27

Overcurrent Protection and Earth Fault Protection

27.1. INTRODUCTION

As the fault impedance is less than load impedance, the fault current is more than load current. If a short circuit occurs the circuit impedance is reduced to a low value and therefore a fault is accompanied by large current. Overcurrent relays sense fault currents and also over-load currents.

Overcurrent protection is that protection in which the relay picks up when the magnitude of current exceeds the pickup level. The basic element in overcurrent protection is an overcurrent relay.

The overcurrent relays are connected to the system, normally by means of CT's. Overcurrent relaying has following types :

— High speed overcurrent protection.

— Definite time overcurrent protection.

— Inverse minimum time overcurrent protection.

— Directional overcurrent protection (of above types).

Over-current protection includes the protection from overloads. This is most widely used protection. Overloading of a machine or equipment (generally) means the machine is taking more current than is rated current. Hence with overloading, there is an associated temperature rise. The permissible temperature rise has limit based on insulation class and material problems. Over-current protection of overloads is generally provided by thermal relays.

Over-current protection includes short-circuit protection. Short circuits can be phase faults, earth faults or winding faults. Short-circuit currents are generally several times (5 to 20) full load current.

Hence fast fault clearance is always desirable on short-circuits.

When a machine is protected by differential protection, the over-current is provided in addition as a back-up and in some cases to protect the machine from sustained through fault.

Several protective devices are used for over-current protection. These include

— Fuses

— Miniature circuit-breakers, moulded-case circuit-breakers.

— Circuit-breakers fitted with overloaded coils or tripped by over-current relays.

— Series connected trip coils operating switching devices.

— Over-current relays in conjunction with current transformers.

The primary requirements of over-current protection are :

— The protection should not operate for starting currents, permissible overcurrents, current surges. To achieve this, the time delay is provided (in case of inverse relays). If time delay cannot be permitted, high-set instantaneous relaying is used.

— The protection should be co-ordinated with neighbouring over-current protections so as to discriminate.

27.2. APPLICATIONS OF OVER-CURRENT PROTECTION

Over-current protection has a wide range of applications. It can be applied where there is an abrupt difference between fault current within the protected section and that outside the protected section and these magnitudes are almost constant. The over-current protection is provided for the following :

Motor Protection. Over-current protection is the basic type of protection used against overloads and short-circuits in stator windings of motors. Inverse time and instantaneous phase and ground over-current relays can be employed for motors above 1000 kW. For small/medium size motors where cost of CT's and protective relays is not economically justified, thermal relays and HRC fuses are employed, thermal relays used for overload protection and HRC fuses for short-circuit protection.

Transformer Protection. Transformers are provided with over-current protection against faults, only, when the cost of differential relaying cannot be justified. However, over-current relays are provided in addition to differential relays to take care of through faults. Temperature indicators and alarms are always provided for large transformers.

Small transformers below 500 kVA installed in distribution system are generally protected by drop-out fuses, as the cost of relays plus circuit-breakers is not generally justified.

Line Protection. The lines (feeders) can be protected by :

1. Instantaneous over-current relays.
2. Inverse time over-current relays.
3. Directional over-current relays.

Lines can be protected by impedance, or carrier current protection also.

Protection of Utility Equipment. The furnaces, industrial installations, commercial, industrial and domestic equipment are all provided with over-current protection.

27.3. RELAYS USED IN OVER-CURRENT PROTECTION

The choice of relay for over-current protection depends upon the time/current characteristic and other features desired. The following relays are used.

1. For instantaneous over-current protection.

Attracted armature type, moving iron type, permanent magnet moving coil type, static.

2. For inverse time characteristic.

Electromagnetic induction type, permanent magnet moving coil type, static.

3. Directional over-current protection.

Double actuating quantity induction relay with directional feature.

4. Static over-current relays. (Ref. Ch. 40)

5. HRC fuses, drop out fuses, etc. are used in low voltage medium voltage and high voltage distribution systems, generally up to 11 kV.

6. Thermal relays are used widely for over-current protection.

27.4. CHARACTERISTICS OF RELAY UNITS FOR OVER-CURRENT PROTECTION

There is a wide variety of relay-units. These are classified according to their type and characteristics. The major characteristic include :

— Definite characteristic

— Extremely Inverse

— Inverse

— Inverse characteristic

— Very Inverse

In definite characteristic, the time of operation is almost definite *i.e.*,

$$I^0 t = K$$

where I = Current in relay coil

t = Relay lime

K = Constant.

In inverse characteristic, time is inversely proportional to current *i.e.*

$$I^1 t K$$

In more inverse characteristic.

$$I^n t = K$$

where n can be between 2 to 8. The choice depends on discrimination desired.

Instantaneous relay are those which have no intentional time lag and which operate in less than 0.1 second, usually less than 0.08 second. As such they are not instantaneous in real sense.

The relays which are not instantaneous are called 'Time Delay Relay'. Such relays are provided with delaying means such as drag magnet, dash pots, bellows, escape mechanisms, back-stop arrangement, etc.

The operating time of a relay for a particular setting and magnitude actuating quantity can be known from the characteristics supplied by the manufacturer. The typical characteristics are shown in Fig. 26.14.

An inverse curve is one in which the operating time; becomes less as the magnitude of the actuating quantity is increased. However for higher magnitudes of actuating quantity the time is constant. Definite time curve is one in which operating time is little affected by magnitude of actuating current. However even definite time relay has a characteristic which is slightly inverse.

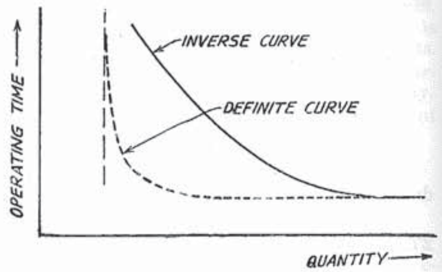


Fig. 27.1. Typical curves of operating time *vs* magnitude of actuating quantity.

The characteristic with definite minimum time and of inverse type is also called Inverse Definite Minimum Time (IDMT); characteristics (Ref. Fig. 26.14 also).

Methods of Ct Connections in Over-current Protection of 3-Phase Circuits.

27.4.1. Connection Scheme with Three Over-current Relays

Over-current protection can be achieved by means of three over-current relays (Fig. 27.2) or by two over-current relays (Fig. 27.3). Ref. Sec. 26.2 for principle of Trip Circuit.

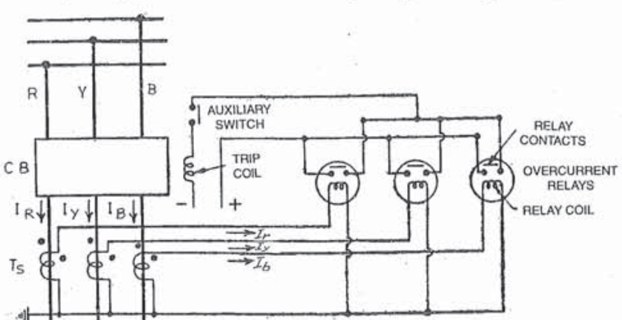


Fig. 27.2. Over-current protection with three over-current relays.

Referring to Fig. 27.2 the three current transformers and relay coils connected in star and the star point is earthed. When short circuit occurs in the protected zone the secondary current of CT's increases. The current flows through coiler and the relay picks-up. The relay close, thereby the trip circuit is closed and the circuit breaker-operates.

The over-current protection scheme with three over-current relays (Fig. 27.2) responds to phase faults and earth faults including single-phase to earth fault. Therefore such schemes are used with solidly earthed systems where phase to phase and phase to earth faults are likely to occur.

In Fig. 27.2 the polarities of CT's are indicated by dots. For proper functioning of over-current and earth fault protection, the choice of CT's and polarity connections should be correct.

Fig. 27.3 illustrates the modified circuit with additional auxiliary relay and a definite time relay. Definite time relay can be set to get desired delay. Auxiliary relay is used to close trip circuit.

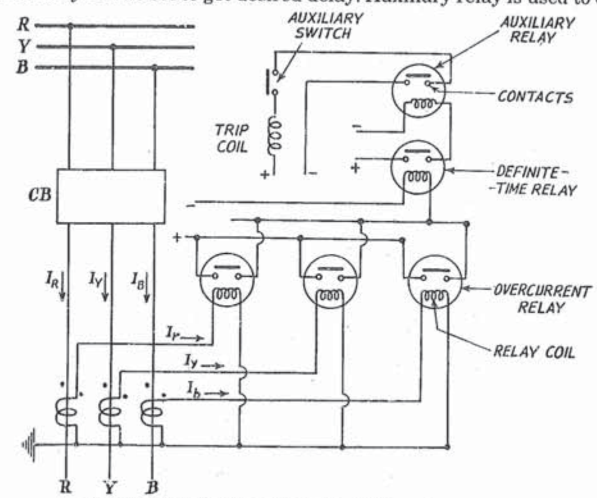


Fig. 27.3. Circuit of Fig. 27.2 with addition of a common time-delay relay and an auxiliary relay.

27.5. EARTH-FAULT PROTECTION

(Called Ground protection in USA)

When the fault current flows through earth return path, the fault is called *Earth Fault.* Other faults which do not involve earth are called *phase faults.* Since earth faults are relatively frequent, earth fault protection is necessary in most cases. When separate earth fault protection is not economical, the phase relays sense the earth fault currents. However such protection lacks sensitivity. Hence separate earth fault protection is generally provided. Earth fault protection senses earth fault current. Following are the method of earth fault protection.

27.6. CONNECTIONS OF CT'S FOR EARTH-FAULT PROTECTION

27.6.1. Residually connected Earth-fault Relay

Referring to Fig. 27.7.

In absence of earth-fault the vector sum of three line currents is zero.

Hence the vector sum of three secondary currents is also zero.

$$\bar{I}_{as} + \bar{I}_{bs} + \bar{I}_{cs} = 0$$

The sum $(\bar{I}_{as} + \bar{I}_{bs} + \bar{I}_{cs})$ is called residual current (I_{RS})

The earth-fault relay is connected such that the residual current flows through it (Ref. Figs. 27.7 and 27.9).

In the absence of earth-fault,

$$\bar{I}_{residual} = \bar{I}_{as} + \bar{I}_{bs} + \bar{I}_{cs} = 0$$

Therefore, the residually connected earth-fault relay does not operate. However, in presence of earth fault the conditions is disturbed and $(\bar{I}_{as} + \bar{I}_{bs} + \bar{I}_{cs})$ is no more zero. Hence residual $I_{residual}$ flows through the earth-fault relay. If the residual current is above the pick-up value, the earth-fault relay operates.

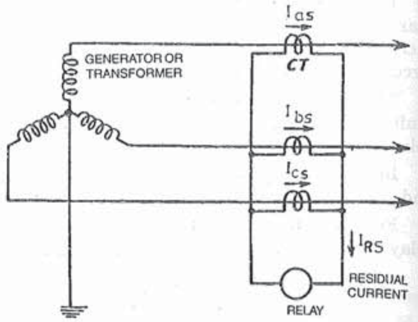
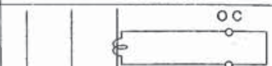
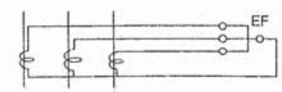
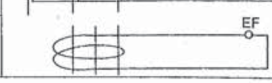


Fig. 27.7. Earth-fault Relay connected in Residual Circuit.

In the scheme discussed here the earth-fault at any location near or away from the location of CT's can cause the residual current flow. Hence the protection zone is not definite. Such protection is called unrestricted earth-fault protection. For selectivity directional earth fault protection is necessary. (Ref. Sec. 27.12).

	Connection	*Description*	*Remarks*
(1)		One OC with one CT for overload protection	For balanced overloads only.
(2)		Two OC relays with two CT's for line to line fault protection and overload protection.	CT's must be in same phase in every station.
(3)		Three OC relays with three CT's for line to line fault protection	Earth fault protection for EF current > 2 × pick-up phase current.
(4)		Three OC and one EF relay for line to earth fault protection and line to line fault protection	EF setting less than phase fault setting.
(5)		Two OC and one EF relays for line to line earth fault protection	EF setting less than full load. (Ref. Fig. 27.10)
(6)		One EF relay with core balance CT	EF setting less than full load. (Ref. Fig. 27.11)

OC = Overcurrent ; EF = Earth fault.
Fig. 27.4. Methods of connections of OC and EF Relays.

27.6.2. Earth-fault Relay connected in Neutral to Earth Circuit (Fig. 27.8).

Another method of connecting an earth-fault relay is illustrated in Fig. 27.8. The relay is connected to secondary of a CT whose primary is connected in neutral to earth connection. Such protection can be provided at various voltage levels by connecting earth-fault relay in the neutral-to-earth connection of that voltage level. The fault current finds the return path through the earth and then flows through the neutral-to-earth connection. The magnitude of earth fault current is dependent on type of earthing (resistance, reactance or solid) and location of fault. In this type of protection, the zone of protection cannot be accurately defined. The protected area is not restricted to the transformer/generator winding alone. The relay senses the earth faults beyond the transformer/generator winding. Hence such protection is called unrestricted earth-fault protection.

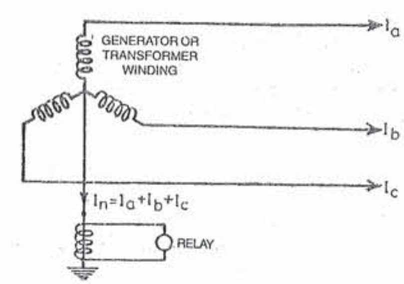


Fig. 27.8. Earth-fault protection by earth-fault-relay connected in neutral-to-earth circuit.

The earth-fault protection by relay in neutral to earth circuit depends upon the type of neutral earthing. In case of large generators, voltage transformer is connected between neutral and earth. The earth-fault relay is connected to Secondary of VT. (Fig. 33.11)

27.7. COMBINED EARTH-FAULT AND PHASE-FAULT PROTECTION

It is convenient to incorporate phase-fault relays and earth-fault relay in a combined phase-fault and earth-fault protection. (Fig. 27.9). The increase in current of phase causes corresponding increase in respective secondary currents. The secondary current flows through respective relay-units. Very often only two phase relays are provided instead of three, because in cause of phase faults current in any at least two phases must increase. Hence two relay-units are enough. The earth-fault relay is residually connected as explained earlier. [Ref. Fig. 35.4 (*b*) in Sec. 35.8]

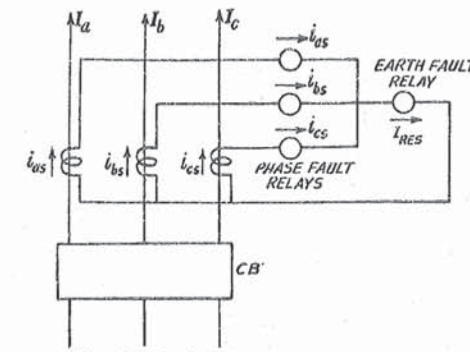
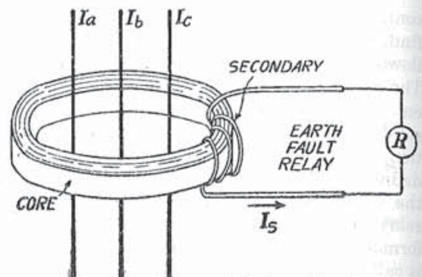


Fig. 27.9. Earth-fault protection combined with phase-fault protection. [Ref. Fig. 35.4 (*b*)]

27.8. EARTH-FAULT PROTECTION WITH CORE BALANCE CURRENT TRANSFORMERS. (ZERO SEQUENCE CT)

In this type of protection Fig. 27.10 (*a*) a single ring shaped core of magnetic material, encircles the conductors of all the three phases. A secondary coil is connected to a relay unit. The cross-section of ring-core is ample, so that saturation is not a problem. During no-earth-fault condition, the components of fluxes due to the fields of three conductors are balanced and the secondary current is negligible. During earth faults, such a balance is disturbed and current is inducted in the secondary. Core-balance protection can be conveniently used for protection of low-voltage and medium voltage systems. The burden of relay and exciting current are deciding factors. Very large cross-section of core are necessary for sensitivity less than 1 A. Thus form of protection is likely to be more popular with static relays due to the less burden of the latter. Instantaneous relay unit is generally used with core balance schemes.

Theory of Core Balance CT. Let $\bar{I}_a, \bar{I}_b$ and $\bar{I}_c$ be the three line currents and $\bar{\phi}_a, \phi_b$ and ϕ_c be corresponding components of magnetic flux in the core. Assuming linearity, we get resultant magnetic flux ϕ_r as,



[I_s flows when there is an earth-fault and $I_a + I_b + I_c \neq 0$]
Fig. 27.10 (*a*). Principle of core-balance CT for earth fault protection.

$$\bar{\phi}_r = k\,(\bar{I}_a + \bar{I}_b + \bar{I}_c)$$

where k is constant $\bar{\phi}_r = k\,I_a$. Referring to theory of symmetrical components (Ref. Ch. 21, Sec. 21.5)

$$\bar{I}_a + \bar{I}_b + \bar{I}_c = 3\bar{I}_c = \bar{I}_n$$

where, I_o is zero sequence current and I_n is current in neutral to ground circuit.

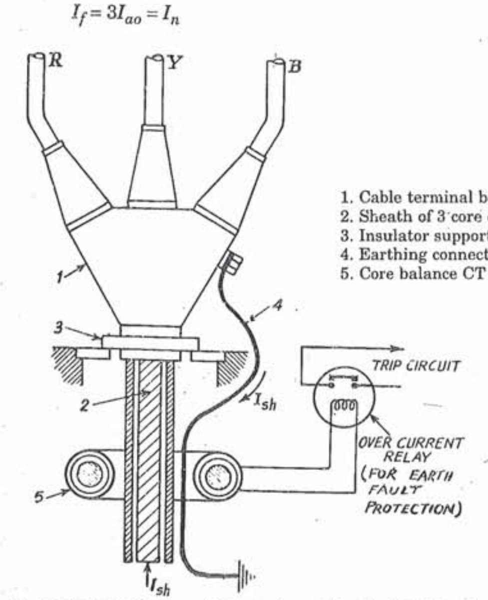
During normal condition, when earth fault is absent,

$$\bar{I}_a + \bar{I}_b + \bar{I}_c = 0$$

Hence $\bar{\phi}_r = 0$ and relay does not operate

During earth fault the earth fault current flows through return neutral path. For example for single line ground fault,

$$I_f = 3I_{ao} = I_n$$



1. Cable terminal box
2. Sheath of 3 core cable connection to (1)
3. Insulator support for 1
4. Earthing connection passing through 5
5. Core balance CT

Fig. 27.10 (*b*). Mounting of Core Balance CT with Cable Terminal Box.

Hence the zero-sequence component of I_o produces the resultant $\bar{\phi}_r$ in the core. Hence core balance current transformer is also called as zero sequence current transformer (ZSCT).

Application for Core Balance CT's with Cable Termination Joints

The termination of a three core cable into three separate lines or bus-bars is through cable terminal box. Ref. Fig. 27.10 (*b*), the Core Balance Protection is used along with the cable box and should be installed before making the cable joint.

The induced current flowing through cable sheath of normal healthy cable need particular attention with respect to the core balance protection.

The sheath currents (I_{sh}) flow through the sheath to the cover cable-box and then to earth through the earthing connection between cable-box. For eliminating the error due to sheath current (I_{sh}) the earthing lead between the cable-box and the earth should be taken through the core of the core balance protection. Thereby the error due to sheath currents is eliminated. The cable box should be insulated from earth. (Ref. Sec. 31.11 also).

27.9. FRAME-LEAKAGE PROTECTION

The metal-clad switchgear can be provided with frame leakage protection. The switchgear is lightly insulated from the earth. The metal-frame-work or enclosure of the switchgear is earthed with a primary of a *CT* in between (Fig. 27.11).

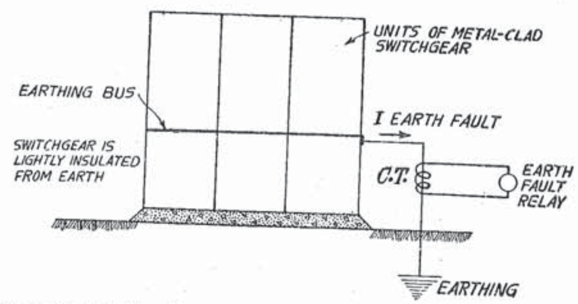


Fig. 27.11. Principle of frame-leakage protection of metal-clad-switchgear.

The concrete foundation of the switchgear and the cable-boxes and other conduits are slightly insulated from earth, the resistance to earth being about 12 ohms. In the event of an earth fault within the switchgear, the earth-fault current finds the path through the neutral connection. While doing so, it is sensed by the earth fault relay.

Circulating current differential protection also responds to earth-faults within its protected zone.

Summary

Earth-fault protection can be achieved by following methods :

— Residually connected relay
— Relay connected in neutral-to-ground circuit
— Core-balance-scheme
— Frame leakage arranged for detecting earth faults on lines. (Ref. Ch. 30).
— Circulating current differential protection. (Ref. Ch. 28).

27.10. DIRECTIONAL OVER-CURRENT PROTECTION

The over-current protection can be given directional feature by adding directional element (Ref. Sec. 26.16.2) in the protection system. Directional over-current protection responds to overcurrents for a particular direction flow. If power flow is in the opposite direction, the directional over-current protection remains un-operative.

Directional over-current protection comprises over-current relay and power directional relay in a single relay casing. The powers directional relay does not measure the power but is arranged to respond to the direction of power flow. (Ref. Fig. 26.21 *b*).

Directional operation of relay is used where the selectivity can be achieved by directional relaying. The directional relay recognizes the direction in which fault occurs, relative to the location of the relay. It is set such that it actuates for faults occurring in one direction only. It does not act for faults occurring in the other direction. Consider a feeder *XY* (Fig. 27.12) passing through sub-section *A*. The circuit breaker in feeder *AY* is provided with a directional relay '*R*' which will trip the breaker CB_y, if fault power flow in direction *A*, alone. Therefore for faults in feeder *AX*, the circuit breaker CB_y does not trip unnecessarily. However for faults in feeder A_y the circuit-breaker CB_y trips because its protective relaying in set with a directional feature to act in direction A_y.

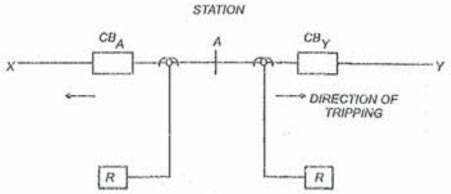


Fig. 27.12. Principle of directional protection.

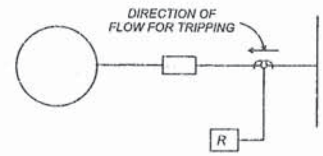


Fig. 27.13. Reverse powers protection against motoring action of a generator.

Another interesting example of directional protection is that of **reverse power protection** of generator (Fig. 27.13). If the prime mover fails, the generator continues to run as a motor and takes power from bus-bars. (Ref. Ch. 28).

Directional power protection operates in accordance with the direction of power flow. (Ref. Sec. 26.15).

Reverse power protection operates when the power direction is reversed in relation to the normal power flow. Reverse power relay is different in construction than directional over-current relay.

In directional over-current relay, the directional current does not measure the magnitude of power. It senses only direction of power flow. However, in Reverse Power Relays, the directional element measures magnitude and direction of power flow.

Relay connections of Single Phase Directional Over-current Relay :

The current coils in the directional over-current relay (Ref. Fig. 26.21 *b*) are normally connected to a secondary of line CT. The voltage coil of directional element is connected to a line VT, having phase to phase output (of 110 V). There are four common methods of connecting the relay depending upon phase angle between current in the current coil and voltage applied to the voltage coil.

Relay Connection. (*e.g.* 90°, 60°, 30° etc) refer to the angle by which the current applied to the relay is displaced from the voltage applied to the relay. (Ref. Fig. 26.22).

The maximum torque angle refers to the angle between the current applied to the relay and the voltage applied to the relay to produce maximum torque.

The choice of relay connection is basically to select the phase across which the voltage coil is connected with respect to current coil. Number of different connections can be used. The suitability of each connection should be examined by considering the limiting conditions of voltage and current for limiting fault conditions, source and line impedances etc.

27.11. DIRECTIONAL EARTH-FAULT PROTECTION

In the directional over-current protection the current coil of relay is actuated from secondary current of line CT. Whereas the current coil of directional earth fault relay is actuated by residual current.

In directional over-current relay, the voltage coil is actuated by secondary of line VT. In directional earth fault relay, the voltage coil is actuated by the residual voltage.

Directional earth fault relays sense the direction in which earth fault occurs with respect to the relay location; and it operates for fault in a particular direction. The directional earth fault relay (single phase unit) has two coils. The polarising quantity is obtained either from residual current ($\bar{I}_{RS} = \bar{I}_a + \bar{I}_b + \bar{I}_c$) or residual voltage ($\bar{V}_{RS} = \bar{V}_{ae} + \bar{V}_{bc} + \bar{V}_{ce}$, where V_{ae} V_{be} V_{ce} are phase voltages.)

Referring to Fig. 27.14 the directional earth-fault relay has two coils. One to the coils is connected in residual current circuits (Ref. Fig. 27.8). This coil gets current earth-faults. The other coil gets residual voltage,

$$\bar{V}_{RS} = \bar{V}_{ae} + \bar{V}_{be} + \bar{V}_{ce}$$

where $\bar{V}_{ae}$, $\bar{V}_{be}$ and $\bar{V}_{ce}$ are secondary voltages of the potential transformer. (Three phase five limb potential transformer or three separate single phase potential transformers connected as shown in Fig. 27.14). The coil connected in potential-transformer secondary circuit gives a polarising field.

The residual current I_{RES} *i.e.* the out of balance current is given to the current coil and the residual voltage V_{RES} is given to the voltage coil of the relay. The torque is proportional to

$$T = I_{RES}, V_{RES} \cos(\phi - \alpha)$$

ϕ = angle between I_{RES}, V_{RES}

α = Angle of maximum torque.

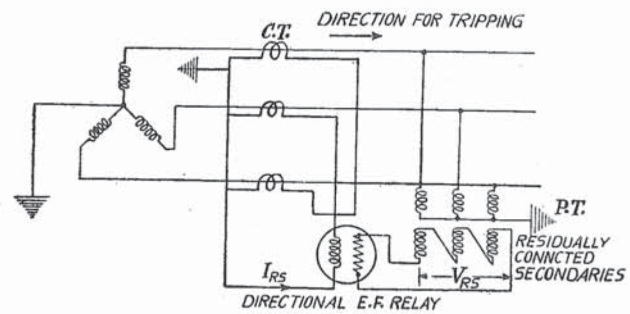


Fig. 27.14. Connections of a directional earth-fault relay.

Summary

Over-current protection responds to increase above the pick-up value overcurrents are caused by overloads and short-circuits. The overcurrent relays are connected the secondary of current transformer. The characteristic of over-current relays include inverse time characteristic, definite time characteristic.

Earth fault protection responds to single line to ground faults and double line to ground faults. The current coil of earth-fault relay is connected either in neutral to ground circuit or in residually connected secondary CT circuit.

Core balance CTs are used for earth-fault protection.

Frame leakage protection can be used for metalclad switchgear.

Directional over-current relay and directional Earth fault relay responds to fault in which power flow is in the set direction from the CT and PT locations. Such directional relays are used when power can flow from both directions to the fault point.

QUESTIONS

1. State the various applications of over-current relaying. Distinguish between "inverse characteristics" and "definite characteristic".
2. With the help of neat sketches explain the principle of following:
   (*a*) Directional Over-current protection.
   (*b*) Earth fault protection by residual connection.
3. Describe Directional earth fault protection.
4. Discuss the following methods of earth fault protection :
   — Core balance CT — Residually connected E.F. relay
   — Relay connected in neutral-to-ground circuit — Frame leakage protection.
5. Describe the principle of a directional over-current relay. How does it help in discrimination in protection of
   — parallel feeder — ring mains.
6. Explain the back-up relaying with graded time lag over-current relays.
7. Explain the time-setting and plug-setting in an induction type overcurrent relay.

28

Differential Protection

Differential protection — Applications — Circulating Current Differential Protection — Differential protection of 3 Ph. circuits — Biased Differential Relay — Balanced Voltage Differential Protection — Summary.

28.1. DIFFERENTIAL PROTECTION

"A differential relay responds to vector difference between two or more similar electrical quantities".

From this definition the following aspects are known :

1. The differential relay has at least two actuating quantities say I_1, I_2.

2. The two or more actuating quantities should be similar *i.e.* current/current.

3. The relay responds to the vector difference between the two *i.e.* to $I_1 - I_2$, which includes magnitude and/or phase angle difference.

Differential protection is generally unit protection. The protected zone is exactly determined by location of CT's or VTs. The vector difference is achieved by suitable connections of current transformer or voltage transformer secondaries.

28.2. APPLICATIONS OF DIFFERENTIAL PROTECTION

Most differential relays are current differential relays in which vector difference between the current entering the winding and current leaving the winding is used for sensing and relay operation.

Differential protection principle is used in the following applications

— Protection of Generator, Protection of Generator-Transformer Unit.
— Protection of Transformer.
— Protection of Feeder (Transmission Line) by Pilot wire differential protection.
— Protection of transmission Line by Phase Comparison Carrier Current Protection.
— Protection of large motors.
— Bus-zone protection.

28.3. PRINCIPLE OF CIRCULATING CURRENT DIFFERENTIAL (MERZ-PRIZE) PROTECTION

Fig. 28.1 (*a*) illustrates the principle of differential protection of generator and transformer. X is the winding of the protected machine. When there is no internal fault, the current entering in X is equal in phase and magnitude to current leaving X. The CT's are of such a ratio that during the normal conditions or for external faults (Through Faults) the secondary currents of CT's are equal. These currents say I_1 and I_2 circulate in the pilot wires. The polarity connections are such that the currents I_1 and I_2 are in the same direction in pilot wires, during normal conditions or