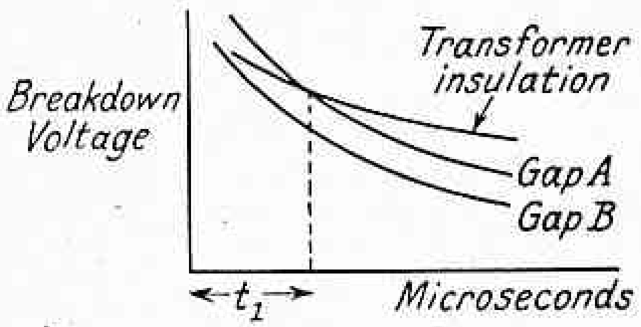

FIG. 257. VARIATIONS OF BREAKDOWN VOLTAGE WITH TIME OF APPLICATION

The earth wire affords an additional protective effect by causing an attenuation of any travelling waves that are set up, by acting as a short-circuited secondary. For this reason its resistance should not be too large. It is usually made of steel, which has a high permeability and thus possesses a resistance which increases with frequency.

Having reduced the magnitude of induced voltages by means of an earth wire, we still find it necessary to install protective apparatus to prevent, or at least minimize, the damage due to the surges that do occur. It is, moreover, essential that the system shall be considered as a whole from the point of view of protection, so that the least essential and most accessible parts protect the more important apparatus; this involves the *co-ordination of system insulation*. The problem is rendered difficult by the fact that the breakdown voltages of the various parts of the system and of the protective apparatus behave differently with time; thus a horn gap which is set to flash-over at 100 kV. at 50 cycles may require 200 kV. in a wave lasting for 20 μsec., or 300 kV. in a wave lasting for 5 μsec. We define the *impulse ratio* of any piece of apparatus as the ratio of the breakdown voltage of a wave of specified duration to the breakdown voltage of a 50-cycle wave; thus the horn gap has an impulse ratio of 2 at 20 μsec., and 3 at 5 μsec. When a method of co-ordinated insulation is considered, the impulse ratio of the various parts must be known or the protection will not be adequate. Fig. 257 illustrates the point. Suppose that the insulation of a transformer to be protected has the breakdown voltage-time characteristic shown. Gap A may be set to break down at a lower voltage than, say, 80 per cent of the breakdown voltage of the insulation at 50 cycles. The gap, nevertheless, does not protect the transformer, as its characteristic rises more rapidly than that

of the transformer insulation as the duration of the wave decreases. Then for waves of duration less than t_1 the transformer insulation breaks down before the gap. It is necessary to narrow the gap so that the characteristic is as shown for gap B before the transformer is completely protected. In practice it is not possible to narrow the gap so much that the insulation is protected for waves of the smallest duration, as then the gap would flash over at very low voltages at 50 cycles; a compromise is reached by protecting the insulation for voltages of waves down to a certain minimum time, which is found experimentally to be comparatively harmless.

Sphere Gap. A sphere gap in which the spacing is small compared with the diameter of the spheres has the useful advantage that the

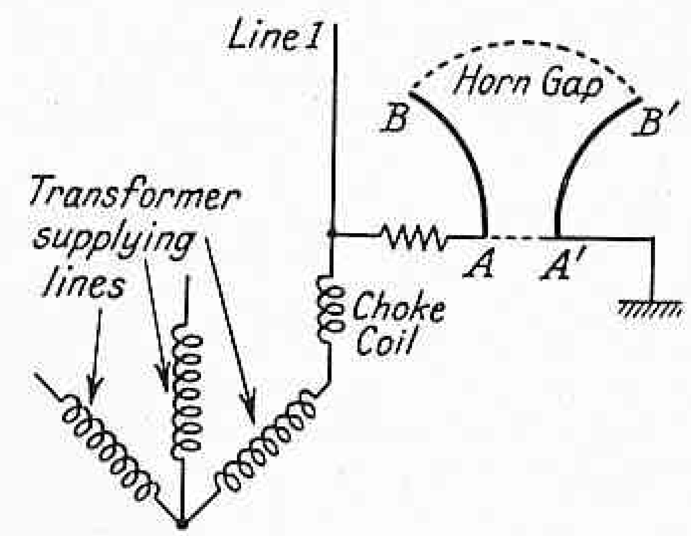

FIG. 258. HORN GAP WITH CHOKE COIL AND RESISTANCE

impulse ratio is unity. If then the apparatus is protected against 50-cycle waves, it is protected against a wave of any duration. Unfortunately, when the sphere gap flashes over, the power current maintains the arc, which requires only a very low voltage to maintain it, and the arc is not self-extinguishing. The circuit-breakers would have to intervene to break the arc current and the service is interrupted. For this reason the sphere gap is not of use.

Horn Gap. Fig. 258 shows a simple sketch of the horn gap. The gap is set so that a flash-over occurs between A and A' at a voltage of 150 to 200 per cent of the normal voltage. The power current creates an arc, which may be considered to be a flexible conductor. A flexible electric circuit moves so as to embrace as many lines of magnetic force as possible, so that the arc is forced up to the position BB'. Another factor tending to blow the arc up to BB' exists when BB' is above AA', for then the arc heats the air and forms a vertical draught. The result is that the arc is forced up to BB', where the gap is wide and the normal voltage is insufficient to maintain it. The arc is thus extinguished, usually in about 3 sec.

The horn gap cannot rupture arc currents much in excess of

10 amperes, and as the arc is a dead short circuit it is necessary to limit the current to a small value. This is done by inserting a resistance, between the line and the horn on the line side, which reduces the current to about 5 amperes. The efficacy of the horn gap is seriously reduced by the resistance. The resistance is a water column, oil-immersed metal wire, carbon rod, or carborundum, and is made as non-inductive as possible.

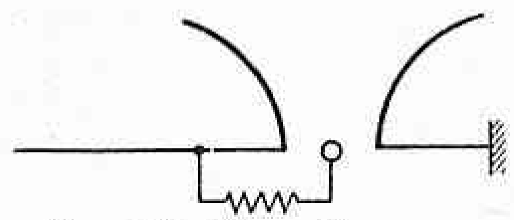

FIG. 259. HORN GAP WITH AUXILIARY ELECTRODE

It is found that high-frequency waves concentrate at the line-end turns of a transformer, so that although the magnitude of the wave on the line is not very great, the stress at the turns near the line is very high and may cause puncture between turns. This difficulty is overcome by the insertion of choke coils, as shown in Fig. 258.

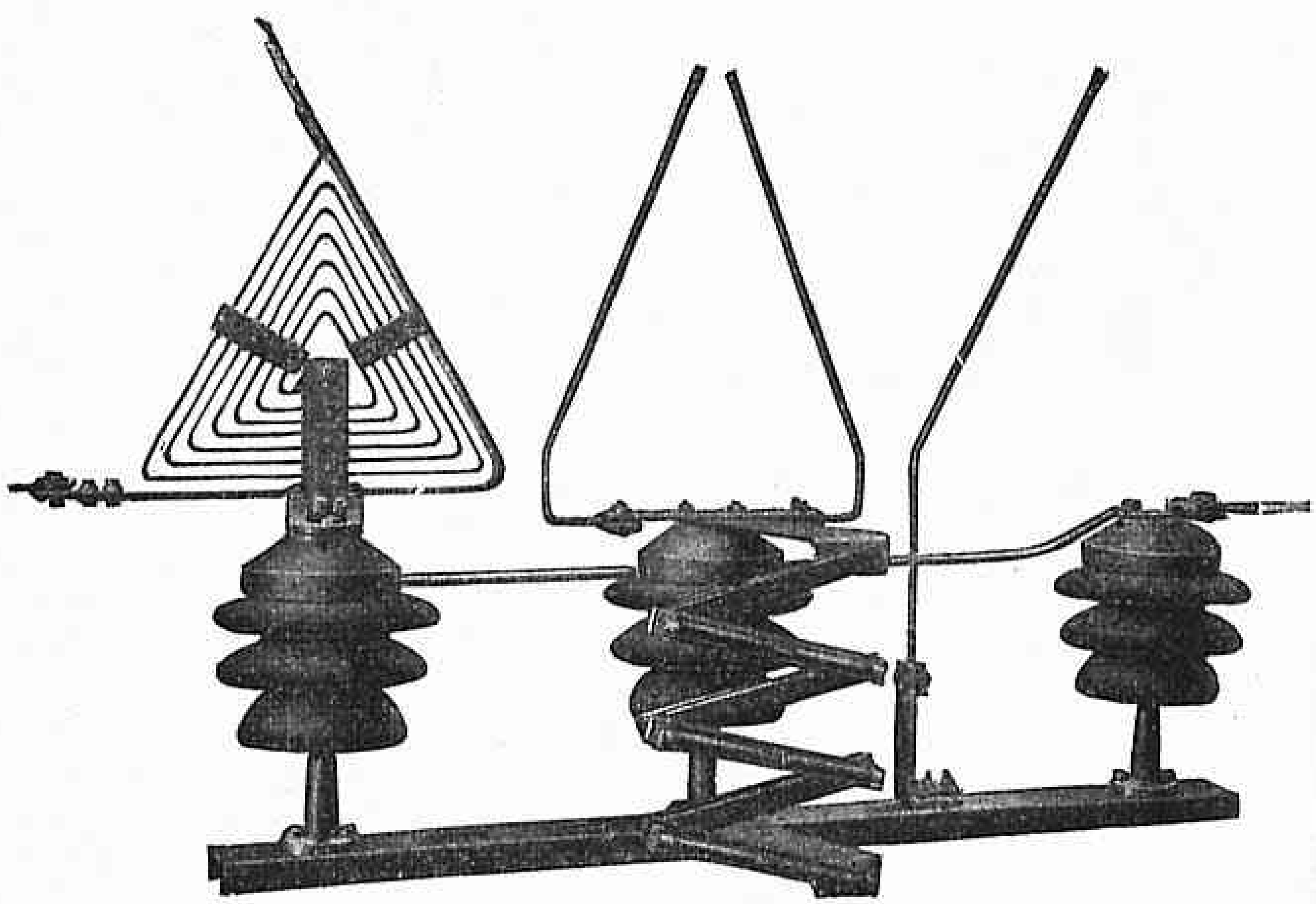

FIG. 260. BURKE ARRESTER
(Metropolitan-Vickers)

The high-frequency wave is then reflected back to the horn gap, where the doubled voltage causes a flash-over. The choke is without effect on the low-frequency power wave.

For small settings the horn gap is sensitive to corrosion or pitting of the horns, so that it does not maintain its setting. This difficulty is overcome in the arrester shown in Fig. 259. The main gap is

set for a voltage well above that to be protected. The auxiliary gap has a platinum electrode, which possesses the character of permanence. When an over-voltage occurs the auxiliary gap flashes over and ionizes the air, and then the main gap flashes over.

Burke Arrester. Fig. 260 shows the Burke arrester. The line current passes through a triangular pancake choke coil, one side of which forms half of the main gap. Severe over-voltages flash across the main and auxiliary gap direct to earth. Less severe voltages flash over the main gap only, and the current is then limited by the resistance.

Multi-gap Arrester. This consists of a number of small gaps in series with a limiting resistance. Another resistance is placed across some of the gaps adjacent to the limiting resistance.

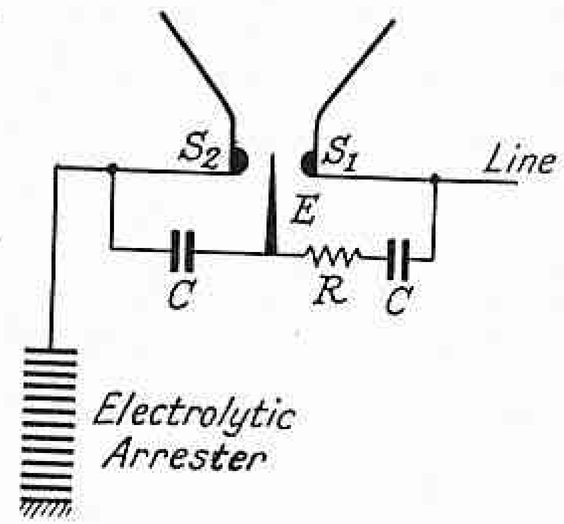

FIG. 261. IMPULSE GAP WITH ELECTROLYTIC ARRESTER

Impulse Protective Gap. It was pointed out that the sphere gap has an impulse ratio of unity, but suffers from the disadvantage that the arc between its electrodes is not self-extinguishing. The horn-gap, however, extinguishes the arc but has a high impulse ratio, 2 or 3. The impulse protective gap is designed to have a low impulse ratio, even less than unity, and to extinguish the arc. Fig. 261 shows a diagram of the impulse gap. S_1 and S_2 are sphere-horn electrodes, and are connected to the line and an electrolytic arrester, respectively. An auxiliary needle electrode E is placed mid-way between S_1 and S_2, and is connected to them via (R, C) and C. At the power frequency the impedance of the capacitances C is very much greater than that of R, so that the potential of E is mid-way between those of S_1 and S_2 and the electrode has no effect on the flash-over between them. At very high frequencies the impedance of C is small, so that E is at the potential of S_2 and the gap is effectively half the previous value. Flash-over takes place between S_1 and E at a voltage less than that required to flash-over between S_1 and S_2. An impulse ratio less than unity can thus be obtained. The electrolytic arrester on the earth side extinguishes the arc.

Electrolytic Arrester. This is the earliest type of arrester with a large discharge capacity. The action depends upon the fact that a thin film of aluminium hydroxide immersed in electrolyte presents a high resistance to a low voltage, but a low resistance to a voltage above a critical value. The critical breakdown voltage is about 400 volts, and voltages higher than this cause a puncture and a free flow of current. The insulating film of hydroxide is formed by applying a direct voltage up to the critical value to aluminium plates immersed in the electrolyte; during the formation of the

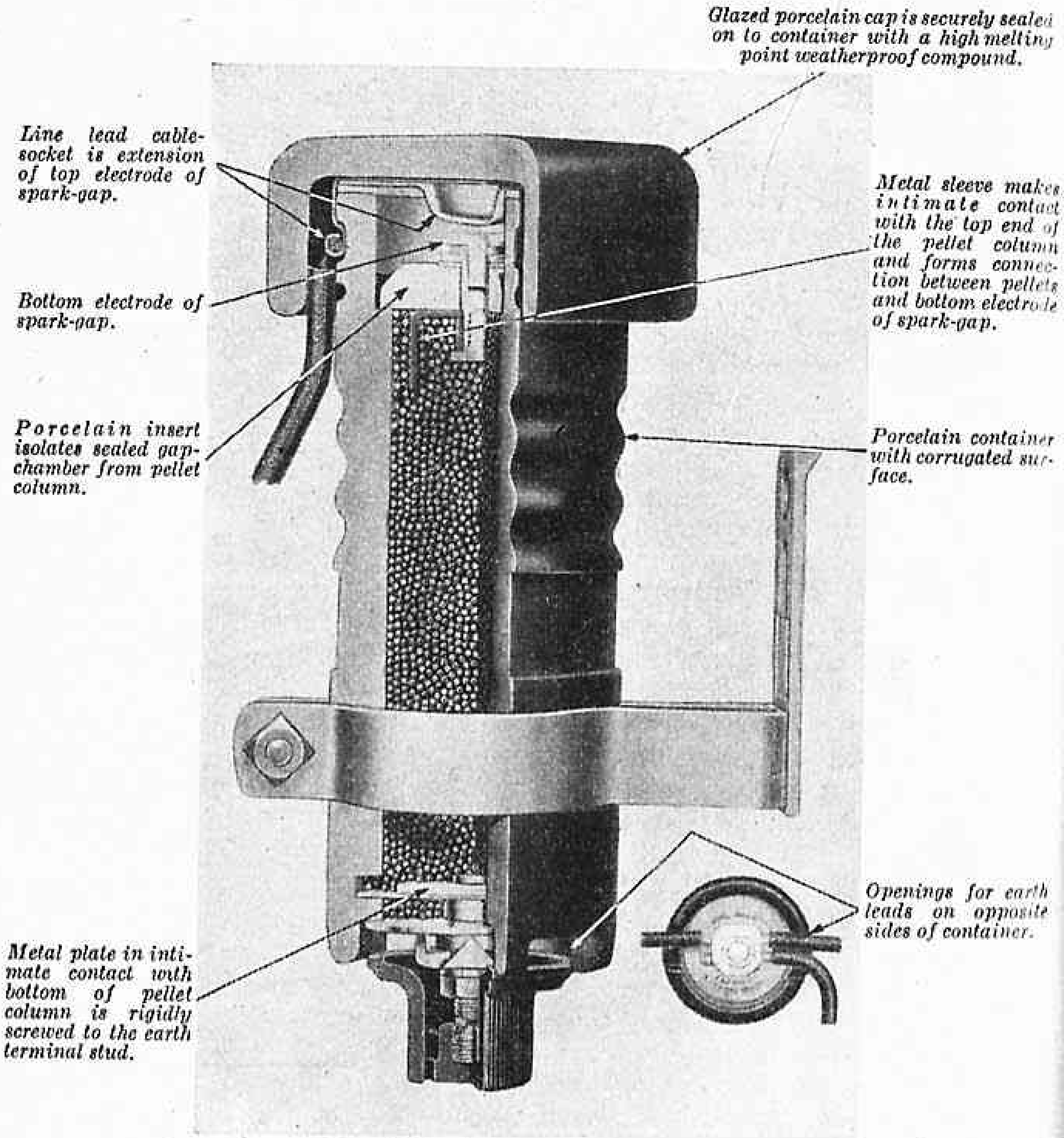

FIG. 262. OXIDE-FILM ARRESTER
(*B. T.-H.*)

film, current passes fairly readily, but when the film is formed the current ceases.

Stacks of films are arranged one above the other and the total critical voltage is equal to the critical voltage of each film multiplied by the number of films.

Daily supervision and reforming of the films is essential, and for

this reason the arrester is being replaced by the more robust oxide-film and auto-valve arresters. The electrolytic arrester is used in conjunction with an impulse gap, for the continual leakage and capacitance currents would damage the arrester.

Oxide-film Arrester. Fig. 262 shows the construction of the oxide-film arrester of the pellet type. The lead peroxide pellets are in a column of $2\frac{1}{4}$ in. diameter, the length of the column being 2 in. per kV. of rating. The tube contains a series spark-gap. A single tube system is available for voltages up to 25 kV. when the neutral is solidly earthed, and 18 kV. when the neutral is isolated or earthed through an inductance coil. For higher voltages several units are placed in series.

The pellets have a diameter of approximately $\frac{3}{32}$ in. and are made of lead peroxide with a thin porous coating of litharge.

Auto-valve Arrester. This consists of a number of flat discs of a porous material stacked one above the other and separated by thin mica rings. The material is made of specially prepared clay with a small admixture of powdered conducting substance. The discharge occurs in the capillaries of the material and is thus constrained to be a glow discharge, in which there is a voltage drop of about 350 volts per unit. The narrow gaps between the blocks are of sufficient total width to prevent flash-over due to the normal voltage, so that no current flows in the arrester under normal conditions. This arrester is very effective, robust and cheap, and is being rapidly introduced into modern high voltage systems.

Thyrite Arrester. Thyrite is a dense inorganic compound of a ceramic nature, which has a resistance that decreases rapidly from a high value at low currents to a low value at high currents. The current increases 12·6 times when the voltage is doubled; thus if the current-voltage relation for a given block of thyrite is

$$E = kI^n,$$

then

$$2E = k(12{\cdot}6I)^n,$$

so that

$$2 = 12{\cdot}6^n,$$

i.e.

$$n = \log 2 \div \log 12{\cdot}6 = 0{\cdot}27.$$

Thus the voltage varies approximately as the fourth root of the current. Fig. 263 shows the current-voltage curve of the 11 kV. thyrite arrester of Fig. 264. There are eleven thyrite discs sprayed on both sides to provide a good surface contact; each disc has a diameter of 6 in. and thickness $\frac{3}{4}$ in., and will discharge several thousand amperes without the slightest tendency to flash over the outside edge. When passing 2 000 amperes each disc has a voltage of only 5 kV. At the normal voltage of 11 kV. to earth, the peak voltage is $(11\sqrt{2} \div \sqrt{3})$ kV. = 9 kV. and the current in the arrester is only 3·2 amperes. When one phase is earthed the peak voltage on the other phases is $11 \times \sqrt{2} = 15{\cdot}6$ kV. and the arrester passes

25 amperes. A series gap is provided to prevent current from flowing at the normal voltage. The value of k for the stack is 6 500, or 600 per disc.

When the gap and arrester flash over, a high current flows for the duration of the surge, which is discharged to earth rapidly as is shown by oscillographic records; there appears to be absolutely no time-lag in the thyrite itself. The normal frequency follow-current is very small, 3·2 amperes in a healthy system, and only 25 amperes in a system with an earthed phase. The gap is easily able to clear this small follow-current.

Some modern modifications of the thyrite arrester include a type in which resistance blocks of a ceramic nature are spaced at equal distances from one another. The total gap length is adjusted so

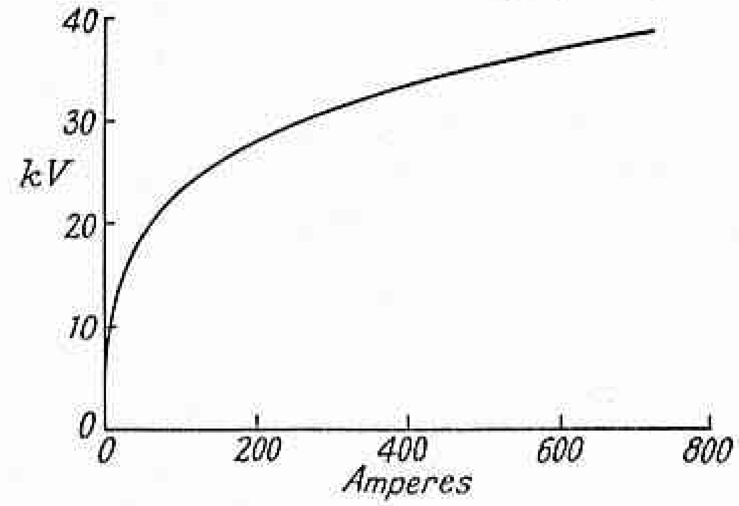

FIG. 263. VOLTAGE-CURRENT CURVE OF THYRITE ARRESTER

that the gaps flash over at twice normal voltage; it is claimed that the distributed gaps behave better than a single gap. Round knobs are provided between the electrodes of the gaps so as to reduce the time-lag. The action of the resistance blocks is similar to that of thyrite.

Condensers. We have shown on pages 290–22 that the effect of a condenser, placed between the line and earth, on a travelling wave is to reduce the steepness of the wave-front. This effect protects the windings of a transformer near the line, since a steep wave-front causes very high stresses in these turns.

The condenser, moreover, protects the transformer against comparatively low-voltage, high-frequency waves. The normal-frequency voltage produces only a very small current in the condenser, so that negligible loss is caused during normal operation.

The latest type of condenser used for protective purposes has a dielectric of acetyl cellulose, the electrodes being silver plating on the strips of the dielectric.

Surge Absorber. A pure condenser of the type described in the previous section cannot dissipate the energy in the wave-front of a travelling wave or in a high-frequency oscillation. It merely reflects

the energy away from the apparatus to be protected, and the energy is dissipated in the resistance of the line conductors and the earthing resistances. If a resistance is placed in series with the condenser, the combination can dissipate part of the energy in addition to diverting it from the apparatus. Such a combination is called a *surge absorber*.

Another type of absorber consists of an inductance across which is placed a resistance. This combination is placed in series with the

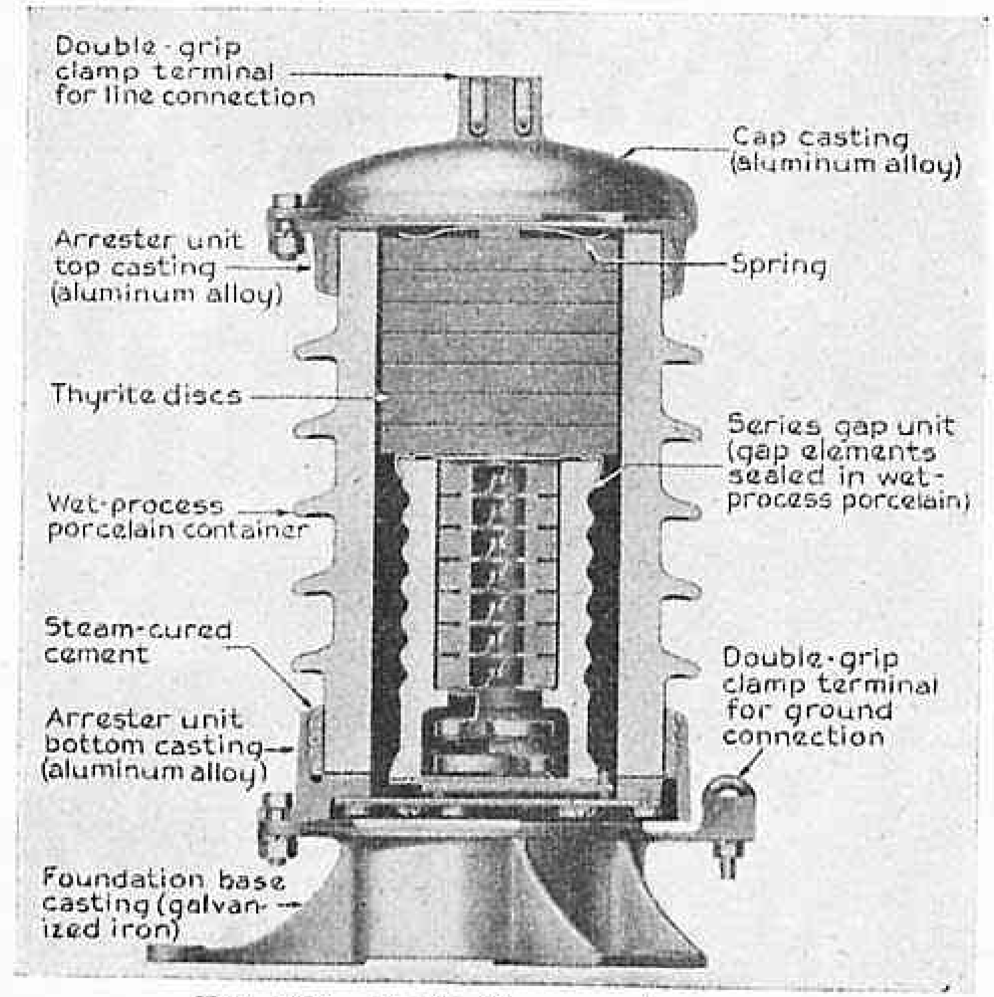

FIG. 264. 11 KV. THYRITE ARRESTER
(*International General Electric Co. of New York, Ltd.*)

line. Steep wave-fronts or high-frequency waves find the inductance a high impedance path and are forced through the resistance, where they are dissipated. The normal-frequency currents find the inductance a low impedance path and pass through it without much loss.

The *Ferranti surge absorber* consists of an inductance coil, which is coupled magnetically, but not electrically, to a metal shield and/or the steel tank which contains it. The coil is of a cylindrical or pancake form, depending upon the voltage; for voltages above 33 kV. the coil is cylindrical and has inside it a metal shield in which currents are induced. The absorber is enclosed in a cylindrical boiler-plate tank, provided with porcelain-guarded terminals, and is vacuum-impregnated with a light transformer oil. Fig. 265 shows a 66 kV. surge absorber of this kind. The equivalent circuit of this absorber is shown in Fig. 266. There is a filter effect which prevents high frequency currents from passing freely through the absorber;

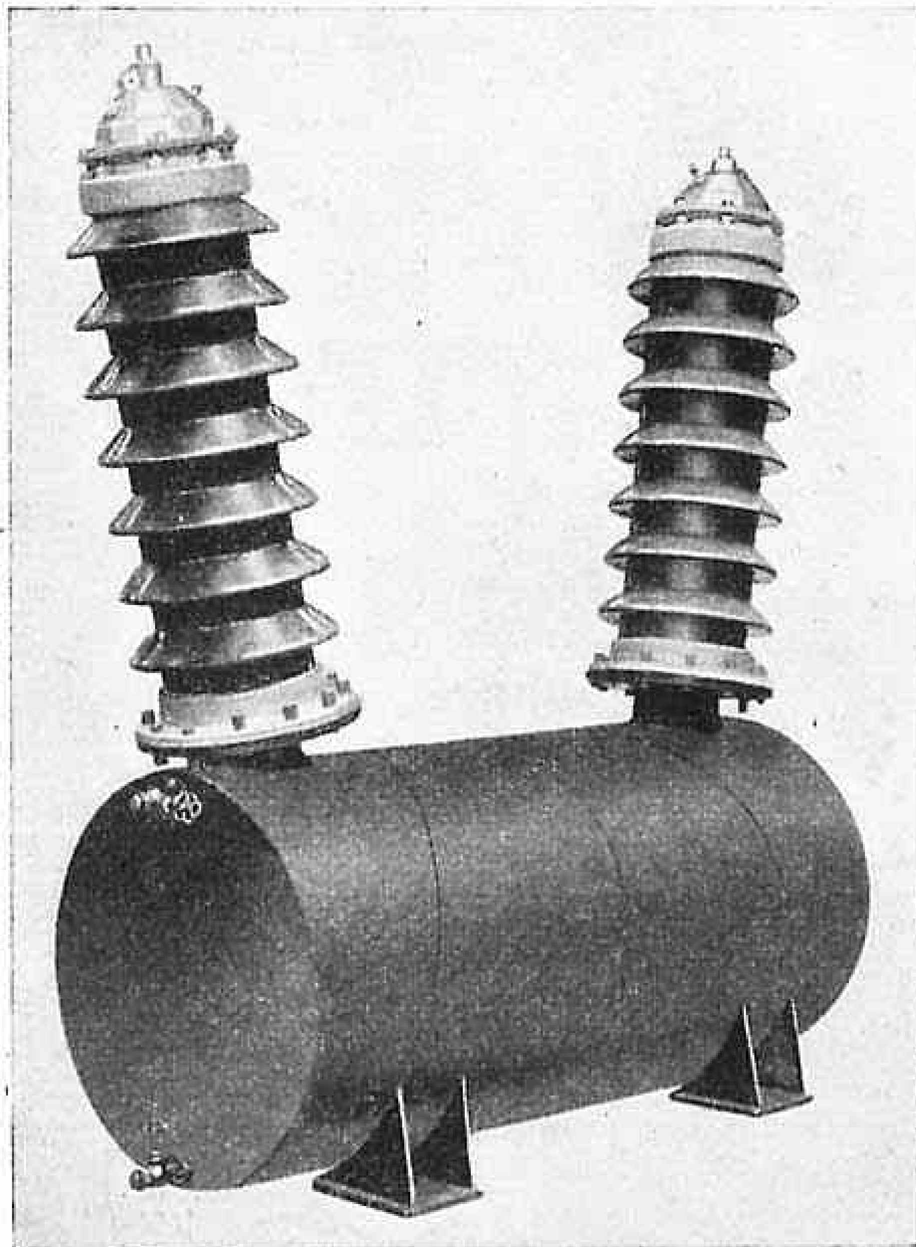

FIG. 265. FERRANTI SURGE ABSORBER
(I.E.E. Students' Journal)

also energy is transferred from the wave by the mutual induction between the coil and the shield and tank into the latter two, where the energy is dissipated as heat.

Recording of Transmission Line Surges. There are three methods of recording transmission line surges, by the high-voltage cathode-ray oscillograph, the klydonograph, and the surge-crest ammeter. These will be described briefly.

HIGH-VOLTAGE CATHODE-RAY OSCILLOGRAPH. This is the only instrument capable of delineating the voltage-time characteristic of a wave. Fig. 267 shows a high-speed cathode-ray oscillograph manufactured by Metropolitan-Vickers. The tube is continuously evacuated and the pressure in the deflection tube is 10^{-4} mm. of mercury or less. The cathode is cold and at a potential of 50 or 60 kV. above the anode, which is earthed.

The essential process is the following. A supply of electrons is obtained by the ionization of the residual gas in the discharge tube, and these are made to travel with an enormous velocity under the accelerative effect of the applied voltage. The electrons pass through a hole in the anode and proceed in a straight line, until they pass between the time deflection plates. The time deflection plates have applied between them a voltage which varies rapidly and uniformly

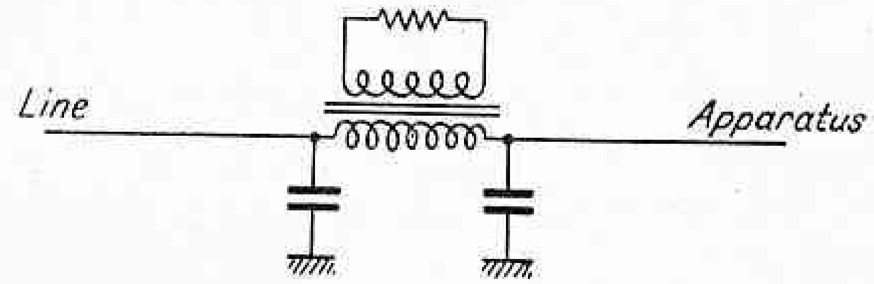

FIG. 266. EQUIVALENT CIRCUIT OF FIG. 268

from zero to a maximum value; the electron beam then undergoes a deflection, that is proportional to the time from a given instant. The beam then passes between the voltage deflection plates, between which the wave (or a fraction of it) is applied. The voltage deflection plates produce a deflection at right angles to the time deflection, so that the electron beam, which strikes the photographic plate at the end of the tube, traces out the voltage-time curve of the wave.

In order to photograph waves of only a few microseconds duration the utmost sensitivity is required. This sensitivity is achieved in the following way. The electron beam impinges directly on the sensitive plate, which must therefore be inside the evacuated tube. The velocity of the electrons must be very great, and a high voltage of 50 kV. or more is used to accelerate the electrons. It is quite clear that the electron beam must not impinge on the plate when there is no wave, otherwise the plate would be completely fogged. The beam is diverted from the photographic chamber by beam trap plates and a beam trap tube. When there is no wave, there is a voltage between the beam trap plates which deflects the beam from the straight path that leads through a small hole in a diaphragm at the bottom of the beam trap tube. It is seen that the axis of the discharge tube is inclined at an angle to the axis of the main tube. The reason for this is that although the electron beam is prevented from reaching the photographic plate by means of the beam trap plates during the absence of a surge or wave, there are retrograde

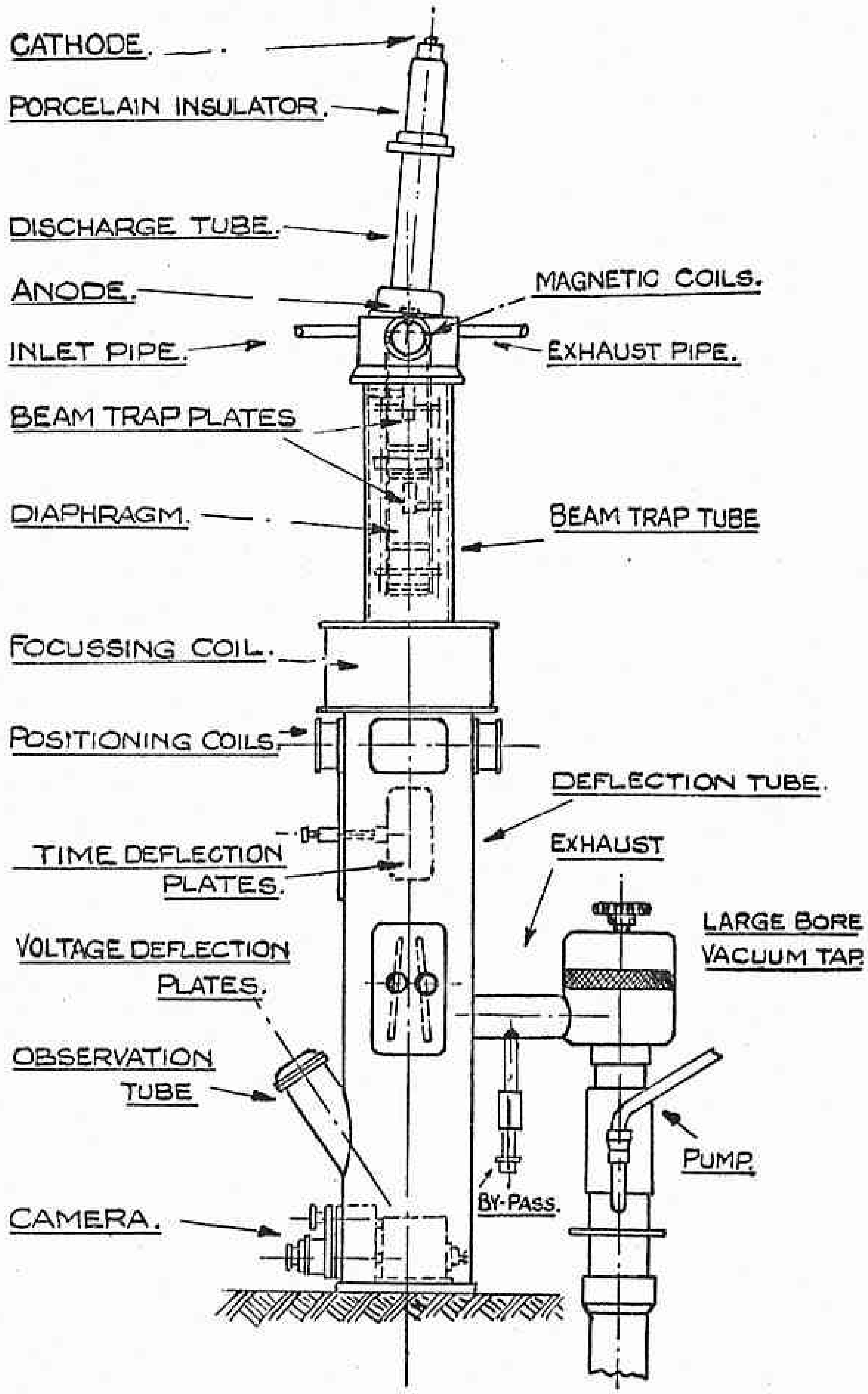

FIG. 267. HIGH-SPEED CATHODE-RAY OSCILLOGRAPH
(*Metropolitan-Vickers*)

rays consisting of atoms that are not much affected by the beam trap. These rays consist of relatively heavy particles and are thus not easily deflected, so that if they are moving along the axis towards the plate they will do so whether the beam trap is operating or not. Their very property of not being deflected easily is used to get rid of them by inclining the axis of the discharge tube. The

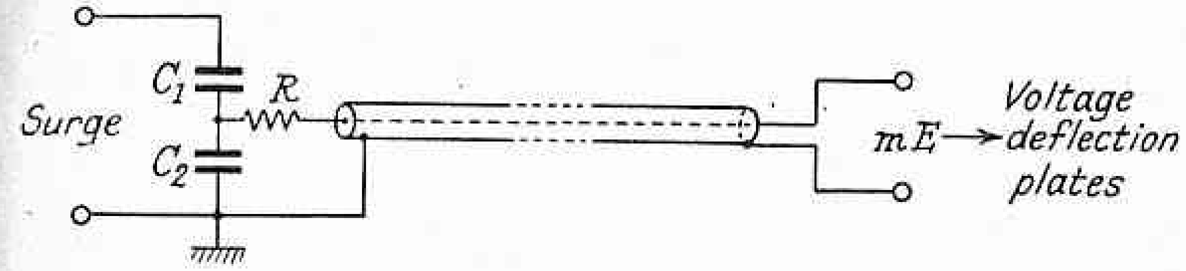

FIG. 268. POTENTIAL DIVIDER AND DELAY CABLE

retrograde rays and the electron beam travel along the axis of the discharge tube towards the anode. Magnetic coils then deflect the electron beam along the main axis, so that the beam can enter the beam trap tube; but the retrograde waves are not deflected from their inclined path and are prevented from entering the main tube.

The electron beam is focused and positioned by magnetic coils.

When a surge arrives it is sent direct to a trigger device which removes the voltage between the beam trap plates, and the electron beam travels to the plate. Meanwhile the surge is put across a potential divider connected to a *delay cable*, which transmits a known fraction of the wave to the voltage deflection plates after a delay of a fraction of a microsecond. The delay cable is a concentric cable, with air or rubber dielectric. Fig. 268 shows the arrangement of the potential divider and the delay cable; R is equal to the surge impedance of the cable. If the capacitance C_1 is ten times the capacitance of the cable, no distortion is introduced and the ratio of step-down is $C_1/(C_1 + C_2)$.

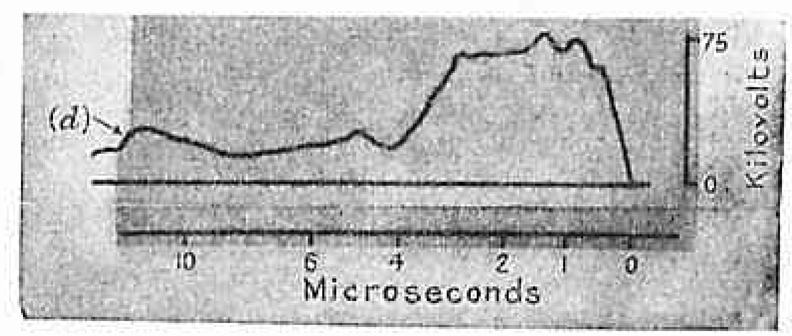

FIG. 269. VOLTAGE ACROSS LINE TURNS OF TRANSFORMER
(*I.E.E. Journal*)

Fig. 269 shows a cathode-ray oscillograph of the voltage appearing across 10 per cent of the line end turns of a transformer winding.* It is seen that in this case the time base is not quite linear.

* Reproduced by kind permission of the Institution of Electrical Engineers from the paper by Miller and Robinson, *Journal of the I.E.E.*

Let us consider the case of an unloaded line first. In this case $r = \infty$, so that

$$|V/E| = [(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2]^{-\frac{1}{2}} \quad . \quad . \quad (112a)$$

If we consider that C can vary, by the insertion of different lengths of cable, $|V/E|$ varies in the manner shown in Fig. 238. The maximum value occurs when

$$C = \frac{1}{\omega^2 L + R^2/L} = \frac{1}{\omega^2 L(1 + R^2/\omega^2 L^2)} \simeq \frac{1}{\omega^2 L},$$

when $$|V/E| = \frac{1}{\omega CR\sqrt{(1 + R^2/\omega^2 L^2)}} \simeq \frac{1}{\omega CR} \simeq \frac{\omega L}{R}.$$

A reasonable value of L in a 33 kV. system is 0·05 henry, and the resonating capacitance is then

$$C \simeq \frac{1}{(2\pi \,.\, 50)^2 \times 0{\cdot}05} = 202\ \mu\text{F.},$$

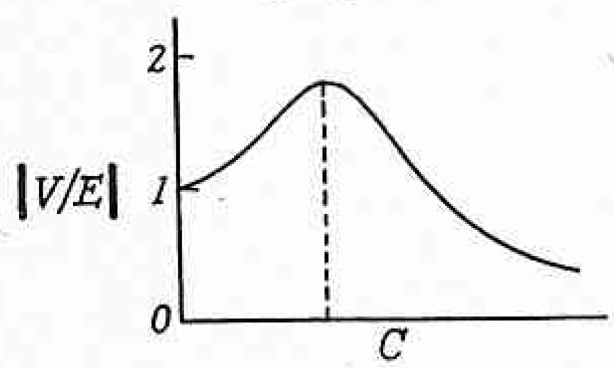

FIG. 238. RESONANCE

which is the capacitance of some hundreds of miles of cable. Resonance in short lines will thus never occur at the fundamental frequency. If we consider the fifth harmonic, which is often present to the extent of 2 or 3 per cent, we see that resonance can occur. The capacitance required is

$$C = \frac{1}{(2\pi \,.\, 250)^2 \times 0{\cdot}05} = 8{\cdot}1\ \mu\text{F.},$$

which is provided by a cable of length about 28 miles. If we assume a 10 per cent harmonic, the value of V_5 is

$$|V_5| = |E_5| \times 2\pi \,.\, 250L/R = 0{\cdot}10\,|E_1| \times 2\pi \,.\, 250L/R,$$

where E_1 is the fundamental, and E_5 the fifth harmonic. If we take $R = 5$, we find that

$$|V_5| = 1{\cdot}57\,|E_1|,$$

so that the fundamental voltage of $E_1 = 33$ kV. has a fifth harmonic of magnitude 52 kV. (r.m.s.). The peak value between phases may then be $\sqrt{2} \times 85$ kV. in place of the normal value of $\sqrt{2} \times 33$ kV.

The effect of a load is seen by comparing equations (112*a*) and (112). It is seen that the term (R/r) is an additive constant in the first term on the right-hand side of the equations and alters the condition for the neutralization of reactance, whilst the term (L/r) causes a considerable damping of the resonance. Let us take $r = 200$ ohms, which corresponds to a load of 5 000 kW. Then with the values of L, C, and E_5 taken above, we find that

$$1 - \omega^2 LC + R/r \simeq 5/200 = 0{\cdot}025$$

and $$\omega(L/r + CR) = \omega CR(1 + L/CRr) = 7{\cdot}2\omega CR = 0{\cdot}46.$$

The first term is thus negligible compared with the second, so that we may take

$$|V_5/E_5| \simeq \frac{1}{\omega(L/r + CR)} = \frac{1}{7{\cdot}2\omega CR} \simeq \frac{\omega L}{7{\cdot}2R},$$

so that V_5 is reduced by the factor 7·2 and has a magnitude of $52 \div 7{\cdot}2 = 7{\cdot}2$ kV. The resonance voltage has been therefore effectively damped by the load.

Switching. A switching operation produces a sudden change in the circuit conditions, and is accompanied by a *transient state* which leads from the earlier to the later steady (a.c.) states. The behaviour

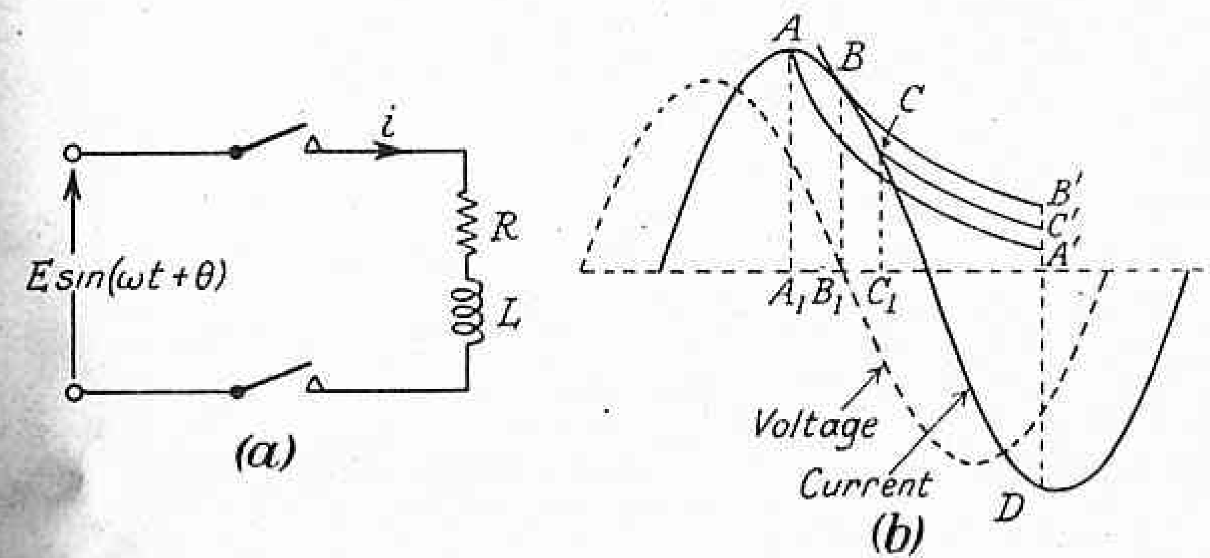

FIG. 239. SWITCHING-IN AN INDUCTIVE RESISTANCE

of the system can be explained with exactness only by means of *travelling waves*, which will be explained later; but in short systems the behaviour is sufficiently well explained if we consider the circuit to be composed of lumped resistances, inductances, and capacitances. The method used is that given on pages 214–16, where we showed that a current of twice the normal peak value can be obtained when an alternator is short-circuited.

Transients in Circuits with Lumped Constants. There are two interesting cases which we will solve, the switching-in of an inductive load and the switching-in of an open-circuited line.

Fig. 239 (*a*) represents the switching-in of a load of inductance L and resistance R. The equation for the circuit is

$$L(di/dt) + Ri = E \sin(\omega t + \theta),$$

of which the solution is (see page 215)

$$i = A\varepsilon^{-(R/L)t} + \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right).$$

KLYDONOGRAPH. It is found that if a potential difference is applied between the faces of a photographic plate, the emulsion is affected and on developing a figure is obtained. When the emulsion side is at a higher potential than the other side, the figure consists of fine lines radiating from the point of contact; when it is at a lower potential, the figure is a complete and fairly definite circle. The latter, or negative, figure is the more useful as its size is definite. The magnitude of the figure depends upon the magnitude of the potential and its frequency or steepness of wave-front. Thus 50-cycle potentials produce only a small figure, whilst high-frequency or steep-fronted waves produce a large figure. If the film is allowed to run past the electrodes (that on the emulsion side is usually pointed and the other flat), the developed film gives a long line with wide bands. The long narrow line corresponds to the normal operating voltage, and the wide bands to high-frequency discharges or steep-fronted surges. Useful qualitative information has been obtained by the use of the klydonograph, but because of the dependence of the size of the figure on frequency or steepness of wave-front the results are not quantitative.

SURGE CREST AMMETER. The principle of this instrument is the measurement of the residual magnetism in a piece of magnetic material, which has been magnetized by the surge current. From the residual magnetism the peak of the surge current is deduced.

EXAMPLES X

1. Explain what is meant by the surge impedance of a transmission line and derive its value in terms of the line constants. Derive expressions for the values of the transmitted and reflected waves of current and voltage relative to those of the incident waves at a point where the surge impedance changes from Z_1 to Z_2.

A rectangular wave of 200 kV. amplitude travels along a line having a surge impedance of 500 Ω. to a transition point where it is connected to a line of 50 Ω. surge impedance. Determine the values of the transmitted and reflected voltage and current waves. (*Lond. Univ.*, 1954.)

2. Describe and explain the occurrences immediately following the sudden application of a steady voltage to one end of a transmission line open at the far end.

A surge voltage e is travelling along a line of surge impedance Z_A connected at its far end to a line of surge impedance Z_B. Show how to calculate the magnitude of the voltage surges transmitted through and reflected from the junction, explaining all assumptions and approximations. (*B.Sc. Lond. Univ.*, 1933.)

3. Describe with the aid of sketches one good type of lightning arrester. What auxiliary equipment is used in conjunction with the arrester to safe guard the apparatus in the power stations? (*Nat. Cert.*, 1935.)

4. An overhead line is joined to a three-phase underground cable. What apparatus is necessary to protect the cable against surges? Give a diagram of connections. Knowing the surge impedance of each circuit show how to calculate the proportion of the surge that enters the cable. (*B.Sc. Lond. Univ.*, 1931.)

5. Enumerate and explain briefly the causes of surges in a transmission line. Describe methods of preventing such surges and of protecting substation apparatus against damage due to them other than by the use of lightning arresters which discharge the surge to earth. (*Lond. Univ.*, 1932.)

6. Explain the reasons leading to the general practice of earthing the neutral point of a power system and discuss the relative merits of earthing it (*a*) solidly, and (*b*) through an impedance.

An earth electrode consists of a pipe 6 ft. long and 1 in. dia. buried vertically with its upper end at ground level in soil having a uniform resistivity of 10 000 Ω. per cm. per cm.[2] Estimate the potential difference between the electrode and a point on the ground 5 ft. away from it when 100 A. are flowing through the electrode to earth. (*Lond. Univ.*, 1934.)

7. Explain the principle of the cathode-ray oscillograph and describe briefly the construction of such an instrument suitable for recording transmission line surges.

What means are employed in an instrument used for this purpose to secure good photographic sensitivity and to prevent fogging of the recording plate by the ray before and after the passage of the surge? (*Lond. Univ.*, 1933.)

8. Two single transmission lines A and B with earth return are connected in series and at the junction a resistance of 2 000 Ω. is connnected between the lines and earth. The surge impedance of line A is 400 Ω. and of B 600 Ω. A rectangular wave having an amplitude of 100 kV. travels along line A to the junction.

Develop expressions for and determine the magnitude of the voltage and current waves reflected from and transmitted beyond the junction. What value of resistance at the junction would make the magnitude of the transmitted wave 100 kV.? (*Lond. Univ.*, 1949.)

9. An underground cable having an inductance of 0·3 mH. per mile and a capacitance of 0·4 μF. per mile is connected in series with an overhead line having an inductance of 2·0 mH. per mile and a capacitance of 0·014 μF. per mile.

Calculate the values of the reflected and transmitted waves of voltage and current at the junction due to a voltage surge of 100 kV. travelling to the junction (*a*) along the cable, and (*b*) along the overhead line.

Explain how the waves would be modified if the cable and line were of considerable length. (*Lond. Univ.*, 1947.)

10. Explain the function and principle of operation of an arc-suppression coil for use on a 3-phase system.

A 33-kV., 3-phase, 50 c/s, overhead line, 50 miles long, has a capacitance to earth for each line of 0·016 μF. per mile.

Determine the inductance and kVA. rating of the arc-suppression coil suitable for this system. (*Lond. Univ.*, 1947.)

11. Describe the construction and explain the operation of a modern type of surge or lightning arrester, and explain at what part of the circuit it would be most satisfactory. (*Lond. Univ.*, 1947.)

12. Describe with the aid of diagrams, the function and operation of the Petersen coil protective device, and derive an expression for the reactance of the coil in terms of the capacitance of the protected line. What are the merits and demerits of the system? (*Lond. Univ.*, 1949.)

The constant A is determined by the fact that $i = 0$ at the time $t = 0$, so that we find that

$$i = -\frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}$$
$$+ \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right) \quad . \quad (103)$$

The first term represents the *transient current* which decays exponentially. It has an initial value equal and opposite to that of the a.c. component at the time of switching (so that the initial current is zero).

If the circuit is very inductive $\omega L \gg R$, and we may put

$$\sqrt{[R^2 + (\omega L)^2]} \simeq \omega L$$

and
$$\tan^{-1}(\omega L/R) = \pi/2.$$

The current then becomes

$$i = (E/\omega L)\,[\sin(\omega t + \theta - \pi/2) - \varepsilon^{-(R/L)t}\sin(\theta - \pi/2)]$$
$$= (E/\omega L)\,[\varepsilon^{-(R/L)t}\cos\theta - \cos(\omega t + \theta)].$$

During the early period after switching $\varepsilon^{-(R/L)t}$ does not decay rapidly from the value of unity, and the current is therefore approximately

$$i = (E/\omega L)\,[\cos\theta - \cos(\omega t + \theta)], \quad (113)$$

and varies between the values of $(E/\omega L)\,[\cos\theta - 1]$ and $(E/\omega L)$ $[\cos\theta + 1]$. The peak value is thus

$$(E/\omega L)\,(1 + |\cos\theta|),$$

i.e. $(1 + |\cos\theta|)$ times the normal peak value. The maximum peak is thus obtained when $\theta = 0$ and is twice the normal peak. This condition occurs when the circuit is closed at zero voltage and the current is

$$i = (E/\omega L)\,[1 - \cos\omega t], \quad . \quad . \quad . \quad (114)$$

which varies between zero (at $t = 0$) and $(2E/\omega L)$ (at $t = \pi/\omega$).

It can be shown that, whatever the power factor of the circuit may be, the maximum "doubling" effect is obtained when the circuit is closed at zero voltage. Fig. 239 (b) shows the normal sinusoidal current. If the circuit is switched in at A the transient has initial amplitude AA_1, if at B the amplitude BB_1, and if at C the amplitude CC_1. The transients corresponding to these switching points are represented by the curves AA', BB', CC' and must be subtracted from the sine wave. The total current at any instant is thus the vertical distance between the sine wave and the appropriate transient curve. It is clear that if the circuit is switched in at position B the current is greater than if switched at any other

position, since the transient curves have the same time factor $\varepsilon^{-Rt/L}$ and have the same decay rate. The topmost curve is clearly seen to be that whose slope at the point of contact with the sine wave is equal to the slope of the sine wave. Let us consider this as the time $t = 0$. Equating slopes we get

$$\left[-\frac{R}{L}\sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}\right]_{t=0}$$
$$= \left[\omega\cos\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right)\right]_{t=0}$$

i.e.
$$-(\omega L/R) = \tan[\theta - \tan^{-1}(\omega L/R)],$$

which gives $\theta = 0$ or π. If $\theta = 0$ or π the voltage is zero at $t = 0$, i.e. the maximum doubling occurs if the circuit is closed at the instant of zero voltage.

Suppose the load has a power factor of 0·8 lagging,

$$\omega L/R = 0{\cdot}6/0{\cdot}8 = 0{\cdot}75.$$

If the circuit is closed at zero voltage the current is

$$i = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\left[\sin\left(\omega t - \tan^{-1}\frac{\omega L}{R}\right) + \sin\left(\tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}\right]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\,[\sin(\omega t - 36^\circ\,52') + 0{\cdot}6\varepsilon^{-1\cdot33\omega t}].$$

For this case the voltage and currents in Fig. 239 (b) must be reversed. The maximum current occurs when $di/dt = 0$, i.e. when

$$\cos(\omega t - 36^\circ\,52') = 0{\cdot}6 \times 1{\cdot}33\varepsilon^{-1\cdot33\omega t} = 0{\cdot}8\varepsilon^{-1\cdot33\omega t}.$$

Let $\omega t - 36^\circ\,52' = \phi$, so that

$$\omega t = \phi + 36^\circ\,52' = \phi + 0{\cdot}64 \text{ radians}.$$

The equation becomes

$$\varepsilon^{1\cdot33\phi}\cos\phi = 0{\cdot}8\varepsilon^{-0\cdot853} = 0{\cdot}34.$$

ϕ . . .	1	1·5	1·54
$\varepsilon^{1\cdot33\phi}$ . .	3·78	7·39	7·76
$\cos\phi$ . .	0·540	0·0707	0·0308
$\varepsilon^{1\cdot33\phi}\cos\phi$.	2·04	0·52	0·24

We may take $\phi = 1{\cdot}53$ radians $= 87^\circ\, 40'$, so that

$$i_{max} = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\,[\sin 87^\circ\,40' + 0{\cdot}6\varepsilon^{-1{\cdot}33\omega t}]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\,[1 + 0{\cdot}34\varepsilon^{-1{\cdot}33\times 1{\cdot}533}]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\,[1{\cdot}044],$$

and the peak does not exceed the normal value by more than 4·5 per cent.

Fig. 240 represents the switching-in of an open-circuited line; we assume for simplicity that the e.m.f. is constant and equal to E,

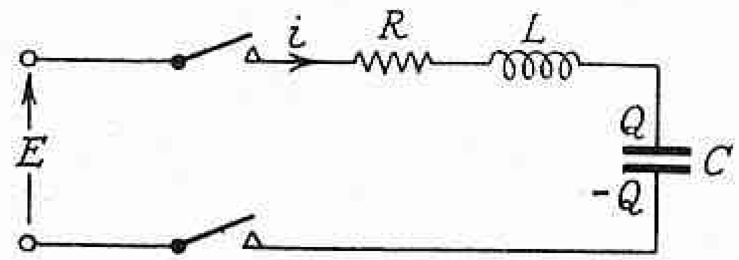

FIG. 240. SWITCHING-IN AN OPEN-CIRCUITED LINE

but the same method is applicable for an a.c. case. The equation for the current is

$$L(di/dt) + Ri + Q/C = E$$

where $i = dQ/dt$.

The voltage at the end of the line is $V = Q/C$. Substituting for i in terms of Q we get

$$L(d^2Q/dt^2) + R(dQ/dt) + Q/C = E,$$

the solution of which is

$$Q = CE + \varepsilon^{-(R/2L)t}\,(A \cos \alpha t + B \sin \alpha t),$$

where $\alpha = \sqrt{[(1/LC) - (R^2/4L^2)]}$, and A and B are constants which are determined by the initial conditions. At the instant, $t = 0$, of switching-in Q and i are zero. These conditions give

$$A = -\,CE \text{ and } B = AR/2L\alpha,$$

so that $\quad V = Q/C = E - E\varepsilon^{-(R/2L)t}\,[\cos \alpha t + (R/2L\alpha)\sin \alpha t]$

$$\left.\begin{aligned} &= E - E[1/\alpha\sqrt{(LC)}]\,\varepsilon^{-(R/2L)t}\cos[\alpha t - \cos^{-1}(\alpha\sqrt{(LC)})],\\ &\text{and } i = dQ/dt = (E/\alpha L)\,\varepsilon^{-(R/2L)t}\sin \alpha t. \end{aligned}\right\} \quad (115)$$

If the resistance is negligible the voltage and current reduce to

$$\left.\begin{aligned} V &= E - E\cos[t/\sqrt{(LC)}]\\ \text{and} \quad i &= [E\sqrt{(C/L)}]\sin[t/\sqrt{(LC)}], \end{aligned}\right\} \quad . \quad . \quad (115a)$$

since $\alpha = 1/\sqrt{(LC)}$ in this case.

The voltage in this case oscillates sinusoidally between 0 and $2E$, whilst the current is a sine wave of peak value $E\sqrt{(C/L)}$. Fig. 241 shows the voltage and current for the case of no resistance (curves A) and for some resistance (curves B).

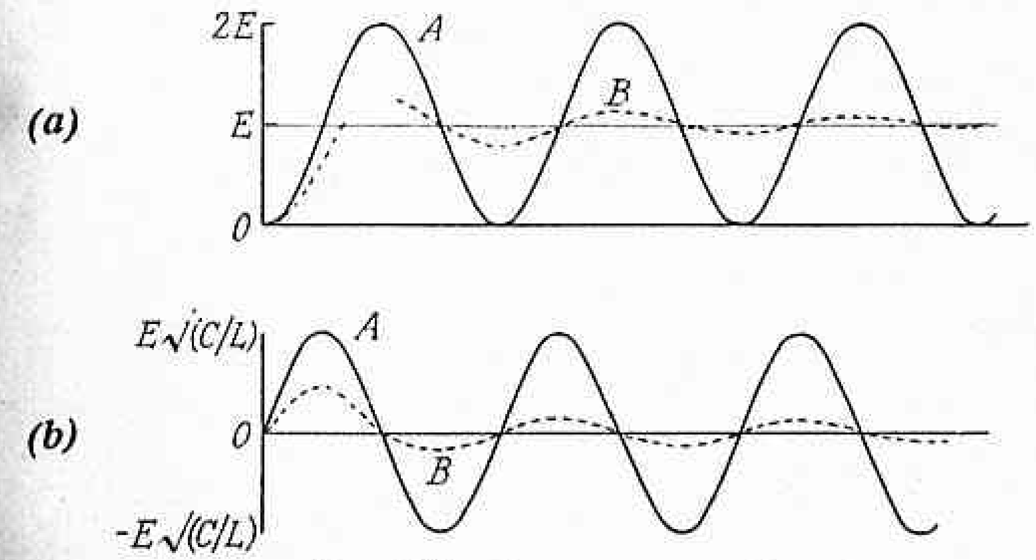

FIG. 241. OPEN-CIRCUITED LINE
(a) Voltage. (b) Current.

Switching Surges. We have found that when an e.m.f. E is switched on to a line, which we replaced by an inductance L and a capacitance C, the voltage oscillates sinusoidally between 0 and $2E$ whilst the current varies similarly between $-\,E\sqrt{(C/L)}$ and

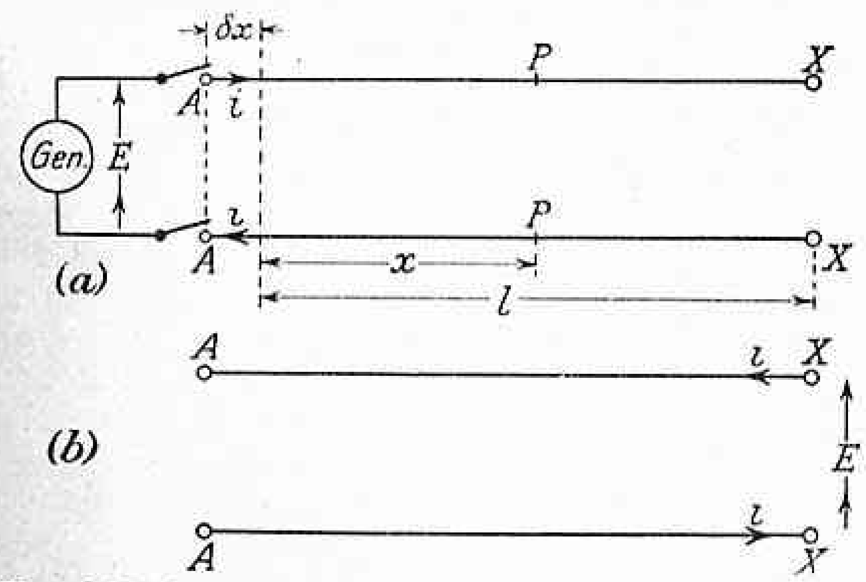

FIG. 242. SWITCHING SURGE ON OPEN-CIRCUITED LINE

$+\,E\sqrt{(C/L)}$. It is clear that this does not represent the state of affairs with exactness, for any transfer of energy must travel with a velocity less than that of light, so that the far end of a line is unaffected for the finite time that it takes the energy wave to reach it. It therefore follows that part of the line may be passing current and maintaining a voltage whilst a further part has neither current nor voltage. We will consider the case of the switching-in of an unloaded line from this point of view, and will make the simplifying assumption that resistance and leakage are negligible. Fig. 242 (*a*) shows the arrangement; the line has inductance L and capacitance C per unit length and is open at the far end XX.

At the instant of switching an e.m.f. E is placed on the line at AA, and a current i passes to the right in the upper conductor and to the left in the lower conductor. Suppose that in a very small time δt the conditions of a current i and a voltage E are established along a length δx of the line. The e.m.f. E is balanced by the back e.m.f. generated by the magnetic flux which is produced by the current in this length of the line. The inductance of the length δx is $L\delta x$, so that the flux built up is $iL\delta x$ and the back e.m.f. is the rate of build-up, viz. $iL(\delta x/\delta t)$. We have therefore

$$E = iL(\delta x/\delta t)$$
$$= iLv, \qquad (116)$$

where v is the velocity of the wave.

The current i carries a charge $i\delta t$ in the time δt, and this charge remains on the line to charge it up to the potential E. Since the capacitance of the length δx of the line is $C\delta x$, its charge is $EC\delta x$. We have therefore

$$i\delta t = EC\delta x,$$

or

$$i = EC(\delta x/\delta t)$$
$$= ECv. \qquad (117)$$

The switching of an e.m.f. E on to the line results therefore in a wave of current i and velocity v where i and v are given by equations (116) and (117). Multiplying these equations we get

$$Ei = iLvECv = EiLCv^2,$$

so that

$$v = 1/\sqrt{(LC)}. \qquad (118)$$

Substituting for v in equation (118) we find that

$$\left.\begin{aligned} i &= E\sqrt{(C/L)} = E/Z \\ \text{where} \quad Z &= \sqrt{(L/C)}. \end{aligned}\right\} \qquad (119)$$

Z is called the *surge impedance* or *natural impedance* of the line; it is a pure resistance for a line without resistance or leakage, and has a value of 400 to 600 ohms for an overhead line and 40 to 60 ohms for a cable. The velocity of the wave on an overhead line is approximately equal to the velocity of light, for

$$L = [1 + 4 \text{ logh } (D/r)] \times 10^{-9} \text{ H. per cm.}$$
$$\simeq 4 \text{ logh } (D/r) \times 10^{-9} \text{ H. per cm.}$$

and

$$C \simeq \frac{1}{4 \text{ logh } (D/r)} \text{ cm. per cm.}$$
$$= \frac{1}{9 \times 10^{11}} \frac{1}{4 \text{ logh } (D/r)} \text{ F. per cm.}$$

so that

$$v = \frac{1}{\sqrt{(LC)}} = \sqrt{(10^9 \times 9 \times 10^{11})} \text{ cm. per sec.}$$
$$= 3 \times 10^{10} \text{ cm. per sec.}$$
$$= c,$$

the velocity of light.

The velocity in a cable is $c/\sqrt{\varepsilon}$, where ε is the dielectric constant. v is thus about 186 000 miles per sec. on an overhead line, and 186 000 $\div \sqrt{3{\cdot}6}$ = 98 000 miles per sec. in a cable.

We have shown that a wave of voltage E and current $i = E/Z$, travels towards the right along the line with a velocity v. Such a wave is called a *pure travelling wave*. At any part PP of the line nothing happens until the wave reaches it (at time $t = x/v$), and then the current jumps from zero to i and the voltage from zero to E. This goes on until the wave reaches the open end of the line (XX) at time $t = l/v$. When the wave reaches XX, the current there is i; but this current has no capacitance to charge up, so that it must cease immediately.

The open end of the line has thus a disturbing influence which neutralizes the current completely; this disturbing influence then travels back along the line towards AA, and can therefore be represented by a pure travelling wave moving towards the left and carrying a current $-i$. A travelling wave must possess a voltage and a current whose ratio is Z, the surge impedance of the line. If the current is to the left in the upper conductor and to the right in the lower from the end XX, it is seen from Fig. 242 (*b*) that the voltage is E, i.e. the upper conductor is E volts above the lower. For if an e.m.f. E were switched in at XX the current would be in the direction required and as shown. The disturbing effect of the open end of the line is thus to introduce another pure travelling wave, which moves to the left with velocity v, has a voltage E, and a current i in the opposite direction to that previously flowing. It is convenient to consider a current to the right in the upper conductor as positive, and a current to the left in the upper conductor as negative. The new travelling wave, which moves to the left, has therefore a voltage E and a current $-E/Z$. In general, a wave (E_1, i_1) moving to the right satisfies the relation

$$i_1 = E_1/Z, \qquad (120)$$

while a wave (E_2, i_2) moving to the left satisfies the relation

$$i_2 = -E_2/Z. \qquad (121)$$

The result of the new travelling wave is to establish an extra voltage E at any point of the line that it passes so that a resulting voltage of $2E$ is produced, whilst the current is neutralized. Thus the conditions at the point PP of the line are such that its voltage and current values are (0, 0) from $t = 0$ until $t = x/v$, (E, i) from $t = x/v$ until $t = (2l - x)/v$, and $(2E, 0)$ from $t = (2l - x)/v$ onwards. This goes on until the disturbing wave reaches the generator at AA at time $t = 2l/v$; by this time the line has voltage $2E$ and zero current at every point. When this instant occurs, the voltage at the generator terminals is $2E$. But the generator is supposed to maintain a voltage E at AA, so that another wave is called into play to reduce $2E$ to E. This wave must therefore have potential $-E$, and as it moves to the right it must have a current $-E/Z = -i$ by equation (120). As this wave travels from AA to XX it reduces the voltage to E and produces a current $-i$. Thus the voltage drops from $2E$ to E at the point PP at time $t = (2l + x)/v$ and the current jumps from zero to $-i$. When this third wave reaches XX it establishes a current $-i$ there, which must be neutralized by a fourth wave travelling to the left with current $+i$, and voltage $-iZ = -E$ by equation (121). As this fourth wave travels from XX to AA, the current vanishes at any point it passes, and the voltage becomes $E - E = 0$ at every point. The line is thus completely discharged and has no current, and a complete cycle of travelling waves has been finished. If the line were completely without resistance and leakage, this cycle would be repeated indefinitely. The current at AA, the current and voltage at the mid-point of the line, and the voltage at XX are shown in Fig. 243.

It is interesting and instructive to compare the exact description of the switching phenomenon with the approximate description derived by considering the line as composed of a lumped inductance and capacitance. In both descriptions the potential at any point varies between 0 and $2E$; but in the exact description the time-variation of the potential depends greatly upon the point considered (see Fig. 243, last two curves) and changes in jumps, whilst in the approximate method the time-variation is sinusoidal. The current varies between $+i$ and $-i$ in both cases, where $i = E/Z$ and $Z = \sqrt{(L/C)}$; but again the time-variations are radically different. There is one further difference, viz. the periodicity of the two descriptions. In the approximate method the frequency is $1/2\pi\sqrt{(LC)}$; whilst in the exact method a complete cycle is of duration $4l/v$, so that the frequency is

$$v/4l = 1/4l\sqrt{(LC)} = 1/4\sqrt{(L_0C_0)},$$

where L_0 and C_0 are the total inductance and capacitance. The difference is therefore in replacing the 2π by 4.

Before entering on a somewhat more general description of

travelling waves, it is worth while considering the energy properties of the simple waves we have described.

Energy Considerations. A wave of voltage E and current i carries a power of Ei. A simple travelling wave therefore transmits a power Ei with a velocity v. As this wave travels it establishes a magnetic field with energy $\frac{1}{2}Li^2$ per cm. length of the line and an electrostatic field with energy $\frac{1}{2}CE^2$ per cm. length. From equations

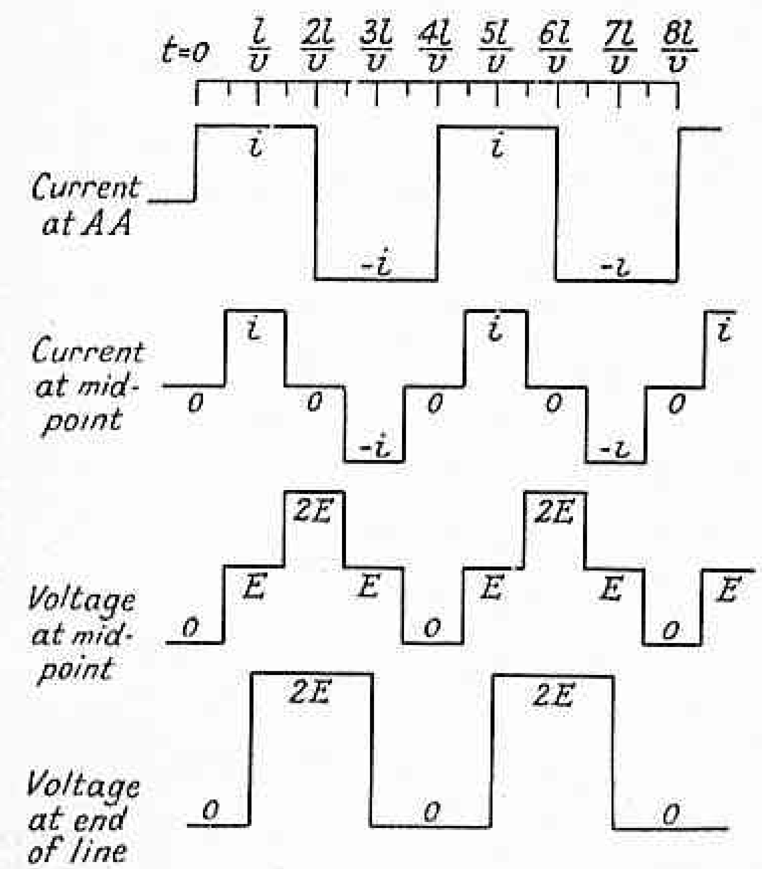

FIG. 243. CURRENT AND VOLTAGE IN SWITCHING SURGE

(116) and (117) it is seen that the magnetic and electrostatic energies delivered by a simple wave are equal, for

$$\begin{aligned}\tfrac{1}{2}Li^2 &= \tfrac{1}{2}(iLv)\,(i/v) = \tfrac{1}{2}(Ei/v)\\ &= \tfrac{1}{2}(E/v)\,(ECv) = \tfrac{1}{2}CE^2.\end{aligned}$$

Each of these is equal to $\frac{1}{2}Ei/v$, which is half the total energy delivered by the wave in the time it passes along the part of the line. The energy of the wave is thus half absorbed as magnetic and half as electrostatic energy.

When a pure travelling wave of voltage E and current i moves to the right and meets an open-circuited line, we said that the disturbing effect of the open end is to bring into action a reflected wave of voltage E and current $-i$ (travelling to the left). It will be seen that this is consistent with the conservation of energy, and is in fact demanded by this principle. For suppose that the disturbance engenders a wave with a current $-i$, the latter being required in order to neutralize the current at the open end of the line. Suppose that the voltage attached to this wave is E'. When the wave has travelled a distance XY (Fig. 244), the voltage over XY is $E + E'$ whilst the current is zero. The energy associated with this part of the line is now

$$\tfrac{1}{2}C \,.\, XY \,.\, (E + E')^2,$$

whereas previously it was

$$\tfrac{1}{2}C \,.\, XY \,.\, E^2 + \tfrac{1}{2}L \,.\, XY \,.\, i^2 = C \,.\, XY \,.\, E^2,$$

since $\frac{1}{2}Li^2 = \frac{1}{2}CE^2$. The gain in energy has been derived from the first (incident) wave, which feeds energy into the section XY at a rate Ei; the gain is thus Ei multiplied by the time that the reflected wave takes to travel from X to Y, viz. $Ei \times (XY/v)$. If the principle of conservation of energy is to hold, then

$$\tfrac{1}{2}C \,.\, XY \,.\, (E + E')^2 = C \,.\, XY \,.\, E^2 + Ei(XY/v),$$

or

$$\tfrac{1}{2}(E + E')^2 = E^2 + Ei/Cv = E^2 + E^2$$

(by equation (117)),

so that $$(E + E')^2 = 4E^2,$$

i.e. $$E' = E.$$

The principle of the conservation of energy thus demands that the reflected wave at an open end shall have a voltage equal to that of the incident wave; the current is equal and opposite to that of the incident wave since no current can leave the open end.

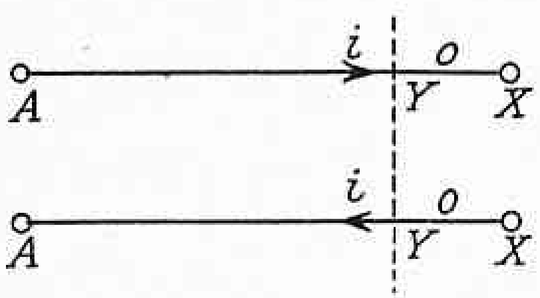

FIG. 244. ENERGY CONSIDERATIONS IN SURGES

Sudden Interruption of a Circuit. We have described in full the surge that takes place when a generator is suddenly switched on to a line that is open at the far end. The phenomenon that takes place when the far end is terminated by a finite impedance will be considered in the section on the reflection and transmission of travelling waves. The method employed above serves to describe the events that occur when a current in a circuit is suddenly interrupted, by the action of a circuit-breaker, say.

Suppose that a circuit has a current i, which is suddenly interrupted by the breakers S, S (Fig. 245). The disturbance produces two travelling waves moving from S, S to the right and to the left. The wave travelling to the right has a current $- i$, and must

therefore have a voltage $- E$, where $E = iZ$; line A is therefore $- E$ volts above line B. The wave travelling to the left has a current $- i$, and must therefore have a voltage $+ E$, where $E = iZ$; C is therefore $+ E$ volts above D. These waves progress in a normal manner until they meet abrupt changes in the line, when they are reflected and transmitted in the ways described later. It should be

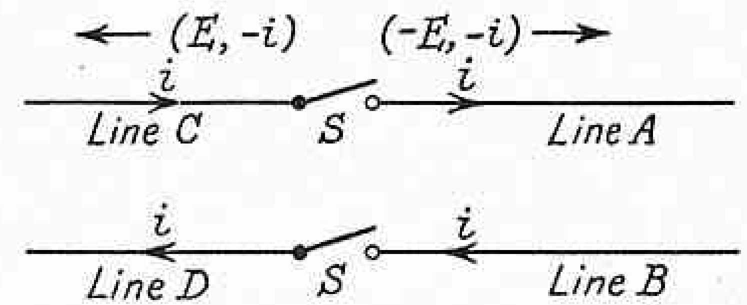

FIG. 245. SUDDEN INTERRUPTION OF A CIRCUIT

noted that if only one break is made, so that B and D are always commoned, the voltage between A and C is $2E$.

The surge voltage E is superposed on the normal voltage in that part of the line which remains connected to the generator.

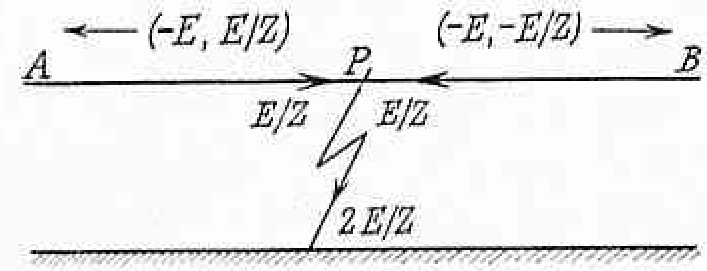

FIG. 246. SURGES DUE TO A FAILURE OF INSULATION

Insulation Failure or Earthing of a Line. Suppose that a line AB, at potential E, is earthed at a point P. The effect of earthing is to introduce a voltage $- E$ at P, and two equal waves of voltage $- E$ travel along PA and PB. The wave travelling to the right has a current of $- E/Z$, and that to the left $+ E/Z$. Both these currents pass through P to earth, so that the current to earth is $2E/Z$. Fig. 246 shows the waves and currents in the system.

As these waves travel to the ends of the line they reduce the voltage to zero; and when they reach the open ends, reflected waves are set up which reduce the voltage to $E - E - E$, i.e. $- E$, and the current is neutralized. When the reflected waves reach P, the portions of the line along which they have travelled will be charged to $- E$. The current at P can be reversed by a flashover in the opposite direction, and the result is a periodic flashover with reversals of potential on the line and currents at P until the stored energy is dissipated by damping.

Reflection and Transmission of Travelling Waves. Suppose that a travelling wave (E, i) moves along a line of surge impedance Z and meets a termination of resistance R (Fig. 247). If R is not equal to Z, the end of the line cannot have the voltage E and current i since $E/i = Z$. There is therefore a disturbance which

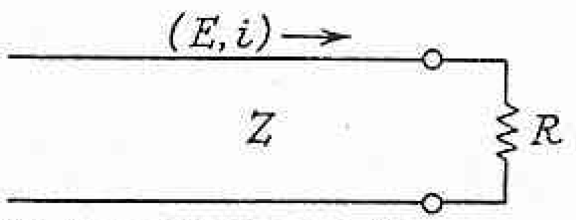

FIG. 247. REFLECTION OF A TRAVELLING WAVE

produces a reflected wave (E', i') moving towards the left. The following relations exist.

$$E = iZ,$$
$$E' = -i'Z.$$

The total voltage at the end is $E + E'$ and the total current is $i + i'$, so that

$$E + E' = R(i + i').$$

These equations give

$$Z(i - i') = R(i + i')$$

so that
and
$$\left.\begin{aligned} i' &= [(Z - R)/(Z + R)]i \\ E' &= -i'Z = [(R - Z)/(Z + R)]E. \end{aligned}\right\} \quad (122)$$

The total current and voltage are

and
$$\left.\begin{aligned} i + i' &= [2Z/(Z + R)]i \\ E + E' &= [2R/(Z + R)]E. \end{aligned}\right\} \quad . \quad . \quad . \quad (123)$$

If the line is open at the end, $R = \infty$ so that the total current is zero and the total voltage is $2E$, as found before.

If the line is shorted at the end, $R = 0$ so that the current is doubled and the voltage drops to zero.

The case for a finite resistance termination is given by equations (122) and (123). When the termination is not a pure resistance, the result is still given by these equations but they must be evaluated by the operational calculus.

Junction of Two Lines. Fig. 248 shows the case of two lines of surge impedances Z_A and Z_B. A wave (E, i) travels along the left-hand line and meets the junction. So far as a travelling wave is concerned the right-hand line can be considered to have an impedance Z_B, so that the case is the same as that shown in Fig. 247,

provided Z is replaced by Z_A and R by Z_B. The reflected wave is thus (E', i') where

and
$$\left.\begin{aligned} i' &= [(Z_A - Z_B)/(Z_A + Z_B)]i \\ E' &= [(Z_B - Z_A)/(Z_A + Z_B)]i. \end{aligned}\right\} \quad . \quad (122a)$$

The transmitted wave must clearly have a voltage equal to the total voltage at the junction and a current equal to the total. Thus the transmitted wave is (E'', i'') where

and
$$\left.\begin{aligned} i'' &= i + i' = (2Z_A/(Z_A + Z_B)]i \\ E'' &= E + E' = (2Z_B/(Z_A + Z_B)]E. \end{aligned}\right\} \quad . \quad (123a)$$

EXAMPLE. Deduce a simple expression for the natural impedance of a transmission line. A transmission line has a capacitance of 0·0125 μF. per mile and an inductance of 1·5 mH. per mile. This overhead line is continued

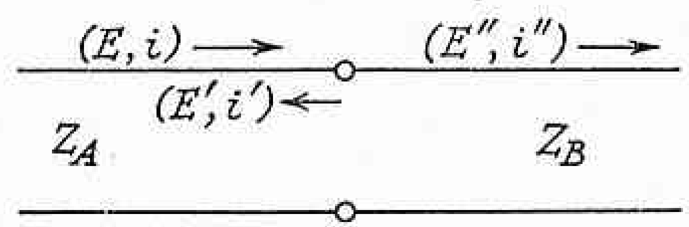

FIG. 248. EFFECT OF A SUDDEN CHANGE IN THE LINE ON TRAVELLING WAVES

by an underground cable with a capacitance of 0·3 μF. per mile and an inductance of 0·25 mH. per mile. Calculate the rise of voltage produced at the junction of the line and cable by a wave with a crest value of 50 kV. travelling along the cable. (*Lond. Univ.*, 1931.)

The natural impedance is $\sqrt{(L/C)}$. The value for the cable is

$$Z_A = \sqrt{\left[\frac{0{\cdot}25 \times 10^{-3}}{0{\cdot}3 \times 10^{-6}}\right]} = \sqrt{833} = 28{\cdot}9\ \Omega.,$$

whilst the value for the overhead line is

$$Z_B = \sqrt{\left[\frac{1{\cdot}5 \times 10^{-3}}{0{\cdot}0125 \times 10^{-6}}\right]} = \sqrt{120\ 000} = 346{\cdot}4\ \Omega.$$

The reflected wave has a crest voltage

$$\begin{aligned} E' &= [(Z_B - Z_A)/(Z_B + Z_A)] \times 50 \text{ kV.} \\ &= (317{\cdot}5/375{\cdot}3) \times 50 \text{ kV.} = \underline{\underline{42{\cdot}3}} \text{ kV.}, \end{aligned}$$

so that the maximum voltage at the junction is 92·3 kV.

The next example shows the calculation of the reflected and transmitted waves at a point where a line forks.

EXAMPLE. Obtain the law for the behaviour of a voltage surge with vertical wave-front which, after travelling in a transmission line of inductance L and capacitance C per unit length, reaches a fork where the line splits into two sections having line constants L_1C_1 and L_2C_2 respectively. Neglect resistance and attenuation and obtain the distribution of voltage and current immediately after the wave-front has reached the fork.

An overhead transmission line has a surge impedance of 700 Ω., and a voltage wave of 10 000 V. travelling along it. The wave is assumed to be of infinite length and the wave-front is vertical. At a certain point the overhead line terminates and the circuit is continued by two cables in parallel. The surge impedance of one cable is 100 Ω., and that of the other is 200 Ω. Calculate the voltage and current in the overhead line and in the two cables immediately after the travelling wave has reached the fork.

(*Lond. Univ.*, 1927.)

Fig. 249 represents the arrangement schematically. The surge impedances are

$$Z = \sqrt{(L/C)},\ Z_1 = \sqrt{(L_1/C_1)},\ \text{and}\ Z_2 = \sqrt{(L_2/C_2)}.$$

Let the incident wave be (E, i) travelling to the right, the reflected wave (E', i') travelling to the left, and the transmitted waves (E'', i_1'') and (E'', i_2'') travelling towards the right. The transmitted waves clearly have the same voltage as they are in parallel. Equations (120) and (121) give the relations

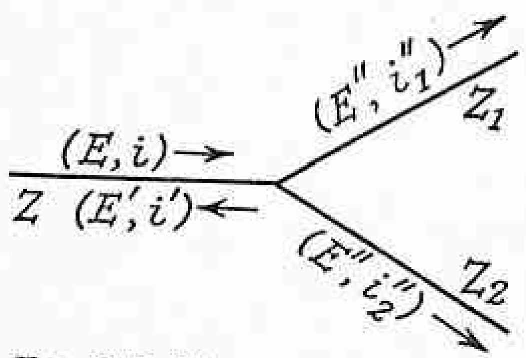

FIG. 249. TRAVELLING WAVES AT JUNCTION OF LINES

$$E = iZ,$$
$$E' = -i'Z,$$
$$E'' = i_1''Z_1,$$
$$\text{and} \quad E'' = i_2''Z_2.$$

The current entering the fork must be equal to the current leaving, so that

$$i + i' = i_1'' + i_2'' \quad . \quad . \quad . \quad . \quad (124)$$

The voltage at the junction is

$$E + E' = E'' \quad . \quad . \quad . \quad . \quad . \quad (125)$$

These six equations are sufficient to find E', E'', i, i', i_1'', and i_2'' for an incident wave of given magnitude E. Substituting for the currents in terms of the voltages we see that equation (124) becomes

$$E - E' = E''Z\left(\frac{1}{Z_1} + \frac{1}{Z_2}\right).$$

Adding this to equation (125) we get

$$2E = E''(1 + Z/Z_1 + Z/Z_2),$$

so that the voltage at the fork is

$$E'' = \frac{2E}{1 + Z/Z_1 + Z/Z_2} = 2E\frac{1/Z}{1/Z + 1/Z_1 + 1/Z_2}.$$

The transmitted currents are

$$i_1'' = E''/Z_1 \text{ and } i_2'' = E''/Z_2,$$

whilst the incident current is $i = E/Z$.

The reflected voltage is

$$E' = E'' - E = E\frac{1/Z - 1/Z_1 - 1/Z_2}{1/Z + 1/Z_1 + 1/Z_2}$$

and the current is $i' = -E'/Z$. It is seen that the reflected wave is zero when

$$1/Z = 1/Z_1 + 1/Z_2,$$

i.e. when the parallel combination of the surge impedances of the outgoing lines at the fork is equal to the surge impedance of the line along which the incident wave travels.

In the example $Z = 700$, $Z_1 = 100$, $Z_2 = 200$, and $E = 10\ 000$. We then have

$$i = 10\ 000/700 = \underline{14{\cdot}3}\ \text{A.},$$

$$E' = 10\ 000\,\frac{\frac{1}{700} - \frac{1}{100} - \frac{1}{200}}{\frac{1}{700} + \frac{1}{100} + \frac{1}{200}} = \underline{-\ 8\ 260}\ \text{V.}$$

$$i' = -E'/Z = 8\ 260/700 = \underline{11{\cdot}8}\ \text{A.},$$

$$E'' = E + E' = 10\ 000 - 8\ 260 = \underline{1\ 740}\ \text{V.},$$

$$i_1'' = E''/Z_1 = \underline{17{\cdot}4}\ \text{A. and } i_2'' = E''/Z_2 = \underline{8{\cdot}7}\ \text{A.}$$

The cables thus have the beneficial effect of reducing the surge voltage from 10 kV. to 1·74 kV.

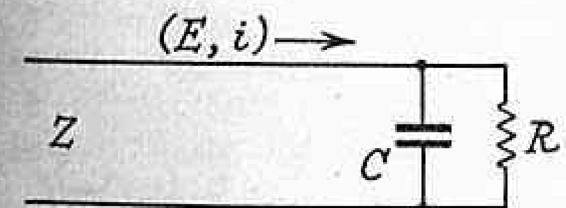

FIG. 250. EFFECT OF SHUNT CAPACITANCE ON TRAVELLING WAVE

Effect of a Capacitance. Suppose that a wave (E, i) meets a termination composed of the parallel combination of a capacitance C and resistance R, as shown in Fig. 250. The problem is the same as that shown in Fig. 247, except that R in equations (123) must be replaced by

$$\frac{(1/pC)R}{1/pC + R} = \frac{R}{1 + pCR},$$

where $p = d/dt$.

CHAPTER VIII

SHORT CIRCUITS : SYMMETRICAL COMPONENTS

Introduction. When a fault occurs on a network such that a large current flows in one or more of the phases, it is said that a short circuit has occurred. The fault may be a short between one phase and earth, between two or more phases and earth, between two phases only, or across all three phases; a short between one phase and earth will cause a short circuit only if the neutral point is earthed. It is necessary to know the maximum short-circuit currents that can occur at the various points of a system in order that circuit-breakers may be selected that are adequate to withstand the currents and operate successfully to cut out the faulty section, and also in order that the protective relays may be selected for correct operation. Moreover, it is necessary to be able to calculate, approximately at least, the size of the protective reactors which must be inserted in the system to limit the short-circuit currents to a value which is not beyond that capable of being withstood by the circuit-breakers.

The short-circuit currents in an alternating current system are determined mainly by the reactance of the alternators, transformers, and lines up to the point of the fault in the case of phase-to-phase faults. When the fault is between a phase and earth, the resistance of the earth path may play an appreciable part in limiting the currents.

Percentage Reactance and Short-circuit Currents. The method of specifying the impedance or reactance of a piece of electrical plant, as described in Appendix III, pages 471–2, is very convenient for the calculation of short-circuit currents. The percentage reactance is given by

$$(\% X) = (IX/E) \times 100, \quad . \quad . \quad . \quad (99)$$

where X is the reactance, E the rated voltage, and I the full-load current. If the piece of apparatus is the only impedance in the circuit, the short-circuit current is given by E/X, which by equation (99) is

$$I_{sh} = E/X = I \times (100/\% X). \quad . \quad . \quad (100)$$

Thus the short-circuit current for a single piece of apparatus is the full-load current multiplied by (100 divided by the percentage reactance). Thus if the percentage reactance is 10 per cent, the short-circuit current is 10 times the full-load current; if it is 40 per cent, the short-circuit current is 2·5 times the full-load current.

A balanced system with *negative phase sequence* is shown in Fig. 182. The order of maxima is E_2'', E_2', E_2, so that the vectors are

$$E_2,\ E_2' = \lambda E_2,\ E_2'' = \lambda^2 E_2. \quad . \quad . \quad . \quad (106)$$

Suppose there is a system of unbalanced vectors E_A, E_B, and E_C. By virtue of the relations $(1 + \lambda + \lambda^2) = 0$ and $\lambda^3 = 1$ we may write

$$\begin{aligned} E_A &= \tfrac{1}{3}(E_A + E_B + E_C) + \tfrac{1}{3}(E_A + \lambda E_B + \lambda^2 E_C) \\ &\quad + \tfrac{1}{3}(E_A + \lambda^2 E_B + \lambda E_C), \\ E_B &= \tfrac{1}{3}(E_A + E_B + E_C) + (\lambda^2/3)\,(E_A + \lambda E_B + \lambda^2 E_C) \\ &\quad + (\lambda/3)\,(E_A + \lambda^2 E_B + \lambda E_C), \end{aligned}$$

and
$$\begin{aligned} E_C &= \tfrac{1}{3}(E_A + E_B + E_C) + (\lambda/3)\,(E_A + \lambda E_B + \lambda^2 E_C) \\ &\quad + (\lambda^2/3)\,(E_A + \lambda^2 E_B + \lambda E_C). \end{aligned}$$

Putting

$$\left.\begin{aligned} \tfrac{1}{3}(E_A + E_B + E_C) &= E_0, \\ \tfrac{1}{3}(E_A + \lambda E_B + \lambda^2 E_C) &= E_1, \\ \tfrac{1}{3}(E_A + \lambda^2 E_B + \lambda E_C) &= E_2, \end{aligned}\right\} \quad . \quad . \quad . \quad (107)$$

and

we have

$$\left.\begin{aligned} E_A &= E_0 + E_1 + E_2, \\ E_B &= E_0 + \lambda^2 E_1 + \lambda E_2, \\ E_C &= E_0 + \lambda E_1 + \lambda^2 E_2. \end{aligned}\right\} \quad . \quad . \quad (108)$$

It is seen from equations (105) and (106) that the terms in E_1 represent a positive phase-sequence system of balanced vectors, whilst the terms in E_2 represent a negative phase-sequence system of balanced vectors. The equal terms E_0 are said to represent a *zero phase-sequence* system of vectors, which are equal. Thus any system of three unbalanced vectors can be resolved into three systems of balanced vectors, a zero phase-sequence system E_0 (1, 1, 1), a positive phase-sequence system E_1 (1, λ^2, λ), and a negative phase-sequence system E_2 (1, λ, λ^2). The values of E_0, E_1, and E_2 are found from the unbalanced vectors E_A, E_B, E_C by means of equations (107) by multiplication of complex numbers or by a graphical method. The former method is described in Appendix II. The graphical method follows from the facts that, since $\lambda = \varepsilon^{j(2\pi/3)}$, multiplication by λ turns a vector in the positive direction through an angle of $2\pi/3$ radians and multiplication by λ^2 turns a vector through $4\pi/3$ radians.

Fig. 183 (*a*) shows an unbalanced system of vectors. Fig. 183 (*b*) shows how these are added to give $E_A + E_B + E_C$, one-third of which is E_0. Fig. 183 (*c*) shows how we obtain $E_A + \lambda E_B + \lambda^2 E_C$, one-third of which is E_1; and Fig. 183 (*d*) shows how we obtain $E_A + \lambda^2 E_B + \lambda E_C$, one-third of which is E_2.

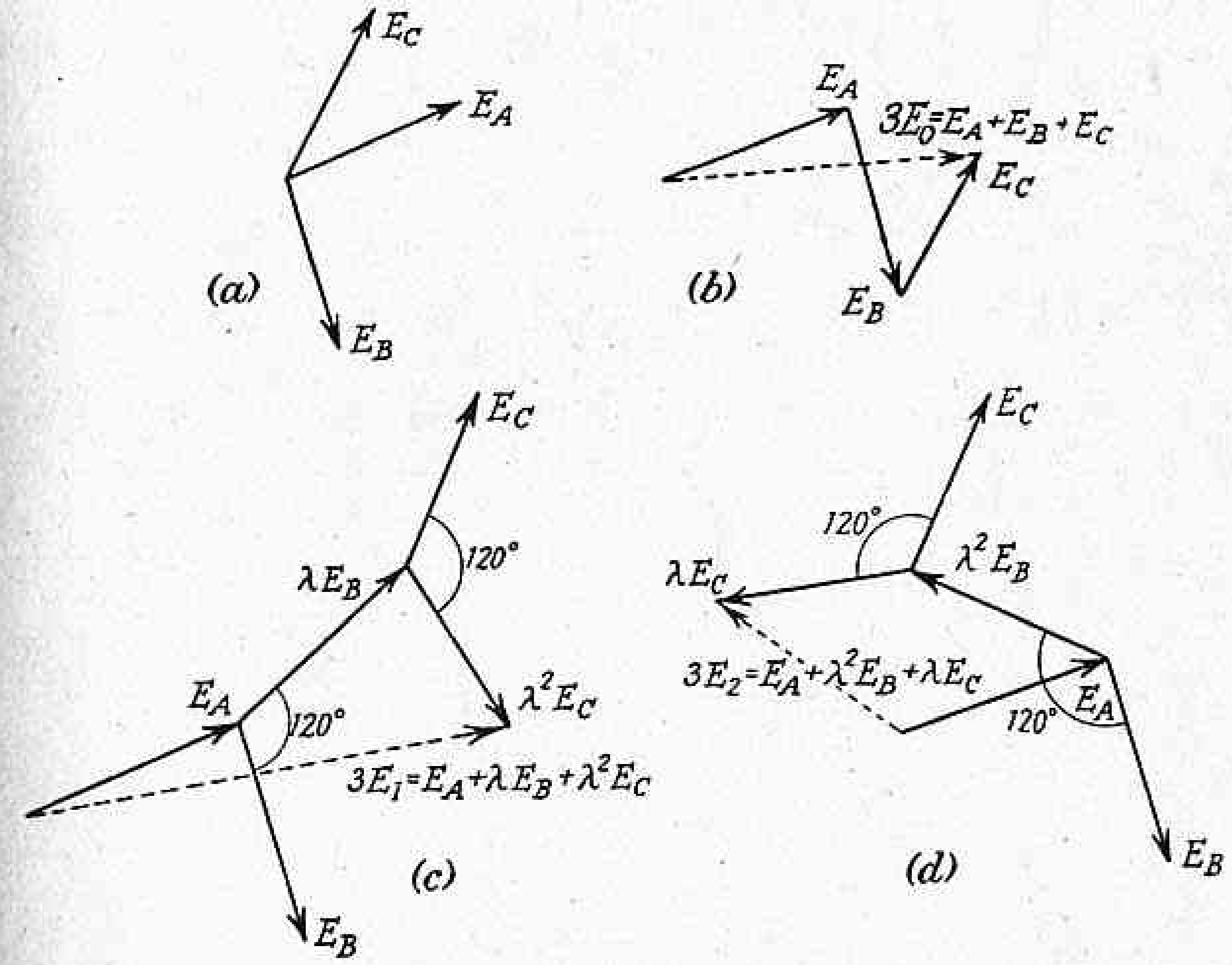

FIG. 183. GRAPHICAL METHOD OF FINDING SYMMETRICAL COMPONENTS

EXAMPLE. Resolve the system $E_A = 1\ 500\,\underline{|30^\circ}$, $E_B = 1\ 800\,\underline{|-70^\circ}$, $E_C = 2\ 000\,\underline{|170^\circ}$ into their symmetrical components.

$$\begin{aligned} E_0 &= \tfrac{1}{3}(E_A + E_B + E_C) \\ &= \tfrac{1}{3}(1\ 500\,\underline{|30^\circ} + 1\ 800\,\underline{|-70^\circ} + 2\ 000\,\underline{|170^\circ}) \\ &= \tfrac{1}{3}(1\ 500 \cos 30^\circ + 1\ 800 \cos 70^\circ + 2\ 000 \cos 170^\circ \\ &\qquad + j1\ 500 \sin 30^\circ - j1\ 800 \sin 70^\circ + j2\ 000 \sin 170^\circ) \\ &= \tfrac{1}{3}(1\ 300 + 615 - 1\ 970 + j750 - j1\ 690 + j347) \\ &= -18 - j198 = 198\,\underline{|264^\circ\ 48'}. \\ E_1 &= \tfrac{1}{3}(E_A + \lambda E_B + \lambda^2 E_C) \\ &= \tfrac{1}{3}(1\ 500\,\underline{|30^\circ} + 1\ 800\,\underline{|-70^\circ + 120^\circ} + 2\ 000\,\underline{|170^\circ + 240^\circ}) \\ &= 1\ 250 + j1\ 220 = 1\ 740\,\underline{|44^\circ\ 14'}. \\ E_2 &= \tfrac{1}{3}(E_A + \lambda^2 E_B + \lambda E_C) \\ &= \tfrac{1}{3}(1\ 500\,\underline{|30^\circ} + 1\ 800\,\underline{|-70^\circ + 240^\circ} + 2\ 000\,\underline{|170^\circ + 120^\circ}) \\ &= -70 - j270 = 280\,\underline{|252^\circ\ 30'}. \end{aligned}$$

It is clear that unbalanced currents can be resolved into symmetrical components in the same way as voltages.

Application of Symmetrical Components. Let us consider the voltage drops in a symmetrically spaced transmission line due to unbalanced currents I_A, I_B, I_C. The line has self-impedances Z_S and mutual impedances Z_M, as shown in Fig. 184, where Z_S per unit length of line is the resistance plus $j\omega L_S$, and

$$L_S = [\tfrac{1}{2} + 2 \text{ logh } (R/r)] \times 10^{-9} \text{ H. per cm. length}$$

according to equation (24). The mutual inductance between lines is

$$L_M = 2 \text{ logh } (R/\mathrm{D}) \times 10^{-9} \text{ H. per cm. length}$$

R is a large distance beyond which the total flux is insignificant. The voltage drops in the lines are

$$V_A = I_A Z_S + I_B Z_M + I_C Z_M$$
$$V_B = I_A Z_M + I_B Z_S + I_C Z_M$$
$$V_C = I_A Z_M + I_B Z_M + I_C Z_S.$$

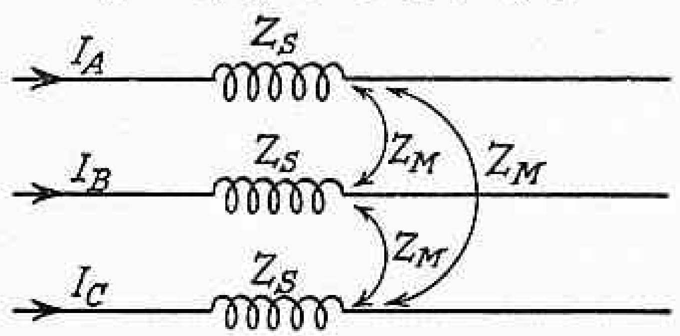

FIG. 184. GENERAL THREE-PHASE LINE

The symmetrical components of the voltages are found in the following way—

$$V_0 = \tfrac{1}{3}(V_A + V_B + V_C) = \tfrac{1}{3}(Z_S + 2Z_M)(I_A + I_B + I_C)$$
$$= I_0(Z_S + 2Z_M),$$
$$V_1 = \tfrac{1}{3}(V_A + \lambda V_B + \lambda^2 V_C) = \tfrac{1}{3}Z_S(I_A + \lambda I_B + \lambda^2 I_C)$$
$$+ \tfrac{1}{3}Z_M(\lambda I_A + \lambda^2 I_A + I_B + \lambda^2 I_B + I_C + \lambda I_C)$$
$$= I_1 Z_S + \tfrac{1}{3}Z_M(-I_A - \lambda I_B - \lambda^2 I_C),$$

using the relation $1 + \lambda + \lambda^2 = 0$. Therefore

$$V_1 = I_1(Z_S - Z_M).$$

Similarly $$V_2 = I_2(Z_S - Z_M).$$

We have therefore

$$\left.\begin{aligned} V_0 &= Z_0 I_0, \\ V_1 &= Z_1 I_1, \\ \text{and} \quad V_2 &= Z_2 I_2, \end{aligned}\right\} \qquad (109a)$$

$$\left.\begin{aligned} \text{where} \quad Z_0 &= (Z_S + 2Z_M) \\ Z_1 &= (Z_S - Z_M) \\ \text{and} \quad Z_2 &= (Z_S - Z_M). \end{aligned}\right\} \qquad (109b)$$

We have thus the important result that *the phase-sequence voltage drops are due to the separate phase-sequence currents.*

Impedances to the Various Phase-sequence Currents. It is seen from equations (109) that the impedances of a transmission line to the zero, positive, and negative phase-sequence currents are Z_0, Z_1, and Z_2. The last two are equal to $(Z_S - Z_M)$, which is due to an inductance of

$$L_S - L_M = [\tfrac{1}{2} + 2 \text{ logh } (\mathrm{D}/r)] \times 10^{-9} \text{ H. per cm. length},$$

which is the inductance to neutral in a balanced system.

It is thus independent of the distance R, but depends only on the radius of the wires r and their spacing D. The zero phase-sequence impedance depends on R, or more particularly it depends upon the return path for the current I_0 which flows along the three wires in parallel, since the distance R is to be chosen to include the return path. It is difficult to calculate Z_0 and it is best found by experiment. If information is not available we may take Z_0 as twice or three times Z_1. It will be shown later that if the neutral is earthed through an impedance, three times this impedance must be added to Z_0.

In order to calculate unsymmetrical short-circuit currents it is necessary to know the various phase-sequence properties of the generators and transformers in the system.

An alternator generates only a positive phase-sequence system of e.m.f.'s. We have already discussed in detail the impedance (or more simply the reactance) of the alternator to positive phase-sequence currents; there is the initial or transient reactance which increases to the *synchronous reactance* by reason of armature reaction. The initial reactance to negative phase-sequence currents is about 70 per cent of the previous transient reactance, and to zero phase-sequence currents 10 to 25 per cent. Under steady short-circuit conditions, the values are less. The following table gives approximate values in terms of the reactances to positive phase-sequence currents.

	REACTANCE TO NEGATIVE PHASE-SEQUENCE CURRENTS (%)	REACTANCE TO ZERO PHASE-SEQUENCE CURRENTS (%)
Transient . . .	70	10 to 25
Steady Short Circuit		
Salient pole . . .	30	5 to 15
Turbo-alternator . .	15	0 to 5

Decrement factors can be used in the way described above to find the currents at intermediate times.

The impedance of a transformer to negative phase-sequence currents is the same as to the positive system. The impedance to the zero phase-sequence currents is the same as for the other sequences provided there is a through circuit for the earth currents and the compensating currents can flow, otherwise the impedance is infinite. Thus in an unearthed star/unearthed star connection the zero phase currents cannot flow and the zero phase impedance is infinite. In the unearthed star/earthed star connection, if an earth fault occurs on the primary side no zero sequence current can flow and the impedance is infinite; if the earth fault occurs on the secondary side there is a complete path for the zero sequence current, but there is no path for the compensating currents in the primary windings, and the zero phase impedance is again infinite. In the earthed star/delta connection, an earth fault in the

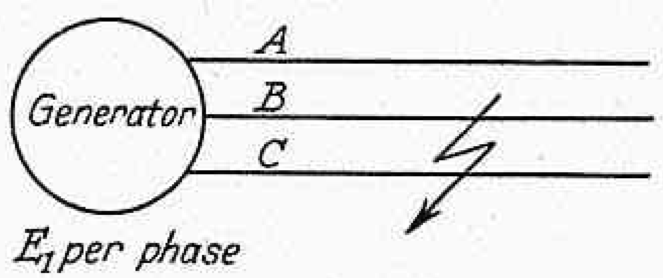

FIG. 185. APPLICATION OF SYMMETRICAL COMPONENTS

primary circuit has a complete path and the compensating currents can flow in the delta, so that the zero sequence impedance is finite; if the fault is in the secondary circuit, the zero phase impedance is infinite.

General Method Using Symmetrical Components. From the conditions of the fault we get three relations between the voltages V_A, V_B, V_C and the currents I_A, I_B, I_C. For instance, if there is an earth fault on line C only, we have $I_A = 0$, $I_B = 0$, and $V_C = 0$. If there is an earth fault on lines B and C, we have $I_A = 0$, $V_B = 0$, and $V_C = 0$. If the earth fault is across all three lines, we have $V_A = 0$, $V_B = 0$, and $V_C = 0$. If there is a short between two lines B and C, we have $I_A = 0$, $I_B + I_C = 0$, and $V_B = V_C$. We can then express the currents and voltages in terms of their symmetrical components. We know that the separate phase-sequence voltage drops are due to the corresponding phase-sequence currents. We thus have two three-phase balanced systems and one single-phase system (the earth return system), and we can apply the simplified method used in a balanced system, in which we replace the system by a single line and impedances to neutral.

As an example let us solve the case when there is a short between two lines, as shown in Fig. 185. The generator produces a positive phase-sequence e.m.f. only of E_1 per phase; it has impedances Z_{G0}, Z_{G1}, and Z_{G2} to the sequence currents. The line has impedances

Z_{L0}, Z_{L1}, and Z_{L2}. Let V_A, V_B, V_C be the voltages and I_A, I_B, I_C the currents near the fault. We have

$$I_A = 0,\ I_B + I_C = 0,\ \text{and } V_B = V_C.$$

The phase-sequence currents are given by equations (106) as

$$\left.\begin{aligned} I_0 &= \tfrac{1}{3}(I_A + I_B + I_C) = 0, \\ I_1 &= \tfrac{1}{3}(I_A + \lambda I_B + \lambda^2 I_C) = \tfrac{1}{3}(\lambda - \lambda^2)I_B, \\ I_2 &= \tfrac{1}{3}(I_A + \lambda^2 I_B + \lambda I_C) = \tfrac{1}{3}(\lambda^2 - \lambda)I_B. \end{aligned}\right\} \quad (110)$$

The phase-sequence voltages are similarly given by

$$\left.\begin{aligned} V_0 &= \tfrac{1}{3}(V_A + V_B + V_C), \\ V_1 &= \tfrac{1}{3}(V_A + \lambda V_B + \lambda^2 V_C) = \tfrac{1}{3}(V + \lambda V_B + \lambda^2 V_B), \\ V_2 &= \tfrac{1}{3}(V_A + \lambda^2 V_B + \lambda V_C) = \tfrac{1}{3}(V_A + \lambda^2 V_B + \lambda V_B). \end{aligned}\right\} \quad (111)$$

The phase-sequence e.m.f.'s are E_1, 0, 0, so that applying equations (108) we get

$$\begin{aligned} V_0 &= 0 - (Z_{G0} + Z_{L0})I_0 = 0, \text{ since } I_0 = 0. \\ V_1 &= E_1 - (Z_{G1} + Z_{L1})I_1, \\ V_2 &= 0 - (Z_{G2} + Z_{L2})I_2. \end{aligned}$$

From equations (111) we see that $V_1 = V_2$ so that

$$E_1 - (Z_{G1} + Z_{L1})I_1 = -(Z_{G2} + Z_{L2})I_2.$$

Substituting for I_1 and I_2 from equations (110) we get

$$\begin{aligned} E_1 &= (Z_{G1} + Z_{L1})I_1 - (Z_{G2} + Z_{L2})I_2 \\ &= (Z_{G1} + Z_{L1} + Z_{G2} + Z_{L2})\tfrac{1}{3}(\lambda - \lambda^2)I_B, \\ &= (Z_{G1} + Z_{L1} + Z_{G2} + Z_{L2})\,(j/\sqrt{3})I_B, \end{aligned}$$

so that the magnitude of I_B is

$$\frac{(\sqrt{3})E_1}{Z_{G1} + Z_{L1} + Z_{G2} + Z_{L2}}.$$

Interference with Communication Circuits. When a communication circuit runs parallel with a high voltage overhead line, high voltages may be induced in the former resulting in acoustic shock and noise. The induced voltages are due to electrostatic and electromagnetic induction, and are reduced considerably by *transposing* the power lines as shown in Fig. 186. See example 9 on page 236. The effect of transposition is to balance the capacitances of the lines, so that the electrostatically induced voltages balance out in the length of a complete set of transpositions; such a length is called a *barrel*. Transposition results also in a diminution of the electromagnetically induced e.m.f. on the wires, since the fluxes due to the positive and negative phase-sequence currents will add up to zero along the barrel. The flux due to the zero phase-sequence or longitudinal current is unaffected by transpositions of the power system, since it flows along the three wires in parallel. In order to reduce the e.m.f. in the telephone circuit due to the zero phase-sequence current, which is called the *longitudinal current*, the telephone line is transposed, as shown in Fig. 186. By a proper co-ordination of transpositions of the power and communication lines, the induced voltages can be reduced to very small proportions under normal working conditions.

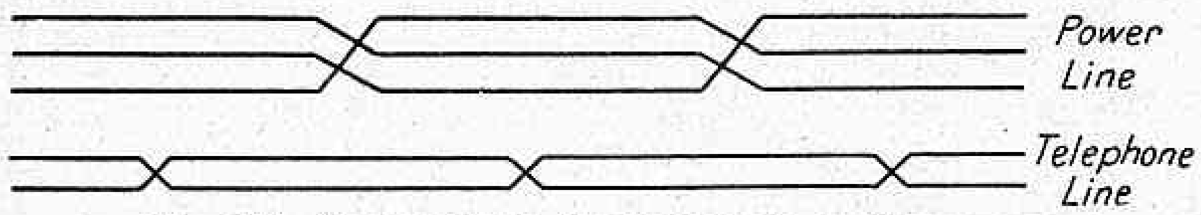

FIG. 186. CO-ORDINATED TRANSPOSITION OF POWER AND COMMUNICATION CIRCUITS

At the ends of a barrel the induced voltage is small and we have *silent points*. At points inside the barrel there may be a high voltage on the telephone line. If it is desired to tap the communication circuit at such a point, it is advisable to insert an isolating transformer, the insulation between the line and telephone windings being adequate to withstand the voltage; the telephone winding is earthed at the mid-point or at one end, so that a high voltage cannot reach the telephone.

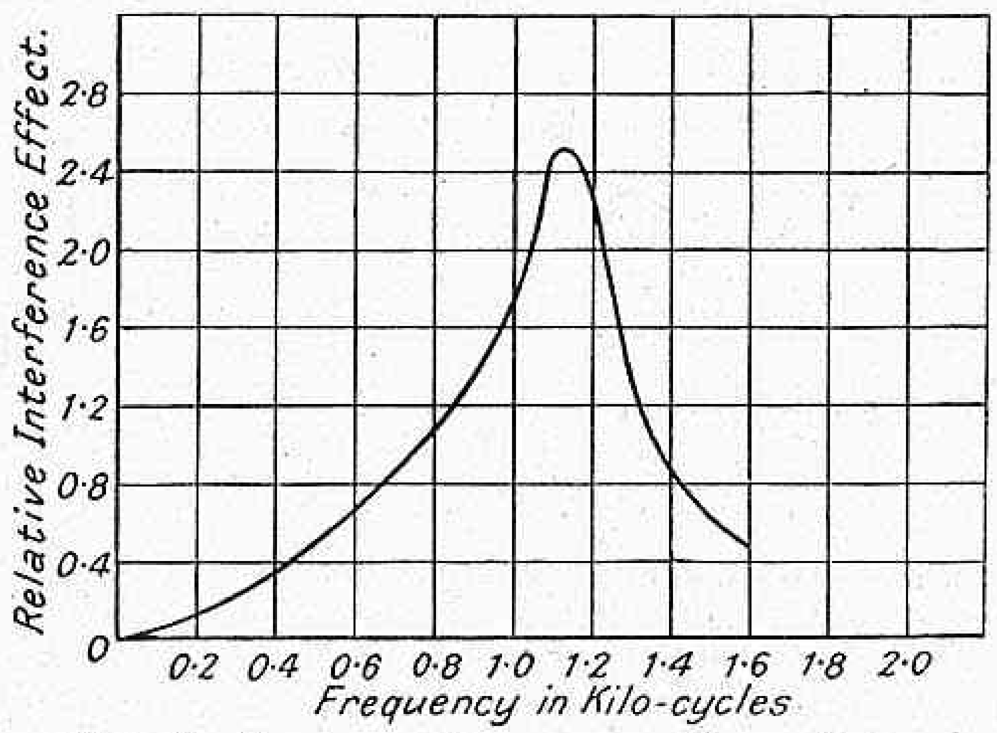

FIG. 187. TELEPHONE INTERFERENCE FACTOR CURVE (Gill)

The interference effect of an induced voltage or current depends greatly upon the frequency. The relative interference effect of different frequencies is shown in Fig. 187, which shows the *T.I.F.* curve, i.e. the telephone interference factor curve.

It is usual to express the interference currents in terms of a current at 800 cycles per sec. which produces the same degree of disturbance according to the curve of Fig. 187. Thus suppose that we have induced currents of 20 μA. at 250 cycles and 10 μA. at 350 cycles; the disturbances caused by them are the same as caused by 800 cycle currents of $20 \times 0{\cdot}25 = 5$ μA. and $10 \times 0{\cdot}3 = 3$ μA., respectively.

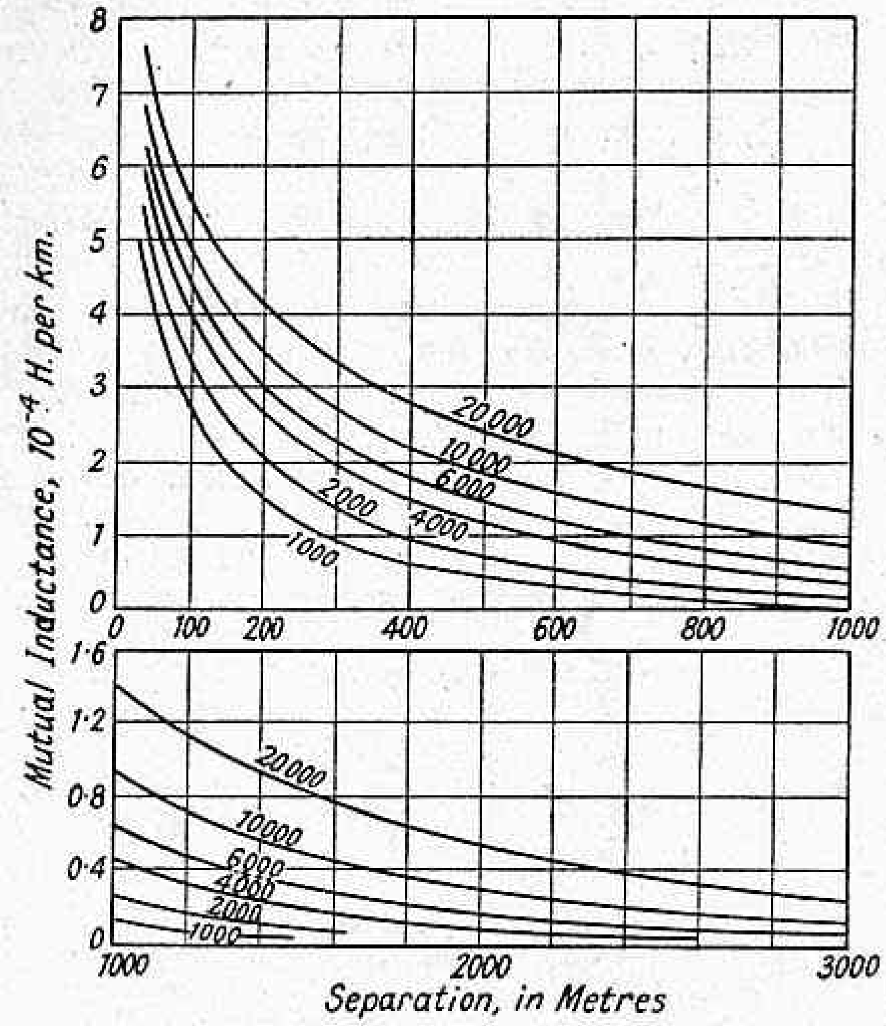

FIG. 188. MUTUAL INDUCTANCE BETWEEN A LINE AND EARTH RETURN AND ANOTHER LINE (CARSON-POLLACZEK FORMULA). FREQUENCY: 50 CYCLES

Curves are for different resistivities of soil (in Ω. per cm. cube).

The total disturbance is considered as due to an 800 cycle current of value $\sqrt{(5^2 + 3^2)} = 5{\cdot}8$ μA.

It is clear that the harmonics in the power system should be kept as low as possible, as they have a high interference factor.

When a short circuit occurs to earth, a large zero phase-sequence or longitudinal current flows along the wires in parallel and through the earth return. In this case the electromagnetic induction is large in magnitude, and depends upon the spacing between the power and telephone lines, the resistivity of the earth, and the frequency of the current. The e.m.f. induced in the telephone line is

$$E = -j\omega MlI,$$

where I is the zero phase-sequence current, $\omega = 2\pi \times$ frequency, l is the length of the parallel, and M the mutual inductance between the power line circuit (with earth return) and the telephone line. Fig. 188 gives the value of M for 1 km. parallel as calculated by

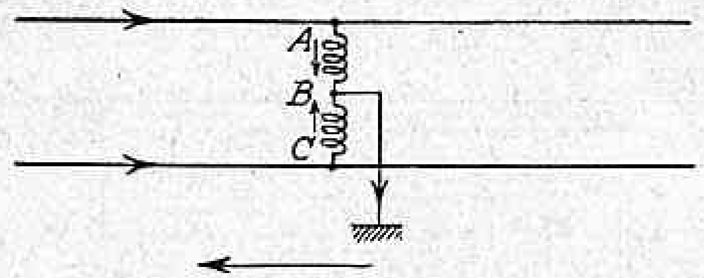

FIG. 189. DRAINAGE COIL

the Carson-Pollaczek theory for different spacings and earth resistivities, the frequency being 50 cycles per sec. It is noticed that M increases as the resistivity increases, because the current spreads out further in a soil of higher resistivity.

The e.m.f. E is induced in each of the telephone wires, so that if

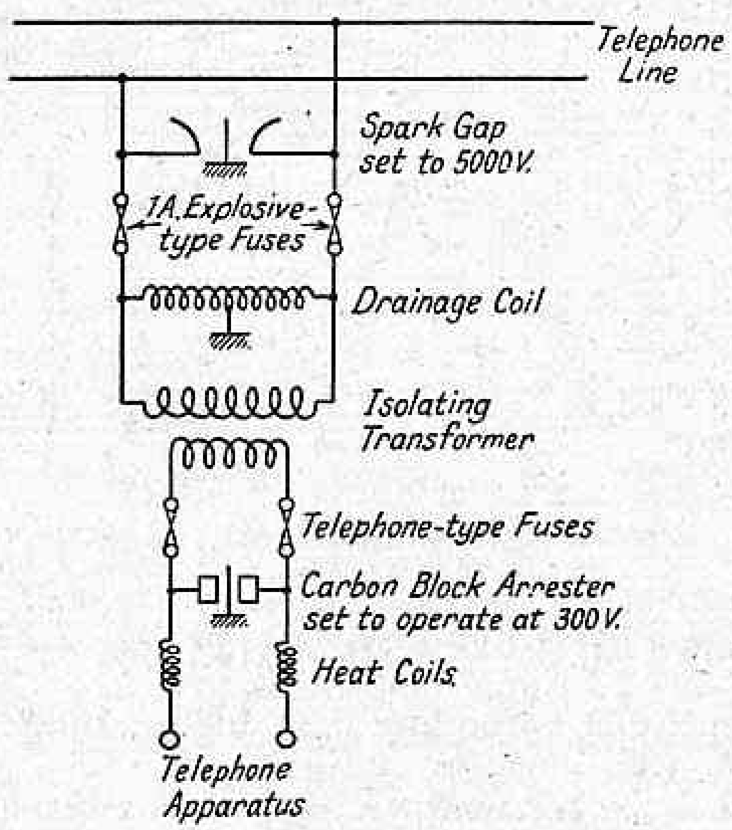

FIG. 190. TELEPHONE CIRCUIT PROTECTIVE SYSTEM

one telephone circuit were perfectly transposed and balanced there would be no voltage *between* the two wires of a circuit. There would, however, be the e.m.f. E between each wire and earth, and the telephone insulators must be capable of withstanding this voltage; for if one wire flashes over to earth, the full e.m.f. is applied to the telephone circuit with a resulting acoustic and electric shock. The

potential between the wires of the telephone circuit is kept low by the use of drainage coils, shown in Fig. 189. The windings AB and BC are series aiding, so that the coil has a high impedance between the terminals A and C (of the order $6\,000\,\underline{|70^\circ}$ at 1 000 cycles), and gives an attenuation of about 2 db. to voice-frequency currents. The mid-point B is earthed, so that the impedance of the coil is very low to currents flowing along the lines in parallel and back through earth. In this way the longitudinal potential of the telephone lines is reduced from the high value E to a very low value, which depends upon the degree of balance of the windings and their resistance.

Acoustic and electric shock are minimized by the use of isolating transformers, drainage coils, spark gaps, and carbon block arresters. Fig. 190 shows an arrangement for the protection of a telephone circuit, as used in a successful installation which runs parallel with a 132 kV. power line in the Punjab.

EXAMPLES VIII

1. Discuss the phenomena of electrostatic and electro-magnetic induction from power transmission lines to adjacent telephone lines.

State the factors upon which the magnitude of the induction depends in each case and the precautions taken in both the power and communication circuits to reduce it. (*Lond. Univ.*, 1949.)

2. Why is automatic voltage regulation required for modern alternators?

Explain, with a diagram of connections, the operation of an automatic voltage regulator suitable for use with a large turbo-alternator. (*Lond. Univ.*, 1950.)

3. A 3-phase overhead line has the following constants: series impedance per conductor, $20 + j\,50\ \Omega$; shunt admittance of each conductor to neutral, $0 + j\,800$ micromhos. The line supplies, through a star/star transformer with a turn ratio of 4 to 1, a load of 40 MW. at 33 kV., unity power factor. The transformer, at 45 MVA. and 33 kV., has an impedance of $0{\cdot}5 + j\,6$ per cent.

Neglecting iron loss and magnetizing current in the transformer, determine the voltage and current at the supply end of the line, and the phase angle between them. (*Lond. Univ.*, 1954.)

4. Describe and compare the methods of interconnecting the bus-bars of a generating station.

Three generators A, B, and C, each of 12% leakage reactance and of MVA. ratings 25, 50, and 25 respectively, are interconnected electrically by a tie-bar through reactors, each of 10% reactance based upon the MVA. rating of the machine to which it is connected. A 3-phase feeder is supplied from the bus-bars of generator A at a line voltage of 11 kV. The feeder has a resistance of $0{\cdot}1\ \Omega$/phase and an inductive reactance of $0{\cdot}3\ \Omega$ phase. Estimate the maximum MVA. which can be fed into a symmetrical short-circuit at the far end of the feeder. (*Lond. Univ.*, 1953.)

5. Explain what is meant by the symmetrical components of a 3-phase 4-wire system.

The p.d.'s to neutral of such a system are $-36 + j\,0$, $0 + j\,48$ and $64 + j\,0$ V. respectively, and the currents in the corresponding line wires R, Y, and B are $-4 + j\,2$, $-1 + j\,5$, and $5 - j\,3$ A. Determine the negative-sequence power and reactive voltamperes. The sequence is RYB. (*Lond. Univ.*, 1954.)

6. Explain briefly the advantages to be gained by the insertion of reactances in the bus-bars of a large generating station. A generating station contains four identical three-phase alternators A, B, C, and D each of 20 000 kVA., 11 kV. rating and having 20% reactance. They are connected to a bus-bar system which has a bus-bar reactor rated at 20 000 kVA. and having 25% reactance inserted between B and C. A 66 kV. feeder is taken off from the bus-bar through a 10 000 kVA. transformer having 5% reactance. If a short circuit occurs across all phases at the high voltage terminals of the transformer, calculate the current fed into the fault. (*Nat. Cert.*, 1935.)

7. The bus-bars of a power station are split into two sections A and B, separated by a 5% reactance (based on 10 000 kVA.). A 30 000 kVA. generator with 10% reactance is connected to section A and a 50 000 kVA. generator with 12% reactance is connected to section B. Each section supplies a transmission line through a 40 000 kVA. transformer with 6% reactance which steps the voltage up to 132 kV. If a three-phase short-circuit occurs on the high-tension terminals of the transformer connected to section A, calculate the maximum initial value of current which may occur at a short circuit.

Describe how you would estimate the current which a circuit-breaker operating after 0·3 sec. would have to interrupt, and explain why this value would be different from the maximum initial value as calculated.

8. A three-phase system of voltages is given by

$$V_A = 1\,000\,\underline{|35^\circ} \qquad V_B = 3\,000\,\underline{|100^\circ} \qquad V_C = 2\,000\,\underline{|270^\circ}$$

Resolve these voltages into their symmetrical components, namely, a balanced positive sequence component, a balanced negative sequence component and a zero sequence component.

Explain how the method of symmetrical components can be used for the calculation of short-circuit currents under unbalanced fault conditions.

(*Lond. Univ.*, 1934.)

9. Two 3-phase, 6·6 kV. generators G_1 and G_2 feed into common bus-bars, which are linked by reactors R to a second set of bus-bars: the latter are also linked to a grid system of large capacity by an interconnector I. From the bus-bars, feeders F_1 and F_2 supply a network N, as in Fig. 191. The percentage reactances are as follows—

G_1 and G_2, each 15% at 50 MVA.; R, 5% at 10 MVA.; grid system through I, 10% at 40 MVA.; N, between F_1 and F_2, 10% at 100 MVA. The impedance of each feeder is $0{\cdot}01 + j0{\cdot}02$ ohm per core.

Determine the maximum symmetrical fault current that a circuit-breaker at X may have to clear, in the event of either one or the other of the feeders being disconnected. (*Lond. Univ.*, 1949.)

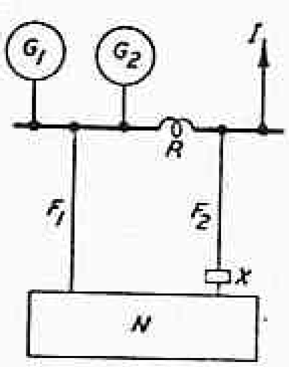

FIG. 191

If there are several reactances in series of magnitudes X_1, X_2, and X_3, the short-circuit current is

$$\frac{E}{X_1+X_2+X_3} = \frac{E}{(E/I)(\% X_1) + (E/I)(\% X_2) + (E/I)(\% X_3)} \times 100$$

$$= I \times \frac{100}{(\% X_1) + (\% X_2) + (\% X_3)},$$

by application of equation (99) to the various reactances.

It often happens that the system contains plant of different ratings, and the percentage reactances are given for the respective values. It is then necessary to allow for the different ratings in the following way. Suppose the generator has a rating of 10 000 kVA. and a percentage reactance of 7, and a transformer has a rating of 8 000 kVA. and a percentage reactance of 5. The full-load current of the generator is $(10\ 000\ 000/E) = I_1$, say, so that its reactance is

$$X_1 = (E \times 7)/(I_1 \times 100).$$

Similarly the reactance of the transformer is

$$X_2 = (E \times 5)/(I_2 \times 100)$$

where $I_2 = (8\ 000\ 000/E)$.

The total reactance is

$$X_1 + X_2 = \frac{E \times 7}{I_1 \times 100} + \frac{E \times 5}{I_2 \times 100}$$

$$= \frac{E}{I_1 \times 100}\left[7 + 5 \times \frac{I_1}{I_2}\right] = \frac{E}{I_1 \times 100}\left[7 + 5\frac{EI_1}{EI_2}\right]$$

$$= \frac{E}{I_1 \times 100}\left[7 + 5 \times \frac{10\ 000}{8\ 000}\right],$$

and the total percentage reactance referred to the rating of 10 000 kVA. is

$$(\% X) = \frac{I_1(X_1 + X_2)}{E} \times 100$$

$$= 7 + 5 \times \frac{10\ 000}{8\ 000}$$

$$= 7 + 6{\cdot}25 = 13{\cdot}25.$$

Thus the percentage reactance of the transformer is multiplied by the ratio of the generator rating to the transformer rating in order that it may be expressed with respect to the generator rating.

If there are several pieces of apparatus in the circuit with different ratings, *we choose a basic rating and refer all percentage reactances to this rating by appropriate multipliers.* We can then add the

percentages, if the pieces of apparatus are in series, and the short-circuit current is then found by equation (100). The following example illustrates the method.

EXAMPLE. Find the short-circuit current in the single-phase system of Fig. 165, if the fault is a short circuit between lines at the point F which is 10 miles from the transformer T. The reactance per mile is 0·2 Ω. The voltage is 6·6 kV.

We take 2 000 kVA. as the basic rating, so that full-load current is

$$I = 2\ 000/6{\cdot}6 = 300 \text{ A}.$$

The percentage reactance of the generator is 8, and of the transformer T, $7 \times (2\ 000 \div 1\ 200) = 11{\cdot}7$. The line reactance is 2 Ω., so that its percentage reactance is

$$\frac{300 \times 2}{6\ 600} \times 100 = 9{\cdot}1.$$

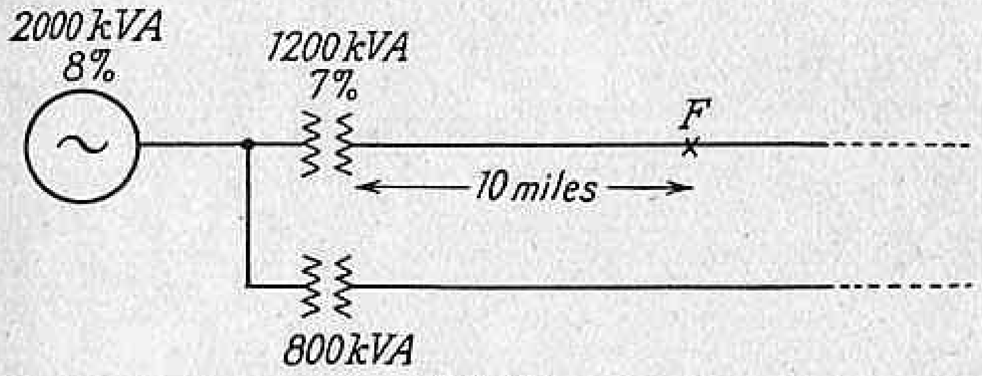

FIG. 165

The total percentage reactance is

$$8 + 11{\cdot}7 + 9{\cdot}1 = 28{\cdot}8,$$

so that the short-circuit current is

$$I_{sh} = I \times (100/\% X) = 300 \times (100/28{\cdot}8)$$

$$= \underline{1\ 040 \text{ A}}.$$

We could use the *direct method*, which consists in the reduction of percentage reactances to actual reactances. Thus the reactance of the generator is

$$\frac{E \times (\% X)}{I \times 100} = \frac{6\ 600 \times 8}{300 \times 100} = 1{\cdot}76\ \Omega.$$

The reactance of the transformer is similarly

$$\frac{6\ 600 \times 7}{300 \times \left(\frac{1\ 200}{2\ 000}\right) \times 100} = 2{\cdot}57\ \Omega.$$

The total reactance is $1{\cdot}76 + 2{\cdot}57 + 2{\cdot}00 = 6{\cdot}33$ ohms, and the short-circuit current is

$$I_{sh} = 6\,600/6{\cdot}33 = 1\,040 \text{ A.}$$

If some of the pieces of apparatus are in parallel, their reactances, and hence their percentage reactances, must be compounded by the method used for parallel impedances. Thus a percentage reactance of 10 in parallel with another of 15 gives a resultant value of

$$\frac{1}{\frac{1}{10} + \frac{1}{15}} = \frac{10 \times 15}{10 + 15} = 6.$$

This method can be used for generators in parallel, as shown in the following example. In the calculation of such problems it is

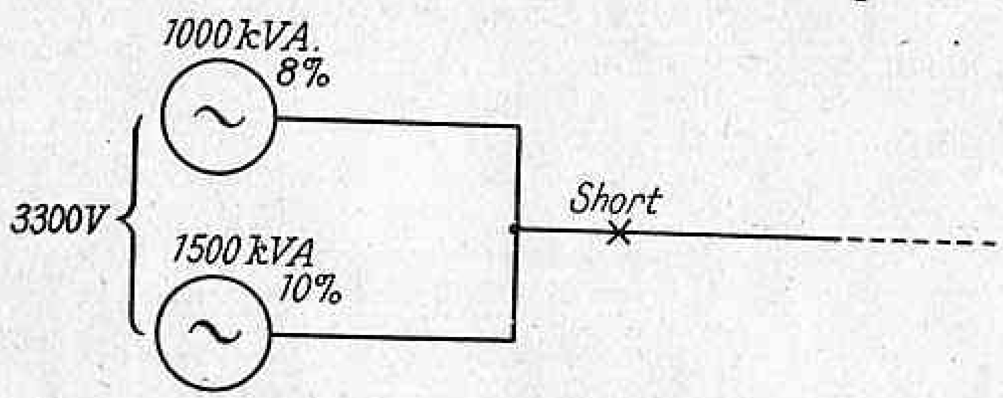

FIG. 166

assumed that the generators have equal voltages which are in phase; the error caused by this assumption should not be serious.

EXAMPLE. Two three-phase generators of ratings 1 000 and 1 500 kVA. and of voltage 3·3 kV. have percentage reactances of 8 and 10, with respect to their ratings. A short across all phases occurs near the common bus-bars. Find the short-circuit current.

The system is shown in Fig. 166.

Let us assume a basic kVA. of 2 500, which is the sum of both ratings. The percentage reactances with respect to this rating are

$$8 \times (2\,500/1\,000) = 20$$

and

$$10 \times (2\,500/1\,500) = 16{\cdot}7.$$

The resultant percentage reactance is

$$\frac{1}{\frac{1}{20} + \frac{1}{16{\cdot}7}} = \frac{1}{0{\cdot}05 + 0{\cdot}06} = \frac{1}{0{\cdot}11} = 9{\cdot}1.$$

The short-circuit kVA. is therefore

$$2\,500 \times (100/9{\cdot}1) = 27\,500.$$

If I_{sh} is the short-circuit current per conductor, the kVA. per phase is

$$I_{sh} \times (3\,300/\sqrt{3}) = \tfrac{1}{3} \times 27\,500\,000,$$

so that

$$I_{sh} = \frac{27\,500\,000 \times \sqrt{3}}{3 \times 3\,300} = \underline{4\,810 \text{ A.}}$$

The full load current is one-eleventh of this, i.e. 437 A.

Symmetrical Short-circuit Currents. The short-circuit currents are symmetrical, i.e. equal in the different conductors, if the short circuit occurs across both lines in a single-phase system or across the three wires of a three-phase system. The methods developed in the last section are adequate to calculate such short-circuit currents, and the two examples illustrate the methods. If there are several generators

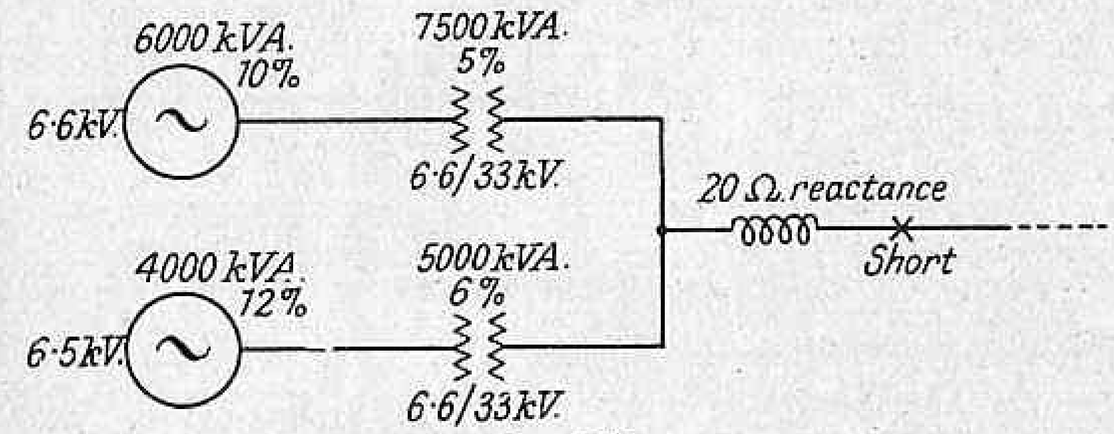

FIG. 167

in the system, it is assumed, as has already been stated, that the e.m.f.'s are equal and in phase with each other. When the system is complicated, the star-delta equivalence of Appendix III is often of great help in effecting a simplification of the network. Sometimes Thévénin's theorem is useful in obtaining the result quickly, especially when generators have unequal e.m.f.'s.

EXAMPLE. Find the short-circuit current in the system of Fig. 167, in which one generator is generating at 6·6 kV. and the other at 6·5 kV. The system is three-phase.

The voltages per phase are $6{\cdot}6\text{ kV}/\sqrt{3} = 3\,820$ V. and $6{\cdot}5\text{ kV.}/\sqrt{3} = 3\,750$ V. The full-load current of the larger generator is

$$\frac{6\,000\,000}{3 \times (6\,600/\sqrt{3})} = \frac{6\,000\,000}{\sqrt{3} \times 6\,600} = 525 \text{ A.},$$

so that its reactance per phase is

$$\frac{(\%\,X) \times E}{I \times 100} = \frac{10 \times 3\,820}{525 \times 100} = 0{\cdot}727\ \Omega.$$

In the same way it is found that the reactance of the other generator is $1{\cdot}31\ \Omega$. It is assumed that the rated voltage in this case also is 6·6 kV., although the generated voltage is 6·5 kV.

Similarly the transformer reactances referred to the low voltage sides are 0·292 and $0{\cdot}525\ \Omega$. The line reactance transferred to the low voltage side is $20 \div (33/6{\cdot}6)^2 = 0{\cdot}8\ \Omega$. The system is then as shown in Fig. 168. We then apply Thévénin's theorem to the system to the left of A. The voltage when the line is disconnected is

$$3\,820 - \frac{(3\,820 - 3\,750)\,(0{\cdot}727 + 0{\cdot}292)}{0{\cdot}727 + 0{\cdot}292 + 1{\cdot}31 + 0{\cdot}525}$$
$$= 3\,795 \text{ V.}$$

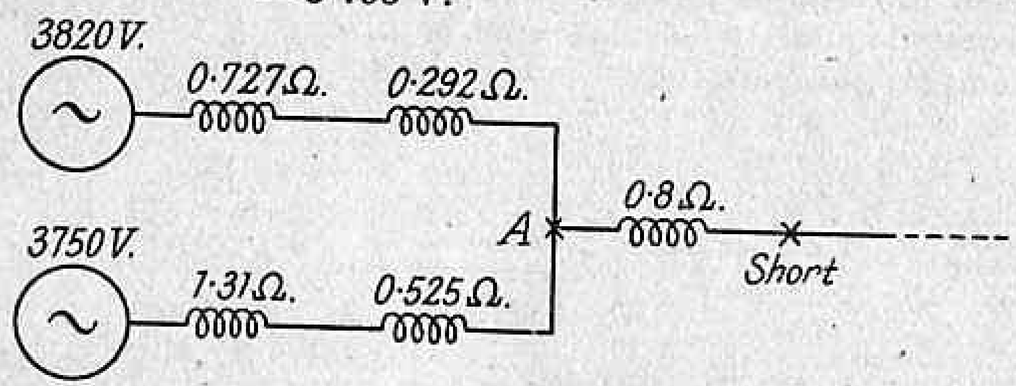

FIG. 168

The impedance is

$$\frac{(0{\cdot}727 + 0{\cdot}292)\,(1{\cdot}31 + 0{\cdot}525)}{0{\cdot}727 + 0{\cdot}292 + 1{\cdot}31 + 0{\cdot}525} = 0{\cdot}654\ \Omega$$

The short-circuit current is thus

$$\frac{3\,795}{0{\cdot}654 + 0{\cdot}8} = \underline{\underline{2\,600 \text{ A.}}}$$

The *actual* short-circuit current is

$$2\,600 \times (6{\cdot}6/33) = 520 \text{ A.}$$

520 A. is the r.m.s. of the steady short-circuit current, whilst the peak value is $520 \times \sqrt{2} = 735$ A. There may be an increased peak value due to a "doubling effect," which, in circuits of normal value of reactance to resistance, is 1·8 times the steady peak. Thus a maximum peak value of $1{\cdot}8 \times 735 = 1\,320$ A. may occur.

Short-circuit Current of Alternators. When an alternator is shorted, across all three phases, say, the current rises rapidly to a high value, about 18 times full-load current in turbo-alternators which have cylindrical rotors, and about 12 times in generators with salient poles. The value of the peak current is limited only by the *transient* or *leakage reactance* of the armature. Moreover if the short circuit occurs at an instant at which the voltage is zero there is a doubling effect, and the current wave is offset from the zero. Fig. 169 shows the kind of current wave obtained. If the short circuit persists, the wave becomes symmetrical; then armature reaction

Armature reaction

reduces the excitation and the current falls to a steady value, which is 4 to 6 times the full-load value. Another way of considering the effect of armature reaction is to consider it as increasing the transient impedance to the synchronous impedance.

The doubling effect may be demonstrated as follows. Let the generator be considered as an e.m.f. $E \sin(\omega t + \theta)$ in series with an impedance (R, L) which is the *transient* or *true impedance*. If a short occurs at $t = 0$, the equation for the short-circuit current is

$$L(di/dt) + Ri = E \sin(\omega t + \theta).$$

The complementary function is given by

$$L(di/dt) + Ri = 0,$$

i.e.
$$i = A\varepsilon^{-(R/L)t} \quad . \quad . \quad . \quad . \quad (101)$$

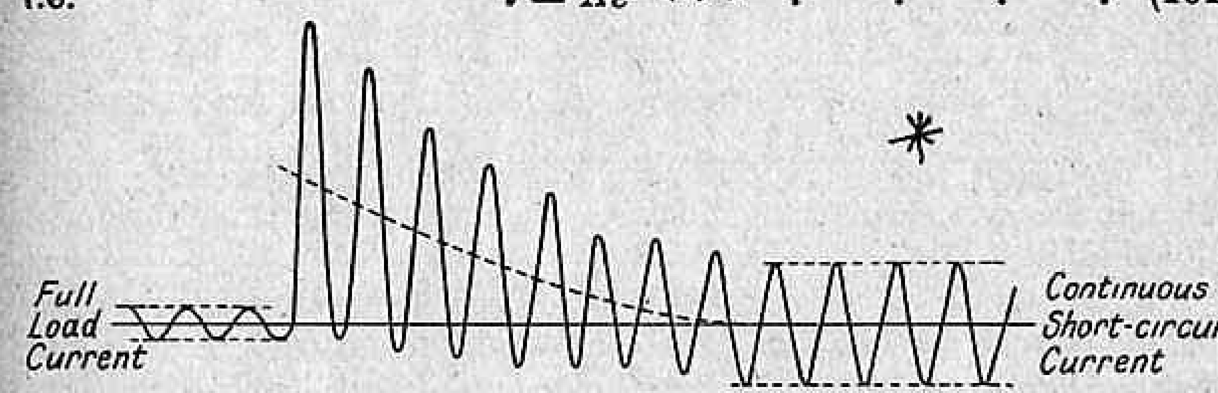

FIG. 169. DOUBLING EFFECT IN SHORT-CIRCUIT CURRENT

The particular integral is

$$i = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right), \quad . \quad . \quad (102)$$

which is the steady current under these conditions. The actual current is the sum of the currents given in equations (101) and (102). At $t = 0$ the current is zero. This gives

$$0 = A + \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right).$$

The current is thus

$$i = -\frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}$$
$$+ \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right) \quad . \quad (103)$$

We may consider ωL as much greater than R. Then the first term, which is considered as a d.c. component which decays exponentially, has magnitude

$$-\frac{E}{\omega L} \sin\left(\theta - \frac{\pi}{2}\right)\varepsilon^{-(R/L)t}$$
$$= \frac{E}{\omega L} \cos\theta \, . \, \varepsilon^{-(R/L)t}.$$

If $\theta = 0$, i.e. the voltage is zero and the current is a maximum at $t = 0$, the d.c. component has the initial value of $E/\omega L$. As the alternating part of the current has a magnitude of nearly $E/\omega L$, the d.c. component doubles the current at the instant when the former has its peak value, and reduces it to zero when the former reaches its negative maximum. The current is thus on one side of the zero to begin with. If, however, $\theta = \pi/2$, i.e. the voltage is a

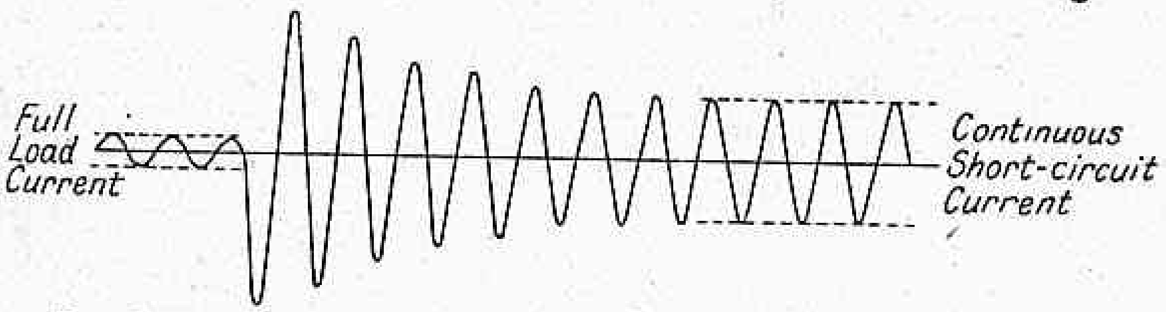

FIG. 170. SHORT-CIRCUIT CURRENT WITHOUT DOUBLING EFFECT

maximum and the current is zero at the instant of short circuit, the d.c. term is zero. The short-circuit current has then the form shown in Fig. 170.

The change from the large current at the instant of short circuit to the comparatively small current after armature reaction has asserted itself is of importance in the design of switchgear operation. The behaviour of an alternator is most easily expressed in terms of *decrement factors*, which are found by extensive tests in the

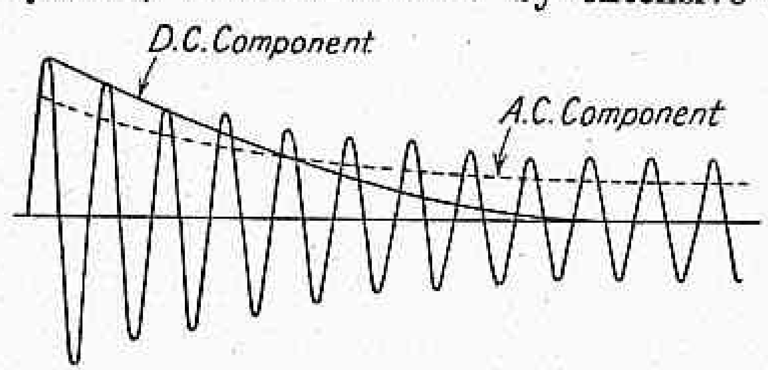

FIG. 171. D.C. AND A.C. COMPONENTS OF SHORT-CIRCUIT CURRENT

following way. The generator excitation is adjusted to the value for full load at 0·8 power factor lagging, and external reactance is put in series with the alternator to bring the value up to some definite amount, 5, 10, 20 . . . per cent. This value includes the transient reactance. A short circuit is applied and an oscillogram of the current taken. In order that the test results should be as severe as possible, it is arranged that the short circuit should take place at an instant when the full doubling effect is incurred, viz. at an instant of zero voltage. The oscillogram is analysed so that the r.m.s. current is found as a function of time. To do this the current wave of Fig. 169 is resolved into the d.c. and a.c. components shown in Fig. 171. The r.m.s. of the a.c. component is shown by the

dotted line. and has a value $I_{A.C.}$ at time t; the d.c. component, which decays exponentially, has a value $I_{D.C.}$ at the same instant, and the total current has an r.m.s. value of $\sqrt{[I_{D.C.}^2 + I_{A.C.}^2]}$. Curves are then drawn giving the r.m.s. of the current (as a multiple of full-load current) against time for different values of the total percentage reactance. Fig. 172 shows a set of such curves for a short circuit across all three phases.

When looking up the decrement factor, the transient reactance of the alternator is added to the external reactance to give the appropriate percentage reactance.

EXAMPLE. A 20 000 kVA. generator, whose decrement curves are shown in Fig. 172, has 15% reactance and feeds a line through a step-up transformer of 6% reactance. Find the breaking capacity of the circuit-breakers, which operate in 0·25 sec. and are on the high voltage side of the transformer.

The total reactance is 21%, and from Fig. 172 it is seen that the decrement factor at 0·25 sec. is 3·4. The current to be interrupted is thus 3·4 times the full-load current. If we assume that the recovery voltage in the breaker is equal to the normal voltage (the matter will be investigated in detail in Chapter IX), the kVA. to be broken is

$$3{\cdot}4 \times 20\,000 = 68\,000 \text{ kVA.}$$

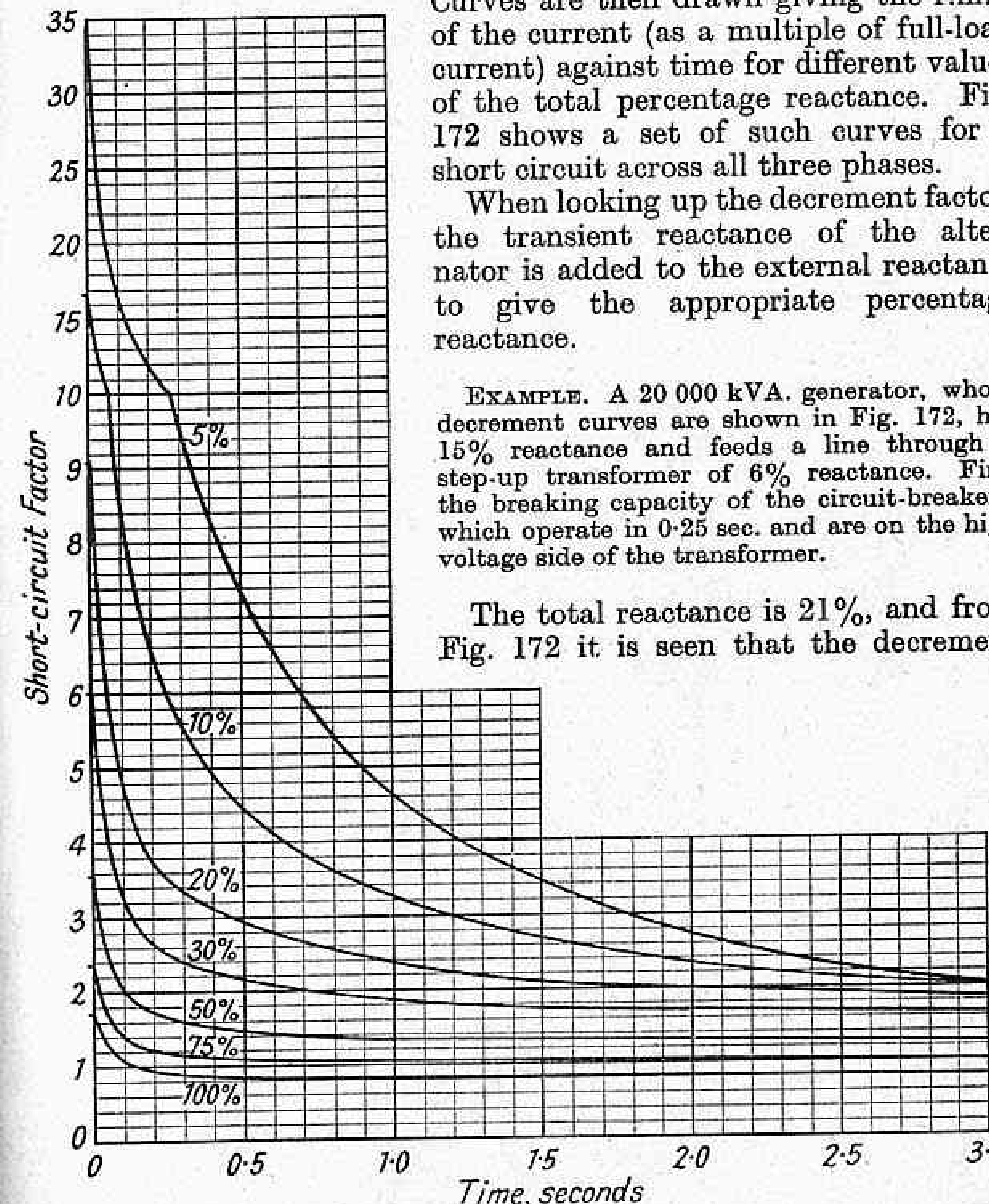

FIG. 172. DECREMENT CURVES FOR ALTERNATOR

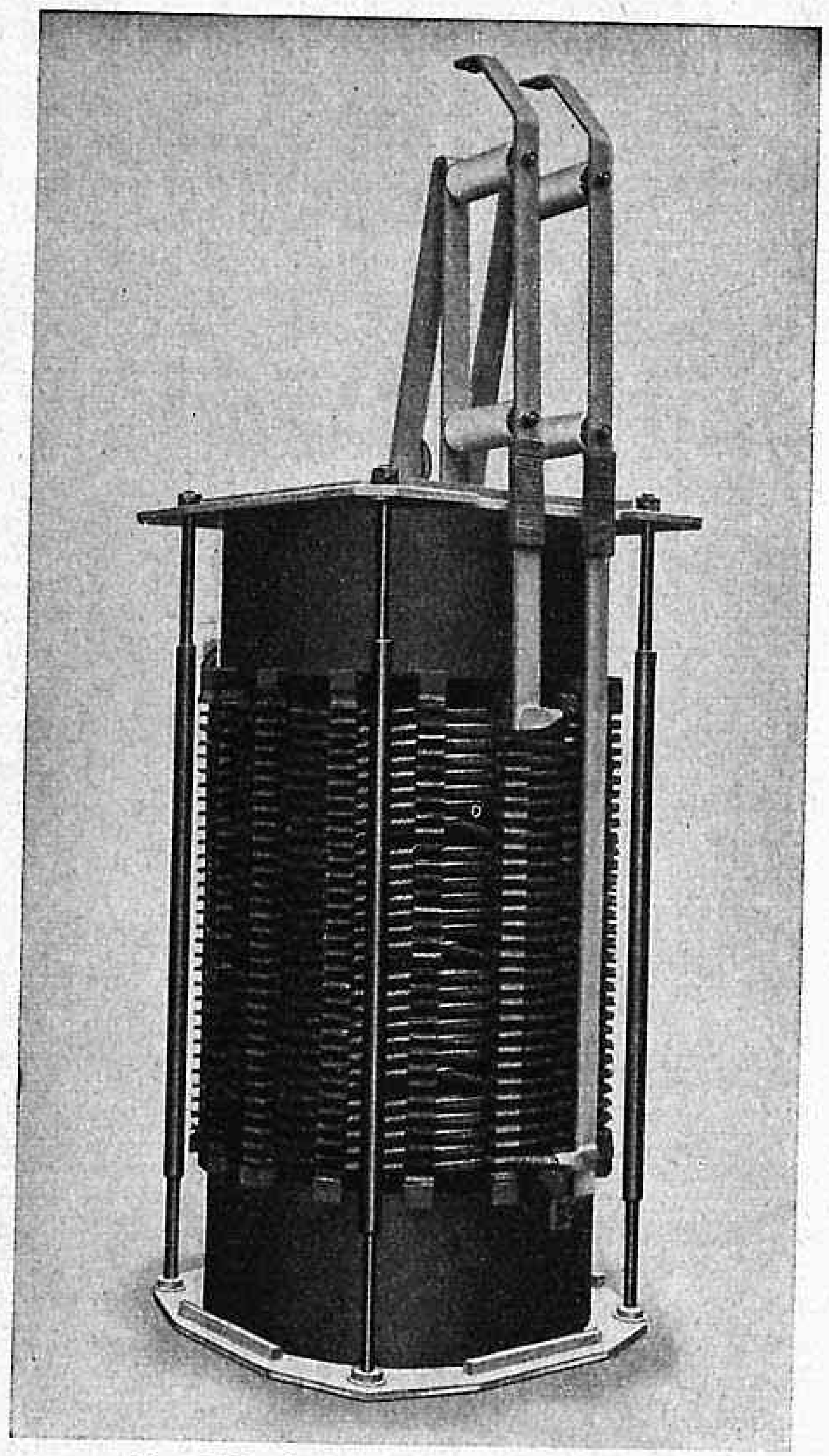

FIG. 173. CURRENT LIMITING REACTOR
(*English Electric Co.*)

Current-limiting Reactors: Sectionalization of Networks. It is clear that the short-circuit currents are decreased by an increase of the percentage reactance in the system. In large interconnected systems the total rating of the generators is very high, and unless precautions are taken, the current fed into a fault will be enormous. The short-circuit current at a fault can be considerably reduced by the judicious placing of protective reactors in the system. It is possible to arrange the reactors so that they do not cause a large voltage drop during normal operation, but prevent a large short-circuit current being fed by most of the generators into the fault. The methods of placing reactors in a system will be considered later.

Reactors are moreover of considerable importance in limiting the currents so that the various circuit-breakers are not called upon to

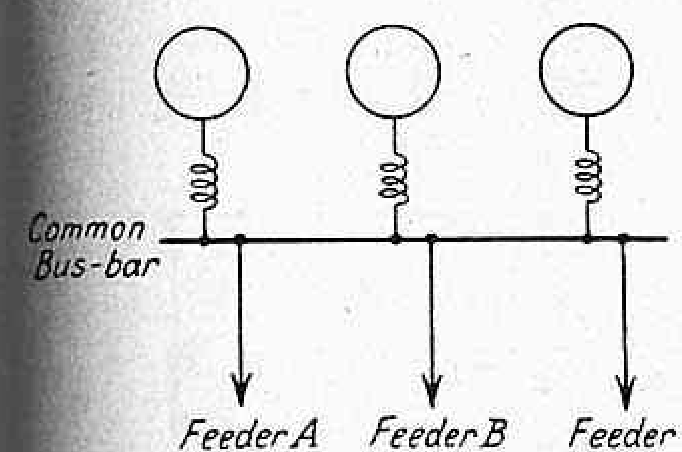

FIG. 174. GENERATOR REACTORS

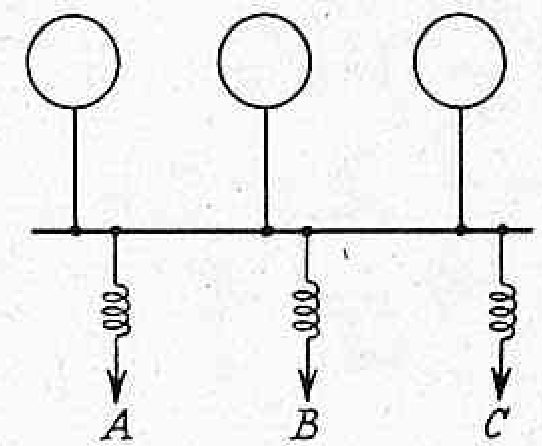

FIG. 175. FEEDER REACTORS

break currents above their rated value. If extensions are made in a system, it is essential that the additional kVA. be virtually segregated from the existing circuit-breakers when a short-circuit occurs. This is done by means of current-limiting reactors.

Fig. 173 shows a reactor. The turns, which are of copper bar or strip, experience large attractive forces under the influence of the short-circuit currents, and they are placed in concrete separators to prevent their being buckled.

Methods of Locating Reactors. Reactors may be inserted in series with each generator, as shown in Fig. 174. The main disadvantage of this method is that if a short occurs on one feeder, the voltage at the common bus-bar drops to a low value and the synchronous machines attached to the other feeders may fall out of step. The whole system is interrupted, and the synchronous machines must be re-synchronized when the faulty feeder is cut out. Moreover in modern alternators the transient reactance is sufficiently large to protect the machine itself against short-circuit currents, and separate reactors are used only with old alternators.

The main disadvantage of the last method is avoided by putting reactances in series with each feeder, as shown in Fig. 175. When a short-circuit occurs on feeder A, the main voltage drop is in its reactor and the bus-bar voltage does not drop unduly. The remaining load and plant are therefore able to continue running. It is true that when a short circuit occurs across the bus-bars, the reactors do not protect the generators. This is, however, of no importance, as bus-bar short circuits seldom occur and the generators are protected by their internal reactances.

A disadvantage from which both the previous methods suffer is that the reactors take the full-load currents under normal operation, so that there is a constant loss and a voltage drop. The voltage drop is eliminated in a new type of reactor in which part of the windings are shunted by a carbon tetrachloride fuse. Under normal conditions the windings are such that they neutralize each other's

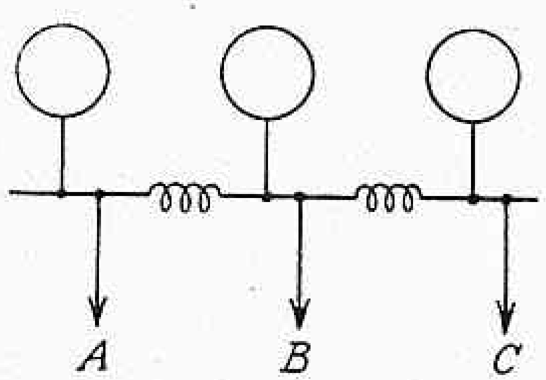

FIG. 176. BUS-BAR REACTORS, RING SYSTEM

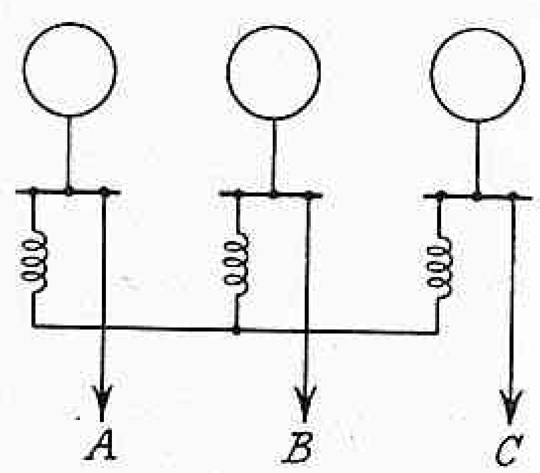

FIG. 177. BUS-BAR REACTORS, TIE-BAR SYSTEM

magnetic field and the reactor has a very small reactance; but when a short circuit occurs and the fuse blows, a large reactance is inserted into the circuit. The constant loss, however, is not eliminated.

The constant loss in reactors can be avoided by inserting the reactors in the bus-bars in the ways shown in Figs. 176 and 177. The former is the *ring* system, and the latter is the *tie-bar* system. In the ring system each feeder is normally fed by one generator, only a small amount of power flowing across the reactances. The reactors can therefore be made with a fairly high ohmic resistance and there is not much voltage drop across it. When a short circuit occurs in one feeder, the current is fed mainly by one generator, the other generators having to feed through the reactances. The tie-bar system acts in the same way, but has the following advantage. If the number of sections in the tie-bar system is increased, the current that flows into the fault will not exceed a certain value which is fixed by the size of the individual reactors. If the switchgear is designed to operate successfully on this limiting value of

current, the system can be extended to any number of sections without modification of the switchgear.

EXAMPLE. Find the ratio of the percentage reactance of the reactors to that of the generators in a tie-bar system, if the short-circuit current is not to exceed three times the current of a single section.

Let the percentage reactance of a generator be G and of a reactor X, and suppose there are n sections. When there is a short circuit on a feeder, the remaining reactors and generators are in parallel, so that their percentage reactance is $(G + X)/(n - 1)$. This reactance is in series with the reactor of the faulty feeder, giving a reactance

$$X + (G + X)/(n - 1) = (G + nX)/(n - 1).$$

This reactance is in parallel with the reactance of the generator which is connected to the faulty feeder, so that the total reactance is

$$\frac{G \times \dfrac{G + nX}{(n-1)}}{G + \dfrac{G + nX}{(n-1)}} = G\frac{G + nX}{nG + nX}.$$

The short-circuit current is thus

$$I \times \frac{100}{G} \times \frac{nG + nX}{G + nX}$$

where I is the normal full-load current.

When $n = 1$, the current is

$$I \times (100/G).$$

The last factor gives the effect of the remaining sections, and increases from unity when $n = 1$ to $(G + X)/X$ when n is infinitely large. Thus if the current is not to exceed three times the short-circuit current due to a single section

$$(G + X)/X = 3$$

i.e. $$X = \tfrac{1}{2}G.$$

If it is certain that the number of sections will not exceed a known number n we have

$$(nG + nX)/(G + nX) = 3$$

i.e. $$X = [(n - 3)/2n]G.$$

Thus if n will not exceed 6, X need not be greater than $\tfrac{1}{4}G$.

Choice of Interconnection to Limit Currents. The cost of reactors is large and their installation is avoided if possible. It is sometimes practicable to make use of the reactance of feeders and transformers so that reactors are unnecessary.

For instance, suppose that two parallel feeders are fed by four transformers, as shown in Fig. 178, and suppose that a short circuit occurs at B. If the parallel feeders are not connected at their ends, the reactance from A to B is

$$\frac{X(3X+2F)}{X+3X+2F}=\frac{X(3X+2F)}{4X+2F}.$$

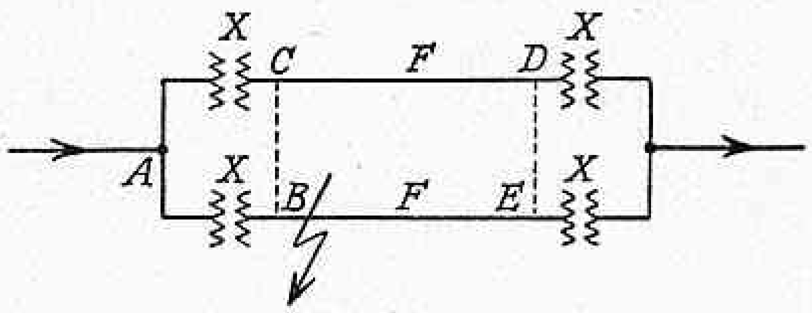

FIG. 178

If the feeders are connected at their ends (between B and C, D and E), the reactance from A to B is $\frac{1}{2}X$. The latter reactance is considerably less than the former; thus if $F = X$, the former is $\frac{5}{6}X$ and the latter only $\frac{1}{2}X$.

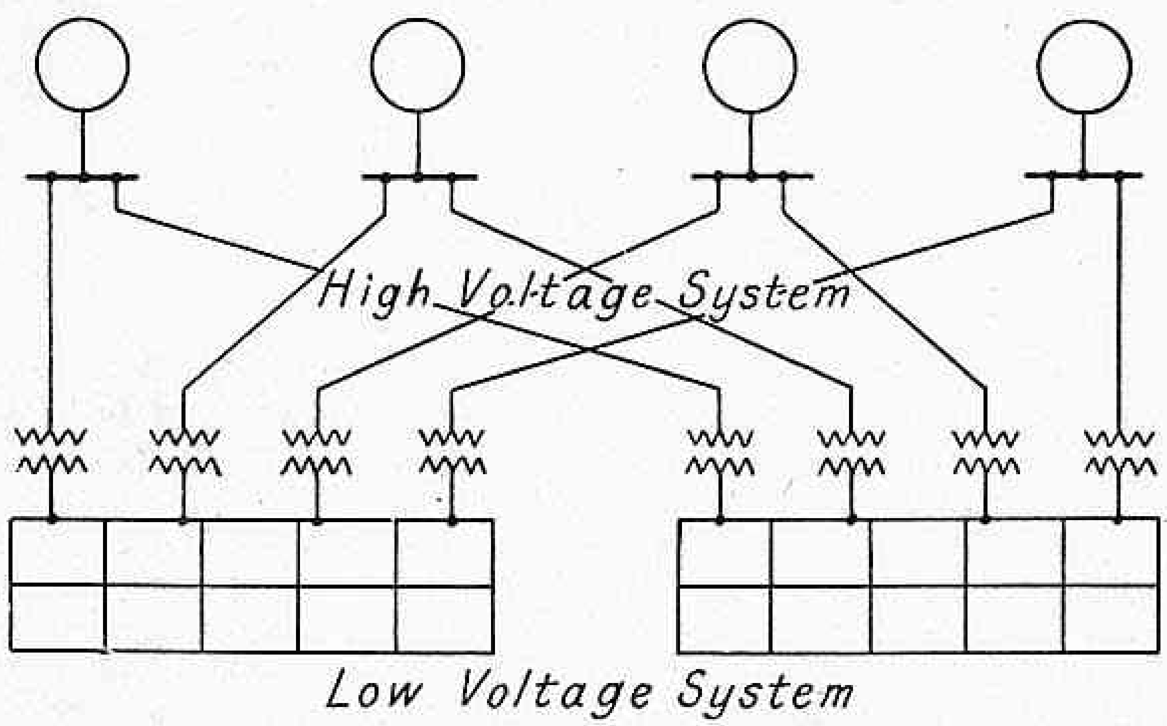

FIG. 179. SYNCHRONIZATION AT THE LOAD

As a general rule it is advisable to keep the parallel connections as few as possible.

An interesting and important application of this rule is shown by the method of interconnection of Fig. 179. The generators are unconnected in the high-tension system, but connected only at the low voltage system. This system is said to be *synchronized at the load.*

Protection of Switchgear by Reactors. A generating station may be extended by the addition of alternators or by a supply from the Grid. It is uneconomical to scrap the existing switchgear, which was adequate for the former output but is not of sufficient rating to meet the extensions. In such a case a protective reactor may be placed between the old system and the extensions to limit the short-circuit currents to a permissible value. An example will show how the requisite reactance is calculated.

EXAMPLE. A small generating station has two alternators of 3 000 and 4 500 kVA., and percentage reactances 7 and 8. The circuit-breakers are rated at 150 000 kVA. It is intended to extend the system by a supply from the Grid via a transformer of 7 500 kVA. rating and 7·5% reactance. Find the reactance necessary to protect the switchgear.

Let us take as the basic rating 7 500 kVA. The reactances of A and B are then

$$(7\,500/3\,000)\times 7 = 17{\cdot}5\%$$

and

$$(7\,500/4\,500)\times 8 = 13{\cdot}3\%,$$

so that their combined reactance is

$$\frac{17{\cdot}5\times 13{\cdot}3}{17{\cdot}5+13{\cdot}3}=7{\cdot}55\%.$$

The short-circuit kVA. with respect to these alone is

$$7\,500\times(100/7{\cdot}55)=99\,300\text{ kVA.}$$

If no protective reactor is present the short-circuit rating due to the Grid supply is

$$(7\,500/7{\cdot}5)\times 100 = 100\,000\text{ kVA.}$$

so that the total is 199 300 kVA. In order to keep the kVA. down the rated value of 150 000 kVA. suppose that a reactor of percentage reactance X is interposed as shown in Fig. 180. The short-circuit kVA. of the Grid supply is then $7\,500/(7{\cdot}5+X)$, and this must not exceed the difference between the ratings of the circuit-breakers and the generators A and B

Therefore

$$\frac{7\,500}{7{\cdot}5+X}\times 100 = 150\,000-99\,300$$

$$= 50\,700,$$

giving

$$7{\cdot}5+X=\frac{7\,500\times 100}{50\,700}$$

$$=14{\cdot}8,$$

so that

$$X = 7{\cdot}3.$$

If the voltage is 3 300 V., the full-load current per phase corresponding to 7 500 kVA. is

$$\frac{7\ 500\ 000}{3\ 300 \times \sqrt{3}} = 1\ 310\ \text{A.},$$

so that the actual reactance of the reactor per phase is

$$\frac{7{\cdot}3 \times (3\ 300/\sqrt{3})}{1\ 310 \times 100} = \underline{\underline{0{\cdot}106\ \Omega.}}$$

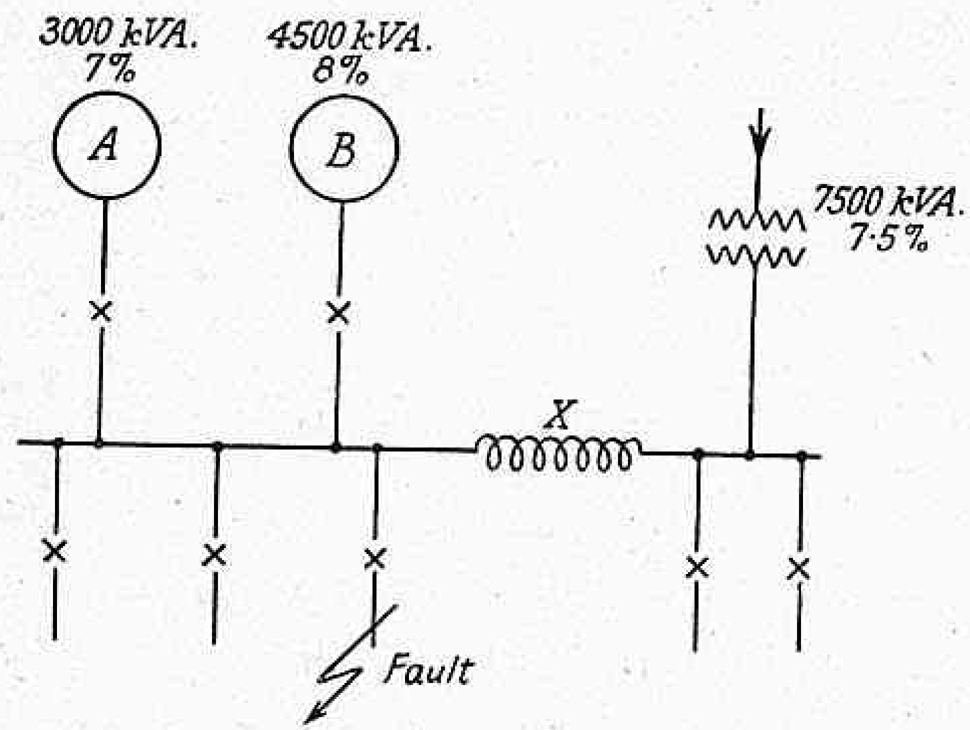

FIG. 180. REACTOR PROTECTING SWITCHGEAR

corresponding to an inductance of

$$\frac{0{\cdot}106}{2\pi \times 50} = 0{\cdot}000337\ \text{H.}$$
$$= 0{\cdot}337\ \text{mH.}$$

Unsymmetrical Short Circuits: Symmetrical Components. The methods of calculating short-circuit currents developed in the previous sections apply only to the cases when the fault occurs across all phases and the currents in the phases are equal. When the fault occurs across two of the three phases or between one or two phases and earth, the currents are unequal and the methods are inadequate. The currents can be found by Kirchhoff's laws, but this method is usually laborious. A method has been devised which uses *symmetrical components* of the currents and voltages.

It will first be shown how three unbalanced vectors can be expressed as the sum of three systems of balanced vectors. Three

balanced vectors are vectors which are equal in magnitude and differ in phase by 120°, so that they can be represented by

$$E_1,\ E_1' = E_1\varepsilon^{j(4\pi/3)},\ E_1'' = E_1\varepsilon^{j(2\pi/3)},$$

if E_1 is taken as a reference vector. Fig. 181 shows the vectors. It should be remembered that multiplication of a vector by the factor $\varepsilon^{j\theta}$ results in a vector of unchanged magnitude but with a phase angle increased by θ; for if the vector has magnitude r and angle α it is represented by

$$r\underline{|\alpha} = r\varepsilon^{j\alpha},$$

and multiplication by $\varepsilon^{j\theta}$ results in a vector

$$r\varepsilon^{j\alpha} \times \varepsilon^{j\theta} = r\varepsilon^{j(\alpha+\theta)} = r\,\underline{|\alpha + \theta}.$$

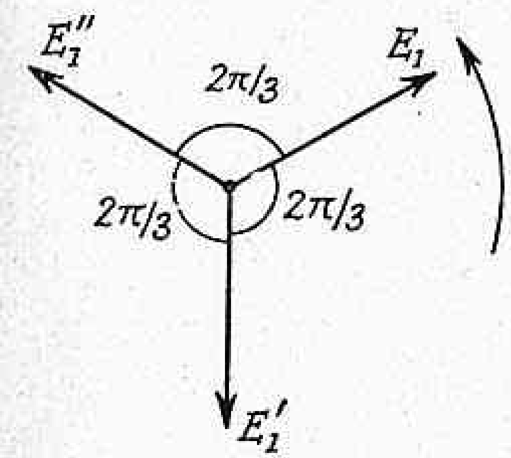

FIG. 181
POSITIVE PHASE SEQUENCE
E_1 leads E_1' leads E_1''

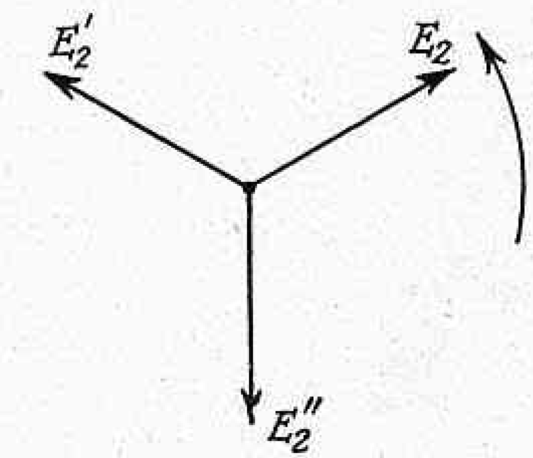

FIG. 182
NEGATIVE PHASE SEQUENCE
E_2 lags E_2' lags E_2''

As is pointed out in Appendix III, the values of the alternating quantities are the horizontal components of these vectors, which are assumed to rotate in the positive (anti-clockwise) direction with an angular velocity $\omega = 2\pi \times$ frequency. *Thus E_1, E_1', and E_1'' correspond to alternating quantities which reach their maxima in the order given.* The system just given is called a system of *positive phase sequence.* It is usual to replace $\varepsilon^{j(2\pi/3)}$ by λ, so that

$$\left.\begin{aligned} \lambda &= \varepsilon^{j(2\pi/3)} = \cos(2\pi/3) + j\sin(2\pi/3) = -0{\cdot}5 + j0{\cdot}866 \\ \text{and}\quad \lambda^2 &= \varepsilon^{j(4\pi/3)} = \cos(4\pi/3) + j\sin(4\pi/3) = -0{\cdot}5 - j0{\cdot}866. \\ \text{It follows that}\quad & 1 + \lambda + \lambda^2 = 0. \end{aligned}\right\} \quad (104)$$

A positive phase-sequence system of vectors is thus represented by

$$E_1,\ \lambda^2E_1,\ \lambda E_1. \quad . \quad . \quad . \quad . \quad (105)$$

It would be symmetrical but unconventional to write these as

$$\lambda^3E_1,\ \lambda^2E_1,\ \lambda E_1,$$

CHAPTER IX

SWITCHGEAR AND PROTECTION

Introduction. With the continued progress of interconnection and the increasing capacity of generating stations the need for reliable protective devices and switchgear has become of paramount importance. When a short circuit occurs, an enormous power can be fed into the fault with considerable damage and interruption of service. The aims of protective gear are to achieve (1) complete reliability. (2) absolutely certain discrimination, (3) quick operation, and (4) non-interference with future extensions.

Complete reliability is required, as the protective gear is added because it is intended to improve the reliability of the whole system. As protective relays are sensitive and must act within fairly fine limits, they should be simple, robust, and easy to inspect and to maintain; furthermore there should be as few as possible.

Discrimination is important, as it is very inconvenient to cut out healthy sections on account of the necessity for synchronization on re-starting. Moreover the protective gear on healthy sections must not be made to operate as a result of fault currents on faulty feeders. This is specially important, as continuity of supply is expected and demanded by the users of electrical energy.

Quick operation is required in order that no damage may be done to generators, transformers, and cables by the short-circuit currents.

Before the various systems of protection are discussed a brief account of switchgear, circuit-breakers, and protective relays will be given; for it is necessary to know the characteristics of the relays and the circuit-breakers in order that the operation of a protective system may be understood.

Principles of Arc Extinguishing. At the instant when the contacts of a circuit-breaker begin to part there is a large current (several hundreds of thousands of amperes) and a small voltage drop. A small separation of the contacts does not result in an immediate cessation of the current, for as the contacts separate the resistance between them increases and the ohmic loss, I^2R, generates sufficient heat to ionize the air or vaporize and ionize the oil. The ionized air or oil vapour acts as a conductor because of the large number of free electrons present, and the current flows without immediate change, across the arc thus formed. The potential drop between the contacts is just sufficient to maintain the arc and is quite small. Separating the contacts draws the arc out, but it is not practicable to draw the arc out to such a length that the voltage available is are produced in the secondaries of the current transformers and no current passes through the relays. The Merz-Price circulating current system just described is clearly effective for earth faults and faults between phases. If another generator feeds current into the fault, it is seen that the currents in a pair of current transformers are opposing and the total current will flow through the relay, and thus operation is aided. The Merz-Price system is, however, unable to operate when there is a fault between turns on the same phase, as the currents at the ends of the phase are still equal.

The alternator can be protected for leakage by means of the leakage relay shown in Fig. 211.

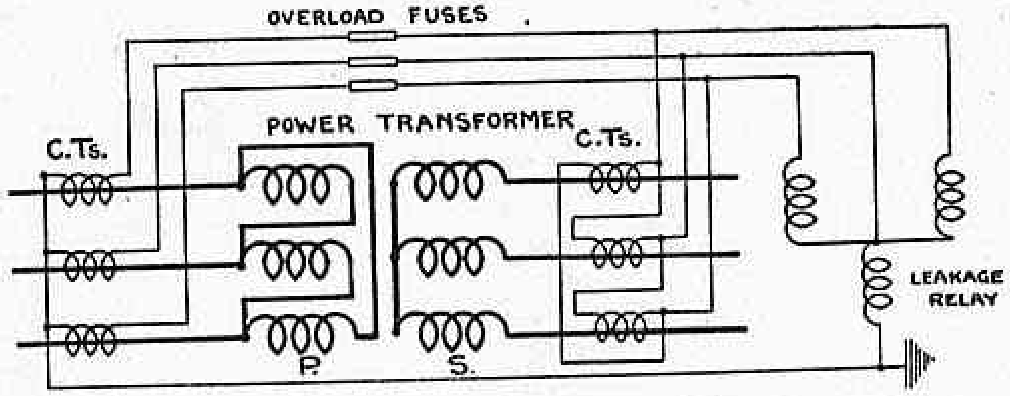

Fig. 211. Merz-Price System for Transformers
(*Automatic Protective Gear* (Henderson))

The Merz-Price system is available for the protection of transformers. Fig. 211 shows the system applied to the protection of a star/delta connected transformer, in which overload and leakage protection is added. The latter is performed by the leakage relay. The former is achieved by the use of overload fuses in the pilot wires between the three pairs of current transformers. When the overload blows a fuse, one of the pair of current transformers is disconnected from the relay, which receives the current from the remaining transformer. The balance is thus upset and the relay operates.

It must be remembered that the currents in the windings of a transformer are not equal, and the current transformers must have the proper numbers of turns, so that their secondaries have equal currents during normal operation. Thus in a star/star connection with a ratio of 11 kV./66 kV., the current transformers must have a turns ratio of 66/11.

Different power-transformer connections demand different connections of the protective transformers. Thus for star/star power transformers, the protective transformers must be connected in delta on both sides, since a fault on one phase of the secondary appears in two phases of the primary. Fig. 212 (*a*) shows the case where the protective transformers are connected in star/star formation for a star/star transformer with earthed neutral in the secondary.

Suppose that an earth fault occurs outside the transformer on the secondary side as shown, and let the fault current be I. We may assume that the transformer has unity ratio for the purpose of explaining the action. Then the currents in the primary windings

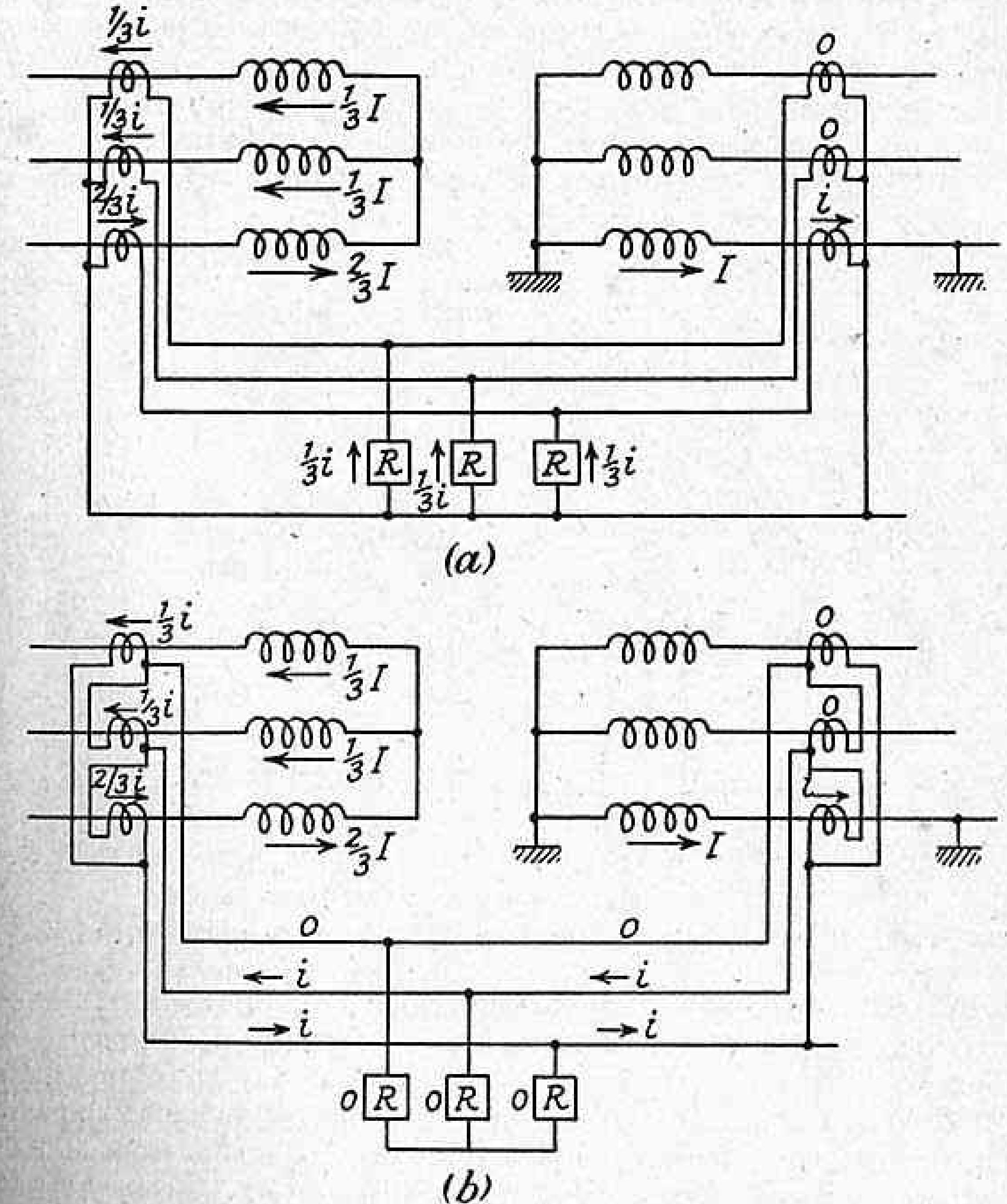

Fig. 212. Merz-Price System
(*a*) In star/star connection. (*b*) In delta/delta connection.

are $\frac{2}{3}I$, $\frac{1}{3}I$, and $\frac{1}{3}I$, the directions being those in the figure: the m.m.f.'s in the three limbs of the transformer are due to $\frac{1}{3}I$ in a winding and they oppose each other, whilst the primary current has no zero phase sequence current, since it is isolated. The currents in the secondaries of the current transformers are $\frac{1}{3}i$, $\frac{1}{3}i$, $\frac{2}{3}i$, and i as shown, so that each relay has a current $\frac{1}{3}i$ and they operate although the transformer is sound. Fig. 212 (*b*) shows the case where the protective transformers are connected in delta/delta. With the same power transformer and earth fault as in Fig. 212 (*a*), the distribution of currents in the protective system is as shown in Fig. 212 (*b*). It is seen that no current passes through the relays, and the healthy transformer is not switched out.

If the power transformer is delta/delta connected, the protective transformers can be star and star. If the power transformer is star/delta connected, " the current transformers on the star side of the power transformer must be connected in delta in the same way as the power transformer, while the current transformers on

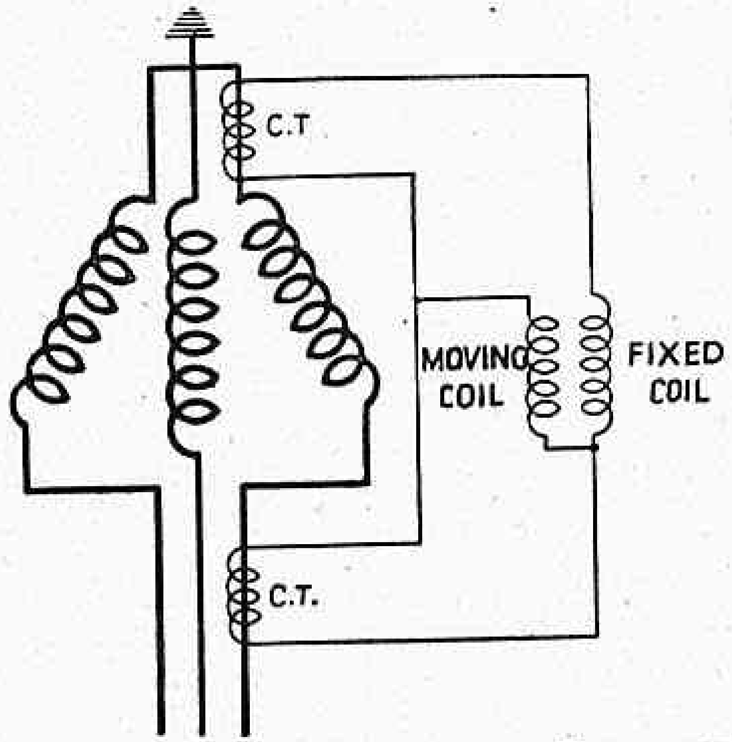

FIG. 213. BIASING BY INTENTIONAL UNBALANCE
(*Automatic Protective Gear* (Henderson))

the delta side of the power transformer must be connected in reversed star relative to the power transformer." (Henderson, *loc. cit.*)

The Merz-Price system cannot be used with tap-changing transformers unless the protective transformers can be varied at the same time, so that the turns ratios are the same in both cases. This is a highly undesirable complication, and the Merz-Price system is replaced by the simpler self-balance method of protection illustrated in Fig. 210; both sets of transformer windings are treated in the same way as the alternator windings.

We have already stated that the self-balance method cannot indicate the presence of short-circuited turns, as the currents at the end of each winding are the same. The Merz-Price system is nominally able to indicate such a fault, since the presence of short-circuited turns causes a change in the turns ratio between the primary and secondary. In practice it is usually too insensitive to do so.

Biased protective systems are being increasingly used, to offset the inaccuracies of current transformers with very high currents. The method is shown in Fig. 209. A biasing method using an intentional unbalance is shown in Fig. 213. The current transformer at the star point is arranged to take 7·0 amperes in the secondary, while the current transformer at the bus-bar takes 7·5 amperes. The relay, which is a reverse-power relay, has under normal conditions a current of 0·5 amperes which keeps the relay in the open position. When a fault occurs, the current near the star-point increases whilst that at the bus-bar end decreases and then reverses; both effects tend to reverse the current in the relay, and if the fault current is greater than the set unbalance of 0·5 ampere, the relay operates.

The Buchholz relay is used for the protection of transformers, and depends upon the formation of gas from the oil. The relay consists of two floats which carry contacts. The upper float indicates the presence of gas which is formed comparatively slowly, and it rings an alarm. The lower float is affected only by a sudden rush of gas formed by a heavy fault current, and when it drops, its contacts complete the trip circuit.

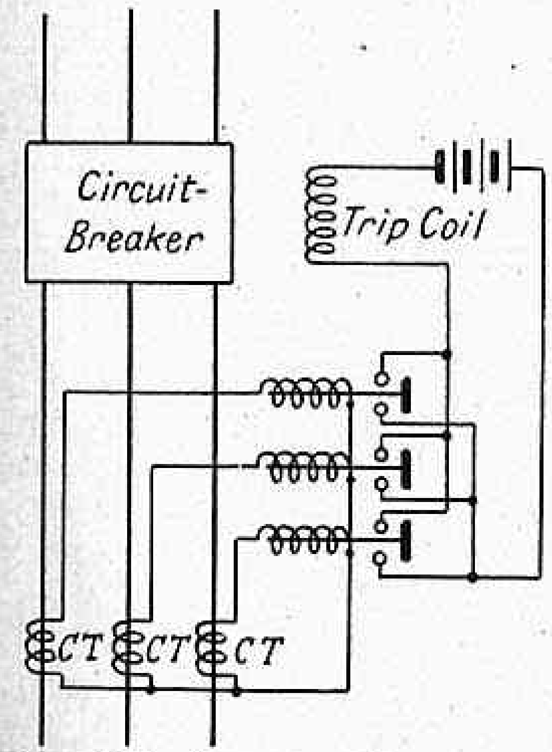

FIG. 214. OVERLOAD PROTECTION

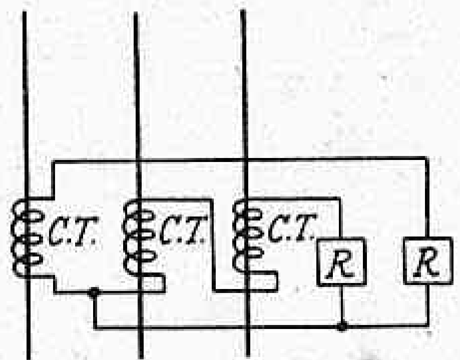

FIG. 215. Z-CONNECTION

Protection of Lines and Cables. The methods used for alternators and transformers are suitable, with modifications, for bus-bars and lines: the modifications required are due to the length of the lines, capacitance currents, and other reasons. Moreover, the need for discrimination in supply networks has called forward many protective schemes which have no application to the comparatively simple cases of alternators and transformers.

OVERLOAD PROTECTION. Fig. 214 shows a simple system of overload protection. Fig. 215 shows the well-known Z-connection, which requires only two relays for the protection of a three-phase circuit.

It is, of course, highly undesirable that all the overload relays in a system should operate as soon as a fault occurs, for then the whole system is shut down.

In a *radial system* the smallest possible part of the system is

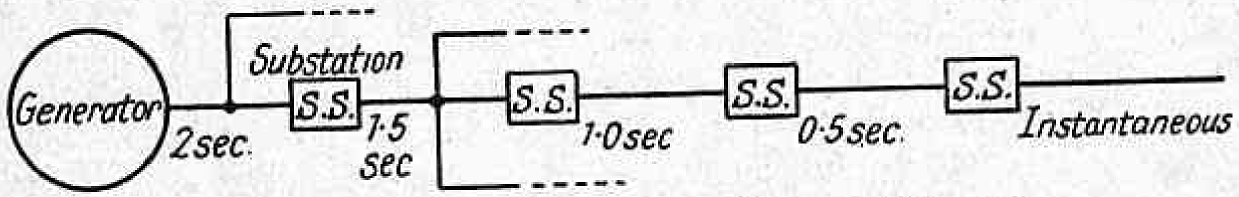

FIG. 216. RADIAL SYSTEM WITH GRADED TIME-LAG

switched out by having relays with an inverse time characteristic with a definite minimum. The minimum time is arranged to decrease from the generator outwards, as shown in Fig. 216. The

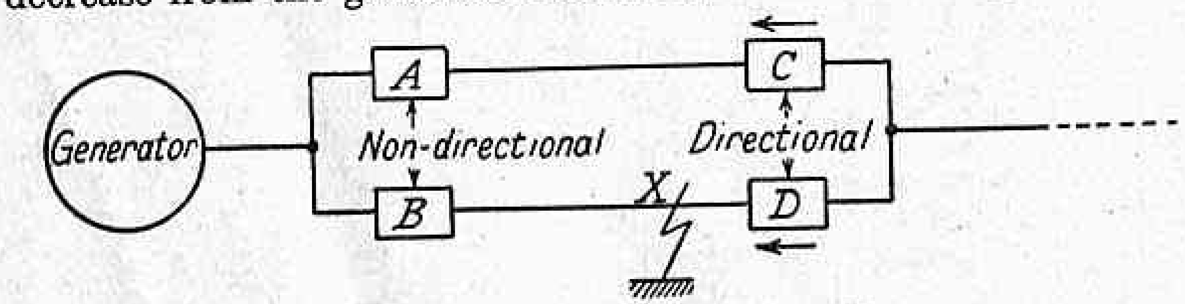

FIG. 217. PROTECTION OF PARALLEL FEEDERS

same applies, of course, to a number of feeders in series, but not to feeders in parallel.

Parallel feeders may be protected by overload (A and B) and reverse power relays (C and D), as shown in Fig. 217. If a fault occurs at X, power flows round $ACDX$ and relay D operates. Then B will operate and the faulty feeder is cut out. This method is not satisfactory unless the fault is heavy and reverses the power at D. It is advisable to apply differential protection to both ends of the parallel feeders in addition to overload protection.

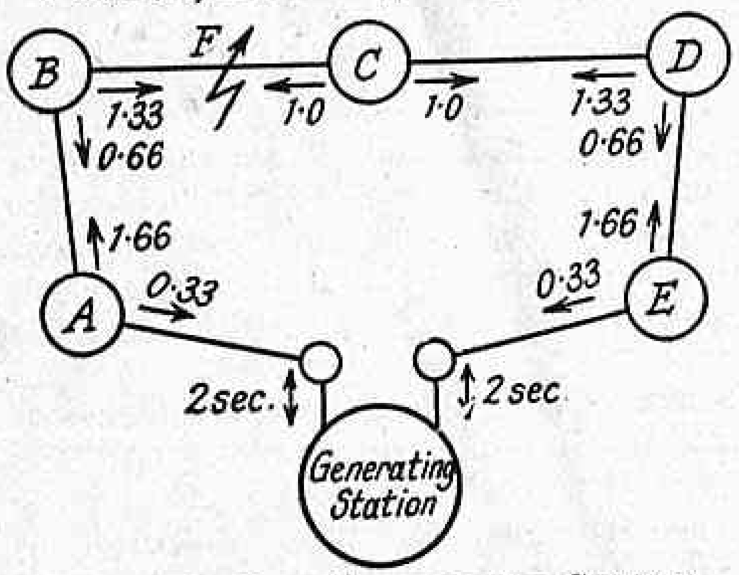

FIG. 218. RING SYSTEM WITH GRADED TIME-LAG

Ring mains can be protected by graded time-lag directional overload relays, as shown in Fig. 218. A relay of this kind is represented by an arrow and a number; the arrow indicates the direction of the power which can make the relay operate, and the number is

the definite minimum time of operation in seconds. At the generator station the relays are non-directional, and are indicated by double-headed arrows. The scheme of time-grading is obvious. If a fault occurs at F, the power fed into the fault is fed by two paths, ABF and $EDCF$. The first relay to operate is that between C and F, and then the power can flow only via ABF; then the relay between B and F operates, and the fault has been cleared. The time grading cannot be closer than $\frac{1}{3}$ to $\frac{1}{2}$ sec., and as the longest time that a fault should be fed is 2 sec., the maximum number of sections that can be protected in this way is six.

The *interlock system* has been designed to overcome the disadvantages just described, and it can be used for any number of sections with a very short time-delay. It can be used for radial or ring systems. Fig. 219 shows the method applied to a radial system. If a section is healthy the same current passes at both ends and the overload relays operate. The operation of the relay at the beginning of the section completes the circuit of the trip coil (contact B), but the operation of the relay at the end of the section closes A, and causes the locking relay to operate and thus break the trip circuit. If the fault occurs within the section, the current entering is high, and causes the contact B to close, but the current leaving is small, and the locking relay does not operate.

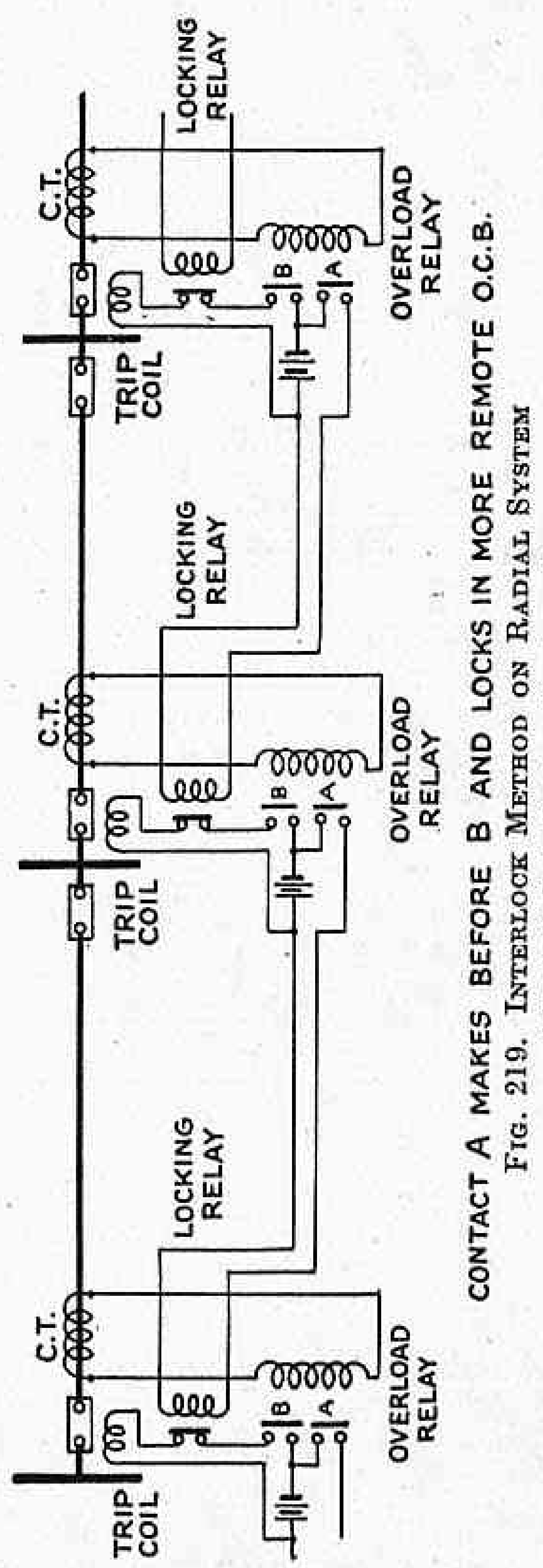

FIG. 219. INTERLOCK METHOD ON RADIAL SYSTEM
(*Automatic Protective Gear* (Henderson))

In order to apply the method to a ring main or any interconnected system, it is necessary merely to have directional relays to close the circuit for the locking relays.

In the above method it is necessary that the locking relay shall be capable of operating before contact B is closed, and for this reason relay B is made to act in 0·3 to 0·5 sec. Methods have been designed for avoiding this delay by sending tripping impulses instead of stabilizing or non-tripping impulses. Duplex telegraph circuits may be used for the transmission of these impulses. Carrier telegraphy along the high-tension line itself has also been used.

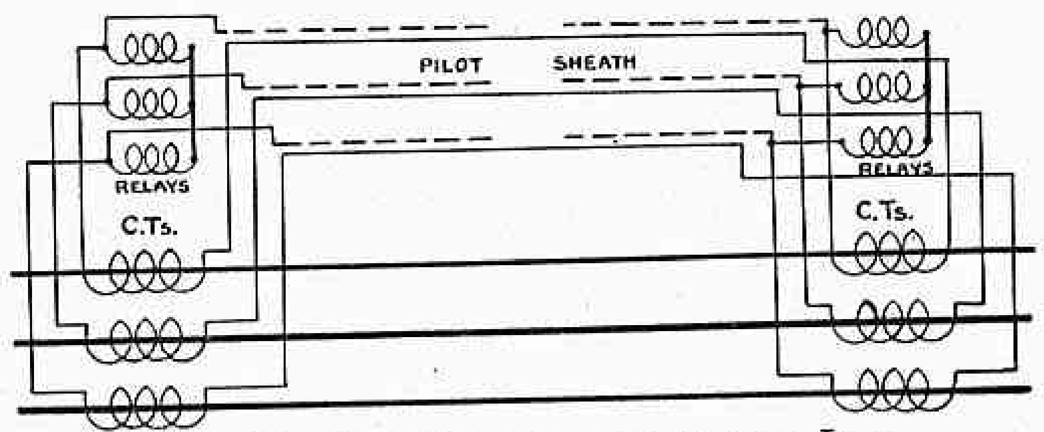

FIG. 220. MERZ-PRICE ON THREE-PHASE LINE
(*Automatic Protective Gear* (Henderson))

BALANCED PROTECTIVE SYSTEMS. The principle of balanced protective systems is shown in Figs. 207 and 208, and examples of the Merz-Price system are shown in Figs. 210 and 211. The use of the McColl biased system to eliminate error due to imperfect

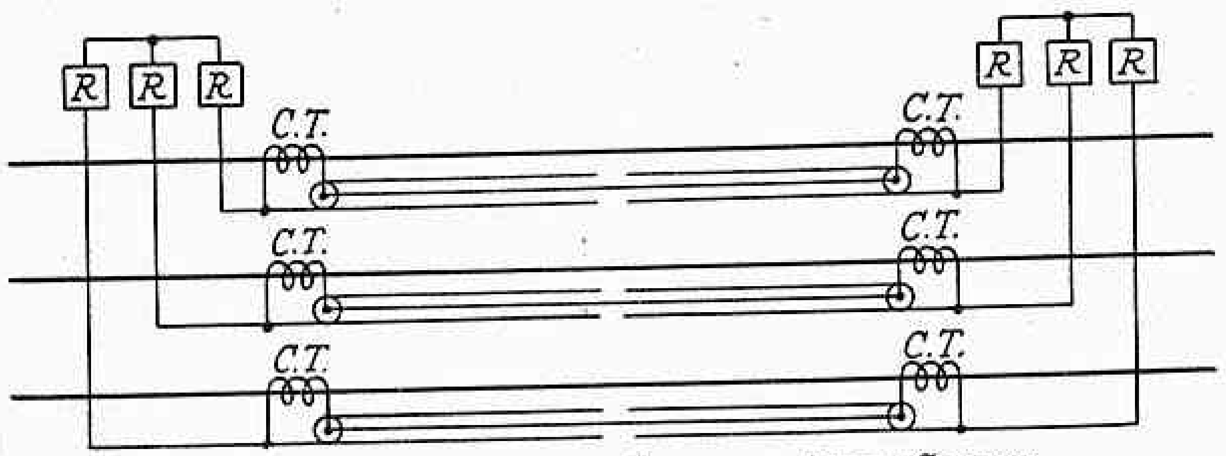

FIG. 221. BEARD-HUNTER SHEATHED PILOT SYSTEM

balancing of current transformers is shown in Figs. 209 and 213. Fig. 220 shows the Merz-Price opposed voltage system applied to a three-phase line. The 3-wire pilot consists of a 3-core, 7/0·029 in. cable. Distributed-air-gap transformers are required in order that they may not be saturated when heavy short-circuit currents flow.

When a short-circuit current passes through a healthy line, the current transformers may have induced in their secondaries equal e.m.f.'s of about 1 000 volts. Although these e.m.f.'s oppose, the capacitance currents that flow may be large enough to cause false operation. The capacitance currents are diverted from the relays

by the Beard-Hunter sheathed pilot cable. In this cable each conductor is surrounded by a metallic screen which is divided at the centre of its length, as shown in Fig. 221. The capacitance currents flow in the local circuits formed by the pilot, sheath, and transformer, and do not flow through the relays.

The *translay system* is one of the modern modifications of the Merz-Price opposed-voltage system. Fig. 222 shows a simple form of translay protection for a single-phase feeder. "So long as the feeder is healthy, the line current transformers 10 and 10*a* at opposite ends of the feeder carry equal currents and the coils 11 and 11*a* connected to them induce equal e.m.f.'s in the windings 12 and 12*a* respectively. Coils 12 and 12*a* are connected in opposition by means of the pilot wires, with the operating windings 13 and 13*a* in series with them."

The translay relay is of the induction disc type, the novel feature being of a transformer character.

Fig. 223 shows a modified scheme for the protection of a three-phase feeder, employing type H (single-element) translay relays.

The upper magnetic circuit has three windings, two primaries, and a secondary. The upper and smaller primary is a phase-fault winding and is connected across the red and blue protective current transformers, whilst the mid-point is connected to the yellow. The lower and larger primary acts as a leakage winding, and is connected between the B transformer and the star-point of the current transformers. The secondary on the upper magnetic circuit behaves like the opposed-voltage transformer in the Merz-Price system and is connected in opposition to a similar winding, via two pilot wires, at the other end of the feeder. The windings on the lower magnetic circuit are in series with the pilot wires. The moving disc is composed of two sectors. Under normal conditions no current flows in the pilot wires as the opposed voltages are equal. When a fault occurs, the voltages in the windings are unequal and a current flows through the lower elements and the pilot wires. The flux produced in the lower magnetic elements interacts with the leakage flux of the upper magnetic elements to give a forward movement of the disc: the phase relation required for this is obtained as in a watt-hour meter. The capacitance currents lead the voltages and tend to rotate the disc in the opposite direction because of a closed copper ring near the end of the projecting limb of the upper magnetic circuit (see 18 and 18*a* of Fig. 222): thus the main disadvantage of the Merz-Price method has been avoided.

The translay relay can be biased by an unsymmetrical phase adjustment, which gives a backward torque when the flux in the upper element is large.

Split-conductor protection has the advantages of a balanced method of protection without the disadvantage of pilot wires. Fig. 224 shows the basic idea of the Merz-Hunter split-conductor system.

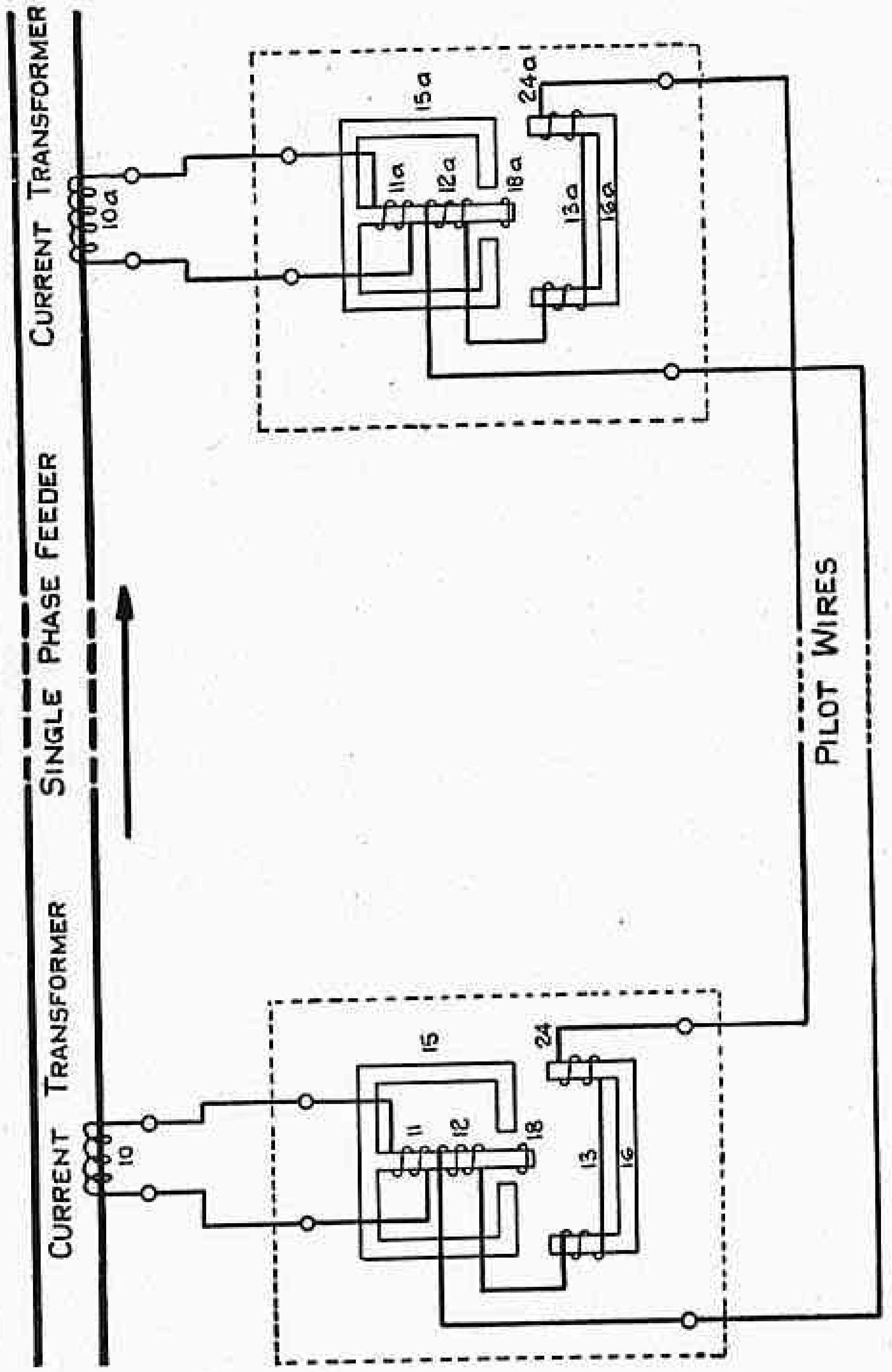

FIG. 222. SIMPLIFIED SCHEME OF CONNECTIONS FOR THE PROTECTION OF A SINGLE-PHASE FEEDER BY MEANS OF THE TRANSLAY SYSTEM
(*Metropolitan-Vickers*)

Each phase of the line is split into two sections which are only lightly insulated from each other. A single-turn current transformer is inserted at each end of the split conductor in the manner shown; the arrangement is identical with that of the well-known clip-on

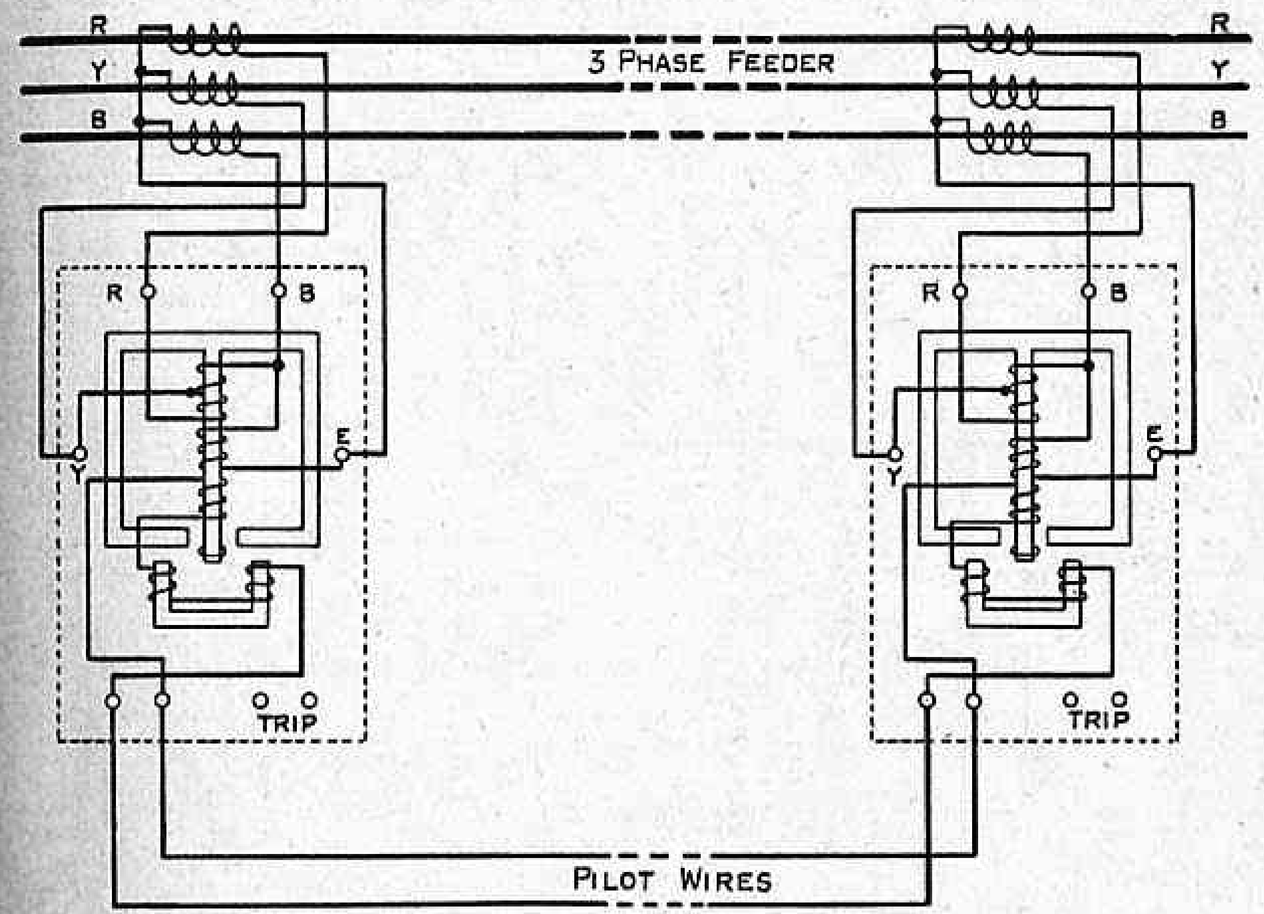

FIG. 223. CONNECTIONS OF TRANSLAY RELAY
(*Metropolitan-Vickers*)

ammeter. When equal currents flow along the two splits, there is zero flux and e.m.f. in the transformers. When a fault occurs one of the splits takes more current than the other, and the relays *R*

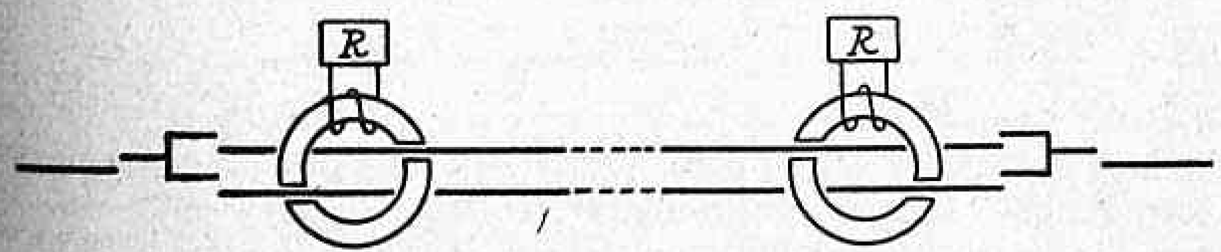

FIG. 224. SPLIT-CONDUCTOR PROTECTION

are energized. In the best arrangement, which is shown diagrammatically in Fig. 224, the splits are carried into the circuit-breakers, so that the splits are both opened by the breakers. The reason is as follows. If the fault is at the receiving end of a long line, the receiving-end breakers operate first; then if the breakers merely open the common end of the splits but leave the splits connected to a common end, the sending-end impedances will be nearly the same and the sending-end breakers will not operate. If the splits are both opened, as indicated, the healthy section takes no current and the faulty section takes a current which operates the sending-end breakers.

Distance or Impedance Protection. The cost of pilot wires

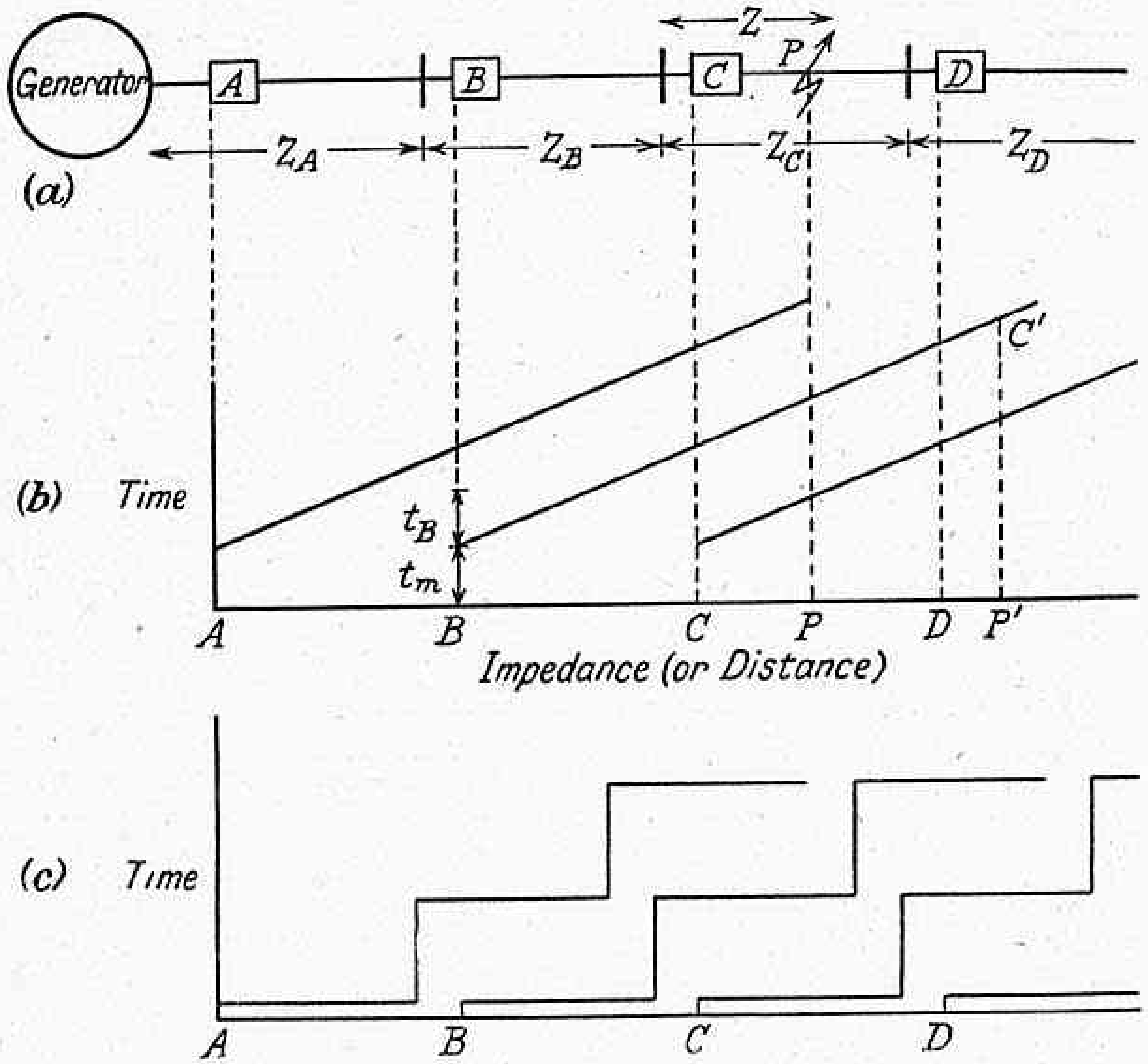

Fig. 225. Distance or Impedance Protection

on long overhead systems is prohibitive, and *distance* protection has been designed to give discriminative protection without pilot wires. Fig. 225 (*a*) shows the simplest system consisting of feeders in series, such that the power can flow only from left to right. If a short circuit occurs at P between C and D, the impedances at A, B, and C are $Z_A + Z_B + Z$, $Z_B + Z$, and Z respectively. The relays are set to operate with impedances less than Z_A, Z_B, and Z_C respectively, so that only relay C will operate. Similarly, if the fault occurs between B and C, only relay B operates. The principle of operation and some types of impedance relays have been described. (See Figs. 205 and 206.)

A system with instantaneous impedance relays, set to act on impedances less than or equal to the impedance of a section, would be difficult to adjust; a fault near the junction of two sections is likely to cause the operation of two relays. Furthermore, if a fault of finite resistance occurs near the end of a section, it is possible that the total impedance is greater than that for relay operation. For these reasons it is advantageous to use impedance-time relays, the characteristics of which are shown in Fig. 225 (*b*), for the system of Fig. 225 (*a*).

If a fault occurs on the right-hand side of a junction, B say, relay B operates in the minimum time t_m and the breaker at B operates t_B sec. later. If t_B is made less than the time difference between consecutive relays, only one relay will operate.

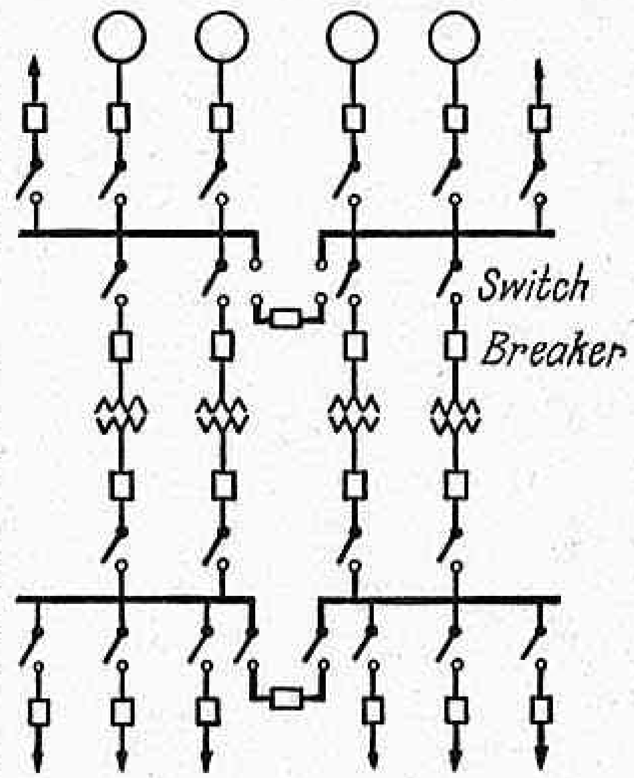

Fig. 226. Single Bus-bar Layout

Suppose that the fault at P has a resistance which causes the total impedance at C to be represented by the point P' (the fault resistance being PP'). Relay C operates in time $P'C'$, whereas in the previous system it would not operate at all.

An impedance-time relay is a delicate mechanism, and it is considered worth while to replace it by three simple impedance-relays with a definite time of operation. The series combination can be arranged to give a three-step-time characteristic, as shown in Fig. 225 (*c*), which does the same thing as the previous linear characteristic.

The effect of arc resistance or the resistance of the earth return path of a fault can be avoided by the use of a *reactance relay*, which operates when the reactance is less than a certain value and ignores the resistance of the circuit. The reactance relay is made in the same way as the impedance relay, but the flux due to the potential coil is shifted in phase.

Bus-bar Arrangements. There are two types of switches, circuit-breakers and isolating switches. The former must be capable of breaking the maximum short-circuit currents; the latter are operated only under conditions of no current, are much cheaper, and are merely knife switches in air or oil.

In small substations there is a single bus-bar, and the arrangement is as shown in Fig. 226. The bus-bar may be sectionalized by a circuit-breaker and isolating switches, so that a fault on one part does not cause a complete shut-down.

Fig. 227 shows a ring bus-bar system. The circuit-breakers are in series with the ring, and each feeder is supplied by two paths, so that the failure of a section does not cause any interruption of the service.

Fig. 228 shows a single circuit-breaker station which was introduced by the C.E.B. and is working successfully. The protective current transformers are so arranged that, when a line or

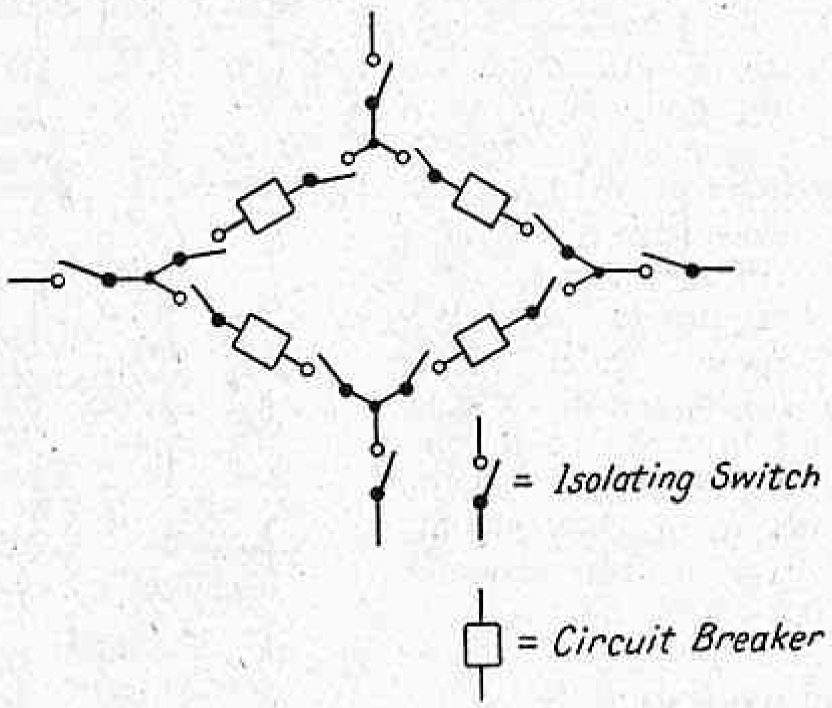

FIG. 227. RING BUS-BAR SYSTEM

transformer fault occurs, both the 132 kV. breaker and the low voltage breaker on the fault side are opened.

On a large system with many circuits it is usual to have duplicate bus-bars. A typical diagram is shown in Fig. 229, in which both the high and low voltage bus-bars are duplicated. In this case it is possible to split the plant into two entirely separate systems, which can be worked at different voltages if so desired. If it were desired to switch a circuit from one bus-bar to another without interruption of service there would have to be two circuit-breakers per circuit. This is too expensive, and the scheme of Fig. 229 is adopted, in which there is only one breaker per circuit and the service must be interrupted for a switch-over. The bus-bar coupling switch is required to effect a quick and easy transfer; the use of a bus-bar coupler and sectionalizing breakers converts the duplicate bus-bars into a ring system, which has great flexibility.

Testing of Transmission Systems. It is necessary to carry out regular and exhaustive tests, in order that the elaborate systems of protection be kept in perfect working order. When a system is

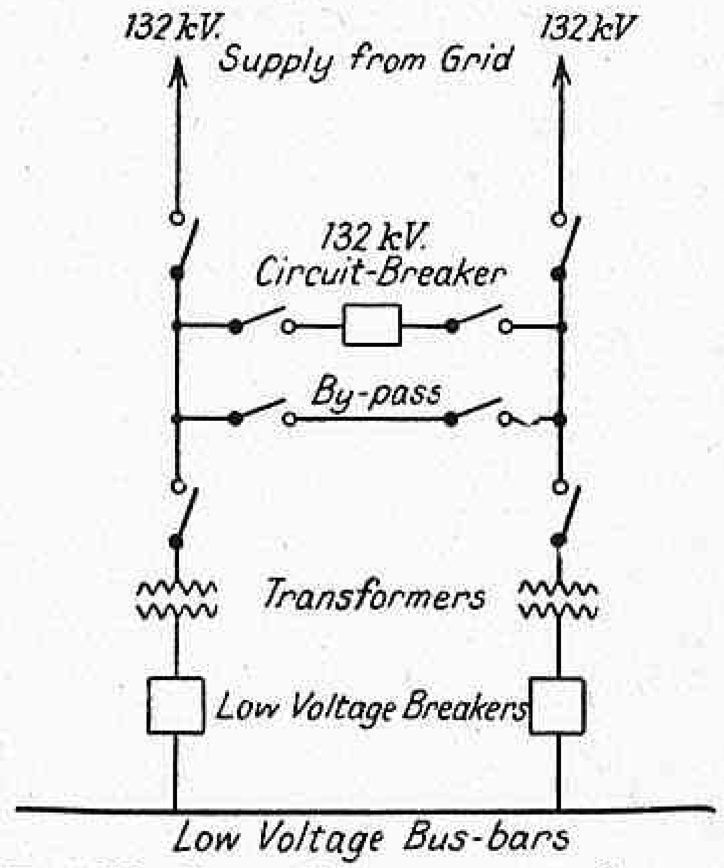

FIG. 228. SINGLE CIRCUIT-BREAKER STATION

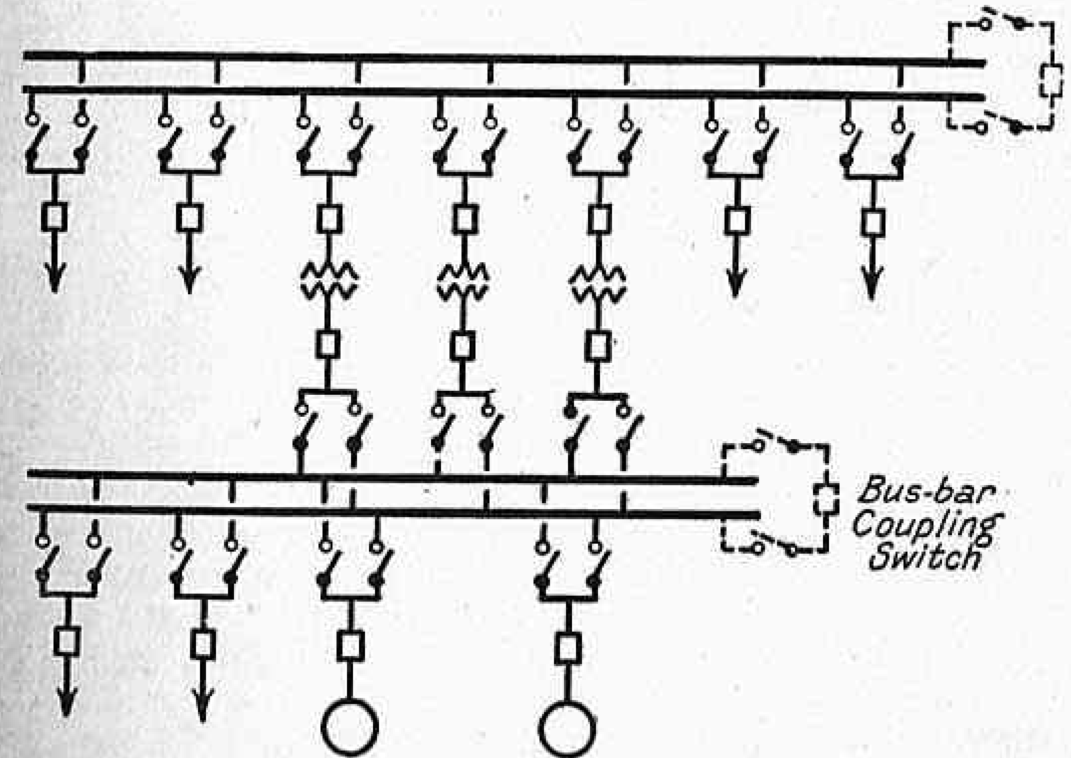

FIG. 229. DUPLICATE BUS-BAR SYSTEM

first installed, it must be tested with short circuits of the various kinds under normal conditions of voltage; alternatively fault currents may be produced at low voltage, but this is not quite so good as the former method.

Staged faults at normal voltage can be carried out by putting an isolating switch between a phase and earth, or arranging a copper conductor to fall across two phases: an arcing earth can be simulated by inserting a fusible link between a phase and earth. The time for a staged fault must be chosen so that extensive preparations against

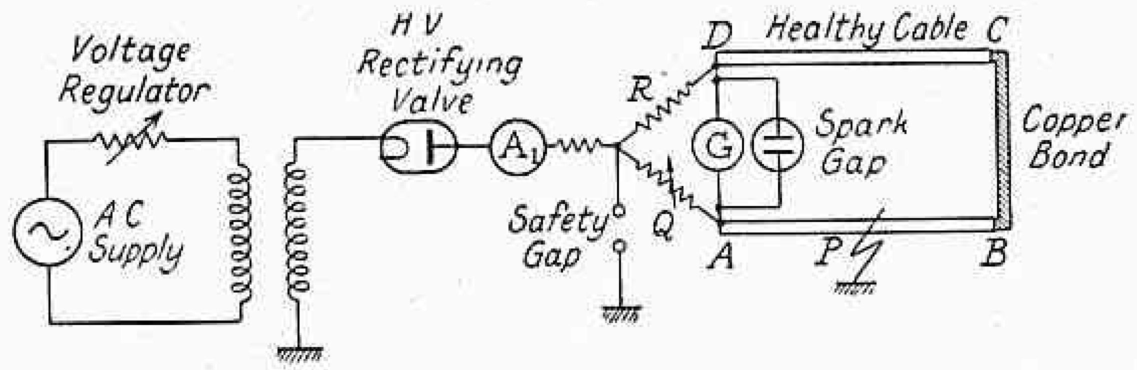

FIG. 230. HIGH VOLTAGE MURRAY LOOP TEST

disturbances can be made; important consumers must be provided with an alternative circuit of supply or they must be advised of the interruption. Considerable organization is required so that the system can be made normal as soon after the test as possible; for instance, telephone communication between the various stations should be maintained throughout the duration of the test.

Fault Location. The most usual types of faults are earth faults and open circuits; occasionally there is a short between two conductors without an earth.

Loop tests are used for earth faults; the fall of potential method can be used for earth faults or short circuits; capacitance tests are used for open circuits; and induction methods can locate earth faults.

If a core has shorted to earth, the ordinary *Murray loop test* is available for location. If the fault seals up after breakdown and is only apparent at high voltage, the H.V. Murray loop test shown in Fig. 230 is usually successful. A healthy cable is bonded with the faulty cable at the far end, and the bridge is supplied with high voltage d.c. through a valve rectifier. The voltage is raised so that a small current is registered by the milliammeter A_1 and a preliminary balance is made. The current is then increased and the balance is more closely approached. At balance

$$\frac{R}{Q} = \frac{\text{Resistance of } (CD + BP)}{\text{Resistance of } AP} = \frac{r_2 CD + r_1 BP}{r_1 AP}$$

$$= \frac{(r_1 + r_2)AB - r_1 AP}{r_1 AP},$$

so that $$AP = \frac{(1 + r_2/r_1)}{(1 + R/Q)} \times AB,$$

where r_1 is the resistance per unit length of AB and r_2 of CD. I equal gauge cables are available, $r_1 = r_2$ and

$$AP = \frac{2}{1 + R/Q} \times AB.$$

Although there is very little voltage on the cable when the fault is present, the voltage will rise to a dangerous value if the fault clears. It is therefore necessary to insulate the controls for the full voltage applied and to use a safety gap. Moreover the galvanometer should be protected by a spark-gap.

Fig. 231 shows the Murray loop test as applied to the location of a short between two cores. The distance AP is found as before.

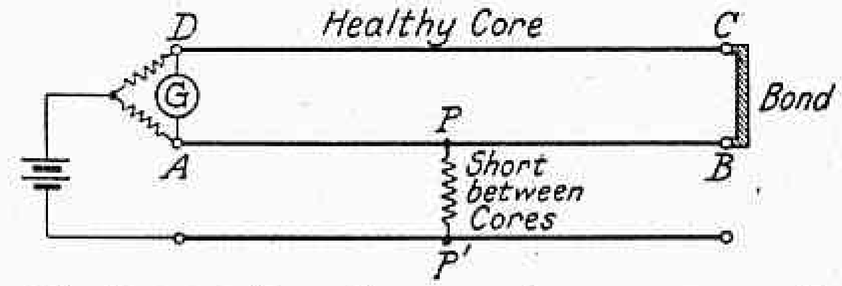

FIG. 231. MURRAY LOOP TEST FOR SHORT BETWEEN CORES

The *Werren (overlap) method* is used to locate a fault involving all conductors, when the conductors are not broken and there is no sound core available. The cores are tested for resistance to earth,

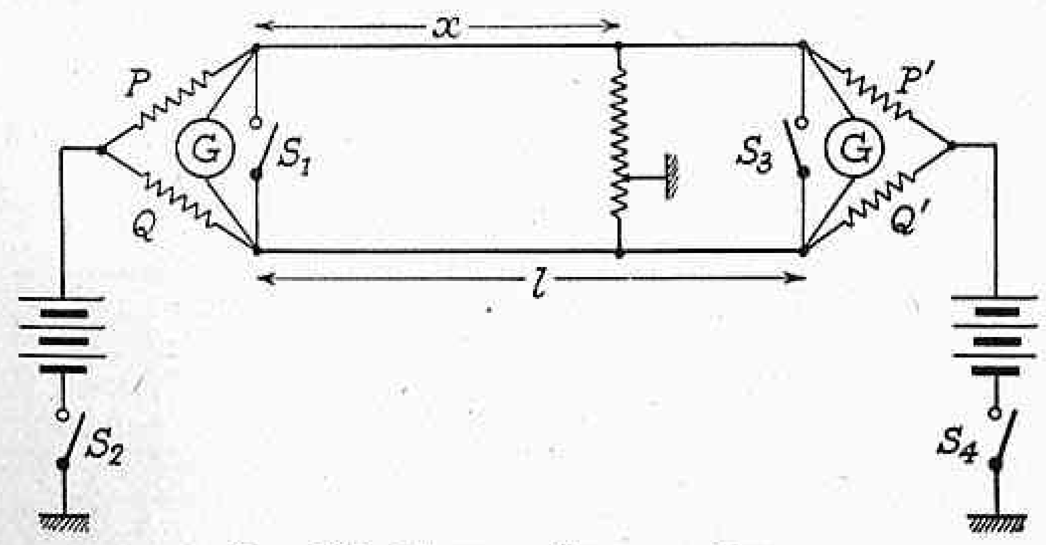

FIG. 232. WERREN OVERLAP METHOD

and the core with the lowest resistance is used in conjunction with that of highest resistance in the way shown in Fig. 232. The loop test is performed from the left end, keys S_2 and S_3 being closed and S_1 and S_4 open; then the test is repeated at the right end, keys

S_1 and S_4 being closed and S_2 and S_3 open. The distance of the fault is given by

$$x = \frac{(P' - Q')}{(P' - Q') + (P - Q)}\, l.$$

The method fails if the cores have equal resistances to earth, since in that case $P = Q$ and $P' = Q'$.

The fall of potential method is illustrated in Fig. 233. The current

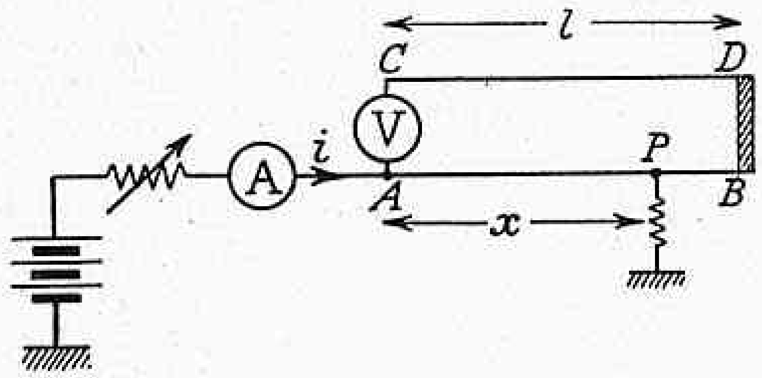

FIG. 233. FALL OF POTENTIAL METHOD

is adjusted to a reasonable value and the voltage between A and C is read; suppose it is V_1. If the current is i and the resistance per unit length is r,

$$V_1 = rxi,$$

since the resistance of the voltmeter is high compared with that of the conductors and all the current flows along AP. Let now the same current be fed in at C instead of A, and let the voltmeter reading be V_2. Then

$$V_2 = r(2l - x)i.$$

We have therefore

$$\frac{x}{2l - x} = \frac{V_1}{V_2} \text{ giving } x = \frac{V_1}{V_1 + V_2}\, 2l.$$

A short between two cores can be located by measuring the resistances between the cores at each end, the cores being open circuited at the other. Fig. 234 illustrates the method. The resistance at A is

$$r_A = 2x + z,$$

where z is the resistance of the fault between the cores and x is now the *resistance* of the line up to the fault.

Similarly

$$r_B = 2R - 2x + z.$$

Subtraction gives

$$4x - 2R = r_A - r_B$$

or

$$x = \tfrac{1}{2}R + \tfrac{1}{4}(r_A - r_B).$$

Knowing the total resistance and the resistance per unit length we can calculate the distance of the fault.

In the *induction method* of fault locating, current is passed along the faulty cable through an interrupter. A search coil, which is connected to a telephone, is moved along the cable. A buzzing noise will be heard until the search coil passes the fault, when the noise ceases. The presence of a lead sheath or armouring makes this method of detection uncertain. If the position of the fault is known approximately, a very effective method of finding the exact position is to use a telephone diaphragm attached to one end of a long stick, the other end of which has a blunt nail driven into it. The blunt nail is run along

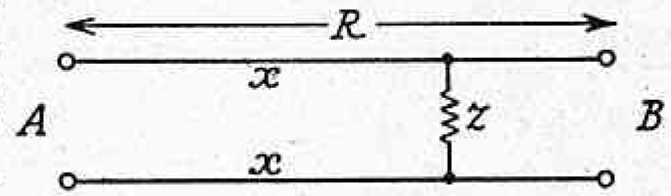

FIG. 234. FAULT BETWEEN CORES BY RESISTANCE MEASUREMENT

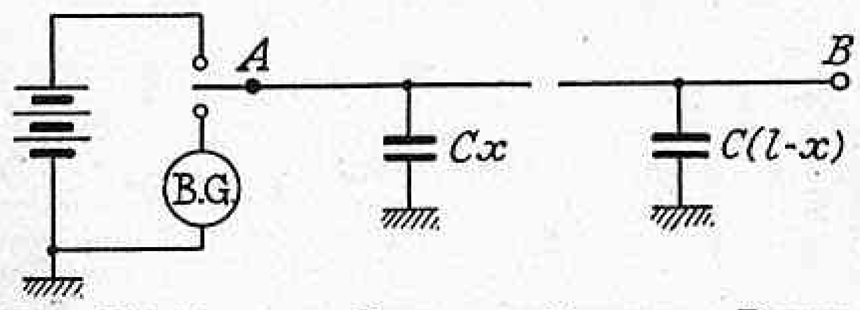

FIG. 235. BALLISTIC METHOD OF FINDING A BREAK

the sheath, and when the position of the fault is reached a loud buzzing is heard in the telephone.

The *capacitance method* of locating a clean break, in which the insulation resistance to earth is high, is indicated in Fig. 235. The

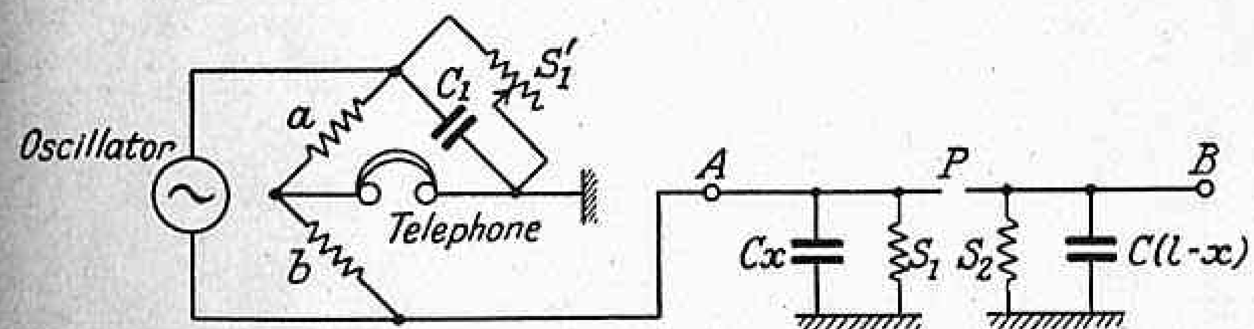

FIG. 236. A.C. BRIDGE METHOD OF FINDING A BREAK

cable is charged up to a potential V at end A and then discharged through a ballistic galvanometer $B.G.$ The kick is

$$d_1 = kCxV,$$

where C is the capacitance per unit length, $AP = x$, and k is a constant of the galvanometer.

The procedure is repeated at end B when the kick is

$$d_2 = kC(l-x)V.$$

By division we have

$$d_1/d_2 = x/(l-x),$$

i.e.

$$x = \frac{d_1}{d_1+d_2}\,l.$$

If the ends of the broken conductor have resistances S_1 and S_2 to earth, an a.c. bridge can measure the capacitances. Fig. 236 shows the method. In the condition shown a balance is attained when

$$Cx = (a/b)C_1 \text{ and } S_1 = (b/a)S_1'.$$

$C(l-x)$ can be found from a similar measurement at end B, and x can be calculated as before.

EXAMPLES IX

1. Discuss the essential considerations in the design of an air-break circuit-breaker for medium power. How can a delay action be incorporated in the switch itself? (*Faraday House*, 1935.)

2. Describe the usual method of rating circuit-breakers. What circuit features decide the severity of the conditions to be met by the breaker? How do these affect the design of *either* air-blast *or* oil circuit-breakers? (*Lond. Univ.*, 1954.)

3. Describe the essential equipment of a short-circuit testing station. What are the special features of the main generator and its exciter? What records are usually taken in testing a large circuit-breaker? (*Lond. Univ.*, 1954.)

4. Describe the process of arc rupture in (i) an air-blast a.c. circuit-breaker, (ii) an oil-break a.c. circuit-breaker with arc control. Discuss the advantages and disadvantages of air-blast and oil-break circuit-breakers for large powers and high voltage.

Describe, with a sketch, the arrangement of the contacts and operating mechanism of one form of air-blast circuit-breaker. (*Lond. Univ.*, 1953.)

5. Give a comparison between the translay, solkor and balanced-voltage systems of protection.

Draw a diagram of connections and explain the operation of one of these systems providing protection at a particular part of a supply network. (*Lond. Univ.*, 1948.)

6. What are the main causes of surges on overhead transmission lines? Explain how the waveform of a surge is specified.

Discuss the protection of the terminal equipment of a line from surges, and describe one method of protection. (*Lond. Univ.*, 1950.)

7. Describe the principle and construction of a relay whose operation in tripping the circuit-breaker of a faulty feeder depends upon the impedance of the arc between the circuit-breaker and the fault and show how such a relay can be used to give selective protection to a network.

Show that with a system protected in the above manner the minimum possible clearance time for a fault at the far end of a section of a transmission line consisting of a number of sections separated by substations is equal to twice the time taken for the circuit-breakers to operate plus the time taken to start the relay.

What modification to the above system of protection can be made in order to render the operation independent of the resistance of the fault?

8. Discuss the advantages of "end balance" methods of protection and explain the principal difficulties to be overcome in the design and operation of such a system. Describe one system applied to the protection of an alternator, stating what controls must be operated by the protective gear. (*Nat. Cert.*, 1935.)

9. Explain, with the aid of a diagram of connections, the principle of operation of a current-balance system of protection against earth and interphase faults for a star-connected 3-phase generator.

A 3-phase, 2-pole, 11-kV., 10 000-kVA., star-connected alternator has a reactance per phase of 2·4 Ω. and a resistance per phase of 0·25 Ω. and the neutral is earthed through a resistance of 7 Ω. If the machine has current-balance protection, which operates when the out-of-balance current exceeds 20% of full load, determine the percentage of the alternator windings protected against an earth fault on one phase. (*Lond. Univ.*, 1950.)

10. Discuss the protection of an alternator running in parallel with others against reverse power and describe in detail a suitable relay system with inverse time limit for operating the isolating circuit-breaker. (*Faraday House*, 1935.)

11. Describe, with a diagram of connections, a form of biased relay protection for either a generator or a transformer, stating how the correct bias may be given to the protection.

A three-phase transformer of 220/11 000 line volts ratio is connected star/delta and the protecting transformers on the 220 V. side have a current ratio of 600/5. What must be the current ratio of the current transformers on the 11 000 V. side and how should they be connected? (*Lond. Univ.*, 1931.)

12. Write a short account of protection of cables against overload and eakage, giving details of methods employed. (*Faraday House*, 1935.)

13. Describe the principle and draw a connection diagram of the Merz-Price balanced protective system as applied to the protection of a three-phase transmission line.

What are the possible causes of false operation of the above system and what modifications can be made to it to guard against this? (*Lond. Univ.*, 1933.)

14. Explain briefly the difficulties associated with balanced systems and with distance systems of protection for the overhead lines of a power system.

Describe a form of interlock protection designed to overcome these difficulties and state the circumstances in which it can be satisfactorily applied. (*Lond. Univ.*, 1934.)

15. Describe with sketches the construction of an over-current relay of the induction type and explain the action. Describe how the over-current and time-lag settings are adjusted, and sketch a typical current-time characteristic.

What advantages has such a relay over one of the plunger type with time-lag? (*Lond. Univ.*, 1949.)

16. Sketch one form of over-current relay operating on the induction principle. Explain its action, and how the current and time settings are adjusted. Draw a diagram of connections and sketch a typical characteristic curve. Discuss the advantages of a relay of this type over one of the plunger type for the over-current protection of a.c. circuits. (*Lond. Univ.*, 1947.)

17. Describe a method of locating each of the following types of fault on a two-core cable, both ends being available for testing.

(i) A short circuit between two cores, one core being completely broken through but neither core being earthed.

(ii) A complete break in both cores with no earth at the break.

(iii) An earth fault on one core only, which seals itself as soon as the voltage is removed.

In a test to locate a short circuit between the cores of a two-core pilot insufficient to maintain the arc; in high voltage systems a separation of many yards would be necessary for this purpose.

The conductance (i.e. the reciprocal of the resistance) of the arc is proportional to the number of electrons per cm.^{3} produced by the ionization, the square of the diameter of the arc, and the reciprocal of the length. As we have stated, we cannot do much by increasing the length of the arc to any reasonable value. What can be done is to decrease the density of the free electrons, i.e. reduce the ionization, and decrease the diameter of the arc.

The process of arc extinction in a d.c. circuit is more prolonged than in an a.c. circuit, and will be discussed first. Free electrons are produced in an arc in two main ways: (1) by thermal ionization, i.e. ionization by collision of the atoms due to thermal agitation; (2) by ionization by bombardment of electrons which attain high speeds under the electrostatic field. Free electrons are withdrawn from the arc in two main ways: (3) by re-combination of electrons and positive ions; (4) and by diffusion of electrons out of the arc. Under steady conditions $(1) + (2) = (3) + (4)$. To extinguish the arc it is necessary to decrease (1) and (2), so that steady

$$(1) + (2) < (3) + (4). \Leftarrow \text{extinguish}$$

The only possible way of doing this is to decrease (1) by cooling the arc. To find the cooling necessary, we imagine that the circuit voltage E acts through an external resistance R across the arc resistance R_a. The rate of heat generated in the arc is

$$E^2R_a/(R + R_a)^2 \text{ watts,}$$

and has a maximum value of $E^2/4R$ when $R_a = R$. When the arc is new R_a is small and the heat generated in the arc is small. If the rate of cooling is high, the arc will get cooler. If the rate of cooling is less than $E^2/4R$, a point will be reached when the rate of heat generated in the arc is equal to the rate of cooling. The arc will then stay at this stable position of equilibrium. If, however, the rate of cooling is greater than $E^2/4R$, cooling is progressive until the arc is extinguished. It is therefore necessary that the rate of cooling be greater than $E^2/4R$ for the extinction of a d.c. arc by cooling.

Arc extinction in a.c. circuits differs from that in d.c. circuits because of the passing of the current and voltage through zero at intervals of $\frac{1}{100}$ sec. It can be shown that if the a.c. arc had to be extinguished by cooling like the d.c. arc, it would be necessary to have a rate of cooling greater than $E^2/2X$, where X is the reactance of the circuit supplying the arc. A circuit-breaker large enough to dissipate heat at such a rate is many times larger than that required in practice. The extinction of an alternating current arc is illustrated in Fig. 192, which represents the main features of many oscillograph records of a.c. arcs. The circuit current is taken as zero to begin with.

A short circuit is applied at the instant when the circuit voltage is zero, so that the doubling effect of the short-circuit current is obtained. The short-circuit current is shown as settling down from the unsymmetrical large value to a somewhat smaller and symmetrical value, until the contacts begin to open 6 half-cycles later. Up to this point the voltage between the contacts is clearly zero, but the circuit voltage is gradually reduced by the effects of armature reaction in the generators. When the contacts open, the arc

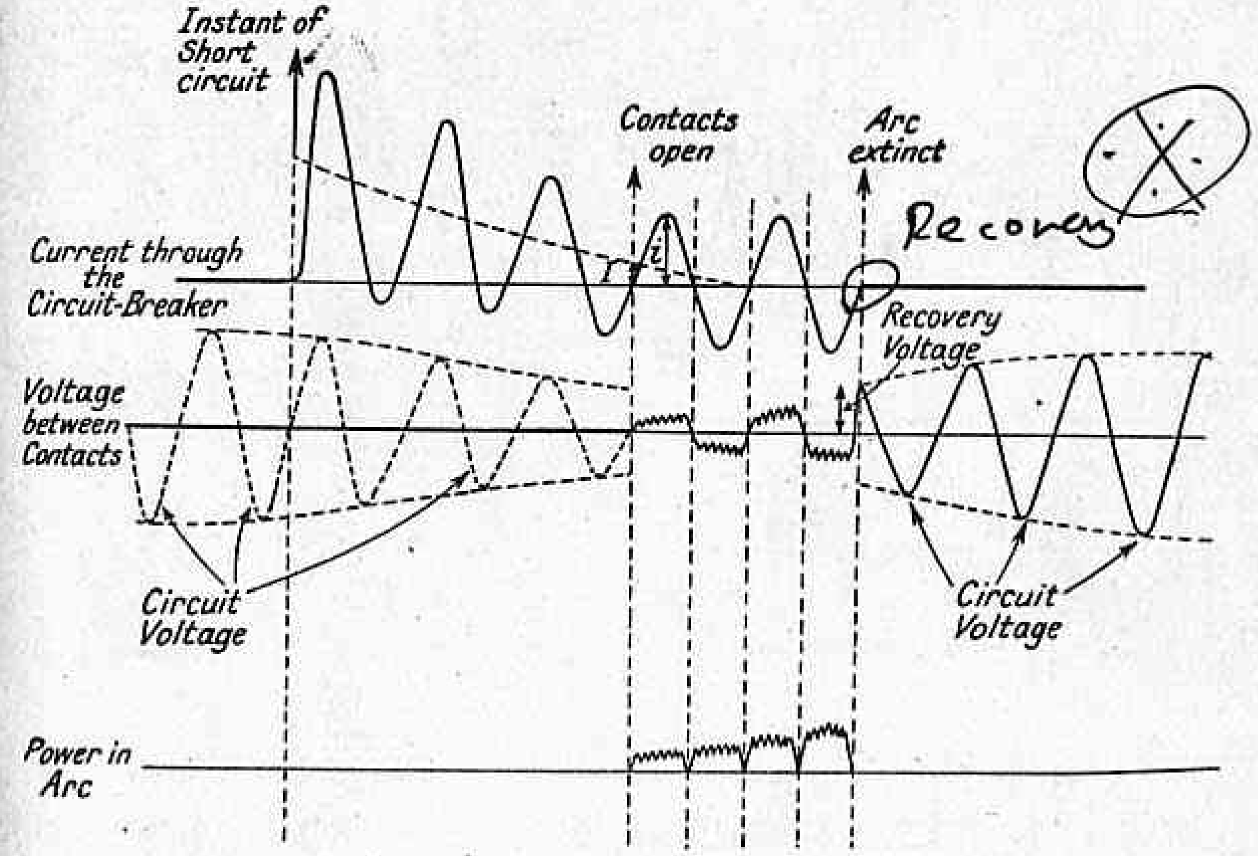

FIG. 192. EXTINCTION OF ALTERNATING CURRENT ARC

is struck, the current is maintained as before, whilst the voltage between the contacts is of the form shown; this voltage is quite small to begin with. When the current reaches its zero position, the arc is automatically extinguished and the voltage between the contacts is zero. The voltage then increases in the opposite direction and soon reaches a value which is sufficient to restrike the arc; during the period of quiescence a certain amount of recombination of ions and cooling takes place, so that the restriking voltage is somewhat greater than the voltage previously required for the maintenance of the arc. This goes on for several half-cycles, at the end of which period sufficient recombination of ions and cooling has taken place for the circuit voltage to be insufficiently large to restrike the arc. The arc is then extinct, the circuit current is zero, and the circuit voltage recovers and increases finally to its normal value. The recovery voltage is somewhat less than the normal circuit voltage, because of armature reaction; its value depends cable AB having length of 3 miles, the following readings were taken by means of a Wheatstone bridge—

Resistance between cores measured at end A with end B open-circuited $= 10\ \Omega$.

Resistance between cores measured at end B with end A open-circuited $= 8{\cdot}15\ \Omega$.

Resistance per mile of each core $= 1{\cdot}77\ \Omega$.

Determine the position of the fault. (*Lond. Univ.*, 1932.)

18. Give a diagram of connections for, and explain the working of, a system of protection suitable for a 3-phase delta-star distribution transformer. There are three line conductors on each side.

What precautions are advisable in current transformers intended for operating protective gear with the likelihood of heavy through faults, and what is the meaning and purpose of "restraint"? (*Lond. Univ.*, 1948.)

19. Explain the nature and behaviour of the arc in an ordinary circuit-breaker.

Describe briefly methods which are being developed with a view to reducing the duration of the arc in circuit-breakers of both the oil and other types. (*Lond. Univ.*, 1936.)

20. Draw a diagram of connections and explain the principle of operation of a current-balancing system of protecting a 3-phase turbo-alternator against internal faults (earth and inter-phase).

A 3-phase, 20-MVA., 11-kV., star-connected generator is protected by the above system. If the ratio of the current transformers is 1 200/5, the minimum operating current of the relay is 0·75 A. and the neutral-point earthing resistance is 6 Ω., calculate the percentage of each phase of the stator winding which is unprotected against earth faults when the machine is operating at normal voltage. (*Lond. Univ.*, 1947.)

21. A 5 000 kVA., 6 600 V., star-connected alternator has a synchronous reactance of 2 Ω. per phase and 0·5 Ω. resistance. It is protected by a Merz-Price balanced-current system which operates when the out-of-balance current exceeds 30 per cent of full load current. Describe this method of protection and determine what proportion of the alternator winding is unprotected if the star point is earthed through a resistance of 6·5 Ω. (*Lond. Univ.*, 1937.)

22. Explain the terms "symmetrical breaking current," "asymmetrical breaking current," "making current," as applied to oil circuit-breakers, and show how these currents are determined from oscillograms taken during short-circuit tests on a 3-phase circuit-breaker. Explain why at least one of such oscillograms of current in a 3-phase short-circuit test shows asymmetry. What is meant by the rated MVA. breaking capacity of a 3-phase circuit-breaker? (*Lond. Univ.*, 1947.)

23. Describe the "star" or "tie-bar" method of interconnecting bus-bar sections and compare it with other bus-bar arrangements.

A generating station contains three bus-bar sections, to each of which is connected a generating unit of 60 000 kVA. having 15% leakage reactance, the bus-bar reactors having a reactance of 10%. Calculate the maximum kVA. fed into a fault and also the maximum kVA. if the number of bus-bar sections is increased to infinity. (*Lond. Univ.*, 1949.)

24. Explain why it is necessary to provide surge protection in the terminal transformers of an overhead transmission line, and briefly describe two methods whereby such protection is obtained.

An overhead line is connected to a transformer by a short cable. If a 50-kV. surge travels along the line towards the transformer, estimate the voltage of the surge reaching the transformer. The inductance per mile of cable and line are 0·56 mH. and 2·8 mH. respectively while the corresponding capacitances per mile are 0·4 μF. and 0·01 μF. Deduce any formula used other than surge-impedance $= \sqrt{L/C}$. (*Lond. Univ.*, 1949.)

also upon circuit conditions. The energy absorbed by the arc can be measured directly on the oscillograph or it can be calculated from the current and voltage curves; the form of the power curve is shown in Fig. 192. Experiment shows that 1 kW.-sec. of energy liberates about 60 cm.^{3} of gas, and it is necessary to design the size and strength of the circuit-breaker to withstand the explosive

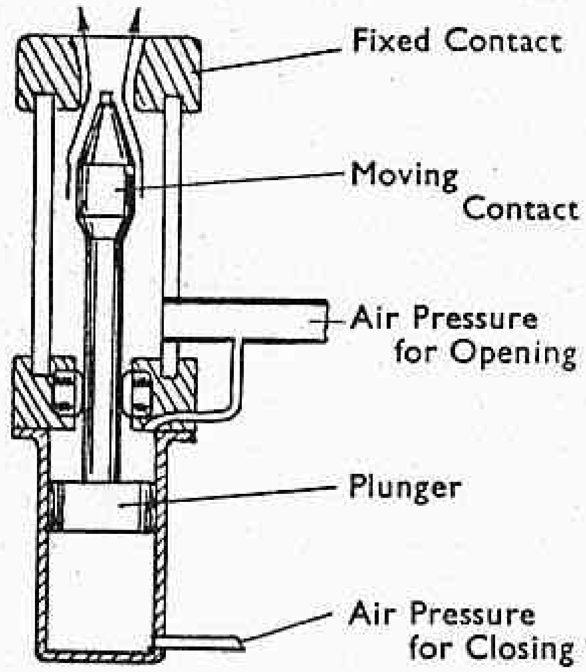

FIG. 193A. AIR-BLAST CIRCUIT-BREAKER

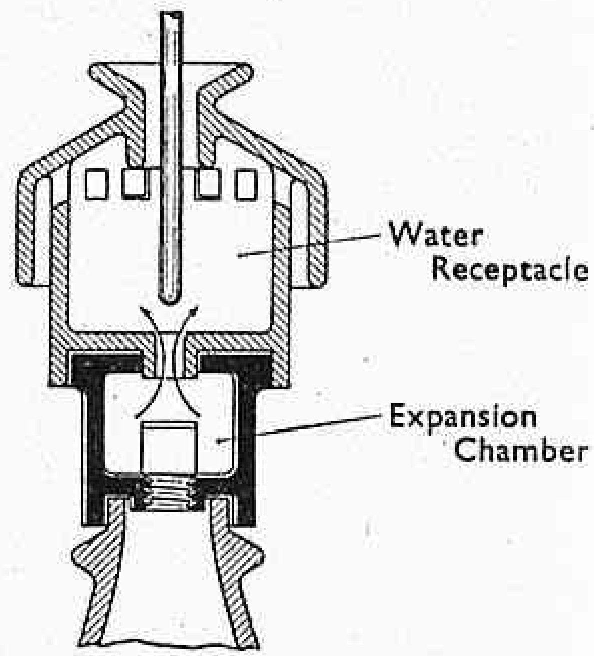

FIG. 193B. WATER CIRCUIT-BREAKER

(I.E.E. Students' Journal)

pressure due to this sudden formation of gas. There is an empirical formula for the arc energy, namely,

$$\text{arc energy} = \text{kVA. interrupted} \times 0{\cdot}1 \times \text{arc time in sec.}$$

Thus if the kVA. interrupted is 500 000 and the arc is extinguished in 4 half-cycles, the energy is

$$500\,000 \times 0{\cdot}1 \times 0{\cdot}04 = 2\,000 \text{ kW.-sec.},$$

and the gas liberated is 120 litres or about 4 ft.^{3} In practice the arc may last for as long as 0·1 sec. or more.

Any method of decreasing the diameter of the arc or reducing the density of the ions will result in an increased restriking voltage and a quicker extinction of the arc.

There are various ways of achieving a reduced diameter and density of ions.

Fig. 193A shows a sketch of the *air-blast circuit-breaker*. The breaker is closed by applying pressure at the lower opening, and opened by applying pressure at the upper opening. When the contacts separate, the cold air rushes round the movable contact

and blows out the arc. Fig. 193B shows the principle of the water circuit-breaker. The contacts are in water, which is turned into steam by the arc and rushes past the opening to blow out the arc. Both these forms of circuit-breaker are much smaller than the oil circuit-breaker, and operate in one or two half-cycles.

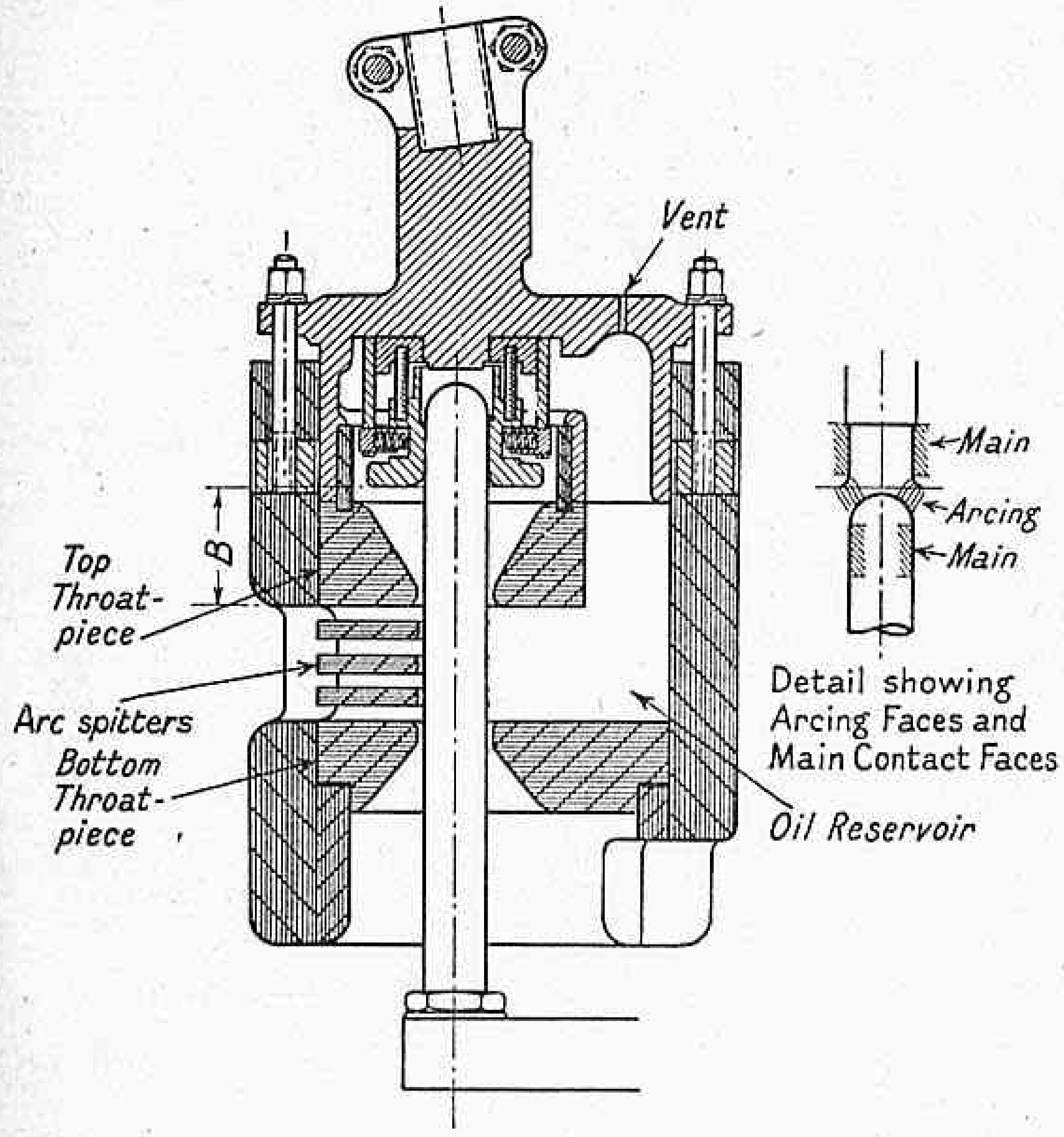

FIG. 194. CROSS-JET EXPLOSION POT
(Outdoor High Voltage Switchgear (Todd and Thompson))

Fig. 194 shows a section of a cross-jet explosion pot. Below the female contact there is a shroud, consisting of a stack of insulating plates with channels at right angles to the arc. When the contacts part the arc breaks up the oil surrounding it into gas at high pressure, and the gas expels a cross-jet of cold oil from the side pocket through the channels across the arc as soon as the movable contact passes an opening. If the short-circuit current is heavy, the pressure of the gas is great and the cross-jet is sufficiently powerful to extinguish the arc at the first or second channel. In order to break relatively low currents it is necessary to have more channels. Fig. 194 shows a 66 kV. breaker which has four channels. Fig. 195 shows a three-phase circuit-breaker operating at 33 kV., fitted with cross-jet contacts.

A recent development is the single-break switch, which has the advantage of a much smaller construction. It is not much less

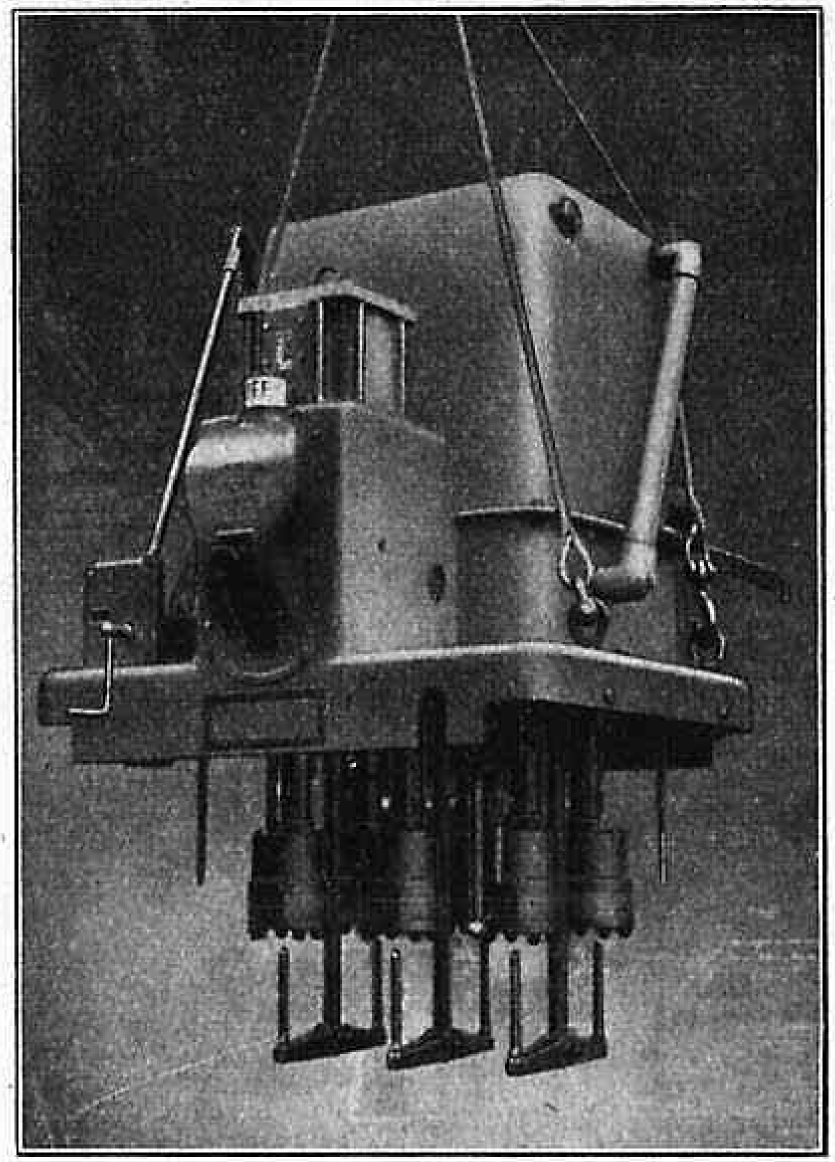

FIG. 195. THREE-PHASE 33 KV. CIRCUIT-BREAKER WITH CROSS-JET CONTACTS
(Metropolitan-Vickers)

effective than the double-break switch for the following reason. Suppose that the fixed contacts A and C have capacitances of 10 $\mu\mu$F. each to the moving contact B, which has a capacitance of 40 $\mu\mu$F. to earth (See Fig. 196). If an earth fault occurs on C, the resulting capacitances are 10 $\mu\mu$F. between A and B and 50 $\mu\mu$F. between B and C. The voltage between A and C is then taken as to five-sixths by the gap AB and one-sixth by BC, so that the arc AB does nearly all the work, and a single-break switch would be nearly as effective as the double-break. Fig. 197 shows a single-break

switch, with cross-jet pot and gang-operated oil-immersed isolators on the bus-bar and cable sides.

In the *deion circuit-breaker* (Fig. 198), a stack of iron plates is magnetized by the arc current, and the resulting magnetic field forces the arc along the cold surface of a grid of insulating stacks, and this results in a rapid cooling and deionization. The arc is in two parts, each of which flows by a stack of iron plates $\frac{1}{16}$ in. thick, separated from each other by $\frac{1}{16}$ in. and protected by an asbestos arc-resisting material.

Rating of Circuit-breakers. The current is taken as the r.m.s. value at the instant that the contacts open. It is seen in Fig. 192 that the current has a d.c. component which decays rapidly: let the value of the d.c. component be I at the instant of contact separation. Let the a.c. component have peak value i. Then the r.m.s. value is

$$\sqrt{(I^2 + \tfrac{1}{2}i^2)},$$

and this is the value taken as the current broken. Continental

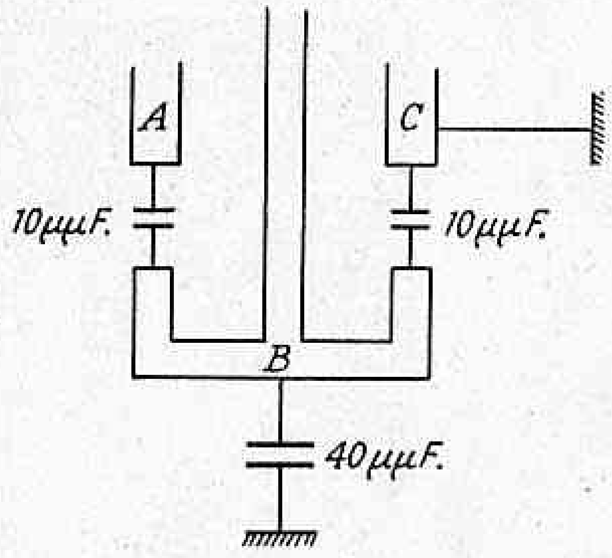

FIG. 196. DOUBLE-BREAK SWITCH

practice ignores the d.c. component. The voltage is taken as the recovery voltage, which is somewhat less than the normal circuit voltage; American practice is to take the normal voltage. The product of the current and the voltage to neutral gives the kVA. rating per phase. The American rating is thus higher than the rating given in this country. Thus the ratings of a certain breaker according to Continental, British, and American practices are 385 000, 456 000, and 526 000 kVA. respectively.

The *conditions of severity* for circuit-breaker operation are the power factor of the load, the recovery voltage, and the rate of rise of recovery voltage.

If the power factor of the circuit to be interrupted is unity the voltage is zero when the current is zero, so that when the arc is temporarily extinguished there is no voltage immediately available to restrike it. If the power factor is zero, the voltage is a maximum at this instant and the arc is more easily restruck. It is found that the duration of the arc is approximately proportional to sin ϕ when the power factor is low. British practice requires that the breaker be capable of interrupting the rated current at 0·1 power factor, which corresponds to short-circuit currents under the worst conditions.

The recovery voltage depends upon the circuit conditions, and there is a desire to consider it as a condition of severity. Thus if there is a three-phase short to earth, the recovery voltage on the first breaker to open is equal to the phase voltage (less the drop due to armature reaction, etc.) if the neutral point of the generator is earthed; but $\sqrt{3}$ times this if the neutral is not earthed. The

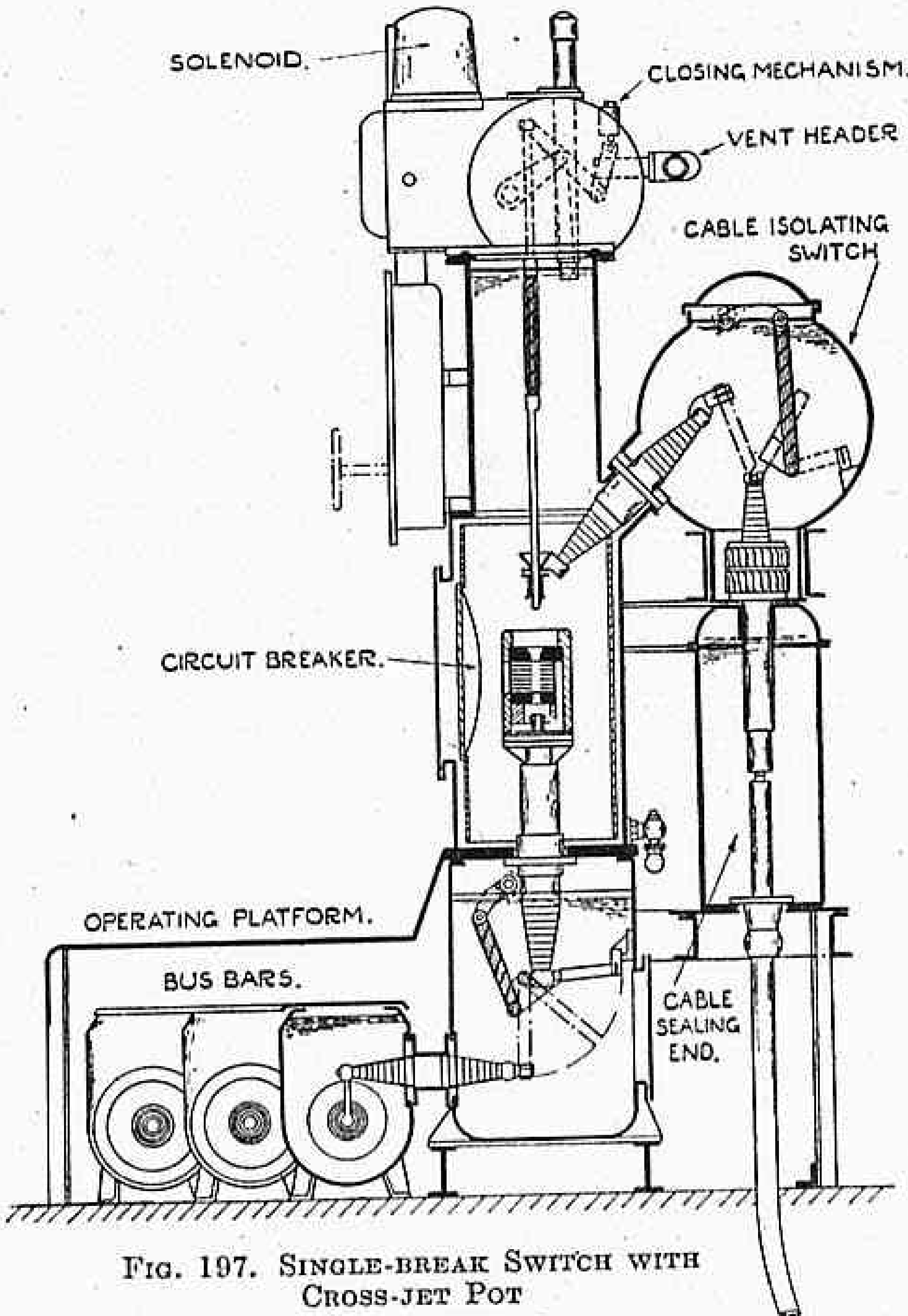

FIG. 197. SINGLE-BREAK SWITCH WITH CROSS-JET POT
(Metropolitan-Vickers)

rate of rise of recovery voltage has an effect on the extinguishing of the arc. When the current falls to zero the ions in the arc recombine and the dielectric strength rises at a rate between 10 and 200 V. per cm. per μsec. At this instant the voltage is zero and is rising. If the rate of rise of voltage is less than the rate of rise of dielectric strength of the gas the arc will not be restruck; if greater, the arc will be restruck. The rate of rise of recovery voltage is affected by

the high-frequency oscillations of the electrical system. If the capacitance of the system is high, i.e. the line is long, the frequency of the oscillations is comparatively low, about 300 cycles per sec., and the rate of rise of recovery voltage is smaller than if the line is short, the capacitance low, and the frequency high (say 3 000 cycles per sec.). It is thus easier for the arc to be extinguished if there is a large capacitance in the system. Circuit-breakers are usually tested by direct connection to a generator, so that the

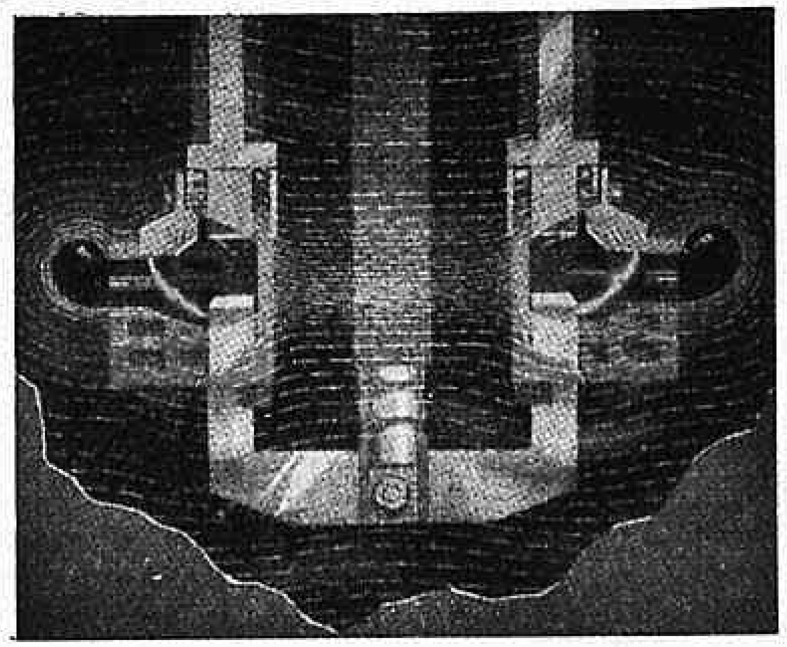

FIG. 198. DEION CIRCUIT-BREAKER
(English Electric)

capacitance is low and the conditions are as severe as will be met in practice.

Air Circuit-breakers. These are much used for d.c. circuits and for low voltage alternating currents. Fig. 199 shows a heavy-current air circuit-breaker. It consists of an upper and a lower contact block fixed to the switchboard panel, and a moving brush contact which bridges under pressure the stationary contacts. In addition to the main contacts, auxiliary copper contacts are provided to protect the main contacts, and also springs carrying carbon contacts on which the final break is made.

To obtain proper contact pressure the link mechanism is designed to toggle, and the links are held in position by a hardened latch, which is tripped by the operation of the various automatic release devices. Various automatic attachments may be provided for overload trip with or without time lag, reverse current trip, under voltage trip, shunt trip, or tripping interlock to ensure simultaneous tripping of two or more breakers. The time delay device usually consists of a dashpot and plunger, which is retarded by oil or by air escapement.

Fuses. The low-voltage fuse or fusible cut-out consists of a short length of conductor, which can carry a certain current indefinitely but will fuse if the current is greater. The time to fuse or blow depends upon the magnitude of the excess current. Small current fuses (up to 100 amperes) are usually the only protective devices included in domestic installations. Fuses for large currents (up to 600 amperes) are made for low-voltage supply systems; one very successful fuse for large currents consists of parallel strips of silver; another consists of a copper strip with a waist which is cut and soldered together. These types of fuse are enclosed in cartridges of porcelain or synthetic heat-resisting substance such as bakelite.

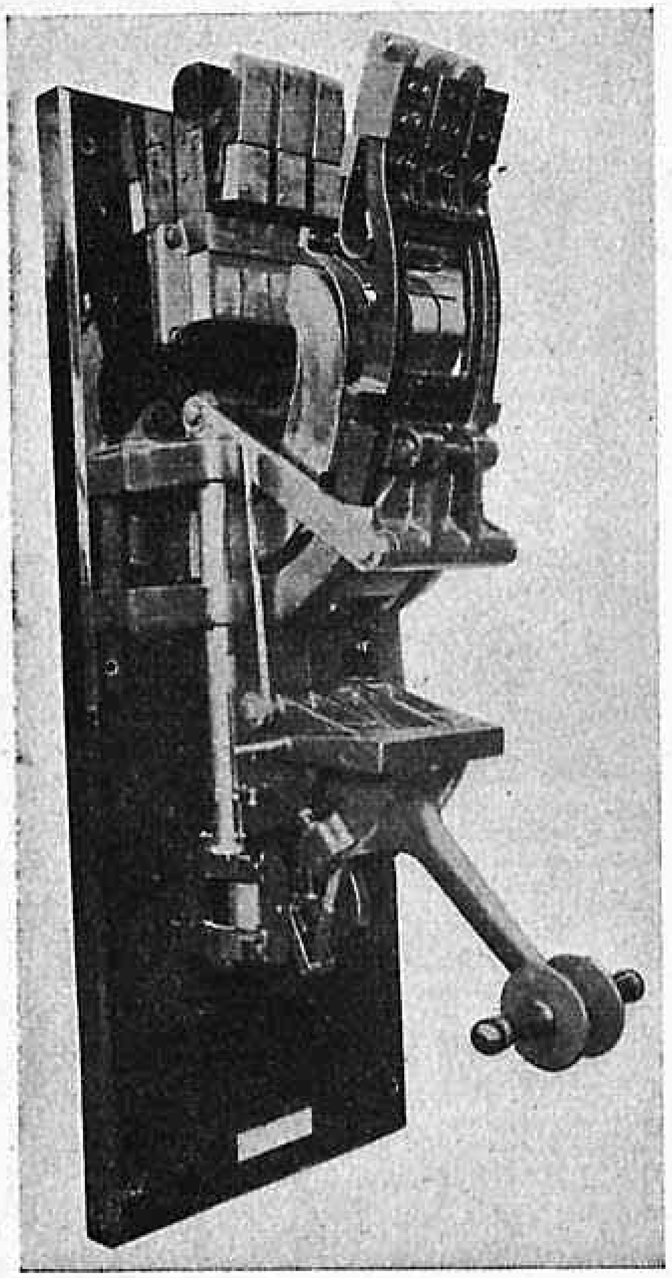

Fig. 199. Heavy-current, Air Circuit-breaker

In high-voltage rural distribution schemes high-voltage fuses are used as alternatives to the oil circuit-breaker. Recent research has produced fuses with a breaking capacity of 900 000 kVA. at 132 kV. and 500 000 kVA. at 11 kV.

The tetrachloride fuse consists of a strong glass tube, sealed at both ends with brass caps, and filled with carbon tetrachloride. A flexible copper conductor is held by a strong spiral spring (usually of phosphor bronze); one end of the spring is fixed to an end cap, and the other end is held by a high-resistance wire which is in parallel with the copper conductor. When the current exceeds a certain value, the high-resistance wire fuses, the spring pulls back the copper conductor, and the arc is quenched by the carbon tetrachloride vapour. The amount of metal vaporized is very small, and the explosive pressure is not unduly great. *Quenchol* is used sometimes instead of carbon tetrachloride.

There is a cartridge-type fuse consisting of a bakelized canvas tube filled with powdered quartz. The conducting element consists of silver and high-resistance wires in parallel: the vaporized silver forms silver silicate which is non-conducting.

Both the above types of fuse will clear a heavy fault in one or two cycles, and thus they compare favourably with a relay-operated circuit-breaker which takes 0·2 to 0·5 sec. The disadvantage of fuses is their complete lack of discrimination, as they will cut out any section which carries the excess current.

Relays. There are many kinds of relays in service in protective systems, and there are many designs of relay for the same purpose. The name attached to a relay indicates its function, e.g. *overload* or *over-current* relay, *reverse power* relay with graded time-lag, etc.

Fig. 200 shows an *instantaneous relay* of the attracted armature type. The a.c. or d.c. through the winding attracts the armature and makes the contacts C and D. At the same time the catch E is released from the movable blade F which springs into the stationary jaws G, making another contact in parallel with CD. The blade F must be reset by hand, and serves as an indication of the operation of the relay.

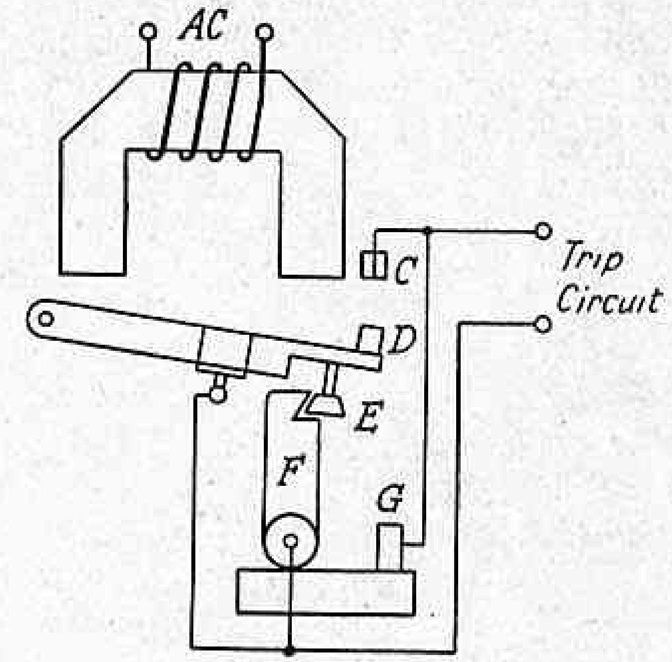

Fig. 200. Instantaneous Relay Attracted Armature Type (*B. T.-H.*)

The *solenoid and plunger* type of relay can be used for instantaneous action; a definite time-lag can be obtained by using an oil dashpot, an air escapement chamber, or clockwork mechanism. It is advisable that the dashpot or escapement chamber be widened at one end, so that there should be a free movement over the last part of the stroke: this makes for a good contact.

As the time of blowing of a fuse varies inversely as the overload, the placing of a fuse in shunt with an instantaneous or definite time relay produces a relay system with inverse time-lag. In the former case the time tends to zero as the current becomes very great, in the latter to a definite time.

Figs. 201 and 202 show an *induction* type *overcurrent relay*. The current enters a tapped primary, the turns of which can be chosen by a plug 7, which thus gives a current setting. A closed secondary is wound on the upper and lower magnets. The fluxes due to the primary and secondary windings are separated in phase and space and produce a torque, as in the shaded-pole induction disc motor. The disc experiences a torque, which depends on the current, and

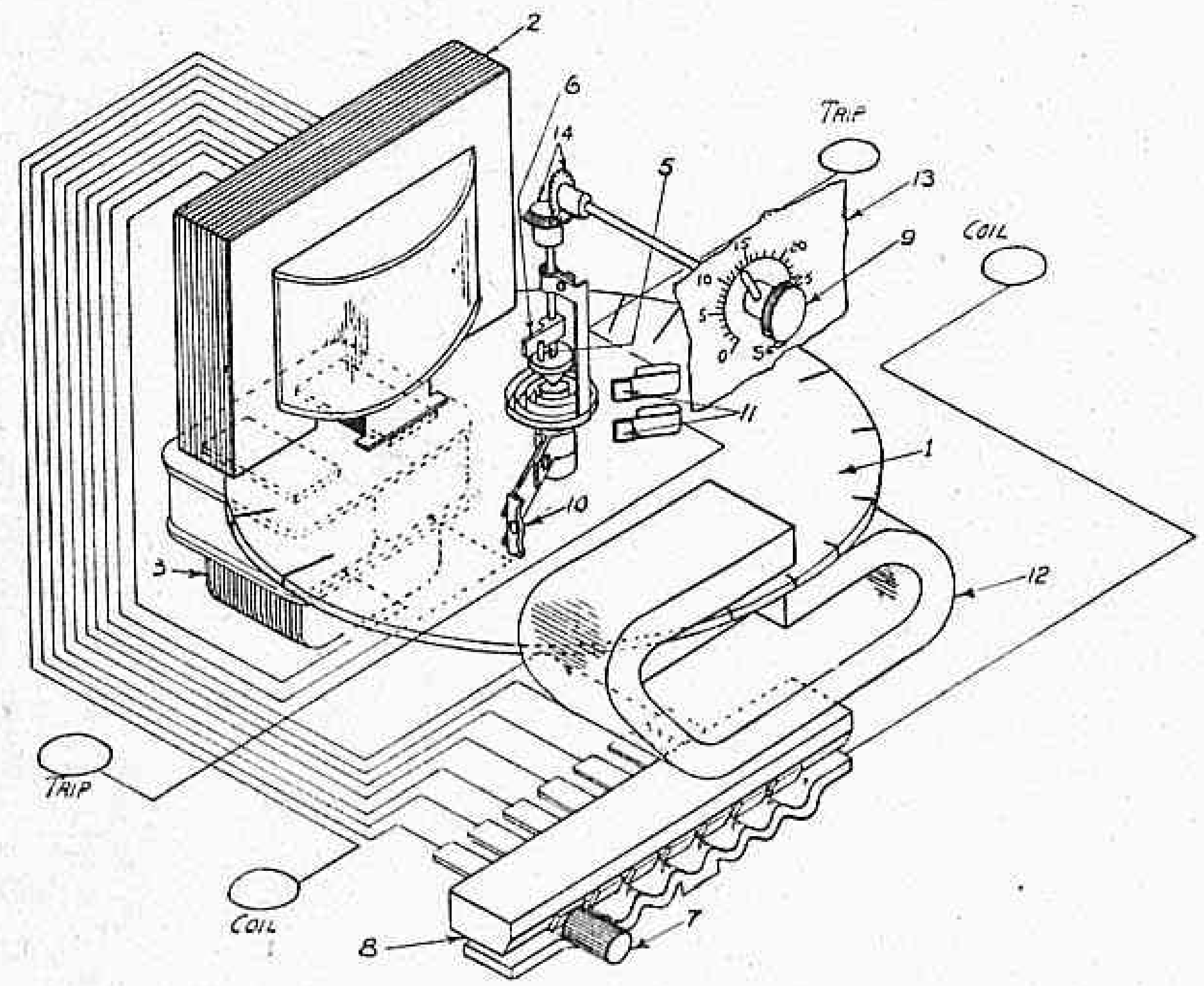

Fig. 201. Induction Type Overcurrent Relay
(*Metropolitan-Vickers*)

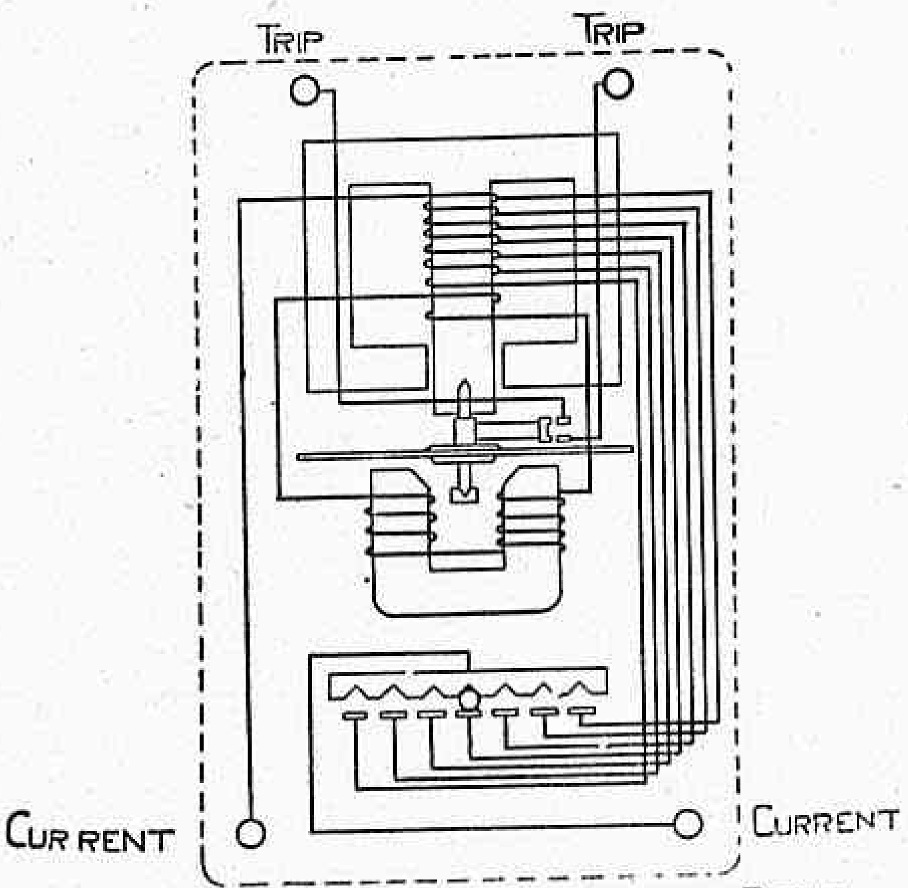

Fig. 202. Induction Type Overcurrent Relay
(*Metropolitan-Vickers*)

will move against a restraining spring provided the current is large enough. The time of travel is adjustable by means of the stop 6, which adjusts the distance of travel to the contacts 11. The torque is kept constant at all positions of the disc by means of graded slits. Since the torque increases with the current, the relay has an inverse time characteristic.

A *reverse power* relay is obtained by having a winding on the

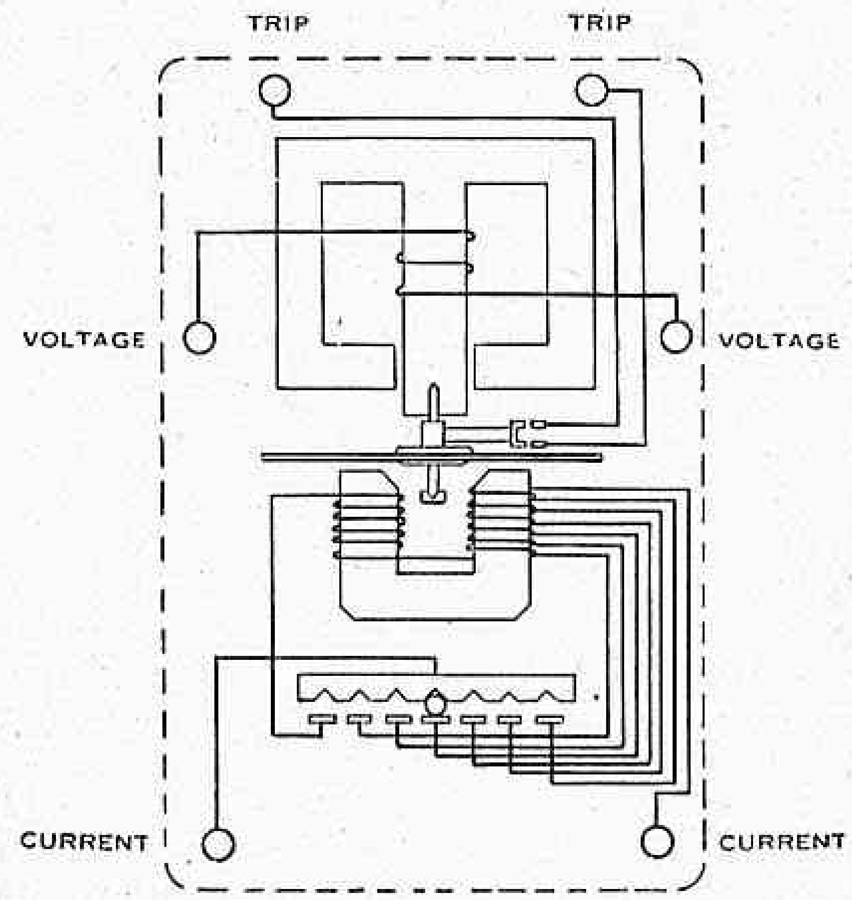

Fig. 203. Reverse Power Relay
(*Metropolitan-Vickers*)

middle limb of the upper magnet operated by the voltage, and a separate winding on the two limbs of the lower magnet operated by the current: the current winding has tappings as before. (See Fig. 203.) When the power flows in the normal direction the fluxes in the windings tend to turn the disc in a direction away from the contacts 11. When the power flows in the reverse direction the torque is in the opposite direction and the contacts 11 are closed. The relay can be made very sensitive by having a very light control spring, so that a very small reversal of power will cause the relay to operate.

A *directional overload* relay can be made of two induction disc type relays, one of which is a simple overload relay as shown in Fig. 202 and the other a reverse power relay as shown in Fig. 203. The two relays are fitted in one case. Their contacts are connected in series, so that the trip-circuit is not energized unless both operate.

Induction type relays have an inverse with definite-minimum time characteristic as shown in Fig. 204. The definite-minimum time is due to the self-braking effect of the fluxes which produce the driving torque.

Distance or *impedance relays* are of several kinds; but a common characteristic of all is the production of a force or torque in one direction by the line current and in the other direction by the voltage. The force or torque due to the voltage tends to prevent the contacts from closing, but that due to the current tends to close the contacts. Suppose the forces are aV^2 and bI^2; the contacts will close if

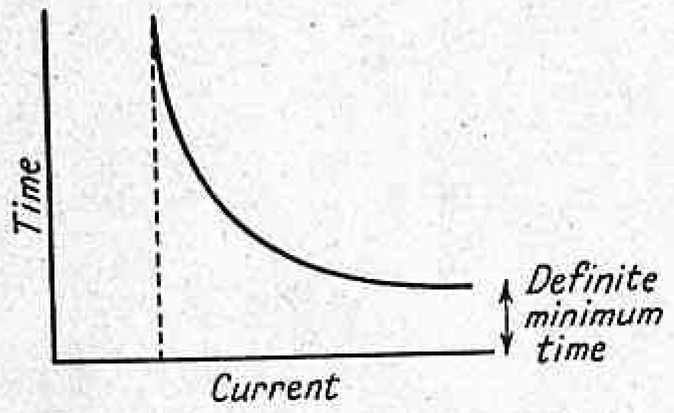

FIG. 204. INVERSE WITH DEFINITE-MINIMUM TIME CHARACTERISTIC

$$bI^2 > aV^2,$$

or $$V^2/I^2 < b/a,$$

i.e. $$Z < \sqrt{(b/a)}.$$

Thus the relay operates if the line impedance falls below a certain value, which can be set as equal to the impedance of a complete section.

One form of impedance relay is like that shown in Figs. 201 and 202, except that there are two magnet systems, one on each side of the disc. One system operates on the line current and the other on the line voltage, and the torques oppose each other. Fig. 205 shows another induction type impedance relay. A potential transformer supplies the cruciform iron path with a rotating flux, which causes drum D to rotate in one direction. A current transformer supplies the iron path X, which has a shaded pole, with a flux which causes D_1 to rotate in the opposite direction. Fig. 206 shows diagrammatically the solenoid-and-plunger type, whose action is obvious.

Impedance relays operate very quickly if the impedance falls below a certain value. *Impedance-time* relays are designed so that the time of operation is small for a certain low impedance, but increases linearly as the impedance increases. In one type of impedance-time relay, the current drives a disc round by induction and a spring is wound up. This spring tends to close the contacts of the trip-circuit but is opposed by an armature attached to the spindle and attracted by a coil carrying a current produced by the line voltage. Until the spring exerts a force as large as the attraction on the armature the spindle does not turn; when the spring is sufficiently wound up, the armature leaves the voltage coil and the trip circuit is made at once.

In many systems of protection it is required that a relay shall

operate when the currents at two points of the system are unequal. For example, if the currents at the two ends of an alternator winding are unequal there is either a fault to earth or between phases.

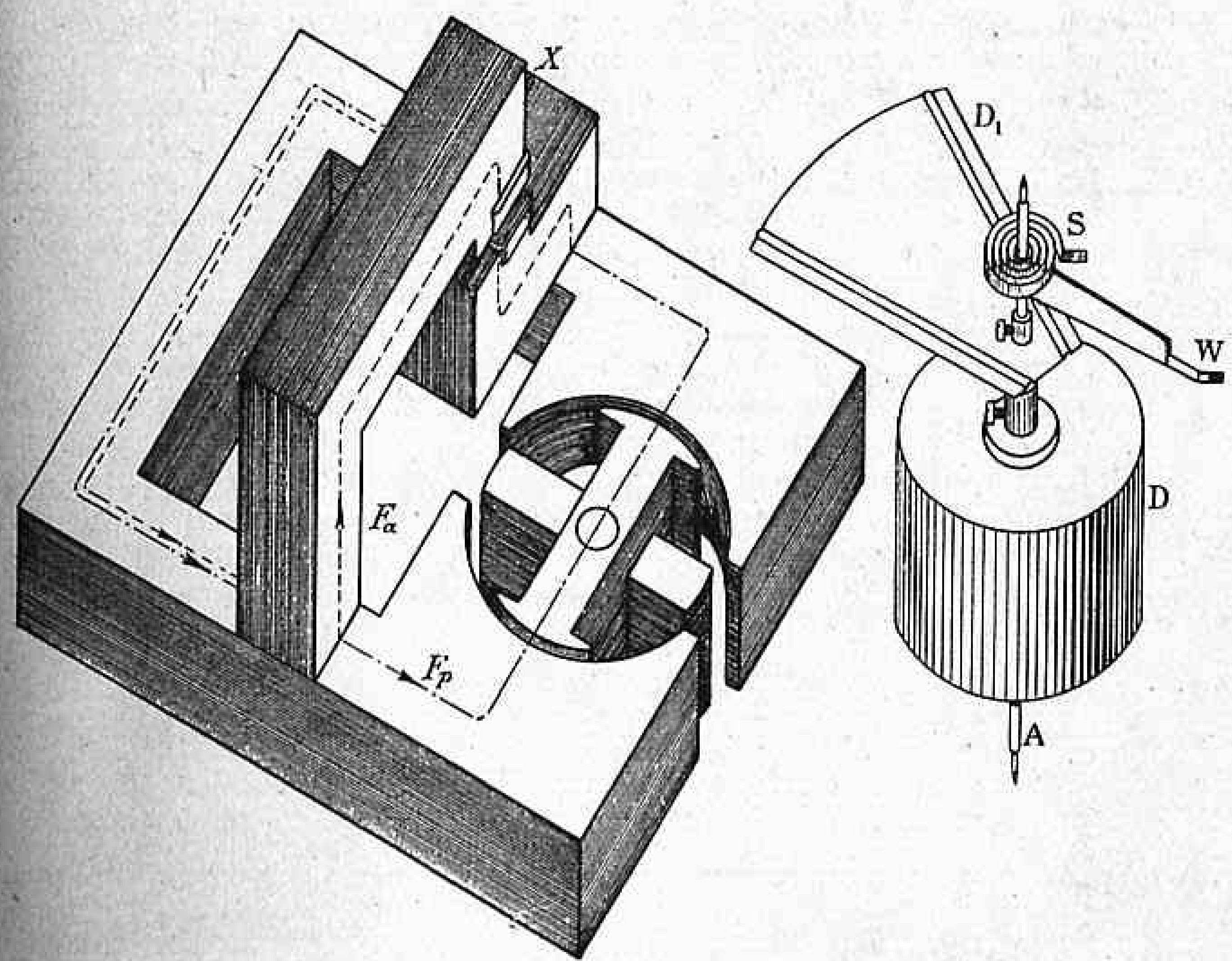

FIG. 205. INDUCTION TYPE IMPEDANCE RELAY
(*I.E.E. Journal*)

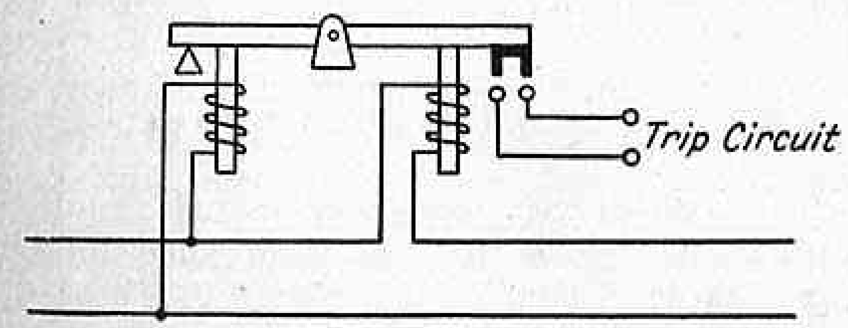

FIG. 206. SOLENOID-AND-PLUNGER TYPE IMPEDANCE RELAY

Fig. 207 shows a method whereby the relay R can be made to operate when I_1 is not equal to I_2. The current transformers, *C.T.*, are identical and are connected so that their secondary e.m.f.'s are in the directions shown. Their secondary currents i_1 and i_2 therefore