

# Alternator Protection

## 6.1.1 Introduction:

The modern electric power system consists of several elements transformers, station bus bars, *e.g.* alternators, 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 most serious faults on alternators which require immediate attention are the stator winding faults. The major faults on transformers occur due to short-circuit 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.

## 6.1.2 Some of Important Faults in Alternator:

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

- (i) Failure of prime-mover
- (ii) Failure of field
- (iii) Over Current
- (iv) Over Speed
- (v) Over Voltage
- (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 condition 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.
- 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.

### **(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.

### **(v) Over-voltage:**

The field excitation system of modern alternators is so designed that overvoltage 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 over speed and thus prevent the occurrence of overvoltage 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

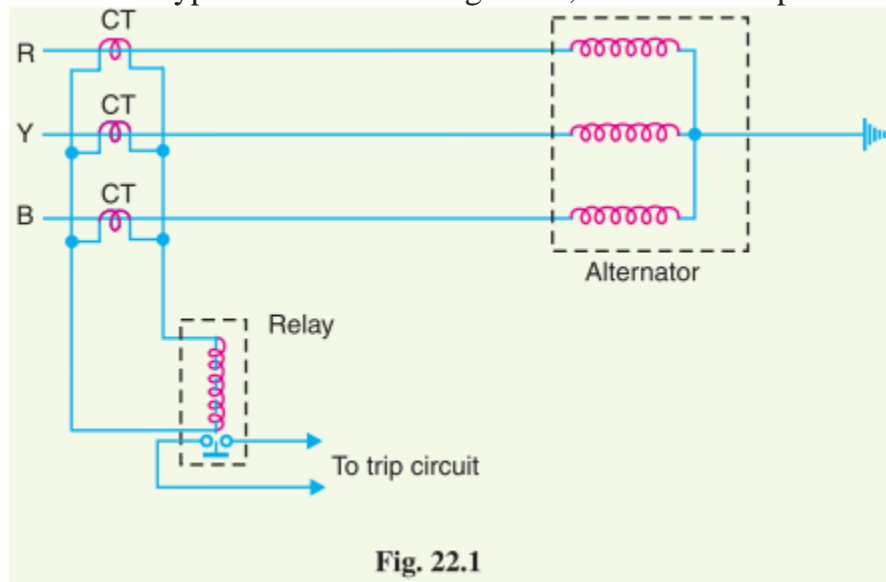
- (a) Trip the main circuit breaker to disconnect the faulty alternator from the system
- (b) disconnect the alternator field circuit

### (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.

### (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 minimize the extent of damage. For protection of alternators against such faults, differential method

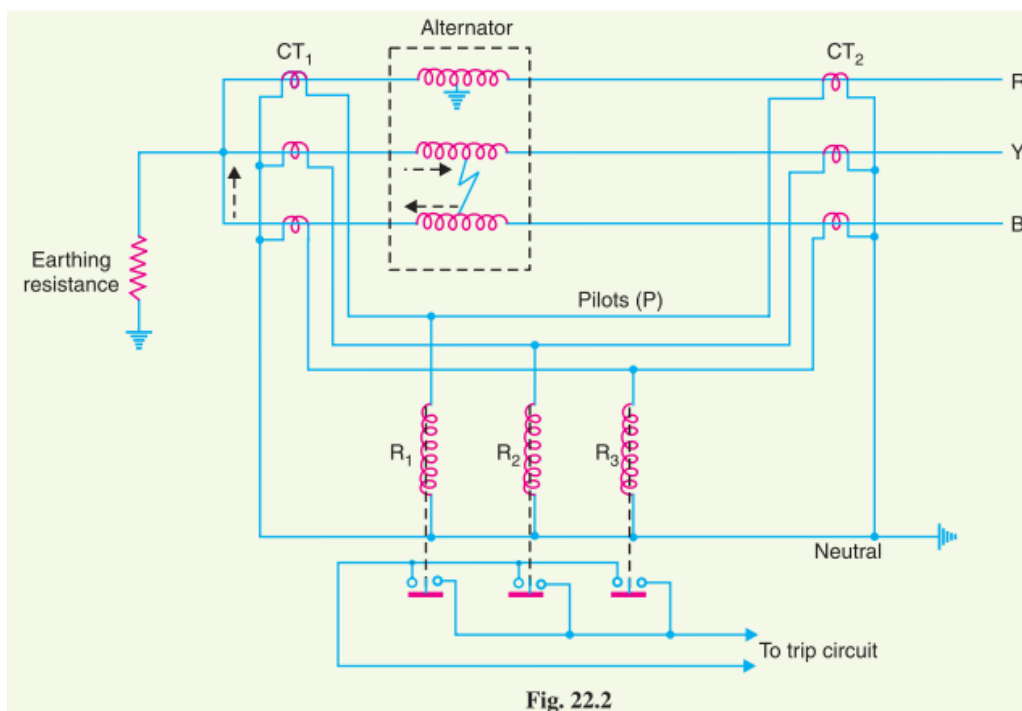
of protection (also known as Merz-Price system) is most commonly employed due to its greater sensitivity and reliability. This system of protection is discussed in the following section.

### 6.1.3 Differential Protection of Alternators:

The most common system used for the protection of stator winding faults employs circulating-current principle. 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:

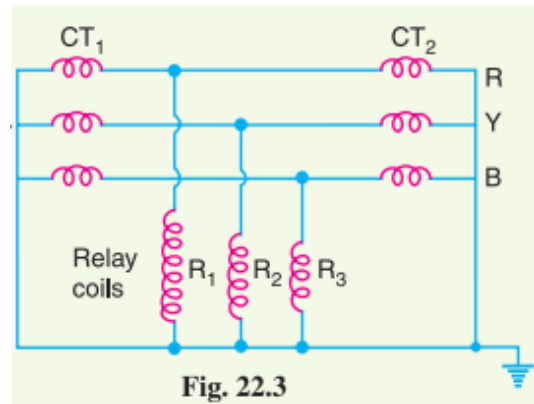
Fig. 22.2 shows the schematic arrangement of **current differential protection for a 3-phase alternator**. Identical current transformer pairs  $CT_1$  and  $CT_2$  are placed on either side of each phase of the stator windings. The secondaries of each set of current transformers are connected in star; 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  $P$ .



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.

### 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.



- (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.

### 6.1.3 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 earths 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.

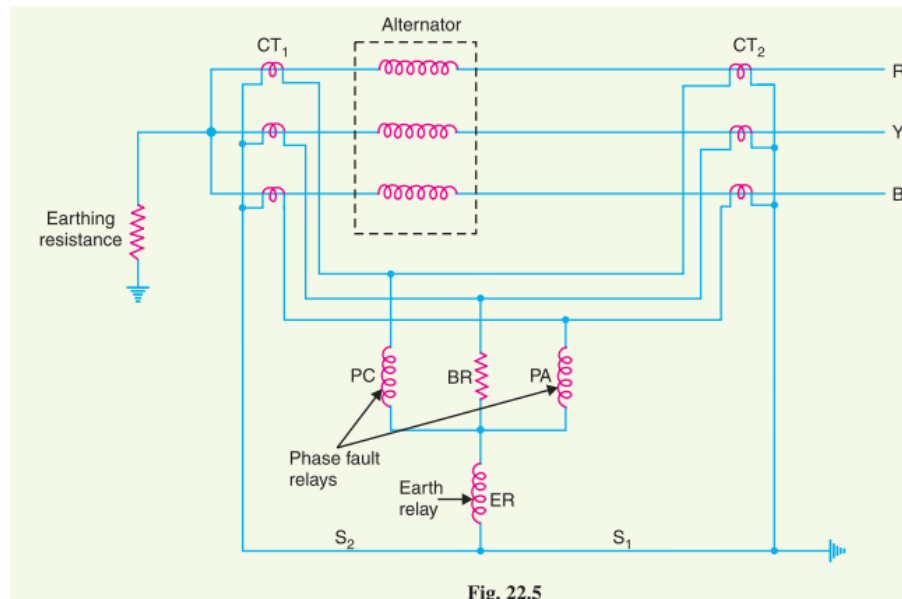


Fig. 22.5

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*<sub>1</sub> or *S*<sub>2</sub> 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 off-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.

## 6.1.4 Balanced Earth-fault Protection:

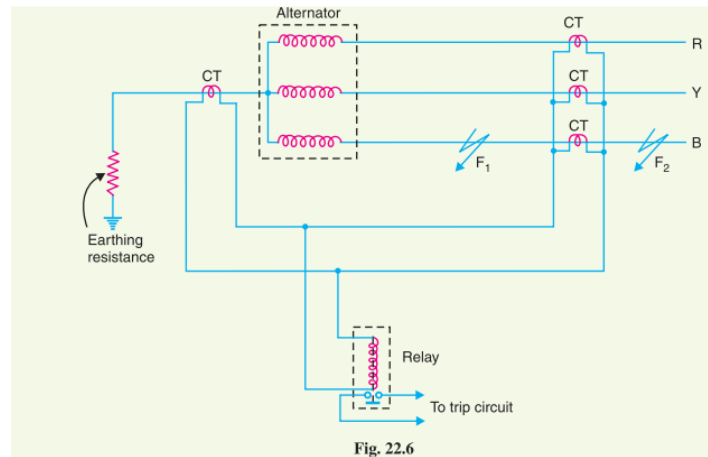
### Schematic arrangement.

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  $F2$  external to the protected zone,

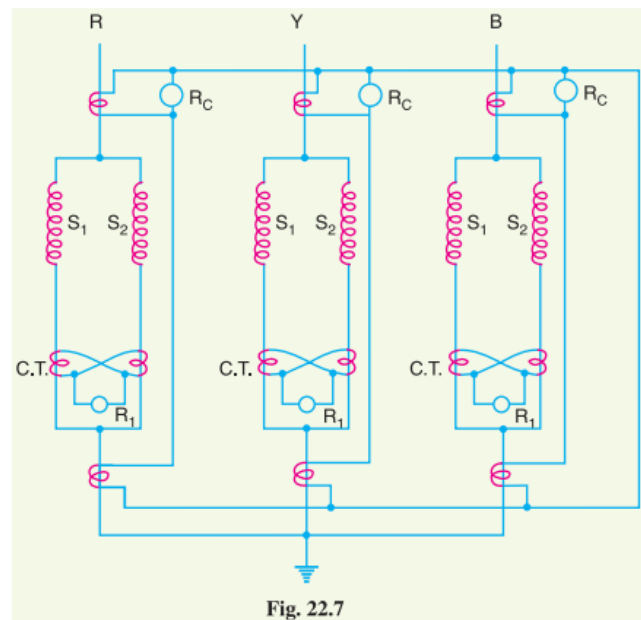
the sum of the currents at the terminals of the alternator is exactly equal to the current in the neutral connection and hence no current flows through the relay. When an earth-fault occurs at  $F1$  or within the protected zone, these currents are no longer equal and the differential current flows through the operating coil of the relay. The relay then closes its contacts to disconnect the alternator from the system.



### 6.1.5 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

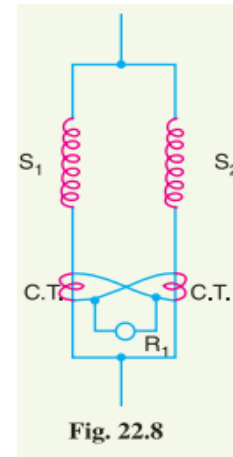
provided for multi-turn generators such as hydro-electric generators. These generators have double-winding armatures (i.e. each phase winding is divided into two halves) owing to the very heavy currents which they have to carry. Advantage may be taken of this necessity to protect inter-turn faults on 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  $RC$  provide protection against phase-to-ground and phase-to-phase faults whereas relays  $R1$  provide protection against inter-turn faults.

Fig. 22.8 shows the duplicate stator windings  $S1$  and  $S2$  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  $S1$  and  $S2$  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  $R1$ . If a short-circuit develops between adjacent turns, say on  $S1$ , the currents in the stator windings  $S1$  and  $S2$  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  $R1$ . The relay then closes its contacts to clear the generator from the system.



**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.

$$\text{Voltage per phase, } V_{ph} = \frac{6.6 \times 10^3}{\sqrt{3}} = 3810 \text{ V}$$

$$\text{Full-load current, } I = \frac{10 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3} = 875 \text{ A}$$

Let the reactance per phase be  $x$  ohms.

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

$$\text{or } x = 0.436 \, \Omega$$

$$\text{Reactance of 10\% winding} = 0.436 \times 0.1 = 0.0436 \, \Omega$$

$$\text{E.M.F. induced in 10\% winding} = V_{ph} \times 0.1 = 3810 \times 0.1 = 381 \text{ V}$$

Impedance offered to fault by 10% winding is

$$Z_f = \sqrt{(0.0436)^2 + r^2}$$

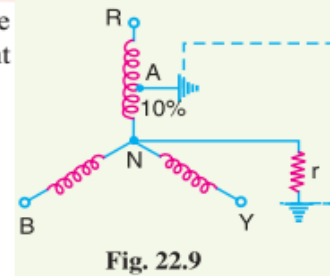
Earth-fault current due to 10% winding

$$= \frac{381}{Z_f} = \frac{381}{\sqrt{(0.0436)^2 + r^2}}$$

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

$$\therefore 175 = \frac{381}{\sqrt{(0.0436)^2 + r^2}}$$

$$\text{or } (0.0436)^2 + r^2 = \left( \frac{381}{175} \right)^2$$





or  
or

$$(0.0436)^2 + r^2 = 4.715$$

$$r = 2.171 \Omega$$

**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  $7.5 \Omega$ . 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,  $r = 7.5 \Omega$

Voltage per phase,  $V_{ph} = 6.6 \times 10^3 / \sqrt{3} = 3810 \text{ V}$

Minimum fault current which will operate the relay

$$= \frac{1000}{5} \times 0.5 = 100 \text{ A}$$

E.M.F. induced in  $x$ % winding =  $V_{ph} \times (x/100) = 3810 \times (x/100) = 38.1x$  volts

Earth fault current which  $x$ % winding will cause

$$= \frac{38.1x}{r} = \frac{38.1x}{7.5} \text{ amperes}$$

This current must be equal to 100 A.

$$\therefore 100 = \frac{38.1x}{7.5}$$

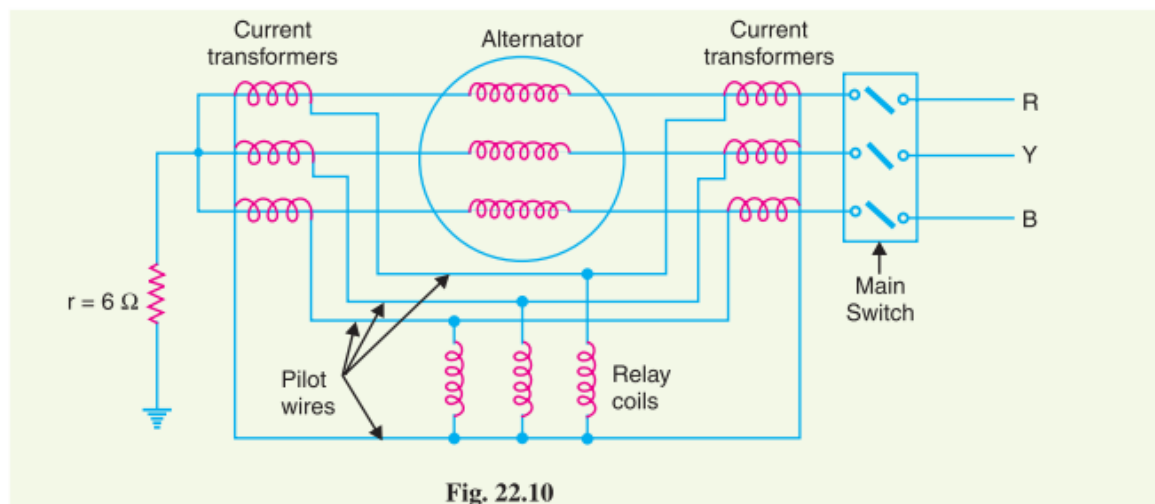
or Unprotected winding,  $x = \frac{100 \times 7.5}{38.1} = 19.69\%$

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  $6 \Omega$ , calculate :

- the percentage of each of the stator windings which is unprotected against earth faults when the machine is operating at normal voltage.
- the minimum resistance to provide protection for 90% of the stator winding.

**Solution.** Fig. 22.10 shows the circuit diagram.



- (i) Let  $x\%$  of the winding be unprotected.

Earthing resistance,  $r = 6 \Omega$

Voltage per phase,  $V_{ph} = 6.6 \times 10^3 / \sqrt{3} = 3810$  volts

Minimum fault current which will operate the relay

$$= \frac{1000}{5} \times 0.75 = 150 \text{ A}$$

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

$$= V_{ph} \times (x/100) = 3810 \times (x/100) = 38.1x \text{ volts}$$

Earth fault current which  $x\%$  winding will cause

$$= \frac{38.1x}{r} = \frac{38.1x}{6} \text{ amperes}$$

This must be equal to 150 A.

$$\therefore 150 = \frac{38.1x}{6}$$

$$\text{or } x = 23.6\%$$

- (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.  $x = 10\%$ .

$$\therefore 150 = \frac{38.1x}{r}$$

$$\text{or } r = \frac{38.1x}{150} = \frac{38.1 \times 10}{150} = 2.54 \Omega$$

**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.

$$\text{Full-load current} = \frac{10 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3} = 876 \text{ A}$$

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

$$= \frac{15}{100} \times \frac{6.6 \times 10^3}{\sqrt{3}} = 330\sqrt{3} \text{ volts}$$

Earth fault current which 15% winding will cause

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

This current must be equal to 175 A.

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

$$\text{or } r = \frac{330\sqrt{3}}{175} = 3.27 \Omega$$

## TUTORIAL PROBLEMS

1. A 10 MVA, 11 kV, 3-phase star-connected alternator is protected by the Merz-Price balance-current system, which operates when the out-of-balance current exceeds 20% of full-load current. Determine what portion of the alternating winding is unprotected if the star point is earthed through a resistance of  $9\ \Omega$ . The reactance of the alternator is  $2\ \Omega$ . **[14.88%]**
2. The neutral point of 25 MVA, 11 kV alternator is grounded through a resistance of  $5\ \Omega$ , the relay is set to operate when there is an out of balance current of 2A. The CTs used have a ratio of 1000/5. Calculate (neglect reactance of alternator) :
  - (i) the percentage of stator winding protected against an earth fault
  - (ii) the minimum value of earthing resistance to protect 95% of the winding **[(i) 68.5% (ii)  $0.8\ \Omega$ ]**
3. A 3-phase, 20 MVA, 11kV star connected alternator is protected by Merz-Price circulating current system. The star point is earthed through a resistance of 5 ohms. If the CTs have a ratio of 1000/5 and the relay is set to operate when there is an out of balance current of 1.5 A, calculate :
  - (i) the percentage of each phase of the stator winding which is unprotected
  - (ii) the minimum value of earthing resistance to protect 90% of the winding **[(i) 23.6% (ii)  $2.12\ \Omega$ ]**