#### UNIT-III

#### **PROTECTION OF GENERATORS AND TRANSFORMERS**

#### **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-move	r ( <i>ii</i> )	failure of field
(iii)	overcurrent	(iv)	Over speed
			unbalanced
(v)	overvoltage	(vi)	loading
(vii)	stator winding faults		

- (i) Failure of prime-mover. When input to the prime-mover fails, the alternator runs as a synchronous motor and draws some current from the supply system. This motoring condition is known as —inverted running.
  - (a) In case of turbo-alternator sets, failure of steam supply may cause inverted running. If the steam supply is gradually restored, the alternator will pick up load without disturbing the system. 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. There-fore, 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 synchronizing 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.

- \* During inverted running (or motoring), there is a reversal of power flow in the stator windings. This causes the operation of reverse power relay.
- <sup>†</sup> This is the case with attendant stations. However, in unattended stations, the use of a field-failure relay may be justified.
- (iv) Over speed. The chief cause of over speed 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 over speed occurs.
- (v) **Over-voltage.** The field excitation system of modern alternators is so designed that overvoltage conditions at normal running speeds cannot occur. However, overvoltage in an alternator occurs when speed of the prime-mover increases due to sudden loss of the alternator load.

In case of steam-turbine driven alternators, the control governors are very sensitive to speed variations. They exercise a continuous check on over speed and thus prevent the occurrence of 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 overvoltage 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

- trip the main circuit breaker to disconnect the faulty alternator from the system
- 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 cur-rents 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.



- (i) **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:
  - Fault between phase and ground Principles of Power System
  - Fault between phases
  - Inter-turn fault involving turns of the same phase winding

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

# 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.

- \* 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 above fig, 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. There- fore, there is balanced circulating current in the pilot wires and no current flows through the operating coils (R1, R2 and R3) of the relays. When an earth-fault or phase-to-phase fault occurs, this condition no longer holds good and the differential current flowing through the relay circuit operates the relay to trip the circuit breaker.



(i) Suppose an earth fault occurs on phase R due to breakdown of its insulation to earth as shown in Fig. 22.2. The current in the affected phase winding will flow through the core and frame of the machine to earth, the circuit being completed through the neutral earthing resistance. The currents in the secondaries of the two CTs in phase R will become unequal and the difference of the two currents will flow through the corresponding relay coil (*i.e.* R1), 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 energizing 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 starconnected alternator during earth-faults. When an earth-fault occurs near the neutral point, there



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.

# 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 be-cause 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.





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 S1 or S2 to the neutral of the current transform-ers. 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.

### **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

Alternator CT 1000000 10 R CT CT 6 1000000 (O) CT 000000 6 F1 Earthing resistance Relay To trip circuit Fig. 22.6

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 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.

### STATOR INTER-TURN PROTECTION

Merz-price circulating-current system protects against phase-to-ground and phase-to- phase faults.



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

In single turn generator (*e.g.*large steam-turbine generators), there is no necessity of protection against inter-turn faults. However, inter-turn protection is provided for multi-turn generators such as hydro- electric generators. These generators have double- winding armatures (*i.e.* each phase winding is divided into two halves) owing to the very heavy currents which they have to carry. Advantage may be taken of this necessity to protect inter-turn faults on the same winding.

Fig. 22.7 shows the schematic arrangement of circulating-current and inter-turn protection of a 3-phase double wound generator. The relays RC provide protection against phase-to-ground and phase-to-phase faults whereas relays R1 provide protection against inter-turn faults.



Fig. 22.8 shows the duplicate stator windings S1 and S2 of one phase only  $S_1$  with a provision against inter-turn faults. Two current transformers are connected on the circulatingcurrent principle. Under normal conditions, the currents in the stator windings S1 and S2 are equal and so will be the currents in the secondaries of the two CTs. The secondary current round the loop then is the same at all points and no current flows through the relay R1. If a short-circuit develops between adjacent turns, say on S1, the currents in the stator windings S1 and S2 will no longer be equal. Therefore, unequal currents will be induced in the secondaries of CTs and the difference of these two currents flows through the relay R1. The relay then closes its contacts to clear the generator from the system.

### **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

- Open circuits
- Overheating
- Winding short-circuits

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 harm-less. 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.

### **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 cur-rent 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

- Buchholz devices providing protection against all kinds of incipient faults i.e. slowdeveloping faults such as insulation failure of windings, core heating, fall of oil level due to leaky joints etc.
- Earth-fault relays providing protection against earth-faults only.
- Over current relays providing protection mainly against phase-to-phase faults and overloading.
- 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

- Size of the trans-former
- Type of cooling
- Location of transformer in the network
- Nature of load supplied and
- Importance of service for which transformer is required.

### 2.2.2 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 in-stalled in the

pipe connecting the conservator to the main tank as shown in Figure. 2.11. It is a universal practice to use Buchholz relays on all such oil immersed trans-formers having ratings in excess of 750 kVA.

Figure.2.12 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.





- 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 conservator and in the process gets entrapped in the upper part of relay chamber. When a pre-determined 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.
- 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

- 1. It is the simplest form of transformer protection.
- 2. It detects the incipient faults at a stage much earlier than is possible with other forms of protection.

# Disadvantages

- 1. It can only be used with oil immersed transformers equipped with conservator tanks.
- 2. The device can detect only faults below oil level in the transformer. Therefore, separate protection is needed for connecting cables.

# 2.2.3 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 over current 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 Figure. 2.13.



#### Figure 2.13 Earth fault protection

The three leads of the primary winding of power trans-former 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.

#### **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.



**Figure 2.14 Combined Leakages and Overload Protection** 

The overload relays have high current setting and are arranged to operate against faults between the phases Figure. 2.14 shows the schematic arrangement of combined leakage and over-load protection. In this system of protection, two overload relays and one leak-age 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.

### **Circulating-Current Scheme for Transformer Protection**

Figure.2.15 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 CTs 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 CTs on the two sides are connected by pilot wires and one relay is used for each pair of CTs. During normal operating conditions, the secondary's of CTs 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 CTs 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 CTs on the high-voltage side and the CTs 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.