Lecture Notes on

SWITCH GEAR AND PROTECTIVE DEVICES

6^{TH} SEMESTER
DIPLOMA

IN

ENGINEERING

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CHAPTER -1

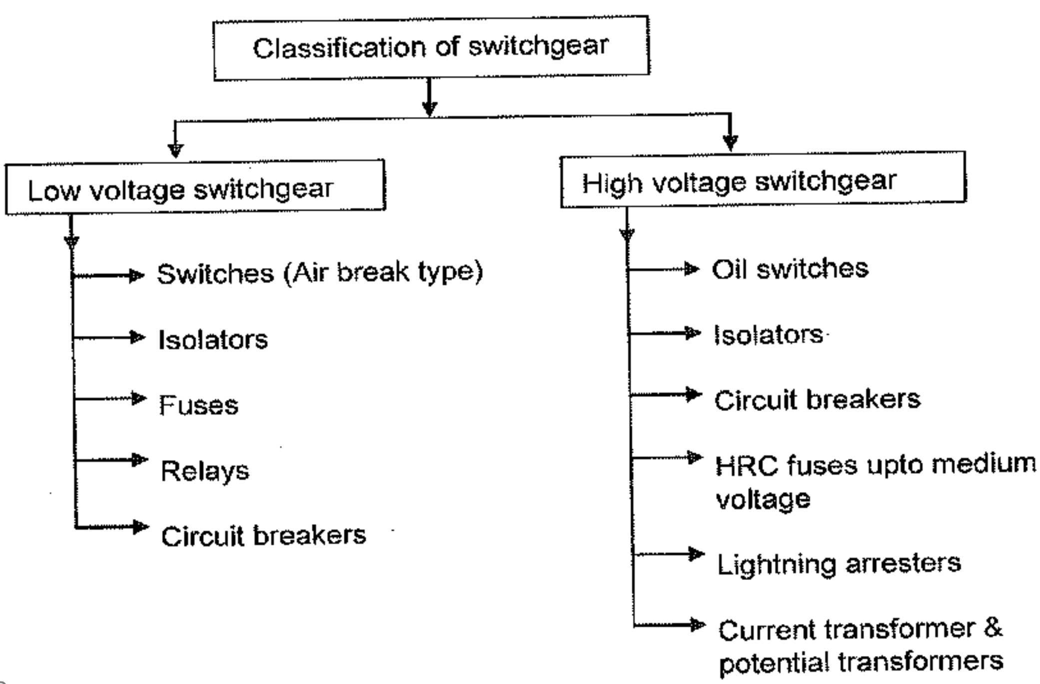
1.1 Fundamentals of Power System Protection

The purpose of an Electric Power System is to generate and supply electrical energy to consumers. The power system should be designed and managed to deliver this energy to the utilization points with both reliability and economically

The capital investment involved in power system for the generation, transmission and distribution is so great that the proper precautions must be taken to ensure that the equipment not only operates as nearly as possible to peak efficiency, but also must be protected from accidents

The normal path of the electric current is from the power source through copper (or aluminium) conductors in generators, transformers and transmission lines to the load and it is confined to this path by insulation. The insulation, however, may break down, either by the effect of temperature and age or by a physical accident, so that the current then follows an abnormal path generally known as Short Circuit or Fault

- Any abnormal operating state of a power system is known as *FAULT*. Faults in general consist of short circuits as well as open circuits. Open circuit faults are less frequent than short circuit faults, and often they are transformed in to short circuits by subsequent events.



1.2 Consequences of occurrence of Faults

Faults are of two type

- Short circuit fault- current
- Open circuit fault- voltage

In terms of seriousness of consequences of a fault , short circuits are of far greater concern than open circuits, although some open circuits present some potential hazards to personnel

Classification of short circuited Faults

- Three phase faults (with or without earth connection)
- Two phase faults (with or without earth connection)
- Single phase to earth faults

Classification of Open Circuit Faults

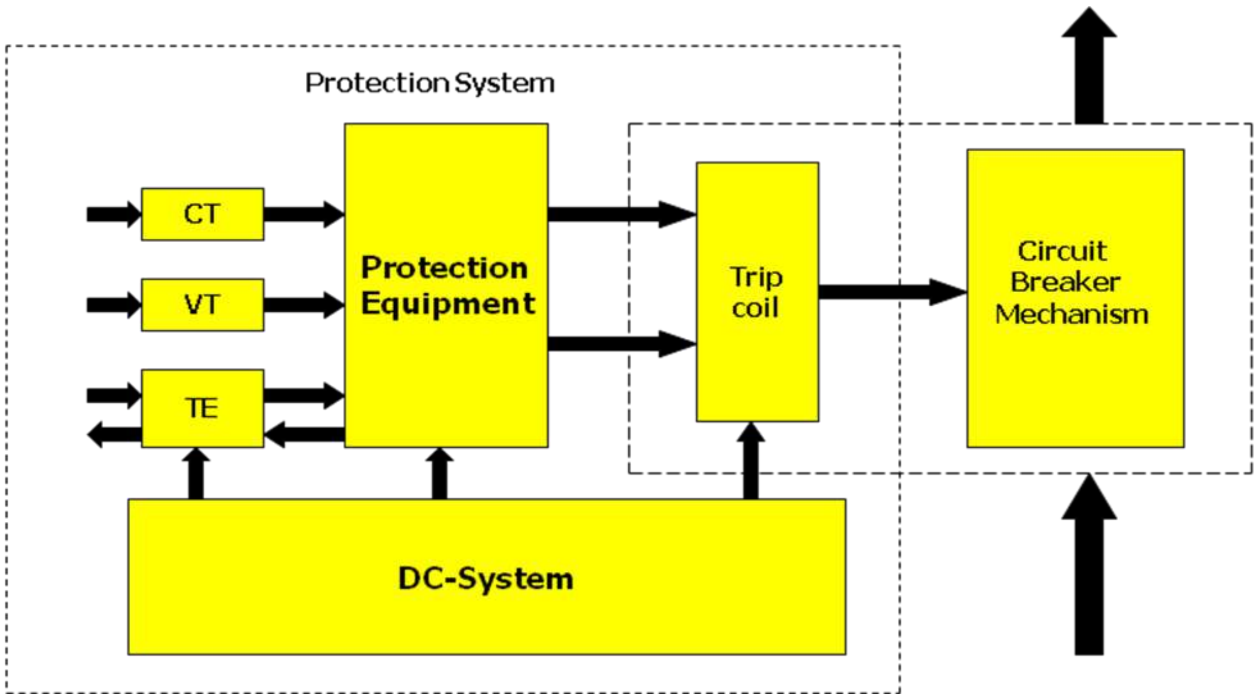
- Single Phase open Circuit
- Two phase open circuit
- Three phase open circuit

Consequences

- Damage to the equipment due to abnormally large and unbalanced currents and low voltages produced by the short circuits
- Explosions may occur in the equipments which have insulating oil, particularly during short circuits. This may result in fire and hazardous conditions to personnel and equipments
- Individual generators with reduced voltage in a power station or a group of generators operating at low voltage may lead to loss of synchronism, subsequently resulting in islanding.

- Risk of synchronous motors in large industrial premises falling out of step and tripping out.

The general layout of a protection system may be viewed as given in the following figure

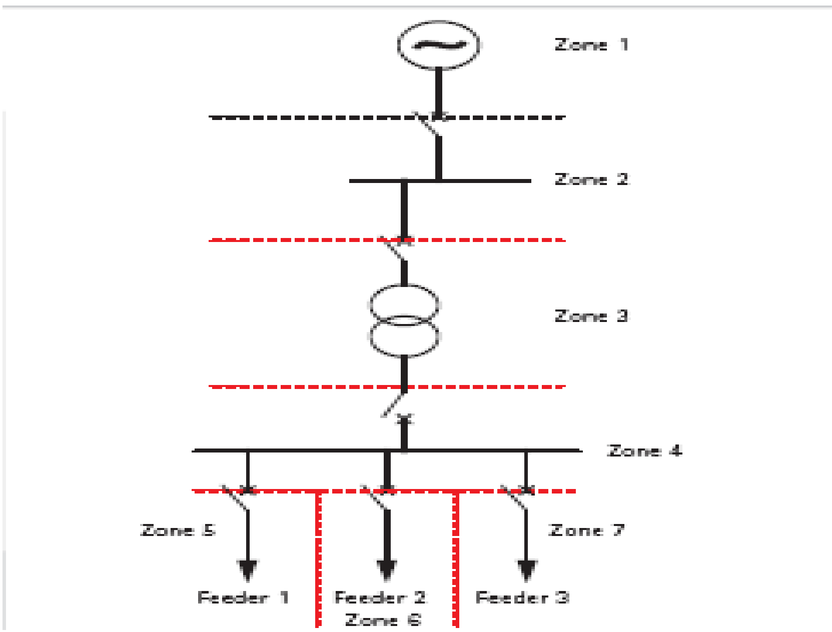


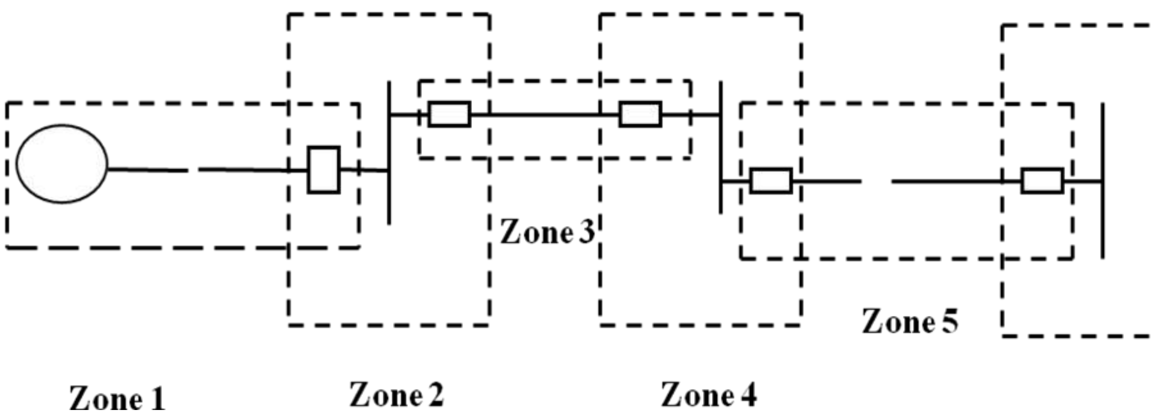
1.3 Zones and types of Protection system

1.3.1 Zones of Protection system

- An electric power system is divided into several zones of protection. Each zone of protection, contains one or more components of a power system in addition to two circuit breakers.
- When a fault occurs within the boundary of a particular zone, then the protection system responsible for the protection of the zone acts to isolate (by tripping the Circuit Breakers) every equipment within that zone from the rest of the system.
- The circuit Breakers are inserted between the component of the zone and the rest of the power system. Thus, the location of the circuit breaker helps to define the boundaries of the zones of protection.

- Different neighbouring zones of protection are made to overlap each other, which ensure that no part of the power system remains without protection. However, occurrence of the fault with in the overlapped region will initiate a tripping sequence of different circuit breakers so that the minimum necessary to disconnect the faulty element





1.3.2 Types of Protection (Primary and Back-up Protection)

1.3.2.1 Primary Protection

- The primary protection scheme ensures fast and selective clearing of any fault within the boundaries of the circuit element, that the zone is required to protect. Primary Protection as a rule is provided for each section of an electrical installation.

However, the primary protection may fail. The primary cause of failure of the Primary Protection system are enumerated below.

1. Current or voltage supply to the relay.
2. D.C. tripping voltage supply
3. Protective relays
4. Tripping circuit
5. Circuit Breaker

1.3.2.2 Back-up Protection

Back-up protection is the name given to a protection which backs the primary protection whenever the later fails in operation. The back-up protection by definition is slower than the primary protection system. The design of the back-up protection needs to be coordinated with the design of the primary protection and essentially it is the second line of defence after the primary protection system.

1.4 Protection System Requirements and some basic terminologies used

- The fundamental requirements for a protection system are as follows:

1.4.1 *Reliability*: It is the ability of the protection system to operate correctly. The reliability feature has two basic elements, which are *dependability* and *security*. The dependability feature demands the certainty of a correct operation of the designed system, on occurrence of any fault. Similarly, the security feature can be defined as the ability of the designed system to avoid incorrect operation during faults. A comprehensive statistical method based reliability study is required before the protection system may be commissioned. The factors which affect this feature of any protection system depends on some of the following few factors.

a) Quality of Component used

b) Maintenance schedule

c) The supply and availability of spare parts and stocks

d) The design principle

e) Electrical and mechanical stress to which the protected part of the system is subjected to.

1.4.2 *Speed*: Minimum operating time to clear a fault in order to avoid damage to equipment. The speed of the protection system consists primarily of two time intervals of interest.

a) *The Relay Time* : This is the time between the instant of occurrence of the fault to the instant at which the relay contacts open.

b) *The Breaker Time:* This is the time between the instant of closing of relay contacts to the instant of final arc extinction inside the medium and removal of the fault.

1.4.3 *Selectivity*: This feature aims at maintaining the continuity of supply system by disconnecting the minimum section of the network necessary to isolate the fault. The property of selective tripping is also known as “discrimination”. This is the reason for which the entire system is divided into several protective zones so that minimum protion of network is isolated with accuracy. Two examples of utilization of this feature in a relaying scheme are as follows

a) Time graded systems

b) Unit systems

1.4.4. Sensitivity: The sensitivity of a relay refers to the smallest value of the actuating quantity at which the relay operates detecting any abnormal condition. In case of an overcurrent relay, mathematically this can be defined as the ratio between the short circuit fault current (I_s) and the relay operating current (I_o). The value of I_o , should not be too small or large so that the relay is either too sensitive or slow in responding.

1.4.5 *Stability*: It is the quality of any protection system to remain stable within a set of defined operating scenarios and procedures. For example the biased differential scheme of differential protection is more stable towards switching transients compared to the more simple and basic Merz Price scheme in differential protection

1.4.6 *Adequacy*: It is economically unviable to have a 100% protection of the entire system in concern. Therefore, the cost of the designed protection system varies with the criticality and importance of the protected zone. The protection system for more critical portions

is generally costly, as all the features of a good protection system is maximized here. But a small motor can be protected by a simple thermally operated relay, which is simple and cheap. Therefore, the cost of the protection system should be adequate in its cost.

1.4.7 Some basic terminologies used in protection system

Some basic terminologies commonly used in the protection system are enlisted below.

i) Measuring Relay ii) Fault Clearing Time iii) Auxilliary relay iv) Relay Time v) Pick up value vi) Reset Value vii) Drop out viii) Reach (under and over reaches) ix) Relay Burden x) Unit/ Non unit protection xi) All or Nothing relay

1.5 Classification and construction of relays

1.5.1 Classification

Protection relays can be primarily classified in accordance with their construction, the actuating signal and application and function

1.5.1.1 According to the Construction principle

Depending upon the principle of construction, the following four brad categories are found.

- Electromechanical
- Solid State
- Microprocessor
- Numerical

1.5.1.2 According to the actuating signals

The actuating signal may be any of the following signals including a numbers of different combinations of these signals depending upon whether the designed relay require a single or multiple inputs for its realization.

- Current
- Voltage
- Power
- Frequency
- Temperature
- Pressure
- Speed
- Others

1.5.1.3 Function

The functions for which the protection system is designed classify the relays in the following few categories.

- Directional Over current
- Distance

- Over voltage
- Differential
- Reverse Power
- Others

It is important to notice that the same set of input actuating signals may be utilized to design to relays having different function or application. For example, the voltage and current input relays can be designed both as a *Distance* and/ or a *Reverse Power* relay.

Electromechanical relays

These relays are constructed with electrical, magnetic & mechanical components & have an operating coil & various contacts,& are very robust & reliable. Based on the construction, characteristics, these are classified in three groups.

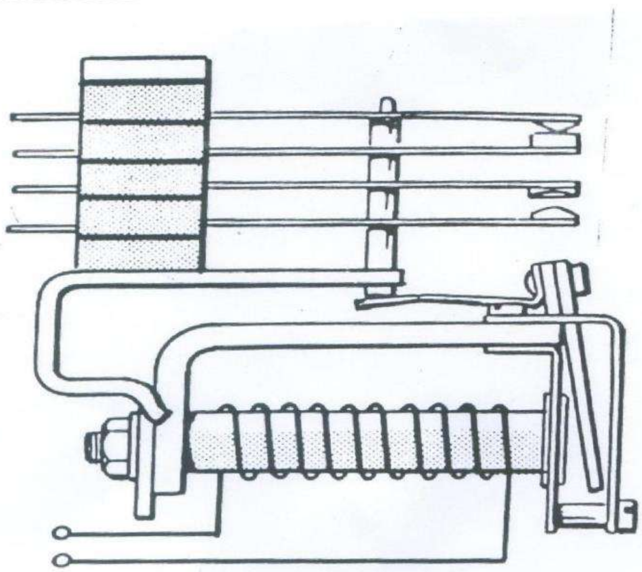
Attraction relays

Attraction relays can be AC & DC and operate by the movement of a piece of iron when it is attracted by the magnetic field produced by a coil. There are two main types of relays:

1. The attracted armature type
2. Solenoid type relay

Attracted armature relays

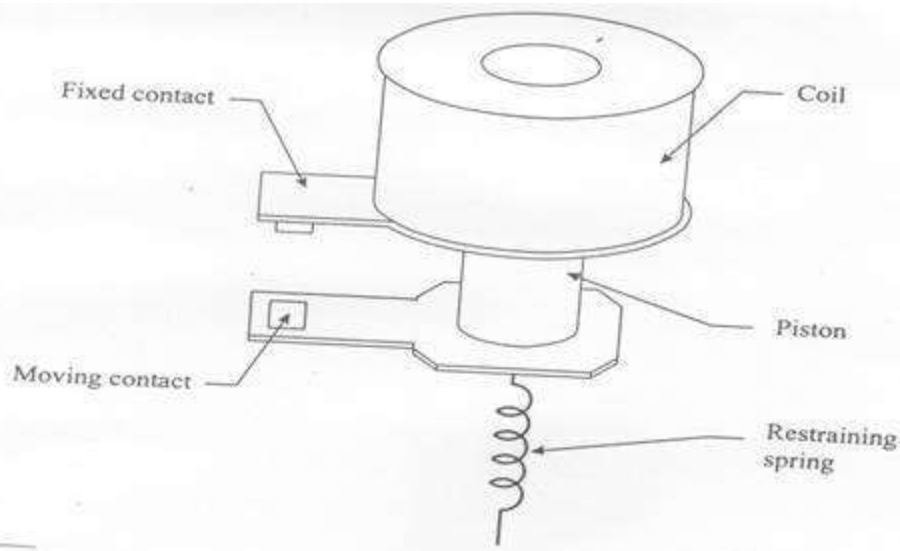
- Consists of a bar or plate (made of iron) that pivots when it is attracted towards the coil.
- The armature carries the moving part of the contact ,which is closed or opened, according to the design, when the armature is attracted to the coil.



Hinged armature relay

Solenoid type relays

In this a plunger or a piston is attracted axially within the field of the solenoid. In this case, the piston carries the moving contacts.



Solenoid-type relay

The force of attraction = $K_1 I^2 - K_2$

Where, K_1 depends on

- The number of turns of the coil
- The air gap
- The effective area
- The reluctance of the magnetic circuit

K_2 is the restraining force, usually produced by spring

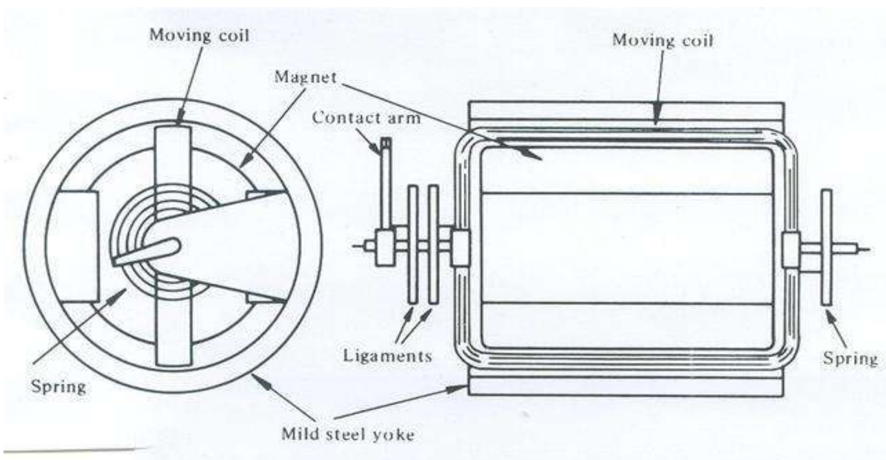
For threshold or balanced condition, the resultant force is zero.

$$K_1 I^2 = K_2 \qquad I = \sqrt{\left(\frac{K_1}{K_2}\right)}$$

In order to control the value of current at which relay operates, the parameters K_1 and K_2 may adjusted. Attraction relays effectively have no time delay and are widely used when instantaneous operation is required.

Relays with movable coils

This type of relay consists of a rotating movement with a small coil suspended or pivoted with the freedom to rotate between the poles of a permanent magnet. The coil is restrained by two special springs which also serve as connections to carry the current to the coil.



Moving-coil relay for protection schemes

The torque produced in the coil is

$$T = BlaNi$$

Where, T= Torque

B= flux density

l= length of the coil

a= distance between the two sides of the coil

i=current flowing through the coil

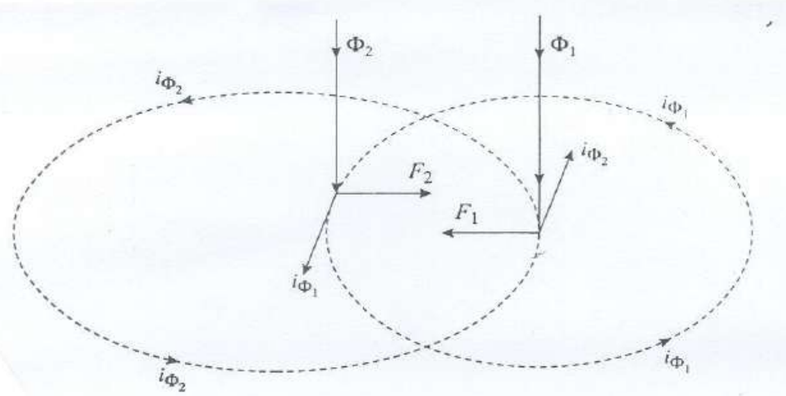
N=number of turns in the coil

- The relay has inverse type characteristic

Induction relays

- An induction relay works only with AC
- It consists of an electromagnetic system Which operates on a moving conductor, generally in the form of a DISC or CUP

Production of actuating torque



Electromagnetic forces in induction relays

Various quantities are shown at instant when

- Both fluxes are directed downward
- Are increasing in magnitude

Let

$$\phi_1(t) = \phi_{m1} \sin(\omega t)$$

$$\phi_2(t) = \phi_{m2} \sin(\omega t + \theta)$$

It may be assumed with negligible error that the paths in which rotor current flow have negligible self inductance.

$$F = F_2 - F_1$$

$$= \alpha\ \phi_2(t) i_{\phi 1}(t) - \phi_1(t) i_{\phi 2}(t)$$

$$= \alpha\ \phi_{m1}\phi_{m2}[\sin(\omega t + \theta)\cos(\omega t) - \sin(\omega t)\cos(\omega t + \theta)]$$

$$= \alpha\ \phi_{m1}\phi_{m2} \sin\theta$$

Since sinusoidal flux waves are assumed, we may substitute the rms values of the fluxes for the crest values in the above equation.

$$F \propto \phi_1\phi_2 \sin\theta$$

- It may be noted that the net force is same at every instant.
- The net force is directed from the point where the leading flux process the rotor towards the point where the lagging flux pierces the rotor.
- Actuating force is produced in the presence of out of phase fluxes.

- Maximum force is produced when θ=90º

Classification of induction relays

1. Shaded pole relay

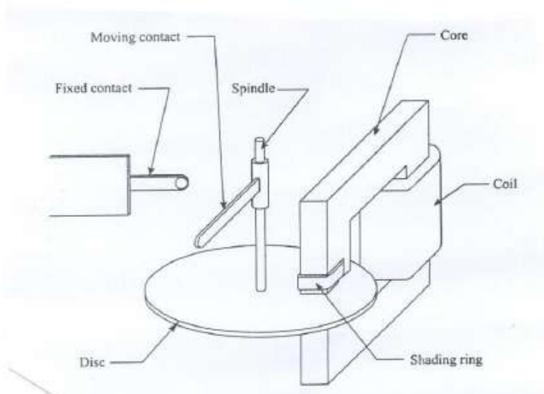
2. Watthour- meter type relay

3. Cup type relay

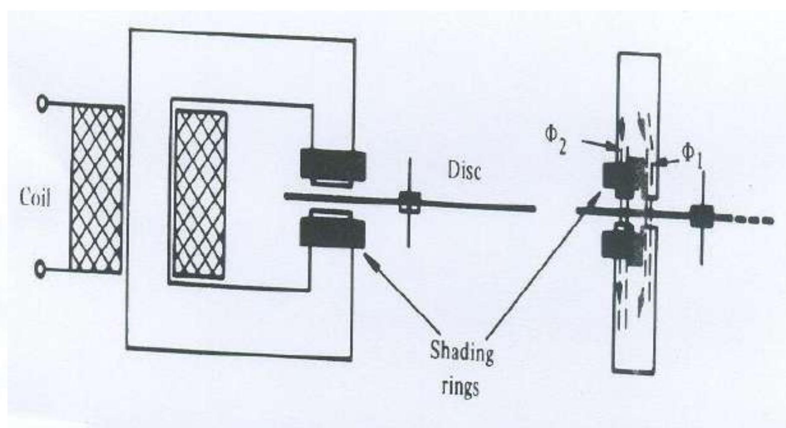
The air gap flux produced by the current flowing in a single coil is split into two out of phase components by a so called „Shading Ring" generally of copper, that encircles part of the pole face of each pole at the air gap.

- The shading ring may be replaced by coils if control of operation of the shaded pole relay is desired.

- The inertia of the disc provides the time delay characteristics.



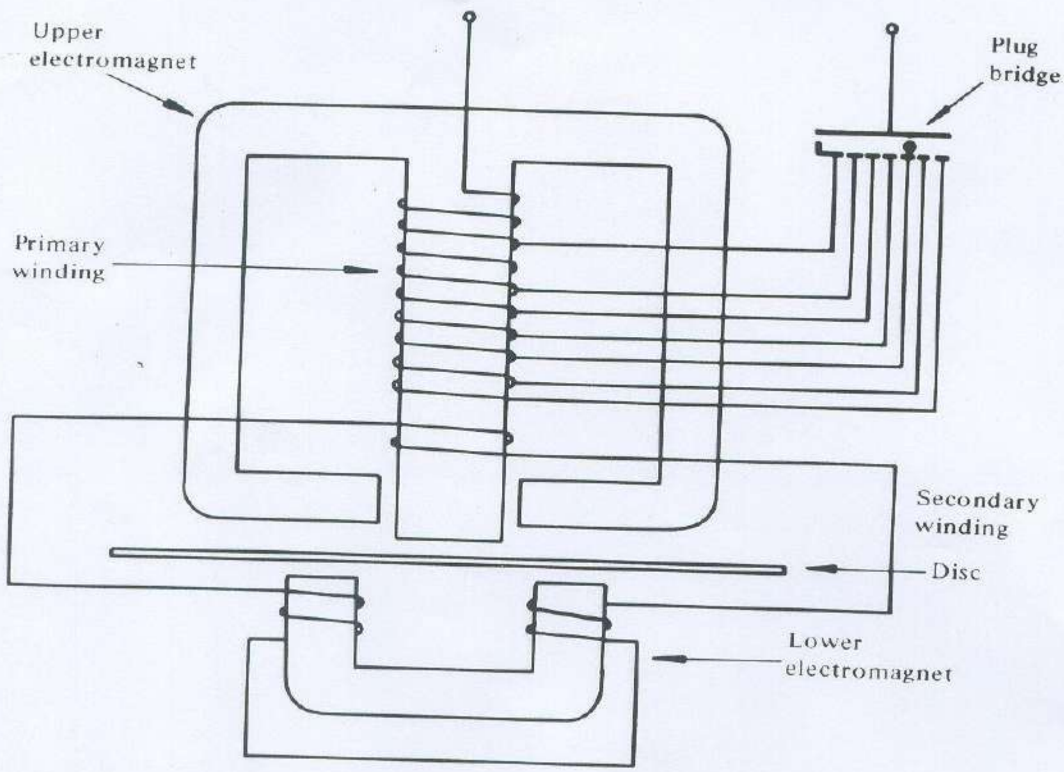
Shaded-pole relay



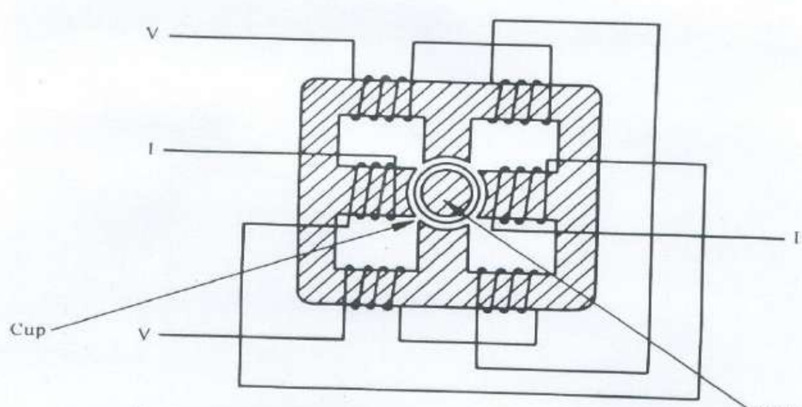
Shaded-pole induction-disc relay

Watt hour –meter structure

- This structure gets its name from the fact that it is used in watt hour meters.
- As shown in the top figure below, it contains two separate coils on two different magnetic circuit, each of which produces one of two necessary fluxes for driving the rotor, which is also a disc



Winding arrangement



Four pole cup relay

Induction-cup

- This type of relay has a cylinder similar to a cup which can rotate in the annular air gap between the poles & the fixed central core. The figure is shown above.
- The operation of this relay is similar to that of an induction motor with salient poles for the windings of the stator.
- The movement of the cup is limited to a small amount by the contact & the stops.
- A special spring provides restraining torque.
- The cup type of relay has a small inertia & is therefore principally used when high speed operation is required, for example in instantaneous units.

General Torque equation of Relay

Before understanding about different other relays, it is first necessary to know the general torque equation that defines any relay. The following equation defines torque in general.

$$T = K_1 I^2 + K_2 V^2 + K_3 VI\ Cos(\theta - \tau) + K_4$$

Where, θ is the power factor angle and τ is the angle of maximum torque.

As seen from the equation, the component of torques may be proportional to current, voltage, power and combination of the three quantities. The constant K_4 is meant for the spring constant of the relay. Depending upon the type of relay, the one or several of the four constants K_1–K_4 are either zero or non zero. In the subsequent discussions this will be elaborated when different types of relays are discussed.

1.6 Overcurrent Relays

- Protection against excess current was naturally the earliest protection systems to evolve
- From this basic principle has been evolved the graded over current system, a discriminate fault protection.
- “over current” protection is different from “over load protection”.

- Overload protection makes use of relays that operate in a time related in some degree to the thermal capability of the plant to be protected.

- Over current protection, on the other hand, is directed entirely to the clearance of the faults, although with the settings usually adopted some measure of overload protection is obtained.

- In terms of the general torque equation the over current relay has both constants K_2 and K_3 equal to zero. Therefore, the equation becomes

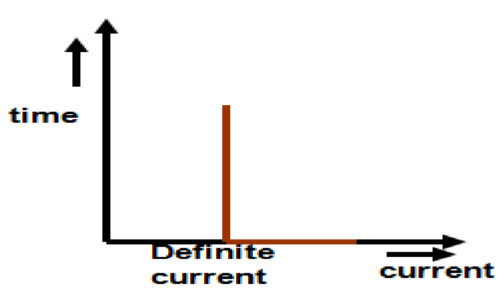
$$T = K_1 I^2 + K_4$$

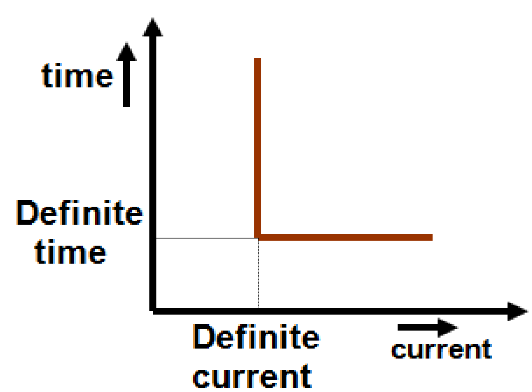
1.6.1 Types of over current relays

- Based on the relay operating characteristics , overcurrent relays can be classified into three groups
  - Definite current or instantaneous
  - Definite time
  - Inverse time

DEFINITE-CURRENT RELAYS

- This type of relay operates instantaneously when the current reaches a predetermined value.





DEFINITE TIME CURRENT RELAYS

- This type of relay operates after a definite time when the current reaches a pre-determined value.

INVERSE TIME RELAYS

- The fundamental property of these relays is that they operate in a time that is inversely proportional to the fault current. Inverse time relays are generally classified in accordance with their characteristic curve that indicates the speed of operation.
- Inverse-time relays are also referred as inverse definite minimum time or IDMT over current relays

SETTING THE PARAMETERS OF TIME DELAY OVERCURRENT RELAY

Pick-up setting

The pick-up setting, or plug setting, is used to define the pick-up current of the relay, and fault currents seen by the relay are expressed as multiples of plug setting.

- Plug setting multiplier (PSM) is defined as the ratio of the fault current in secondary Amps to the relay plug setting.
- For phase relays the pick-up setting is determined by allowing a margin for overload above the nominal current, as in the following expression

$$\text{Pick-up setting} = (OLF \times I_{nom}) / CTR$$

Where, OLF = Overload factor that depends on the element being protected.

I_{nom} = Nominal circuit current rating, and CTR = CT Ratio

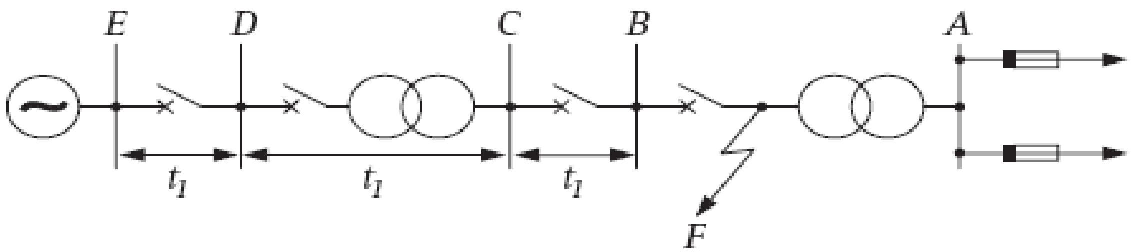
Time dial setting

- The time-dial setting adjusts the time –delay before the relay operates whenever the fault current reaches a value equal to, or greater than the relay setting.
- The time-dial setting is also referred to as time multiplier setting (TMS)

DISCRIMINATION BY TIME

In this method an appropriate time interval is given by each of the relays controlling the CBs in a power system to ensure that the breaker nearest to the fault location opens first.

A simple radial distribution system is considered to illustrate this principle

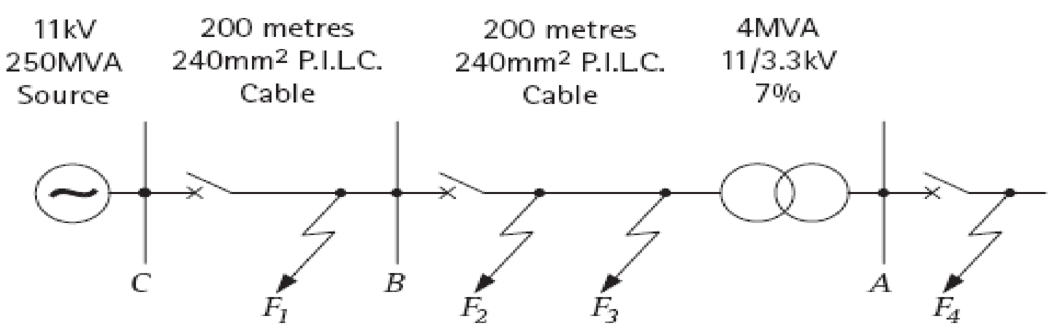


A radial distribution system with time-discrimination

- The main disadvantage of this method of discrimination is that the longest fault clearance time occurs for faults in the section closest to the power source, where the fault level is highest.

DISCRIMINATION BY CURRENT

- Discrimination by current relies on the fact that the fault current varies with the position of the fault, because of the difference in impedance values between the source and the fault.
- The relays controlling CBs are set to operate at suitably tapered values such that only the relay nearest the fault trips its circuit breaker.



Inverse time over current relay characteristic is evolved to overcome the limitations imposed by the independent use of either time or over current coordination.

1.7 Directional Over Current Relays

1. When fault current can flow in both the directions through the relay, at its location. Therefore, it is necessary to make the relay respond for a particular defined direction, so that proper discrimination is possible. This can be achieved by introduction of directional control elements.

2. These are basically power measuring devices in which the system voltage is used as a reference for establishing the relative phase of the fault current.

Basically, an AC directional relay can recognize certain difference in phase angle between two quantities, just as a D.C. directional relay recognize difference in polarity

1.7.1The polarizing quantity of a directional relay

1. It is the reference against which the phase angle of the other quantity is compared. Consequently the phase angle of the polarizing quantity must remain fixed when other quantity suffers wide change in phase angle.

2. The voltage is chosen as the "polarizing" quantity in the current-voltage induction type directional relay.

3. Four pole induction cup construction is normally used.

1.8 Distance relay

Distance relay is used for the protection of transmission line & feeders

In a distance relay, instead of comparing the local line current with the current at far end of line, the relay compares the local current with the local voltage in the corresponding phase or suitable components of them

1.8.1 Principle of operation of distance relay

1. The basic principle of measurement involves the comparison of fault current seen by the relay with the voltage at relaying point; by comparing these two quantities.

2. It is possible to determine whether the impedance of the line up to the point of fault is greater than or less than the predetermined reach point impedance

There are two types of torques

1. Restraining torque

$$T_r \propto V_F^2$$

2. Operating torque

$$T_0 \propto I_F^2$$

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.

1.8.2 Types of distance relay

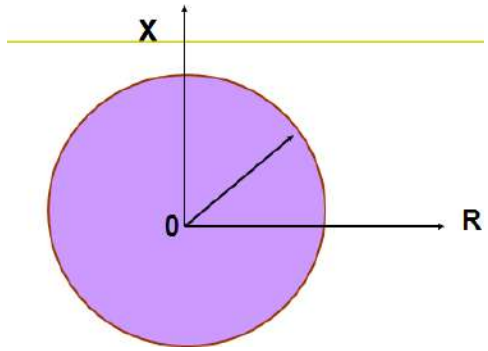
Distance relays are classified depending on their operating characteristic in the R-X plane

- Impedance Relay
- Mho Relay
- Reactance Relay

IMPEDANCE RELAY:

The torque equation T, for such a relay the current actuates the operating torque and the voltage actuates the restraining torque, with the usual spring constant K_4.

$$T = K_1 I^2 + K_2 V^2 + K_4$$



Considering K_2 to be negative (as it produces the restraining torque) and neglecting the torque component due to spring, the equation represents a circle in the R-X plane.

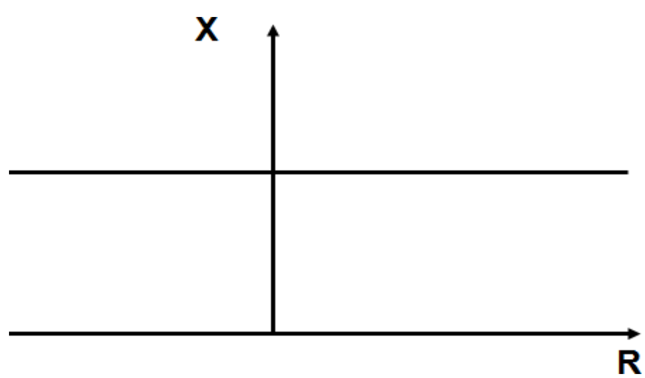
DISADVANTAGE OF IMPEDANCE RELAY

1. It is not directional.
2. It is affected by the Arc resistance
3. It is highly sensitive to oscillations on the power system, due to large area covered by its circular characteristic

REACTANCE RELAY

The reactance relay is basically a directional restrained overcurrent relay. Therefore, the actuating quantity is current and the equation becomes as follows, where the constant K_2 is zero.

$$T = K_1 I^2 + K_3 VI\,Cos(\theta - \tau) + K_4$$



In the above equation, constant K_1 is positive as the current produces operating torque and K_3 is negative as the power direction produces restraining torque. In the above equation the angle τ is considered as 90^0. So the equation derives to

$$T = K_1 I^2 - K_3 VI\, Cos(\theta - 90) + K_4 \geq 0$$

Simplified to

$\frac{V}{I} Sin\theta \leq \frac{K_1}{K_3}$, which gives $ZSin\theta = X \leq \frac{K_1}{K_3}$ in the R-X plane. The characteristics resembles a horizontal line parallel to the R-axis with constant X value. The portion below the line gives the operating zone of the relay.

1. The reactance relay is designed to measure only reactive component of the line reactance.
2. The fault resistance has no affect on the reactance relay

MHO RELAY

The Mho relay combines the properties of impedance and directional relays. Its characteristic is inherently directional and the relay only operates for faults in front of the relay location. In terms of the torque equation the relay characteristics can be obtained by making the constant K_1 equal to zero. It is basically a voltage restrained directional relay and the torque equation becomes.

$$T = K_3 VI\, Cos(\theta - \tau) - K_2 V^2 - K_4 \geq 0$$

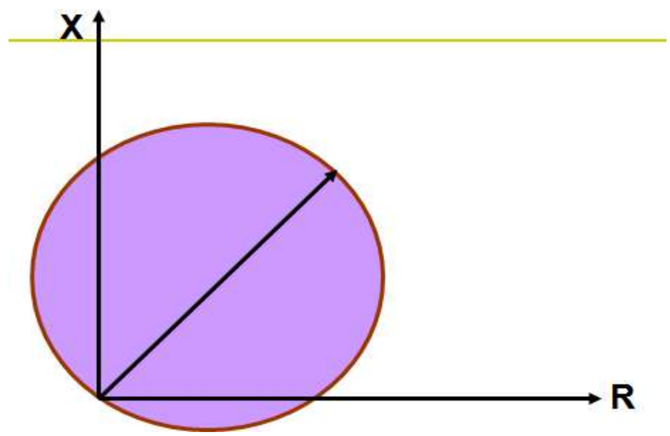
Simplifying,

$\frac{K_3}{K_2} Cos(\theta - \tau) \geq Z + \frac{K_4}{K_2 VI}$, Since $Z = \frac{V}{I}$

Further, neglecting the spring constant K_4,

$$Z \leq Z_R Cos(\theta - \tau)$$

The above equation actually is defined by circle, whose circle is offset from the origin which has a diameter of $Z_R = \frac{K_3}{K_2}$. This relay has a larger coverage of R-X plane and therefore it is least affect ted by condition of power swing. The characteristics is shown below.

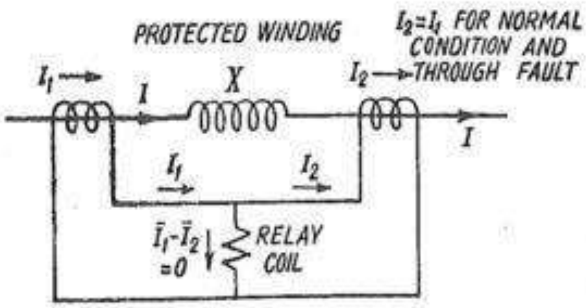


1.9 Differential Relay

One of the most prevalent and successful method of protecting a circuit is to arrange relays to compare the currents entering and leaving it, which should be the same under normal conditions and during an external fault. Any difference current must be flowing in to a fault within the protected circuit

1.9.1 Principle of circulating current differential (MERZ-PRIZE) protection

The figure below illustrates the principle of differential protection of generator and transformer, X is the winding of the protected machine. Where there is no internal fault, the current entering in X is equal in phase and magnitude to current leaving X. The CT's have such a ratio that during the normal conditions or for external faults (Through Faults) the secondary current of CT's are equal. These current say I_1 and I_2 circulate in the pilot wire. The polarity connections are such the current I_1 and I_2 are in the same direction of pilot wire during normal condition or external faults. Relay operation coil is connected at the middle of pilot wires. Relay unit is of over current type.



For Through Fault

Fig. 1 (a). Principle of circulating current relay of generators, transformers.

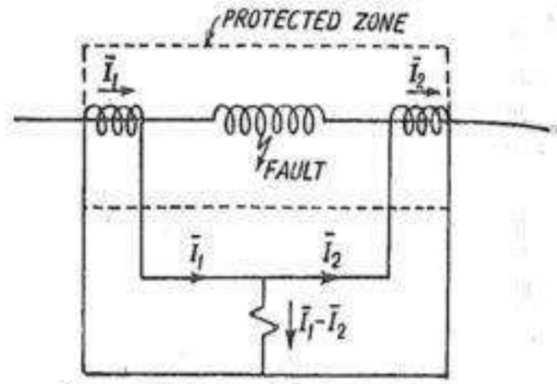


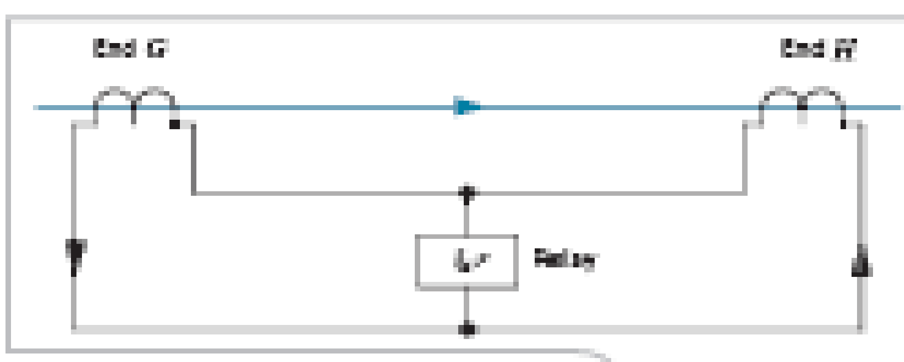
Fig. 1 (b). Internal Fault : $I_1 - I_2 \neq 0$.

During normal condition and external fault the protection system is balanced and the CT's ratios are such that secondary currents are equal. These current circulate in pilot wires. The vector differential current I_1- I_2 which flow through the relay coil is zero.

I_1-I_2 = 0 (normal condition or external faults)

This balance is disturbed for internal faults. When fault occurs in the protected zone, the current entering the protected winding is no more equal to the leaving the winding because some current flows to the fault. The differential I_1-I_2 flows through the relay operating coil and the relay operates if the operating torque is more than the restraining torque.

The current I_1 and I_2 circulate in the secondary circuit. Hence CT's does not get damaged. Polarities of CT's should be proper, otherwise the currents I_1 and I_2 would add up even for normal condition and mal operate the relay.



1.9.2 *Differential Protection current balance*

- When this system is applied to electrical equipment (Generator stator windings, Transformer, Bus bars etc.) it is called differential current protection.
- When it is applied to lines and cables it is called pilot differential protection because pilot wires or an equivalent link or channel is required to bring the current to the relay from the remote end of the line.

The CTs at both ends of the protected circuit connected so that for through load or through fault conditions current circulates between the interconnected CTs. The over-current relay is normally connected across equipotential points and therefore doesn‟t operate.

- Circulating current balance methods are widely used for apparatus protection where CTs are within the same substation area and interconnecting leads between CTs are short (e.g. generator stator windings, Transformer, Bus bars etc.)
- The circulating current balance method is also called longitudinal differential protection or Merz-Price differential protection system.
- The current in the differential relay would be proportional to the phasor difference between the currents that enter and leave the protected circuit. If the current through the relay exceeds the pick-up value, then the relay will operate.

1.9.3 *Demerits of a Differential Relay(Merz Price Scheme)*

1. **Unmatched characteristics of C.T.s** : Though the saturation is avoided, there exist difference in the C.T. characteristics due to ratio error at high values of short circuit currents. This causes an appreciable difference in the secondary currents which can operate the relay. So the relay operates for through external faults.

This difficulty is overcome by using percentage differential relay. In this relay, the difference in current due to the ratio error exists and flows through relay coil. But at the same time the average current ($I_1 + I_2/2$) flows through the restraining coil which produces enough restraining torque. Hence relay becomes inoperative for the through faults.

2. **Ratio change due to tap change**: To alter the voltage and current ratios between high voltage and low voltage sides of a power transformer, a tap changing equipment is used. This is an important feature of a power transformer. This equipment effectively alters the turns ratio. This causes unbalance on both sides. To compensate for this effect, the tapping can be provided on C.T.s also which are to be varied similar to the main power transformer. But this method is not practicable.

The percentage differential relays ensure relays ensure the stability with respect to the amount of unbalance occurring at the extremities of the tap change range.

3. **Difference in lengths of pilot wires**: Due to the difference in lengths of the pilot wires on both sides, the unbalance condition may result. The difficulty is overcome by connecting the adjustable resistors in pilot wires on both sides. These are called balancing resistors. With the help of these resistors, equipotential points on the pilot wires can be adjusted. In percentage differential relays the taps are provided on the operating coil and restraining coil to achieve an accurate balance.

4. **Magnetizing current inrush**: When the transformer is energized, the condition initially is of zero induced E.m.f. A transient inflow of magnetizing current occurs in to the transformer. This current is called magnetizing inrush current. This current may be as great as 10 times the full load current of the transformer. This decays very slowly and is bound to operate differential protection of the transformer falsely, because of the temporary difference in magnitude of the primary and secondary currents.

The factors which affect the magnitude and direction of the magnetizing inrush current can be one of the following reasons.

a. Size of the transformer.

b. Size of the power system

c. Type of magnetic material used for the core.

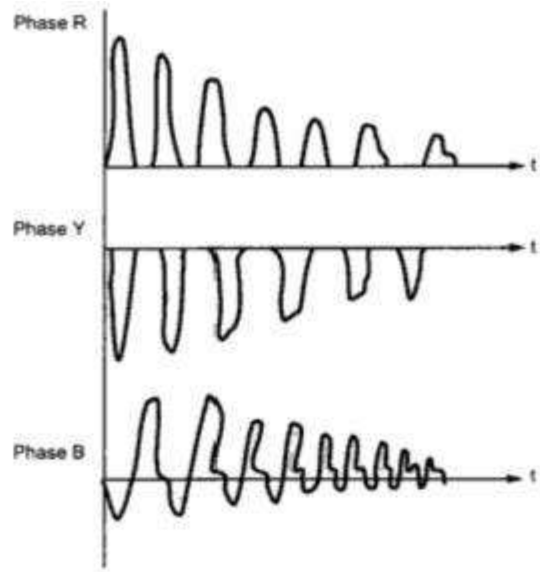
d. The amount of residual flux existing before energizing the transformer.

e. The method by which transformer is energized.

If the transformer is energized when the voltage wave is passing through zero, the magnetizing current inrush is maximum. At this instant, the current and flux should be maximum in highly inductive circuit. And in a half wave flux reversal must take place to attain maximum value in the other half cycles. If the residual flux exists, the required flux may be in same or opposite direction. Due to this magnetizing current inrush is less or more. If it is more, it is responsible to saturate the core which further increases its component.

This current decays rapidly for first few cycles and then decays slowly. The time constant L/R of the circuit is variable as inductance of circuit varies due to the change in permeability of the core. The losses in the circuit damp the inrush currents. Depending on the size of the transformer, the time constant of inrush current varies from 0.2 sec to 1 sec.

The waveforms of magnetizing inrush current in three phases are shown in the figure below.



1.9.4 Biased or per cent Differential Relay

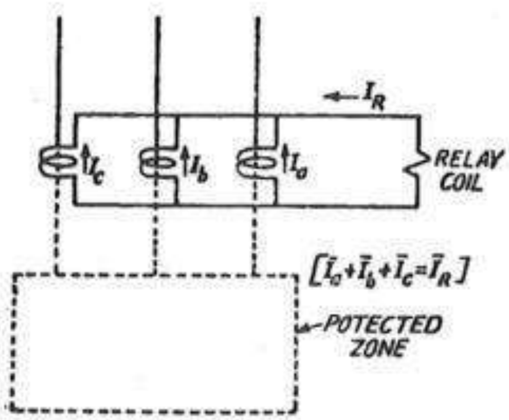
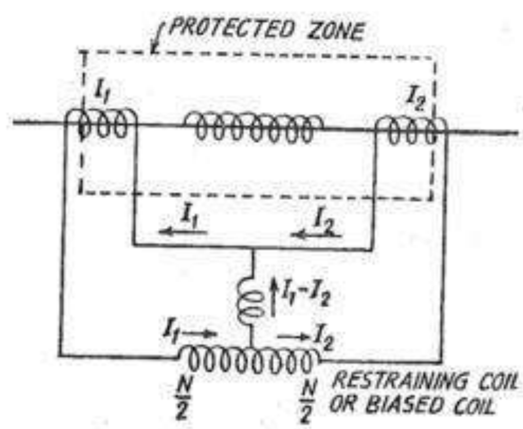


Fig. 2. Differential Protection of 3-phase circuit.



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

Fig. 3. Per cent Differential Relay. (Biased Differential Relay.)

The reason for using this modification in the circulating current scheme, is to overcome the trouble arising out of differences in CT ratios for high values of external short circuit currents. The percentage differential relay has an additional restraining coil connected in the pilot wire as shown in the above figure.

In this relay the operating coil is connected to the mid-point of the restraining coil. The restraining torque therefore is proportional to the sum of ampere turns in its two halves, i.e $(I_1N/2) + (I_2N/2)$ which gives the average restraining current of $(I_1 + I_2)/2$ in N turns. For external faults both I_1 and I_2 increase and thereby the restraining torque increases which prevents the mal-operation. The operating characteristic of the relay is given in the figure below.

The ratio of differential operating current to average restraining current is a fixed percentage and the value of which decides the nature of the characteristics. Therefore, the relay is also called *'percentage differential relay'*. The relay is also called *'Biased differential relay'* because the restraining coil (bias coil) biases the main flux by some additional flux.

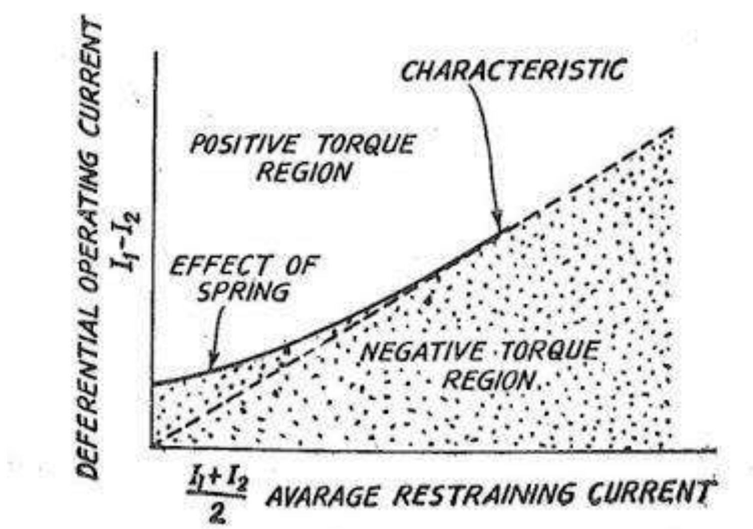


Fig. 4. Operating characteristic of differential relay.

The percentage of biased differential relay has a rising single pick up characteristic. As the magnitude of through current increases, the restraining current decreases.

1.9.5 Setting of differential relay:

The circulating current differential relay has tow principle settings namely,

- Setting of operating coil circuit.
- Setting of restraining coil circuit.

Setting of operating coil circuit (Basic setting). The percentage setting of (Basic setting) of operating coil circuit is defined as the ratio:

$$\%\text{Basic Setting} = \frac{\text{Smallest current in oprerating coil to cause operation}}{\text{Rated current of the operating coil}} \times 100$$

(when the current in restraining coil is zero)

Setting of restraining coil circuit (pick up value). It is defined as the ratio :

$$= \frac{\text{Current in operating coil for causing operation}}{\text{Current in restraining coil}} \times 100$$

$$\%\text{Pick-up Value} = \frac{I_1 - I_2}{(I_1 + I_2)/2} \times 100$$

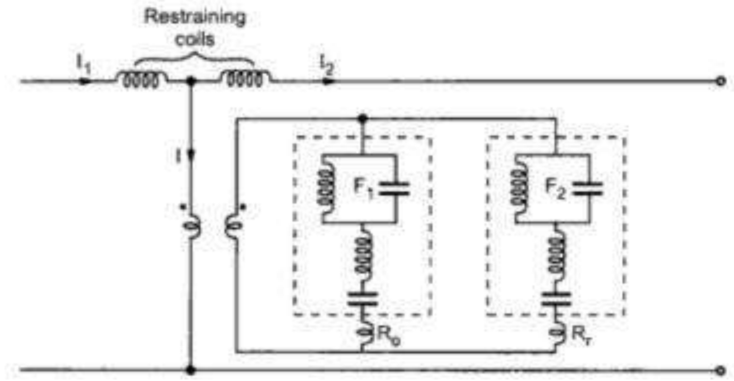
While determining this setting the factors which needs to be considered include

- CT Errors   -Tap-changing
- Resistance of pilot wires   - Stability of through faults

In case of power transformers, percentage basic setting is of the order of 20 % and percentage pick-up value of the order of 25%.

1.9.6 Harmonic restraint Feature in Differential Relay

Thus more the harmonic contents in the inrush current, more is the restraining torque and the relay does not operate. So use of percentage differential protection rather than simple differential protection is preferred. The circuit used to compensate the effect of magnetizing current using harmonic restraint method is shown in the figure below.



Magnetizing current compensation

The filter F_1 is designed to pass the fundamental 50 Hz component which excites the operating coil R_o. The magnetizing current has large third harmonic component. There is an additional restraining coil R_r. The filter F_2 is designed to pass the third harmonic component which energizes the additional restraining coil R_r. The current passing through normal restraining coil and current passing through additional restraining coil R_r produce sufficient restraining torque. This compensates for the differential current resulting due to the flow of magnetizing current.

The separate blocking relay in series with the differential relay is used. The operation of this relay is based on harmonic component of inrush current. This relay consists of 100 Hz blocking filter in operating coil while 50 Hz filter in restraining coil. At the time of inrush current, second harmonic component is maximum and thus blocking relay is blocked with its contacts remain open.

In short circuit case, the harmonic component is negligible and 50 Hz compensated is dominant. Hence the blocking relay operates to close its contact. This principle is called harmonic blocking.

1.10 Comparators

Looking at the general torque equation and any of the other relays used, it can be seen that the net operating torque component can be derived by comparing the operating and restraining torques. Therefore in all static relays, the comparator is the primary component.

In a general two input comparator

$\overline{S_1} = K_1 \overline{V_L} + \overline{Z_{R1}}\, \overline{I_L}$

$\overline{S_2} = K_2 \overline{V_L} + \overline{Z_{R2}}\, \overline{I_L}$

Where K_1 and K_2 are real constants Z_{R1} and Z_{R2} are the complex impedances

1.10.1 Classification of comparators

- Amplitude Comparator
- Phase Comparator
- Hybrid Comparators

Phase comparator gives output if α the phase difference between $\overline{S_1}$ and $\overline{S_2}$ satisfies

$\lambda_1 \leq \alpha \leq \lambda_2$

Amplitude Comparator gives output if

$S_1 > S_2$

Amplitude Comparator classification

Amplitude Comparators can be classified into several categories such as

a)Integrating Type b) Instantaneous type c) Sampling Type

The Integrating type is further classified into

i) Circulating current type ii) Voltage opposed type

Similarly the Instantaneous type is further classified into

i) Averaging type ii) Phase splitting type

1.10.2 General equation of phase comparator

$\overline{S_1} = K_1 \overline{V_L} + \overline{Z_{R1}}\, \overline{I_L}$

$= a + jb = S_1 \angle \alpha_1$

$\overline{S_2} = K_2 \overline{V_L} + \overline{Z_{R2}}\, \overline{I_L}$

$= c + jd = S_2 \angle \alpha_2$

Let

$\alpha = \alpha_1 - \alpha_2$

$$\cos\alpha = \frac{ac + bd}{\sqrt{[(ac + bd)^2 + (bc - ad)^2]}}$$

Let

$\overline{V_L} = V_L\angle 0$ $\qquad \overline{Z_{R1}} = Z_{R1}\angle\theta_1$

$\overline{I_L} = I_L\angle - \phi_L$ $\qquad \overline{Z_{R2}} = Z_{R2}\angle\theta_2$

The phase comparator can be categorized into several categories. They are as given below.

i) Coincident type ii) Block and spikes type iii)Phase splitting type

iv) Integrating type v) Integrating type with rectifier and *AND* gate.

vi) Vector product type vii) Cosine type

1.10.3 Cosine type phase comparator

The cosine type phase comparator gives output for

$-\pi/2 \leq \alpha \leq \pi/2$

The criterion for operation thus becomes

$\cos\alpha \geq 0$

1.10.4 The Duality Principle of Phase/Amplitude Comparators

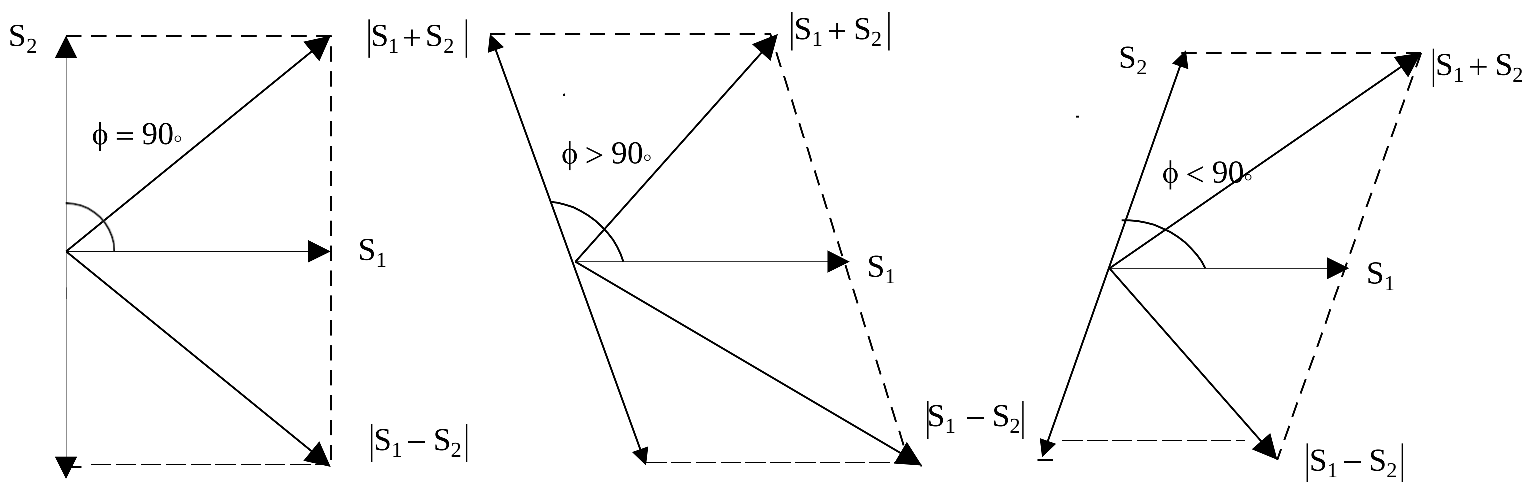
A comparator (amplitude/phase) can be utilized as a phase or amplitude comparator. If the original two inputs are changed to the inputs which signals are derived by adding and subtracting the original signals.

If two inputs are S_1 and S_2 with phase angle between them is ϕ, the changed signals are $S_1 + S_2$, $S_1 - S_2$.

$\phi = 90^\circ$ ------- $|S_1 + S_2| = |S_1 - S_2|$

$\phi < 90^\circ$ ------- $|S_1 + S_2| < |S_1 - S_2|$

$\phi > 90^\circ$ ------- $|S_1 + S_2| > |S_1 - S_2|$



1.10.5: Hybrid type of comparator:

These comparators are those which are formulating by combining the circuits of both amplitude and phase comparators. These comparators can achieve many of the complex relaying actions.

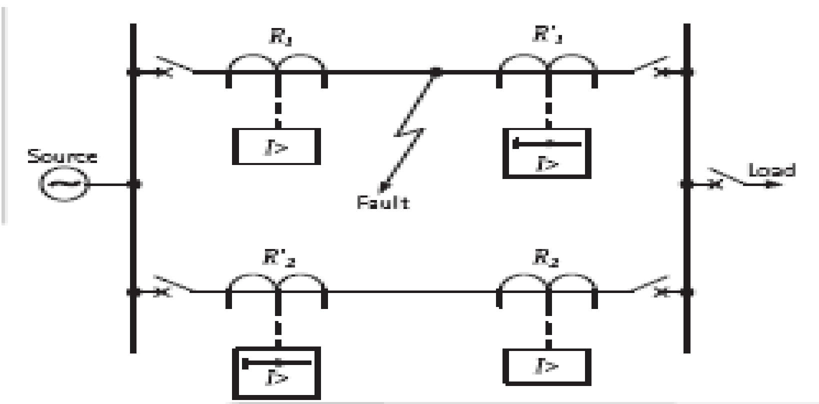
PROTECTION OF FEEDERS

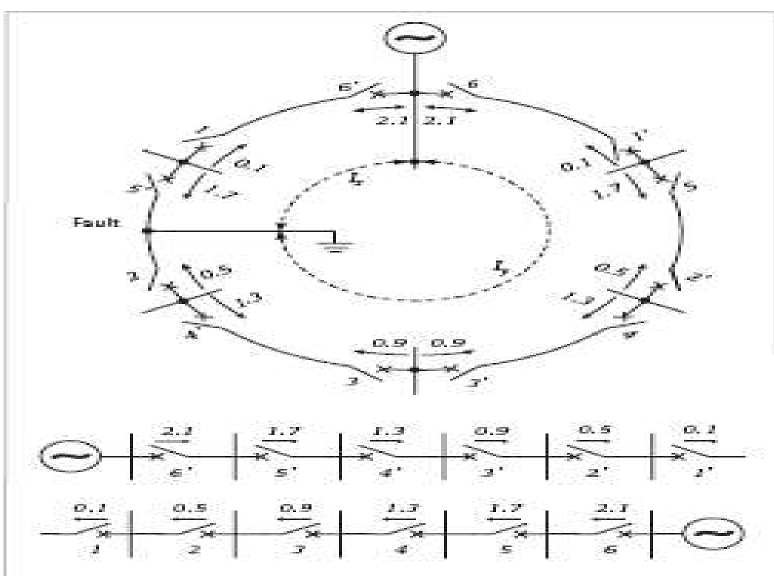
2.1 Over current and earth fault protection

It is customary to have two elements of over current and one element of earth fault protection system in the most elementary form of protection of three phase feeders. Different types of feeders employ the over current protection along with the directional relay so that proper discrimination of an internal fault is possible. Some examples are illustrated below.

2.1.1 Application of directional relays to parallel feeders

It may be seen from the below given parallel feeders that the relays placed at the load side of both the lines use directional element which respond to a direction away from the bus bars. Similarly, the relays placed at the source side do not require any directional element.

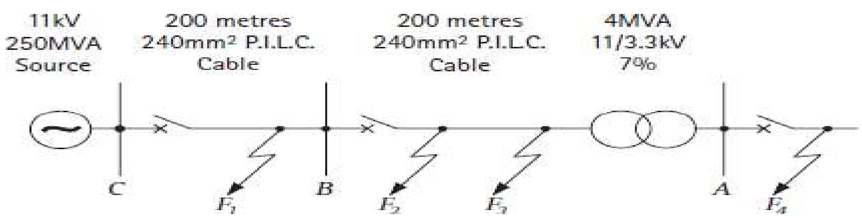




2.1.2 Application of directional relays to ring mains

A similar concept of discrimination is also utilized in the below given ring main feeder and a feeder fed from both the sides. It can be observed that relays placed near the bus connecting the sources, don not have any directional feature, where as the rest of the buses, respond to a direction always away from the source. It is good practice to locate a fault any where among different sections of the feeders and check whether that particular section only is isolated without disrupting the power flow in other sections.

2.1.3 Over current protection radial system



2.2 Pilot wire schemes for feeder protection

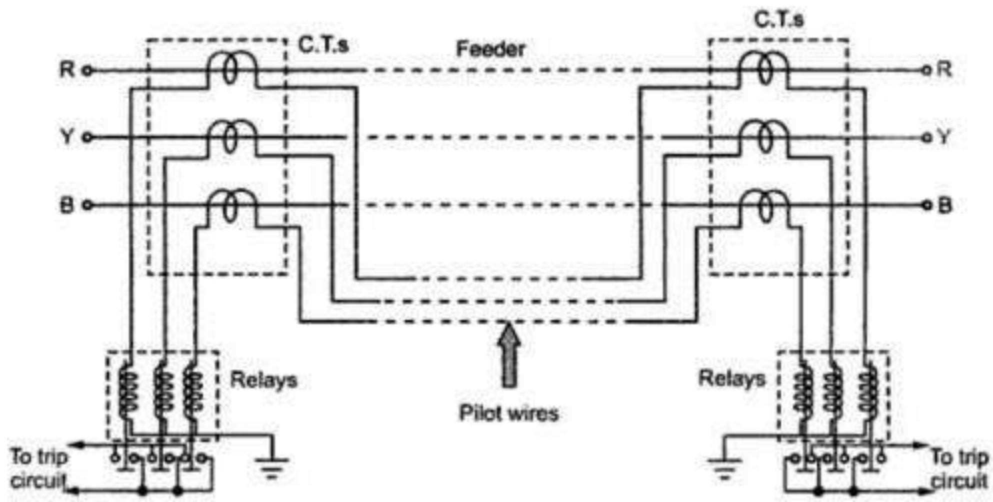
In differential protection scheme, the current entering at one end of the line and leaving from other end of the line is compared. The pilot wires are used to connect the relays. Under normal working condition, the two currents at both ends are equal and pilot wires do not carry any current, keeping relays inoperative. Under an internal fault condition, the two currents at both the ends are no longer same, this causes circulating current flow through pilot wires and makes the relay to trip.

The various schemes used with this method of protection are,

1. Merz-Price Voltage Balance System
2. Translay Scheme

2.2.1 Merz-Price Voltage Balance System

The figure below shows Merz-Price voltage balance system used for the three phase feeders.



Under normal condition, current entering the line at one end is equal to current leaving from the other end. Therefore, equal and opposite voltages are induced in the secondaries of C.T.s. at the two ends resulting in no current flow, through the relay.

Under fault condition, two currents at the two ends are different. Thus the secondary voltages of both the end C.T.s differ from each other. This circulates a circulating current through the pilot wires and the relays. Thus the relays trip the circuit breakers to isolate the faulty section.

The **advantages** of this method are as follows

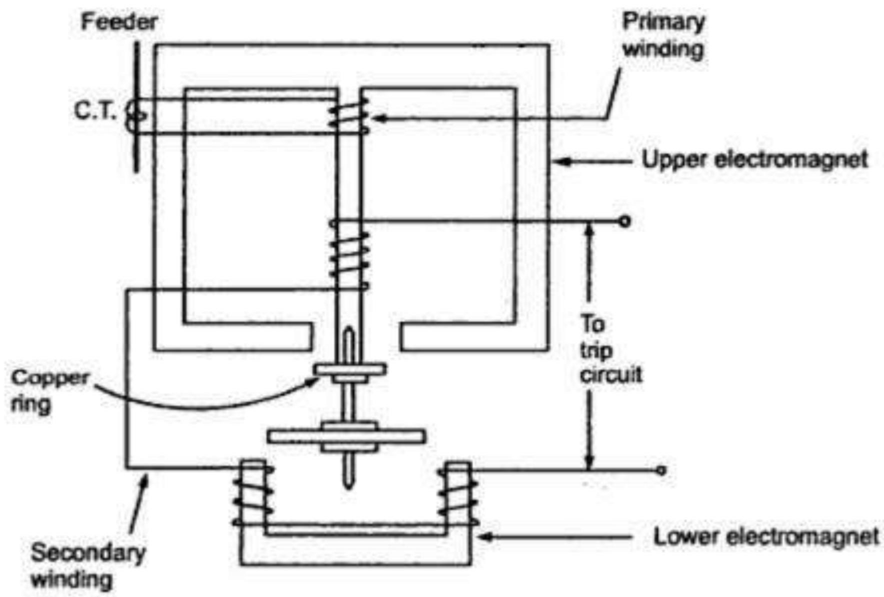
1. It can be used for parallel as well as ring main system.
2. It provides instantaneous protection to ground faults.

The **limitations** of this method are as follows

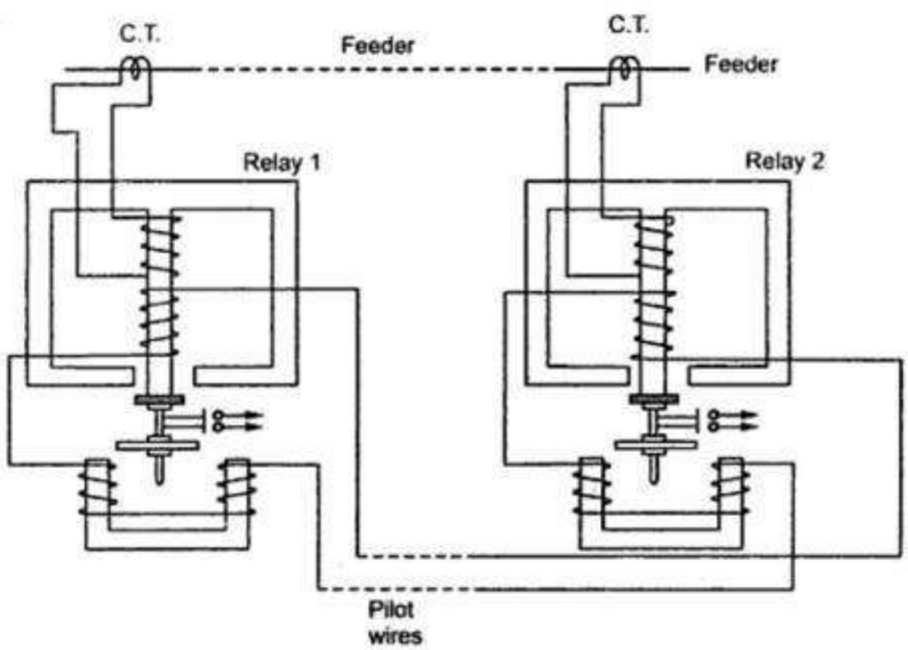
1. The C.T.s used must match accurately.
2. The pilot wires must be healthy without discontinuity.
3. Economically not suitable as the cost is high due to long pilot wires.
4. Due to long pilot wires, capacitive effects adversely bias the operation of the relays.
5. The large voltage drop in the pilot wires requiring better insulation.

2.2.2 Translay Scheme

The translay relay is another type of differential relay. The arrangement is similar to overcurrent relay but the secondary winding is not closed on itself. Additionally copper ring or copper shading bands are provided on the central limb as shown in the figure below.



In this scheme, two such relays are employed at the two ends of feeder as shown in the figure below.



The secondaries of the two relays are connected to each other using pilot wires. The connection is such that the voltages induced in the two secondaries oppose each other. The copper coils are used to compensate the effect of pilot wire capacitance currents and unbalance between two currents transformers.

Under normal operating conditions, the current at the two ends of the feeder is same. The primaries of the two relays carry the same currents inducing the same voltage in the secondaries. As these two voltages are in opposition, no current flows through the two secondaries circuits and no torque is exerted on the discs of both the relays.

When the fault occurs, the currents at the two ends of the feeder are different. Hence unequal voltages are induced in the secondaries. Hence the circulating current flows in the secondary circuit causing torque to be exerted on the disc of each relay. But as the secondaries are in opposition, hence torque in one relay operates so as to close the trip circuit while in other relay the torque restricts the operation. Care must be taken so that, at least one relay operates under the fault condition.

Role of copper ring: Mainly relays may operate because of unbalance in the current transformers. The copper rings are so adjusted that the torque due to current induced in the copper ring due to primary winding of relay is restraining and do not allow the disc to rotate. It is adjusted just to neutralize the effect of unbalance existing between the current transformers. The copper rings also neutralize the effect of pilot capacitive currents. Though the feeder current is same at two ends, a capacitive current may flow in the pilots. This current leads the secondary voltage by 90^o. The copper rings are adjusted such that no torque is exerted on the disc, due to such capacitive pilot currents. Therefore in this scheme the demerits of pilot relaying scheme is somewhat taken care of.

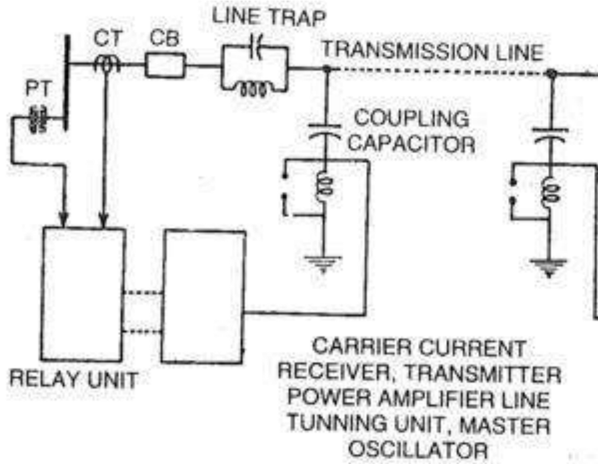
The **advantages** of this scheme are,

1. Only two pilot wires are required.
2. The cost is very low.
3. The current transformers with normal design can be employed.
4. The capacitive effects of pilot wire currents do not affect the operation of the relays.

2.3 Carrier Current unit protection system

2.3.1 The basic block diagram and various components

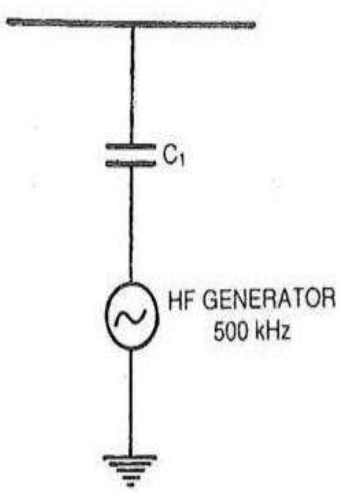
The



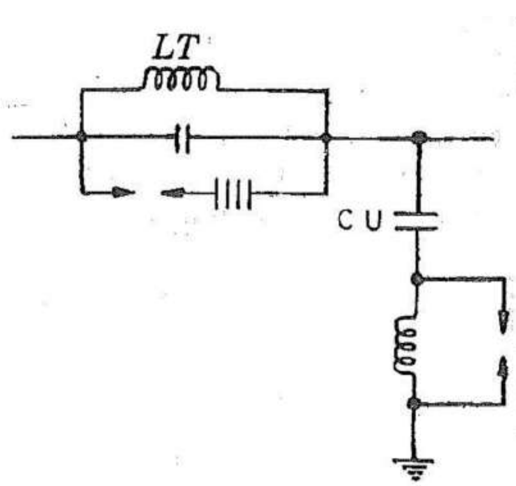
Schematic diagram of the carrier current scheme is shown below. Different basic components of the same are discussed below.

The Coupling capacitor

These coupling capacitors (CU) which offer low reactance to the higher frequency carrier signal and high reactance to the power frequency signal. Therefore, it filters out the low (power) frequency and allows the high frequency carrier waves to the carrier current equipments. A low inductance is connected to the CU, to form a resonant circuit.



$$Z = \frac{1}{\omega C_1}$$
$= 1.5$ mega ohms for 50 Hz.
$= 150$ ohms for 500 kHz.



Wave Traps

The Wave traps (also known as Line Trap) are inserted between the busbar and the connection of the CU. These traps are L and C elements connected in parallel, and they are tuned in such a manner that they offer low reactance to the power frequency signals and high reactance to the carrier waves. They ensure that neither of these different frequency signals get mixed up before being received at the bus bar.

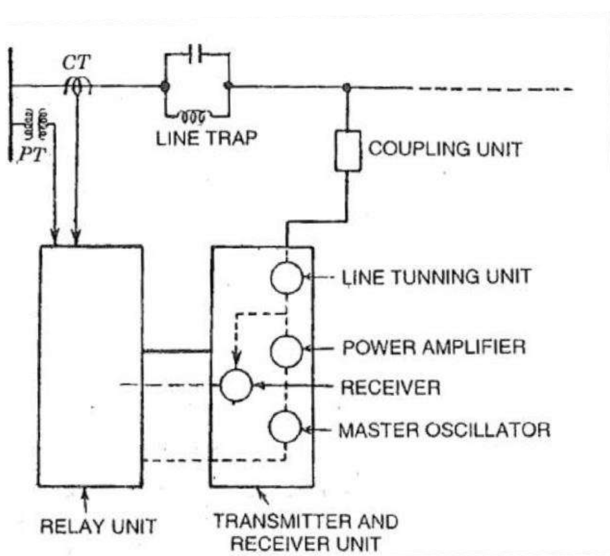
Both the CU and the Wave traps are protected from switching and lightening surges, with the help suitably designed *Spark Gaps* or *Varistors*.

Frequency spacing

Different frequencies are used in adjacent lines and the wave traps ensure that carrier signals of other lines do not enter a particular line section. Therefore, proper choice of frequency bands for different lines are adopted.

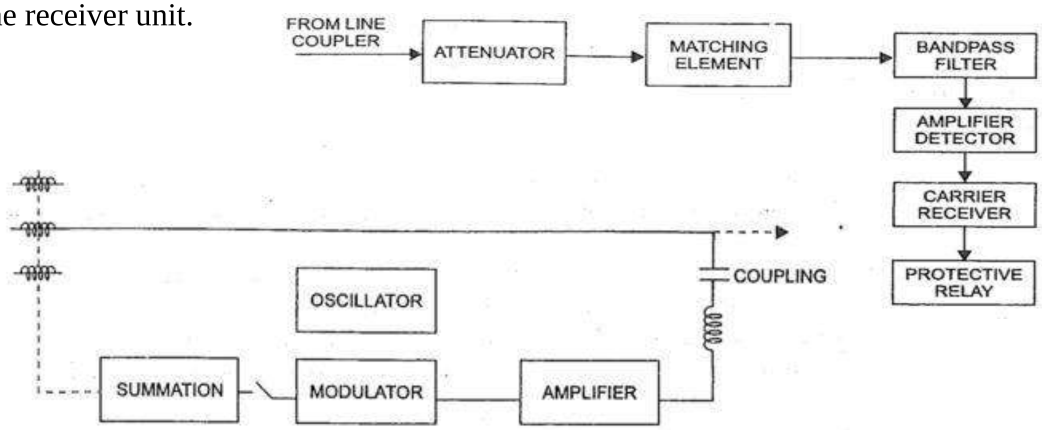
Transmitter Unit

In a Transmitter unit, the carrier frequency in the range of 50 to 500 KHz of constant magnitude is generated in the oscillator, which is fed to an amplifier. Amplification is required to overcome any loss in the coupling equipments, weather conditions, Tee connections in the lines of different size and length. The amplifier and the oscillators are constantly energized and a connection is made between the two with the help of a control unit.

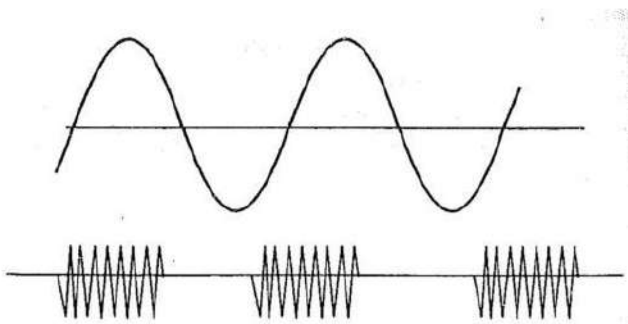


Receiver Unit

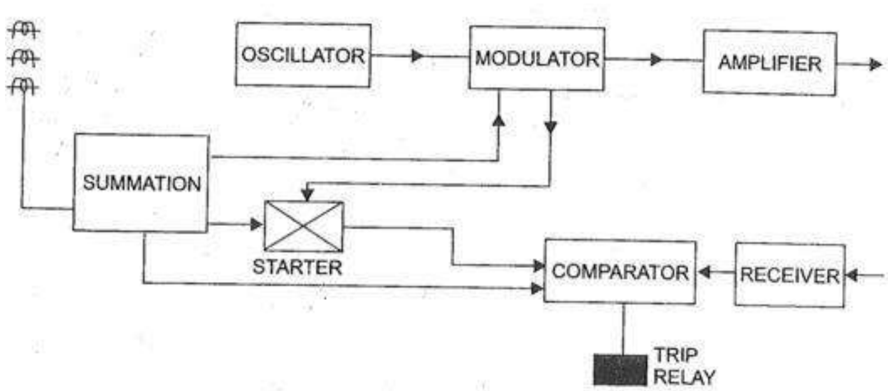
The Receiver unit consists of an attenuator and a Band pass filter, which restricts the acceptance of any unwanted signals. The unit also has matching transformer to match the line impedance and that of the receiver unit.



MODULATOR

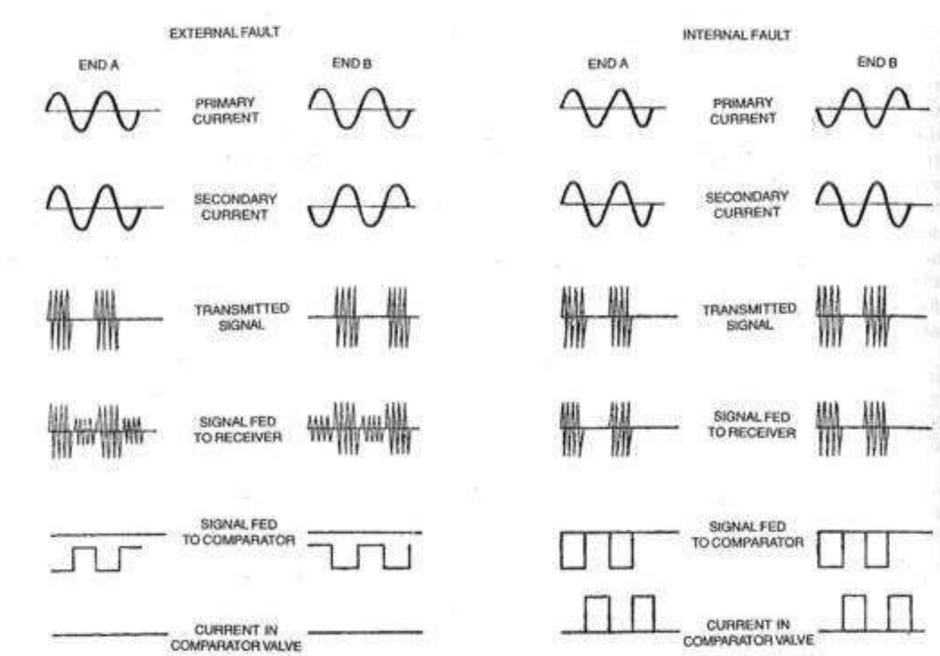


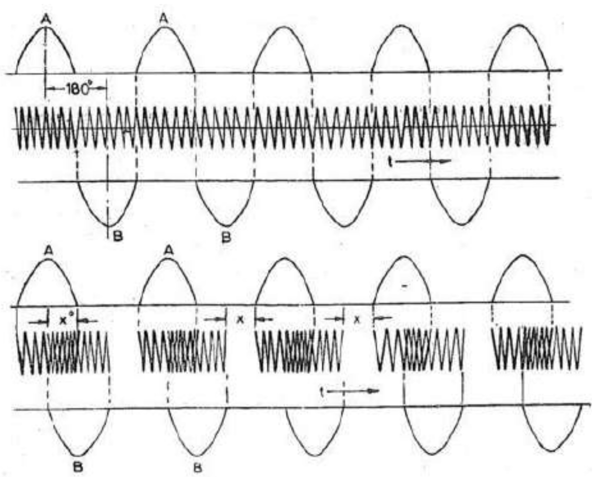
The Modulator modulates, the 50 Hz power signals with high frequency carrier waves and the modulated signal is fed to an amplifier. The amplifier output is transmitted via a CU. It takes half a cycle of power signal to produce requisite *Blocks of carrier* as shown above.



The Schematic of CCE

The CTs connected to the transmission line feed the Summation block which consist of Network sequence filters. It transforms the CT output to a single phase voltage signal that is representative of the fault condition. The voltage signal is used to control the output from the local transmitter unit, through the starting relay known as *Starte*r. It therefore initiates comparison between the local transmitter output and the signal received from the remote receiver in the comparator. The comparator output condition then initiates the *Trip relay*.





The principle of *Phase Comparison* is one of the methods that involve decision of tripping. As shown above, the presence of blocks of carrier signals abort any tripping and its absence initiates the tripping. Therefore, in a section of transmission line, where CTs at both end buses are connected 180 degree out of phase, an absence of carrier signal can only be possible if an internal fault has occurred. However, it can be seen that such absencve of carrier blocks is not possible for an external fault.

2.3.2 Application advantages and multiple roles of CCE

Pilot channel such are carrier current over the power line provides simultaneous tripping of circuit-breakers at both the ends of the line in one to three cycles. Thereby high speed fault clearing is obtained, which improves the stability of the power system. Besides there are several other merits of carrier current relaying. There are :

1. Fast, simultaneous operating of circuit-breakers at both ends.
2. Auto-reclosing simultaneous reclosing signal is sent thereby simultaneous (1 to 3 cycles) reclosing of circuit breaker is obtained.
3. Fast clearing prevents shocks to systems.
4. Tripping due to synchronizing power surges does not occur, yet during internal fault clearing is obtained.
5. For simultaneous faults, carrier current protection provides easy discrimination.
6. Fast (2 cycle) and auto-reclosing circuit breakers such as air blast circuit breaker require faster relaying. Hence, the carrier current relaying is best suited for fast relaying in conjunction with modern fast circuit breaker.
7. The carrier current equipment is used for several other application besides protection. They are as follows

(a) Station to station communication. In power station, receiving stations and sub-stations telephones are provided. These are connected to carrier current equipment and conversion can be carried out by means of "Current Carrier Communication".

(b) Control. Remote control of power station equipment by carrier signals.

(c) Telemetering.

2.3.4 Media used for protection signaling

- Power - line - carrier circuits
- Pilot wires

GENERATOR PROTECTION

INTRODUCTION

- The range of size of generators extends from a few hundred KVA to more than 500MVA
- Small and Medium sized sets may be directly connected to the distribution system

A larger unit is usually associated with an individual transformer, through which the set is coupled to the EHV transmission system. No switchgear is provided between the generator and transformer, which are treated as a unit.

2.4 Biased Differential scheme (Merz-Price Scheme) for protection of Generators.

This is most commonly used protection scheme for the alternator stator windings. The scheme is also called biased differential protection and percentage differential protection.

The figure below shows a schematic arrangement of Merz-Price protection scheme for a star connected alternator.

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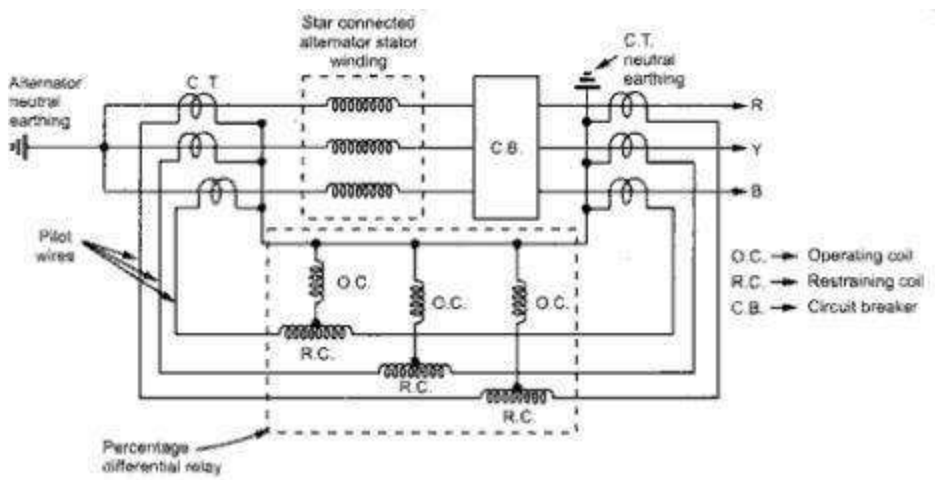
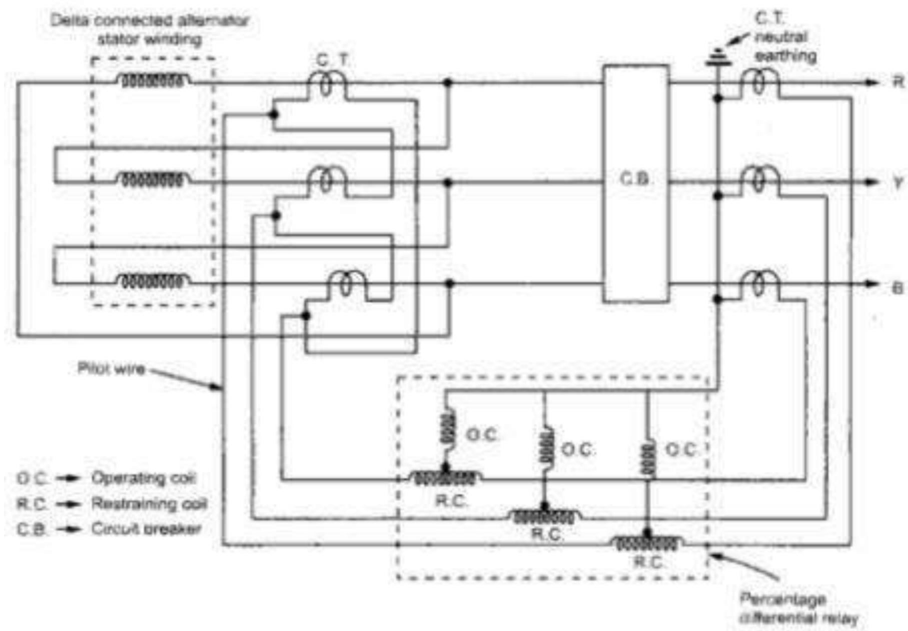


The differential relay gives protection against short circuit fault in the stator winding of a generator. When the neutral point of the windings is available then, the C.T.s may be connected in star on both the phase outgoing side and the neutral earth side, as shown in the above figure. But, if the neutral point is not available, then the phase side CTs are connected in a residual connection, so that it can be made suitable for comparing the current with the generator ground point CT secondary current. The restraining coils are energized from the secondary connection of

C.T.s in each phase, through pilot wires. The operating coils are energized by the tappings from restraining coils and the C.T. neutral earthing connection.

The similar arrangement is used for the delta connected alternator stator winding, as shown below.



This scheme provides very fast protection to the stator winding against phase to phase faults and phase to ground faults. If the neutral is not grounded or grounded through resistance then additional sensitive earth fault relay should be provided.

The advantages of this scheme are,

1. Very high speed operation with operating time of about 15 msec.
2. It allows low fault setting which ensures maximum protection of machine windings.
3. It ensures complete stability under most severe through and external faults.
4. It does not require current transformers with air gaps or special balancing features.

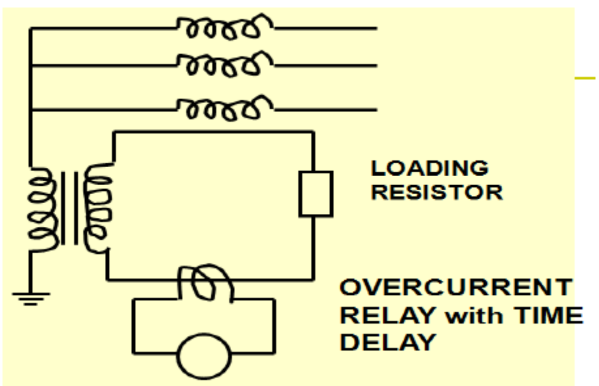
2.5 Earth fault protection of Generators.

The neutral point of the generator is usually earthed, so as to facilitate the protection of the stator winding and associated system. Impedance is inserted in the earthing lead to limit the magnitude of the earth fault current. Generators which are directly connected to the transmission or distribution system are usually earthed through a resistance which will pass approximately rated current to a terminal earth fault. In case of generator-transformer unit, the generator winding and primary winding of a transformer can be treated as an isolated system that is not influenced by the earthing requirements of the transmission system.

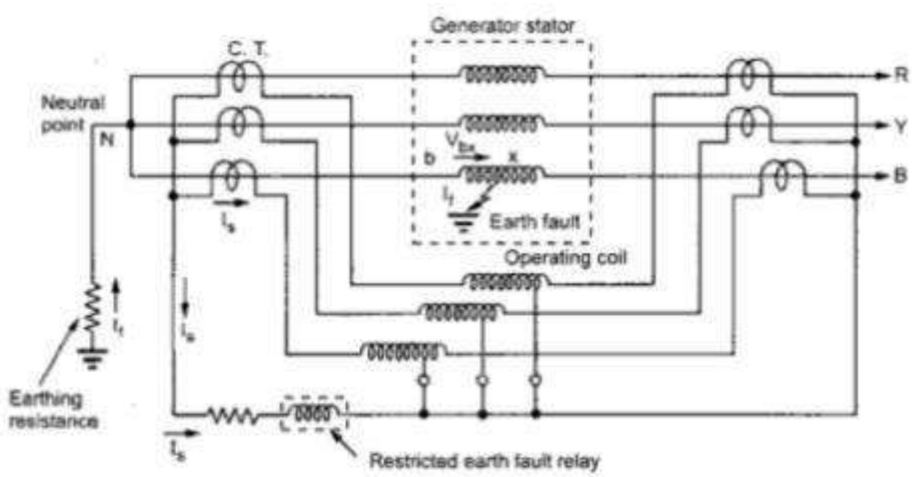
Modern practice is to use a large earthing transformer (5-100 KVA) – the secondary winding which is designed for 100-500V is loaded with a resistor of a value, which when referred through the transformer ratio, will pass a suitable fault current. The resistor is therefore of low value and can be of rugged construction. It is important that the earthing transformer never becomes saturated, otherwise a very undesirable condition of ferro resonance may occur

EARTH FAULT PROTECTION

- Earth fault protection can be obtained by applying a relay to measure the transformer secondary current by connecting a voltage measuring relay in parallel with the load resistor



2.5.1 Restricted earth fault protection



Generally Merz-Price protection based on circulating current principle provides the protection against internal earth faults. But for large costly generators, an additional protection scheme called restricted earth fault protection is provided.

When the neutral is solidly grounded then the generator gets completely protected against earth faults. But when neutral is grounded through earth resistance, then the stator windings gets partly protected against earth faults. The percentage of windings protected depends on the value of earthing resistance and the relay setting.

In this scheme, the value of earth resistance, relay setting, current rating of earth resistance must be carefully selected. The earth faults are rare near the neutral point as the voltage of neutral point with respect to earth is very less. But when earth fault occurs near the neutral point, then the insufficient voltage across the fault results in a low fault current, that is less than the pickup current of relay coil. Hence the relay coil remains unprotected in this scheme. As it is able to protect a restricted portion of generator winding from earth faults, it is called a *restricted earth fault protection*. It is usual practice to protect 85% of the winding.

The restricted earth fault protection scheme is shown in the above figure.

Consider that earth fault occurs on phase B due to breakdown of its insulation to earth, as shown in the Fig. 1. The fault current I_f will flow through the core, frame of machine to earth and complete the path through the earthing resistance. The C.T. secondary current I_s flows through the operating coil and the restricted earth fault relay coil of the differential protection. The setting of restricted earth fault relay and setting of overcurrent relay are independent of each other. Under this secondary current I_s, the relay operates to trip the circuit breaker. The voltage V_{bx} is sufficient to drive the enough fault current I_f when the fault point x is away from the neutral point.

If the fault point x is nearer to the neutral point then the voltage V_{bx} is small and not sufficient to drive enough fault current I_f. And for this I_f, relay can‟t operate. Thus part of the winding from the neutral point remains unprotected. To overcome this, if relay setting is chosen very low to make it sensitive to low fault currents, then wrong operation of relay may result. The relay can operate under the conditions of heavy through faults, inaccurate C.T.s, saturation of C.T.s etc. Hence practically 15% of winding from the neutral point is kept unprotected, protecting the remaining 85% of the winding against phase to earth faults.

Let us see the effect of earth resistance on the percentage of winding which remains unprotected. Consider the earth resistance R is used to limit earth fault current. If it is very small i.e. the neutral is almost solidly grounded, then the fault current is very high. But high fault currents are not desirable hence small R is not preferred for the large machines.

For low resistance R, the value of R is selected such that full load current passes through the neutral, for a full line to neutral voltage V. In medium resistance R, the earth fault current is limited to about 200A for full line to neutral voltage V, for a 60 MW machine.

In high resistance R, the earth fault current is limited to about 10 A. This is used for distribution transformers and generator-transformer units. Now higher the value of earth resistance R, less is the earth fault current and less percentage of winding gets protected. Large percentage of winding remains unprotected.

Let V= Full line to neutral voltage

I = Full load current of largest capacity generator

R = Earth resistance

The value of the resistance R is,

$$R = V/I$$

And the percentage of winding unprotected is given by,

% of winding protected = $(I_0 R/V)\times 100$

Where, I_o = Maximum operating current in the primary of C.T.

If relay setting used is 15% then I_o is 15% of full load current of the largest machine and so on.

Example 1 : A generator is protected by restricted earth fault protection. The generator ratings are 13.2 kV, 10 MVA. The percentage of winding protected against phase to ground fault is 85%. The relay setting is such that it trips for 20% out of balance. Calculate the resistance to be added in the neutral to ground connection.

Solution : The given values,

V_L = 13.2 kV Rating = 10 MVA

From rating, calculate the full load current,

$$I = \text{Rating in VA} / (\sqrt{3}\, V_L) = (10\times10^6)/(\sqrt{3} \times 13.2 \times 10^3)$$