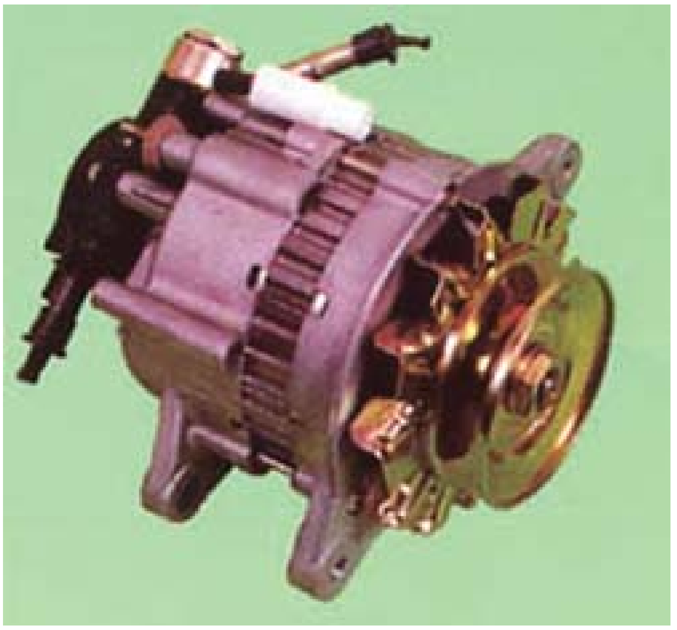
CHAPTER

22



Protection of Alternators and Transformers

Introduction

The modern electric power system consists of several elements *e.g.* alternators, transformers, station bus-bars, transmission lines and other equipment. It is desirable and necessary to protect each element from a variety of fault conditions which may occur sooner or later. The protective relays discussed in the previous chapter can be profitably employed to detect the improper behaviour of any circuit element and initiate corrective measures. As a matter of convenience, this chapter deals with the protection of alternators and transformers only.

The most serious faults on alternators which require immediate attention are the stator winding faults. The major faults on transformers occur due to short-circuits in the transformers or their connections. The basic system used for protection against these faults is the differential relay scheme because the differential nature of measurements makes this system much more sensitive than other protective systems.

22.1 Protection of Alternators

The generating units, especially the larger ones, are relatively few in number and higher in individual cost than most other equipments. Therefore, it is desirable and necessary to provide protection to cover the wide range of faults which may occur in the modern generating plant.

Some of the important faults which may occur on an alternator are :

(*i*) failure of prime-mover
(*ii*) failure of field
(*iii*) overcurrent
(*iv*) overspeed
(*v*) overvoltage
(*vi*) unbalanced loading
(*vii*) stator winding faults

(*i*) **Failure of prime-mover.** When input to the prime-mover fails, the alternator runs as a synchronous motor and draws some current from the supply system. This motoring conditions is known as "inverted running".

(*a*) In case of turbo-alternator sets, failure of steam supply may cause inverted running. If the steam supply is gradually restored, the alternator will pick up load without disturbing the system. If the steam failure is likely to be prolonged, the machine can be safely isolated by the control room attendant since this condition is relatively harmless. Therefore, automatic protection is not required.

(*b*) In case of hydro-generator sets, protection against inverted running is achieved by providing mechanical devices on the water-wheel. When the water flow drops to an insufficient rate to maintain the electrical output, the alternator is disconnected from the system. Therefore, in this case also electrical protection is not necessary.

(*c*) Diesel engine driven alternators, when running inverted, draw a considerable amount of power from the supply system and it is a usual practice to provide protection against motoring in order to avoid damage due to possible mechanical seizure. This is achieved by applying reverse power relays to the alternators which *isolate the latter during their motoring action. It is essential that the reverse power relays have time-delay in operation in order to prevent inadvertent tripping during system disturbances caused by faulty synchronising and phase swinging.

(*ii*) **Failure of field.** The chances of field failure of alternators are undoubtedly very rare. Even if it does occur, no immediate damage will be caused by permitting the alternator to run without a field for a short-period. It is sufficient to rely on the control room attendant to disconnect the faulty alternator manually from the system bus-bars. Therefore, it is a universal practice not to provide †automatic protection against this contingency.

(*iii*) **Overcurrent.** It occurs mainly due to partial breakdown of winding insulation or due to overload on the supply system. Overcurrent protection for alternators is considered unnecessary because of the following reasons :

(*a*) The modern tendency is to design alternators with very high values of internal impedance so that they will stand a complete short-circuit at their terminals for sufficient time without serious overheating. On the occurrence of an overload, the alternators can be disconnected manually.

(*b*) The disadvantage of using overload protection for alternators is that such a protection might disconnect the alternators from the power plant bus on account of some momentary troubles outside the plant and, therefore, interfere with the continuity of electric service.

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* During inverted running (or motoring), there is a reversal of power flow in the stator windings. This causes the operation of reverse power relay.

† This is the case with attendant stations. However, in unattended stations, the use of a field-failure relay may be justified.

(*iv*) Overspeed. The chief cause of overspeed is the sudden loss of all or the major part of load on the alternator. Modern alternators are usually provided with mechanical centrifugal devices mounted on their driving shafts to trip the main valve of the prime-mover when a dangerous overspeed occurs.

(*v*) Over-voltage. The field excitation system of modern alternators is so designed that over-voltage conditions at normal running speeds cannot occur. However, overvoltage in an alternator occurs when speed of the prime-mover increases due to sudden loss of the alternator load.

In case of steam-turbine driven alternators, the control governors are very sensitive to speed variations. They exercise a continuous check on overspeed and thus prevent the occurrence of over-voltage on the generating unit. Therefore, over-voltage protection is not provided on turbo-alternator sets.

In case of hydro-generator, the control governors are much less sensitive and an appreciable time may elapse before the rise in speed due to loss of load is checked. The over-voltage during this time may reach a value which would over-stress the stator windings and insulation breakdown may occur. It is, therefore, a usual practice to provide over-voltage protection on hydro-generator units. The over-voltage relays are operated from a voltage supply derived from the generator terminals. The relays are so arranged that when the generated voltage rises 20% above the normal value, they operate to

(*a*) trip the main circuit breaker to disconnect the faulty alternator from the system

(*b*) disconnect the alternator field circuit

(*vi*) Unbalanced loading. Unbalanced loading means that there are different phase currents in the alternator. Unbalanced loading arises from faults to earth or faults between phases on the circuit external to the alternator. The unbalanced currents, if allowed to persist, may either severely burn the mechanical fixings of the rotor core or damage the field winding.

Fig. 22.1 shows the schematic arrangement for the protection of alternator against unbalanced loading. The scheme comprises three line current transformers, one mounted in each phase, having their secondaries connected in parallel. A relay is connected in parallel across the transformer secondaries. Under normal operating conditions, equal currents flow through the different phases of the alternator and their algebraic sum is zero. Therefore, the sum of the currents flowing in the secondaries is also zero and no current flows through the operating coil of the relay. However, if unbalancing occurs, the currents induced in the secondaries will be different and the resultant of these currents will flow through the relay. The operation of the relay will trip the circuit breaker to disconnect the alternator from the system.

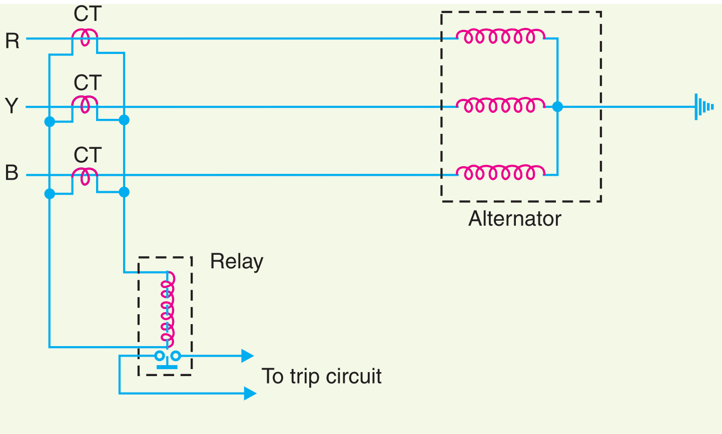

Fig. 22.1

(*vii*) Stator winding faults. These faults occur mainly due to the insulation failure of the stator windings. The main types of stator winding faults, in order of importance are :

(*a*) fault between phase and ground

(b) fault between phases

(c) inter-turn fault involving turns of the same phase winding

The stator winding faults are the most dangerous and are likely to cause considerable damage to the expensive machinery. Therefore, automatic protection is absolutely necessary to clear such faults in the quickest possible time in order to minimise the *extent of damage. For protection of alternators against such faults, differential method of protection (also knows as Merz-Price system) is most commonly employed due to its greater sensitivity and reliability. This system of protection is discussed in the following section.

22.2 Differential Protection of Alternators

The most common system used for the protection of stator winding faults employs circulating-current principle (Refer back to Art. 21.18). In this scheme of protection, currents at the two ends of the protected section are compared. Under normal operating conditions, these currents are equal but may become unequal on the occurrence of a fault in the protected section. The difference of the currents under fault conditions is arranged to pass through the operating coil of the relay. The relay then closes its contacts to isolate protected section from the system. This form of protection is also known as *Merz-Price circulating current scheme*.

Schematic arrangement. Fig. 22.2 shows the schematic arrangement of current differential protection for a 3-phase alternator. Identical current transformer pairs CT_1 and CT_2 are placed on either side of each phase of the stator windings. The secondaries of each set of current transformers are connected in star ; the two neutral points and the corresponding terminals of the two star groups being connected together by means of a four-core pilot cable. Thus there is an independent path for the currents circulating in each pair of current transformers and the corresponding pilot *P*.

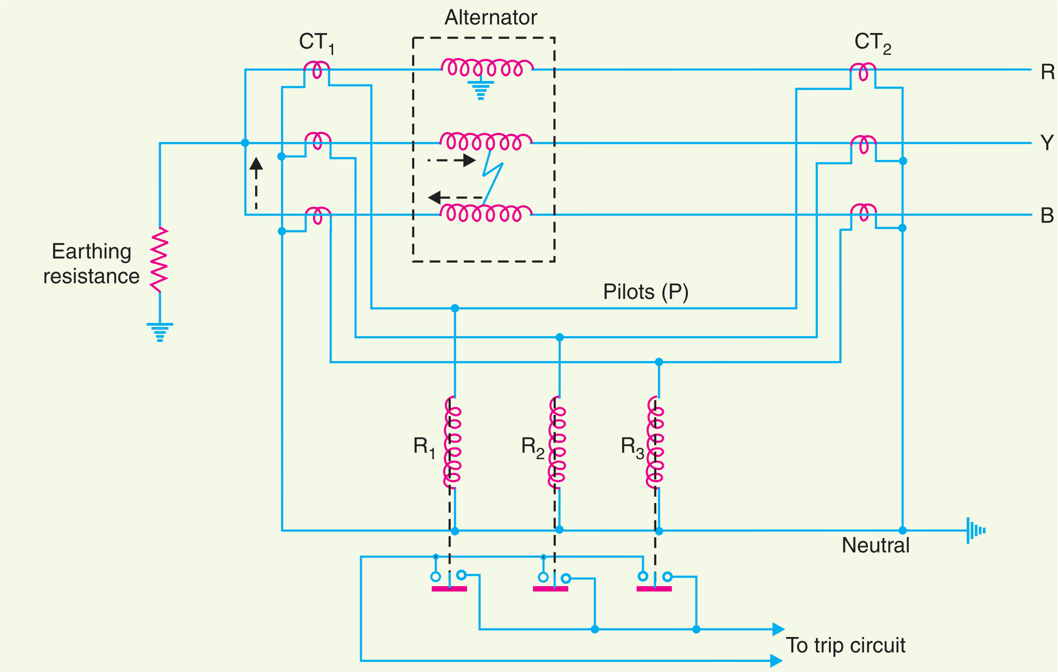

Fig. 22.2

* If the stator winding fault is not cleared quickly, it may lead to

(*i*) burning of stator coils

(*ii*) burning and welding-up of stator laminations

The relay coils are connected in star, the neutral point being connected to the current-transformer common neutral and the outer ends one to each of the other three pilots. In order that burden on each current transformer is the same, the relays are connected across equipotential points of the three pilot wires and these equipotential points would naturally be located at the middle of the pilot wires. The relays are generally of electromagnetic type and are arranged for instantaneous action since fault should be cleared as quickly as possible.

Operation. Referring to Fig. 22.2, it is clear that the relays are connected in shunt across each circulating path. Therefore, the circuit of Fig. 22.2 can be shown in a simpler form in Fig. 22.3. Under normal operating conditions, the current at both ends of each winding will be equal and hence the currents in the secondaries of two CTs connected in any phase will also be equal. Therefore, there is balanced circulating current in the pilot wires and no current flows through the operating coils (R_1, R_2 and R_3) of the relays. When an earth-fault or phase-to-phase fault occurs, this condition no longer holds good and the differential current flowing through the relay circuit operates the relay to trip the circuit breaker.

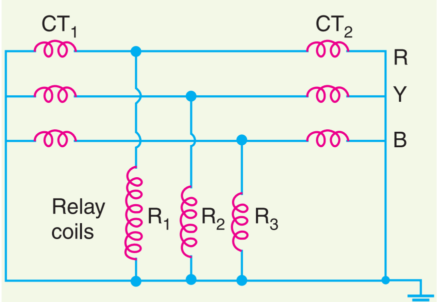

Fig. 22.3

(*i*) Suppose an earth fault occurs on phase *R* due to breakdown of its insulation to earth as shown in Fig. 22.2. The current in the affected phase winding will flow through the core and frame of the machine to earth, the circuit being completed through the neutral earthing resistance. The currents in the secondaries of the two CTs in phase *R* will become unequal and the difference of the two currents will flow through the corresponding relay coil (*i.e.* R_1), returning via the neutral pilot. Consequently, the relay operates to trip the circuit breaker.

(*ii*) Imagine that now a short-circuit fault occurs between the phases *Y* and *B* as shown in Fig. 22.2. The short-circuit current circulates *via* the neutral end connection through the two windings and through the fault as shown by the dotted arrows. The currents in the secondaries of two CTs in each affected phase will become unequal and the differential current will flow through the operating coils of the relays (*i.e.* R_2 and R_3) connected in these phases. The relay then closes its contacts to trip the circuit breaker.

It may be noted that the relay circuit is so arranged that its energising causes (*i*) opening of the breaker connecting the alternator to the bus-bars and (*ii*) opening of the *field circuit of the alternator.

It is a prevailing practice to mount current transformers CT_1 in the neutral connections (usually in the alternator pit) and current transformers CT_2 in the switch-gear equipment. In some cases, the alternator is located at a considerable distance from the switchgear. As the relays are located close to the circuit breaker, therefore, it is not convenient to connect the relay coils to the actual physical mid-points of the pilots. Under these circumstances, balancing resistances are inserted in the shorter lengths of the pilots so that the relay tapping points divide the whole secondary impedance of two sets of CTs into equal portions. This arrangement is shown in Fig. 22.4. These resistances are usually adjustable in order to obtain the exact balance.

Limitations. The two circuits for alternator protection shown above have their own limitations. It is a general practice to use neutral earthing resistance in order to limit the destructive effects of earth-fault currents. In such a situation, it is impossible to protect whole of the stator windings of a star-connected alternator during earth-faults. When an earth-fault occurs near the neutral point, there

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* Although disconnection of faulty alternator prevents other alternators on the system feeding into the fault, it is necessary to suppress the field of faulty alternator to stop the machine itself feeding into the fault.

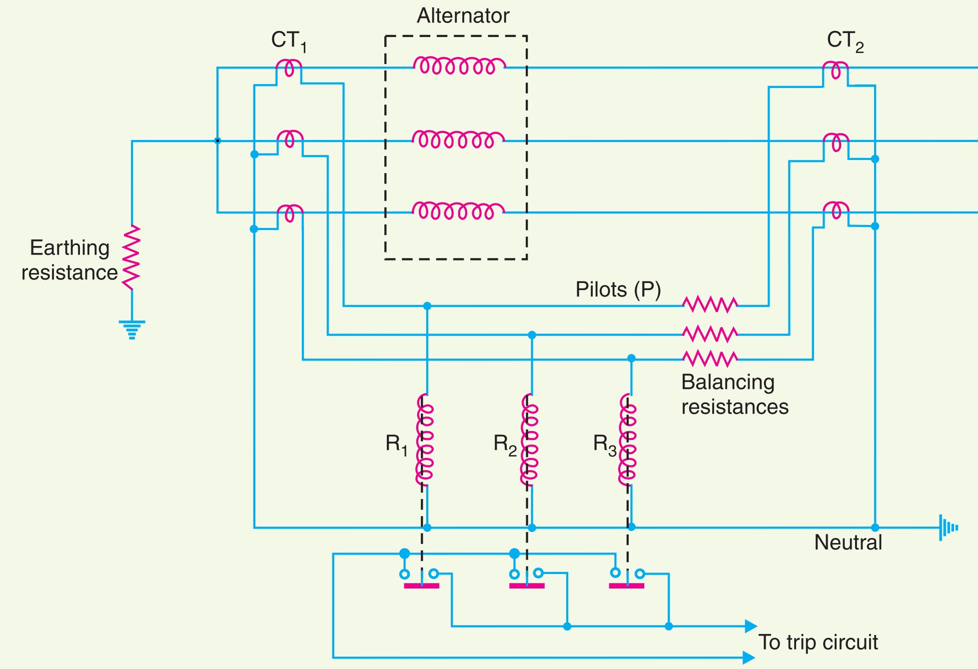

Fig. 22.4

may be insufficient voltage across the short-circuited portion to drive the necessary current round the fault circuit to operate the relay. The magnitude of unprotected zone depends upon the value of earthing resistance and relay setting.

Makers of protective gear speak of "protecting 80% of the winding" which means that faults in the 20% of the winding near the neutral point cannot cause tripping *i.e.* this portion is unprotected. It is a usual practice to protect only 85% of the winding because the chances of an earth fault occurring near the neutral point are very rare due to the uniform insulation of the winding throughout.

22.3 Modified Differential Protection for Alternators

If the neutral point of a star-connected alternator is earthed through a high resistance, protection schemes shown in Fig. 22.2 or 22.4 will not provide sufficient sensitivity for earth-faults. It is because the high earthing resistance will limit the earth-fault currents to a low value, necessitating relays with low current settings if adequate portion of the generator winding is to be protected. However, too low a relay setting is undesirable for reliable stability on heavy through phase-faults. In order to overcome this difficulty, a modified form of differential protection is used in which the setting of earth faults is reduced without impairing stability.

The modified arrangement is shown in Fig. 22.5. The modifications affect only the relay connections and consist in connecting two relays for phase-fault protection and the third for earth-fault protection only. The two phase elements (PC and PA) and balancing resistance (BR) are connected in star and the earth relay (ER) is connected between this star point and the fourth wire of circulating current pilot-circuit.

Operation. Under normal operating conditions, currents at the two ends of each stator winding will be equal. Therefore, there is a balanced circulating current in the phase pilot wires and no current flows through the operating coils of the relays. Consequently, the relays remain inoperative.

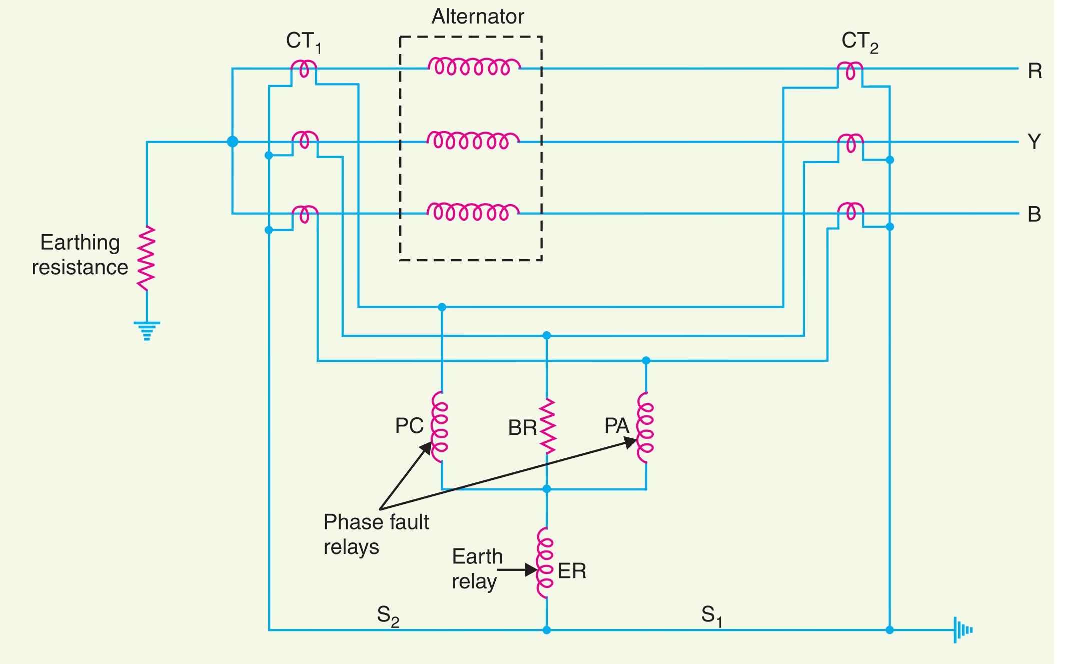

Fig. 22.5

If an earth-fault occurs on any one phase, the out-of-balance secondary current in CTs in that phase will flow through the earth relay *ER* and *via* pilot S_1 or S_2 to the neutral of the current transformers. This will cause the operation of earth relay only. If a fault occurs between two phases, the out-of-balance current will circulate round the two transformer secondaries *via* any two of the coils *PA*, *BR*, *PC* (the pair being decided by the two phases that are faulty) without passing through the earth relay *ER*. Therefore, only the phase-fault relays will operate.

22.4 Balanced Earth-fault Protection

In small-size alternators, the neutral ends of the three-phase windings are often connected internally to a single terminal. Therefore, it is not possible to use Merz-Price circulating current principle described above because there are no facilities for accommodating the necessary current transformers in the neutral connection of each phase winding. Under these circumstances, it is considered sufficient to provide protection against earth-faults only by the use of balanced earth-fault protection scheme. This scheme provides no protection against phase-to-phase faults, unless and until they develop into earth-faults, as most of them will.

Schematic arrangement. Fig. 22.6 shows the schematic arrangement of a balanced earth-fault protection for a 3-phase alternator. It consists of three line current transformers, one mounted in each phase, having their secondaries connected in parallel with that of a single current transformer in the conductor joining the star point of the alternator to earth. A relay is connected across the transformers secondaries. The protection against earth faults is limited to the region between the neutral and the line current transformers.

Operation. Under normal operating conditions, the currents flowing in the alternator leads and hence the currents flowing in secondaries of the line current transformers add to zero and no current flows through the relay. Also under these conditions, the current in the neutral wire is zero and the secondary of neutral current transformer supplies no current to the relay.

If an earth-fault develops at F_2 external to the protected zone, the sum of the currents at the terminals of the alternator is exactly equal to the current in the neutral connection and hence no

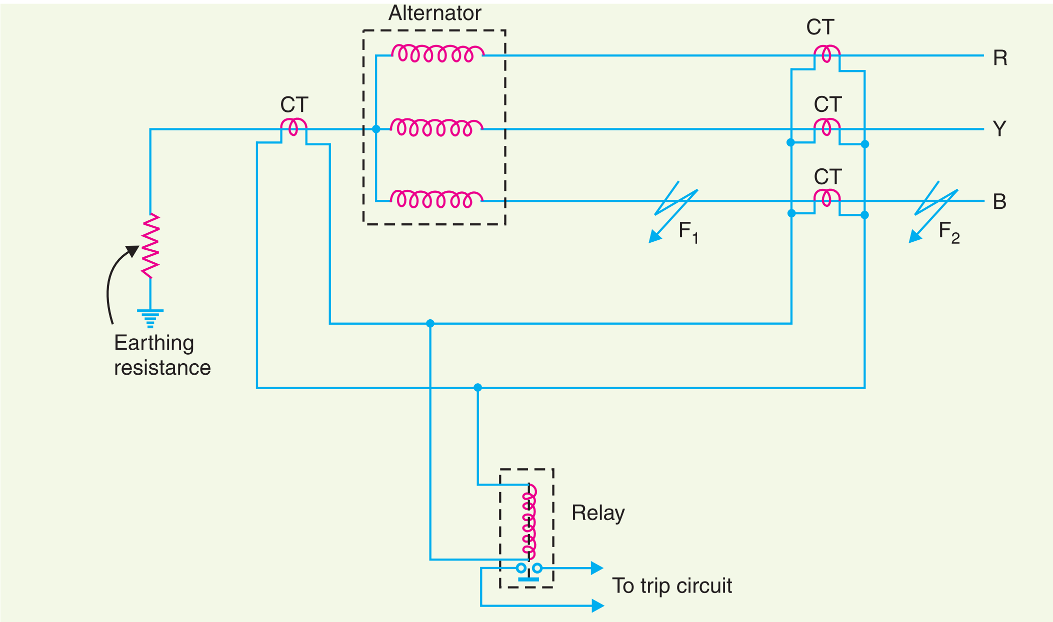

Fig. 22.6

current flows through the relay. When an earth-fault occurs at F_1 or within the protected zone, these currents are no longer equal and the differential current flows through the operating coil of the relay. The relay then closes its contacts to disconnect the alternator from the system.

22.5 Stator Inter-turn Protection

Merz-price circulating-current system protects against phase-to-ground and phase-to-phase faults. It does not protect against turn-to-turn fault on the same phase winding of the stator. It is because the current that this type of fault produces flows in a local circuit between the turns involved and does not create a difference between the currents entering and leaving the winding at its two ends where current transformers are applied. However, it is usually considered unnecessary to provide protection for inter-turn faults because they invariably develop into earth-faults.

In single turn generator (*e.g.* large steam-turbine generators), there is no necessity of protection against inter-turn faults. However, inter-turn protection is provided for multi-turn generators such as hydro-electric generators. These generators have double-winding armatures (*i.e.* each phase wind-

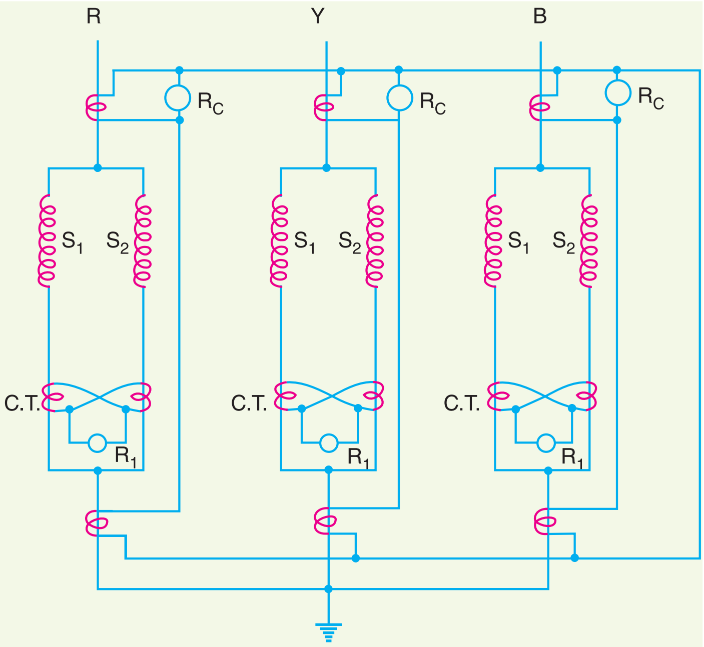

Fig. 22.7

ing is divided into two halves) owing to the very heavy currents which they have to carry. Advantage may be taken of this necessity to protect inter-turn faults on the same winding. Fig. 22.7 shows the schematic arrangement of circulating-current and inter-turn protection of a 3-phase double wound generator. The relays R_C provide protection against phase-to-ground and phase-to-phase faults whereas relays R_1 provide protection against inter-turn faults.

Fig. 22.8 shows the duplicate stator windings S_1 and S_2 of one phase only with a provision against inter-turn faults. Two current transformers are connected on the circulating-current principle. Under normal conditions, the currents in the stator windings S_1 and S_2 are equal and so will be the currents in the secondaries of the two CTs. The secondary current round the loop then is the same at all points and no current flows through the relay R_1. If a short-circuit develops between adjacent turns, say on S_1, the currents in the stator windings S_1 and S_2 will no longer be equal. Therefore, unequal currents will be induced in the secondaries of CTs and the difference of these two currents flows through the relay R_1. The relay then closes its contacts to clear the generator from the system.

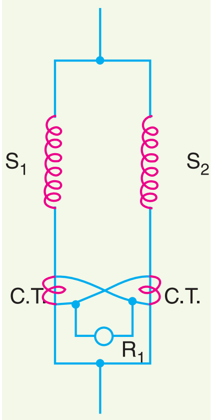

Fig. 22.8

Example 22.1. *A star-connected, 3-phase, 10-MVA, 6·6 kV alternator has a per phase reactance of 10%. It is protected by Merz-Price circulating-current principle which is set to operate for fault currents not less than 175 A. Calculate the value of earthing resistance to be provided in order to ensure that only 10% of the alternator winding remains unprotected.*

Solution. Let r ohms be the earthing resistance required to leave 10% of the winding unprotected (portion NA). The whole arrangement is shown in the simplified diagram of Fig. 22.9.

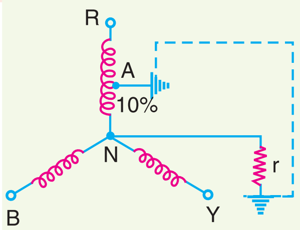

Fig. 22.9

$$\text{Voltage per phase, } V_{ph} = \frac{6 \cdot 6 \times 10^3}{\sqrt{3}} = 3810 \text{ V}$$

$$\text{Full-load current, } I = \frac{10 \times 10^6}{\sqrt{3} \times 6 \cdot 6 \times 10^3} = 875 \text{ A}$$

Let the reactance per phase be x ohms.

$$\therefore \quad 10 = \frac{\sqrt{3} \times x \times 875}{6600} \times 100$$

or $\quad x = 0{\cdot}436\ \Omega$

$$\text{Reactance of 10\% winding} = 0{\cdot}436 \times 0{\cdot}1 = 0{\cdot}0436\ \Omega$$

$$\text{E.M.F. induced in 10\% winding} = V_{ph} \times 0{\cdot}1 = 3810 \times 0{\cdot}1 = 381 \text{ V}$$

Impedance offered to fault by 10% winding is

$$Z_f = \sqrt{(0 \cdot 0436)^2 + r^2}$$

Earth-fault current due to 10% winding

$$= \frac{381}{Z_f} = \frac{381}{\sqrt{(0 \cdot 0436)^2 + r^2}}$$

When this fault current becomes 175 A, the relay will trip.

$$\therefore \quad 175 = \frac{381}{\sqrt{(0 \cdot 0436)^2 + r^2}}$$

or $$(0{\cdot}0436)^2 + r^2 = \left(\frac{381}{175}\right)^2$$

or $(0{\cdot}0436)^2 + r^2 = 4{\cdot}715$

or $r = \mathbf{2{\cdot}171\ \Omega}$

Example 22.2. *A star-connected, 3-phase, 10 MVA, 6·6 kV alternator is protected by Merz-Price circulating-current principle using 1000/5 amperes current transformers. The star point of the alternator is earthed through a resistance of 7·5 Ω. If the minimum operating current for the relay is 0·5 A, calculate the percentage of each phase of the stator winding which is unprotected against earth-faults when the machine is operating at normal voltage.*

Solution. Let x % of the winding be unprotected.

Earthing resistance, $r = 7{\cdot}5\ \Omega$

Voltage per phase, $V_{ph} = 6{\cdot}6 \times 10^3/\sqrt{3} = 3810$ V

Minimum fault current which will operate the relay

$$= \frac{1000}{5} \times 0{\cdot}5 = 100 \text{ A}$$

E.M.F. induced in x% winding $= V_{ph} \times (x/100) = 3810 \times (x/100) = 38{\cdot}1\,x$ volts

Earth fault current which x% winding will cause

$$= \frac{38{\cdot}1\,x}{r} = \frac{38{\cdot}1\,x}{7{\cdot}5} \text{ amperes}$$

This current must be equal to 100 A.

$$\therefore \quad 100 = \frac{38{\cdot}1\,x}{7{\cdot}5}$$

or Unprotected winding, $x = \dfrac{100 \times 7{\cdot}5}{38{\cdot}1} = \mathbf{19{\cdot}69\%}$

Hence 19·69% of alternator winding is left unprotected.

Example 22.3. *A 10 MVA, 6·6 kV, 3-phase star-connected alternator is protected by Merz-Price circulating current system. If the ratio of the current transformers is 1000/5, the minimum operating current for the relay is 0·75 A and the neutral point earthing resistance is 6 Ω, calculate :*

(*i*) *the percentage of each of the stator windings which is unprotected against earth faults when the machine is operating at normal voltage.*

(*ii*) *the minimum resistance to provide protection for 90% of the stator winding.*

Solution. Fig. 22.10 shows the circuit diagram.

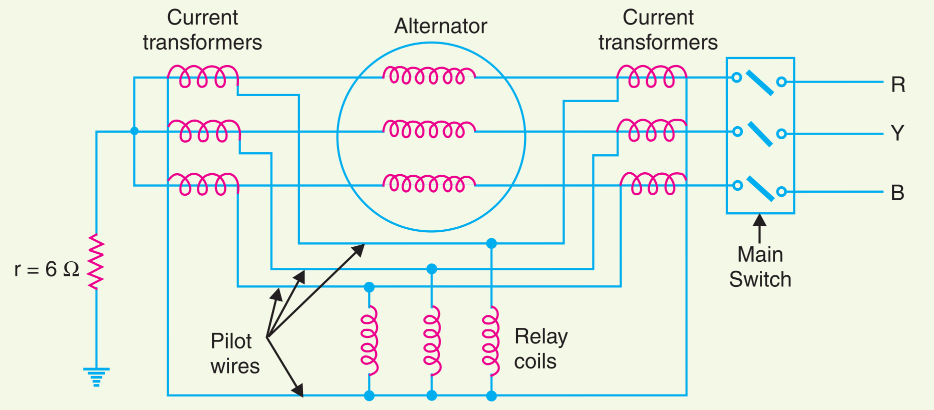

Fig. 22.10

(*i*) Let x% of the winding be unprotected.

Earthing resistance, $r = 6\,\Omega$

Voltage per phase, $V_{ph} = 6{\cdot}6 \times 10^3/\sqrt{3} = 3810$ volts

Minimum fault current which will operate the relay

$$= \frac{1000}{5} \times 0{\cdot}75 = 150 \text{ A}$$

E.M.F. induced in x% of stator winding

$$= V_{ph} \times (x/100) = 3810 \times (x/100) = 38{\cdot}1\,x \text{ volts}$$

Earth fault current which x% winding will cause

$$= \frac{38{\cdot}1\,x}{r} = \frac{38{\cdot}1\,x}{6} \text{ amperes}$$

This must be equal to 150 A.

$$\therefore \quad 150 = \frac{38{\cdot}1\,x}{6}$$

or $x = $ **23·6%**

(*ii*) Let r ohms be the minimum earthing resistance required to provide protection for 90% of stator winding. Then 10% winding would be unprotected *i.e.* $x = 10\%$.

$$\therefore \quad 150 = \frac{38{\cdot}1\,x}{r}$$

or $r = \dfrac{38{\cdot}1\,x}{150} = \dfrac{38{\cdot}1 \times 10}{150} = $ **2·54 Ω**

Example 22.4. *A star-connected, 3-phase, 10 MVA, 6·6 kV alternator is protected by circulating current protection, the star point being earthed via a resistance r. Estimate the value of earthing resistor if 85% of the stator winding is protected against earth faults. Assume an earth fault setting of 20%. Neglect the impedance of the alternator winding.*

Solution. Since 85% winding is to be protected, 15% would be unprotected. Let r ohms be the earthing resistance required to leave 15% of the winding unprotected.

$$\text{Full-load current} = \frac{10 \times 10^6}{\sqrt{3} \times 6{\cdot}6 \times 10^3} = 876 \text{ A}$$

Minimum fault current which will operate the relay

= 20% of full-load current

$$= \frac{20}{100} \times 876 = 175 \text{ A}$$

Voltage induced in 15% of winding

$$= \frac{15}{100} \times \frac{6{\cdot}6 \times 10^3}{\sqrt{3}} = 330\sqrt{3} \text{ volts}$$

Earth fault current which 15% winding will cause

$$= \frac{330\sqrt{3}}{r}$$

This current must be equal to 175 A.

$$\therefore \quad 175 = \frac{330\sqrt{3}}{r}$$

or $r = \dfrac{330\sqrt{3}}{175} = $ **3·27 Ω**