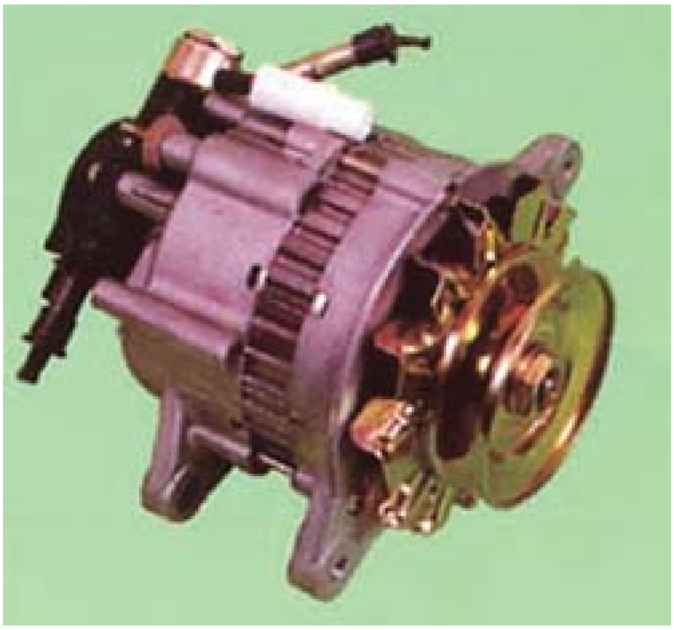
CHAPTER

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.

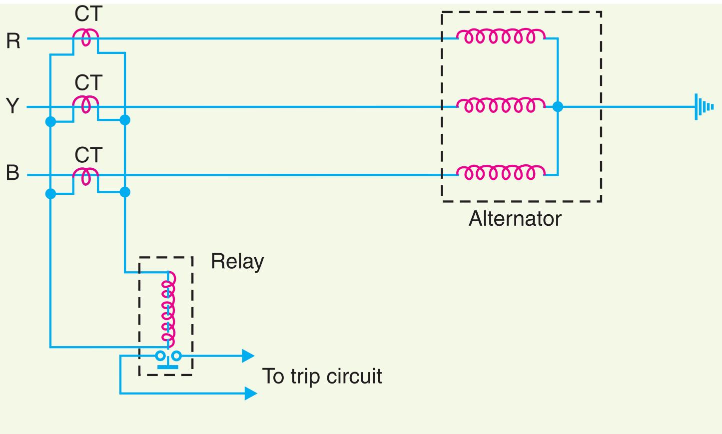

Fig. 22.1

(*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*.

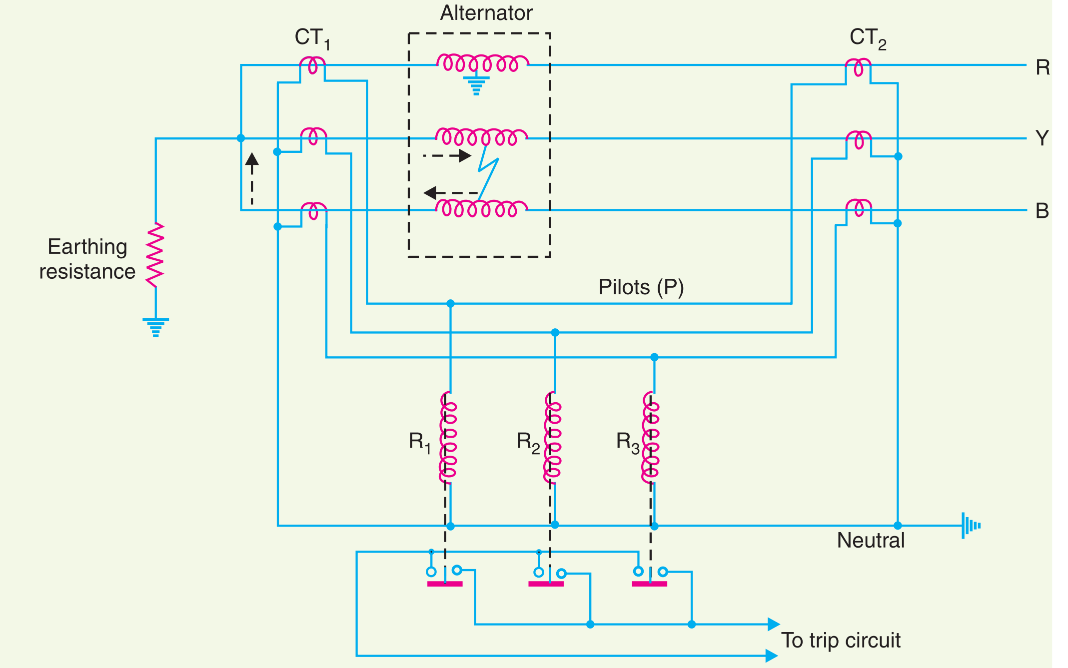

Fig. 22.2

* 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.

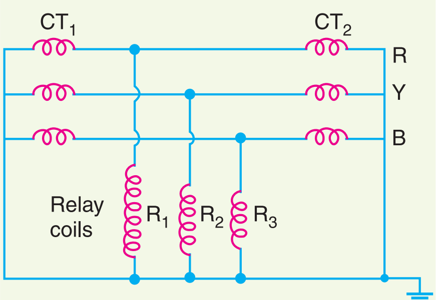

Fig. 22.3

(*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

* 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.

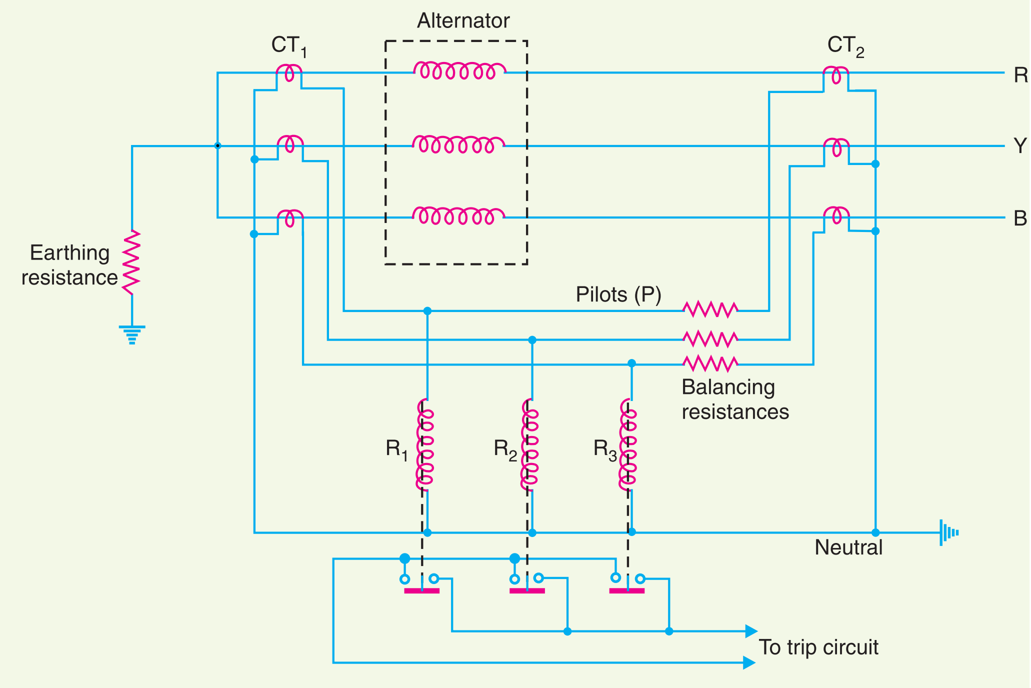

Fig. 22.4

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.

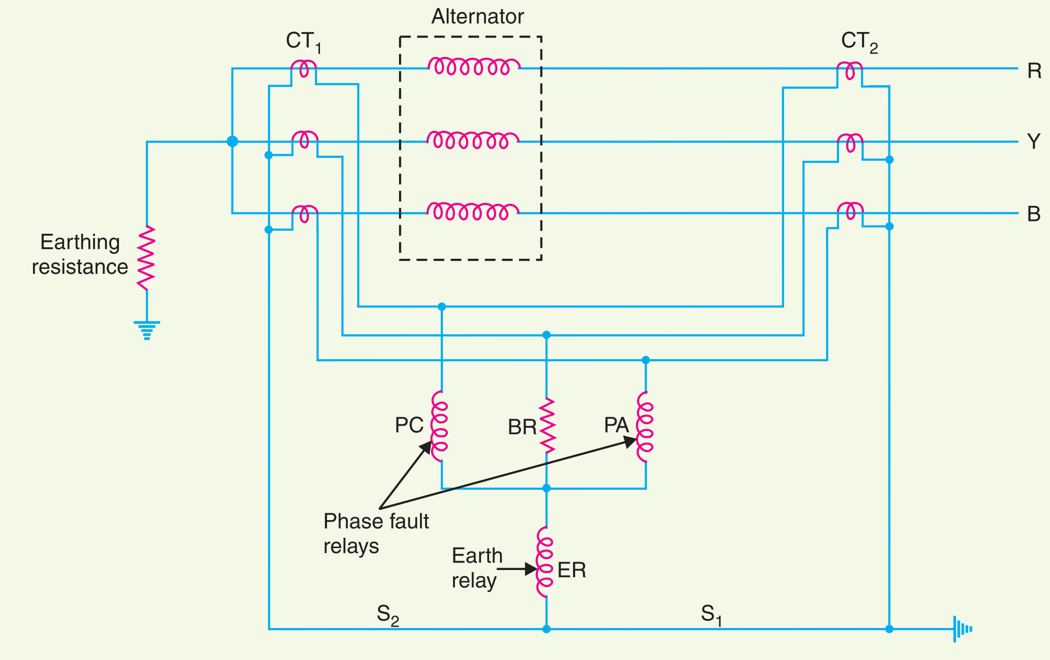

Fig. 22.5

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

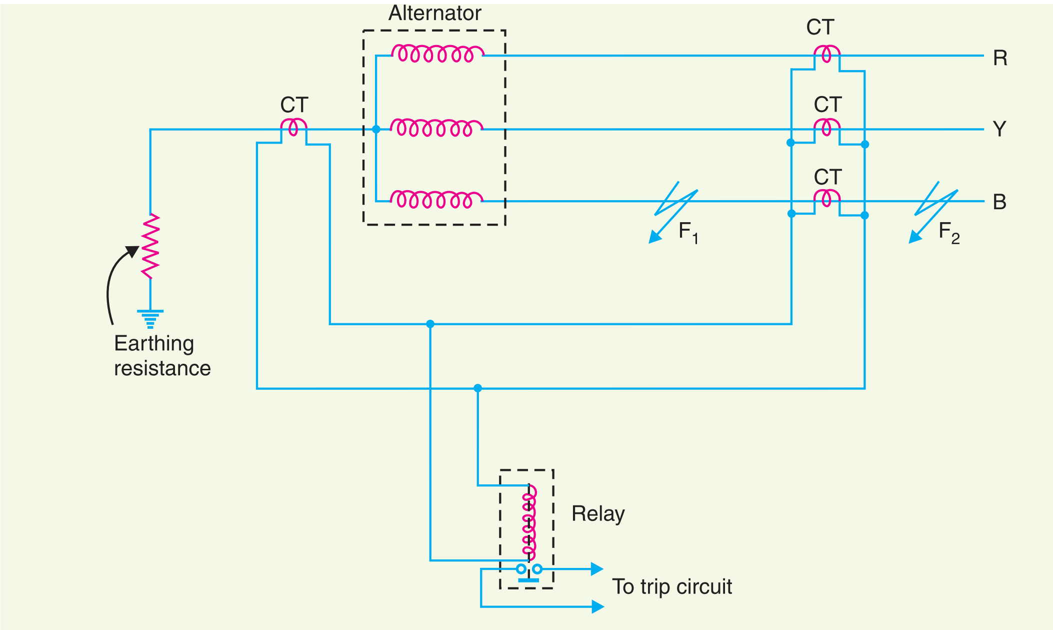

Fig. 22.6

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-

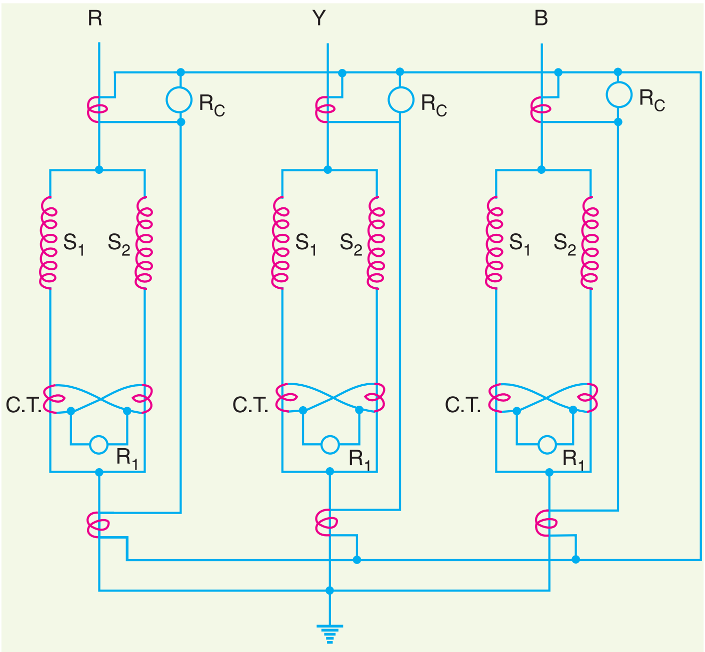

Fig. 22.7

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.

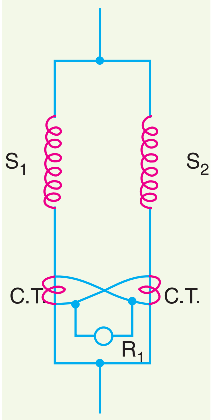

Fig. 22.8

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.

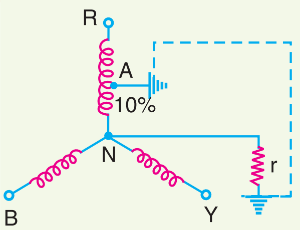

Fig. 22.9

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

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

Let the reactance per phase be x ohms.

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

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

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

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

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.

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

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

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

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

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, $\qquad r = 7{\cdot}5\ \Omega$

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

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

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

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.

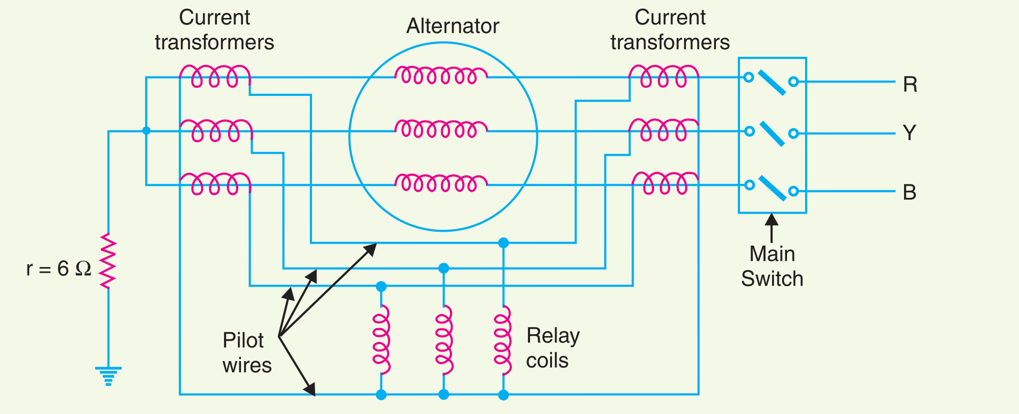

Fig. 22.10

(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.* $x = 10\%$.

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

$$\text{or} \quad r = \frac{38{\cdot}1\,x}{150} = \frac{38{\cdot}1 \times 10}{150} = \mathbf{2{\cdot}54\ \Omega}$$

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.

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

Minimum fault current which will operate the relay

$$= 20\% \text{ of full-load current}$$

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

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.

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

$$\text{or} \quad r = \frac{330\sqrt{3}}{175} = \mathbf{3{\cdot}27\ \Omega}$$

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 Ω. The reactance of the alternator is 2 Ω. **[14·88%]**

2. The neutral point of 25 MVA, 11 kV alternator is grounded through a resistance of 5 Ω, 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 Ω]**

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 Ω]**

22.6 Protection of Transformers

Transformers are static devices, totally enclosed and generally oil immersed. Therefore, chances of faults occurring on them are very rare. However, the consequences of even a rare fault may be very serious unless the transformer is quickly disconnected from the system. This necessitates to provide adequate automatic protection for transformers against possible faults.

Small distribution transformers are usually connected to the supply system through series fuses instead of circuit breakers. Consequently, no automatic protective relay equipment is required. However, the probability of faults on power transformers is undoubtedly more and hence automatic protection is absolutely necessary.

Common transformer faults. As compared with generators, in which many abnormal conditions may arise, power transformers may suffer only from :

(*i*) open circuits
(*ii*) overheating
(*iii*) winding short-circuits *e.g.* earth-faults, phase-to-phase faults and inter-turn faults.

An open circuit in one phase of a 3-phase transformer may cause undesirable heating. In practice, relay protection is not provided against open circuits because this condition is relatively harmless. On the occurrence of such a fault, the transformer can be disconnected manually from the system.

Overheating of the transformer is usually caused by sustained overloads or short-circuits and very occasionally by the failure of the cooling system. The relay protection is also not provided against this contingency and thermal accessories are generally used to sound an alarm or control the banks of fans.

Winding short-circuits (also called *internal faults*) on the transformer arise from deterioration of winding insulation due to overheating or mechanical injury. When an internal fault occurs, the transformer must be disconnected quickly from the system because a prolonged arc in the transformer may cause oil fire. Therefore, relay protection is absolutely necessary for internal faults.

22.7 Protection Systems for Transformers

For protection of generators, Merz-Price circulating-current system is unquestionably the most satisfactory. Though this is largely true of transformer protection, there are cases where circulating current system offers no particular advantage over other systems or impracticable on account of the troublesome conditions imposed by the wide variety of voltages, currents and earthing conditions invariably associated with power transformers. Under such circumstances, alternative protective systems are used which in many cases are as effective as the circulating-current system. The principal relays and systems used for transformer protection are :

(*i*) *Buchholz devices* providing protection against all kinds of incipient faults *i.e.* slow-developing faults such as insulation failure of windings, core heating, fall of oil level due to leaky joints etc.

(*ii*) *Earth-fault relays* providing protection against earth-faults only.

(*iii*) *Overcurrent relays* providing protection mainly against phase-to-phase faults and overloading.

(*iv*) *Differential system* (or circulating-current system) providing protection against both earth and phase faults.

The complete protection of transformer usually requires the combination of these systems. Choice of a particular combination of systems may depend upon several factors such as (*a*) size of the transformer (*b*) type of cooling (*c*) location of transformer in the network (*d*) nature of load supplied and (*e*) importance of service for which transformer is required. In the following sections, above systems of protection will be discussed in detail.

22.8 Buchholz Relay

Buchholz relay is a gas-actuated relay installed in oil immersed transformers for protection against all kinds of faults. Named after its inventor, Buchholz, it is used to give an alarm in case of incipient (*i.e.* slow-developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults. It is usually installed in the pipe connecting the conservator to the main tank as shown in Fig. 22.11. It is a universal practice to use Buchholz relays on all such oil immersed transformers having ratings in *excess of 750 kVA.

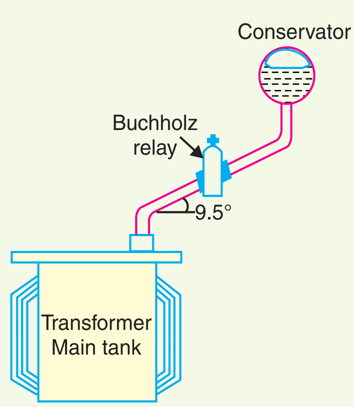

Fig. 22.11

Buchholz Relay

Construction. Fig. 22.12 shows the constructional details of a Buchholz relay. It takes the form of a domed vessel placed in the connecting pipe between the main tank and the conservator. The device has two elements. The upper element consists of a mercury type switch attached to a float. The lower element contains a mercury switch mounted on a hinged type flap located in the direct path of the flow of oil from the transformer to the conservator. The upper element closes an alarm circuit during incipient faults whereas the lower element is arranged to trip the circuit breaker in case of severe internal faults.

Operation. The operation of Buchholz relay is as follows :

(*i*) In case of incipient faults within the transformer, the heat due to fault causes the decomposition of some transformer oil in the main tank. The products of decomposition contain more than 70% of hydrogen gas. The hydrogen gas being light tries to go into the conserva-

* Its use for oil immersed transformers of rating less than 750 kVA is generally uneconomical.

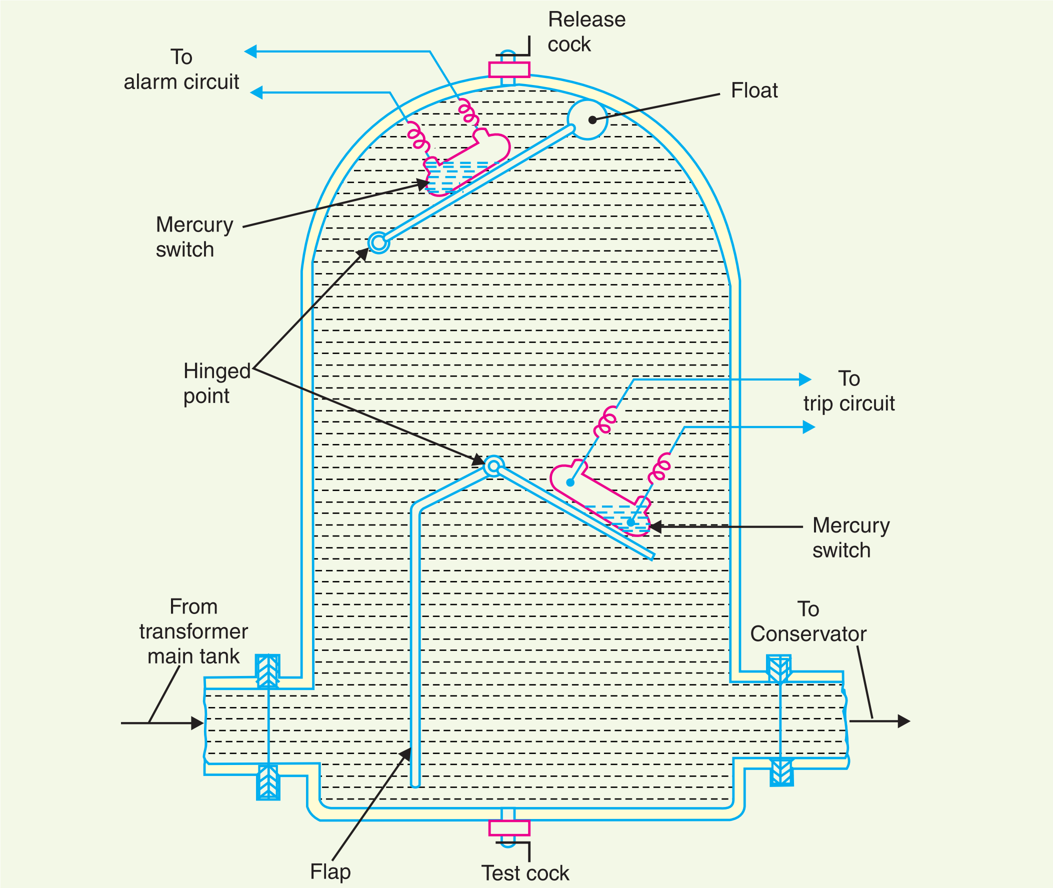

Fig. 22.12

tor and in the process gets entrapped in the upper part of relay chamber. When a predetermined amount of gas gets accumulated, it exerts sufficient pressure on the float to cause it to tilt and close the contacts of mercury switch attached to it. This completes the alarm circuit to sound an *alarm.

(ii) If a serious fault occurs in the transformer, an enormous amount of gas is generated in the main tank. The oil in the main tank rushes towards the conservator *via* the Buchholz relay and in doing so tilts the flap to close the contacts of mercury switch. This completes the trip circuit to open the circuit breaker controlling the transformer.

Advantages

(i) It is the simplest form of transformer protection.

(ii) It detects the incipient faults at a stage much earlier than is possible with other forms of protection.

Disadvantages

(i) It can only be used with oil immersed transformers equipped with conservator tanks.

(ii) The device can detect only faults below oil level in the transformer. Therefore, separate protection is needed for connecting cables.

---

* The conditions described do not call for the immediate removal of the faulty transformer. It is because sometimes the air bubbles in the oil circulation system of a healthy transformer may operate the float. For this reason, float is arranged to sound an alarm upon which steps can be taken to verify the gas and its composition.

22.9 Earth-Fault or Leakage Protection

An earth-fault usually involves a partial breakdown of winding insulation to earth. The resulting leakage current is considerably less than the short-circuit current. The earth-fault may continue for a long time and cause considerable damage before it ultimately develops into a short-circuit and removed from the system. Under these circumstances, it is profitable to employ earth-fault relays in order to ensure the disconnection of earth-fault or leak in the early stage. An earth-fault relay is essentially an overcurrent relay of low setting and operates as soon as an earth-fault or leak develops. One method of protection against earth-faults in a transformer is the **core-balance leakage protection* shown in Fig. 22.13.

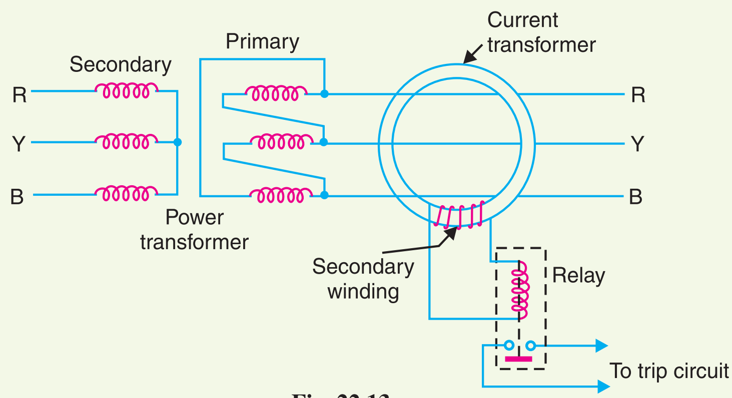

Fig. 22.13

The three leads of the primary winding of power transformer are taken through the core of a current transformer which carries a single secondary winding. The operating coil of a relay is connected to this secondary. Under normal conditions (*i.e.* no fault to earth), the vector sum of the three phase currents is zero and there is no resultant flux in the core of current transformer no matter how much the load is out of balance. Consequently, no current flows through the relay and it remains inoperative. However, on the occurrence of an earth-fault, the vector sum of three phase currents is no longer zero. The resultant current sets up flux in the core of the C.T. which induces e.m.f. in the secondary winding. This energises the relay to trip the circuit breaker and disconnect the faulty transformer from the system.

Earth Leakage Relay

22.10 Combined Leakage and Overload Protection

The core-balance protection described above suffers from the drawback that it cannot provide protection against overloads. If a fault or leakage occurs between phases, the core-balance relay will not operate. It is a usual practice to provide combined leakage and overload protection for transformers. The earth relay has low current setting and operates under earth or leakage faults only. The overload relays have high current setting and are arranged to operate against faults between the phases.

---

* An earth-fault relay is also described as a core-balance relay. Strictly the term 'core-balance' is reserved for the case in which the relay is energised by a 3-phase current transformer and the balance is between the fluxes in the core of the current transformer.

Fig. 22.14 shows the schematic arrangement of combined leakage and overload protection. In this system of protection, two overload relays and one leakage or earth relay are connected as shown. The two overload relays are sufficient to protect against phase-to-phase faults. The trip contacts of overload relays and earth-fault relay are connected in parallel. Therefore, with the energising of either overload relay or earth relay, the circuit breaker will be tripped.

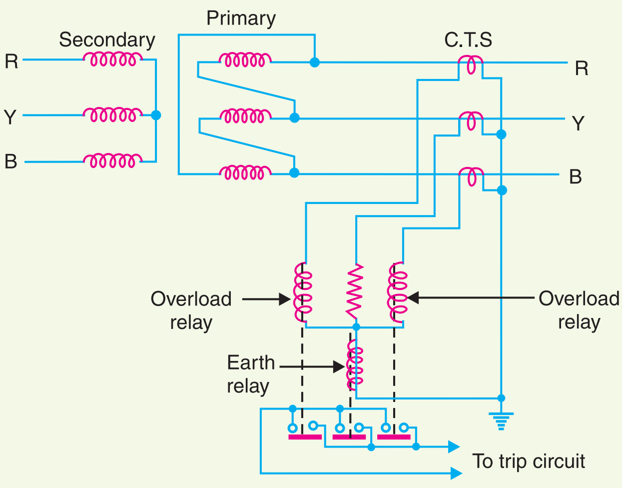

Fig. 22.14

22.11 Applying Circulating-current System to Transformers

Merz-Price circulating -current principle is commonly used for the protection of power transformers against earth and phase faults. The system as applied to transformers is fundamentally the same as that for generators but with certain complicating features not encountered in the generator application. The complicating features and their remedial measures are briefed below :

(*i*) In a power transformer, currents in the primary and secondary are to be compared. As these two currents are usually different, therefore, the use of identical transformers (of same turn ratio) will give differential current and operate the relay even under no load conditions.

The difference in the magnitude of currents in the primary and secondary of power transformer is compensated by different turn ratios of CTs. If T is the turn-ratio of power transformer, then turn-ratio of CTs on the *l.v.* side is made T times that of the CTs on the *h.v.* side. Fulfilled this condition, the secondaries of the two CTs will carry identical currents under normal load conditions. Consequently, no differential current will flow through the relay and it remains inoperative.

(*ii*) There is usually a phase difference between the primary and secondary currents of a 3-phase power transformer. Even if CTs of the proper turn-ratio are used, a differential current may flow through the relay under normal conditions and cause relay operation.

The correction for phase difference is effected by appropriate connections of CTs. The CTs on one side of the power transformer are connected in such a way that the resultant currents fed into the pilot wires are displaced in phase from the individual phase currents in the same direction as, and by an angle equal to, the phase shift between the power-transformers primary and secondary currents. The table below shows the type of connections to be employed for CTs in order to compensate for the phase difference in the primary and secondary currents of power transformer.

S. No.	Power transformer connections		Current transformer connections	
	Primary	Secondary	Primary	Secondary
1	Star with neutral earthed	Delta	Delta	Star
2	Delta	Delta	Star	Star
3	Star	Star with neutral earthed	Delta	Delta
4	Delta	Star with neutral earthed	Star	Delta

Thus referring to the above table, for a delta/star power transformer, the CTs on the delta side must be connected in star and those on the star side in delta.

(*iii*) Most transformers have means for tap changing which makes this problem even more difficult. Tap changing will cause differential current to flow through the relay even under normal operating conditions.

The above difficulty is overcome by adjusting the turn-ratio of CTs on the side of the power transformer provided with taps.

(*iv*) Another complicating factor in transformer protection is the magnetising in-rush current. Under normal load conditions, the magnetising current is very small. However, when a transformer is energised after it has been taken out of service, the magnetising or in-rush current can be extremely high for a short period. Since magnetising current represents a current going into the transformer without a corresponding current leaving, it appears as a fault current to differential relay and may cause relay operation.

In order to overcome above difficulty, differential relays are set to operate at a relatively high degree of unbalance. This method decreases the sensitivity of the relays. In practice, advantage is taken of the fact that the initial in-rush currents contain prominent second-harmonic component. Hence, it is possible to design a scheme employing second-harmonic bias features, which, being tuned to second-harmonic frequency only, exercise restrain during energising to prevent maloperation.

While applying circulating current principle for protection of transformers, above precautions are necessary in order to avoid inadvertent relay operation.

22.12 Circulating-Current Scheme for Transformer Protection

Fig. 22.15 shows Merz-Price circulating-current scheme for the protection of a 3-phase delta/delta power transformer against phase-to-ground and phase-to-phase faults. Note that *CT*s on the two sides of the transformer are connected in star. This compensates for the phase difference between the power transformer primary and secondary. The *CT*s on the two sides are connected by pilot wires and one relay is used for each pair of *CT*s.

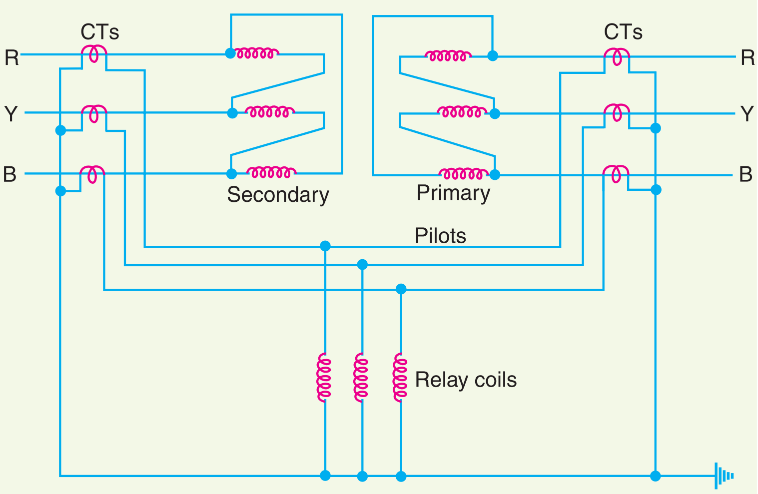

Fig. 22.15

During normal operating conditions, the secondaries of *CT*s carry identical currents. Therefore, the currents entering and leaving the pilot wires at both ends are the same and no current flows through the relays. If a ground or phase-to-phase fault occurs, the currents in the secondaries of *CT*s will no longer be the same and the differential current flowing through the relay circuit will clear the breaker on both sides of the transformer. The-protected zone is limited to the region between *CT*s on the high-voltage side and the *CT*s on the low-voltage side of the power transformer.

It is worthwhile to note that this scheme also provides protection for short-circuits between turns on the same phase winding. When a short-circuit occurs between the turns, the turn-ratio of the power transformer is altered and causes unbalance between current transformer pairs. If turn-ratio of power transformer is altered sufficiently, enough differential current may flow through the relay to cause its operation. However, such short-circuits are better taken care of by Buchholz relays.

Example 22.5. *A 3-phase transformer of 220/11,000 line volts is connected in star/delta. The protective transformers on 220 V side have a current ratio of 600/5. What should be the CT ratio on 11,000 V side ?*

Solution. For star/delta power transformers, *CT*s will be connected in delta on 220 V side (*i.e.* star side of power transformer) and in star on 11,000 V side (*i.e.* delta side of power transformer) as shown in Fig. 22.16.

Suppose that line current on 220 V side is 600 A.

∴ Phase current of delta connected *CT*s on 220V side

$$= 5 \text{ A}$$

Line current of delta connected *CT*s on 220 V side

$$= 5 \times \sqrt{3} = 5\sqrt{3} \text{ A}$$

This current (*i.e.* $5\sqrt{3}$) will flow through the pilot wires. Obviously, this will be the current which flows through the secondary of *CT*s on the 11,000 V side.

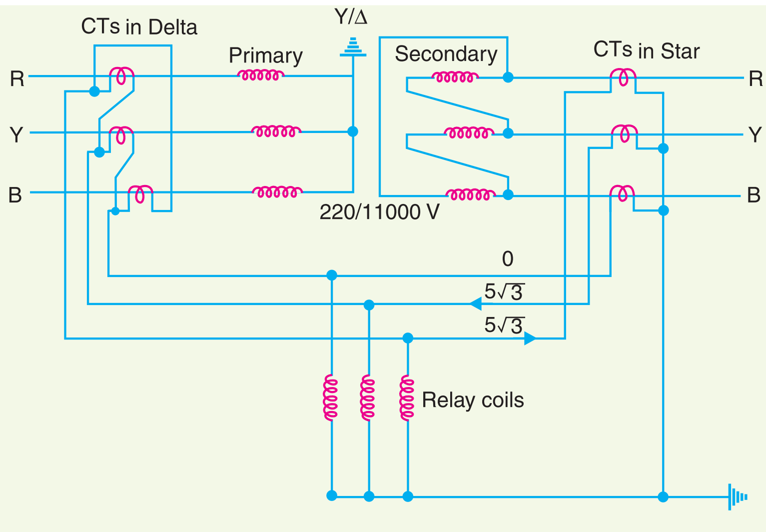

Fig. 22.16

∴ Phase current of star connected *CT*s on 11,000 V side = $5\sqrt{3}$ A

If *I* is the line current on 11,000 V side, then,

$$\text{Primary apparent power} = \text{Secondary apparent power}$$

or $$\sqrt{3} \times 220 \times 600 = \sqrt{3} \times 11{,}000 \times I$$

or $$I = \frac{\sqrt{3} \times 220 \times 600}{\sqrt{3} \times 11000} = 12 \text{ A}$$

∴ Turn-ratio of *CT*s on 11000 V side

$$= 12 : 5\sqrt{3} = \mathbf{1{\cdot}385 : 1}$$

Example 22.6. *A 3-phase transformer having line-voltage ratio of 0·4 kV/11kV is connected in star-delta and protective transformers on the 400 V side have a current ratio of 500/5. What must be the ratio of the protective transformers on the 11 kV side ?*

Solution. Fig. 22.17 shows the circuit connections. For star/delta transformers, *CTs* will be connected in delta on 400 V side (*i.e.* star side of power transformer) and in star on 11,000 V side (*i.e.* delta side of power transformer).

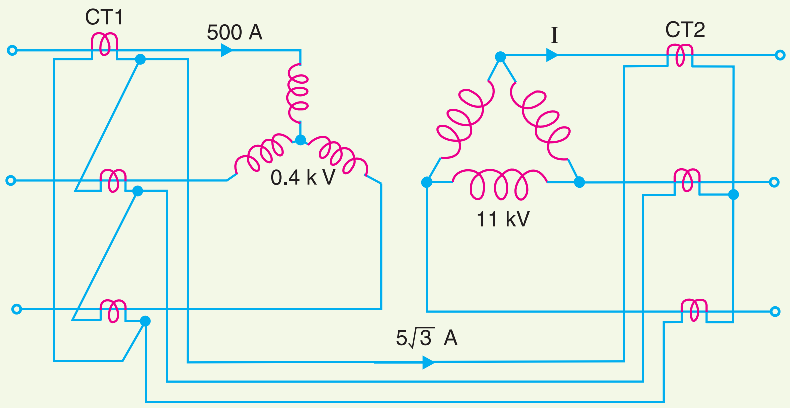

Fig. 22.17

Suppose the line current on 400 V side is 500 A.

∴ Phase current of delta connected *CTs* on 400 V side

$$= 5 \text{ A}$$

Line current of delta connected *CTs* on 400 V side

$$= 5 \times \sqrt{3} = 5\sqrt{3} \text{ A}$$

This current (*i.e.* $5\sqrt{3}$ A) will flow through the pilot wires. Obviously, this will be the current which flows through the secondary of the *CTs* on 11000 V side.

∴ Phase current of star-connected *CTs* on 11000 V side

$$= 5\sqrt{3} \text{ A}$$

If *I* is the line current on 11000 V side, then,

Primary apparent power = Secondary apparent power

or $$\sqrt{3} \times 400 \times 500 = \sqrt{3} \times 11000 \times I$$

or $$I = \frac{\sqrt{3} \times 400 \times 500}{\sqrt{3} \times 11000} = \frac{200}{11} \text{ A}$$

∴ C.T. ratio of *CTs* on 11000 V side

$$= \frac{200}{11} : 5\sqrt{3} = \frac{200}{11 \times 5\sqrt{3}} = \frac{10 \cdot 5}{5} = \mathbf{10 \cdot 5 : 5}$$

TUTORIAL PROBLEMS

1. A 3-phase, 33/6·6 kV, star/delta connected transformer is protected by Merz-Price circulating current system. If the CTs on the low-voltage side have a ratio of 300/5, determine the ratio of CTs on the high voltage side. **[60 : $5\sqrt{3}$]**
2. A 3-phase, 200 kVA, 11/0·4 kV transformer is connected as delta/star. The protective transformers on the 0·4 kV side have turn ratio of 500/5. What will be the C.T. ratios on the high voltage side ? **[18·18 : 8·66]**

SELF - TEST

1. Fill in the blanks by inserting appropriate words/figures.

(*i*) The most commonly used system for the protection of generator is ....

(*ii*) Automatic protection is generally .... provided for field failure of an alternator.

(*iii*) The chief cause of overspeed in an alternator is the ....

(*iv*) Earth relays have .... current settings.

(*v*) Buchholz relay is installed between .... and conservator.

(*vi*) Buchholz relays can only be used with oil immersed transformers equipped with ....

(*vii*) For the protection of a delta/star power transformers, the CTs on delta side must be connected in .... and those on the star side in ....

(*viii*) Overload protection is generally not provided for ....

(*ix*) Buchholz relay is a .... relay.

(*x*) Automatic protection is generally not provided for .... transformer.

2. Pick up the correct words/figures from the bracket and fill in the blanks.

(*i*) Buchholz relay can detect faults .... oil level in the transformer. (*below, above*)

(*ii*) The most important stator winding fault of an alternator is .... fault. (*earth, phase-to-phase, inter-turn*)

(*iii*) Balanced earth-fault protection is generally provided for ....generators. (*small-size, large-size*)

(*iv*) An earth-fault current is generally .... than short-circuit current. (*less, greater*)

(*v*) Merz-Price circulating current principle is more suitable for .... than .... (*generators, transformers*)

ANSWERS TO SELF-TEST

1. (*i*) circulating-current system (*ii*) not (*iii*) sudden loss of load (*iv*) lower (*v*) main tank (*vi*) conservator (*vii*) star, delta (*viii*) alternators (*ix*) gas actuated (*x*) small distribution

2. (*i*) below (*ii*) earth (*iii*) small-size (*iv*) less (*v*) generators, transformers

CHAPTER REVIEW TOPICS

1. Discuss the important faults on an alternator.
2. Explain with a neat diagram the application of Merz-Price circulating current principle for the protection of alternator.
3. Describe with a neat diagram the balanced earth protection for small-size generators.
4. How will you protect an alternator from turn-to-turn fault on the same phase winding ?
5. What factors cause difficulty in applying circulating current principle to a power transformer ?
6. Describe the construction and working of a Buchholz relay.
7. Describe the Merz-Price circulating current system for the protection of transformers.
8. Write short notes on the following :

   (*i*) Earth-fault protection for alternator

   (*ii*) Combined leakage and overload protection for transformers

   (*iii*) Earth-fault protection for transformers

DISCUSSION QUESTIONS

1. What is the difference between an earth relay and overcurrent relay ?
2. How does grounding affect relay application ?
3. Why is overload protection not necessary for alternators ?
4. Can relays be used to protect an alternator against (*i*) one-phase open circuits (*ii*) unbalanced loading (*iii*) motoring (*iv*) loss of synchronism ?
5. How many faults develop in a power transformer ?

GO To FIRST

CONTENTS

CHAPTER

23

Protection of Busbars and Lines

Introduction

Busbars and lines are important elements of electric power system and require the immediate attention of protection engineers for safeguards against the possible faults occurring on them. The methods used for the protection of generators and transformers can also be employed, with slight modifications, for the busbars and lines. The modifications are necessary to cope with the protection problems arising out of greater length of lines and a large number of circuits connected to a busbar. Although differential protection can be used, it becomes too expensive for longer lines due to the greater length of pilot wires required. Fortunately, less expensive methods are available which are reasonably effective in providing protection for the busbars and lines. In this chapter, we shall focus our attention on the various methods of protection of busbars and lines.

23.1 Busbar Protection

Busbars in the generating stations and sub-stations form important link between the incoming and outgoing circuits. If a fault occurs on a busbar, considerable damage and disruption of supply will occur unless some form of quick-acting automatic

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protection is provided to isolate the faulty busbar. The busbar zone, for the purpose of protection, includes not only the busbars themselves but also the isolating switches, circuit breakers and the associated connections. In the event of fault on any section of the busbar, all the circuit equipments connected to that section must be tripped out to give complete isolation.

The standard of construction for busbars has been very high, with the result that bus faults are extremely rare. However, the possibility of damage and service interruption from even a rare bus fault is so great that more attention is now given to this form of protection. Improved relaying methods have been developed, reducing the possibility of incorrect operation. The two most commonly used schemes for busbar protection are :

(*i*) Differential protection (*ii*) Fault bus protection

(*i*) **Differential protection.** The basic method for busbar protection is the differential scheme in which currents entering and leaving the bus are totalised. During normal load condition, the sum of these currents is equal to zero. When a fault occurs, the fault current upsets the balance and produces a differential current to operate a relay.

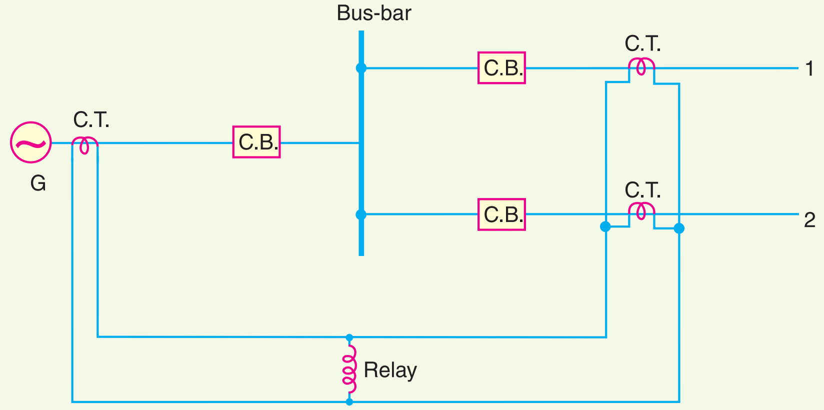


Fig. 23.1

Fig. 23.1 shows the single line diagram of current differential scheme for a station busbar. The busbar is fed by a generator and supplies load to two lines. The secondaries of current transformers in the generator lead, in line 1 and in line 2 are all connected in parallel. The protective relay is connected across this parallel connection. All *CT*s must be of the same ratio in the scheme regardless of the capacities of the various circuits. Under normal load conditions or external fault conditions, the sum of the currents entering the bus is equal to those leaving it and no current flows through the relay. If a fault occurs within the protected zone, the currents entering the bus will no longer be equal to those leaving it. The difference of these currents will flow through the relay and cause the opening of the generator, circuit breaker and each of the line circuit breakers.

(*ii*) **Fault Bus protection.** It is possible to design a station so that the faults that develop are mostly earth-faults. This can be achieved by providing earthed metal barrier (known as *fault bus*) surrounding each conductor throughout its entire length in the bus structure. With this arrangement, every fault that might occur must involve a connection between a conductor and an earthed metal part. By directing the flow of earth-fault current, it is possible to detect the faults and determine their location. This type of protection is known as fault bus protection.

Fig. 23.2 show the schematic arrangement of fault bus protection. The metal supporting structure or fault bus is earthed through a current transformer. A relay is connected across the secondary of this CT. Under normal operating conditions, there is no current flow from fault bus to ground and the relay remains inoperative. A fault involving a connection between a conductor and earthed supporting structure will result in current flow to ground through the fault bus, causing the relay to operate. The operation of relay will trip all breakers connecting equipment to the bus.

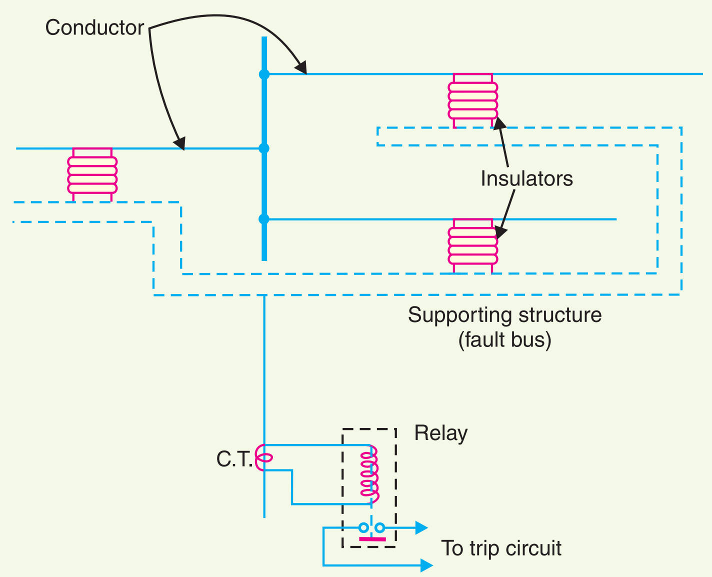


Fig. 23.2

23.2 Protection of Lines

The probability of faults occurring on the lines is much more due to their greater length and exposure to atmospheric conditions. This has called for many protective schemes which have no application to the comparatively simple cases of alternators and transformers. The requirements of line protection are :

(*i*) In the event of a short-circuit, the circuit breaker closest to the fault should open, all other circuit breakers remaining in a closed position.

(*ii*) In case the nearest breaker to the fault fails to open, back-up protection should be provided by the adjacent circuit breakers.

(*iii*) The relay operating time should be just as short as possible in order to preserve system stability, without unnecessary tripping of circuits.

The protection of lines presents a problem quite different from the protection of station apparatus such as generators, transformers and busbars. While differential protection is ideal method for lines, it is much more expensive to use. The two ends of a line may be several kilometres apart and to compare the two currents, a costly pilot-wire circuit is required. This expense may be justified but in general less costly methods are used. The common methods of line protection are :

(*i*) Time-graded overcurrent protection

(*ii*) Differential protection

(*iii*) Distance protection

Fig. 23.3

Fig. 23.3 shows the symbols indicating the various types of relays.

5 Busbar Protection

5.1 Introduction

The word *bus* is derived from the Latin word *omnibus* which means common for all. Busbars are the *nerve-centres* of the power system where various circuits are connected together. These are the nodes of the electrical circuit. Figure 5.1 shows a busbar having an N_1 number of incoming lines and an N_2 number of outgoing lines. The protective zone, to be generated by the protective relays, is also shown. It may be noted that under the normal power flow condition the sum of incoming currents is equal to the sum of outgoing currents, i.e

$$\boxed{\sum_{k=1}^{N_1} I_{\text{in}_k} = \sum_{m=1}^{N_2} I_{\text{out}_m}}$$

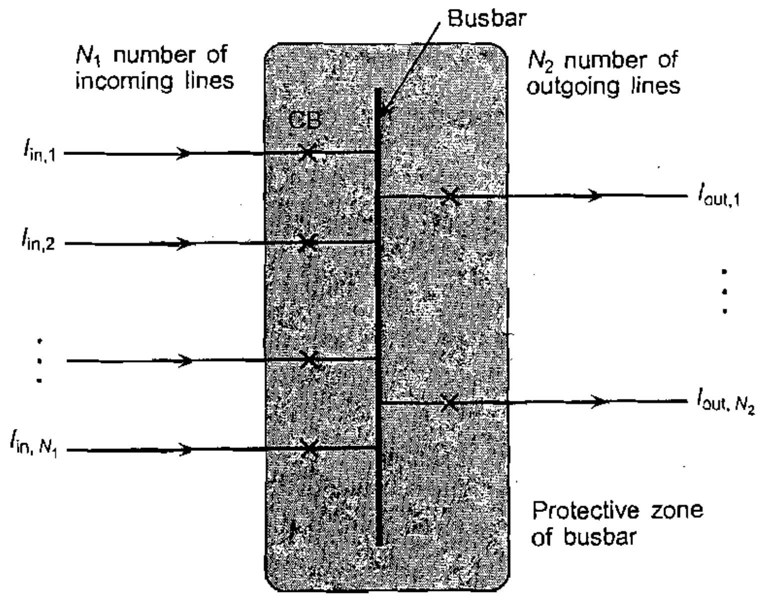


Figure 5.1 Introduction to busbars.

Thus, there is a large concentration of short-circuit capacity at the busbars. A fault on the busbar, though rare, causes enormous damage. When protective relays operate to isolate the busbar from the system, there is a large disruption to the loads. Busbars are located in switchyards, substations, and supply kiosks. The switchyards are well shielded from direct lightening strokes but because of their outdoor nature, are subject to the vagaries of weather. The substations are well protected in all respects and fault probability is indeed very low. Similarly, supply kiosks are totally enclosed and sealed.

The causes of faults experienced on busbars are: weakening of insulation because of ageing, corrosion beccause of salty water, breakdown of insulation because of over-voltages, foreign objects, and so on. For example, rodents, lizards and snakes are known to have caused busbar faults in remote unmanned substations.

Because of the low probability of busbar faults, for many years, it was considered unnecessary to provide explicit protection to busbars. It was felt at that time that maloperations of the busbar protection systems will be problematic by themselves and of little help in sensing genuine faults. It should be noted that busbars fall in the overlap between protective zones on either side, so they do get back-up protection. Hence, protection engineers hesitated from providing exclusive busbar protection.

However, as the system voltage went on increasing and short-circuit capacities went on building up, it was no longer advisable to leave busbars unprotected on a primary basis.

What form of protection is best suited for busbars? A little reflection will convince the reader that differential protection will suit this situation best because the ends (terminals) of the system are physically near to each other. Thus, by installing CTs on the two sides, we can simply compare the current entering the busbar with that leaving it. Any discrepancy between the two will immediately signal an internal fault.

In Section 5.2, we have explained the protection of busbars by the differential protection scheme.

5.2 Differential Protection of Busbars

5.2.1 Selection of CT Ratios in Case of Busbar Protection: Wrong Method

Figure 5.2 shows a busbar, having two incoming feeders and one outgoing feeder, being protected by a simple differential protection scheme. The currents shown are for normal load flow. Let us decide the CT ratios on the basis of maximum primary load current seen by each CT. Thus, the CTs on the incoming feeder will have CT ratios of 1000/1 A and 2000/1 A, respectively. The CT on the outgoing feeder will have a CT ratio of 3000/1 A. However, with this choice of CT ratios, it can be seen from the diagram that there is a spill current even during the healthy condition. Thus, the method of selecting CT ratio on the basis of maximum primary current seen by the feeder is not correct.

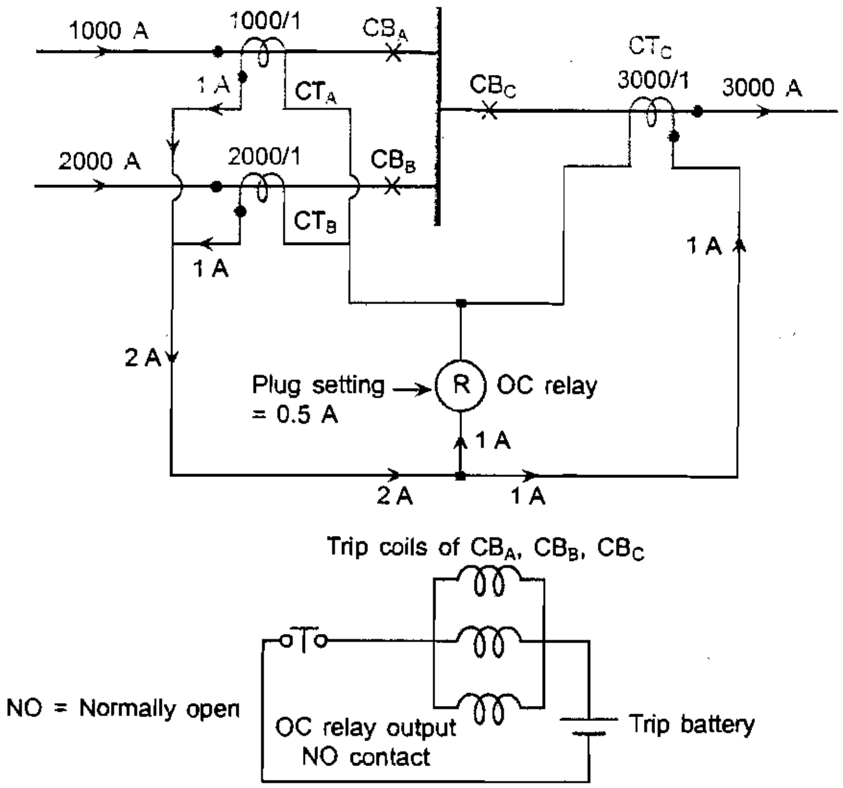


Figure 5.2 Wrong method of selection of CT ratios for differential protection of busbars.

5.2.2 Selection of CT Ratios in Case of Busbar Protection: Correct Method

Figure 5.3 shows the correct method of setting the CT ratios for the busbar differential protection. It can be seen that the CT ratios of all the CTs are equal and are based on the primary current of that feeder which carries the maximum current. Thus, all the CT

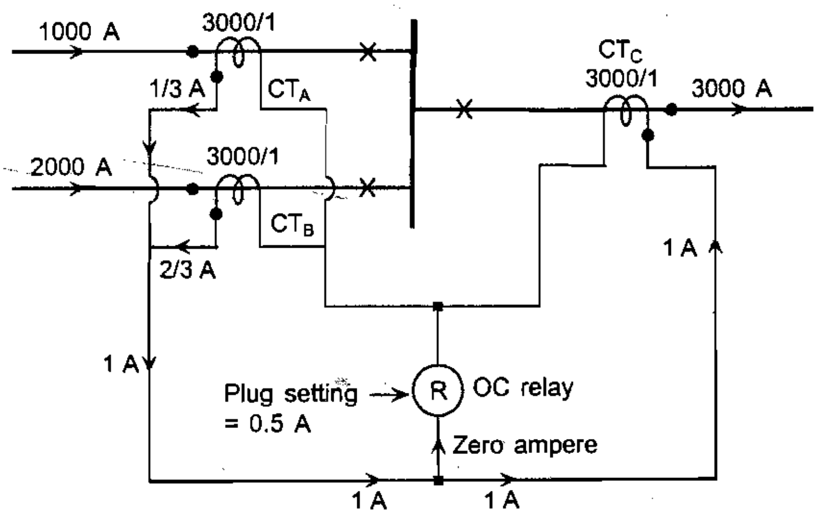


Figure 5.3 Correct method of selection of CT ratios for differential protection of busbars.

ratios are 3000/1 A. Therefore, as can be seen from the figure, there is no spill current through the OC relay connected in the spill path and the scheme remains stable.

We draw an important rule for the selection of CT ratios for all the CTs in a busbar differential protection, namely:

$$\boxed{\text{CT ratio for all CTs in bus differential scheme} = \frac{\text{Maximum out of all the feeder currents}}{1\text{ A or } 5\text{ A}}}$$

5.3 External and Internal Fault

In the preceding discussion, we have assumed that the CTs are ideal. When the CT primary current, or the burden on it, is within its design limits, the CT can indeed be assumed to be more or less ideal. However, as the primary current exceeds the design value or the CT burden (output of CT in VA) becomes excessive, the CT no longer behaves in an ideal fashion. The non-ideal behaviour of the CT has very serious implications for the protective schemes.

Figure 5.4 shows currents during an external fault beyond CT_C. It can be seen that CT_C, the CT on the faulted feeder, has to carry the sum of all currents fed into the fault by various feeders. Therefore, CT_C sees a substantially larger primary current than either CT_A or CT_B. In all likelihood, CT_C will therefore become saturated. We can, therefore, no longer assume that CT_C will faithfully transform the fault current. For the sake of illustration, we have assumed that the secondary current of CT_C is only 4 A instead of 10 A. It can be seen from Figure 5.4 that this results into a spill current of 6 A, causing the scheme to maloperate, i.e. lose stability on external fault.

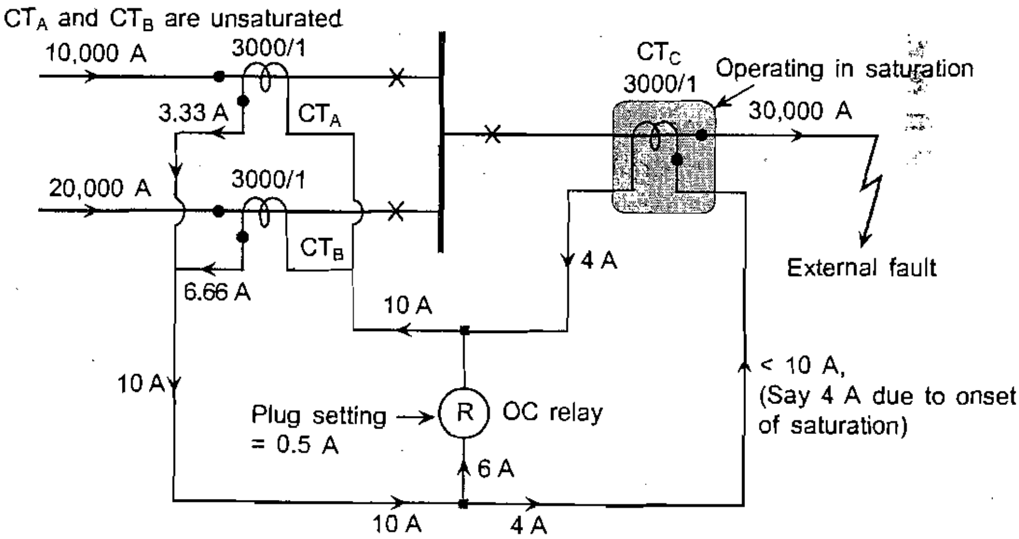


Figure 5.4 Behaviour of busbar differential scheme on external fault.

In the worst case scenario, CT_A and CT_B continue to transform faithfully as per their nameplate CT ratio but CT_C, which carries the total fault current, gets completely saturated. This clearly indicates the occurrence of an imbalance in transformed secondary currents, resulting in substantial spill current. This situation most likely will cause the scheme to operate. Operation of a differential scheme under external faults is, therefore, clearly a case of maloperation.

Interestingly, as the fault shifts by a small distance to the left and becomes an *internal fault, still drawing the same current, the situation dramatically changes* as far as CT_C is concerned. This is depicted in Figure 5.5, wherein it can be seen that CT_C now does not carry any fault current (assuming a single-end-fed system with source on left-hand side). Since CT_A and CT_B are not carrying excessive primary currents, they transform the current without too much error. There is thus a spill current in the spill path and the scheme operates as expected.

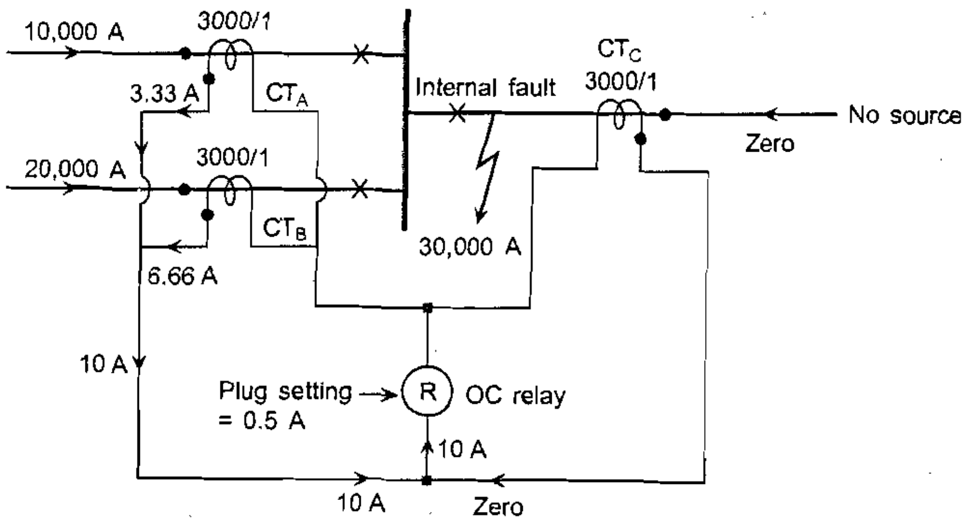


Figure 5.5 Behaviour of busbar differential scheme on internal fault.

The maloperation of the busbar differential scheme on external faults is caused due to non-ideal behaviour of a CT carrying excessive primary current. It will, therefore, be pertinent, at this point to take a closer look at the actual behaviour of protective current transformers.

5.4 Actual Behaviour of a Protective CT

Figure 5.6 shows the equivalent circuit of a current transformer referred to the secondary side. R'_p and X'_p are the primary winding resistance and leakage reactance, respectively, referred to the secondary side. R_s and X_s are the resistance and leakage reactance of the secondary winding, respectively. The excitation is modelled by X'_0 and core loss by R'_0 in the equivalent circuit (referred to secondary).

At low values of primary current I_p, and therefore I_s, voltage E_s to be induced by the secondary winding, which is approximately equal to ($Z_{burden}\ I_s$), is quite low. The working flux in the CT, which is equal to ($E_s/4.44\ fN$) is also very low. The magnetizing current requirement is, therefore, correspondingly low. Thus, the secondary current I_s is substantially equal to I_p/N.

If the primary current increases, initially, the secondary current also increases proportionately. This causes the secondary induced voltage to increase as well. Increased secondary voltage can only be met with an increase in the working flux of the CT. As the flux increases, the transformer needs to draw a higher magnetizing current. However, because of the nonlinear nature of the B-H curve for the CT, as the knee of the excitation

8 Generator Protection

8.1 Introduction

A generator could be part of:

- water turbine based hydropower station
- gas turbine based power station
- steam turbine based thermal power station
- nuclear power station

In all the above installations, the protection of the generator presents a very challenging problem because of its system connections on three different sides as shown in Figure 8.1. On the one side, it is connected to the prime mover and on the other side, it has to run in synchronism with the grid because of its connection to the power system. On yet another (third) side, it is connected to the source of DC excitation. It is thus obvious that generator protection is very complex compared to protection for other elements of the power system.

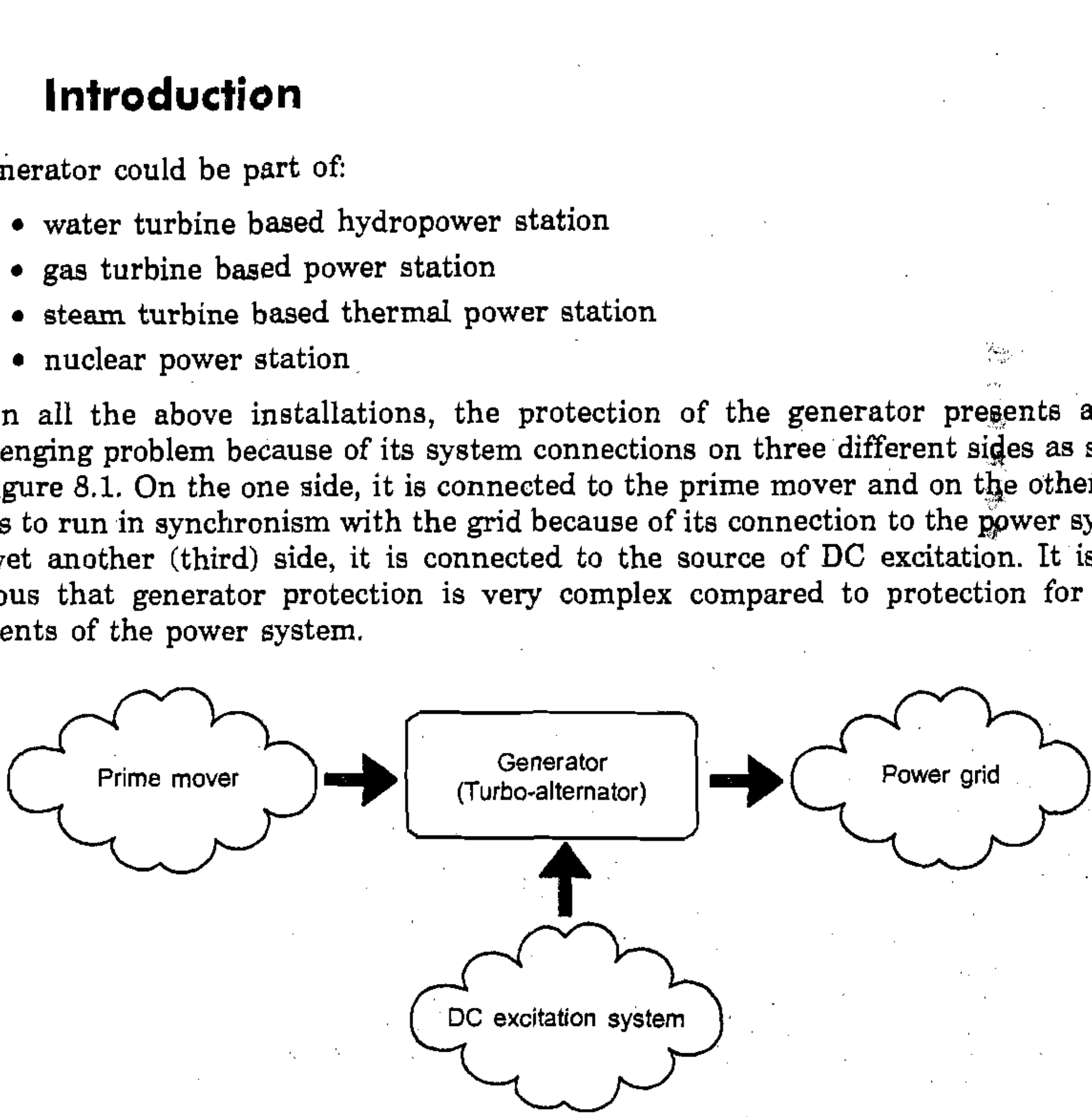


Figure 8.1 Complexities of generator protection.

In this book, we will restrict ourselves to various aspects of protection of a large (200 MW or higher) *steam turbine based turbo-alternator.*

In case of a fault on a turbo-alternator, it is not enough to open the main circuit breaker connecting it to the power grid. For example, when a turbo-alternator driven by a steam turbine is tripped, the following must be done:

- Steam supply to the turbine is stopped or bypassed.
- Firing of the boiler is stopped.
- Coal mills are stopped.
- Coal supply to the coal mills is stopped.
- Field circuit of the alternator is interrupted.
- Field coils are connected across a resistor to dissipate the stored energy.
- Alternator is kept running at a slow speed (few rpm) with the help of barring gear till it cools down uniformly, so as to avoid uneven expansions.

Putting back the alternator on line is rather a slow process because all the parameters (temperatures and pressures) have to be progressively built up to avoid thermal shock resulting in uneven expansions which might cause unacceptable vibrations. Therefore, unscheduled outage of a thermal power station is avoided as far as possible.

We have to keep in mind that a modern large turbo-alternator is a huge mass rotating at a very high speed (3000 rpm) in a very small air-gap. Thus, apart from the large electrical energies involved, there is tremendous amount of mechanical energy in the form of moment of inertia of the rotating mass and resultant forces on the shaft, the rotor body and the stator structure.

Thus, any slight increase in temperature or uneven heating of the rotor may cause eccentricity, which gets accentuated because of the high speed of rotation and small air-gap. The entire system has, therefore, to be run in a narrow range of various parameters like temperatures and pressures, displacements, flows, voltages, currents, power factor, and so forth. The operation outside the specified parameter range may cause a substantial decrease in the life of the equipment.

Since the power station equipment represents a very high investment of money, the operation of the power plant is very closely monitored and controlled.

Figure 8.2 illustrates the complexities of a turbo-alternator in a more detailed manner.

It is said that running a large power station is like flying a supersonic jet aircraft without any forced landings or crashes!

8.2 Electrical Circuit of the Generator

The electrical circuit of the generator is very simple in spite of the complexity of the overall system. This is shown in Figures 8.3(a), 8.3(b) and 8.3(c). It is to be noted that the generator is never solidly grounded. If it were solidly grounded, the single line-to-ground fault current would be dangerously high. Apart from the high value of fault current, the resulting asymmetry in the rotating magnetic field inside the generator would cause unacceptably large vibrations and result in mechanical damage to the rotor. Hence, in order to limit the short-circuit current, the neutral of the generator is grounded through a resistance. In order to get a practicable value of the grounding resistor, it is connected through a step-down transformer, known as **grounding transformer**.

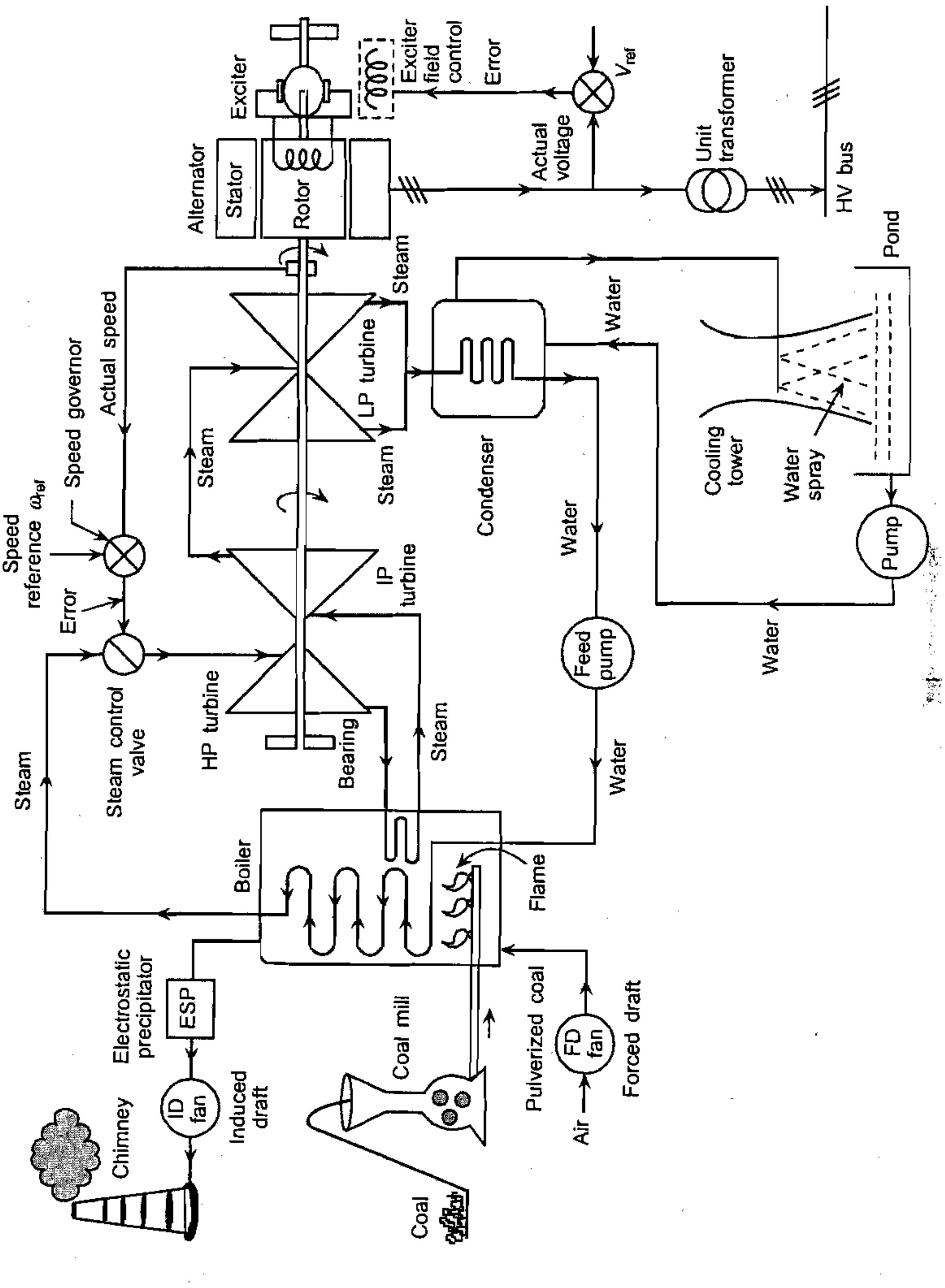


Figure 8.2 Complexities of turbo-alternator protection.

The power plant has a sizeable auxiliary electrical load of its own, of the order of 10% of the power rating of the generator, which is supplied through the *unit auxiliary transformer (UAT)*. It is to be noted that these auxiliaries require power even before the generator can be started, run up to speed and synchronized with the grid. Hence, there is the switching facility to energize the UAT directly from the grid.

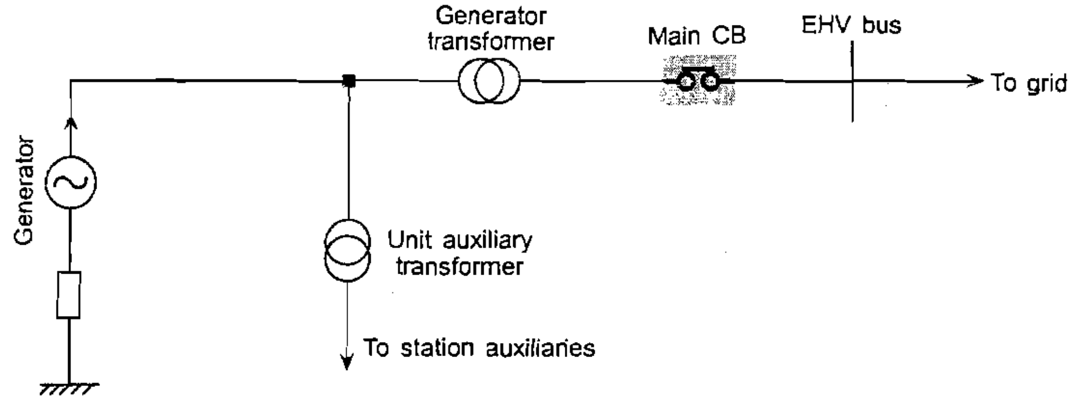


Figure 8.3(a) Alternator unit auxiliary transformer and main CB.

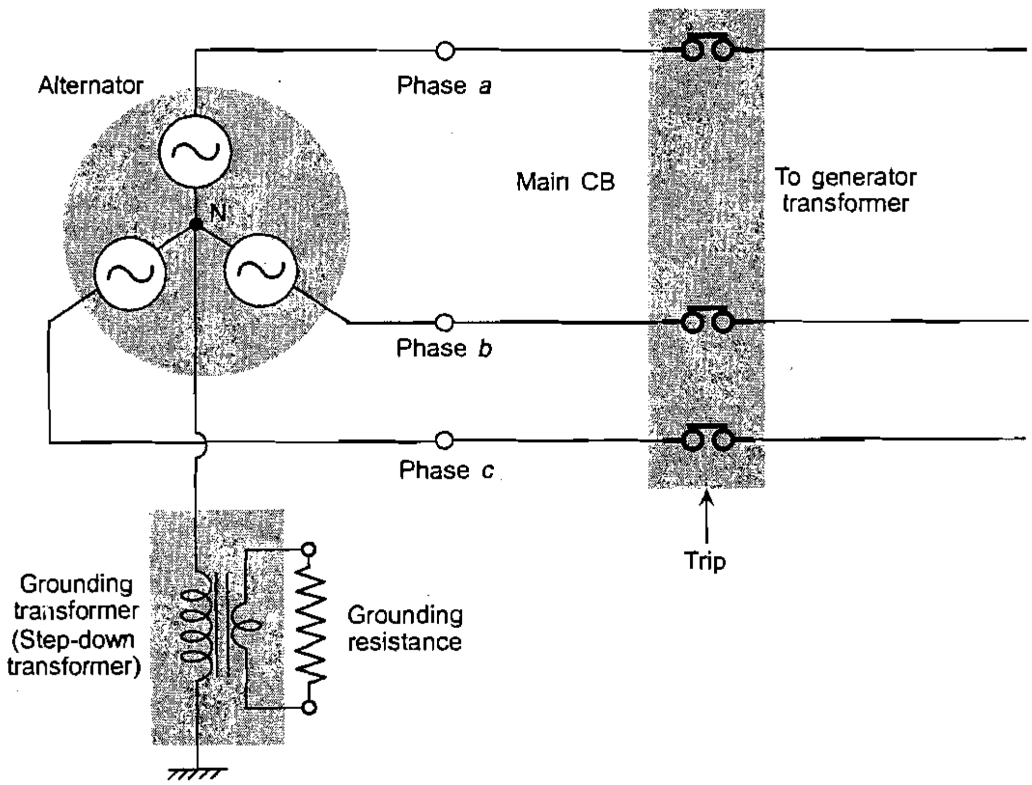


Figure 8.3(b) Alternator and neutral grounding transformer.

The rotor of the generator houses the field winding. A separate dc generator, which is mounted on the turbo-alternator shaft, feeds the field. The dc system is kept floating with respect to the ac ground, i.e. neither the +ve nor the –ve terminal is grounded. The field interrupter and the arrangement for field suppression is also shown in Figure 8.3(c).

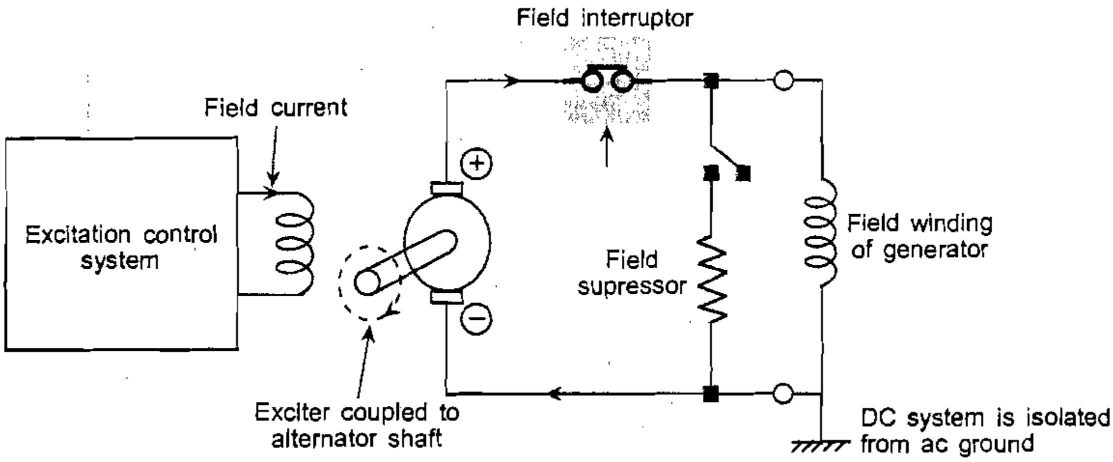


Figure 8.3(c) Electrical circuit of the exciter of the generator.

8.3 Various Faults and Abnormal Operating Conditions

In addition various electrical faults, a generator goes through many abnormal operating conditions, which need to be understood. Figure 8.4(a) and Figure 8.4(b) show the hierarchy of the electrical faults and abnormal operating conditions.

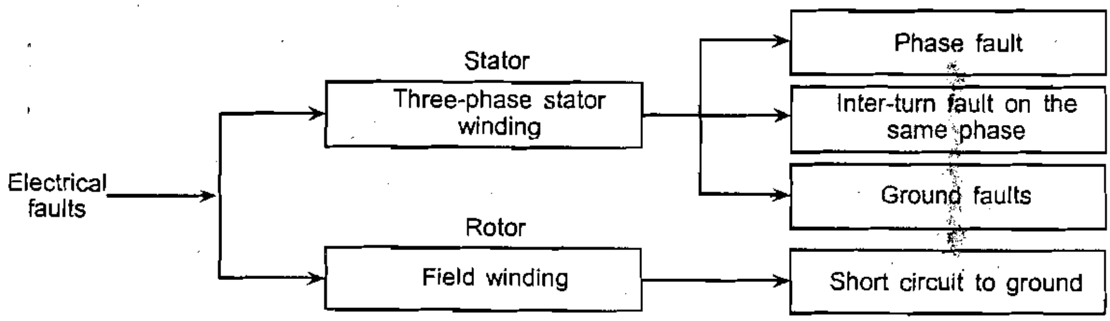


Figure 8.4(a) Various electrical faults on a turbo-alternator.

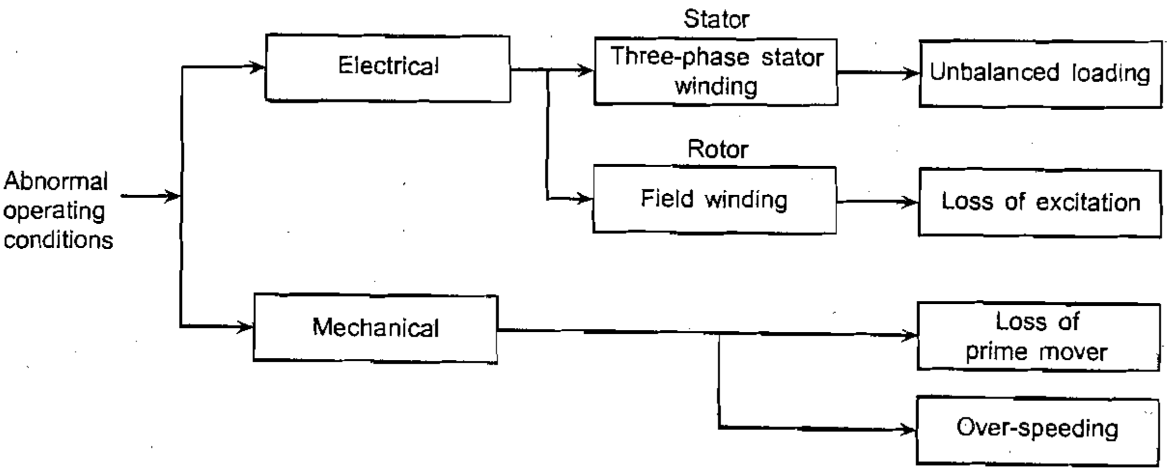


Figure 8.4(b) Various abnormal operating conditions of a turbo-alternator.

8.3.1 Stator Faults

The three-phase armature winding on the stator can develop phase as well as ground faults. Another possibility is inter-turn faults between turns of the same phase.

8.3.2 Stator Phase and Ground Faults

Phase and ground faults on the stator armature winding can be easily detected by a conventional percentage differential protection scheme as shown in Figure 8.5. This type of scheme is also known as *longitudinal differential scheme* in order to differentiate it from another differential scheme, known as *transverse differential scheme* which is used to detect inter-turn faults.

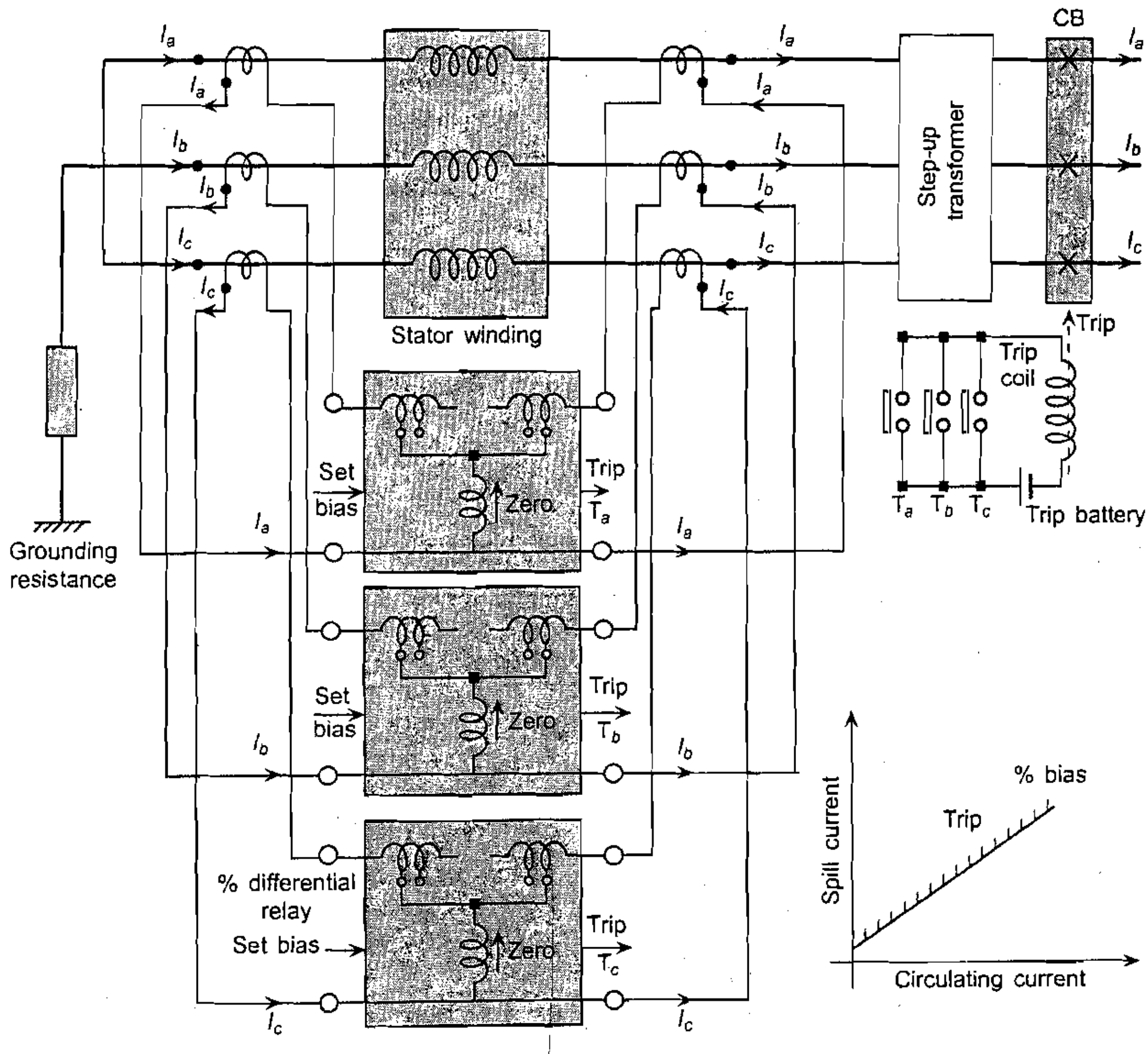


Figure 8.5 Longitudinal percentage differential protection.

It may be noted that there are differences between the differential protection of a power transformer and that of a generator as shown in Table 8.1. As a result of these differences, the percentage bias setting for the generator differential relay is quite small compared to that for the power transformer.

Table 8.1 Difference between transformer and generator differential protection

Power transformer	*Generator*
Primary and secondary voltages are in general different	Same voltage for CTs on two sides of the generator winding
Turns-ratio of the CTs are different because of ratio of transformation of the transformer	Turns-ratio of CTs on the two sides of the generator winding is same
Tap changer may be present	No such device is present

This gives rise to a larger spill current, during normal load and external faults, in case of the transformer differential protection than in case of the generator differential protection. Normally, the percentage bias setting of 5–10% is adequate for longitudinal differential protection of the generator stator winding whereas a setting of 20–40% may be required in case of power transformers.

The longitudinal differential scheme caters for phase as well as ground faults on the stator winding. However, it is unable to detect the inter-turn faults between the turns of the same phase. This is discussed in the following Section 8.3.3.

8.3.3 Transverse Differential Protection

In order to apply this type of protection, a special type of split winding is required as shown in Figure 8.6. Current in each parallel section is now compared with that in the other section. If there is an inter-turn fault in one section then the currents will differ and flow as spill current through the OC relay, as shown in Figure 8.6.

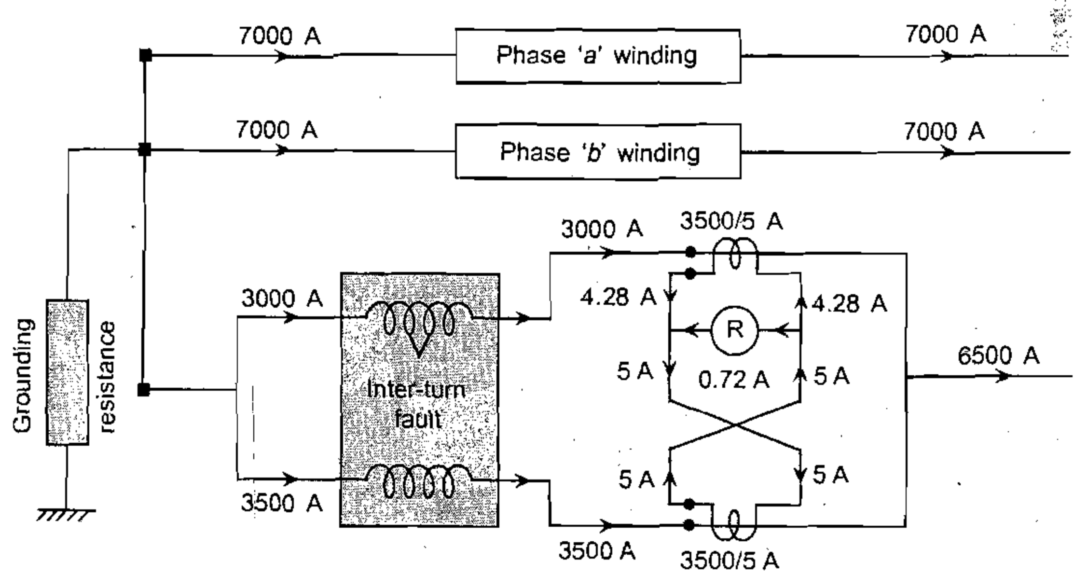


Figure 8.6 Transverse protection of generator winding.

In Figure 8.6, only the winding with the inter-turn fault is shown in detail. The half of the winding in which there is an inter-turn fault is shown to carry 3000 A whereas the healthy half carries 3500 A. As seen from the figure, the current entering the phase *c* winding, as a whole, is 6500 A which is the same as that leaving it. Therefore, a longitudinal differential relay would be incapable of detecting such faults.

However, because of the splitting of the winding and transverse connection of the CTs, there is a spill current of 0.72 A in the transverse differential relay. Thus, a setting of, say, 0.5 A will be enough to detect such an inter-turn fault.

8.4 Rotor Faults

The rotor carries the field winding which is kept isolated from the ground. Neither the positive nor the negative terminal of the dc supply is grounded. Thus, any ground fault on the rotor field winding does not affect the working of the alternator. However, a subsequent fault would cause a section of the rotor winding to be short circuited, giving rise to a secondary flux which opposes the main flux in the proximity of the shorted turns, causing distortion in the distribution of main flux. The flux will get concentrated on one pole but dispersed over the other and intervening surfaces. The resulting asymmetry in the electromagnetic forces will cause severe vibrations of the rotor. In a modern turbo-alternator, the inertia of rotation is very large and the rotor-to-stator clearances are very small, therefore, there is a likelihood of permanent damage to the turbo-alternator. Instances have been reported where, during rotor faults, because of severe mechanical stresses structural damage was caused.

In the light of the above, the very first fault on the field winding must be detected and the set tripped in a controlled manner. An arrangement for rotor earth fault detection and protection is shown in Figure 8.7, wherein an external voltage source is superimposed

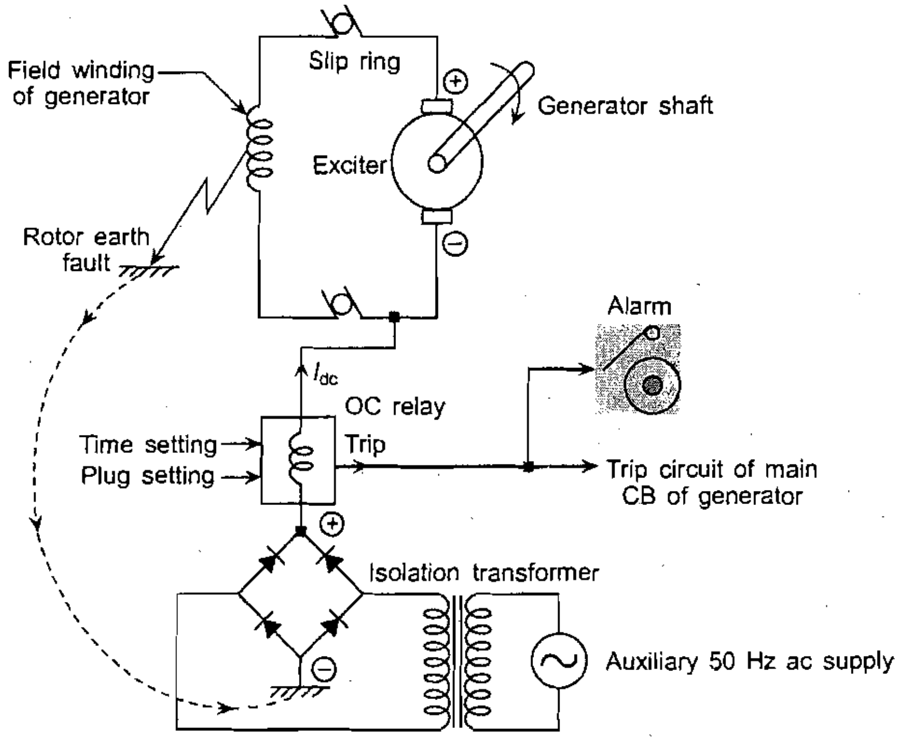


Figure 8.7 Protection against rotor faults.

on the rotor circuit. This external voltage source is grounded so that the very first rotor earth fault causes a dc fault current to flow which is easily detected by an OC relay.

8.5 Abnormal Operating Conditions

As pointed out earlier, a generator cannot be considered in isolation because of a very large number of other equipment connected to it. Even though there is no electrical fault in the generator, if one of its associated equipment develops a fault, then it has serious implications for the generator. Every auxiliary equipment connected to the generator is a likely source of trouble. There are a large number of possible faults, as well as combinations of faults, on these equipment, that threaten the operation of the generator. Instances where there is no direct electrical fault in the generator but one or more of its associated equipment develop a fault or an abnormality, may lead to an abnormal operating condition, which may or may not be serious. However, all abnormal operating conditions need to be detected as quickly and as sensitively as possible so that the corrective action can be taken and a possible shutdown averted or anticipated.

In the following sections, we consider some prominent abnormal operating conditions that need to be carefully considered while providing protection to the generator.

8.5.1 Unbalanced Loading

If there is an unbalanced loading of the generator then the stator currents have a negative sequence component. The stator field due to these negative sequence currents, rotates at synchronous speed but in a direction opposite to the direction of the field structure on the rotor. Thus, the negative sequence stator armature mmf rotates at a speed $-N_S$ while the rotor field speed is $+N_S$. Therefore, there is a relative velocity of $2N_S$ between the two. This causes double frequency currents, of large amplitude, to be induced in the rotor conductors and iron. Recall that the eddy current loss component of iron loss in the rotor is proportional to $f^2(B_{max})^2$ while the hysteresis loss is proportional to $f(B_{max})^n$ where $n = 1.6$ to 2 depending upon the core material. Therefore, both the eddy current as well as the hysteresis losses increase due to these double frequency induced currents in the rotor. This is shown in Figure 8.8.

Thus, if the stator carries unbalanced currents, then it is the rotor, which is overheated. How long the generator can be allowed to run under unbalanced loading, depends upon the thermal withstand capacity of the machine, which in turn depends upon the type of cooling system adopted. The rate of heat generation is proportional to I_2^2R while the heat energy is proportional to I_2^2Rt, where t is the time and I_2 is negative sequence current. Since the capacity of a particular machine, to safely dissipate energy, is limited to a certain value k, we can write

$$I_2^2Rt = k$$

Assuming R to be a constant, and $K = k/R$, we get the thermal characteristics of the machine as

$$I_2^2t = K$$

In other words, the time t for which the offending current I can be allowed to flow should be less than or equal to K/I_2^2.

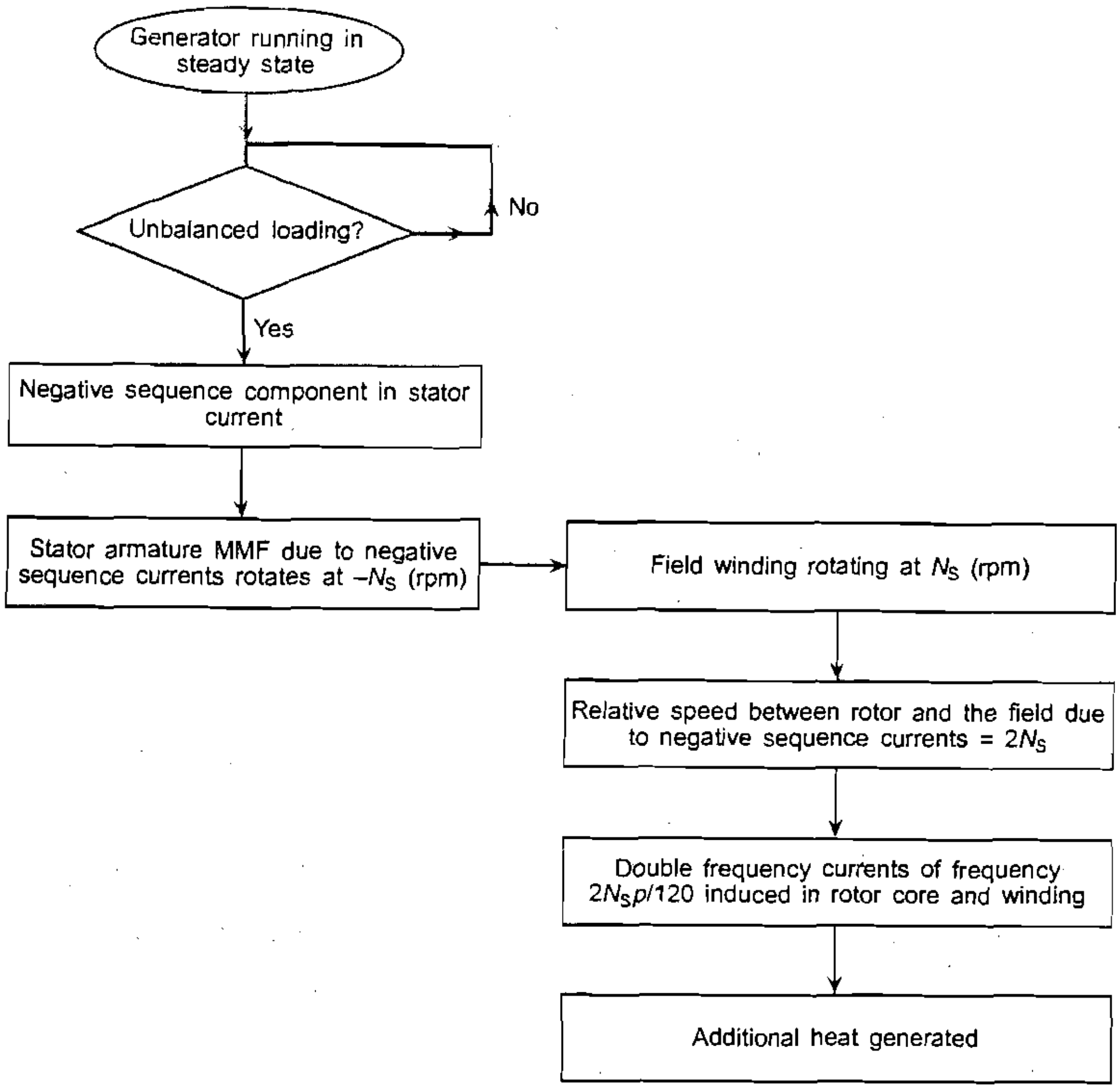


Figure 8.8 Unbalanced loading of stator causes the rotor to overheat.

Thus, the current-time characteristic can be written as

$$\boxed{t \leq \frac{K}{I_2^2}}$$

The readers will recall that this characteristic is similar to that of the inverse time over-current relay. Thus an inverse type of over-current relay, which is fed with the negative sequence component of stator current, gives protection against unbalanced loading of the generator.

The preceding discussion suggests that if we could, somehow, extract the negative sequence component of the stator current then the protection against unbalanced loading can be implemented by applying the inverse-time OC relay as shown in Figure 8.9.

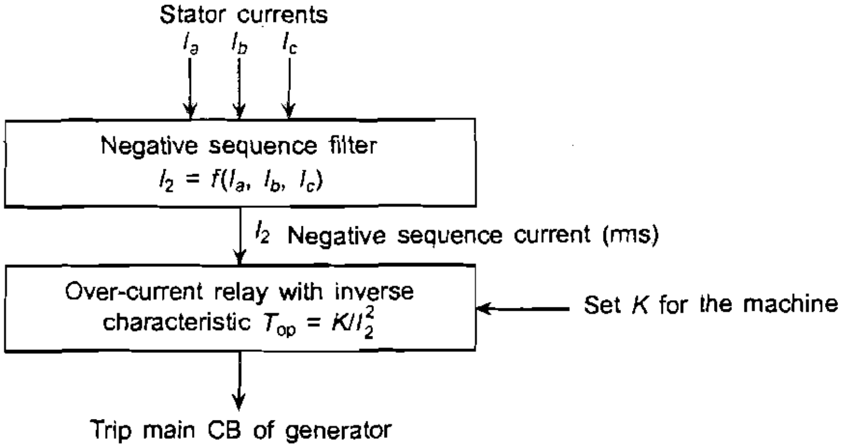


Figure 8.9 Logic of the protection against unbalanced loading.

8.5.2 Over-speeding

Consider that a turbo-alternator is supplying its rated real electrical power P_e to the grid. Its mechanical input P_m is nearly equal to P_e (except for the losses) and the machine runs at constant synchronous speed N_S.

Now, consider that due to some fault the generator is tripped and disconnected from the grid. Thus, P_e becomes zero. However, the mechanical power input P_m cannot be suddenly reduced to zero. Therefore, we land up in a situation where the generator has full input mechanical power but no output electrical power. This would cause the machine to accelerate to dangerously high speeds, if the mechanical input is not quickly reduced by the speed-governing mechanism.

The protection against such an eventuality can be provided by sensing the over-speeding and taking steps such as operating the steam valve so as to stop steam input to the turbine. The speed-governing mechanism or the speed governor of the turbine is basically responsible for detecting this condition. The over-speeding can also be detected either by an over-frequency relay or by monitoring the output of the tachogenerator mounted on the generator shaft. The logic of protection against over-speeding is shown in Figure 8.10.

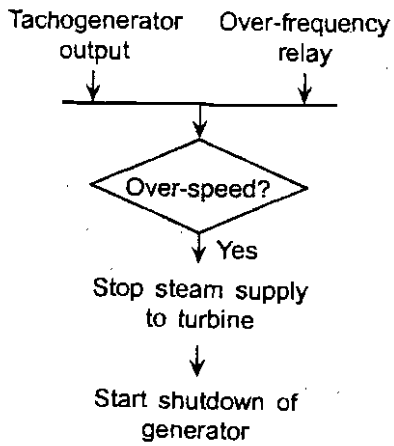


Figure 8.10 Protection against over-speeding.

8.5.3 Loss of Excitation

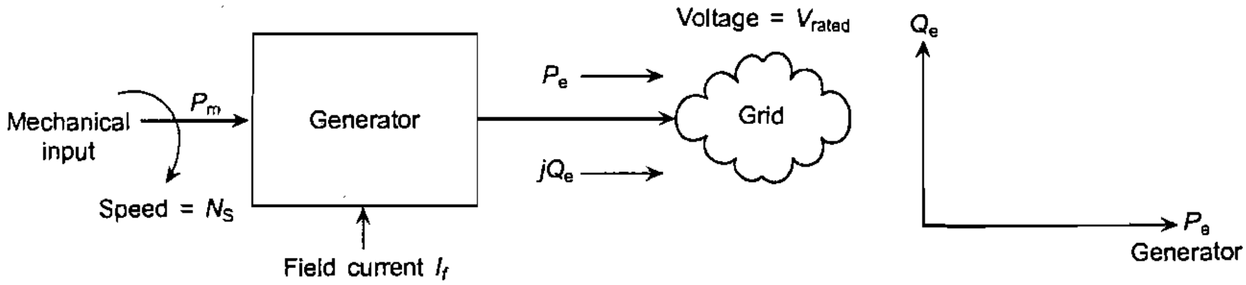
There are several possible causes due to which field excitation may be lost, namely:

- Loss of field to main exciter
- Accidental tripping of the field breaker
- Short circuit in the field winding
- Poor brush contact in the exciter
- Field circuit breaker latch failure
- Loss of ac supply to excitation system

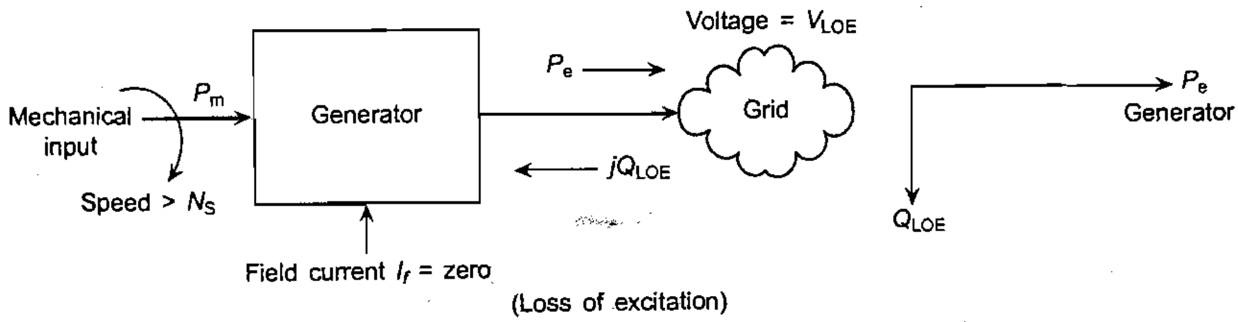
The generator delivers both real as well as reactive power to the grid. The real power comes from the turbine while the reactive power is due to the field excitation. Consider a generator delivering the complex power, $S = P_e + jQ_e$, to the grid.

Corresponding to real power P_e, there is the shaft mechanical power input P_m and corresponding to reactive power Q_e, there is the field current I_f as shown in Figure 8.11(a) and (b).

Now, consider that the field excitation is lost while the mechanical input remains intact. Since the generator is already synchronized with the grid, it would attempt to remain synchronized by running as an *induction generator*. As an induction generator, the machine speeds up slightly above the synchronous speed and draws its excitation from the grid. This is shown in Figure 8.11(b). Operation as an induction generator necessitates the flow of slip frequency current in the rotor, the current flowing in the damper winding and also in the slot wedges and the surface of the solid rotor body.



(a) Before loss of excitation



(b) After loss of excitation

Figure 8.11 Loss of excitation.

Now, there are two possibilities. Either the grid is able to meet this reactive power demand fully or meet it partially. If the grid is able to fully satisfy this demand for reactive power, the machine continues to *deliver* active power of P_e MW but *draws* reactive power of Q_{LOE} MVA and there is no risk of instability. However, the generator is not designed as an induction machine, so abnormal heating of the rotor and overloading of the stator winding will take place.

If the grid were able to meet the reactive power demand only partially then this would be reflected by a fall of the generator terminal voltage. The generator would be under excited. There are certain limits on the degree to which a generator can be operated within the under-excited mode. Therefore, the operation in case of loss of excitation must be quickly detected and checked to avert any shutdown of the generator.

The simplest method by which loss of excitation can be detected is to monitor the field current of the generator. If the field current falls below a threshold, a *loss of field* signal can be raised. A complicating factor in this protection is the slip frequency current induced in the event of loss of excitation and running as an induction generator.

The quantity which changes most when a generator loses field excitation is the impedance measured at the stator terminals. On loss of excitation, the terminal voltage begins to decrease and the current begins to increase, resulting in a decrease of impedance and also a change of power factor.

Thus, loss of excitation can be unambiguously detected by a mho relay located at the generator terminals as shown in the following Section 8.5.4.

8.5.4 Protection Against Loss of Excitation Using Offset Mho Relay

During normal steady-state operation, the impedance seen from the stator terminals, i.e. the apparent impedance lies in quadrant I, of the R-X plane as shown in Figure 8.12.

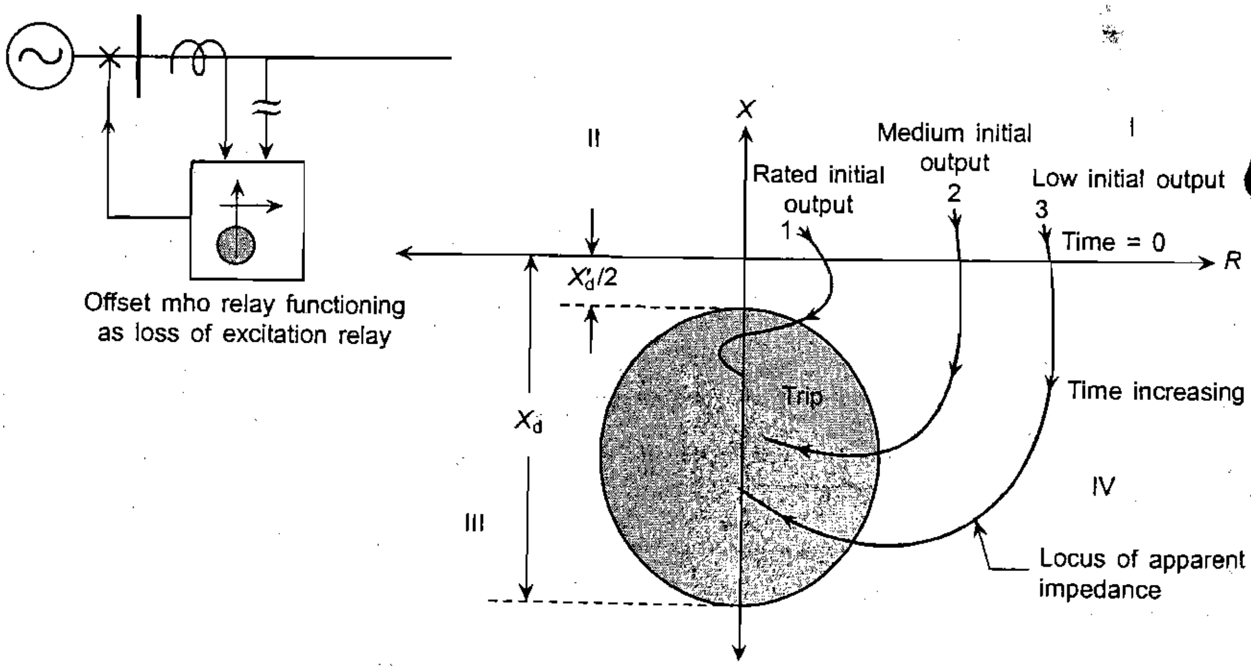


Figure 8.12 Protection against loss of excitation.

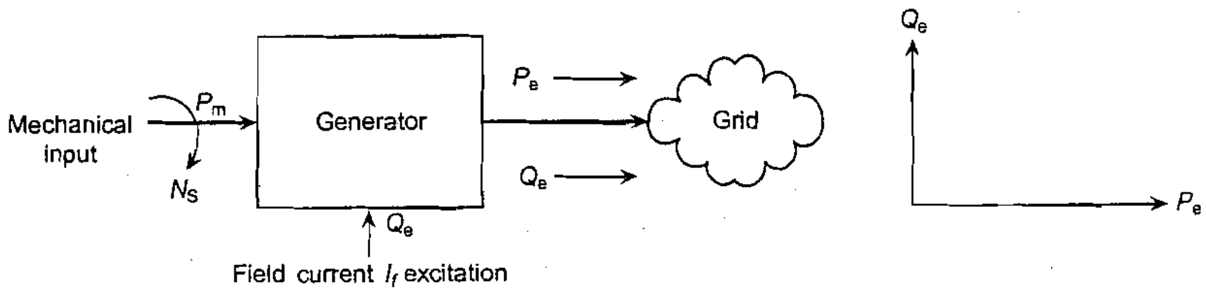
After the loss of excitation, the apparent impedance enters quadrant IV. The exact locus of the apparent impedance and the rate at which it is traced out depends upon the initial complex power that was being delivered by the generator. If the initial power output was high then the locus is traced out quickly. However, if the initial power output was low then the locus is traced out rather slowly (taking up to a few seconds).

In order to keep the generator online as long as it is safe, the generator may not be instantaneously tripped in case of loss of excitation. As soon as loss of excitation is detected by the relay, an alarm may be sounded and an attempt may be made to see if excitation can be restored.

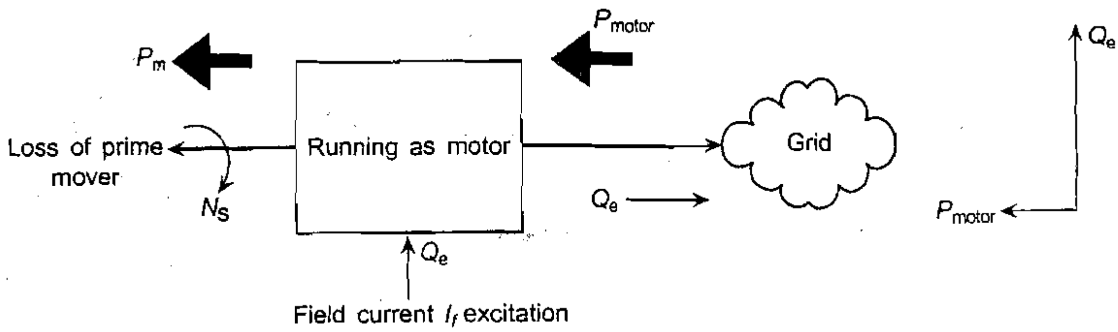
A mho type distance relay with offset characteristic may be used for protection against loss of excitation. The offset is by an amount equal to $X'_d/2$. The impedance setting of the relay is $|X_d|$ at an angle of –90° as shown in Figure 8.12. In order to give time for change over to the standby exciter by the control circuitry, the relay operation can be delayed by about 0.5–3 s.

8.5.5 Loss of Prime Mover

In case of loss of prime mover, i.e. loss of mechanical input, the machine continues to remain synchronized with the grid, running as a synchronous motor. The machine, now, draws a small amount of active power (compared to its rating) from the grid in order to drive the turbine and meet the losses taking place in the machine. At the same time, the machine supplies reactive power to the grid since its excitation is intact. This is depicted in Figure 8.13(a) and (b). Running in this mode is not harmful to the generator, but is definitely harmful to a prime mover like a steam turbine.



(a) Before loss of prime mover



(b) After loss of prime mover

Figure 8.13 Loss of prime mover.

Normally, loss of steam supply to the turbine causes loss of prime mover. When the machine runs as a motor, there is a churning of trapped steam in the turbine causing objectionable temperature rise and damage to the blades. Therefore, the loss of prime mover needs quick detection followed by tripping of generator.

When the prime mover is lost, the generator starts drawing real power from the grid, supplying the reactive power to the grid as before. The real power drawn from the grid is quite small compared with the generator rating. The generator draws real power which is just enough to meet the losses and the load put on it by the turbine. Hence, the magnitude of stator current is smaller than when it was generating, but the stator current undergoes 180° phase shift as shown in Figure 8.14.

This suggests that if we use a directional relay with an MTA of 180° (using generator phase angle conventions) as shown then it would detect the loss of prime mover as the current phasor would reverse and enter the trip region. However, the magnitude of this reversed current phasor is quite small compared to the forward current as the generator draws just enough real power to meet the losses and drive the turbine. Hence, the directional relay for detecting the loss of prime mover needs to have a high degree of sensitivity compared to directional relays used for over-current application.

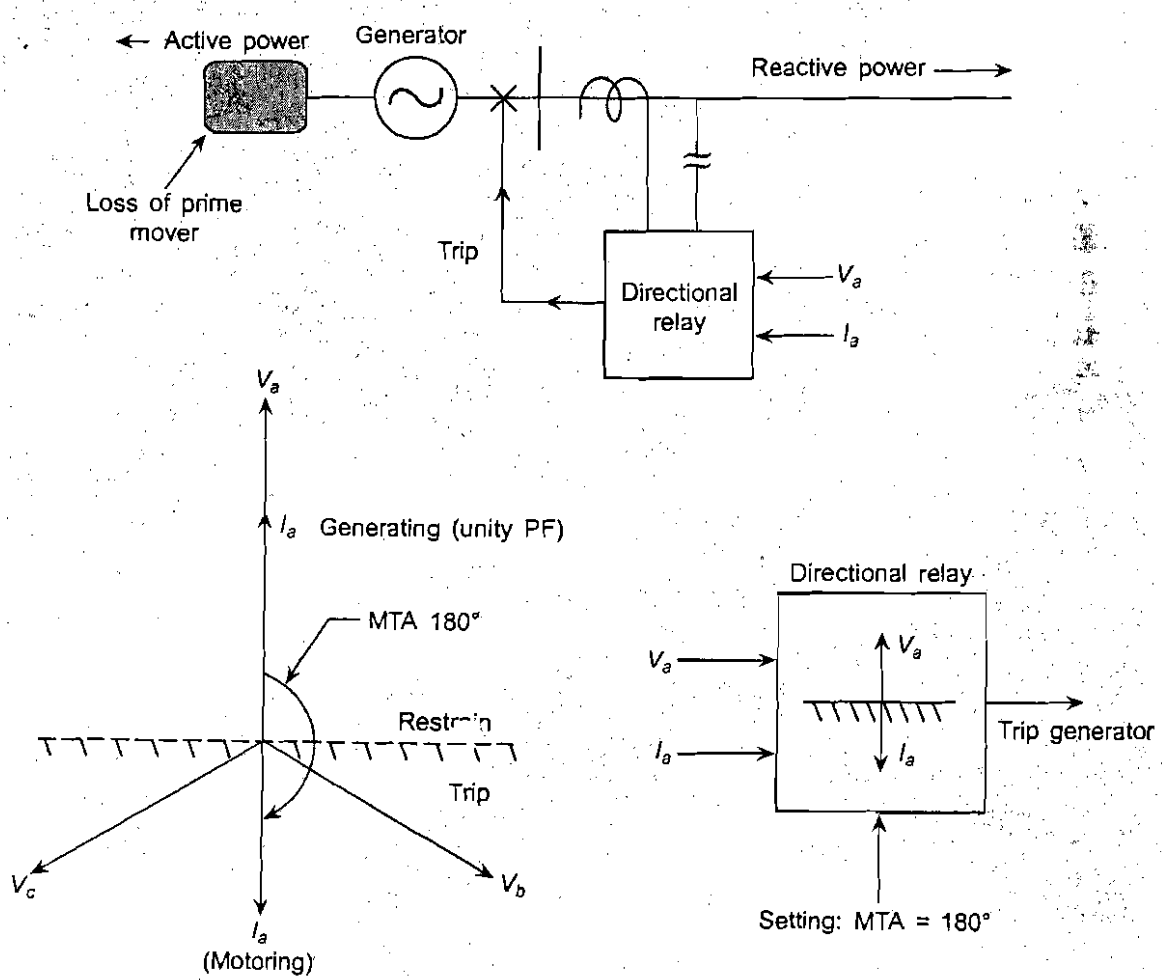


Figure 8.14 Directional relay for protection against loss of prime mover.

Review Questions

1. Discuss the scenario that the turbo-alternator presents to the protection engineer.
2. Tripping the main circuit breaker is not enough protection for a generator. Explain.
3. What are the various faults to which a turbo-alternator is likely to be subjected?
4. Differentiate between longitudinal and transverse differential protection.
5. Why conventional differential protection cannot detect inter-turn faults on the same phase?
6. What are the typical values of % bias used for generator protection? How does this setting compare with that of similar protection for transformer?
7. What special type of winding construction is required in case of transverse differential protection?
8. What are the various abnormal operating conditions to which a modern turbo-alternator is likely to be subjected?
9. Why the first ground fault on the rotor does not cause any damage while a second fault can be catastrophic?
10. What do you mean by loss of excitation (LOE) (in the context of generator protection)?
11. Why does a generator need to be tripped in case of loss of excitation?
12. Why is loss of excitation difficult to detect by monitoring the field current?
13. How does a LOE distance relay work?
14. What causes over-speeding? Explains the remedial action that needs to be taken to prevent over-speeding.
15. What causes loss of prime mover?
16. Can a generator be allowed to run with its prime mover lost? If not, why?
17. How is loss of prime mover detected? What are the problems encountered in implementing this protection?

9 Induction Motor Protection

9.1 Introduction

A stupendous number of induction motors are being used in the industry. The induction motor is truly the *workhorse* of the modern age. Even though the speed control of induction motor is not simple and efficient, the reason for the motor's popularity is its ruggedness and simplicity. However, with the introduction of power electronic controllers, the case of speed/torque control of the induction motor is now comparable with that of the dc motor.

Induction motors come in a wide range of ratings, from fractional horsepower motors used in tools and domestic appliances to motors of megawatt rating used for boiler feed pump in thermal power stations. A broad classification is presented in Table 9.1.

Table 9.1 Broad classification of induction motors

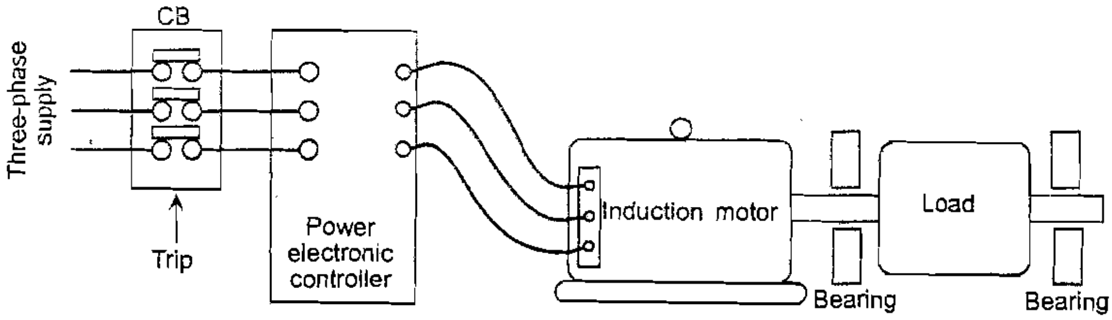
Small	*Medium*	*Big*
FHP	> 50 HP	> 1500 HP
< 1 kW	> 40 kW	> 1000 kW

It is not possible to make any general statements about the protection of induction motor, since the protection scheme depends on the size (horsepower/kW rating) of the motor and its importance in the system. This is the reason why induction motor protection has not been standardized to the extent that other protection schemes have been.

However, regardless of what protection we may provide, all motors, big or small, are subjected to similar faults and abnormal operating conditions.

9.2 Various Faults and Abnormal Operating Conditions

The induction motor cannot be considered in isolation. On the one side, it is connected to the supply, possibly through some kind of power electronic controller and on the other side, it is mechanically coupled to the load. Therefore, the induction motor is subjected to a large number of faults and abnormal operating conditions as depicted in Figure 9.1.



Supply	Motor	Load
1. Fault on motor terminals	1. Phase faults	1. Failure of bearing
2. Unbalanced supply voltage	2. Ground faults	2. Prolonged overload
3. Single phasing	3. Inter-turn faults	3. Rotor jam
4. Reduced supply voltage		
5. Reversal of phases		

Figure 9.1 Abnormal operating conditions and faults experienced on induction motors.

9.3 Starting Current

An induction motor draws a very large starting current, of the order of 6 to 8 times the full-load current if started direct-on-line. The amplitude of the starting current may be comparable to fault current. Therefore, the over-current protection provided to the motor must be able to discriminate between a genuine fault and an over-current due to starting of the motor. Hence, coordination between the starting characteristic of the motor and the over-current relay is required. Figure 9.2 shows the starting current superimposed on the thermal capability curve of the motor, and the characteristic of an over-current relay, which might be used for protection of the motor. It can be seen from Figure 9.2 that the OC relay characteristic must be above the starting characteristics but below the thermal characteristics of the motor. This will ensure that the protective relay does not operate during starting phase the motor but will positively operate when the load exceeds the motor's thermal capability.

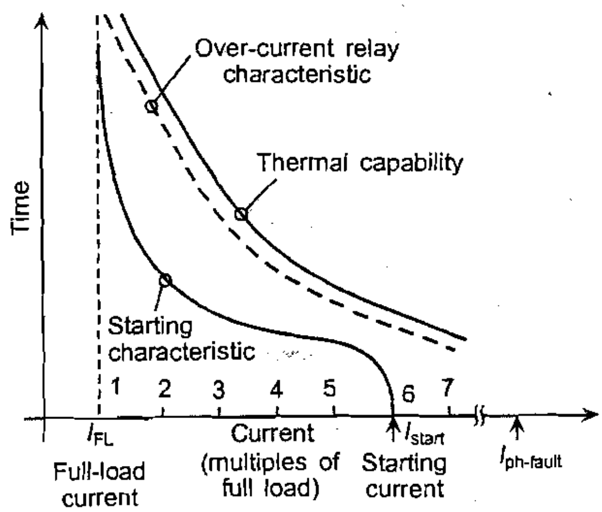


Figure 9.2 Starting and thermal characteristics of induction motor.

9.4 Electrical Faults

9.4.1 Fault on Motor Terminals

The phase-fault current at the terminals of a motor is considerably larger than any normal current such as starting current or any internal-fault current. Hence, a high set instantaneous over-current relay is recommended for fast, reliable, inexpensive and simple protection.

9.4.2 Phase Faults Inside the Motor

Protection against phase faults as well as ground faults can be provided using either fuses or over-current relays depending upon the voltage rating and size of the motor. Most motors will be protected by HRC fuses (Figure 9.3). The fusing current should be greater than the starting current of the motor. The fuse operating time should be less than the permissible *locked rotor time* of the motor. The locked rotor time is the time for which the rotor can be safely stalled with full supply voltage applied to the stator.

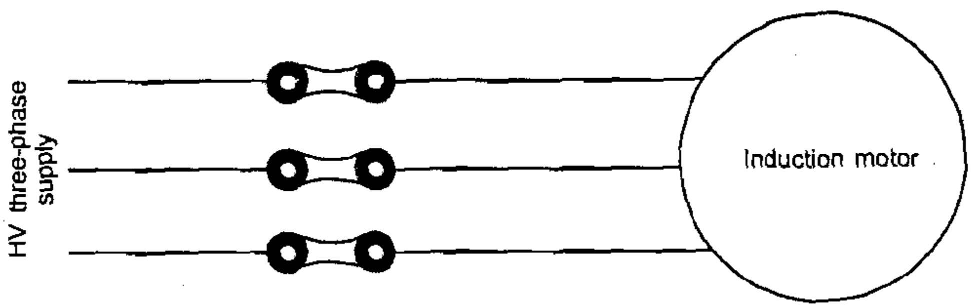


Figure 9.3 HRC fuses for protection of induction motor.

Big motors, which are high voltage motors, will need to be provided with an over-current protection for increased accuracy of protection as shown in Figure 9.4. The thermal capability characteristic of the motor should be kept in mind while applying over-current protection. The OC relay characteristic should be below the thermal capability characteristic as shown in Figure 9.2.

In case of high impedance ground faults inside the motor, the fault current may happen to be less than the full-load current. Such faults are difficult to detect using over-current approach. A current balance type of protection caters for such faults as explained in Section 9.4.3.

In case of big motors whose kVA rating is more than half of the supply transformer kVA rating, the current for a three-phase fault may be less than five times the current for locked rotor condition. In such cases, it is recommended to use percentage differential protection as shown in Figure 9.5. If the motor kVA rating is less than half of the supply transformer kVA rating, over-current relays can be relied upon. The logic for this criterion can be explained as follows:

Assume a motor is connected to a supply transformer with 8% impedance. The maximum fault current at the transformer secondary with an infinite source is:

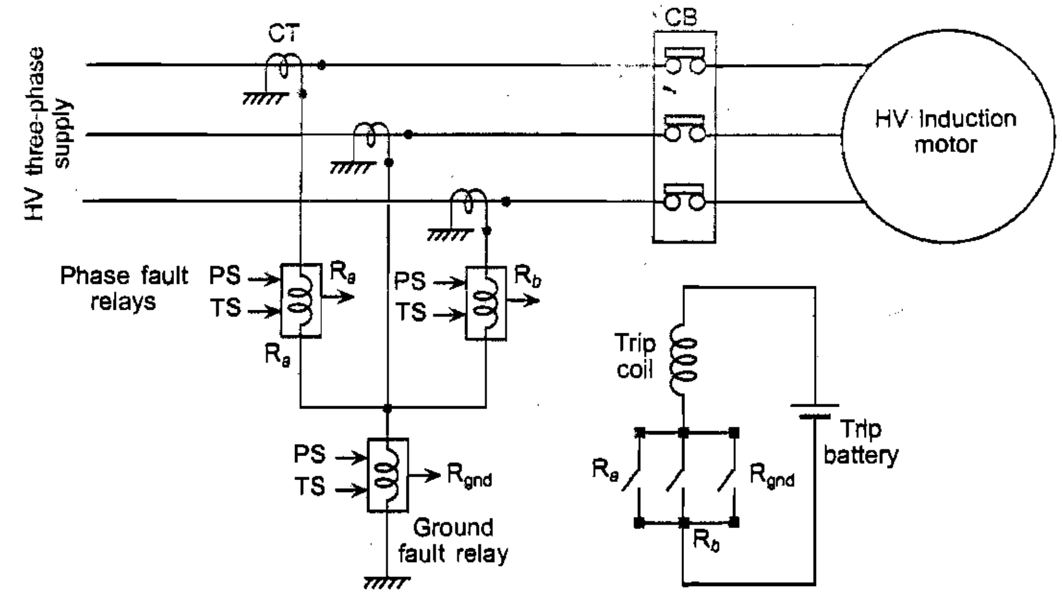


Figure 9.4 Phase fault and ground fault protection of HV induction motor.

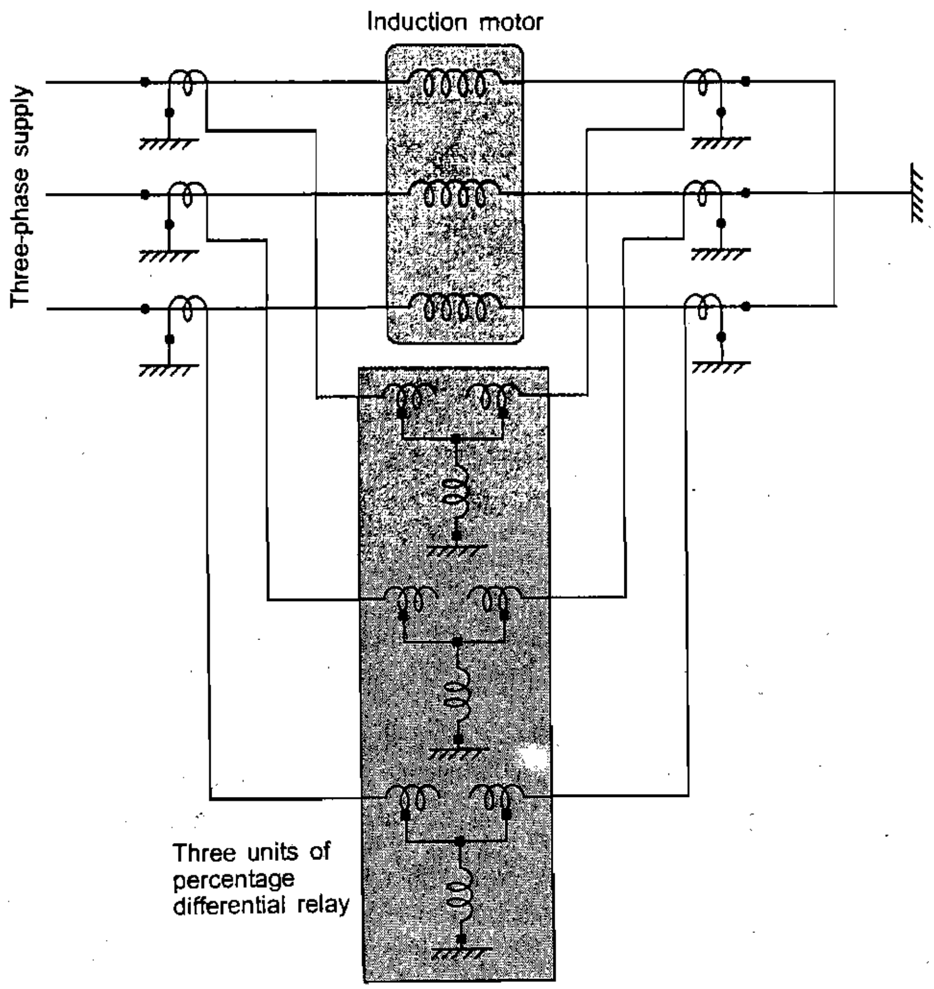


Figure 9.5 Percentage differential relay for protection of induction motor.

$$I_{3\text{-ph}} = \frac{1}{0.08} = 12.5 \text{ per unit on transformer base}$$

The maximum motor starting current in this case is

$$I_{LR} = \frac{1}{0.08 + X_M}$$

where X_M is the motor impedance. In order that $(I_{3\text{-ph}}/I_{LR}) > 5$, X_M must be greater than 0.32 per unit on the transformer kVA base.

If the motor has a full-voltage starting current of six times the full load, then $X_M = 1/6 = 0.167$ on the motor rated kVA base. With a motor kVA of half of the transformer kVA, an X_M of 0.167 would be 0.333 on the transformer base, which is greater than 0.32. Clearly, this rule of thumb should only be applied when there is no appreciable deviation from the parameters assumed above.

9.4.3 Ground Faults Inside the Motor

Figure 9.6 shows an arrangement for detecting high impedance ground faults. The three-phase line conductors carrying current to the motor form the primary of a transformer. The secondary consists of a pick-up coil wound on the core.

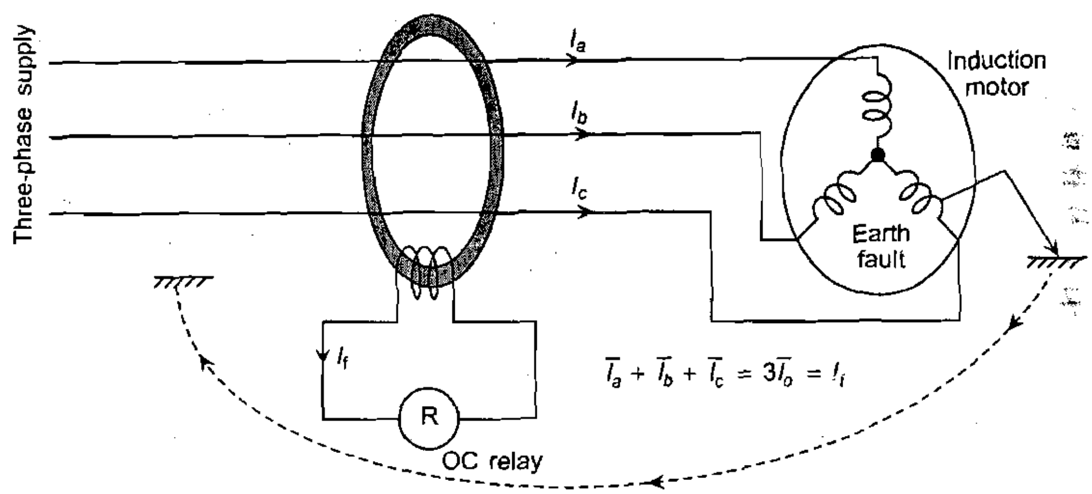


Figure 9.6 Earth fault protection for induction motor.

When the motor is running normally, the instantaneous sum of all the three line currents is zero. Thus, there is no net flux in the core. Hence, the pick-up coil does not have any voltage induced in it.

Now, consider a ground fault as shown. The three line currents do not sum up to zero. Thus, there is a net primary mmf proportional to the fault current I_f, returning to the supply neutral through the fault path. There is, thus, a flux in the CT core. The pick-up coil has a voltage induced which can be sensed by an electronic circuitry or the pick-up coil can be made to drive the operating coil of a sensitive relay.

If an electronic circuit is used to sense the voltage developed by the pick-up coil, the current balance relay described above can be made extremely sensitive and can detect earth fault currents down to a few tens of milliamperes. Very high sensitivity, however, is likely to cause some nuisance tripping.

9.4.4 Inter-turn Faults

Inter-turn faults on the same phase are difficult to detect because they do not cause appreciable change in the current drawn by the motor. However, such faults cause hot spots to develop, leading to deterioration of insulation.

No specific protection against inter-turn faults is needed for most motors except very big motors. Embedded temperature detectors may be relied upon to provide protection against inter-turn faults.

9.5 Abnormal Operating Conditions from Supply Side

An induction motor is subject to many abnormal operating conditions as far as the electric supply side is concerned. In some cases, quick disconnection of the motor may be needed and, in others, only an alarm may be sounded for an operator to take corrective action or be ready for shutdown.

9.5.1 Unbalanced Supply Voltage

Large induction motors are very sensitive to unbalances in supply voltage. The negative sequence component, which comes into picture because of the unbalance in the supply, is particularly troublesome. This is because the motor offers very small impedance to the negative sequence currents. In fact, the negative sequence impedance is less than the positive sequence standstill-impedance as shown in Figure 9.7. Thus, a 4% negative sequence supply voltage causes more than 24% negative sequence current to be drawn by the motor, if the starting current of the motor is six times the full-load current. This causes increased heating of the stator.

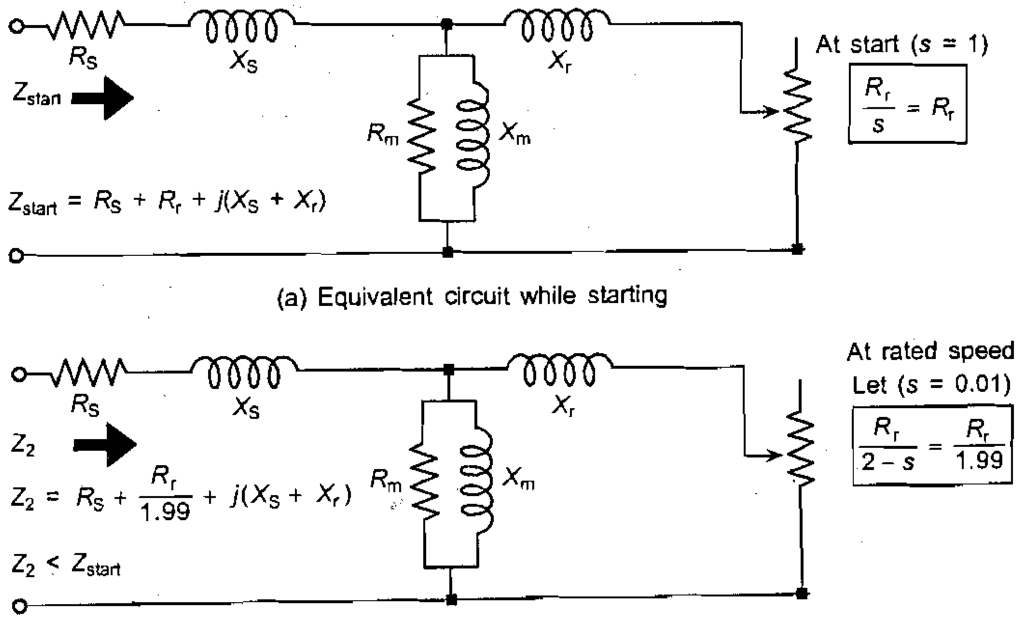


Figure 9.7 Equivalent circuit of induction motor.

Further, the magnetic field due to negative sequence rotates at synchronous speed N_S in a direction opposite to that of the rotor which is rotating at a speed equal to (sN_S), which is slightly less than the synchronous speed, where s is the slip of the motor. This causes currents of $[f(2 - s)]$ frequency, i.e. almost double the supply frequency, to be induced in the rotor circuit. Because of skin effect, the rotor offers five to ten times its normal resistance to these double frequency currents, thus, causing excessive heating of the rotor.

Therefore, for large motors any unbalance in the supply voltage needs to be quickly detected and corrective action taken. A scheme for detecting unbalanced supply voltage is shown in Figure 9.8.

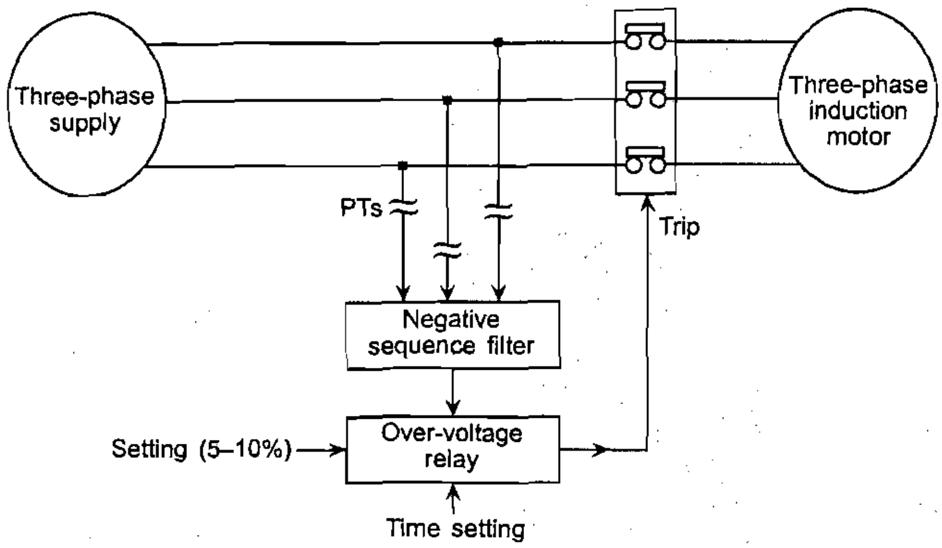


Figure 9.8 Negative sequence voltage relay for protection against unbalance in supply voltage.

There are certain situations where the negative sequence relay does not operate correctly. For example, if there is an open circuit fault between the supply and the relay then the relay measures the negative sequence voltage across the motor, which is substantial and, therefore, the relay operates correctly. This is shown in Figure 9.9.

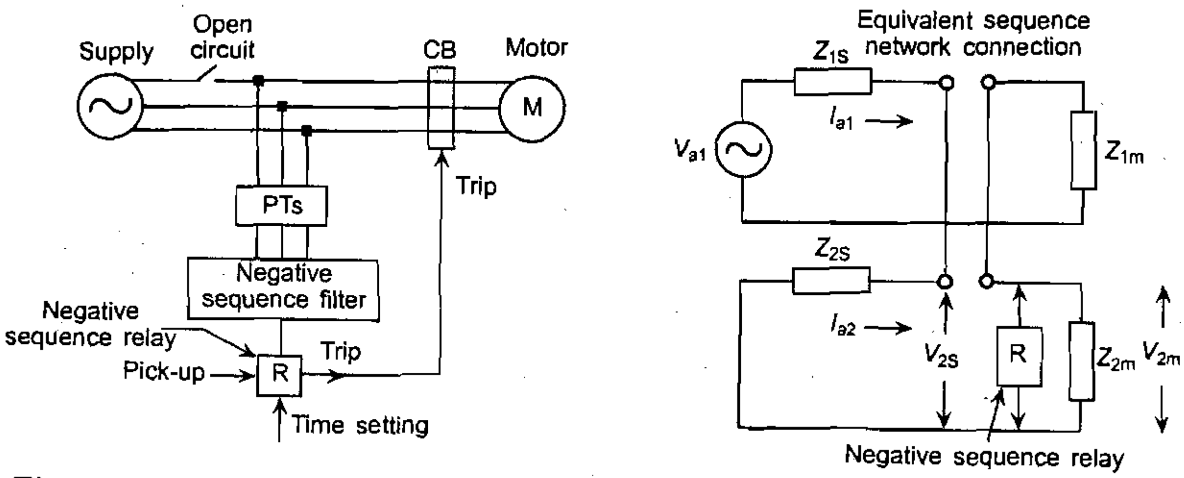


Figure 9.9 Negative sequence voltage relay correctly detects an open circuit between supply and relay.

However, if the open circuit is between the relay and the motor then the negative sequence relay ends up measuring the negative sequence component of the supply voltage, which is very small and does not cause the relay to pick up as shown in Figure 9.10.

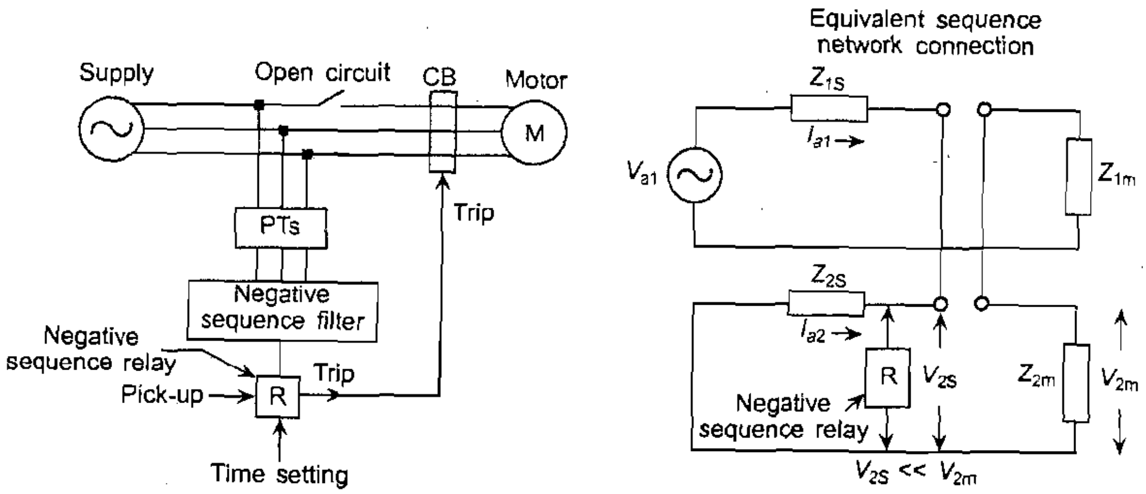


Figure 9.10 Negative sequence voltage relay fails to detect an open circuit between relay and motor.

For positive detection of such faults, we need to detect the negative sequence component in the line currents. This is described in Section 9.5.2.

9.5.2 Single Phasing

Single phasing can occur because of a non-closure of one pole of a three-phase contactor or circuit breaker, a fuse failure or similar causes.

Single phasing causes negative sequence current to flow. The motor has a limited ability to carry negative sequence currents, because of thermal limitations.

Single phasing causes the motor to develop insufficient torque, leading to stalling, making the motor to draw excessive current and finally leads to burn out unless the motor is tripped.

Thus, there is a thermal limit on the amount of the negative sequence current that can be safely carried by the motor. The quantity $I_2^2 t$ represents the energy liberated as heat due to negative sequence current I_2.

$I_2^2 t = 40$ is conventionally used as the thermal capability of motor to carry negative sequence current.

Figure 9.11 shows the characteristic of a relay for detecting imbalance in the line currents. The relay consists of two units. One unit balances I_a against I_b while the other balances I_b against I_c. When the currents become sufficiently unbalanced, torque is developed in one or both units causing the relay to trip. The relay can be set to pick up when negative sequence current I_2 = 5–30% of the full-load current.

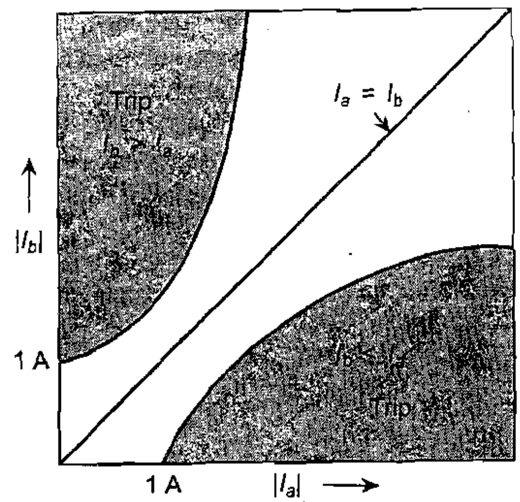


Figure 9.11 Negative sequence current relay to detect single phasing.

9.5.3 Reduction in Supply Voltage

The torque developed by an induction motor is proportional to the square of the applied voltage, therefore, any small reduction in voltage has a marked effect on the developed torque. The reduced torque may cause the motors to lose speed and draw more current.

Large motors should be disconnected when a severe low voltage condition persists for more than a few seconds.

Under-voltage relays may be used for protection against reduced supply voltage.

9.5.4 Reversal of Phases

When there is a reversal of phase sequence, possibly due to reversal of phases, the motor rotates in a direction opposite to its normal direction of rotation. In several applications, such as hoists and elevators, this is a serious hazard. In such situations, a phase sequence detector, which is generally a part of under-voltage/over-voltage, or a negative phase sequence protection scheme, can be used to instantaneously trip the motor.

9.6 Abnormal Operating Conditions from Mechanical Side

9.6.1 Failure of Bearing and Rotor Jam

Bearing failure or rotor jam causes excessive load torque on the motor. This is reflected in the increase in stator current. In order to discriminate between rotor jam and other operating conditions that can also cause over-current, the high current is not recognized as a jam condition unless the motor has reached its rated speed and the current is in excess of 20% of full load persisting for at least twice the locked rotor time setting.

9.6.2 Overload

Thermal overload relays offer good protection against short, medium, and long duration overloads but may not provide protection against heavy overloads shown in Figure 9.12.

The long time induction over-current relays provide good protection against heavy overloads but over-protection against light and medium overloads, as shown in Figure 9.13. Therefore, a combination of both the relays provides adequate protection as shown in Figure 9.14.

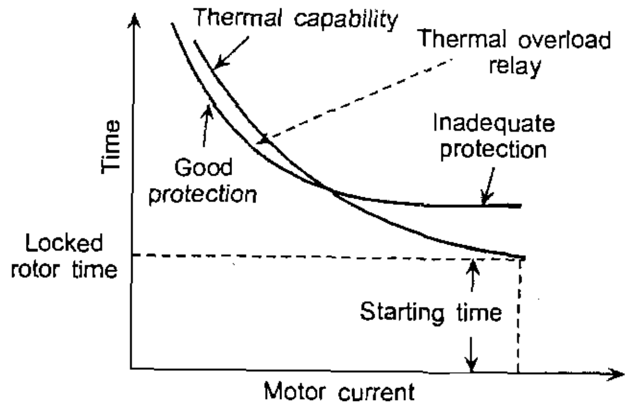


Figure 9.12 Thermal overload relays offer good protection against short, medium, and long duration overloads.

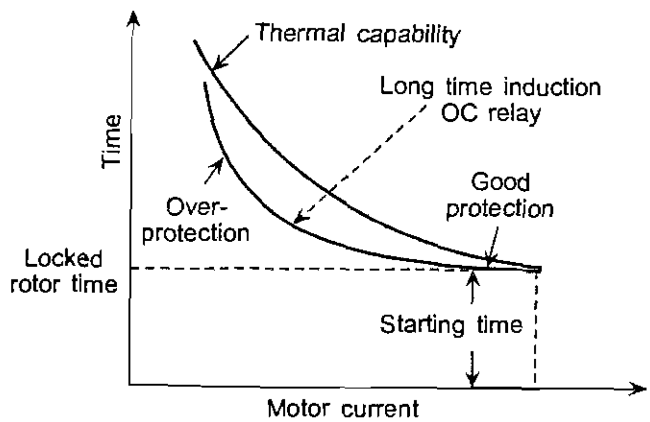


Figure 9.13 Long time induction OC relays offer good protection against heavy overloads.

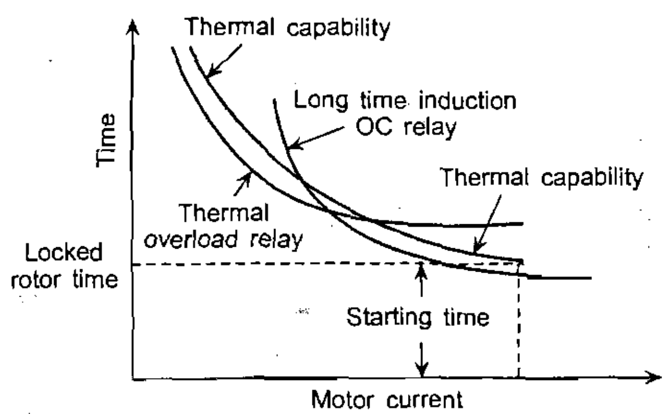


Figure 9.14 Combination of thermal overload relays and OC relays provides complete thermal protection.

Resistance temperature detector relays (RTDs)

These relays operate from one or more RTDs that monitor the temperature of the machine winding, motor or load bearings or load case. They are usually applied to large motors of 1500 HP and above.

Figure 9.15 shows an RTD which is embedded in the machine connected to a Wheatstone bridge. The arms of the bridge are adjusted so that the bridge is balanced at normal temperature. A sensitive relay in the form of a contact making dc galvanometer may be connected as a detector.

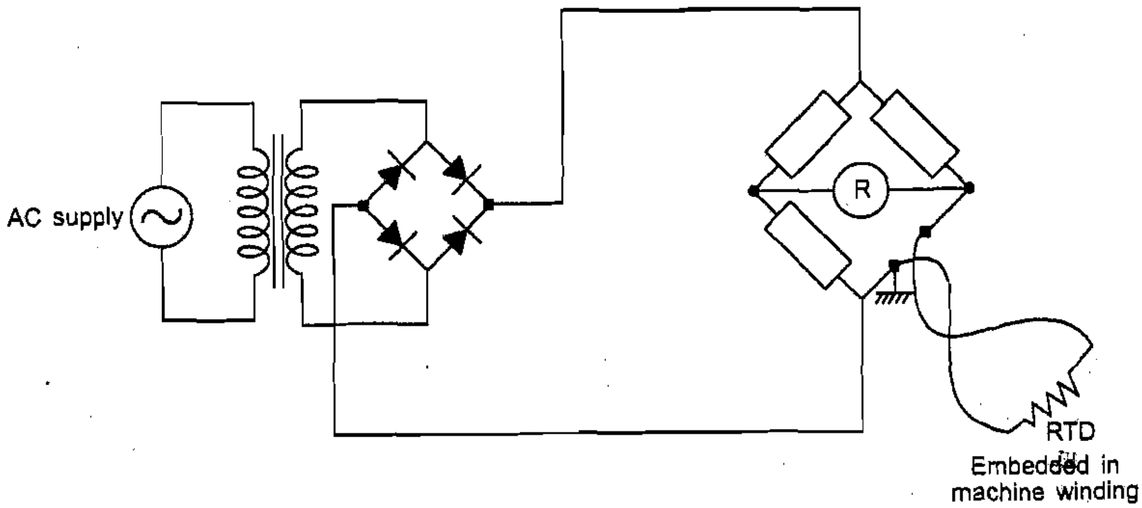


Figure 9.15 RTD embedded in the machine connected to a bridge.

The RTD is an excellent indicator of average winding temperature, however, it is influenced by ambient temperature, ventilation conditions and recent loading history. Several types of RTDs are available for use in temperature monitoring, namely 10 Ω copper, 100 Ω nickel, 120 Ω nickel, 120 Ω platinum.

Thermal replica relays

Replica type relays are designed to replicate, within the relay operating unit, the heating characteristics of the machine. Thus, when current from the CT secondary passes through the relay, its time over-current characteristic approximately parallels that of the machine capability curve at moderate overload.

The thermal replica relays are recommended when the embedded temperature detectors are not available, otherwise the RTD input type relays may be used.

Replica relays are typically temperature compensated and operate in a fixed time at a given current regardless of relay ambient variations. Although this characteristic is desirable for the stated condition, it produces under-protection for high motor ambient and over-protection for low motor ambient.

9.7 Data Required for Designing Motor Protection Schemes

The following data is required for designing the various motor protection schemes:

- HP rating
- Supply voltage
- Full-load current
- Permissible continuous allowable temperature rise
- Locked rotor current
- Permissible maximum time with locked rotor
- Accelerating time
- Starting voltage

Review Questions

1. What are the various abnormal operating conditions from supply side to which an induction motor is likely to be subjected?
2. What are the various abnormal operating conditions from the load (mechanical) side to which an induction motor is likely to be subjected?
3. Why is an induction motor very sensitive to unbalance in supply voltage?
4. What are the consequences of running an induction motor on unbalanced supply voltage?
5. What are the effects of running an induction motor at reduced supply voltage?
6. Why is protection of an induction motor against reversal of phase sequence required?
7. What kind of protection is provided to an induction motor against overload?
8. How is the thermal replica relay used to protect the induction motor?
9. What are the effects of single phasing on the induction motor?
10. What is the effect of blocked rotor on the motor? What protection is provided against blocked rotor?
11. Why a negative sequence voltage relay cannot detect single phasing between relay and motor but can detect single phasing between the supply and the relay?
12. What data is required for designing a scheme for motor protection?

STATIC RELAYS

The term static relay generally refers to a relay where active semiconductor devices such as diodes, transistors, ICs thyristors, logic gates, etc are employed for processing the electrical input signals in order to obtain the desired relay characteristic.

Static relays may include a dc polarised relay as a slave relay. The slave relay is an output device and does not perform the function of measurement or comparison. It simply closes contacts. It is used because of its low cost. In a fully static relay, a thyristor is used in place of the electromagnetic slave relay. The electromechanical relay used as a slave relay provides a number of output contacts at low cost. Electromagnetic multicontact tripping arrangements are much simpler than an equivalent group of thyristor circuits.

Advantages of static Relays over Electromagnetic Relays

1. Reduced Burden : static relays pose a reduced burden on protective CT. & PTs as compared to electromagnetic relays because of lower VA requirements of the static circuits.

   The reduced burden leads to (i) better accuracy of CTs & PTs, (ii) ~~to~~ less chances of CT saturation, (iii) reduced size ~~of~~ & cost of CTs & PTs due to lower VA rating.

2. No Moving Parts : Solid-state devices have no moving elements. Hence, in static relays there are no problems of contact bounce, arcing, contact erosion, dry contact, spring restraint, etc. Moreover, the static relays have operational advantages like high torque, absence of friction, etc.

3. Fast Response: Very small operating time of the order of one [illegible] or even less can be achieved with static relays.

4. Characteristic: complex relaying characteristics can easily & precisely be achieved.

5. Sensitivity: The ease of providing amplification enables greater sensitivities to be achieved.

6. Miniaturisation: Since compact & small sized ICs are available the size of the static relay gets reduced. This saves panel space.

7. Robustness: High resistance to shocks & vibration as there are no moving parts.

8. Less Maintenance: With the absence of bearing friction and contact trouble, maintenance required is greatly reduced.

9. Low Resetting Time: Resetting time can be reduced using static circuitry. Where fast automatic reclosing of circuit breakers is involved, the resetting time of a relay may be a critical parameter for obtaining selectivity.

10. Low Overshoot: As the overtravel time is practically negligible in static relays, discrimination time between successive relays can be reduced.

Limitations of Static Relays

1. Vulnerability to Voltage Transients: Voltage spikes can easily override the signal and cause serious malfunctions of the static relay or can even damage the semiconductor components.

Good filtering of the auxiliary supply, surge suppression & shielding can be used to avoid/minimise these problems.

2. <u>Temperature Sensitivity</u>: Characteristics of static relays ~~are~~ may vary with the variation of temperature.

Temperature compensation can be made by using thermistors and by using digital techniques for measurements, etc.

There were ~~are~~ other concerns like overload capacity ~~&~~ and reliability as compared to electromechanical relays, but the situation is much improved now and as such do not pose any problem if designed & implemented carefully.

BASIC ELEMENTS OF STATIC RELAYS

The trend is towards the use of ICs wherever possible instead of building complicated circuits with discrete components like diodes, transistors, resistors, capacitors, etc...

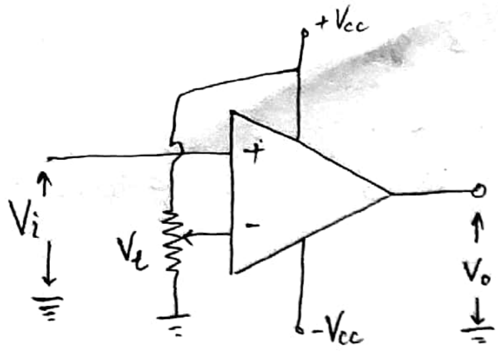
ICs of logic circuits, OP-AMPs, registers, counters, ADCs, DACs, and a lot of other devices are available commercially.

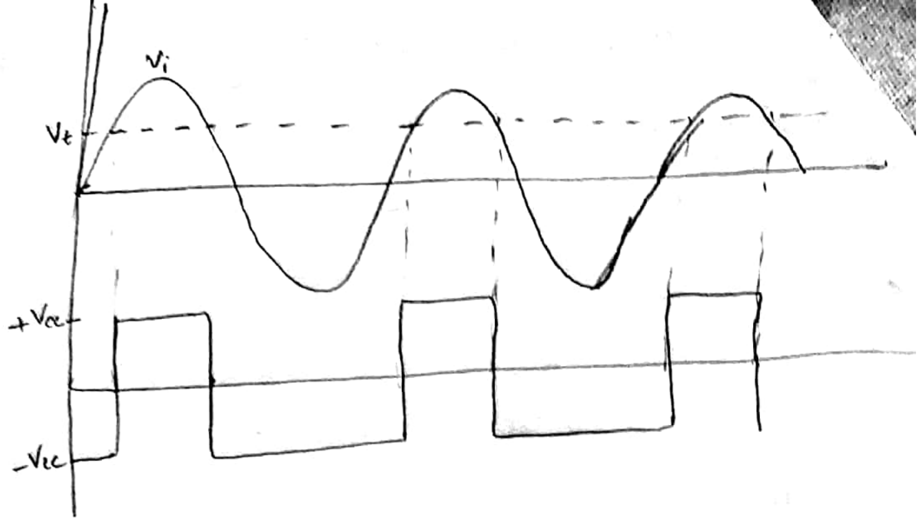
Transistors, which form the bricks of the ICs are now available in the fractional micron ranges, thus leading to very high densities and consequent reduced sizes of chips. Application specific ICs (ASICs), which are custom-built for particular specific applications have also come to the fore now. Thus it would be possible to build ICs functioning as a particular type of protective relay or a combination of two or three types.

The operational amplifier (OP-Amp) is a very powerful circuit element useful for a variety of analog operations. Fundamentally it is a differential amplifier with additional stages incorporated to get a convenient output level.

* <u>Level Detector</u>

An OP-AMP based level detector and corresponding typical waveforms are shown in next figure.





The same circuit can be modified to act as Zero Crossing Detector (ZCD) by making the reference as zero.

* Comparators

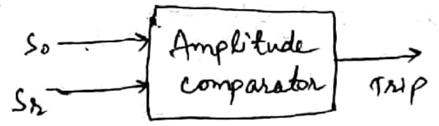
When fault occurs on a system, the magnitude of voltage, current and phase angle between voltage & current may change. These quantities during faulty conditions are different from those under healthy conditions. The static relay circuitry is designed to recognise the changes and to distinguish between healthy & faulty conditions. ~~Eithe~~ Either magnitudes of voltage/ current (or corresponding derived quantities) are compared or phase angle between voltage & current (or corresponding derived quantities) are measured by the static relay circuitry and a trip signal is sent to the circuit breaker when a fault occurs.

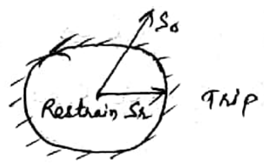
The part of the circuitry which compares the two actuating quantities either in amplitude or phase is known as the comparator.

Amplitude Comparator

An amplitude comparator compares the magnitudes of two input quantities, irrespective of the angle between them. The amplitude comparator has two inputs S_o & S_r and a trip output. Both are phasors. The input S_o is called the operating quantity and the input phasor S_r is called the restraining quantity. The amplitude comparator follows the simple law

If $|S_o| > |S_r|$ then trip ; else restrain





Phase Comparator

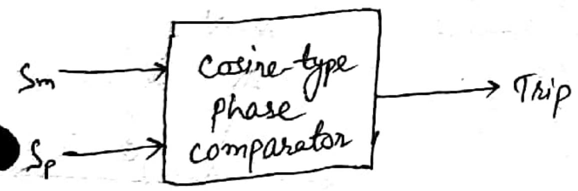
Phase comparators are of two types : the cosine type & the sine type

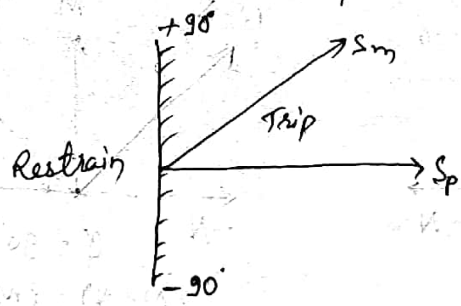
The Cosine-type Phase Comparator

This comparator has two phasors S_p & S_m at its input and has a trip output. The input phasor designated as S_p, is called the polarizing or reference input. The other input phasor S_m, is called the measured input.

The cosine type phase comparator follows the trip law:

If $-90° < Arg(S_m/S_p) < +90°$ then trip ; else restrain

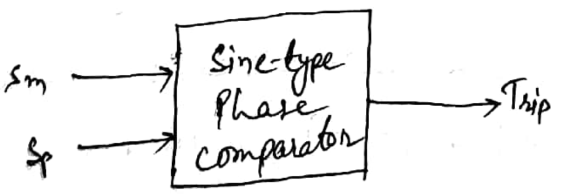




The Sine-type Phase Comparator

This comparator, having the same input quantities as cosine-type, follows the following trip law:

If $0° < Arg(S_m/S_p) < 180°$ then trip ; else restrain

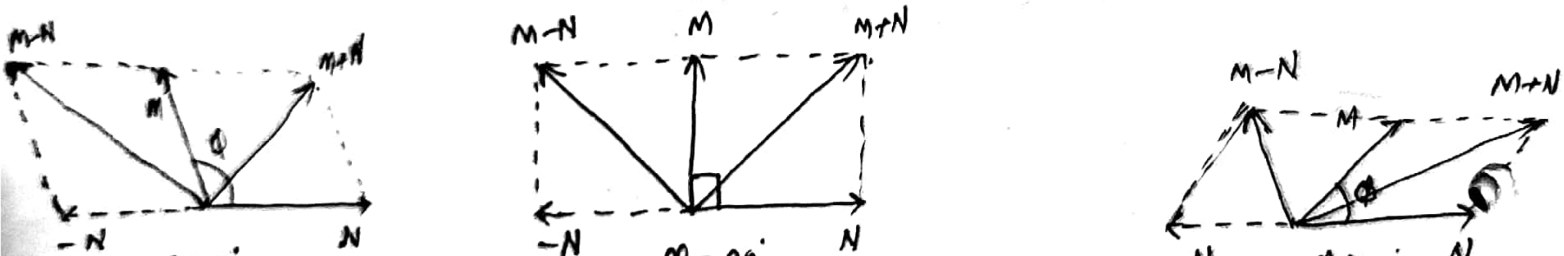


Duality between Amplitude and Phase Comparators

An amplitude comparator can be converted to a phase comparator and vice versa if the input quantities to the comparator are modified. The modified input quantities are the sum and difference of the original two input quantities.

~~Let S_o & S_r be the original inputs to an amplitude comparator. If S_m & S_p are derived from S_o & S_r such that, $S_m = (S_o + S_r)$ and $S_p = (S_o - S_r)$~~

Consider the operation of an amplitude comparator which has two input signals M & N. It operates when $|M| > |N|$. Now change the input quantities to $(M+N)$ & $(M-N)$. As the circuit is designed for amplitude comparison, now with the changed input, it will operate when $|M+N| > |M-N|$. This condition will be satisfied only when the phase angle between M & N is less than 90°.



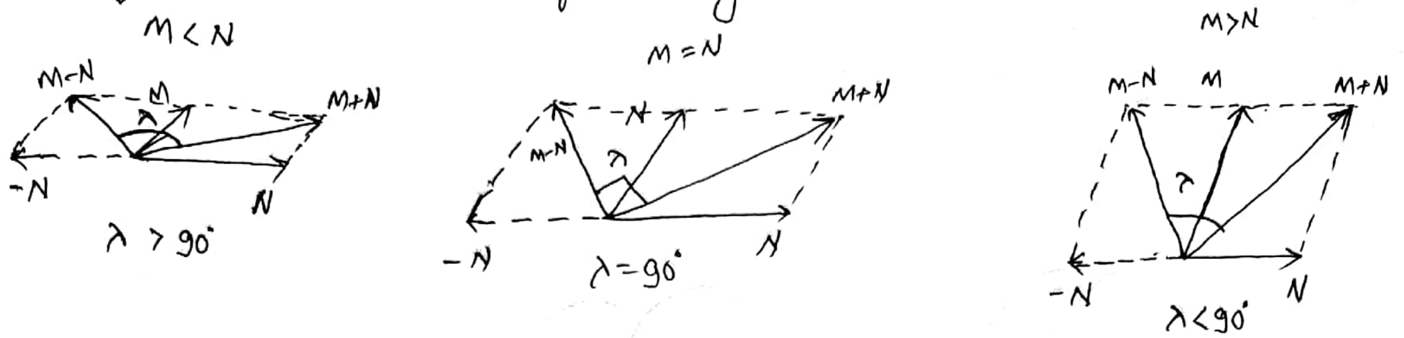
$\phi > 90°$ & $(M+N) < (M-N)$

$\phi = 90°$ $(M+N) = (M-N)$

$\phi < 90°$ $(M+N) > (M-N)$

Above phasor diagrams shows that the comparator with the modified inputs has now become a phase comparator for the original input signals M & N.

Similarly, consider a phase comparator which compares the phases of input signals M & N. If the phase angle between M & N i.e. angle ϕ is less than 90°, the comparator operates. Now change the input signals to $(M+N)$ & $(M-N)$. With these changed inputs, the comparator will operate when phase angle between $(M+N)$ & $(M-N)$ i.e. angle λ (say) is less than 90°. This condition will be satisfied only when $|M| > |N|$.

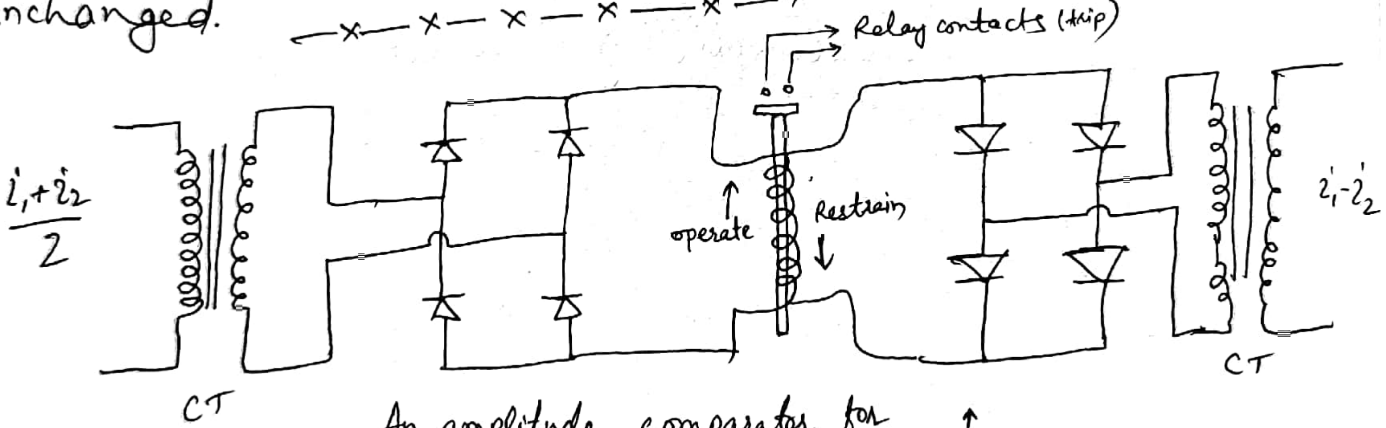


Thus the phase comparator with changed inputs has now become an amplitude comparator for the original input signals M & N.

Thus, the duality theorem can be stated as:

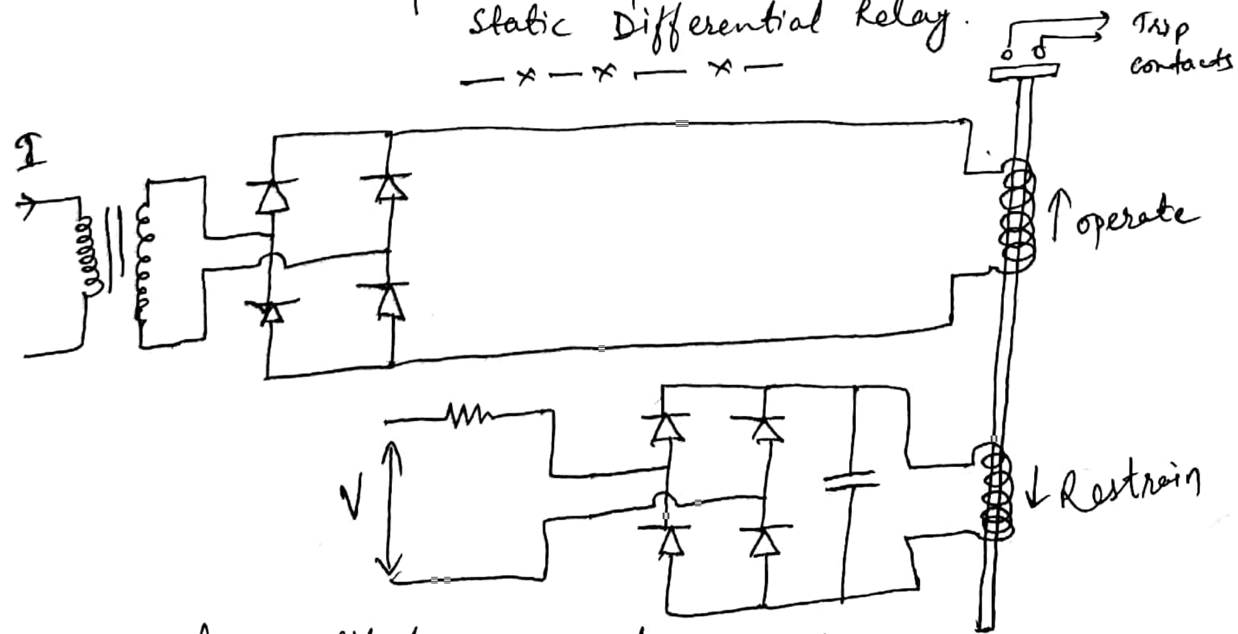
"The two signals, obtained by adding & subtracting the inputs to a comparator, are the inputs suitable for its dual. If such signals are fed to the dual, the output would remain unchanged.

—x—x—x—x—x—x—x—



An amplitude comparator for Static Differential Relay.

—x—x—x—



An amplitude comparator for static Distance relay

NUMERICAL PROTECTION

Protective relays, which started out as meters with contacts, have undergone tremendous evolution over the years. They were soon replaced by electromechanical relays which were sensitive & accurate.

When vaccum tubes were popular, protection engineers implemented relays using vacuum tubes. Then within a year of inventio of the transistor, its use to make static relays was report With the development of large-scale integrated circuits, they were extensively used in the protective relays. The microprocessor that was invented around 1971, revolutionized th electronics scene totally and the development of microprocesso based relay followed soon thereafter.

As the processor based relays work on numbers represe instantaneous values of the signals, hence they are named a numerical relay Other popular names for such relays are dig relay, computer-based relay & microprocessor based relay.

With the tremendous developments in VLSI and comput hardware technology, microprocessors have evolved and ma remarkable progress in recent years. The latest fascinati innovation in the field of computer technology is the devel of microcontrollers, digital signal processors (DSPs) & Field Programmable Gate Arrays (FPGAs) which are making in-road in every activity of the mankind. With the development of f economical powerful & sophisticated microprocessors, microcont llers, DSPs & FPGAs, there is a growing trend to develop numerical relays based on these devices.

The conventional relays of electromechanical and static types had no significant drawbacks in their protection functions, but the additional features offered by micro-processor technologies encouraged the evolution of numerica relays that introduced many changes in power industry.

The numerical relay is the latest development in the area of power system protection and differs from conventio ones both in design & methods of operation. It is based on numerical (digital) devices such as microprocessors, microcontro DSPs, etc. This relay acquires sequential samples of the sig in numeric (digital) data form through the data acquisition system (DAS or DAQ), and processes the data numerically using a relaying algorithm to calculate the fault discrimi and make trip decisions. Thus a numerical relay has an addi entity, the software, which runs in the background and mak the relay functional. Hardware is more or less the same in almost all the numerical relays. The software used i a numerical relay depends upon the processor used and t type of the relay. Hence, with the advent of the numeri relay, the emphasis has shifted from hardware to software

Advantages of Numerical Relays

1. **Compactness & Reliability** : Numerical relays are compact in size and reliable in operation.

2. **Flexibility** : Some general purpose hardware can be used to perform a variety of protection functions with the change of stored program only. Drastic addition and/or alteration of the protection logic hardly require any hardware replacement.

3. **Adaptive Relaying** : Adaptive protection is a recent protection philosophy that permits and acts to make adjustments in various protection functions automatically in order to make them more suitable to prevailing power system conditions.

The behaviour of the processor can be made to change automatically depending on the external conditions which change with time. The basis of this change can be either local information available to the processor, or an external source such as data link or the central computer system.

4. **Self-monitoring & self-testing** Numerical relays have the ability to perform self-monitoring & self-testing functions. The features reduce the need for routine maintenance because the relays automatically take themselves out of service and alert the operator of the problem when they detect function abnormalities.

5. **Economical** : The cost per function of numerical relays is low compared to the cost of their electromechanical & static counterparts. The reduction in cost is due to the lower cost of components, production equipment & production techniques. Numerical relays provide greater functionality at a reduced price.

6. Less Panel Space: Numerical protection systems require significa[ntly] less panel space than required by electromechanical & static systems that provide similar functions. The reduction in size is [a] result of the high level of integration of the hardware and the ability of using one physical device for perform[ing] multiple protection functions.

7. Very low burden: Numerical relays offer very low burden on CTs and PTs. This is helpful in fulfilling the ideal requireme[nt] that sensors should not consume any power. If a sensor consumes power from the quantity it measures, it will lead to distortion of the measured signal. In addition, numerical relays can be programmed to detect saturation of instrument transformers for minimizing incorrect operations.

8. Storage of Historical Data: Reporting features, including sequence of events recording & oscillography are a natural byproduct of numerical protection system. Pre- & Post-fault data can be used for measurement of fault current and statistical analysis of fault occurances.

9. Communication facility: Communication makes the relay more intelligent and the operating personnel can set the relay and also download the fault information with the help of computer. It is also possible to upload the revised software to the relay at site.

10. Merging of Protection, control & metering: Numerical relays ~~of~~ have features meeting the control and metering

the control & metering requirements. So merging them into a single entity is possible. Nowadays, there is a new term introduced for this entity, namely, IED (Intelligent Electronic Device). Any device incorporating one or more processors with the capabili to receive or send data/control signals from or to an externa source is known as IED. Electronic multifunction meters, digital relays, are examples of IEDs. IEDs help in implementing the conce of unmanned substations in electrical distribution systems where all control, metering & protection functions can be done in a remote control room.

Limitations of Numerical Relays

1. **Short Life cycle**: All microprocessor-based sytems, includin numerical protection systems, have short life cycles. Since eact generation of microprocessor based systems increases the functionality as compared with the previous generation, the pace of change makes the numerical protection systems obsolete in shorter times. Because of this, it becomes diffic for the users to maintain expertise in using the latest designs of the equipment. Another variation of this disadvantage is in the form of changes in the software used on the existing hardware platforms.

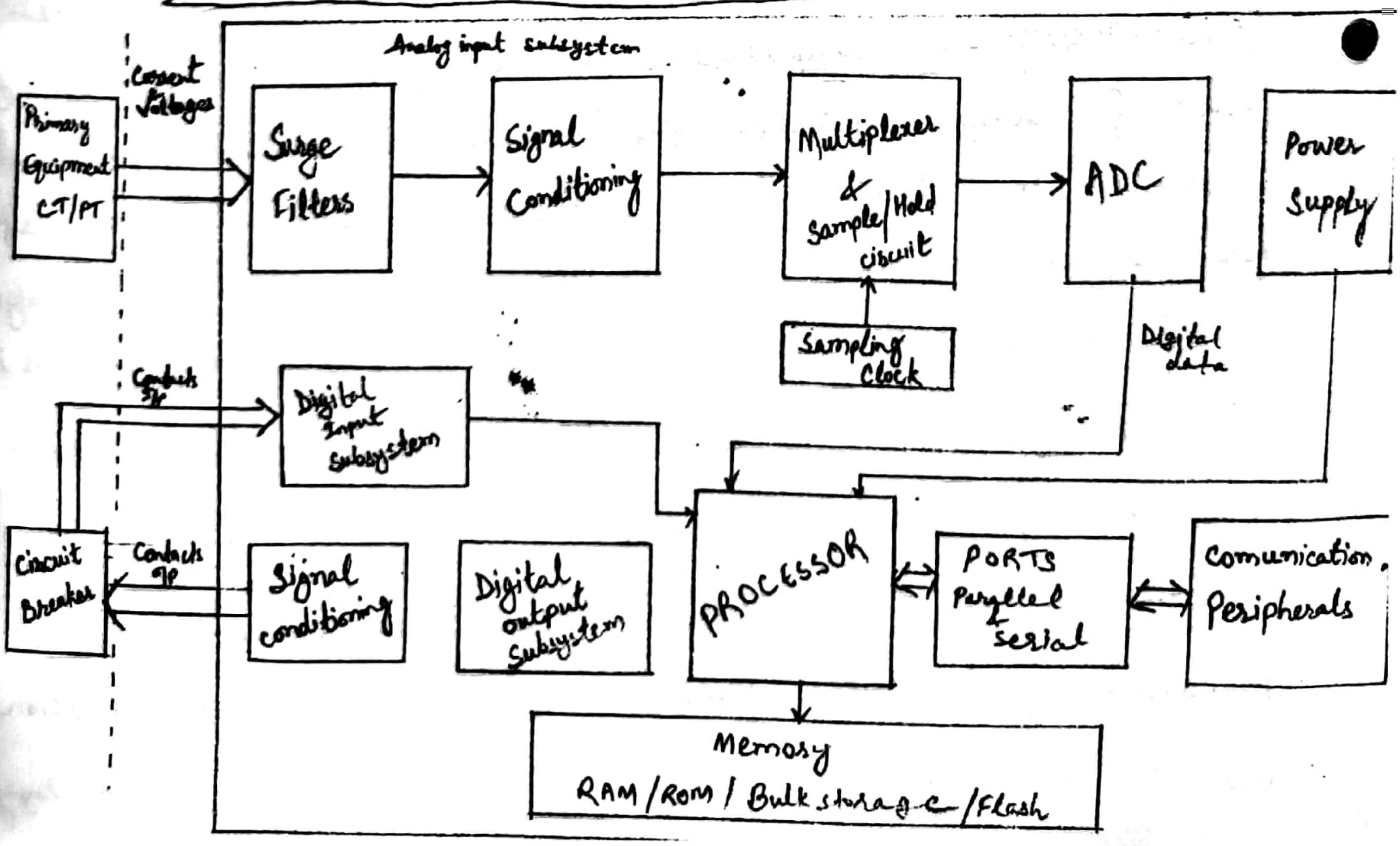
2. **Susceptibility to Transients**: Microprocessor-based numerical protection systems are more susceptible to incorrect operations due to transients because of the nature of the technology

compared to the systems built with the electromechanical technology.

3. <u>Setting & Testing Complexities</u>: Numerical relays, which are designed to replace the functions of electromechanical or static relays, offer programmable functions that increase the applic flexibility compared with the fixed function relays. The multi-function numerical relays, therefore, have a number of settings. There may be problems in management of the increased number of settings and in conduction of functional tests.

Numerical relays are generally tested by using special testing techniques, specifically the ability to enable & disable selected functions. This increases the possibility that the desired settings may not be invoked after testing.

ORGANIZATION OF NUMERICAL RELAY



Numerical relays have inbuilt computing devices, and digital techniques are used to acquire data regarding current & voltag derived from power system through CTs & PTs. These are calle analog inputs, which when processed, helps to decide whethe to trip or not trip the associated circuit breaker.

The online computing device is a fast acting microprocess or digital signal processor (DSP). The relay operates on in-built software which includes the settings governed by the relay tripping logic. These settings can be set by communicat. channels from local or remote or HMI (Human Machine Interface)

Previous figure shows the internal organization of a numerical rel The important components are:

* **Analog Input Subsystem:**

Analog signals like currents & voltages are derived from the switchyard of the substation. These analog signals are the multiplexed, sampled & converted to digital signals. This process is known as discretization in the area of digital signal processing. Moreover, surge filters are required for protection of the low-voltage digital components. Signal conditioning is required to adjust and match voltage levels to the input range of an ADC. An analog low-pass filter is also required to block the higher unwanted frequency components to avoid aliasing.

* **Digital Input Subsystem:**

Digital input consists of the status of other relays and the circuit breaker in the associated network

* **Processor:**

Fast acting microprocessor and microcontrollers were typically used in earlier times. Nowadays, digital signal processors (DSP) are used in numerical relays, which are faster in comparison to microcontrollers. Clock speeds of current mainstream DSPs have increased between 50 MHz to 100 MHz, with the latest DSPs ~~ex~~ executing at 200 MHz or higher

* <u>Data & Program Storage</u>:

The RAM holds the acquired samples from the input system. It also acts as a buffer storage for additional samples if the. ~~the~~ relaying algorithm takes time. Apart from this, the RAM also acts as 'data scratch pad', i.e., a temporary storage to be used during the filtering algorithm & relay algorithm execution.

The ROM is used for storing the relay logic and the monitor program required for ~~ise~~ interaction between the operator and the relay

The Flash memory (earlier, EEPROM) is needed for storing parameters which need to be changed from time-to-time e.g. relay settings.

The bulk storage memory is required for storing historical data files.

* <u>Digital output subsystem</u>:

This subsystem is used to give trip signals, alarm & control signals to the external system.

* <u>Power Supply</u>:

The relay has to be operative even if the station supply is not available. Thus an uninterrupted dc supply is provided to the numerical relay by means of battery along ...

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Summary of Numerical Relay organization

The numerical relay samples voltages & currents, which at power system level, are in the range of two hundreds of kilo volts & kilo amperes respectively. The levels of these signal are reduced by voltage & current transformers. The outpu of the transducers are applied to the signal conditioner. Signal conditioner brings real-world signals into digitizer. In this case, the signal conditioner electrically isolates the rel from the power system, reduces the level of the input volt converts currents to equivalent voltages and removes high frequency components from from the signals using analog filte

The relay is isolated from the power system by using auxiliary transformers which receive analog signals and reduc their levels to make them suitable for use in relays.

Since the ADC accepts voltage signals only, the current signals are converted into proportional voltage signals by us I/V converters or by passing through precision shunt resistor

The outputs of the signal conditioner are applied to analog interface, which includes sample & hold (S/H) circuits, multiplexers, & ADCs. These components sample the reduc level signals and convert their analog levels to equivalent nu that are stored in memory. The status of isolators & c in the power system is provided to the relay via the input subsystem and are read into the processor memory

After quantization by the ADC, analog electrical sig are represented by discrete ~~numbers~~ values of the sc taken at specified instants of time. The signals in the form of discrete numbers are processed by a relaying algorithm using numerical methods, to decide the fault condition and send the trip command to circuit breaker, accordingly.

DATA ACQUISITION SYSTEM (DAS or DAQ)

Data acquisition is the process of sampling of real-world analog signals and conversion of the resulting samples into digital numeric values that can be manipulated by a computer (processor). The system which performs data acquisition is called data acquisition system.

The components of data acquisition system include CT/PT, transducers, Antialiasing filters, Multiplexers, sample & Hold circuit & ADC

The CTs & PTs are used for two purposes. Firstly, they are used to scale down the levels to become compatible with that of the digital subsystem. Secondly, they provide isolation between the power circuit and the measuring & protective hardware

For other electrical & thermal signals, suitable transducers are used, which convert the primary relaying quantities to equivalent dc analog quantities.

Digital inputs to the numerical relay are usually the contact status, obtained from other relays or circuit breakers.

When the digital inputs are derived from contacts ~~status~~. ~~Obtained~~ ~~from~~ within the yard, it is necessary to apply surge filtering and/or optical isolation in order to isolate the numerical relay from the transient surges. The surges are produced d to faults and switching operations on the power system or the control room itself. Suppression of these surges can be achieve by careful grounding & shielding of leads & equipments as well low pass filtering. Surge filters are low pass filters with cu off frequencies of the order of hundreds of kHz. Additionaly, mo may also be used.

SAMPLING

Sampling is the process of converting a continuous time sign such as current, voltage, temperature etc to a discrete time signal. [The signals used in the real world, such as voices, air pressure, etc are analog signals which are continuous in both ti & amplitude. To process these signals in computers (processor they need to be converted to digital form which is discret in both time & amplitude. To convert a signal from continu time to discrete time, a process called sampling is used. T value of the signal is measured at certain intervals in time. Eac measurement is referred to as a sample]

In order that the samples represents the analog signal uniquely and contain enough information to recreate the original waveform, a continuous signal has to be sampled properly. Wi the unique collection of numerical values of samples, the original waveform can be easily recreated.

Aliasing & Sampling Theorem

The sampling theorem states that in order to preserve the information contained in a signal, ~~of frequency~~ it must be sampled at a sampling frequency f_s of at least twice the largest frequency f_m present in the sampled information. i.e. $f_s \geq 2f_m$. The sampling theorem is also known as Shannon sampling theorem or Nyquist sampling theorem.

The lower limit on sampling frequency, equal to $2f_m$ is known as the Nyquist limit. If the signal is sampled below the Nyquist limit, it gives rise to the phenomenon of aliasing. Aliasing is the phenomenon of the given signal being lost in the process of digitization, and its place being taken by a different lower frequency wave.

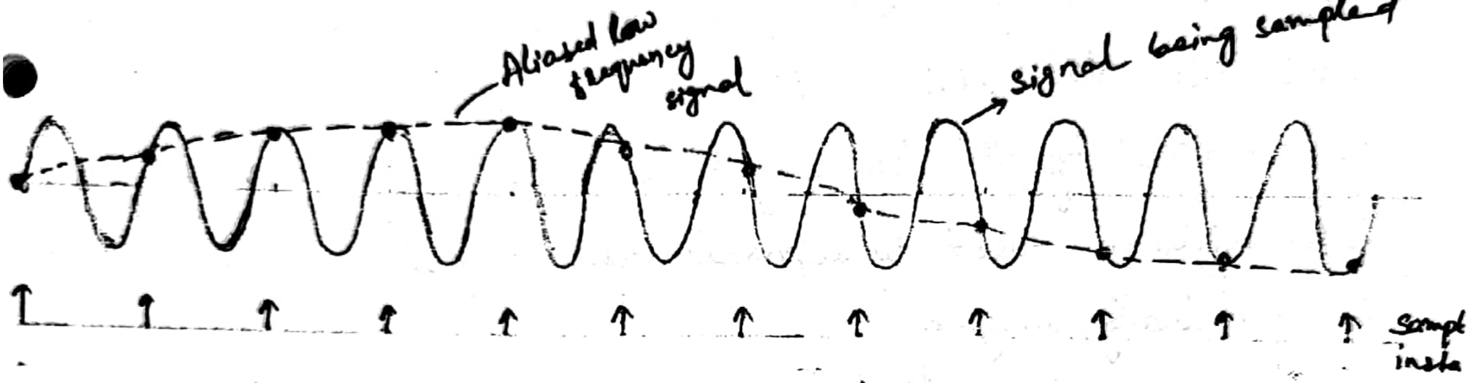
[The phenomenon of a high-frequency component in an input signal manifesting itself as a low-frequency signal is called aliasing.]

Aliasing is the presence of unwanted components in the reconstructed signal. These components were not present when the original signal was sampled. In addition, some of the frequencies in the original signal may be lost in the reconstructed signal. Aliasing occurs because signal frequencies can overlap if the sampling frequency is too low. Frequencies "fold" around half the sampling frequency - which is why this frequency is often ~~half~~ referred to as the folding frequency.

If the samples of signal, which is sampled below the Nyquist rate, are fed to a digital to analog converter (DAC), then the DAC does not reproduce the original analog signal Instead, it recreates a different low frequency signal. The information contained in the original waveform is thus lost.

The effect of aliasing can be understood in simple way with the help of following ~~wat~~ waveforms.

Consider a sinusoidal high frequency signal being sampled at sampling frequency slightly less than the signal frequency (for the sake of simple understanding).



The samples thus obtained, if recreated, will produce a sinusoidal signal with very low frequency compared to the original sig. Thus the original signal is lost and low frequency signal is saved, if the sampling rate is very slow.

Therefore, for obtaining a correct estimate of the ~~Ht Hrs~~ component of a selected frequency, the sampling rate shou be chosen in such a manner that components of higher frequ do not appear to ~~the~~ belong to the frequency of interest.

Since it is not possible to select a sampling frequency t would prevent the appearance of all high frequency componen as components of frequency of interest, the analog signals a applied to low-pass filters and their outputs are processed further. This process of band-limiting the input is done by low pass filters known as Anti-Aliasing filters.

Digital Filtering

Filtering is a very important and most frequently needed operation in numerical relaying.

Basically, filters have two uses: signal separation and signal restoration.

Signal separation is needed when a signal has been contaminated with interference, noise, or other signals. For example, imagine a device for measuring the electrical activity of a baby's heart (ECG) while still in the womb. The raw signal will likely be corrupted by the breathing & heartbeat of the mother. A filter might be used to separate these signals so that they can be individually analyzed.

Signal restoration is used when a signal has been distorted in some way. For example, an audio recording made with poor equipment may be filtered to better represent the sound as it actually occurred, or the deblurring of an image acquired with an improperly focused lens, or a shaky camera.

These problems can be dealt with familiar analog filters consisting of R-L-C circuits and active filters using OP-Amps. However, there are certain drawbacks associated with analog and active analog filters, like:

* They are bulky, specially inductors require a large space.
* High precision components are needed, making them expensive.
* Their characteristics drift with respect to time & temperature.
* Filters for very low frequencies need impracticably high component values
* Their characteristics are limited to the certain well known conventional characteristics.

* They are not adaptable, i.e. they cannot change their characte in response to the input signal
* They are not programmable

Digital filters offer advantages with respect to all of th above points. The most important advantage of digital filters is that they do not require high precision & high quality R-L-C compon All types of digital filters require the same basic hardware consisting of anti-aliasing filters, sample & hold circuits and ADCs. The underlying software decides the filtering action. Thus, the digital filter exists in software. This has several advantag e.g., it is easy to change the characteristic of the filter by simply using another program. Digital filters do not need any tuning & maintenance. There is no ageing and no drift caused by time or temperature.

Digital filters can achieve thousands of times better performance than analog filters. This makes a dramatic difference in how filteri problems are approached. With analog filters, the emphasis is on handl limitations of the ~~signal~~ electronics, such as the accuracy & stabili of the resistors & capacitors. In comparison, digital filters are so good that the performance of the filter is frequently ignored. T emphasis shifts to the limitations of the signals, and the theorit issues regarding their processing.

Basic examples of Digital filtering:

A simple Low-pass filter:

If we form the output by

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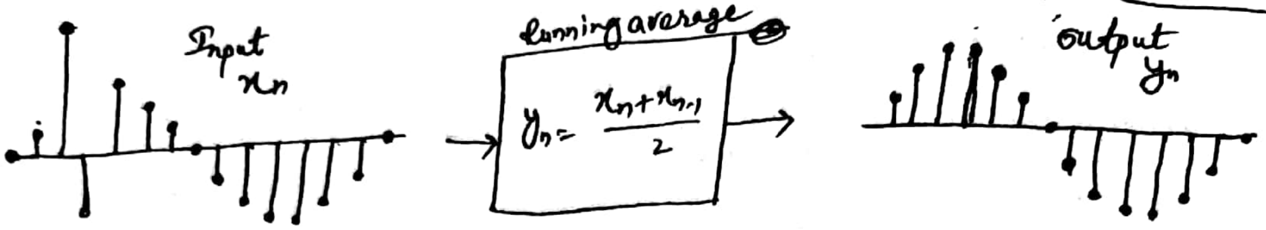
simply taking the running average of last two samples then this simple mathematical operation has the effect of performing a low-pass filtering operation.

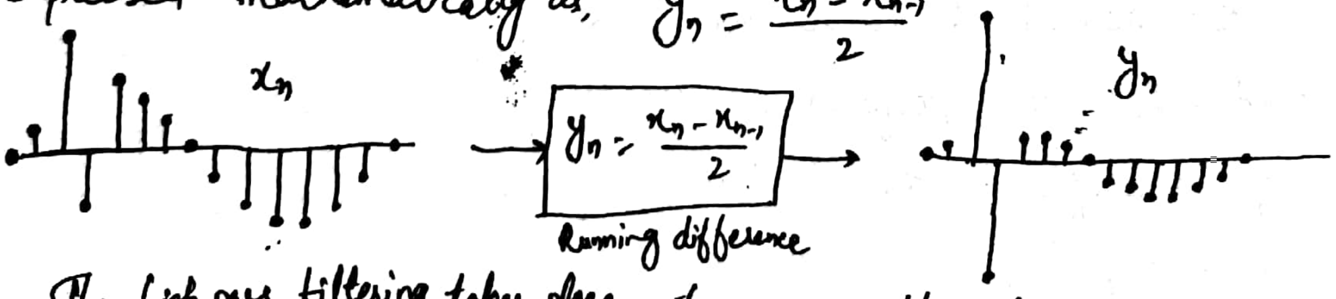
The filter can be expressed mathematically as, $\boxed{y_n = \frac{x_n + x_{n-1}}{2}}$



Consider a signal as shown above. At sample no. 3, there is a large noise signal of +ve polarity. At sample no. 4, there is a noise signal of appropriate magnitude but of opposite polarity. Thus there is a high frequency noise signal riding over the low frequency information carrying signal. Now, since the output signal is formed by taking a running average, the effect of a +ve spike, followed by a negative spike, is totally cancelled out and we get a smoother signal.

A simple High-pass Filter

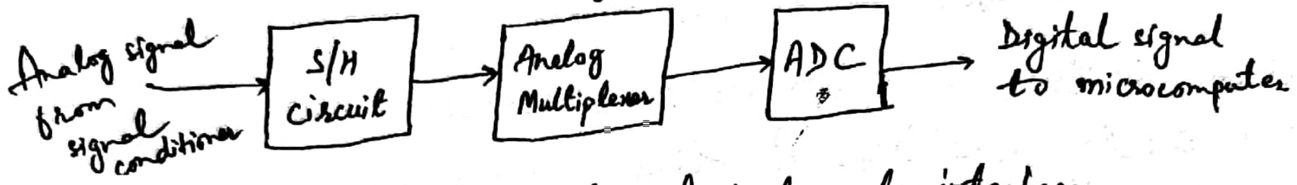
If the output sequence is formed by taking a running difference of the samples of the input sequence then it has the effect of high-pass filtering as shown below: The filter can be expressed mathematically as, $y_n = \frac{x_n - x_{n-1}}{2}$



The high-pass filtering takes place when any sudden changes of sign of the samples get amplified as a result of taking the difference. Slowly varying samples of signal almost cancel out each other in the output. Thus only the high frequency component appears at the output.

Analog Interface

The analog interface makes the signal compatible with processor. The outputs of the signal conditioner are applied to analog interface which includes sample & hold (S/H) circuits, analog multiplexers, & ADCs. These ~~sampler~~ components sample the re level signals and convert their analog levels to equivalent numb that are stored in memory for processing



Block diagram of a typical analog interface

A sample & hold circuit is used to acquire the samples of the t varying analog signal and keep the instantaneous sampled values con during the conversion period of ADC. A S/H circuit has two mode of operation namely Sample mode & Hold mode. In the sample m the output follows the input with unity gain, while in the Hold mode the output of the S/H circuit retains the last value had until the command switches for the sample mode again. T S/H circuitry is basically an operational amplifier which charge a capacitor during the sample mode and retains the value charge of the capacitor during the hold mode.

An analog multiplexer has many input channels and only one output. It selects one out of the multiple inputs and transfers it to a common output. Any input channel can be selected by sending proper commands to the multiplexer.

Analog to digital converters (ADCs) take the instantaneous (sa) values of the continuous time signal, convert them to equivalent represent the analog signals at the instants of sampling.

Thus after quantization by the ADC, analog electrical signals are represented by discrete values of the samples taken at specified instants of time. The signals in the form of discrete numbers are processed by a relaying algorithm using numerical methods. Relaying algorithm which processes the acquired information is a part of the software.

The microprocessor accepts signals in digital form. Therefore analog signals must be converted into digital form before feeding them to the microprocessor for processing. Both voltage & current are analog quantities. As the microprocessor accepts only voltage signal (in digital form), the current signal is converted into proportional voltage signal, and then the voltage signal is converted into digital form for applying to the microprocessor. An ADC is used to convert analog signals into digital forms. If more than one analog quantity is to be converted into digital form by using only one ~~AC~~ ADC, analog multiplexers are used to select any one analog quantity at a time for conversion. For time varying quantities such as ac, a Sample & Hold circuit is used to keep the desired instantaneous voltage constant during conversion period.