High Voltage Engineering & Power System Protection – 21EE71

Module- 4

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Course Module Details

Module-4

- **Distance Protection:** Introduction, Impedance Relay, Reactance Relay, Mho Relay, Effect of Power Surges, Line Length and Source Impedance on Performance of Distance Relays.
- **Pilot Relaying Schemes:** Introduction, Wire Pilot Protection, Carrier Current Protection**.**
- **Differential Protection:** Introduction, Differential Relays, Percentage Differential Relay, Balanced Voltage Differential Protection.
- **Protection of Generators, Transformer and Bus zone Protection:** Introduction, Protection of Generators. Transformer Protection, Bus zone Protection.

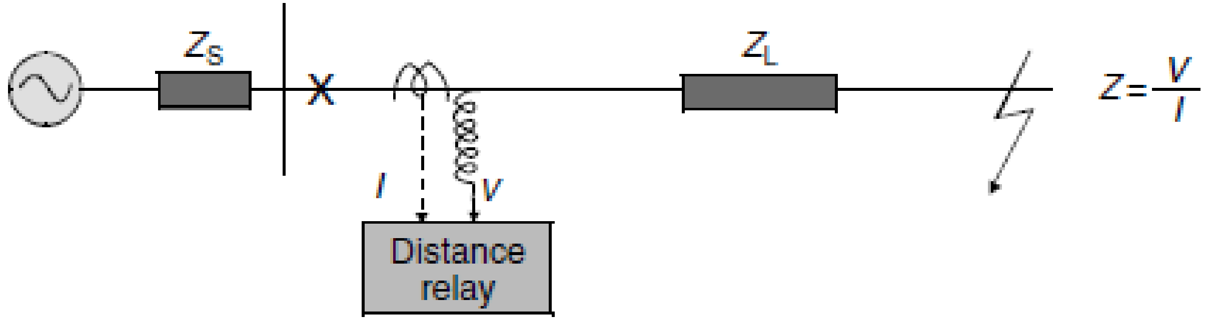
Distance Protection

Basic principle of operation

A distance relay, as its name implies, has the ability to detect a fault within a pre-set distance along a transmission line or power cable from its location.

A distance relay is set operate up to a particular value of impedance, for a impedance greater than this set value the relay should not operate. This impedance or the corresponding distance is known as the reach of the relay

Every power line has a resistance and reactive per kilometer related to its design and construction so its total impedance will be a function of its length or distance. A distance relay therefore looks at current and voltage and compares these two quantities on the basis of Ohm's law



- The working principle of distance relay or impedance relay is very simple.
- There is one voltage element from potential transformer and a current element fed from current transformer of the system.
- The deflecting torque is produced by secondary current of CT and restoring torque is produced by voltage of potential transformer

A simple example of measuring impedance of the line up to the point of fault is shown in Fig

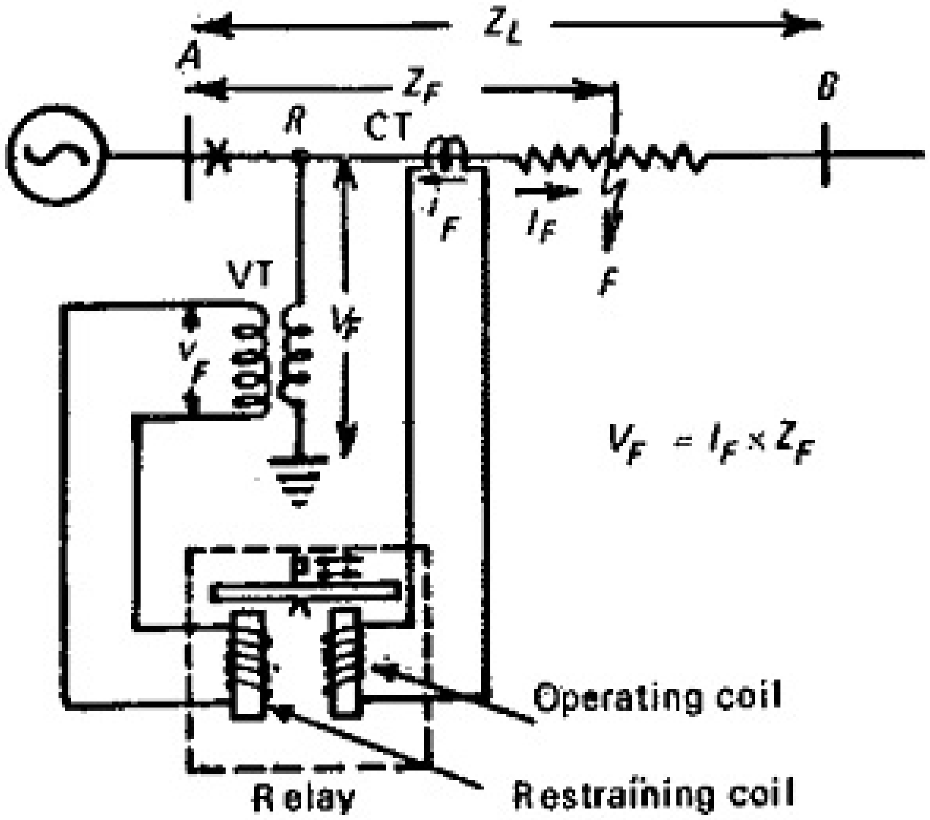
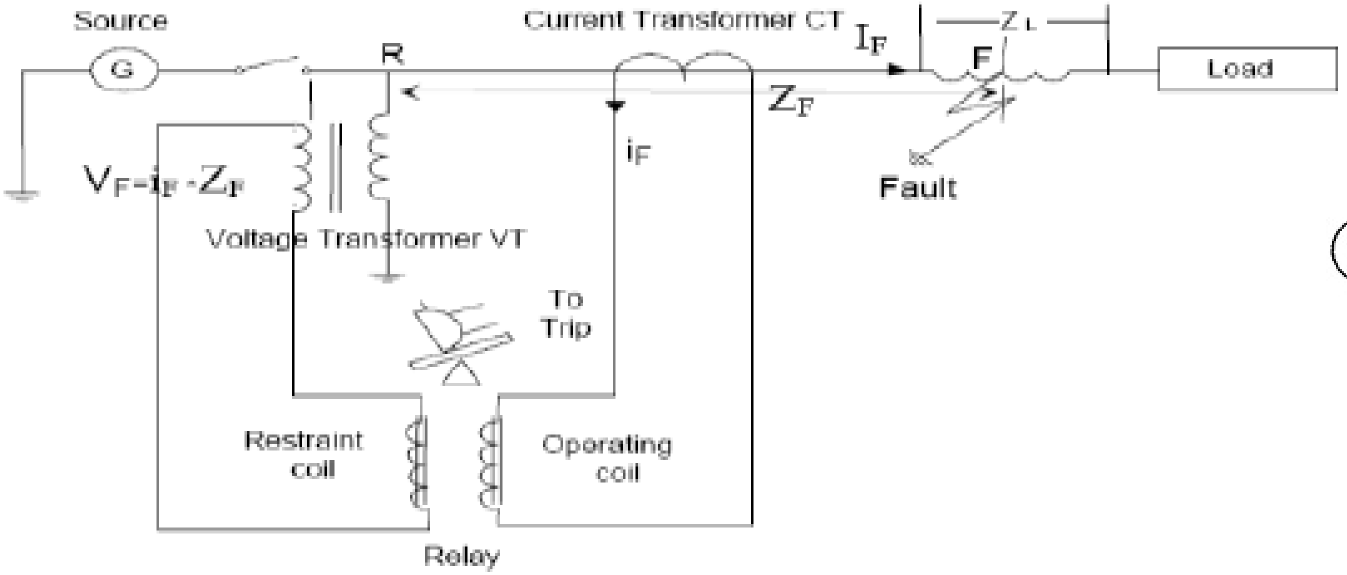
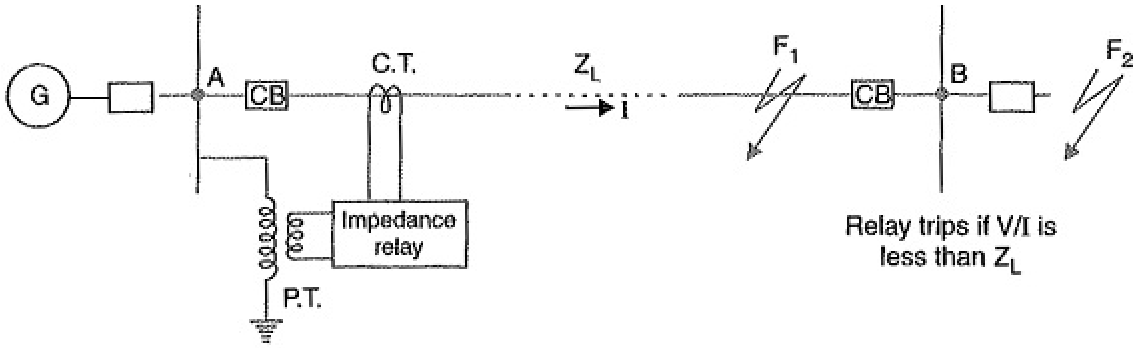


Fig: Simple impedance relay balanced beam type connections.

The relay is connected at point R and the two coils of the relay operating and restraining coils receive current (i_F) and voltage (v_F) proportional to the fault current I_F and the faulted loop voltage V_F.

Below a particular value of Z=V/I the relay operates, whereas above this value of Z the relay restrains; it is possible to select a setting comparable to the length of the line to be protected.





There are two types of torques

1. Restraining torque $T_r \alpha V_F^2$

2. Operating torque $T_0 \alpha I_F^2$

The relay trips when T_0 greater than T_r

$$KI_F^2 > V_F^2$$

$$\frac{V_F}{I_F} < \sqrt{K}$$

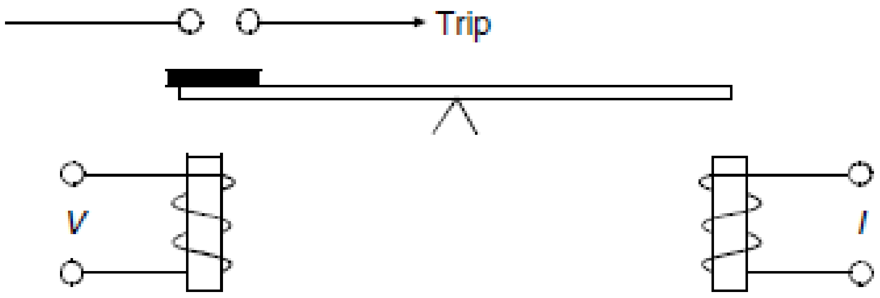
The constant K depends on the design of the electromagnets.

The concept can best be appreciated by looking at the pioneer-type balanced beam

- The voltage is fed onto one coil to provide restraining torque, whilst the current is fed to the other coil to provide the operating torque.

- Under healthy conditions, the voltage will be high (i.e. at full-rated level), whilst the current will be low (at normal load value), thereby balancing the beam, and restraining it so that the contacts remain open.

- Under fault conditions, the voltage collapses and the current increase dramatically, causing the beam to unbalance and close the contacts

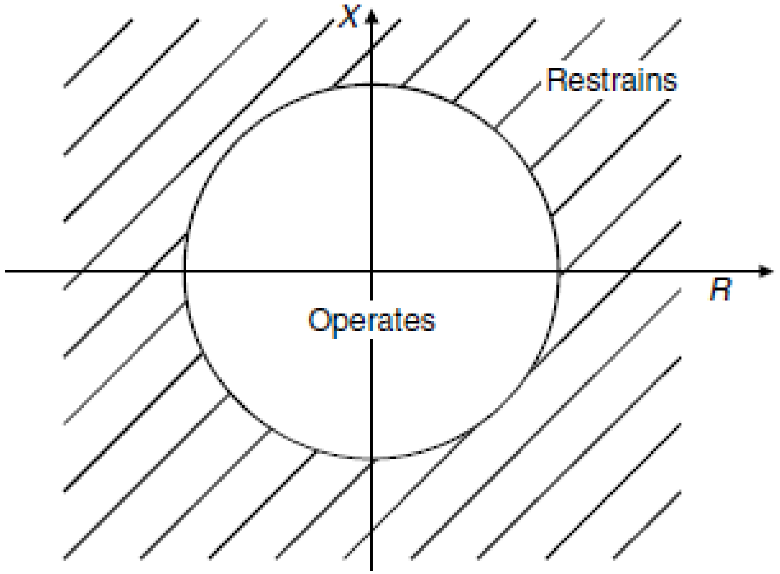


The Current Produces a positive torque,(operating Torque)
and
Voltage produces a negative torque(restraining Torque)

Balanced beam principle

Tripping characteristics

If the relay's operating boundary is plotted, on an R/X diagram, its impedance characteristic is a circle with its center at the origin of the coordinates and its radius will be the setting (reach) in ohms



The relay will operate for all values less than its setting i.e. is for all points within the circle.

This is known as a plain impedance relay and it will be noted that it is non-directional, in that it can operate for faults behind the relaying point. It takes no account of the phase angle between voltage and current.

Distance Protection

Distance relay group is perhaps the most interesting and versatile family of relays. Principle types of distance relays are

- Impedance relay
- Reactance relay
- Admittance or mho relay

Application of Distance Protection Relay

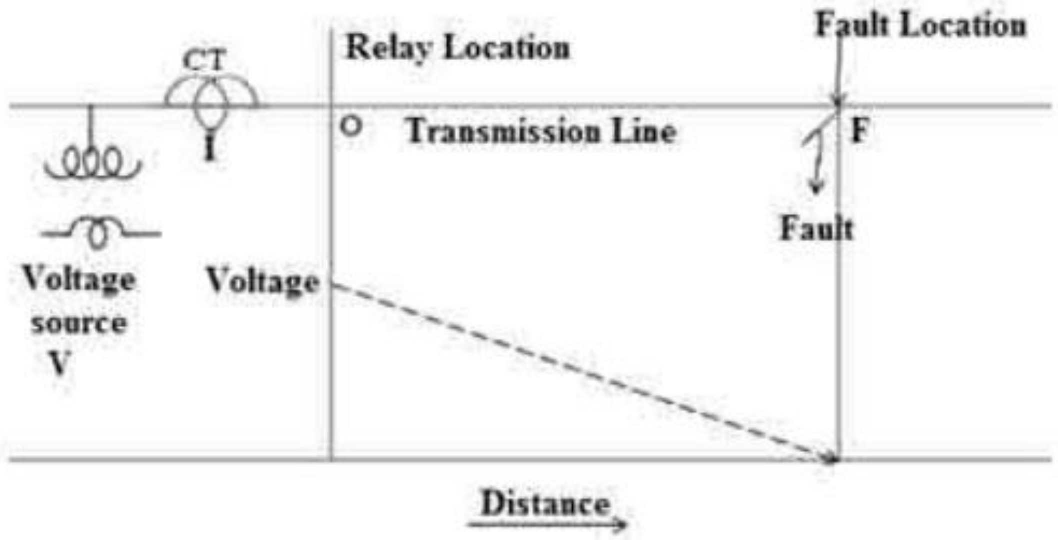
Distance protection relay is widely spread employed for the protection of high-voltage AC transmission line and distribution lines.

They have replaced the overcurrent protection because of the following reasons.

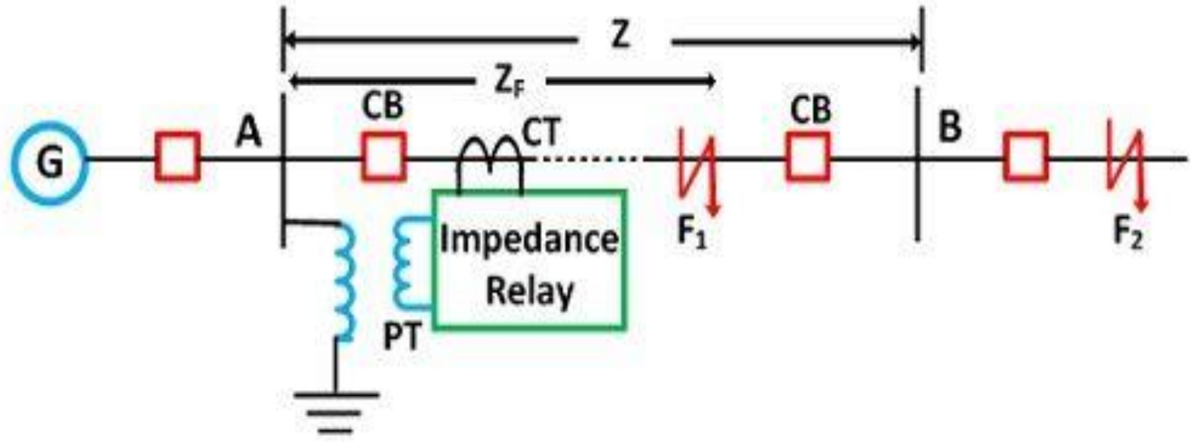
- It provides faster protection as compared to overcurrent relay.
- It has a permanent setting without the need for readjustments.
- Direct protection relay has less effect of an amount of generation and fault levels.
- Their fault current magnitude permits the high line loading.

Impedance Relay

An impedance relay measures the impedance of the line at the relay location. When a fault occurs in the protected line section the measured impedance is the impedance of the line section between the relay location and the point of fault. It is proportional to the length of the line and hence to the distance along the line as shown below.



OF is the distance along the line between the relay location and the fault location, The voltage drop along **OF** and the current I flowing in the line are taken for measurement by the relay and the ratio of the both quantities(V/I) is nothing but impedance.



Principle of operation of an Impedance Relay

Circuit Globe

Reach: A distance relay operates when the impedance (or a component of the impedance) as seen by the relay is less than a preset value. This preset impedance (or a component of the impedance) or corresponding distance is called the reach of the relay. In other words, Reach is the maximum length of the line up to which the relay can protect.

The maximum distance from the relay location to a fault for which a particular relay will operate. The reach may be stated in terms of miles

- Overreach Errors in relay measurement resulting in wrong operation
- Under reach Errors in relay measurement resulting in failure to operate

Overreach: Sometimes a relay may operate even when a fault point is beyond its present reach (i.e. its protected length). Overreach occurs under presence of DC offset in fault current wave in transient fault

- The tendency of a distance relay to operate even when a fault point is beyond its preset reach (i.e., its protected length) is known as over-reach
- The important reason for overreach of the distance relay is the presence of dc offset in the fault current wave. Because of presence of the dc offset in the fault current, the impedance seen by the relay is smaller than the actual impedance of the line up to the fault.

Underreach: Sometimes a relay may fail to operate even when the fault point is within its reach, but it is at the far end of the protected line. This phenomenon is called underreach.

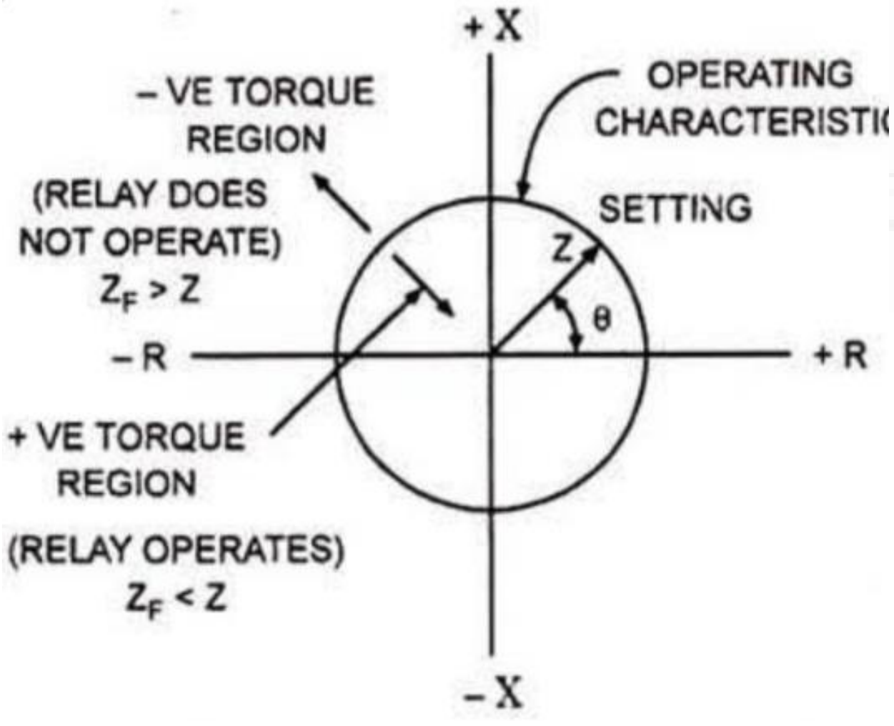
Effect of presence of arc resistance in fault path which causes distance relay to under reach

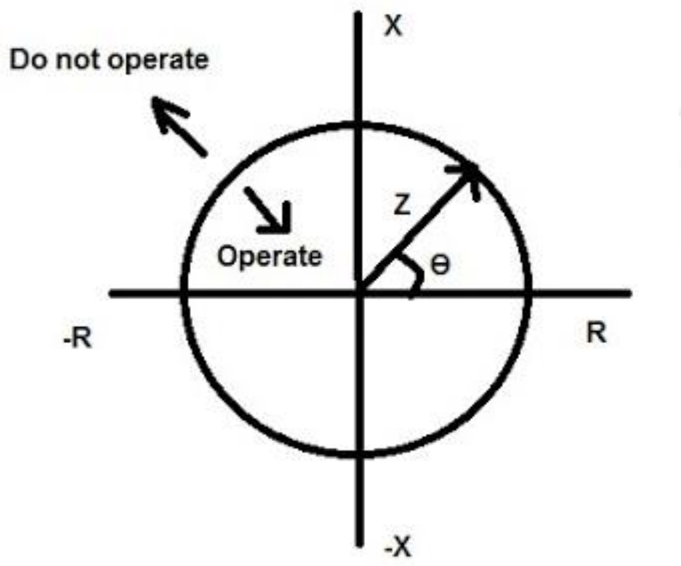
- Distance relays have under reaching and over-reaching tendencies depending on the fault conditions.
- When a distance relay fails to operate even when the fault point is within its reach, but it is at the far end of the protected line; it is called under-reach.
- The main reason for under-reach is the presence of arc resistance in the fault. Due to presence of arc resistance, the impedance seen by the relay is more than the actual impedance of the line up to the fault point. Hence are resistance causes underreach of the distance relay.

R-X plot / characteristics on a complex Plane

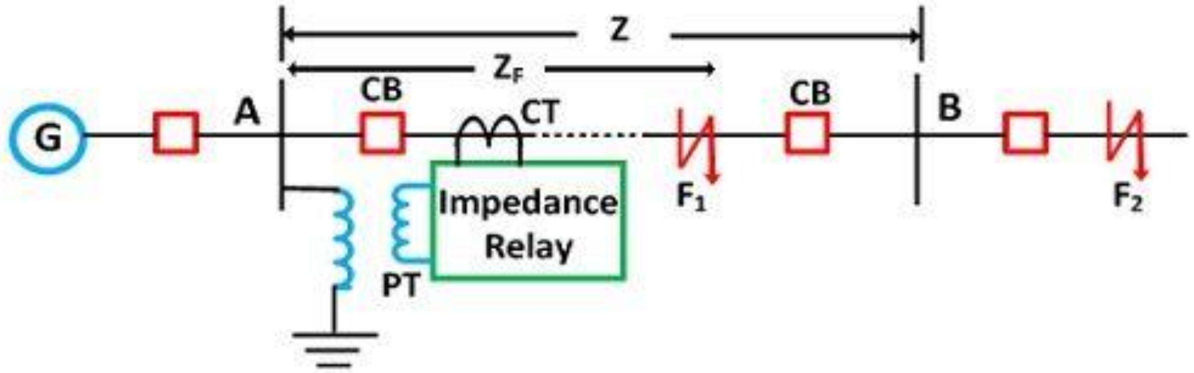
A graphical method of showing the characteristics of a relay element in terms of the ratio of voltage to current and the angle between them.

For example, if a relay barely operates with 10 V and 10 A in phase, one point on the operating curve of the relay would be plotted as 1 Ohm on the R axis (that is, R = 1, X = O).





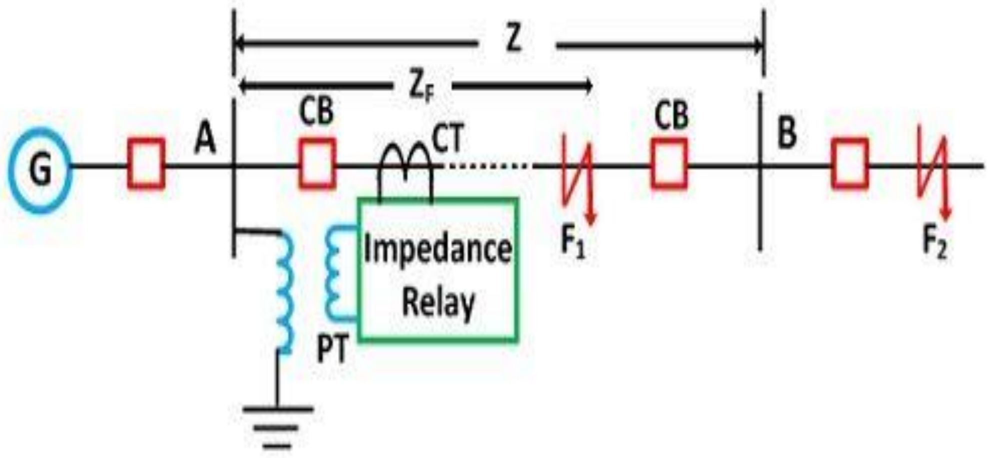
Impedance Type Distance Relay



Principle of operation of an Impedance Relay

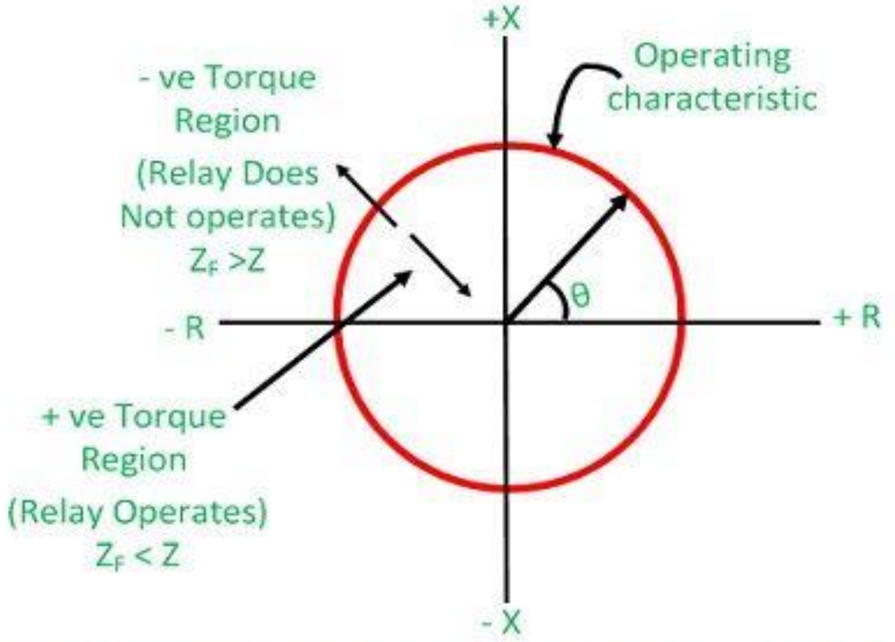
The impedance relay is a double actuating quantity relay and essentially consists of two elements—current-operated element and voltage-operated element. The current element produces a positive or pick-up torque while the voltage element develops a negative or reset torque.

Impedance Type Distance Relay (Plain Impedance Characteristic)



Principle of operation of an Impedance Relay

Circuit Globe



Operating Characteristic of an Impedance Relay on an R-X Diagram

Circuit Globe

The impedance of the line is represented by the radius of the circle. The phase angle between the X and R axis represents the position of the vector. If the impedance of the line is less than the radius of the circle, then it shows the positive torque region. If the impedance is greater than the negative region, then it represents the negative torque region

As from Universal Relay Torque Equation,

$$T = K_1I^2+K_2V^2+K_3VICos(\Theta\text{-}T)+K_4$$

Where K_1 = Constant K_2 = Constant K_3 = Constant K_4 = Spring Torque

V = Voltage fed to the Relay

I = Current fed to the Relay

T = is the angle of maximum Torque

Putting $K_4 = 0$ and introducing negative sign to the Voltage term, the Torque equation for Impedance Relay is obtained. $\mathbf{T = K_1I^2 - K_2V^2}$

Therefore from Torque Equation of Impedance Relay, it is clear that operating torque in Impedance Relay is produced by the current whereas restraining torque is by voltage. Therefore, Impedance Relay is Voltage Restrained over-current Relay.

For Relay to operate the Operating Torque must be greater than the Restraining Torque, which means

Operating Characteristic of an Impedance Relay:

- To realize the characteristics of an impedance relay, current is compared with voltage at the relay location.
- The current produces a positive torque $K_1 I^2$(operating torque) and the voltage produces a negative torque $K_2 V^2$(restraining torque).
- The equation for the operating torque of an electromagnetic relay can be written as

$$T = K_1 I^2 - K_2 V^2 - K_3$$

where K1, K2 and K3 are constants, K3 being the torque due to the control-spring effect/mechanical restraining torque Neglecting the effect of the spring used, which is very small, the torque equation can be written as

$$T = K_1 I^2 - K_2 V^2$$

for the operation of the relay, the following condition should be satisfied.

$$K_1 I^2 > K_2 V^2 \quad \text{or} \quad K_2 V^2 < K_1 I^2$$

or $\frac{V^2}{I^2} < \frac{K_1}{K_2}$ or $\frac{V}{I} < K$ or $Z < K$ Where K is constant

Operating Characteristic of an Impedance Relay:

For static and microprocessor-based relays, I is compared with V. For the operation of the relay, the following condition should be satisfied.

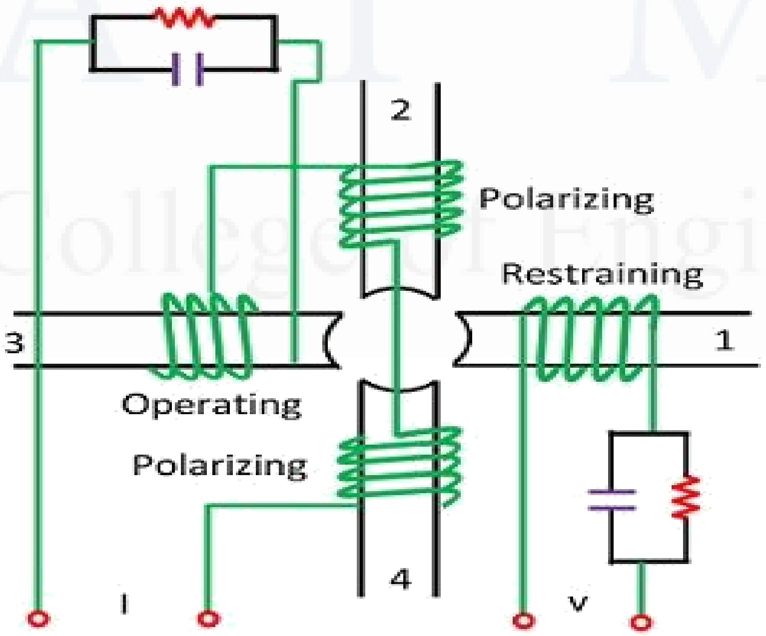
$$K_1 I > K_2 V \quad \text{or} \quad K_2 V < K_1 I$$

$$\frac{V}{I} < \frac{K_1}{K_2} \quad \text{or} \quad Z < K$$

The above expression explains that the relay is on the verge of operation when the ratio of V to I, i.e. the measured value of line impedance is equal to a given constant. The relay operates if the measured impedance Z is less than the given constant

Reactance Relay

- A typical reactance relay using the induction cup structure is shown in the figure below.
- It has a four-pole structure carrying operating, polarizing, and restraining coils, as shown in the figure below.
- The operating torque is developed by the interaction of fluxes due to current carrying coils, i.e., the interaction of fluxes of 2, 3 and 4 and the restraining torque is produced by the interaction of fluxes due to poles 1, 2 and 4.

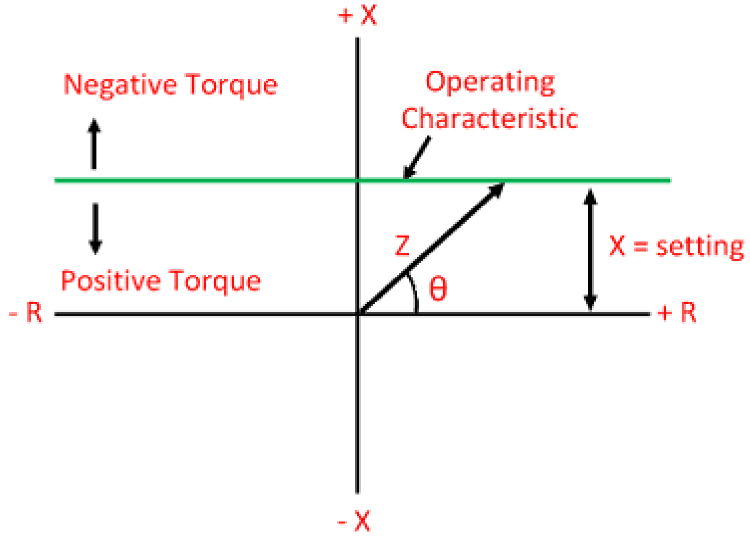


Reactance Type Distance Relay

Circuit Globe

Reactance Relay

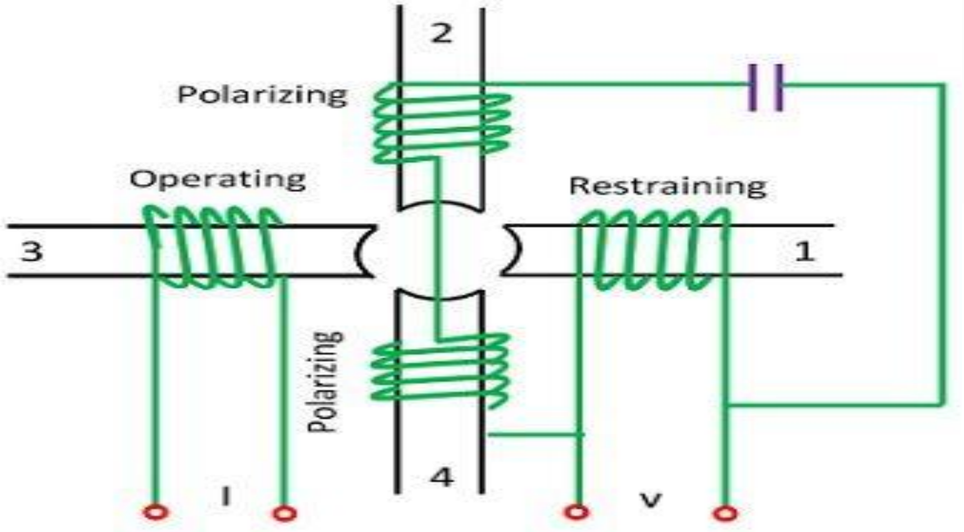
- The operating characteristic of a reactance relay is shown in the figure below.
- X is the reactance of the protected line between the relay location and the fault point, and R is the resistance component of the impedance.
- The characteristic shows that the resistance component of the impedance has no consequence on the working of the relay, the relay reacts solely to the reactance component.
- The point below the operating characteristic is called the positive torque region



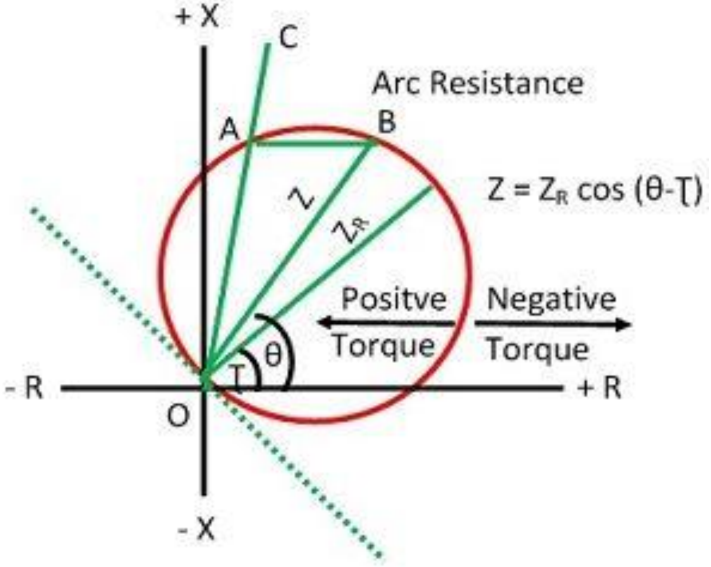
Operating Characteristic of Reactance Type Distance Relay

Mho Relay

- A mho Relay is a high-speed relay and is also known as the admittance relay. In this relay operating torque is obtained by the volt-amperes element and the controlling element is developed due to the voltage element. It means a mho relay is a voltage controlled directional relay.
- A mho relay using the induction cup structure is shown in the figure below.
- The operating torque is developed by the interaction of fluxes due to pole 2, 3, and 4 and the controlling torque is developed due to poles 1, 2 and 4.



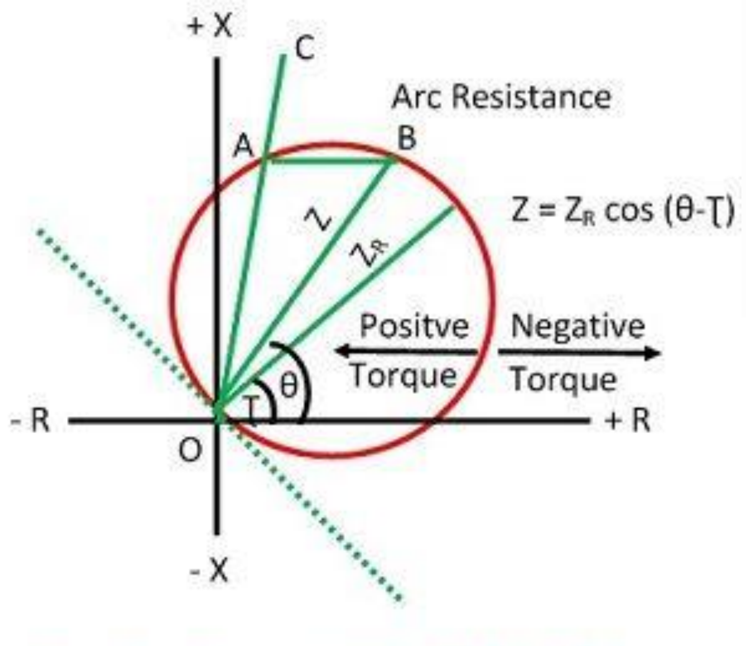
Schematic Diagram of Mho Relay



Operating Characteristic of Mho Relay
Circuit Globe

Mho Relay

The relay operates when the impedance seen by the relay within the circle. The operating characteristic showed that circle passes through the origin, which makes the relay naturally directional. The relay because of its naturally directional characteristic requires only one pair of contacts which makes it fast tripping for fault clearance and reduces the VA burdens on the current transformer.



Operating Characteristic of Mho Relay

Mho relay is suitable for EHV/UHV heavily loaded transmission lines as its threshold characteristic in Z-plane is a circle passing through the origin, and its diameter is ZR. Because of this, the threshold characteristic is quite compact enclosing faulty area compactly and hence, there is lesser chance to operate during power swing and also it is directional

Effect of the Ratio Source Impedance to Line Impedance (Z_S/Z_L)

Any system could be represented by a single line diagram shown in Fig. representing the source and the line to be protected, R being the relay location.

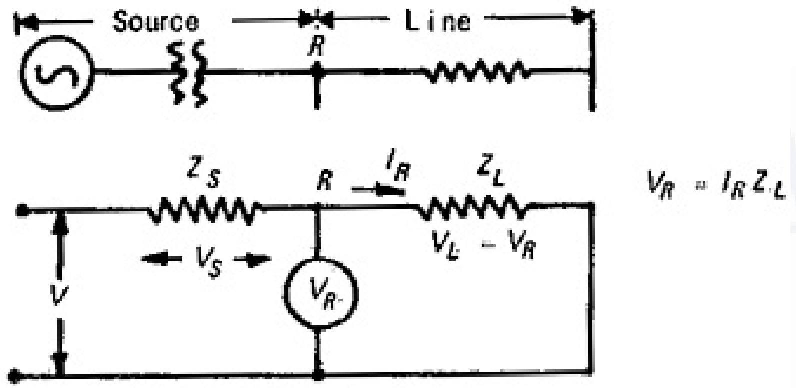


FIGURE Power system arrangement.

Z_S and Z_L are the source impedance and the line impedance respectively.

Z_S is a measure of fault MVA at the relaying point, and for faults involving earth, is also dependent on the method of system earthing behind the relaying point.

Z_L is a measure of the impedance of the protected section.

This simple impedance loop has a voltage V applied to it which actually depends on the type of fault whether phase fault or ground fault.

I_R and V_R are the current and voltage applied to the relay respectively.

The voltage V_R applied to the relay is thus $I_R Z_L$ for a fault at the reach point, and this may be alternatively expressed in terms of Z_S/Z_L ratio

$$V_R = I_R Z_L$$

$$I_R = \frac{V}{Z_S + Z_L}$$

$$V_R = \frac{Z_L}{Z_S + Z_L} V$$

$$V_R = \frac{1}{\left(\frac{Z_S}{Z_L} + 1\right)} V$$ Equation (1)

Equation (1) is true for all types of faults with the following rule being observed:

(1) With phase-faults V is the delta voltage and Z_S/Z_L is the positive sequence source impedance/positive sequence line impedance, i.e.

$$V_R = \frac{1}{\left(\frac{Z_{S1}}{Z_{L1}} + 1\right)} V_\Delta$$

(2) With earth-faults V is the star voltage and Z_S/Z_L is a composite ratio involving positive and zero sequence impedance, i.e.

$$V_R = \frac{1}{\left(\frac{Z_S}{Z_L}+1\right)} V_Y$$

Equation (2)

$$Z_S = 2Z_{S_1} + Z_{S_0}$$

$$Z_L = 2Z_{L_1} + Z_{L_0}$$

$$V_Y = V_\Delta / \sqrt{3}$$

EFFECT OF LINE LENGTH AND SOURCE IMPEDANCE ON DISTANCE RELAYS

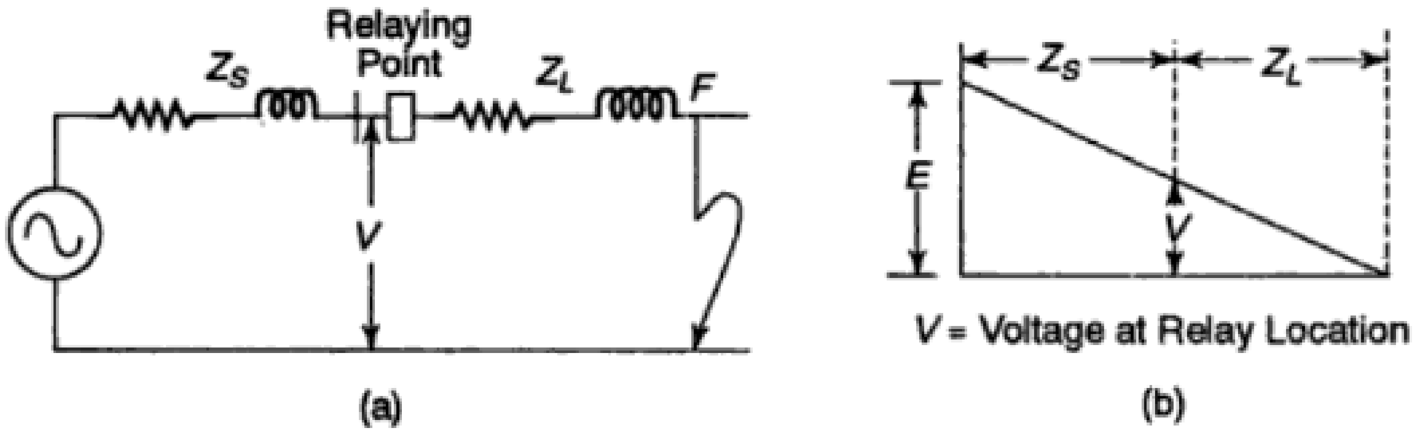


FIGURE (a) Oneline diagram of the system during fault condition
(b) Voltage at the relaying point

Zs is the source impedance behind the relay. ZL is the line impedance from the relaying point to the fault point F.

The current flowing through the relay is given by $I = \frac{E}{Z_S + Z_L}$

The voltage at the relay location which is applied to the distance relay is

$$V = IZ_L = \frac{EZ_L}{Z_S + Z_L}$$

$$= \frac{E}{\frac{Z_S}{Z_L} + 1}$$

Relay manufactures specify the minimum voltage for the relay operation.

For example an induction cup MHO relay can operate down to 8 volts within 5% accuracy. We can find the limiting value of Zs / ZL, for V = 8 V.

$$8 = \frac{E}{\frac{Z_S}{Z_L} + 1}$$

E can be taken equal to the normal secondary CT voltage, which is 110 V

$$8 = \frac{110}{\frac{Z_S}{Z_L} + 1}$$

$$\frac{Z_S}{Z_L} = \frac{110}{8} - 1 = 13.75 - 1 \cong 13$$

If the value of Zs/ZL is less than 13, the voltage at the relay point is more than 8 volts and the relay will operate.

If the ratio Zs/ZL, is more than 13, the voltage at the relay point is less than 8 volts and the relay will fail to operate. ZS is constant for the system under consideration.

The value of ZL, depends on the position of the fault point. The relay will fail to operate if

$$\frac{Z_S}{Z_L} > 13$$

$$Z_L < \frac{Z_S}{13}$$

Modern induction cup relays can operate down to 3 volts. Corresponding to this value of voltage, Z_S/Z_L = 36 V.

The relay will fail to operate if

$$Z_L < \frac{Z_S}{36}$$

Differential Protection

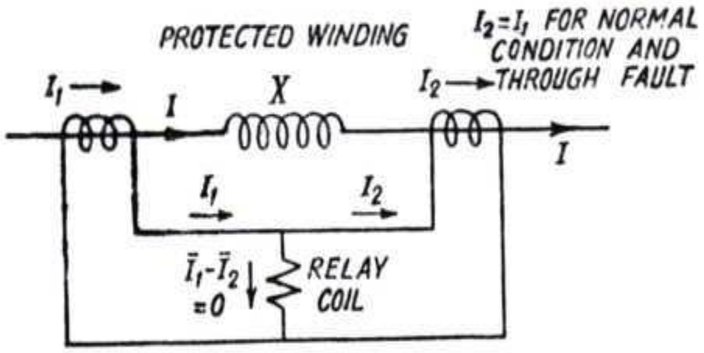
"A differential relay responds to vector difference between two or more similar electrical quantities".

From this definition the following aspects are known:

- The differential relay has at least two actuating quantities say i_1, i_2.
- The two or more actuating quantities should be similar *i.e.* current/current.
- 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

CIRCULATING CURRENT DIFFERENTIAL (MERZ-PRIZE) PROTECTION.



For Through Fault

Fig. a). Principle of circulating current relay of generators, transformers.

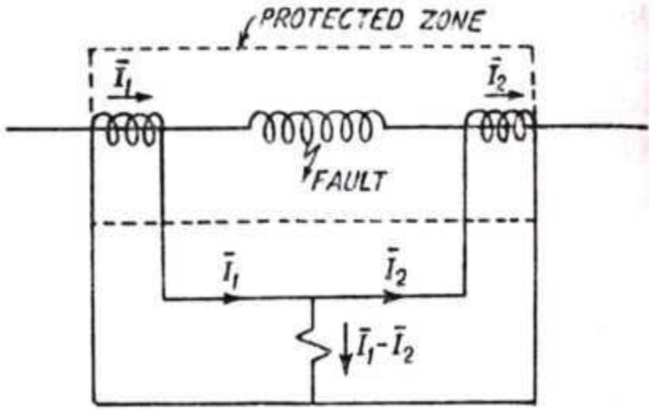


Fig. (b). Internal Fault : $I_1 - I_2 \neq 0$.

DIFFICULTIES IN DIFFERENTIAL PROTECTION

- **Difference in pilot wire lengths**. The current transformers and machine to be protected are located at different sites and normally it is not possible to connect the relay coil to the equipotential points. The difficulty is overcome by connecting adjustable resistors in series with the pilot wires. These are adjusted on site to obtain the equipotential points.

CT Ratio errors during short-circuits. The current transformer may have almost equal ratio at normal currents. But during short-circuit conditions, the primary currents are very large.

The ratio errors of CT’s on either sides differ during these conditions due to

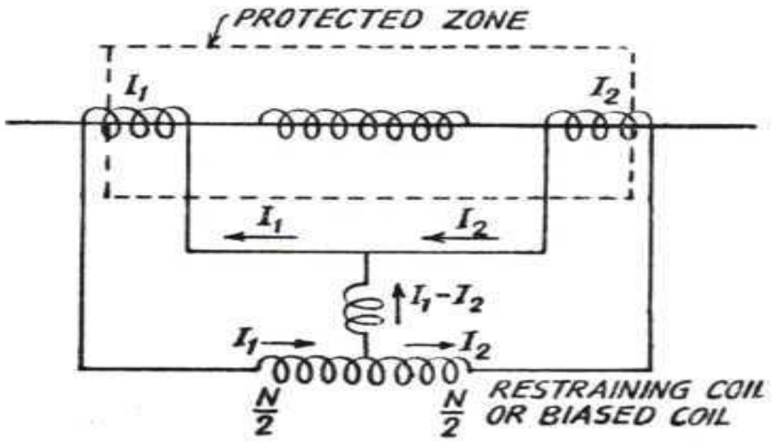
1) Inherent difference in CT characteristic arising out of difference in magnetic circuit, saturation conditions etc.

2) Unequal D.C. components in the short circuit-currents.

Tap-changing. The tap-changing causes change in transformation ratio of a transformer. Thereby the CT ratios do not match with the new-tap settings, resulting in current in pilot wires even during healthy condition. This aspect is taken care of by biased differential relay

**Pilot Wire help compare the current entering and leaving a section of the transmission line*

BAISED OR PERCENT DIFFERENTIAL RELAY



$$A.T. = \left(\frac{I_1 + I_2}{2}\right) N$$

Fig. Per cent Differential Relay.
(Biased Differential Relay.)

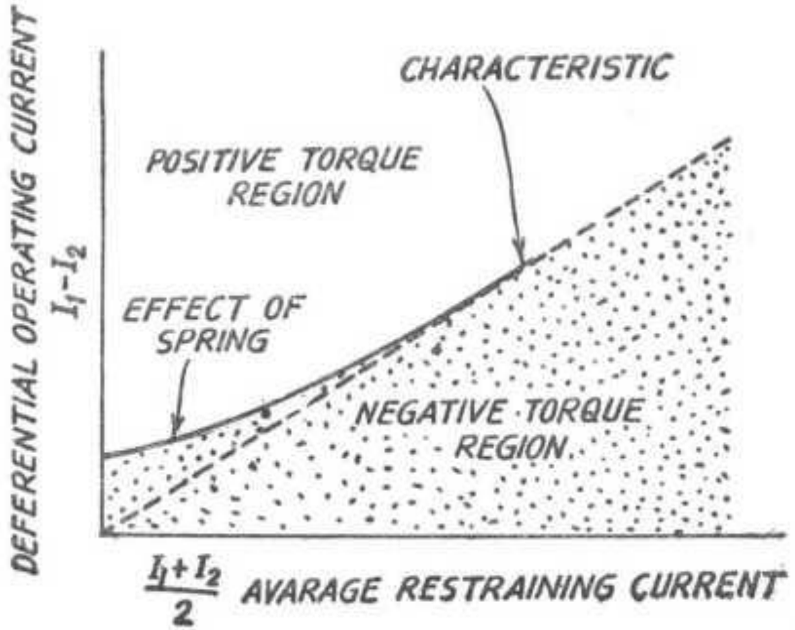
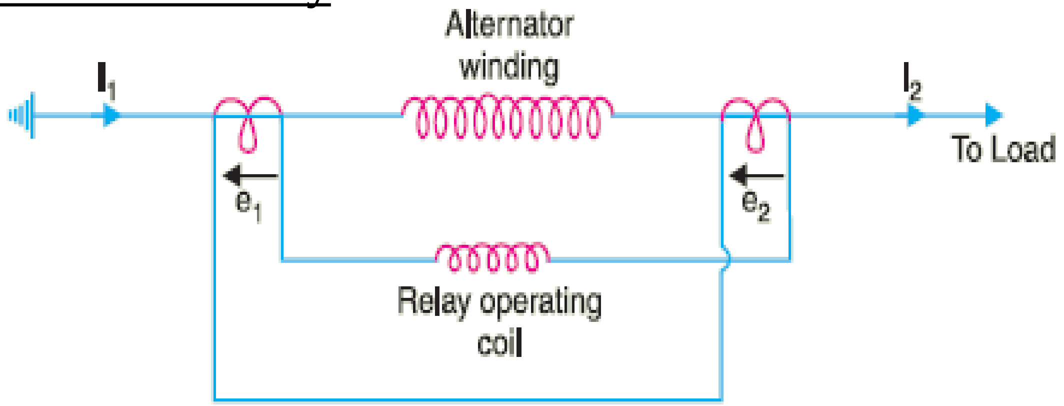


Fig. Operating characteristic of differential relay.

Balanced (Opposed) Voltage Differential Relay



Objective of Today's Session

1. **Pilot Relaying Schemes:** Introduction, Wire Pilot Protection, Carrier Current Protection.

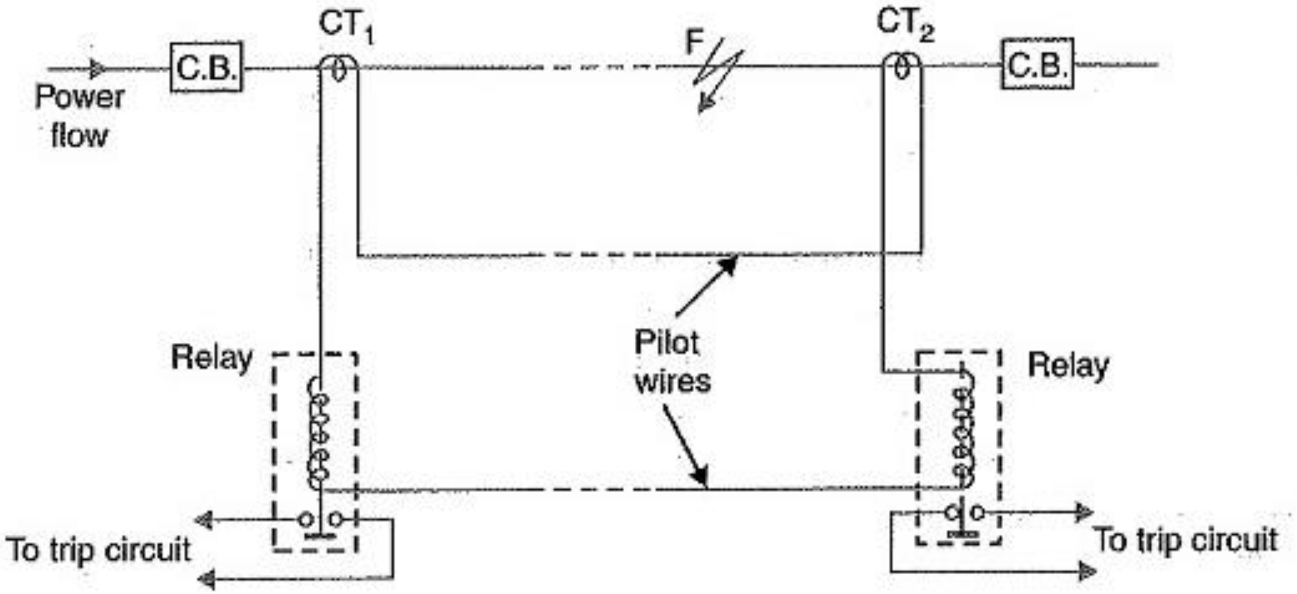
2. **Protection of Generators, Transformer and Bus zone Protection:** Introduction, Protection of Generators. Transformer Protection, Bus zone Protection

1. Pilot Relaying Schemes:

- Wire Pilot Protection,
- Carrier Current Protection.

A Pilot wire is a communication cable between the two relays located at different ends. Whenever a transmission line or equipment is to be protected by using a **differential relay**, a wire is connected between the **CTs (current transformer)** which are located in different ends of the protection zone to provide the path for the circulating current produced in an abnormal condition(fault) which is sensed by the relay and therefore breaker trips.

This protection is also called as **Differential Pilot Wire Protection.**

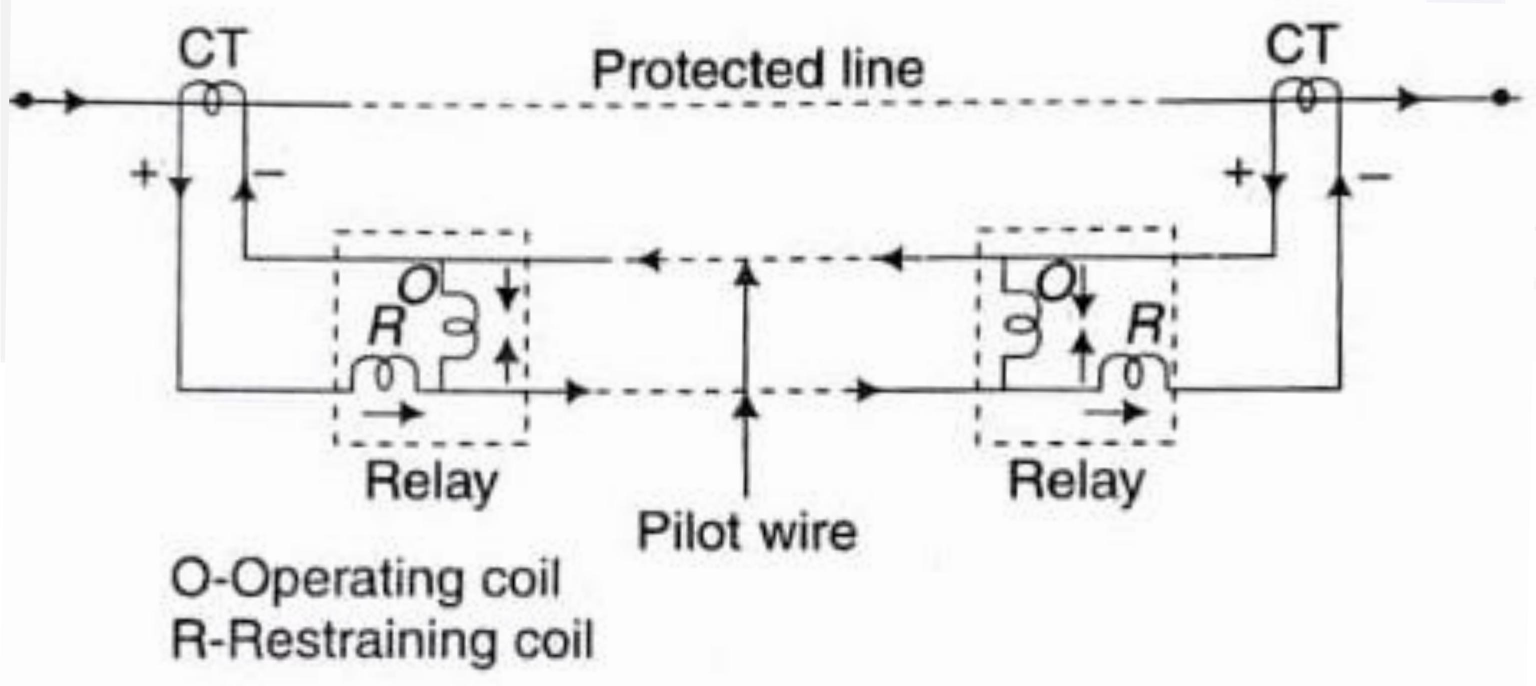


WIRE PILOT PROTECTION

- In a wire pilot relaying scheme, two wires are used to carry information signals from one end of the protected line to the other.
- A wire pilot may be buried cable or a pair of overhead auxiliary wires other than the power line conductors.
- The scheme is a unit protection and operates on the principle of differential protection.
- The comparison is made between the CT secondary currents at the two ends of the line.
- As the pilot channels are very expensive, a single phase current is derived from three-phase currents at each end of the line, thereby using only a pair of pilot wires to carry information signal

CARRIER CURRENT PROTECTION

The most widely used scheme for the protection of EHV and UHV power lines. In this scheme a carrier channel at high frequency is employed. The carrier signal is directly coupled to the same high voltage line that is to be protected. The frequency of the carrier signal is 50Hz to 700kHz



GENERATOR PROTECTION

A modern generating set is generally provided with the following protective schemes.

(i) Stator protection

(a) Percentage differential protection

(b) Protection against stator inter-turn faults

(c) Stator-overheating protection

(ii) Rotor protection

(a) Field ground-fault protection

(b) Loss of excitation protection

(c) Protection against rotor overheating because of unbalanced three-phase stator currents

(iii) Miscellaneous

(a) Overvoltage protection
(b) Overspeed protection
(c) Protection against motoring
(d) Protection against vibration
(e) Bearing-overheating protection
(f) Protection against auxiliary failure
(g) Protection against voltage regulator failure

GENERATOR PROTECTION

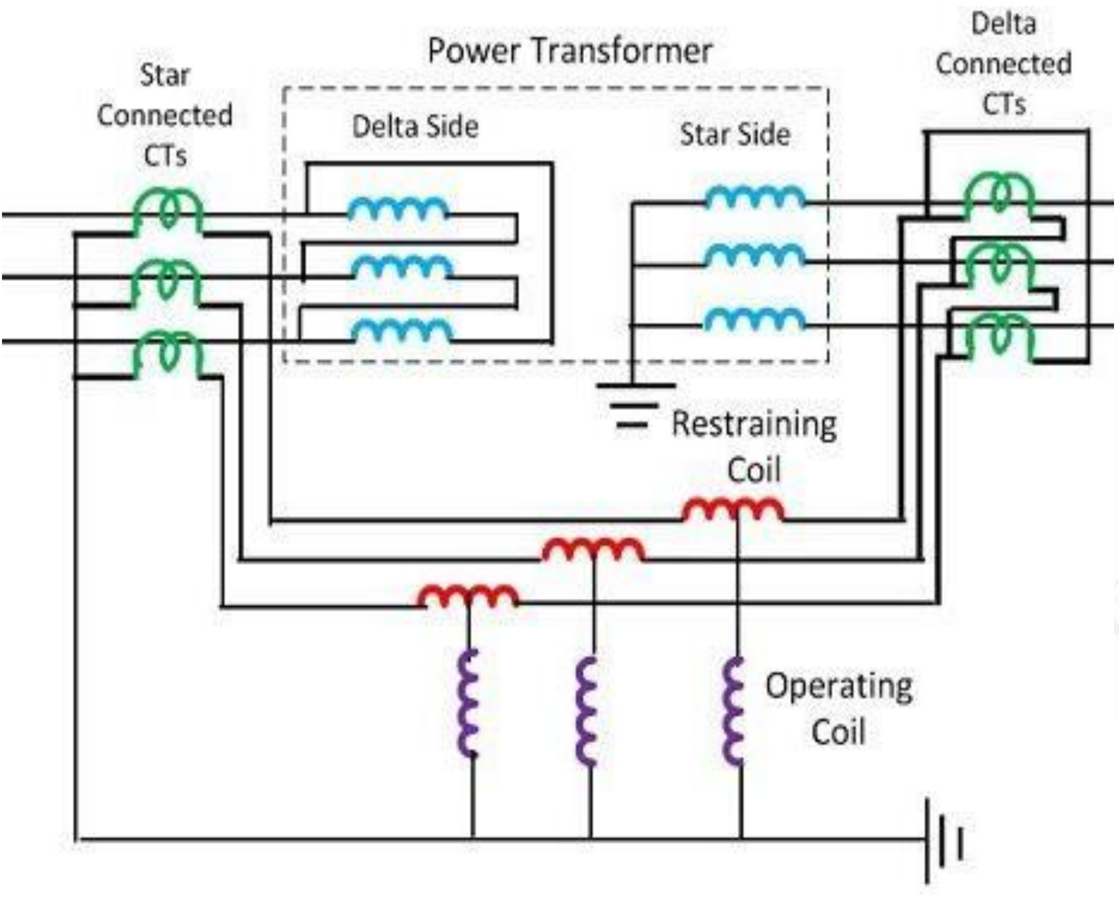
- A generator is the heart of an electrical power system, as it converts mechanical energy into its electrical equivalent, which is further distributed at various voltages.
- The capacity of generators has increased in recent times from 50 MW to 500 MW, with the result that the loss of any single unit may cause system instability.
- Power-generating plants contribute to approximately 50% of the capital cost in an electrical power system, and the generator is the most expensive electrical equipment in a power plant. The protection of generators requires more consideration, to reduce the outage period by rapid clearance of faults.
- Multifunction numerical relays are capable of providing complete protection, including differential protection, stator ground fault protection, generator field winding fault protection, stator winding turn-to-turn fault protection, out-of-step protection, and loss-of-excitation protection, to generators of all sizes at low cost.

Differential Protection

- Differential protection is generally applied to generators with ratings more than1 MVA.
- It provides protection to the stator windings of a generator against various types of phase faults.
- If a generator is solidly grounded, then the magnitude of ground fault current is very high which can be easily detected by the differential relaying scheme.
- However, if the generator is grounded through high impedance, then the ground fault currents may not have sufficient magnitude to operate the differential relay, particularly when the fault occurs closer to the neutral point of the generator stator winding.

Transformer Protection

Differential Protection of a Transformer

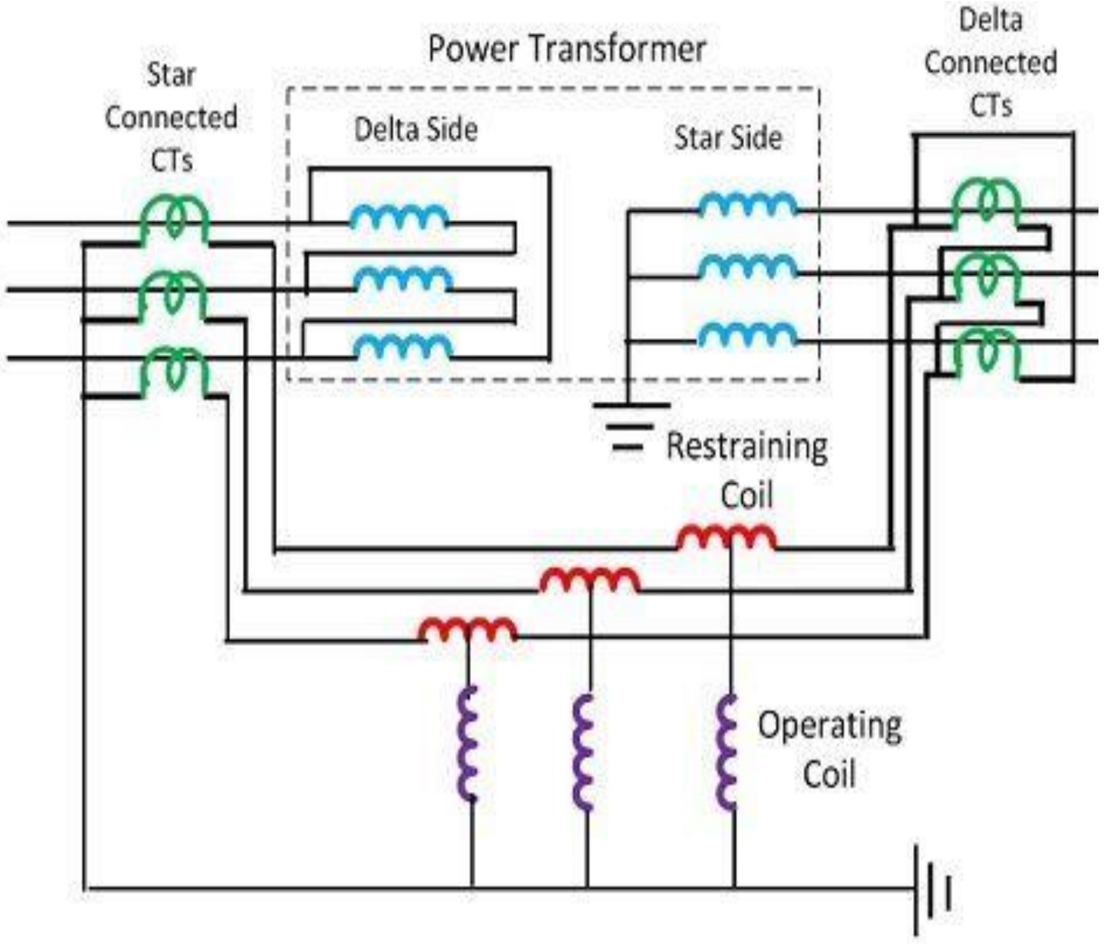


Differential Protection for Power Transformers

- The power transformer is star connected on one side and delta connected on the other side.
- The CTs on the star connected side are delta-connected and those on delta-connected side are star-connected.
- The neutral of the current transformer star connection and power transformer star connections are grounded.
- The restraining coil is connected between the secondary winding of the current transformers.
- Restraining coils controls the sensitive activity occurs on the system. The operating coil is placed between the tapping point of the restraining coil and the star point of the current transformer secondary windings.

Working of Differential Protection System

Normally, the operating coil carries no current as the current are balanced on both the side of the power transformers. When the internal fault occurs in the power transformer windings the balanced is disturbed and the operating coils of the differential relay carry current corresponding to the difference of the current among the two sides of the transformers. Thus, the relay trip the main circuit breakers on both sides of the power transformers.



Differential Protection for Power Transformers

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 g. earth-faults, phase-to-phase faults and inter-turn faults

- **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.
- **Earth fault relays** providing protection against earth-faults only.
- **Overcurrent 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 Transformers usually requires the combination of these systems. Choice of a particular combination of systems may depend upon several factors such as

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

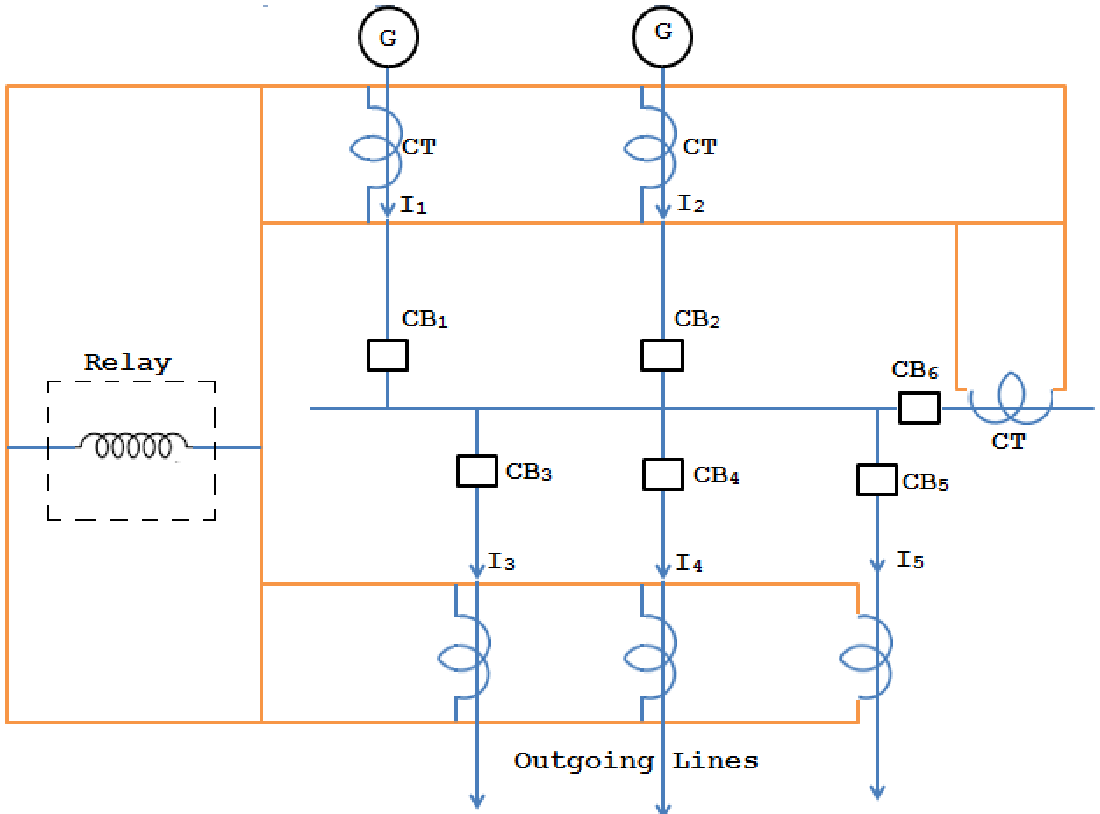
Bus-Bar Protection

Bus-Bar Protection

- When the fault occurs on the bus bars whole of the supply is interrupted, and all the healthy feeders are disconnected.
- The majority of the faults is single phase in nature, and these faults are temporary.
- The bus zone fault occurs because of various reasons likes failure of support insulators, failure of circuit breakers, foreign object accidentally falling across the bus bar, etc., For removing the bus fault, all the circuits connecting to the faulty section needs to be open.

Bus Zone Protection by Differential Principle

A simple **differential protection scheme** is shown in the figure below. It is based in simple **circulating current principle** that during normal load conditions or external fault conditions, the sum of currents entering the bus equals the sum of the currents leaving the busbar, i.e., $I_1 + I_2 = I_3 + I_4 + I_5$.



Differential Protection of Busbar