

Lecture Notes on
SWITCH GEAR AND PROTECTIVE DEVICES

7TH SEMESTER BTECH (EE)

SUBJECT CODE: BEE 1701



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SYLLABUS

SWITCHGEAR AND PROTECTIVE DEVICES (3-1-0)

MODULE-I (10 HOURS)

Protective Devices: Philosophy of protection, Nature, Causes and consequences of faults, Zone of protection, Requirements of a protective scheme, Basic terminology components of protection scheme. Relay classification, Principle of different types of electromagnetic relay. General equation of phase and magnitude comparators, Duality of comparators, Electromagnetic relays, over current relays Directional relays, Distance relay- impedance, Reactance and Mho type, Differential relays.

MODULE-II (10 HOURS)

Feeder: Protection: Over current and earth fault protection, Distance protection, Pilot wire protection, Carrier current protection.

Generator Protection: Biased differential protection, restricted earth fault protection, Field suppression, Negative sequence protection, Earth fault detection in rotor circuit

Power transformer Protection: Biased differential protections, restricted earth fault protection, Buchholz relay Protection of combined transformer and alternator.

Bus Zone Protection: frame leakage and circulating current scheme-use of Translay relay.

MODULE-III (10 HOURS)

Circuit Breakers: Formation of arc during circuit breaking. Characteristics of electric arc. Theories of arc Interruption. Recovery and restriking voltage, interruption of capacitive and inductive currents. Current chopping. Principle of A.C. and D.C. circuit breaking requirements of good circuit breaker circuit breaker rating.

Different types of circuit breakers. Air break and Air blast circuit breaker. Plain break and controlled break all circuit breakers. Minimum oil circuit breakers. Vacuum circuit breaker, SF₆ circuit breaker. D.C. Circuit breaker.

H.R.C. Fuse: Construction and characteristics

MODULE-IV (10 HOURS)

Static Relays : Development and classification of static relays, Different types of phase and amplitude capacitors, Basic static relays used in protective scheme, Elementary idea about digital & numerical protection. Testing and maintenance of protective gear, Protection against surge-surge absorber, Surge-diverter.

Arrangement of Bus bar, Circuit breaker and isolator. Current limiting reactors in power system and their arrangement calculation of fault MVA for symmetrical short circuits. Circuit breaker capacity.

BOOKS

- [1]. Van C Warrington, "*Protective Relays*" Vol.-I & II
- [2]. Ravindranath, M.Chander, "*Power System Protection and SwitchGear*", Wiley Eastern Ltd. New Delhi
- [3]. T S Madhav Rao, "*Power System Protection*", TMH Pulication
- [4]. Sunil S.Rao, "*Switch Gear and Protection*", Khanna Publication

MODULE-I

Lesson Plan

1.1 Fundamentals of Power System Protection

1.2 Consequences of occurrence of fault

1.3 Zones of Protection

1.4 Protection System Requirements and some basic terminologies used

1.5 Classification and principle of different types of electromagnetic relays

1.6 Over current relays

1.7 Directional relay

1.8 Distance relay

1.9 Differential relay

1.10 General equation of Comparators and the duality principle

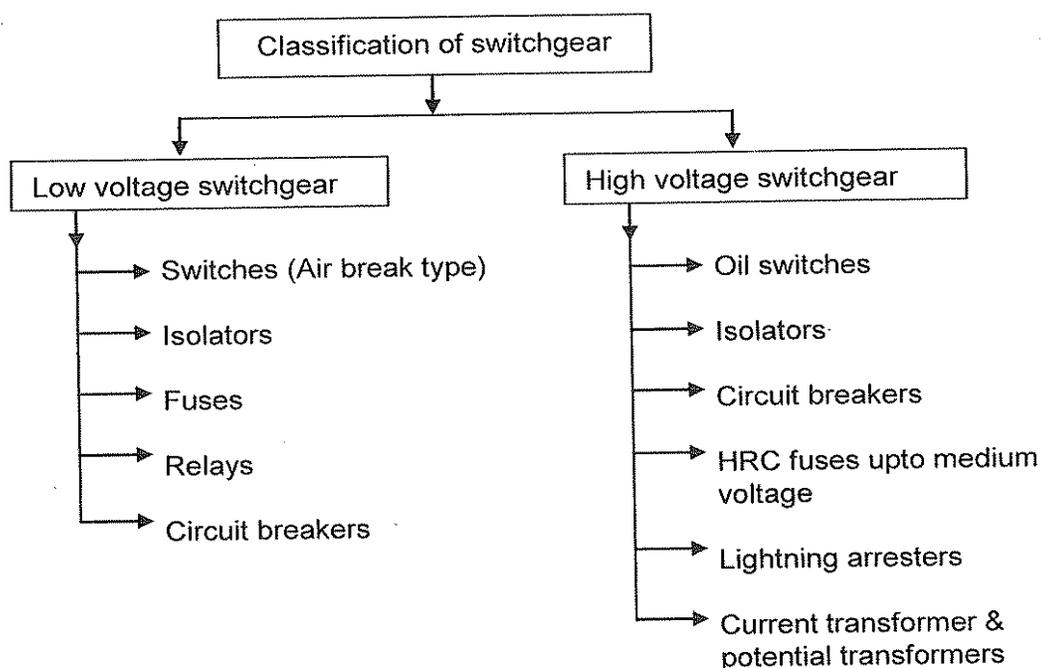
1.1 Fundamentals of Power System Protection

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

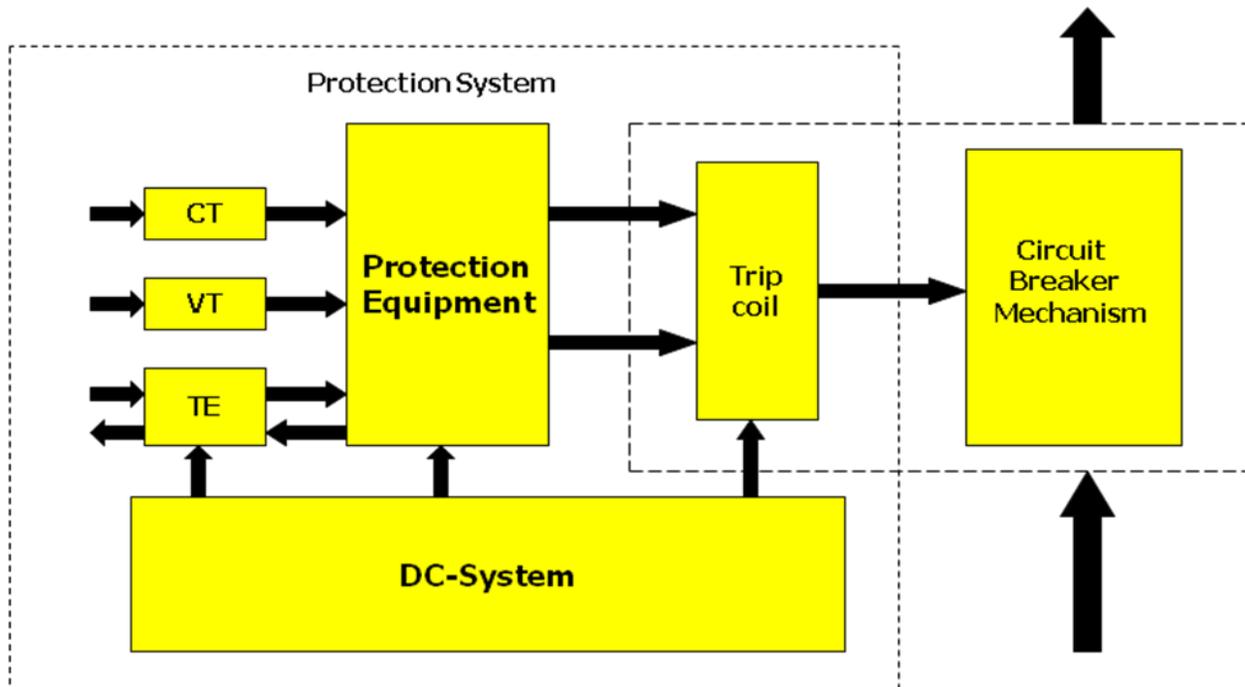
- Single Phase open Circuit
- Two phase open circuit
- Three phase open circuit

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

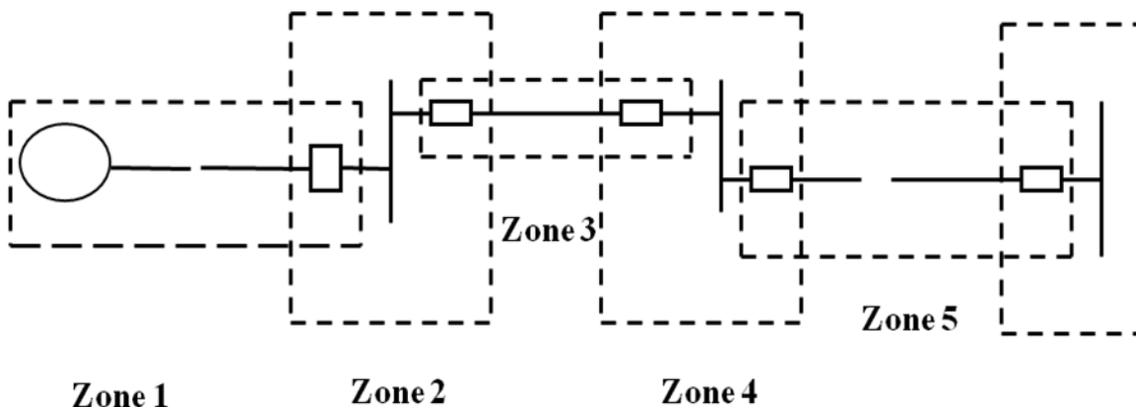
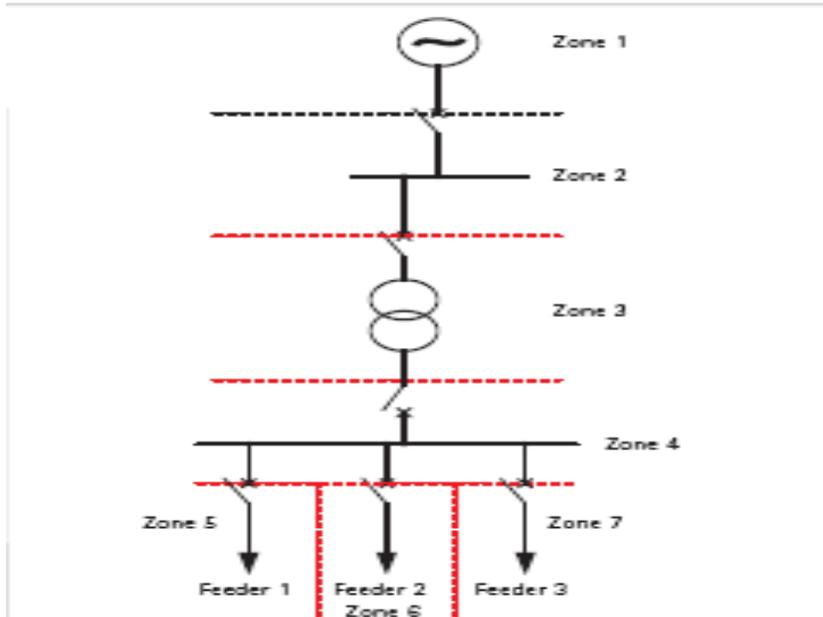


1.3 Zones and types of Protection system

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 portion 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 broad 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 number of different combinations of these signals depending upon whether the designed relay requires 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.

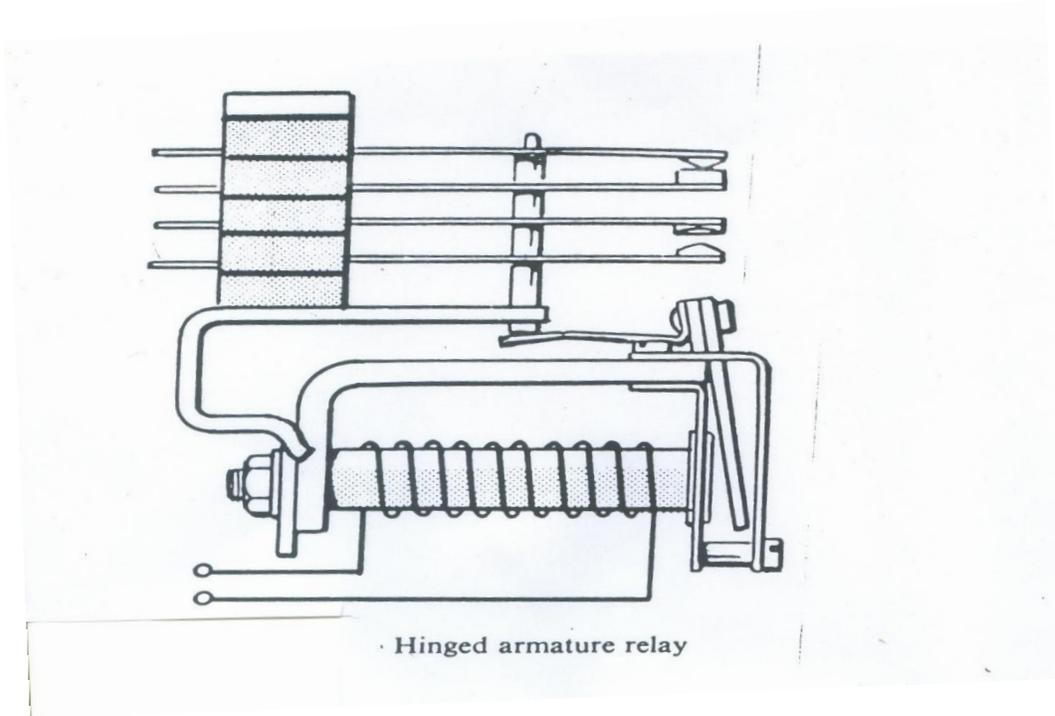
Attraction relays

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

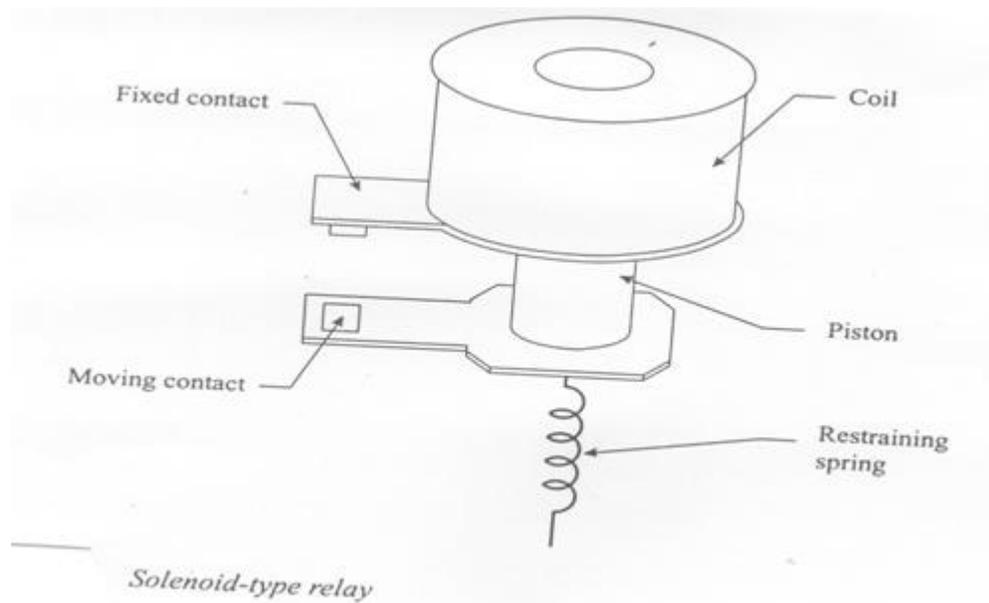
Attracted armature relays

- 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.



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.



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

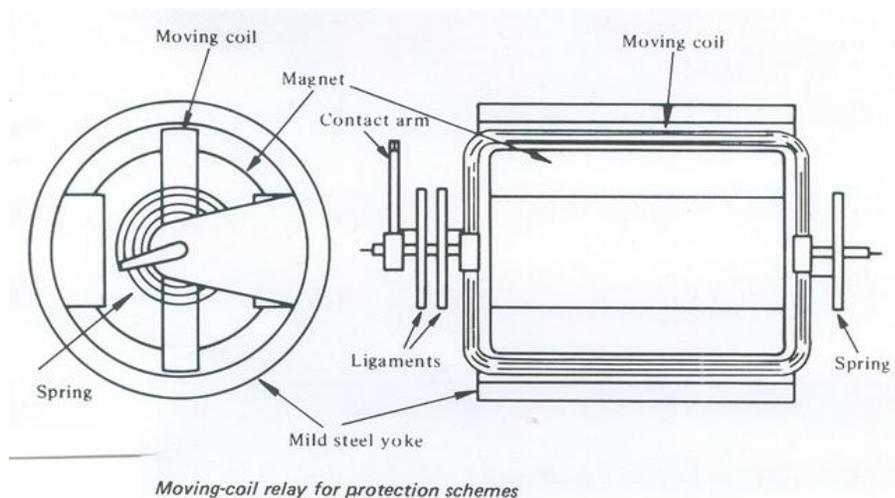
For threshold or balanced condition, the resultant force is zero.

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

In order to control the value of current at which relay operates, the parameters K_1 and K_2 may be 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.



The torque produced in the coil is

$$T = B l a N i$$

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

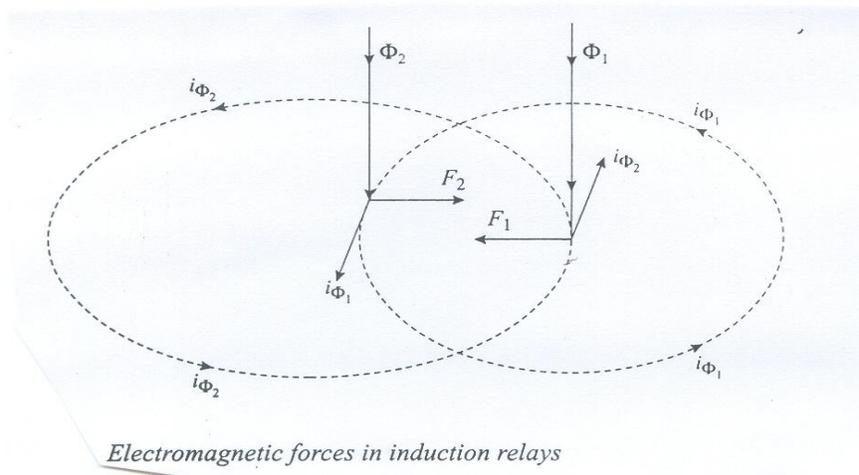
N=number of turns in the coil

- 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



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.

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

- 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 pierces the rotor towards the point where the lagging flux pierces the rotor.
- Actuating force is produced in the presence of out of phase fluxes.

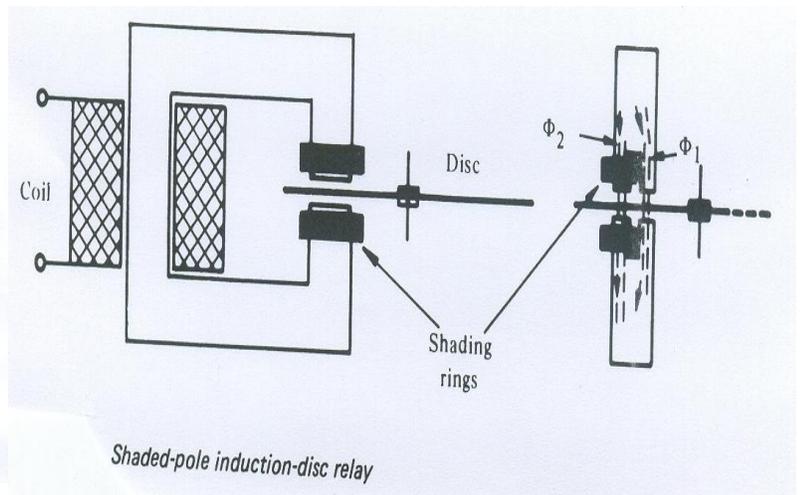
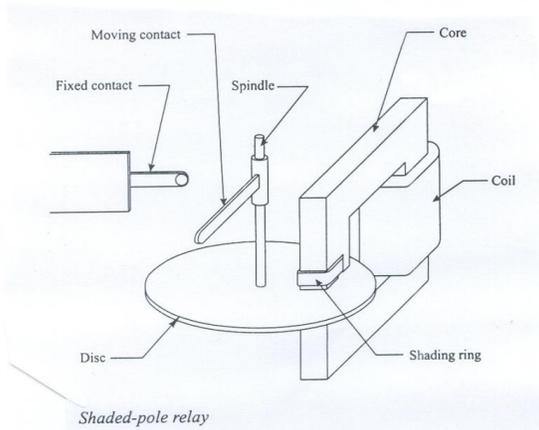
- Maximum force is produced when $\theta=90^\circ$

Classification of induction relays

1. Shaded pole relay
2. Watthour- meter type relay
3. Cup type relay

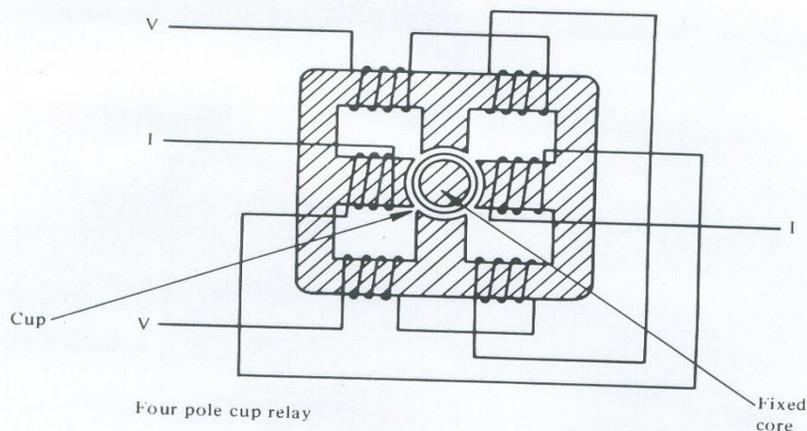
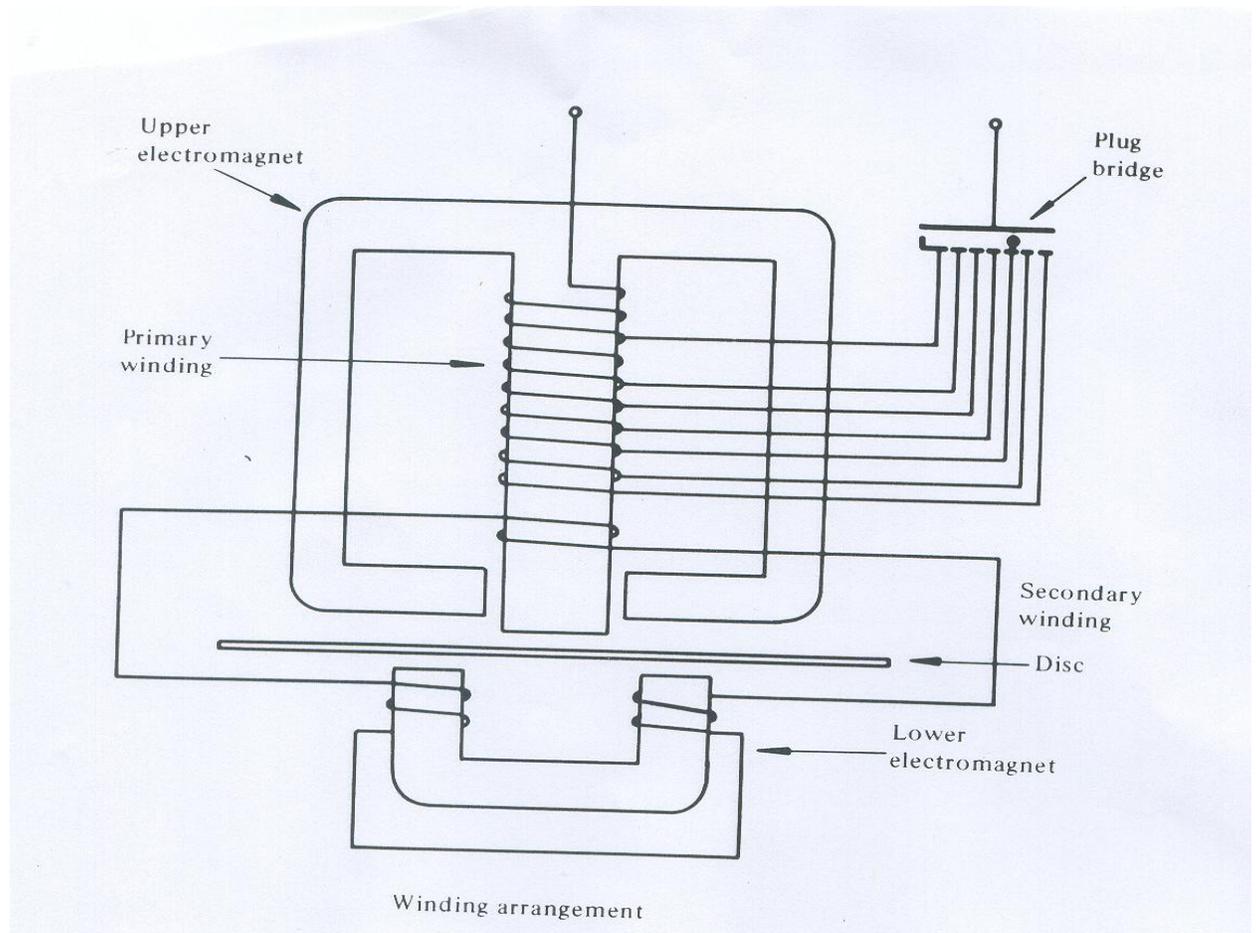
The air gap flux produced by the current flowing in a single coil is split into two out of phase components by a so called 'Shading Ring' generally of copper, that encircles part of the pole face of each pole at the air gap.

- 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.



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



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

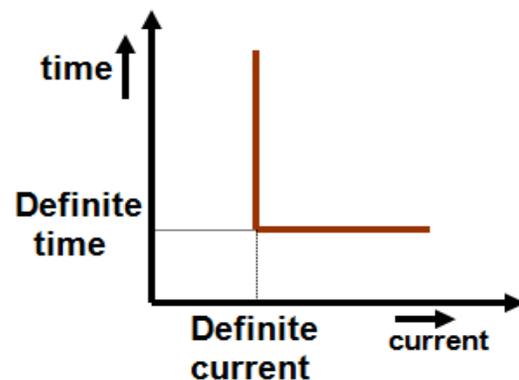
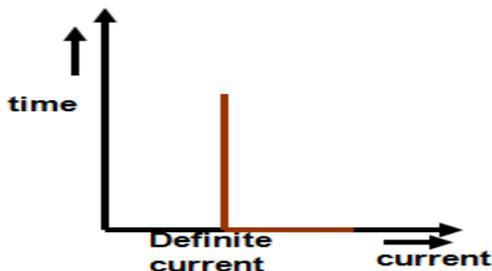
$$T = K_1 I^2 + K_4$$

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

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

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

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

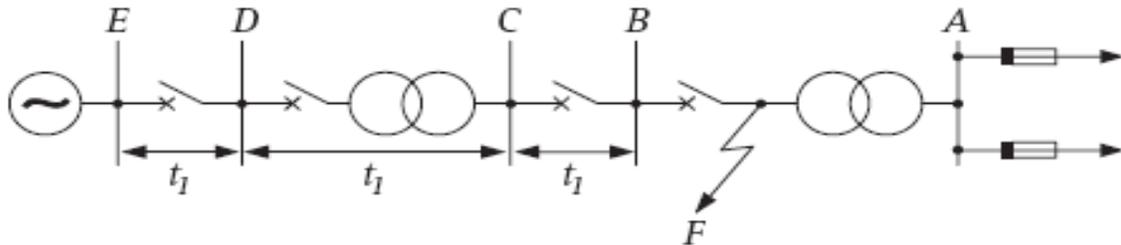
Time dial setting

- 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

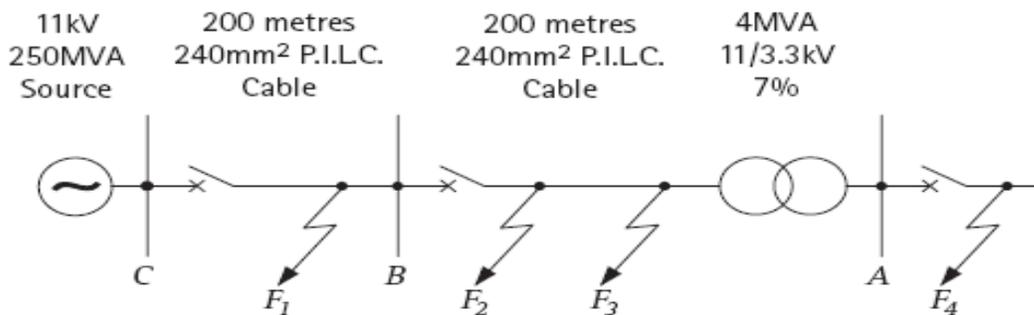


A radial distribution system with time-discrimination

- 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

1.7.1 The 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

$$T_o \propto I_F^2$$

The relay trips when T_o 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

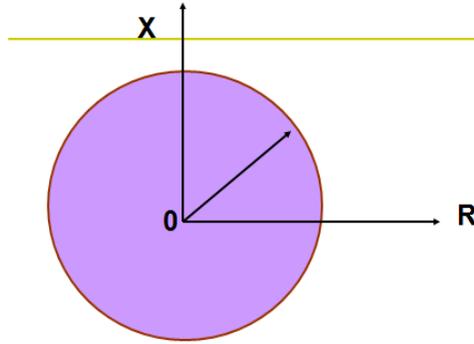
Distance relays are classified depending on their operating characteristic in the R-X plane

- 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.

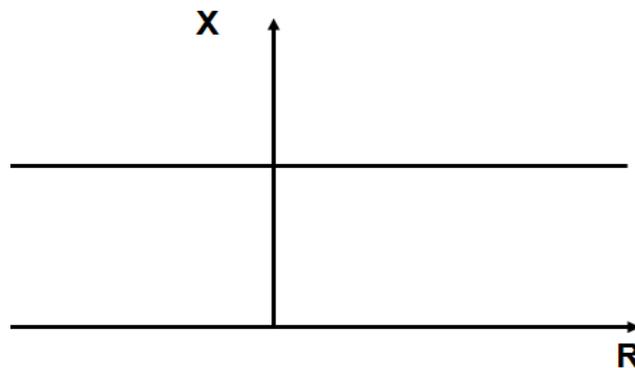
DISADVANTAGE OF IMPEDANCE RELAY

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° . So the equation derives to

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

Simplified to

$\frac{V}{I} \sin \theta \leq \frac{K_1}{K_3}$, which gives $Z \sin \theta = X \leq \frac{K_1}{K_3}$ 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.

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

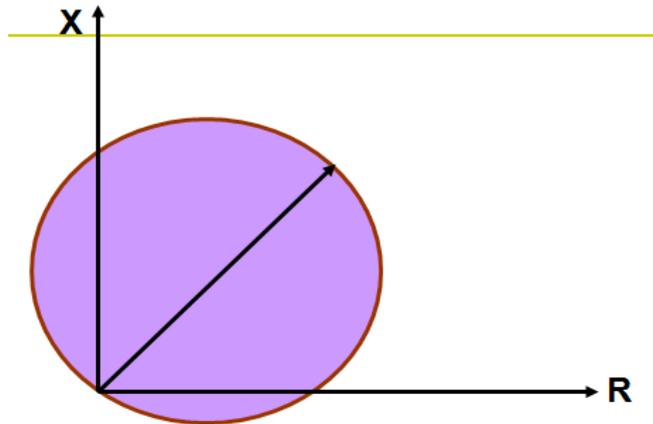
Simplifying,

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

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 affected by condition of power swing. The characteristics is shown below.

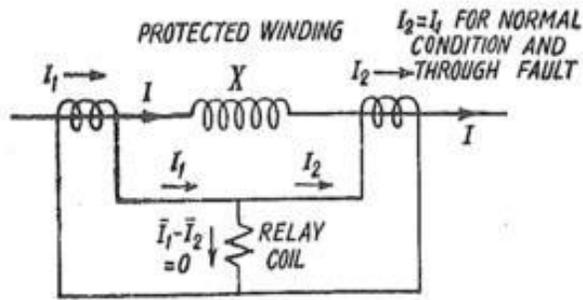


1.9 Differential Relay

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.

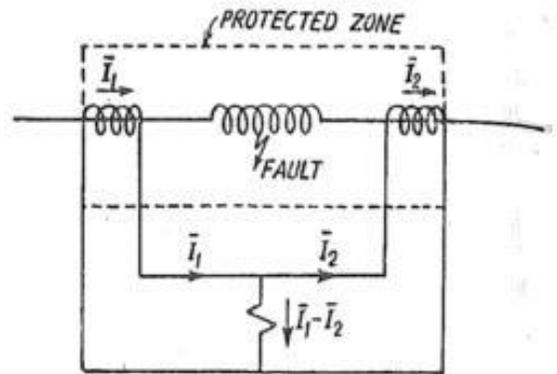


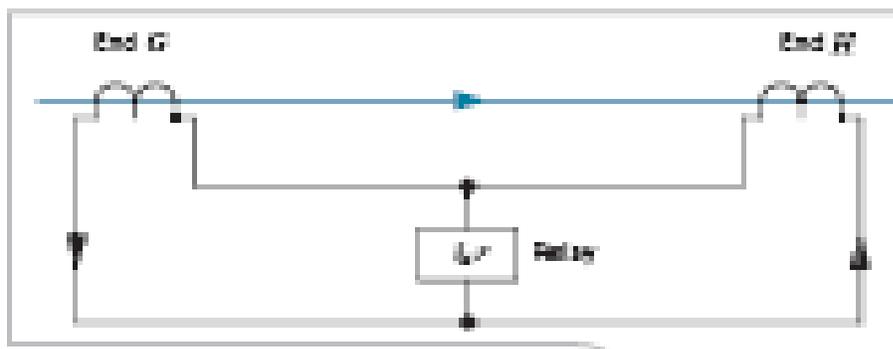
Fig. 1 (b). Internal Fault : $I_1 - I_2 \neq 0$.

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.

$$I_1 - I_2 = 0 \text{ (normal condition or external faults)}$$

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.

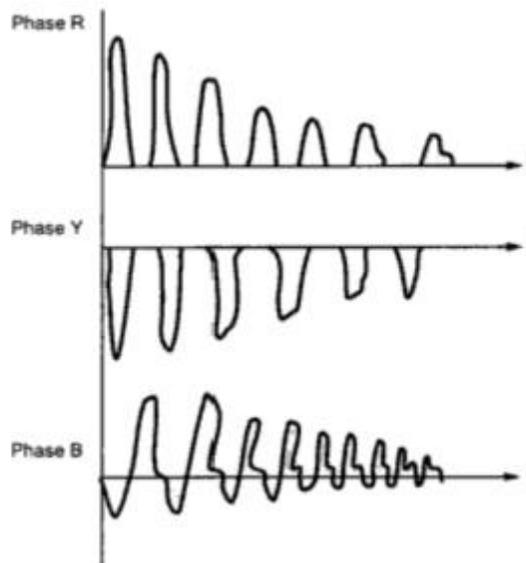
- a. Size of the transformer.
- b. Size of the power system
- c. Type of magnetic material used for the core.
- d. The amount of residual flux existing before energizing the transformer.
- e. The method by which transformer is energized.

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

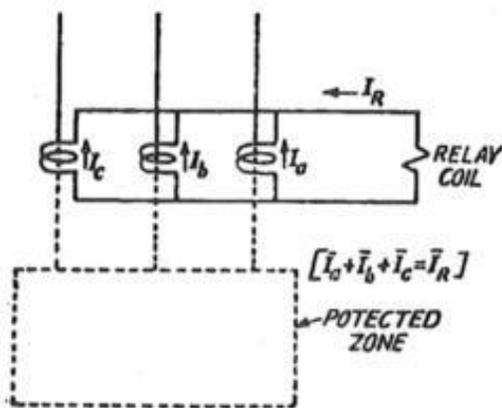
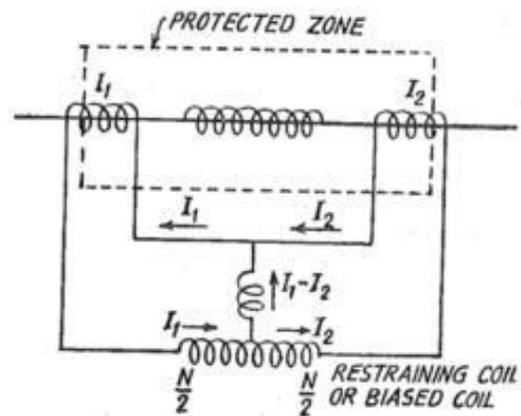


Fig. 2. Differential Protection of 3-phase circuit.



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

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.

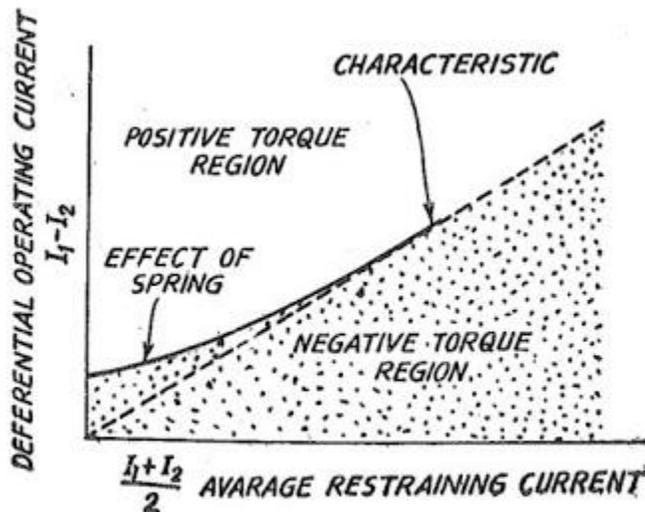
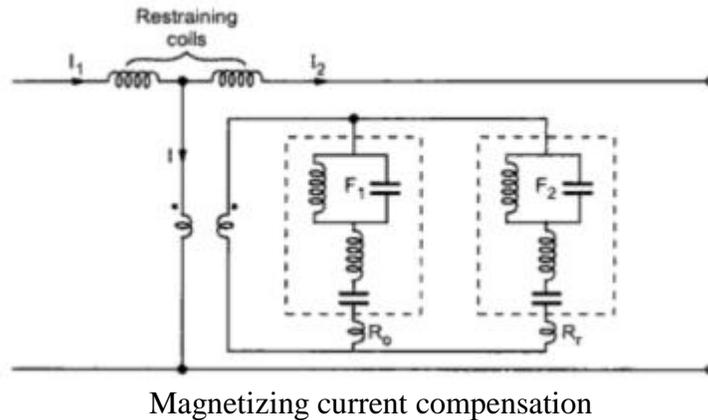


Fig. 4. Operating characteristic of differential relay.

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 filter F_1 is designed to pass the fundamental 50 Hz component which excites the operating coil R_0 . 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

$$\overline{V}_L = V_L \angle 0 \quad \overline{Z}_{R1} = Z_{R1} \angle \theta_1$$

$$\overline{I}_L = I_L \angle -\phi_L \quad \overline{Z}_{R2} = Z_{R2} \angle \theta_2$$

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

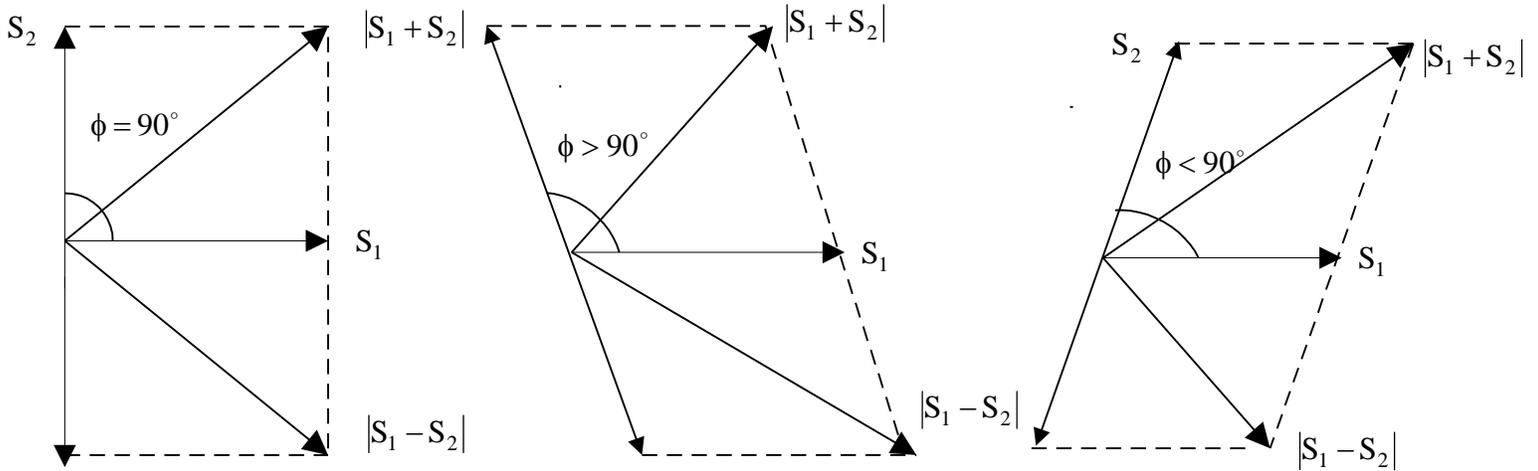
A comparator (amplitude/phase) can be utilized as a phase or amplitude comparator. If the original two inputs are changed to the inputs which signals are derived by adding and subtracting the original signals.

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

$$\phi = 90^\circ \quad \text{-----} \quad |S_1 + S_2| = |S_1 - S_2|$$

$$\phi < 90^\circ \quad \text{-----} \quad |S_1 + S_2| < |S_1 - S_2|$$

$$\phi > 90^\circ \quad \text{-----} \quad |S_1 + S_2| > |S_1 - S_2|$$



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.

MODULE-II

OUTLINE OF LESSON PLAN

PROTECTION OF FEEDERS

2.1 Over current and earth fault protection

2.2 Pilot wire protection

2.3 Carrier current protection

GENERATOR PROTECTION

2.4 Biased differential protection

2.5 Earth fault protection

2.6 Negative sequence protection

TRANSFORMER PROTECTION

2.7 Transformer Differential protection

2.8 Buchholz Relay

BUSBAR PROTECTION

2.9 Frame-earth Protection

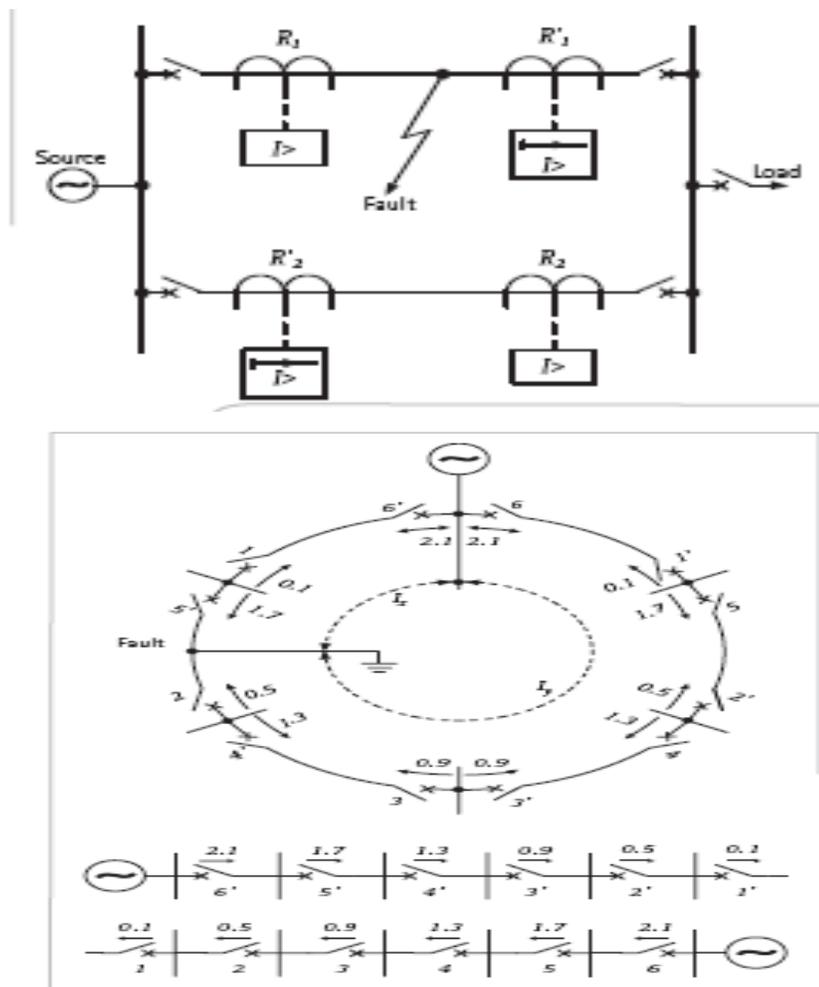
PROTECTION OF FEEDERS

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

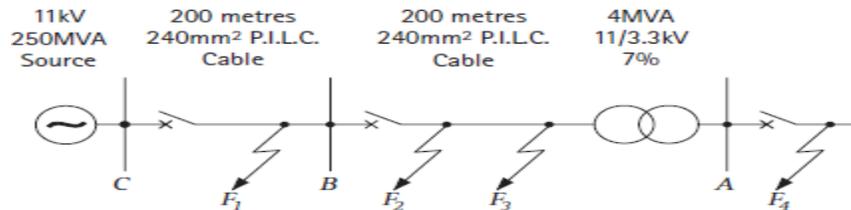
It may be seen from the below given parallel feeders that the relays placed at the load side of both the lines use directional element which respond to a direction away from the bus bars. Similarly, the relays placed at the source side do not require any directional element.



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, do not have any directional feature, whereas the rest of the buses, respond to a direction always away from the source. It is good practice to locate a fault anywhere 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

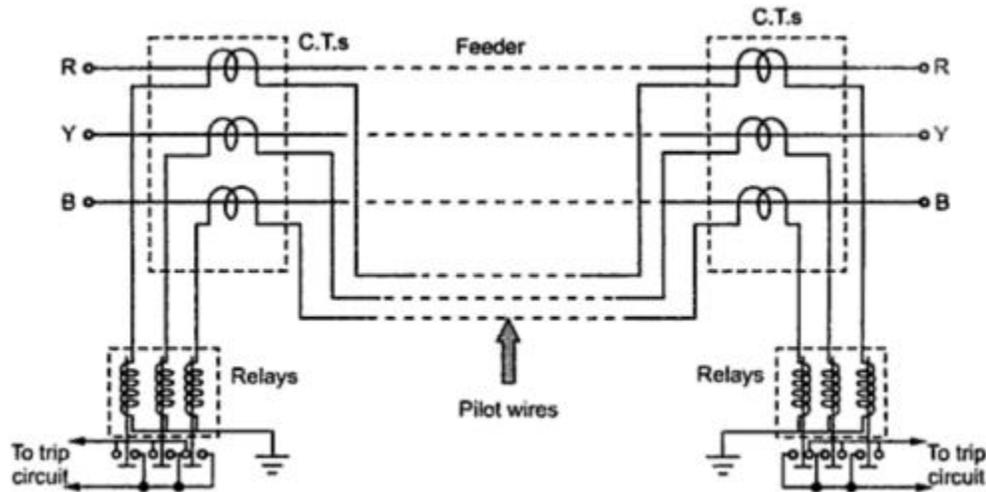
In differential protection scheme, the current entering at one end of the line and leaving from other end of the line is compared. The pilot wires are used to connect the relays. Under normal working condition, the two currents at both ends are equal and pilot wires do not carry any current, keeping 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

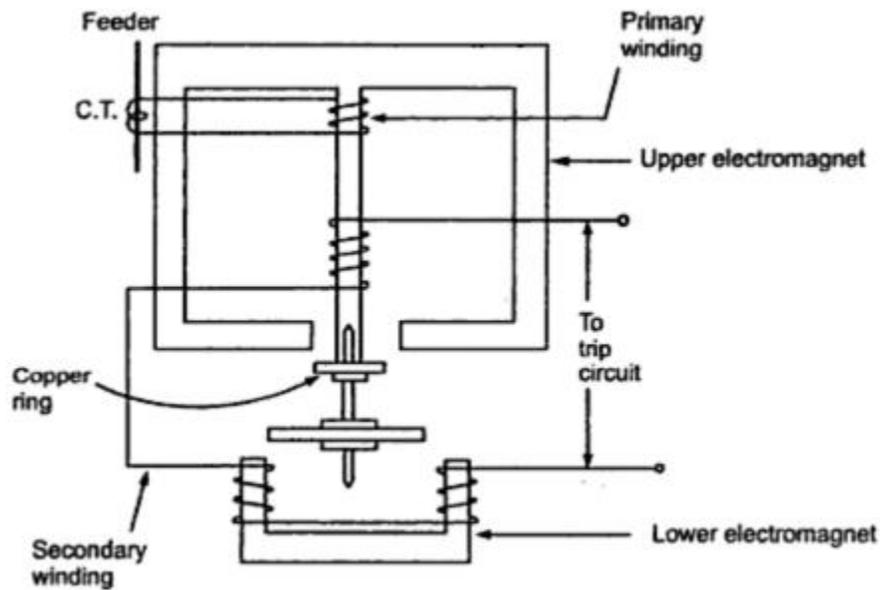
1. It can be used for parallel as well as ring main system.
2. It provides instantaneous protection to ground faults.

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

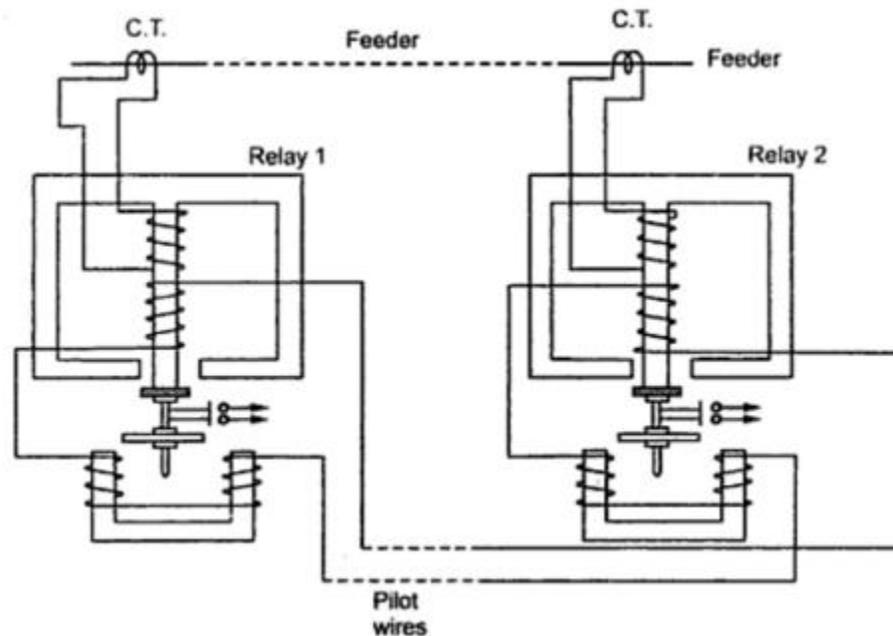
1. The C.T.s used must match accurately.
2. The pilot wires must be healthy without discontinuity.
3. Economically not suitable as the cost is high due to long pilot wires.
4. Due to long pilot wires, capacitive effects adversely bias the operation of the relays.
5. The large voltage drop in the pilot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

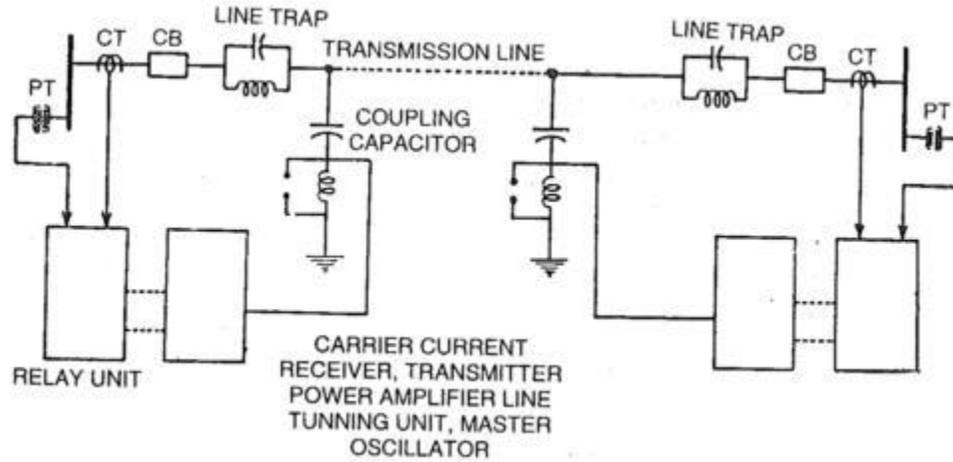
The **advantages** of this scheme are,

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

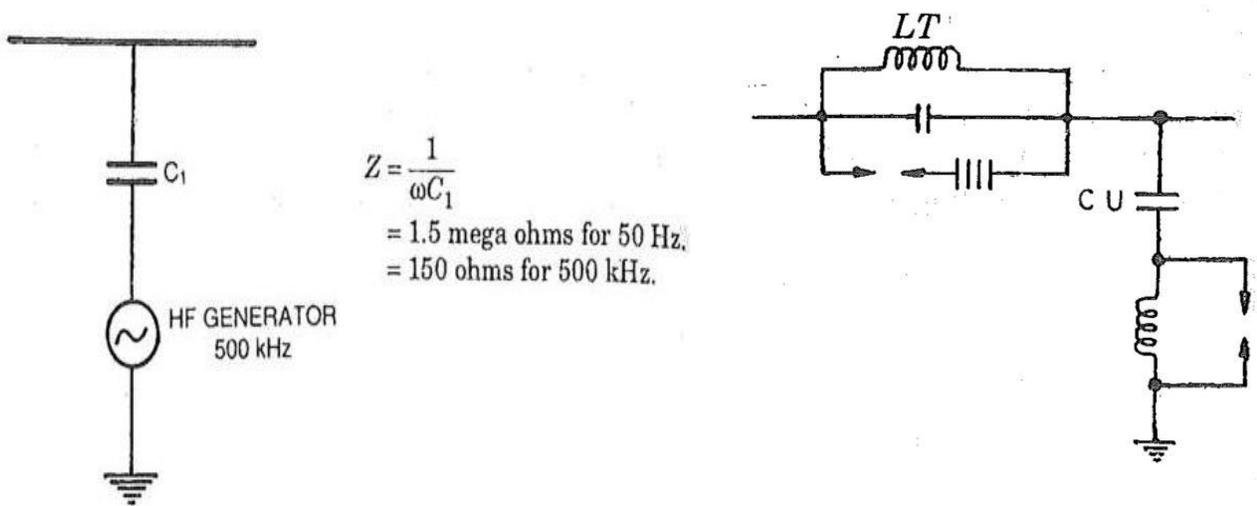
The



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.



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*.

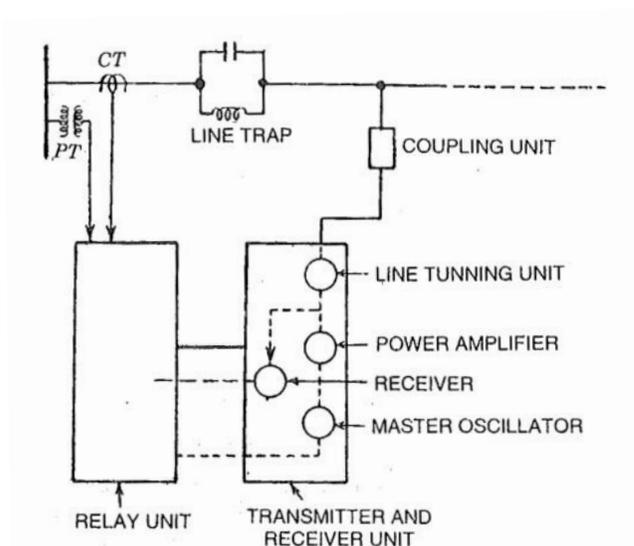
Frequency spacing

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.

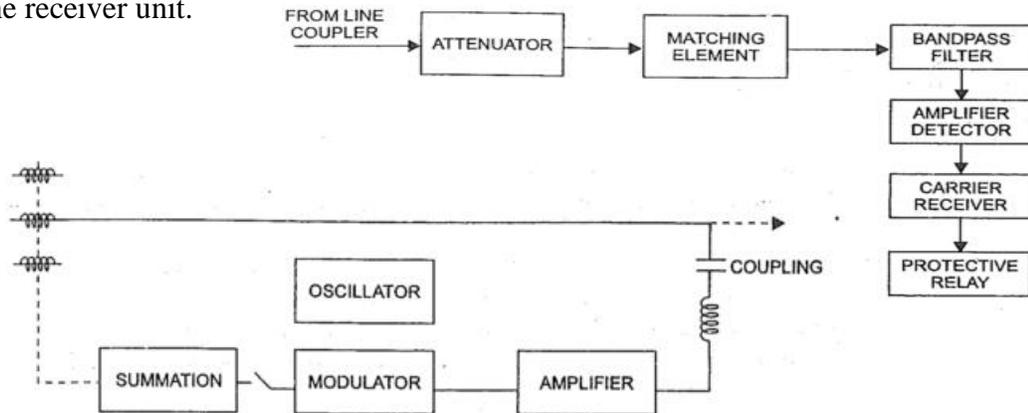
Transmitter Unit

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.

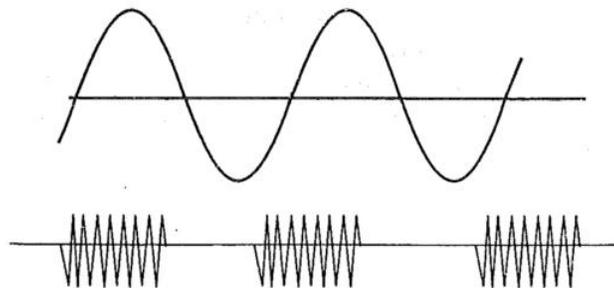
Receiver Unit



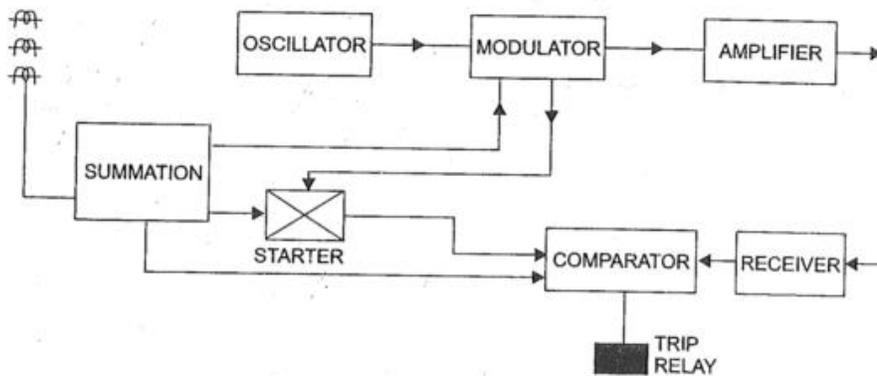
The Receiver unit consists of an attenuator and a Band pass filter, which restricts the acceptance of any unwanted signals. The unit also has matching transformer to match the line impedance and that of the receiver unit.



MODULATOR

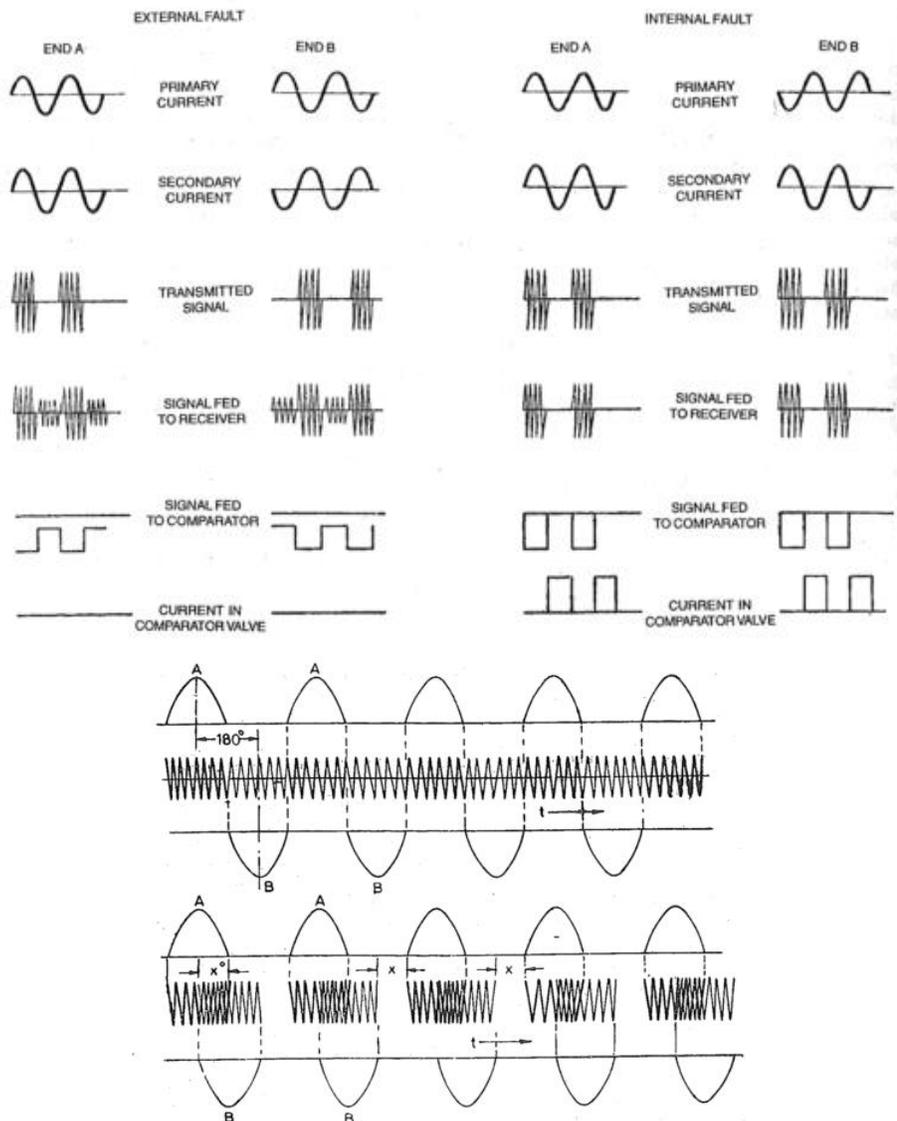


The Modulator modulates, the 50 Hz power signals with high frequency carrier waves and the modulated signal is fed to an amplifier. The amplifier output is transmitted via a CU. It takes half a cycle of power signal to produce requisite *Blocks of carrier* as shown above.



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 *Starter*. 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 absence of carrier blocks is not possible for an external fault.

2.3.2 Application advantages and multiple roles of CCE

Pilot channel such as 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 conversation 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

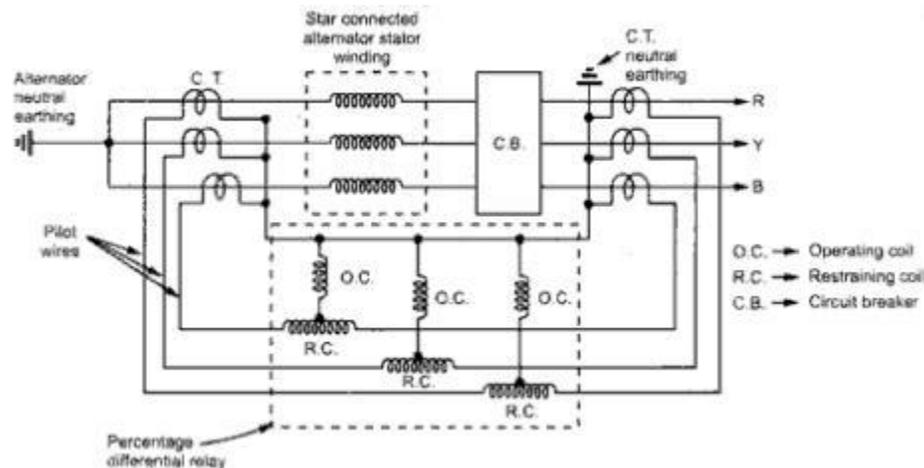
- The range of size of generators extends from a few hundred KVA to more than 500MVA
- Small and Medium sized sets may be directly connected to the distribution system

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.

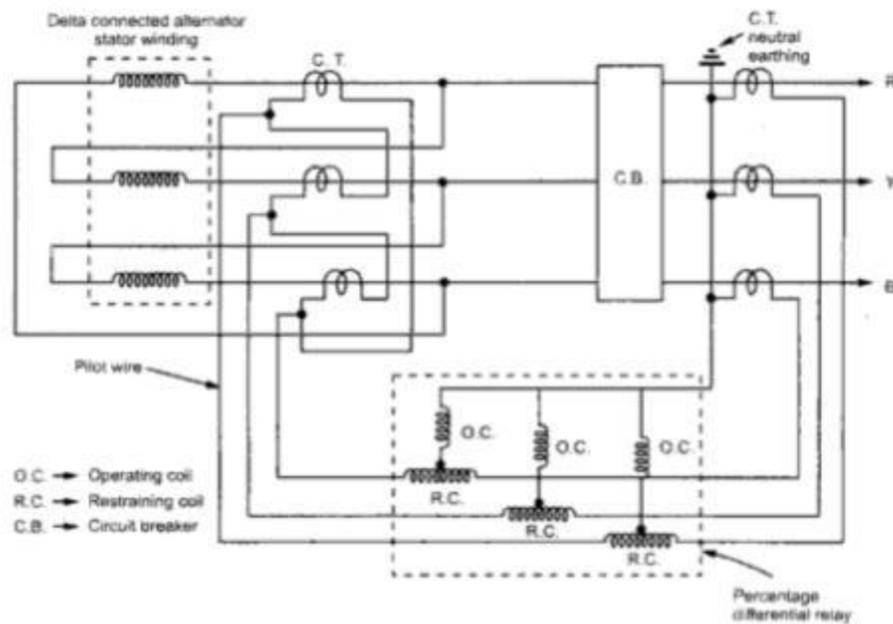
The figure below shows a schematic arrangement of Merz-Price protection scheme for a star connected alternator.



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 tapplings 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.

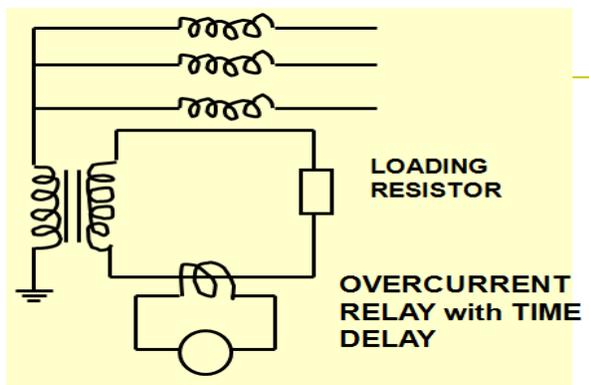
The neutral point of the generator is usually earthed, so as to facilitate the protection of the stator winding and associated system. Impedance is inserted in the earthing lead to limit the magnitude of the earth fault current. Generators which are directly connected to the transmission or distribution 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.

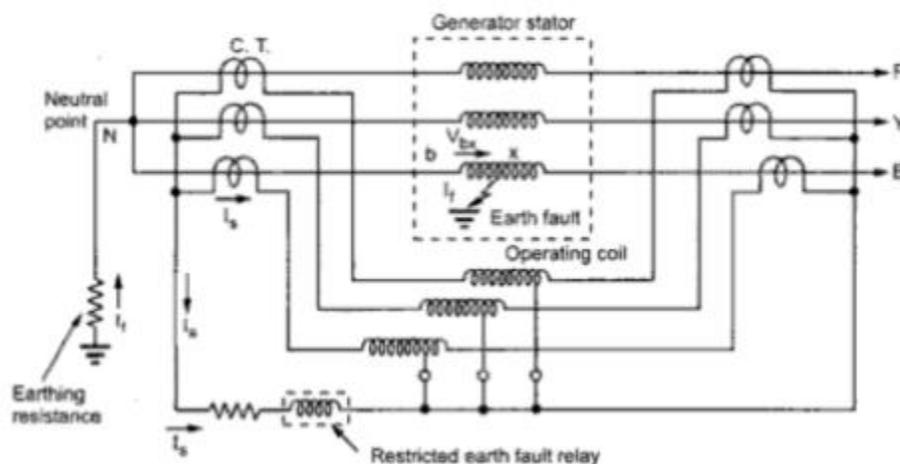
Modern practice is to use a large earthing transformer (5-100 KVA) – the secondary winding which is designed for 100-500V is loaded with a resistor of a value, which when referred through the transformer ratio, will pass a suitable fault current. The resistor is therefore of low value and can be of rugged 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,

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

Where, I_0 = Maximum operating current in the primary of C.T.

If relay setting used is 15% then I_0 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,

$$V_L = 13.2 \text{ kV} \quad \text{Rating} = 10 \text{ MVA}$$

From rating, calculate the full load current,

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

$$= 437.386 \text{ A}$$

Relay setting is 20% out of balance i.e. 20% of the rated current activities the relay.

$$I_o = 4387.386 \times (20/100) = 87.477 \text{ A}$$

= Minimum operating current

$$V = \text{Line to neutral voltage} = V_L/\sqrt{3}$$

$$= (13.2 \times 10^3)/\sqrt{3} = 7621.02 \text{ V}$$

% of winding unprotected = 15% as 85% is protected

$$\therefore 15 = (RI_o/V) \times 100$$

$$\therefore = ((R \times 87.477)/7621.02) \times 100$$

$$\therefore R = 13.068 \Omega$$

Example 2 : A star connected 3 phase, 12 MVA, 11 kV alternator has a phase reactance of 10%. It is protected by Merz-Price circulating current scheme which is set to operate for fault current not less than 200 A. Calculate the value of earthing resistance to be provided in order to ensure that only 15% of the alternator winding remains unprotected.

Solution : The given values are,

$$V_L = 11 \text{ kV} \quad \text{Rating} = 12 \text{ MVA}$$

$$\text{Rating} = \sqrt{3} V_L I_L$$

$$\therefore 12 \times 10^6 = \sqrt{3} \times 11 \times 10^3 \times I_L$$

$$\therefore I_L = (12 \times 10^6) / (\sqrt{3} \times 11 \times 10^3)$$

$$= 629.8366 \text{ A} = I = \text{rated current}$$

$$V = V_L/\sqrt{3} = (11 \times 10^3)/\sqrt{3} = 6350.8529 \text{ V}$$

$$\% \text{ Reactance} = (IX / V) \times 100$$

Where X = reactance per phase

and I = rated current

$$\therefore 10 = (629.8366X / 6350.82529) \times 100$$

$$\therefore X = 1.0083 \Omega$$

\therefore Reactance of unprotected winding

$$= (\% \text{ of unprotected winding}) \times (X)$$

$$= (15/100) \times 1.0083$$

$$= 0.1512 \Omega$$

v = Voltage induced in unprotected winding

$$= (15/100) \times V = 0.15 \times 6350.8529$$

$$= 952.6279 \text{ V}$$

i = Fault current
 = 200 A

Z = Impedance offered to the fault

$$= v/i = 952.6279/200$$

$$= 4.7631 \Omega \quad \dots\dots\dots(1)$$

$Z = r + j$ (reactance of unprotected winding)

$$Z = r + j (0.1512) \Omega$$

$$\therefore |Z| = \sqrt{(r^2 + 0.1512^2)} \quad \dots\dots\dots(2)$$

Equation (1) and (2),

$$4.7631 = \sqrt{(r^2 + 0.1512^2)}$$

$$\therefore 22.6875 = r^2 + 0.02286$$

$$\therefore r^2 = 22.6646$$

$$\therefore r = 4.7607 \Omega$$

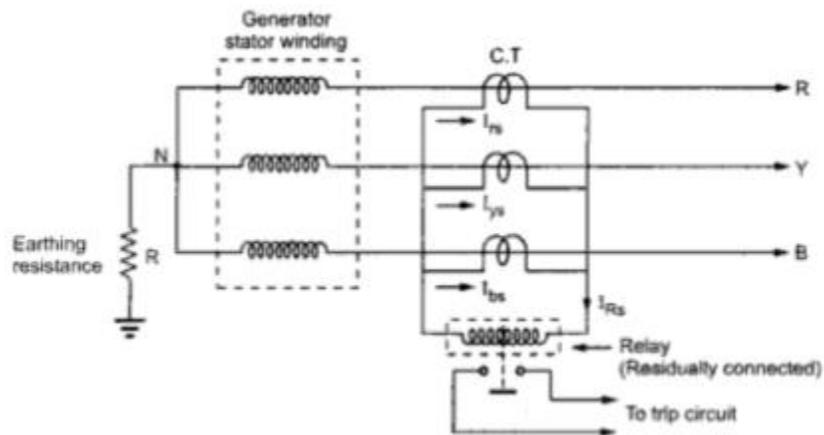
This is the earthing resistance required.

2.5.1 The unrestricted earth fault protection

The unrestricted earth fault protection uses a residually connected earth fault relay. It consists of three C.T.s, one in each phase. The secondary windings of three C.T.s are connected in parallel. The earth fault relay is connected across the secondaries which carries a residual current. The scheme is shown in the figure below.

Where there is no fault, under normal conditions, vector sum of the three line currents is zero. Hence the vector sum of the three secondary currents is also zero.

So if I_{rs} , I_{ys}
 C.T.



and I_{bs}
 secondary

currents then under normal conditions we can write,

$$\bar{I}_{rs} + \bar{I}_{ys} + \bar{I}_{bs} = 0$$

The sum of the three currents is residual current I_{Rs} which is zero under normal conditions.

The earth fault relay is connected in such a way that the residual current flows through the relay operating coil. Under normal condition, residual current is zero so relay does not carry any current and is inoperative. However in presence of earth fault condition, the balance gets disturbed and the residual current I_{Rs} is no more zero. If this current is more than the pickup value of the earth fault relay, the relay operates and opens the circuit breaker through tripping of of the trip circuit.

In the scheme shown in the figure, the earth fault at any location near or away from the location of C.T.s can cause the residual current. Hence the protected zone is not definite. Such a scheme is hence called unrestricted earth fault protection.

2.5.2 *Generator and Transformer Unit Biased Differential Protection*

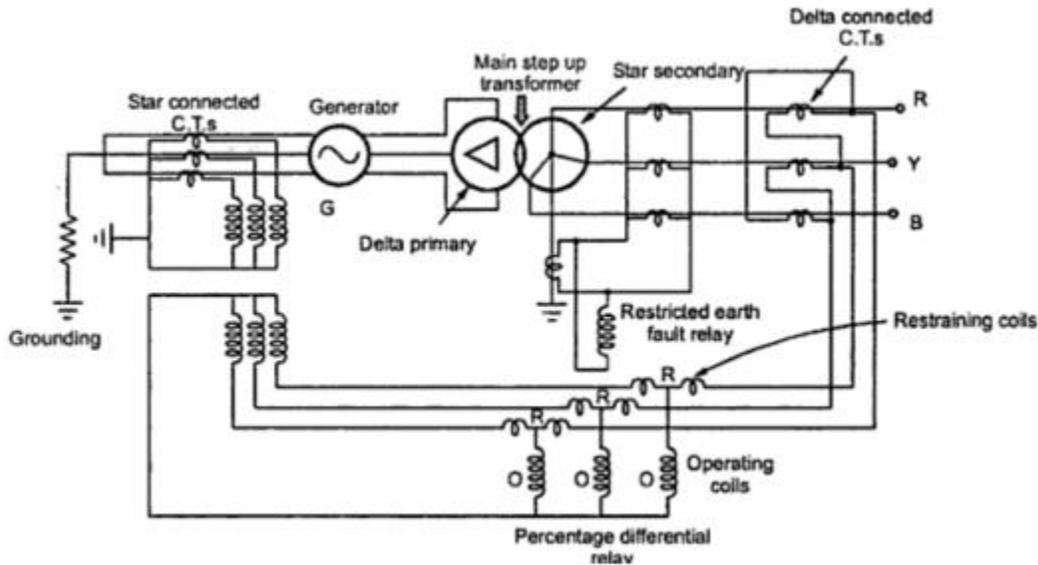
In a high voltage transmission system, the bus bars are at very high voltages than the generators. The generators are directly connected to step up transformer to which it is connected, together from a generator transformer unit. The protection of such a unit is achieved by differential protection scheme using circulating current principle. While providing protection to such a unit, it is necessary to consider the phase shift and current transformation in the step up transformer.

The figure in the following page, shows a biased differential protection scheme used for generator transformer unit. The zone of such a scheme includes the stator windings, the step up transformer and the intervening connections.

The transformer is delta-star hence the current transformers on high voltage side are delta connected while those on generator side are star connected. This cancels the displacement between line currents introduced by the delta connected primary of the transformer. Where there is no fault, the secondary currents of the current transformer connected on generator side are equal to the currents in the pilot wires from the secondaries of the delta connected current transformers on the secondary of main transformer. When a fault occurs, the pilot wires carry the differential current to operate the percentage differential relay.

For the protection against the earth faults, an earth fault relays is put in the secondary winding of the main step up transformers as shown. In such a case, differential protection acts as

a backup protection to the restricted earth fault protection. This overall differential protection scheme does not include unit transformer as a separate differential scheme is provided to it.



PHASE FAULT

- Phase-phase faults clear of earth are less common. They may occur on the end portion of stator coils or in the slots if the winding involves two coil sides in the same slot. In the later case the fault will involve earth in a very short time.
- Phase fault current is not controlled by the method of earthing the neutral point.

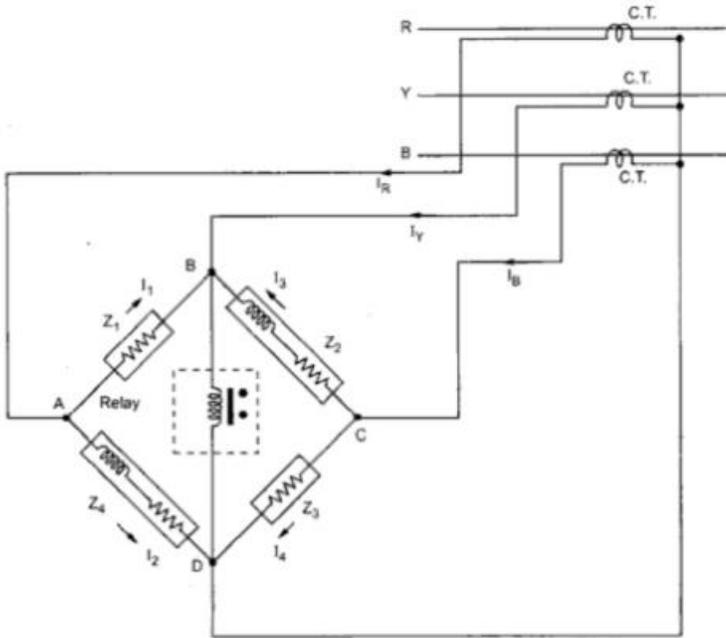
INTERTURN FAULTS

- Interturn faults are also uncommon, but not unknown
- A greatest danger arising from failure to deal with interturn faults quickly is fire. A large portion of the insulation is inflammable

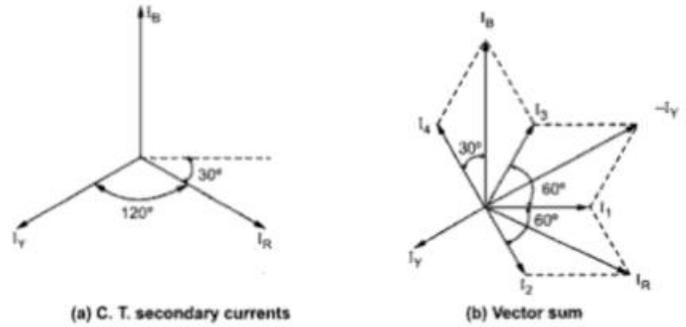
2.6 Negative sequence protection

The negative sequence component can be detected by the use of a filter network. Many negative sequence filter circuits have been evolved.

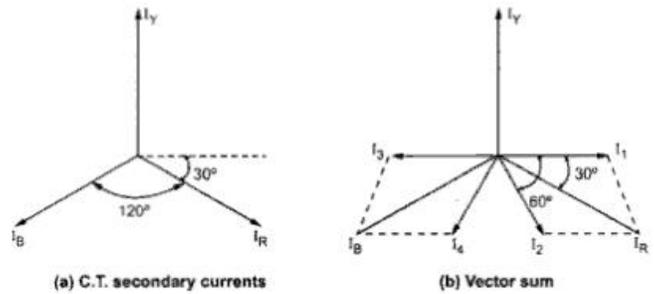
One typical negative sequence filter circuit is as follows



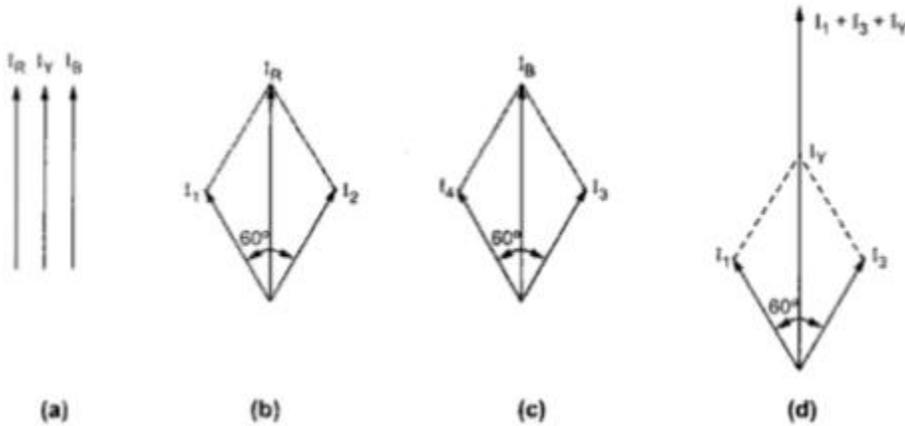
Positive Sequence



Negative Sequence



Zero Sequence



Basically it

consists of a resistance bridge network as depicted in the first figure showing the circuit connection. The magnitudes of the impedances of all the branches of the network are equal. The impedances Z_1 and Z_3 are purely resistive while the impedances Z_2 and Z_4 are the combinations of resistance and reactance. The currents in the branches Z_2 and Z_4 lag by 60° from the currents in the branches Z_1 and Z_3 . The vertical branch B-D basically consists of an over current element

with inverse time characteristics having negligible impedance compared to the bridge impedances.

POSITIVE SEQUENCE OPERATION

The current I_R gets divided into two equal parts I_1 and I_2 . And I_2 lags I_1 by 60° . The phasor diagram is shown in the figure.

$$\bar{I}_1 + \bar{I}_2 = \bar{I}_{rs}$$

Let $I_1 = I_2 = I$

The perpendicular is drawn from point A on the diagonal meeting it at point B, as shown in the Figure. This bisects the diagonal.

$$\therefore OB = I_R/2$$

Now in triangle OAB,

$$\cos 30 = OB/OA$$

$$\therefore \sqrt{3}/2 = (I_R/2)/I$$

$$\therefore I = I_R/\sqrt{3} = I_1 = I_2 \quad \dots\dots\dots(1)$$

Now I_1 leads I_R by 30° while I_2 lags I_R by 30° .

Similarly the current I_B gets divided into two equal parts I_3 and I_4 . The current I_3 lags I_4 by 60° . From equation (1) we can write,

$$I_B/\sqrt{3} = I_3 = I_4 \quad \dots\dots\dots(2)$$

The current I_4 leads by I_B while current I_3 lags I_B by 30° .

The current entering the relay at the junction point B in the figure is the vector sum of 3 components of currents as below.

$$\begin{aligned} I_{\text{relay}} &= \bar{I}_1 + \bar{I}_3 + \bar{I}_Y \\ &= I_Y + (I_R/\sqrt{3}) (\text{leads } I_R \text{ by } 30^\circ) + I_B/\sqrt{3} (\text{lags } I_B \text{ by } 30^\circ) \end{aligned}$$

The vector sum as shown in the figure, is equal to zero.

As

$$\bar{I}_1 + \bar{I}_3 = -\bar{I}_Y$$

$$\therefore \bar{I}_1 + \bar{I}_3 + \bar{I}_Y = 0$$

Thus the current entering the relay at point B is zero. Similarly the resultant current at junction D is also zero. Thus the relay is inoperative for a balanced system.

NEGATIVE SEQUENCE OPERATION

Now consider that there is unbalanced load on generator or motor due to which negative sequence currents exist. The phase sequence of C.T. secondary currents is as shown in the figure for negative sequence. The vector diagram of I_1 , I_3 and I_Y is redrawn under this condition also. The component I_1 and I_3 are equal and opposite to each other at the junction point B. Hence I_1 and I_3 cancel each other. Now the relay coil carries the current I_Y and when this current is more than a predetermined value, the relay trips closing the contacts of trip circuit which opens the circuit breaker.

Zero Sequence operation

$$\bar{I}_R = \bar{I}_1 + \bar{I}_2, \quad \bar{I}_B = \bar{I}_3 + \bar{I}_4, \quad \bar{I}_1 + \bar{I}_3 = \bar{I}_Y$$

The total current through relay is $\bar{I}_1 + \bar{I}_3 + \bar{I}_Y$. Thus under zero sequence currents the total current of twice the zero sequence current flows through the relay. Hence the relay operates to open the circuit breaker.

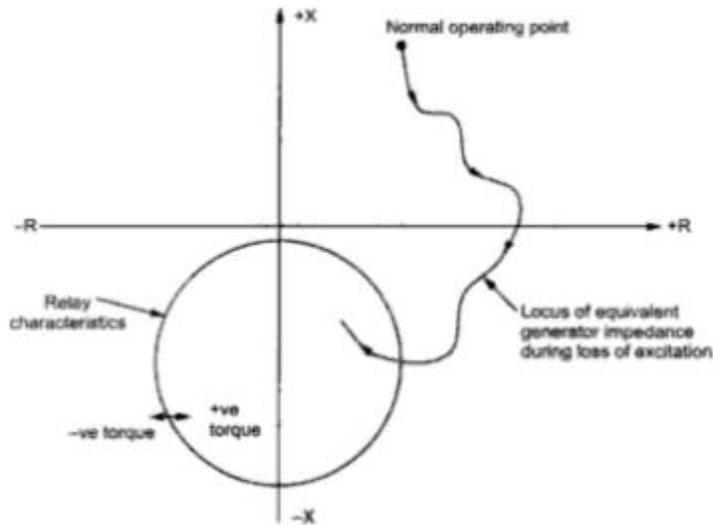
To make the relay sensitive to only negative sequence currents by making it inoperative under the influence of zero sequence currents is possible by connecting the current transformers in Delta, as in that case no zero sequence current can flow in the network.

LOSS OF EXCITATION PROTECTION OF GENERATORS

The loss of excitation of the generator may result in the loss of synchronism and slightly increase in the generator speed. The machine starts behaving as an induction generator. It draws reactive power from the system which is undesirable. The loss of excitation may lead to the pole slipping condition. Hence protection against loss of excitation must be provided.

The protection is provided using directional distance type relay with the generator terminals.

When there is loss of excitation, the equivalent generator impedance varies and traces a curve as shown in the following figure. The figure shows the loss of excitation characteristics along with the relay operation characteristic, on R-X diagram.



The equivalent generator impedance locus traces a path from first quadrant of R-X diagram to the fourth quadrant. The distance relay is used which covers the portion of the fourth quadrant where impedance locus path exists. Thus when the impedance takes value in the region covered by the relay characteristics, the relay operates. The relay operates when generator first starts to slip poles. Then relay trips the field circuit breaker. And it disconnects the generator from the system, too. When the excitation is regained and becomes normal, the generator can then be returned to service instantly.

TRANSFORMER PROTECTION

INTRODUCTION

- The power transformer is one of the most important links in a power transmission and distribution system.
- It is a highly reliable piece of equipment. This reliability depends on
 - adequate design
 - careful erection
 - proper maintenance
 - application of protection system.

PROTECTION EQUIPMENT INCLUDES

1. Surge diverters

2. Gas relay: It gives early warning of a slowly developing fault, permitting shutdown and repair before severe damage can occur.

3. Electrical relays.

- The choice of suitable protection is also governed by economic considerations. Although this factor is not unique to power transformers, it is brought in prominence by the wide range of transformer ratings used (few KVA to several hundreds MVA)
- Only the simplest protection such as fuses can be justified for transformers of lower ratings.
- for large transformers best protection should be provided.

TYPES OF FAULTS AFFECTING POWER TRANSFORMER

• THROUGH FAULTS

- a) Overload conditions.
- b) External short-circuit conditions.

The transformer must be disconnected when such faults occur only after allowing a predetermined time during which other protective gears should have operated.

• INTERNAL FAULTS

The primary protection of a power transformer is intended for conditions which arises as a result of faults inside the protection zone.

1. Phase-to-earth fault or phase-to-phase fault on HV and LV external terminals
2. Phase-to-earth fault or phase-to-phase fault on HV and LV windings.
3. Interturn faults of HV and LV windings.
4. Earth fault on tertiary winding, or short circuit between turns of a tertiary windings.

5. So called 'incipient' faults which are initially minor faults, causing gradually developing fault. These types of faults are not easily detectable at the winding terminals by unbalance current or voltage.

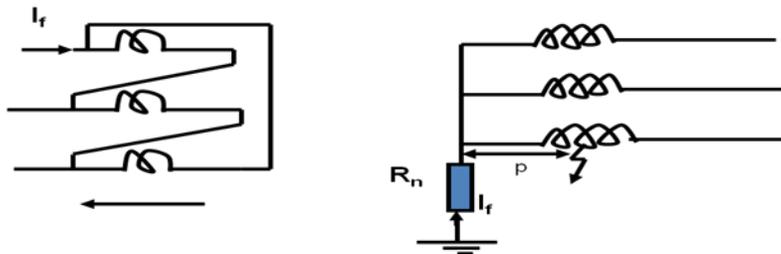
NATURE & EFFECT OF TRANSFORMER FAULTS

A faults on transformer winding is controlled in magnitude by

- Source & neutral earthing impedance
- Leakage reactance of the transformer
- Position of the fault on the winding.

Following distinct cases are examined below

- (1) Star connected winding with neutral point earthed through an impedance



Earth fault on resistance earthed star winding

2.7 Transformer differential protection

Basic discussions related to the Merz-Price Scheme and its limitations which are taken care by the biased differential scheme, are omitted for repetition

2.7.1 Basic considerations

a. Transformation ratio

The nominal currents in the primary and secondary sides of the transformer vary in inverse ratio to the corresponding voltages. This should be compensated for by using different transformation ratios for the CTs on the primary and secondary sides of the transformer.

b. Current Transformer Connections

- When a transformer is connected in star/delta, the secondary current has a phase shift of 30° relative to the primary
- This phase shift can be offset by suitable secondary CT connections

- The zero-sequence currents flowing on the star-side of the transformer will not produce current outside the delta on the other side. The zero sequence current must therefore be eliminated from the star-side by connecting the CTs in delta.
- The CTs on delta side should be connected in star in order to give 30^0 phase shift.
- When CTs are connected in delta, their secondary ratings must be reduced to 1/3 times the secondary ratings of the star-connected transformer, in order that the currents outside the delta may balance with the secondary currents of the star-connected CTs.
- If transformers were connected in star/star, the CTs on both sides would need be connected in delta-delta.

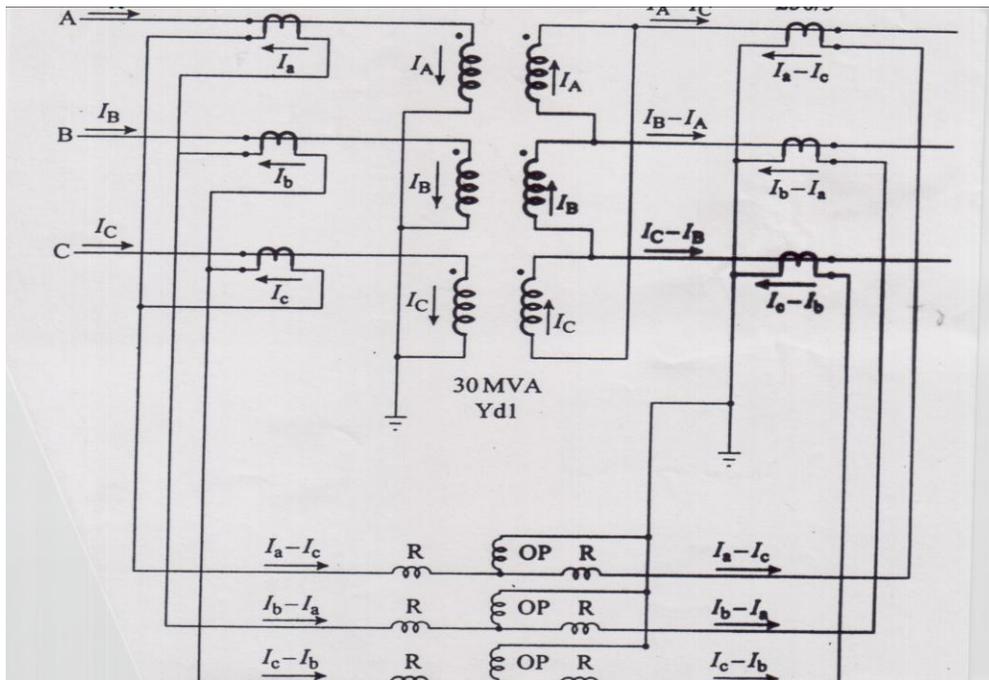
c. Bias to cover tap-changing facility and CT mismatch

- If the transformer has the benefit of a tap changer, it is possible to vary its transformation ratio for voltage control.
- The differential protection system should be able to cope with this variation.
- This is because if the CTs are chosen to balance for the mean ratio of the power transformer, a variation in ratio from the mean will create an unbalance proportional to the ratio change. At maximum through fault current, the spill output produced by the small percentage unbalance may be substantial
- Differential protection should be provided with a proportional bias of an amount which exceeds in effect the maximum ratio deviation. This stabilizes the protection under through fault conditions while still permitting the system to have good basic sensitivity.

d. Magnetization Inrush

- The magnetizing inrush produces a current flow into the primary winding that does not have any equivalent in the secondary winding. The net effect is thus similar to the situation when there is an internal fault on the transformer.
- Since the differential relay sees the magnetizing current as an internal fault, it is necessary to have some method of distinguishing between the magnetizing current and the fault current using one or all of the following methods.

- Using a differential relay with a suitable sensitivity to cope with the magnetizing current, usually obtained by a unit that introduces a time delay to cover the period of the initial inrush peak.
- Using a harmonic-restraint unit, or a supervisory unit, in conjunction with a differential unit.
- Inhibiting the differential relay during the energizing the transformer.



Compared to the differential protection used in generators, there are certain important points discussed below which must be taken care of while using such protection for the power transformers.

1. In a power transformer, the voltage rating of the two windings is different. The high voltage winding is low current winding while low voltage winding is high current winding. Thus there always exists difference in current on the primary and secondary sides of the power transformer. Hence if C.T.s of same ratio are used on two sides, then relay may get operated through there is no fault existing.

To compensate for this difficulty, the current ratios of C.T.s on each side are different. These ratios depend on the line currents of the power transformer and the connection of C.T.s. Due to

the different turns ratio, the currents fed into the pilot wires from each end are same under normal conditions so that the relay remains inoperative. For example if K is the turns ratio of a power transformer then the ratio of C.T.s on low voltage side is made K times greater than that of C.T.s on high voltage side.

2. In case of power transformers, there is an inherent phase difference between the voltages induced in high voltage winding and low voltage winding. Due to this, there exists a phase difference between the line currents on primary and secondary sides of a power transformer. This introduces the phase difference between the C.T. secondary currents, on the two sides of a power transformer. Through the turns ratio of C.T.s are selected to compensate for turns ratio of transformer, a differential current may result due to the phase difference between the currents on two sides. Such a different current may operate the relay though there is no fault. Hence it is necessary to correct the phase difference.

To compensate for this, the C.T. connections should be such that the resultant currents fed into the pilot wires from either sides are displaced in phase by an angle equal to the phase shift between the primary and secondary currents. To achieve this, secondaries of C.T.s on star connected side of a power transformer are connected in delta while the secondaries of C.T.s on delta connected side of a power transformer are connected in star.

The table.1 gives the way of connecting C.T. secondaries for the various types of power transformer connections.

Power Transformer Connections		C. T. Connections	
Primary	Secondary	Primary	Secondary
Star	Delta	Delta	Star
Delta	Delta	Star	Star
Star	Star	Delta	Delta
Delta	Star	Star	Delta

With such an arrangement, the phase displacement between the currents gets compensated with the oppositely connected C.T. secondaries. Hence currents fed to the pilot wires from both the sides are in phase under normal running conditions and the relay is ensured to be inoperative.

3. The neutrals of C.T. star and power transformer stars are grounded.

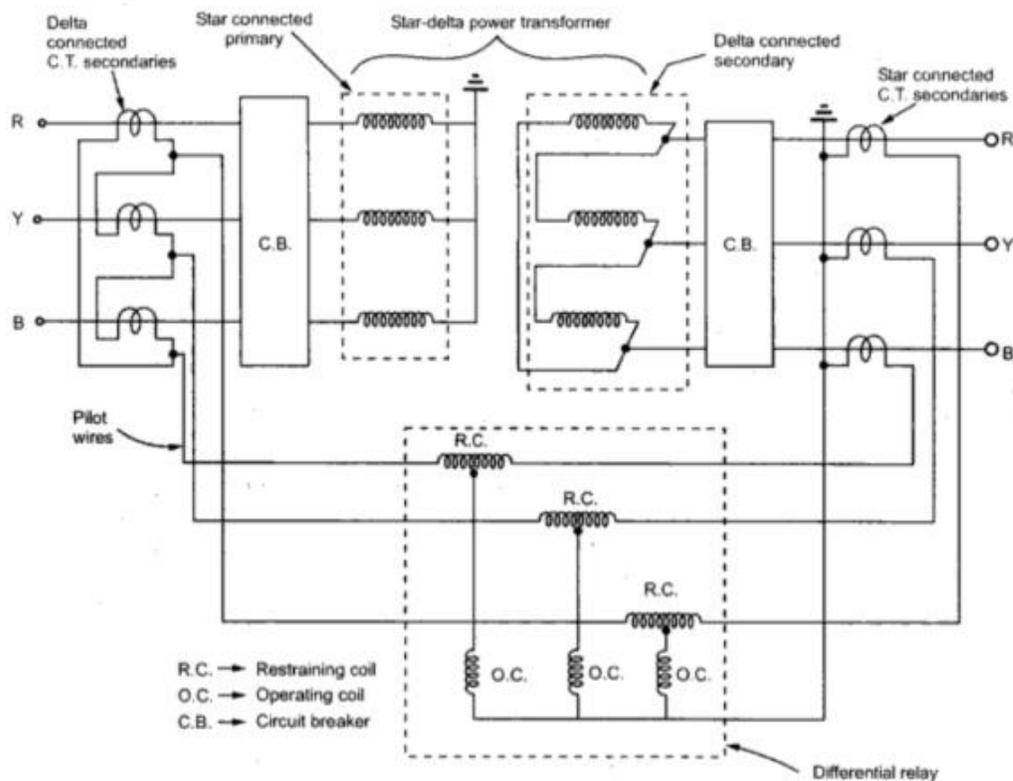
4. Many transformers have tap changing arrangement due to which there is a possibility of flow of differential current. For this, the turns ratio of C.T.s on both sides of the power transformer are

provided with tap for of C.T.s on both sides of the power transformer are provided with tap for their adjustment.

For the sake of understanding, the connection of C.T. secondaries in delta for star side of power transformer and the connection of C.T. secondaries in star for delta

STAR/DELTA UNIT

Let us study the Differential protection for the star-delta power transformer. The primary of the power transformer is star connected while the secondary is delta connected. Hence to compensate for the phase difference, the C.T. secondaries on primary side must be connected in delta while the C.T. secondaries on delta side must be connected in star.

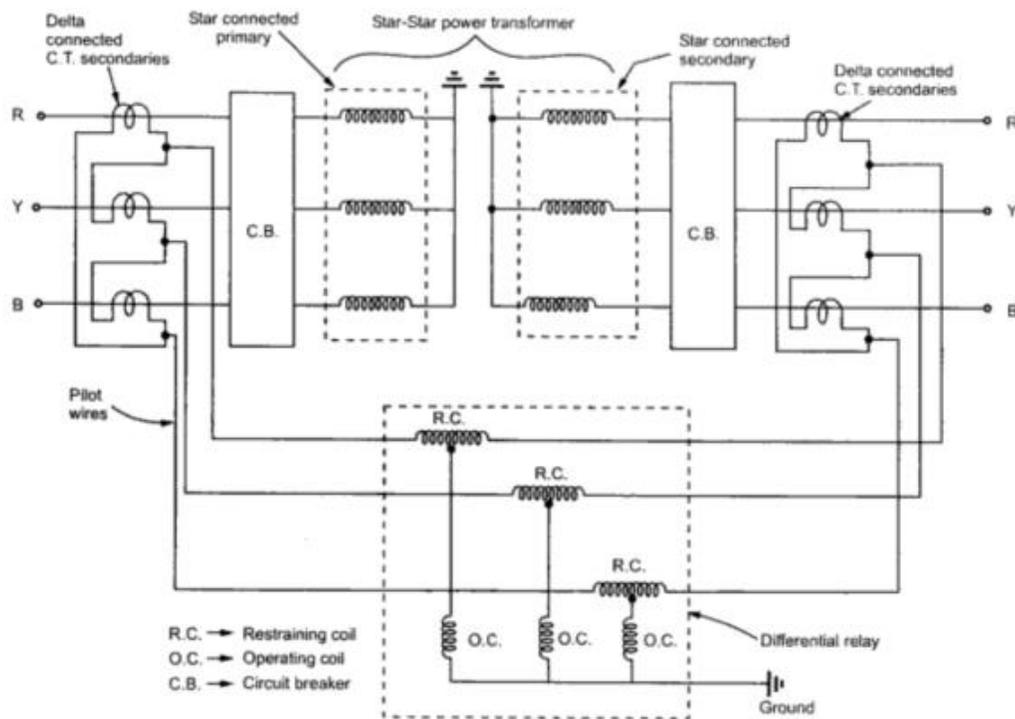


The star point of the power transformer primary as well as the star connected C.T. secondaries must be grounded. The restraining coils are connected across the C.T. secondary windings while the operating coils are connected between the tapping points on the restraining coils and the star point of C.T. secondaries.

With the proper selection of turns ratio of C.T.s the coils are under balanced condition during normal operating conditions. The C.T. secondaries carry equal currents which are in

phase under normal conditions. So no current flows through the relay and the relay is inoperative.

It is important to note that this scheme gives protection against short circuit faults between the turns i.e. interturn faults also. This is because when there is an interturn fault, the turns ratio of power transformer gets affected. Due to this the currents on both sides of the power transformer become unbalanced. This causes an enough differential current which flows through the relay and the relay operates.

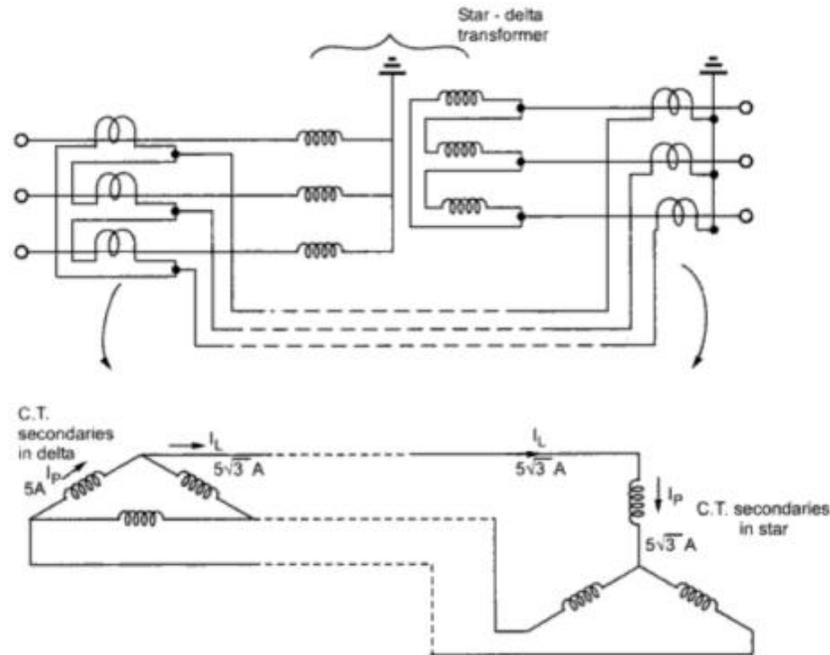


STAR/STARUNIT

The figure above shows the Merz-Price protection system for the star-star power transformer. Both primary and secondary of the power transformer are connected in star and hence C.T. secondaries. The operating coils are connected between the tapping on the restraining coil and the ground. The operation of the scheme remains same for any type of power transformer as discussed for star-star power transformer.

Example : A three phase power transformer having a line voltage ratio of 400 V to 33 kV is connected in star-delta. the C.T.s on 400 V side have current ratio as 1000/5. What must be the C.T. ratio on 33 kV side.

Assume current on 400 V side of transformer to be 1000 A.



Solution :
arrangement

shown in the Fig. 4.

On the primary side, which is 400 V side of transformer the current is 1000 A.

Hence C.T.s primary will carry current of 1000 A.

The C.T. ratio is 1000/5 on the primary side hence the current in C.T.

Secondaries which is phase current of delta connected C.T.s is,

$$I_p = 1000 \times (5/1000) = 5 \text{ A}$$

This is shown in the Fig.4

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

This is balance the C.T. secondaries are connected in delta.

The same current flows through the star connected C.T. secondaries. Hence each secondaries of C.T. on the secondary side of transformer carries a current of $5\sqrt{3}$ A.

For the power transformer the apparent power on both sides must be same.

Primary apparent power = Secondary apparent power

The
is

$$\sqrt{3} V_{L1} I_{L1} = \sqrt{3} V_{L2} I_{L2}$$

$$\sqrt{3} \times 400 \times 1000 = \sqrt{3} \times 33000 \times I_{L2}$$

$$I_{L2} = (400 \times 1000)/33000 = 12.12 \text{ A}$$

Thus each primary of C.T.s connected in star carries a current of 12.12 A. while each secondary of C.T.s connected in star carries a current of $5\sqrt{3}$ A.

Hence the C.T. ratio on 33 kV side is,

$$\text{C.T. ratio} = \text{Primary current}/\text{Secondary current} = 12.12/5\sqrt{3} = 1.4 : 1$$

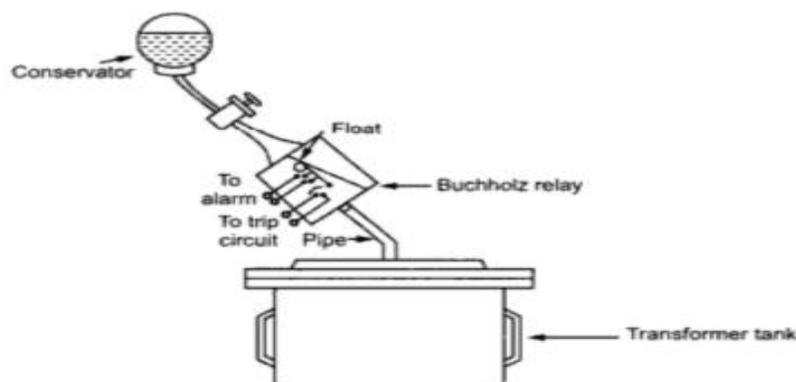
This is the required C.T. ratio on 33 kV side.

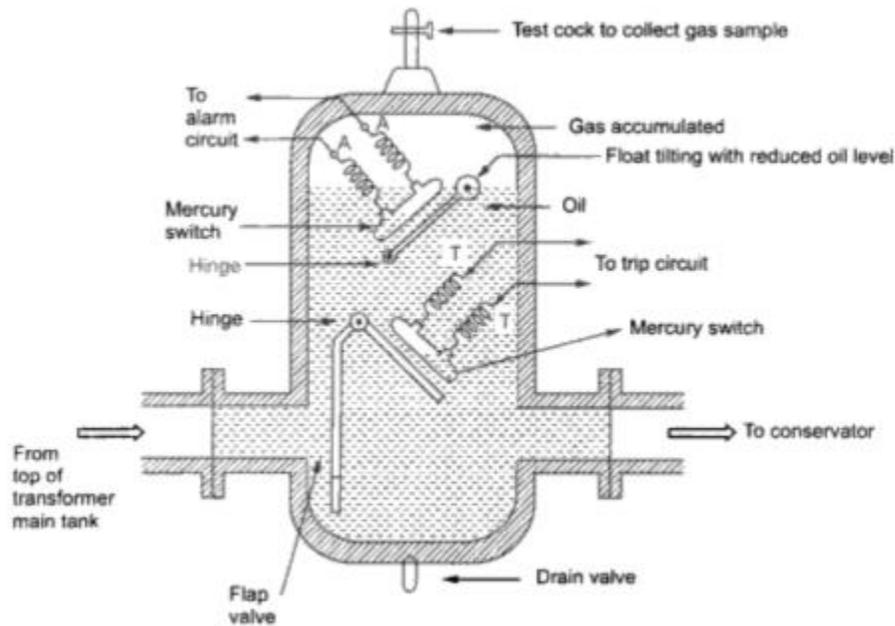
2.8 Buchholz relay

All faults below the oil in transformer result in the localized heating & breakdown of the oil, some degree of arcing will always take place in a winding fault & the resulting decomposition of it will release gases such as hydrogen, carbon monoxide & hydrocarbons.

- When the fault is of a very minor type, such as hot joints gas is released slowly, but a major fault involving severe arcing causes rapid release of large volumes of gas as well as oil vapour.
- Such incipient faults of smaller or larger magnitudes can be detected by a gas actuated relay known as Buchholtz Relay.

The Buchholtz Relay is contained in a cast housing which is connected as shown below between the conservator tank and main tank of the transformer.





Under normal conditions, the Buchholz relay is full of oil. It consists of a cast housing containing a hinged hollow float. A mercury switch is attached to a float. The float being rotated in the upper part of the housing. Another hinged flap valve is located in the lower part which is directly in the path of the oil between tank and the conservator. Another mercury switch is attached to a flap valve. The float closes the alarm circuit while the lower flap valve closes the trip circuit in case of internal faults.

2.8.1 Operation

There are many types of internal faults such as insulation fault, core heating, bad switch contacts, faulty joints etc. which can occur. When the fault occurs the decomposition of oil in the main tank starts due to which the gases are generated. As mentioned earlier, major component of such gases is hydrogen. The hydrogen tries to rise up towards conservator but in its path it gets accumulated in the upper part of the Buchholz relay. Through passage of the gas is prevented by the flap valve.

When gas gets accumulated in the upper part of housing, the oil level inside the housing falls. Due to which the hollow float tilts and closes the contacts of the mercury switch attached to it. This completes the alarm circuit to sound an alarm. Due to this operator knows that there is some incipient fault in the transformer. The transformer is disconnected and the gas sample is tested. The testing results give the indication, what type of fault is started developing in the

transformer. Hence transformer can be disconnected before grows into a serious one. The alarm circuit does not immediately disconnect the transformer but gives only an indication to the operator. This is because sometimes bubbles in the oil circulating system may operate the alarm circuit even though actually there is no fault.

However if a serious fault such as internal short circuit between phases, earth fault inside the tank etc. occurs then the considerable amount of gas gets generated. In that case, due to a fast reduction in the level of oil, the pressure in the tank increases. Due to this the oil rushes towards the conservator. While doing so it passes through the relay where flap valve is present. The flap valve gets deflected due to the rushing oil and operates the mercury switch, thereby energizing the trip circuit which opens the circuit breaker of transformer is totally disconnected from the supply.

The connecting pipe between the tank and the conservator should be as straight as possible and should slope upwards conservator at a small angle from the horizontal. This angle should be around 10° .

For the economic considerations, Buchholz relays are not provided for the transformer having rating below 500 KVA.

2.8.2 Advantages

The various advantages of the Buchholz relay are,

1. Normally a protective relay does not indicate the appearance of the fault. It operates when fault occurs. But Buchholz relay gives an indication of the fault at very early stage, by anticipating the fault and operating the alarm circuit. Thus the transformer can be taken out of service before any type of serious damage occurs.
2. It is the simplest protection in case of transformers.

2.8.3 Limitations

The various limitation of the Buchholz relay are,

1. Can be used only for oil immersed transformers having conservator tanks.
2. Only faults below oil level are detected.
3. Setting of the mercury switches cannot be kept too sensitive otherwise the relay can operate due to bubbles, vibration, earthquakes mechanical shocks etc.
4. The relay is slow to operate having minimum operating time of 0.1 seconds and average time of 0.2 seconds.

2.8.4 Applications

The following types of transformer faults can be protected by the Buchholz relay and are indicated by alarm:

1. Local overheating
2. Entrance of air bubbles in oil
3. Core bolt insulation failure
4. Short circuited laminations
5. Loss of oil and reduction in oil level due to leakage
6. Bad and loose electrical contacts
7. Short circuit between phases
8. Winding short circuit
9. Bushing puncture
10. Winding earth fault.

BUSBAR PROTECTION

The protection scheme for a power system should cover the whole system against all probable types of faults. Unrestricted forms of line protection such as over current and distance systems, meet this requirement, although faults in the Bus bar zone are cleared only after some time delay. If unit protection is applied to feeder and plant the bus bars are not inherently protected. Bus bars have been left without specific protection. Different bus bar faults are as follows.

BUSBAR FAULTS

- Majority of bus faults involve one phase and earth, but faults arise from many causes and a significant number are inter-phase clear of earth.
- With fully phase-segregated metal clad gear, only earth faults are possible ,and a protective scheme need have earth fault sensitivity only.
- For outdoor busbars , protection schemes ability to respond to inter-phase faults clear of earth is an advantage

TYPES OF PROTECTION SCHEMES

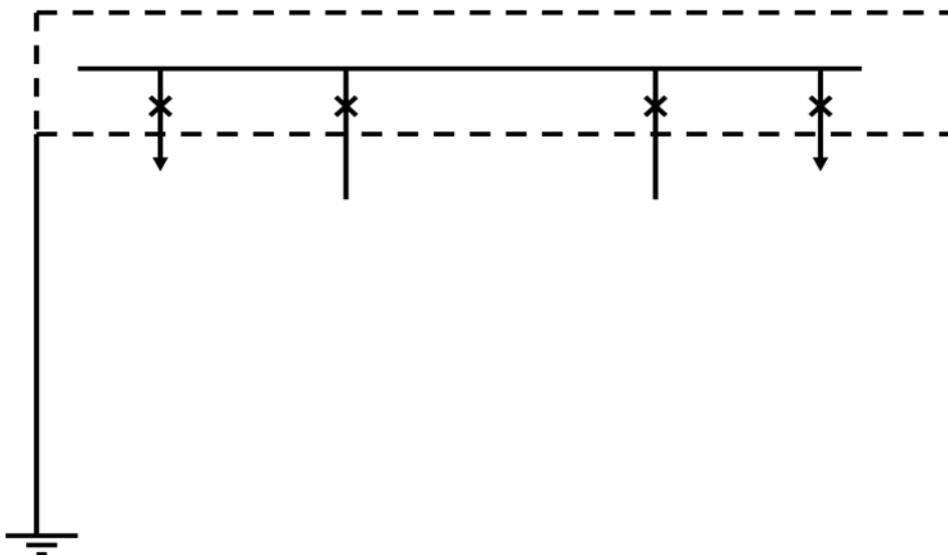
- System protection used to cover bus bars
- Frame –earth protection
- Differential protection

SYSTEM PROTECTION

- A system protection that includes over current or distance systems will inherently give protection cover to the bus bars.
- *Over current protection* will only be applied to relatively simple distribution systems, or as a back-up protection set to give considerable time delay. *Distance protection* will provide cover with its second zone.
- In both cases, therefore, the bus bar protection so obtained is slow

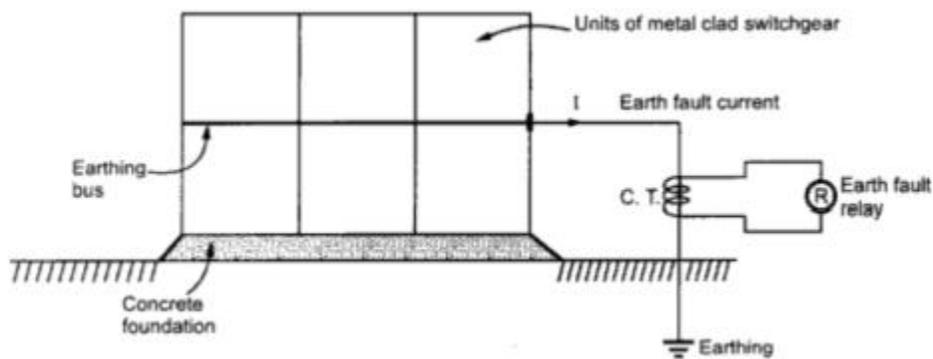
2.9 Frame-earth Protection

- This is purely an earth fault system, and in principle involves simply measuring the fault current flowing from the switchgear frame to earth. To this end a current transformer is mounted on the earthing conductor and is used to energize a simple instantaneous relay.



This protection is nothing but the method of providing earth fault protection to the bus bar assembly housed in a frame. This protection can be provided to the metal clad switchgear. The arrangement is shown in the figure below. The metal clad switchgear is lightly insulated from the earth. The enclosure of the frame housing different switchgears and bus bars is grounded through a primary of current transformer in between.

The concrete foundation of switchgear and the other equipments are lightly insulated from the ground. The resistance of these equipments with earth is about 12 ohms. When there is an earth fault, then fault current leaks from the frame and passes through the earth connection provided. Thus the primary of C.T. senses the current due to which current passes through the sensitive earth fault relay, thereby operating the relay.



MODULE-III

OUTLINE OF LESSON

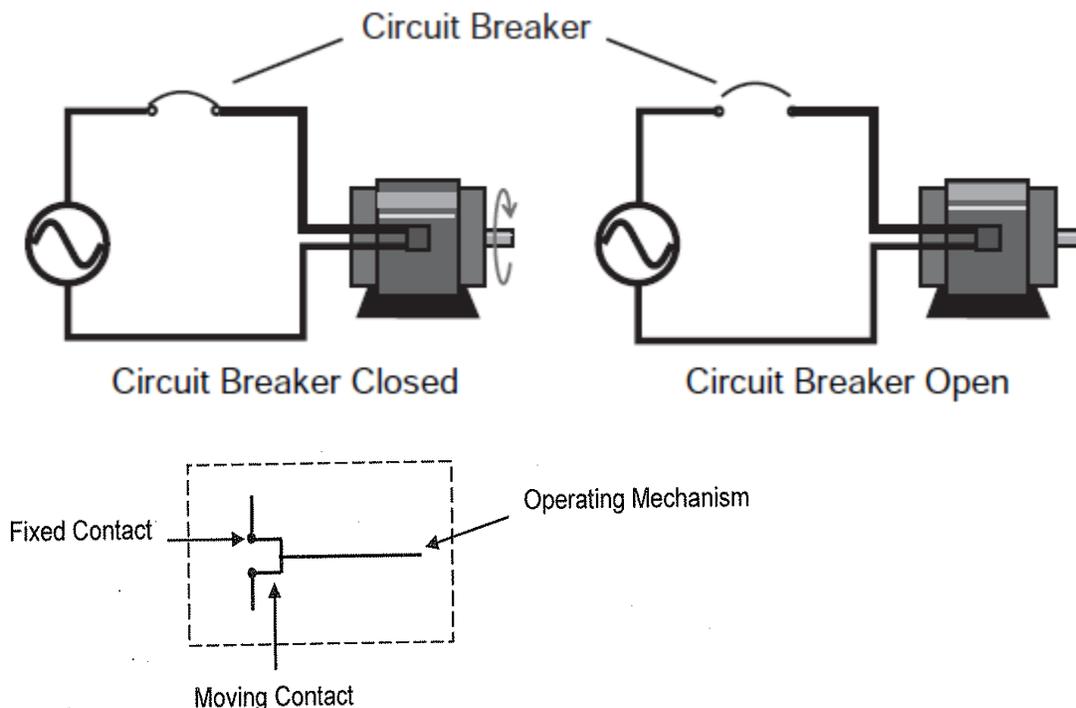
- 3.1 Circuit Breaker**
- 3.2 Formation of arc during circuit breaking**
- 3.3 Arc interruption**
- 3.4 Circuit Breaker rating**
- 3.5 Air Circuit Breaker and Air Blast Circuit Breaker**
- 3.6 Minimum Oil Circuit Breaker or MOCB**
- 3.7 Vacuum Circuit Breaker or VCB**
- 3.8 SF₆ Circuit Breaker**
- 3.9 D.C circuit breakers**
- 3.10 HRC Fuse or High Rupturing Capacity Fuse**

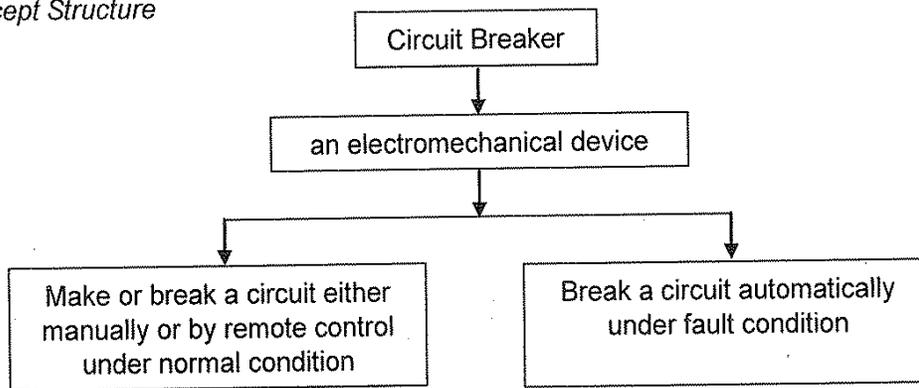
3.1 Circuit Breaker

Circuit breakers provide a manual means of energizing and de-energizing a circuit. Unlike fuses, which must be replaced when they open, a circuit breaker can be reset once the overcurrent condition has been corrected. Pushing the handle to the “OFF” position then back to the “ON” position restores the circuit. If a circuit reopens upon reset to the “ON” position, the circuit should be checked by a qualified electrician.

3.1.1 The fundamental of Circuit breaker operation

In the following illustration, an AC motor is connected through a circuit breaker to a voltage source. When the circuit breaker is closed, a complete path for current exists between the voltage source and the motor allowing the motor to run. Opening the circuit breaker breaks the path of current flow and the motor stops. The circuit breaker automatically opens when it senses a fault. After the fault has been cleared, the breaker can be closed, allowing the motor to operate.



Concept Structure**3.2 Formation of arc during circuit breaking***3.2.1 The phenomena of Arc*

During opening of current carrying contacts in a circuit breaker the medium in between opening contacts become highly ionized through which the interrupting current gets low resistive path and continues to flow through this path even after the contacts are physically separated. During the flowing of current from one contact to other the path becomes so heated that it glows in the form of an arc.

3.2.2 Arc in circuit breaker

Whenever, the contacts of circuit breaker open while carrying load there is an arc in the medium between the separating contacts of the circuit breaker. As long as this arc is sustained in between the contacts, the current through the circuit breaker will not be interrupted totally. For total interruption of current, the arc needs to be quenched as quickly as possible. The main designing criteria of a circuit breaker is to provide appropriate technology of arc quenching in circuit breaker to fulfill quick and safe current interruption. So before going through different arc quenching techniques employed in circuit breaker, it is first necessary to understand the phenomena of arc in circuit breaker.

THERMAL IONIZATION OF GAS

There are numbers of free electrons and ions present in the medium separating the two contacts of the circuit breaker. These free electrons and ions are so few in number that they are insufficient to sustain conduction of electricity. The gas molecules move randomly at room

temperature. It is found an air molecule at a temperature of 300°K (Room temperature) moves randomly with an approximate average velocity of 500 meters/second and collides other molecules at a rate of 10^{10} times/second. These randomly moving molecules collide each other in very frequent manner but the kinetic energy of the molecules is not sufficient to extract an electron from atoms of the molecules. If the temperature is increased the air will be heated up and consequently the velocity on the molecules increased. Higher velocity means higher impact during inter molecular collision. During this situation some of the molecules are disassociated in to atoms. If temperature of the air is further increased many atoms are deprived of valence electrons and make the gas ionized. Then this ionized gas can conduct electricity because of sufficient free electrons. This condition of any gas or air is called plasma. This phenomenon is called thermal ionization of gas.

IONIZATION DUE TO ELECTRIC FIELD

As we discussed that there are always some free electrons and ions presents in the air or gas but they are insufficient to conduct electricity. Whenever these free electrons come across a strong electric field, these are attracted by the field and acquire sufficiently high velocity. In other words, the electrons are accelerated along the direction of the electric field due to high potential gradient. During their travel these electrons collide with other atoms and molecules of the air or gas and extract valance electrons from their orbits. After extracted from parent atoms, the electrons will also run along the direction of the same electric field due to potential gradient. These electrons will similarly collide with other atoms and create more free electrons which will also be directed along the electric field. Due to this conjugative action the numbers of free electrons in the gas will become so high that the gas starts conducting electricity. This phenomenon is known as ionization of gas due to electron collision.

DEIONIZATION OF GAS

If all the causes of ionization of gas are removed from an ionized gas it rapidly come back to its neutral state by recombination of the positive and negative charges. The process of recombination of positive and negative charges is known as deionization process. In deionization by diffusion, the negative ions or electrons and positive ions move to the walls under the influence of concentration gradients and thus completing the process of recombination.

3.2.3 Role of arc in circuit breaker

When two current carrying contacts open, an arc bridges the contact gap through which the current gets a low resistive path to flow so there will not be any sudden interruption of current. As there is no sudden and abrupt change in current during opening of the contacts, there will not be any abnormal switching over voltage in the system. Let i is the current flowing through the contacts just before they open and L is the system inductance, switching over voltage during opening of contacts, may be expressed as $V = L.(di/dt)$ where di/dt rate of change of current with respect to time during opening of the contacts. In the case of alternating current arc is momentarily extinguished at every current zero. After crossing every current zero the medium between separated contacts gets ionized again during next cycle of current and the arc in circuit breaker is reestablished. To make the interruption complete and successful, this re-ionization in between separated contacts to be prevented after a current zero.

If arc in circuit breaker is absence during opening of current carrying contacts, there would be sudden and abrupt interruption of current which will cause a huge switching overvoltage sufficient to severely stress the insulation of the system. On the other hand, the arc provides a gradual but quick, transition from the current carrying to the current breaking states of the contacts.

3.3 Arc Interruption or Arc Quenching or Arc Extinction Theory

3.3.1 Arc column characteristics

At high temperature the charged particles in a gas move rapidly and randomly, but in absence of electric field, no net motion occurs. Whenever an electric field is applied in the gas, the charged particles gain drift velocity superimposed on their random thermal motion. The drift velocity is proportional to the voltage gradient of the field and particle mobility. The particle mobility depends upon the mass of the particle, heavier particles, lower the mobility. The mobility also depends upon mean free paths available in the gas for random movement of the particles. Since every time a particle collides, it loses its directed velocity and has to be re-accelerated in the direction of electric field again. Hence net mobility of the particles is reduced. If the medium has high pressure, it becomes denser and hence, the gas molecules come closer to each other, therefore collision occurs more frequently which lowers the mobility particles. The total current by charged particles is directly proportional to their mobility. Therefore the mobility

of charged particles depends upon the temperature, pressure of the gas and as well as nature of the gas. Again the mobility of gas particles determines the degree ionization of gas.

So from above explanation we can say that ionization process of gas depends upon nature of gas (heavier or lighter gas particles), pressure of gas and temperature of gas. As we said earlier the intensity of arc column depend up on the presence of ionized media between separated electrical contacts, hence, special attention should be given in reducing ionization or increasing deionization of media between contacts. That is why the main designing feature of circuit breaker is to provide different pressure control methods, cooling methods for different arc media in between circuit breaker contacts.

HEAT LOSS FROM ARC

Heat loss from an arc in circuit breaker takes place through conduction, convection as well as radiation. In circuit breaker with plain break arc in oil, arc in chutes or narrow slots nearly all the heat loss due to conduction. In air blast circuit breaker or in breaker where a gas flow is present between the electrical contacts, the heat loss of arc plasma occurs due to convection process. At normal pressure the radiation is not a significant factor but at higher pressure the radiation may become a very important factor of heat dissipation from arc plasma. During opening of electrical contacts, the arc in circuit breaker is produced and it is extinguished at every zero crossing, getting established again during the next cycle. The final arc extinction or arc quenching in circuit breaker can be achieved by rapid increase of the dielectric strength in the medium between the contacts so that the arc gets quenched after the first zero crossing. This rapid increase of dielectric strength in between circuit breaker contacts is achieved either by deionization of gas in the arc media or by replacing ionized gas by cool and fresh gas.

There are various deionization processes applied for arc extinction in circuit breaker, let us discussed in brief.

DEIONIZATION OF GAS DUE TO INCREASING PRESSURE

If pressure of the arc path increases, the density of the ionized gas is increased which means, the particles in the gas come closer to each other and as a result the mean free path of the particles is reduced. This increases the collision rate and as we discussed earlier at every collision the charged particles loss their directed velocity along electric field and again they are re-accelerated towards field. It can be said that over all mobility of the charged particles is

reduced so the voltage required to maintain the arc is increased. Another effect of the increased density of particles is a higher rate of deionization of gas due to the recombination of oppositely charged particles.

The rate of ionization of gas depends upon the intensity of impact during collision of gas particles. The intensity of impact during collision of particles again depends upon velocity of random motions of the particles. This random motion of a particle and its velocity increases with increase of temperature of the gas. Hence it can be concluded like that if temperature of a gas is increased; its ionization process is increased and opposite statement is also true that is if the temperature is decreased the rate of ionization of gas is decreased means deionization of gas is increased. Therefore more voltage required to maintain arc plasma with a decreased temperature. Finally it can be said that the cooling effectively increases the resistance of the arc.

The insulating material (may be fluid or air) used in circuit breaker should serve two important functions as follows:

1. It should provide sufficient insulation between the contacts when circuit breaker opens.
2. It should extinguish the arc occurring between the contacts when circuit breaker opens.

3.3.2 *Methods of arc interruption*

There are two methods by which interruption is done.

1. High resistance method.
2. Low resistance method or zero interruption method.

In high interruption method we can increase the electrical resistance many times to such a high value that it forces the current to reach to zero and thus restricting the possibility of arc to be struck again. Proper steps must be taken in order to ensure that the rate at which the resistance is increased or decreased is not abnormal because it may lead to generation of harmful induced voltages in the system. The arc resistance can be increased by various methods like lengthening or cooling of the arc etc.

Limitations of high resistance method: Arc discharge has a resistive nature due to this most of the energy is received by circuit breaker itself hence proper care should be taken during the manufacturing of circuit breaker like mechanical strength etc. Therefore this method is applied in dc power circuit breaker, low and medium ac power circuit breaker.

Low resistance method is applicable only for ac circuit and it is possible there because of presence of natural zero of current. The arc gets extinguished at the natural zero of the ac wave and is prevented from restriking again by rapid building of dielectric strength of the contact space.

There are two theories which explains the phenomenon of arc extinction:

1. Energy balance theory,
2. Voltage race theory.

Before going in details about these theories, we should know the following terms.

- *Restriking voltage*: It may be defined as the voltage that appears across the breaking contact at the instant of arc extinction.
- *Recovery voltage* : It may be defined as the voltage that appears across the breaker contact after the complete removal of transient oscillations and final extinction of arc has resulted in all the poles.
- *Active recovery voltage* : It may be defined as the instantaneous recovery voltage at the instant of arc extinction.
- *Arc voltage* : It may be defined as the voltage that appears across the contact during the arcing period, when the current flow is maintained in the form of an arc. It assumes low value except for the point at which the voltage rise rapidly to a peak value and current reaches to zero.

1. *Energy Balance Theory*: When the contact of circuit breaker are about to open, re striking voltage is zero, hence generated heat would be zero and when the contacts are fully open there is infinite resistance, therefore no production of heat again. We can conclude from this that the maximum generated heat is lying between these two cases and can be approximated, now this theory is based on the fact that, if the rate of generation of heat between the contacts of circuit breaker is lower than the rate at which heat between the contact is dissipated, then the established arc shall be extinguished successfully. Thus if it is possible to remove the generated heat by cooling, lengthening and splitting the arc at a high rate the generation, arc can be extinguished.

2. *Voltage Race Theory*: The arc is due to the ionization of the gap between the contact of the circuit breaker. Thus the resistance at the initial stage is very small i.e. when the contact are closed and as the contact separates the resistance starts increasing. If we remove ions at the

initial stage either by recombining them into neutral molecules or inserting insulation at a rate faster than the rate of ionization, the arc can be interrupted. The ionization at zero current depends on the restriking voltage. The theory states that if the rate of rise of restriking voltage is lesser than the rate at which the dielectric strength of the medium increases, then the arc will be successfully extinguished.

Let us define an expression for restriking voltage. For loss-less or ideal system we have,

Here V = restriking voltage.

V = value of voltage at the instant of interruption.

L and C are series inductor and shunt capacitance up to fault point.

Thus from above equation we can see that lower the value of product of L and C , higher the value of restriking voltage.

Recovery process

$$L \frac{di}{dt} + \frac{1}{C} \int i dt = V_m \cos \omega t$$

Transient Recovery Voltage (TRV)

$$LC \frac{d^2 v_{TRV}}{dt^2} + v_{TRV} = V_m u(t)$$

$$v_{TRV} = V_m \left(1 - \cos \frac{t}{\sqrt{LC}}\right)$$

At $t = \pi\sqrt{LC}$, v_{TRV} doubles, arc initiates again sustain for longer time.

$$RRRV = \frac{d}{dt}(v_{TRV}) = \text{rate of rise of recovery voltage}$$

The value of RRRV w.r.t. the rate of rise of dielectric strength of medium will decide whether arc is re-struck or ignited or sustained for longer time.

$$v_{TRV} = V_m \left(1 - \cos \frac{t}{\sqrt{LC}}\right)$$

$$\frac{d}{dt}(v_{TRV}) = RRRV = \frac{V_m}{\sqrt{LC}} \sin \frac{t}{\sqrt{LC}}$$

At $t = \pi\sqrt{LC}$ v_{TRV} is maximum

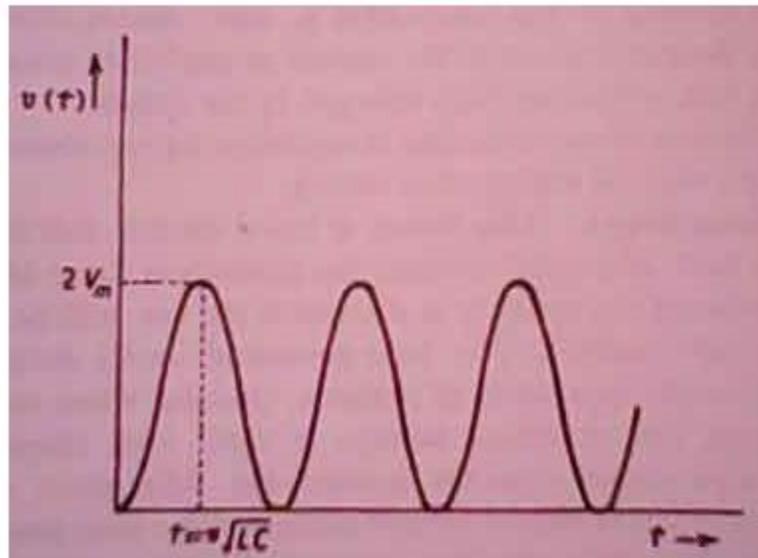
$$TRV_{\max} = 2V_m$$

$$RRRV_{\text{avg}} = \frac{2V_m}{\pi\sqrt{LC}}$$

$$RRRV_{\max} = \frac{V_m}{\sqrt{LC}}$$

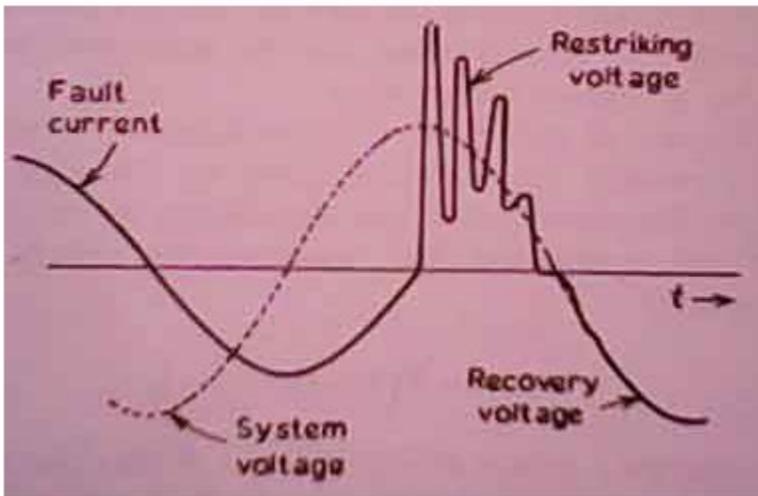
$$t \text{ at which } RRRV_{\max} \text{ occurs} = \frac{\pi}{2}\sqrt{LC}$$

The variation of V versus time is plotted below:

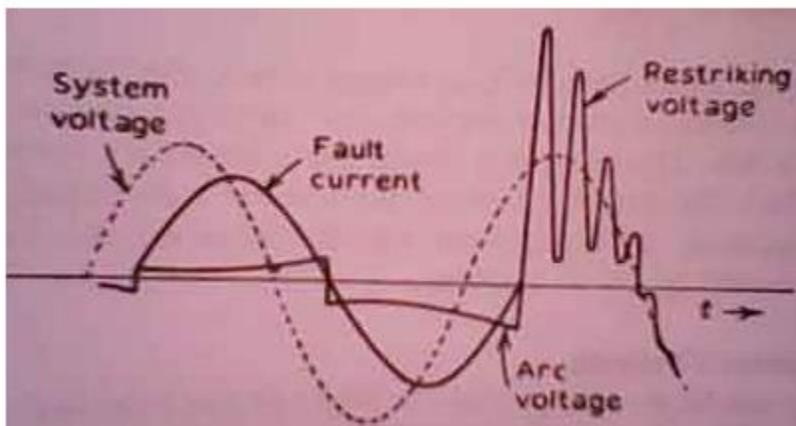


Restriking voltage across breaker contacts

Now let us consider a practical system, or assume there finite loss in the system. As shown in the figure below in this case the restriking voltage is damped out due to the presence of some finite resistance. Here it is assumed that the current lags behind the voltage by an angle (measured in degrees) of 90. However in practical situation angle may vary depending upon time in cycle at which the fault occurs.



Let us consider the effect of arc voltage, if arc voltage is included in the system, there is an increment in the restriking voltage. However this is offset by another effect of an arc voltage which opposes the current flow and making change in the phase of current, thus bringing it more into phase with the applied voltage. Hence the current is not at its peak value when voltage passes through zero value.



Rate of Rise of Restriking Voltage (RRRV): It is defined as the ratio of peak value of restriking voltage to time taken to reach to peak value. It is one of the most important parameter as if the rate at which the dielectric strength developed between the contacts is greater than RRRV, then the arc will be extinguishes.

Factor affecting TRV

1. Natural frequency of oscillation which depends on X_s of generator and the capacitance value of the breaker zone.

2. If the high power factor (p.f) of current load is delivered, then the severity is less.
3. Reactance drop i.e L affects frequency and voltage.
4. Armature reaction reduces TRV
5. Phase factor (more severe for first pole that is opened)

Re-ignition

If the C.B contact space breaks down within $1/4^{\text{th}}$ of natural frequency or if it takes more time or above $1/4^{\text{th}}$ of a cycle, it is restriking.

$$V_r = K_1 K_2 K_3 V_{\max} \sin\phi$$

K_1 = factor of demagnetization

K_2 = phase factor, 1.5 for first pole or 1 for other poles

K_3 = line or phase value, $\sqrt{3}$ or 1.

Arc extinction

1. Recombination
2. Diffusion: help in reducing ionisation
3. Drift: depends on density of the medium.

Arc current depends on external circuit condition. It does not depends on pole voltage from where it arises.

3.4 Rating of Circuit Breaker

The **rating of a circuit breaker** includes,

- 1) Rated short circuit breaking current.
- 2) Rated short circuit making current.
- 3) Rated operating sequence of circuit breaker.
- 4) Rated short time current.

3.4.1 Short circuit breaking current of circuit breaker

This is the maximum short circuit current which a circuit breaker can withstand before it. Finally cleared by opening its contacts. When a short circuit flows through a circuit breaker,

there would be thermal and mechanical stresses in the current carrying parts of the breaker. If the contact area and cross-section of the conducting parts of the circuit breaker are not sufficiently large, there may be a chance of permanent damage in insulation as well as conducting parts of the CB.

The short circuit current has a certain value at the instant of contact separation. The breaking current refers to value of current at the instant of the contact separation. The rated values of transient recovery voltage are specified for various rated voltage of circuit breakers. For specified conditions of rated TRV and rated power frequency recovery voltage, a circuit breaker has a certain limit of breaking current. This limit is determined by conducting short circuit type tests on the circuit breaker. The waveforms of short circuit current are obtained during the breaking test. The evaluation of the breaking current is explained in Fig. 3. The breaking current is expressed by two values. The *r.m.s* values of *a.c.* components are expressed in KA. the standard values being 8, 10, 12.5, 16, 20, 25, 31.5, 40, 45, 63, 80 and 100KA.

The earlier practice was to express the rated breaking capacity of a circuit breaker in terms of MVA given as follows

$$\text{Rated Breaking MVA capacity} = \sqrt{3} \times \text{KV} \times \text{KA}$$

Where MVA = Breaking capacity of a circuit breaker kV

KV = Rated voltage

KA = Rated breaking current

This practice of specifying the breaking capacity in terms of MVA is convenient while calculating the fault levels. However, as per the revised standards, the breaking capacity is expressed in KA for specified conditions of TRV and this method takes into account both breaking current and TRV. The breaking capacity can be both symmetrical and asymmetrical in nature. In asymmetrical breaking capacity the DC component of the current is added.

While selecting the circuit breaker for a particular location in the power system the fault level at that location is determined. The rated breaking current can then be selected from standard range.

3.4.2 Rated short circuit making capacity

The short circuit making capacity of circuit breaker is expressed in peak value not in rms value like breaking capacity. It may so happen that circuit breaker may close on an existing fault. In such cases the current increase to the maximum value at the peak of first current loop. The circuit breaker should be able to close without hesitation as contact touch. The circuit breaker should be able to withstand the high mechanical forces during such a closure. These capabilities are proved by carrying out making current test. The rated short circuit making current of a circuit breaker is the peak value of first current loop of short circuit current (I_{pk}) which the circuit breaker is capable of making at its rated voltage.

The rated short circuit making current should be least 2.5 times the r.m.s. value of a.c. component of rated breaking current .

$$\begin{aligned} \text{Rated making current} &= 1.8 \times \sqrt{2} \times \text{Rated short circuit breaking} \\ &= 2.5 \times \text{Rated short circuit breaking current} \end{aligned}$$

In the above equation the factor $\sqrt{2}$ convert the r.m.s value to peak value. Factor 1.8 takes into account the doubling effect of short circuit current with consideration to slight drop in current during the first quarter cycle .

3.4.3 Rated operating sequence or duty cycle of circuit breaker

This is mechanical duty requirement of circuit breaker operating mechanism. The sequence of rated operating duty of a circuit breaker has been specified as

$$O - t - CO - t' - CO$$

Where O indicates opening operation of the CB. CO represents closing operation immediately followed by an opening operation without any intentional time delay. t' is time between two operations which is necessary to restore the initial conditions and / or to prevent undue heating of conducting parts of circuit breaker. $t = 0.3$ sec for circuit breaker intended for first auto re closing duty, if not otherwise specified.

Suppose rated duty circle of a circuit breaker is $0 - 0.3 \text{ sec} - CO - 3 \text{ min} - CO$.

This means, an opening operation of circuit breaker is followed by a closing operation after a time interval of 0.3 sec, then the circuit breaker again opens without any intentional time delay. After this opening operation the CB is again closed after 3 minutes and then instantly trips without any intentional time delay.

3.4.4 *Rated short time current*

This is the current limit which a circuit breaker can carry safely for certain specific time without any damage.

The circuit breakers do not clear the short circuit current as soon as any fault occurs in the system. There always some intentional and an intentional time delays present between the instant of occurrence of fault and instant of clearing the fault by CB. This delay is present because of time of operation of protection relays, time of operation of circuit breaker and also there may be some intentional time delay imposed in relay for proper coordination of power system protection. Hence, after fault, a circuit breaker has to carry the short circuit for certain time. The summation of all time delays should not be more than 3 seconds, hence a circuit breaker should be capable of carrying a maximum fault current for at least this short period of time.

The short circuit current may have two major affects inside a circuit breaker.

1. Because of the high electric current, there may be high thermal stress in the insulation and conducting parts of CB.
2. The high short circuit current, produces significant mechanical stresses in differentcurrent carrying parts of the circuit breaker.

A circuit breaker is designed to withstand these stresses. But no circuit breaker has to carry a short circuit current not more than a short period depending upon the coordination of protection. So it is sufficient to make CB capable of withstanding affects of short circuit current for a specified short period.

The rated short time current of a circuit breaker is at least equal to rated short circuit breaking current of the circuit breaker.

3.4.5 *Rated voltage of circuit breaker*

Rated voltage of circuit breaker depends upon its insulation system. For below 400 KV system, the circuit breaker is designed to withstand 10% above the normal system voltage. For above or equal 400 KV system the insulation of circuit breaker should be capable of withstanding 5% above the normal system voltage. That means, rated voltage of circuit breaker

corresponds to the highest system voltage. This is because during no load or small load condition the voltage level of power system is allowed rise up to highest voltage rating of the system.

A circuit breaker is also subject to two other high voltage condition.

1) Sudden disconnection of huge load for any other cause, the voltage imposed on the CB and also between the contacts when the CB is open, may be very high compared to higher system voltage. This voltage may be of power frequency but does not stay for very long period as this high voltage situation must be cleared by protective switchgear.

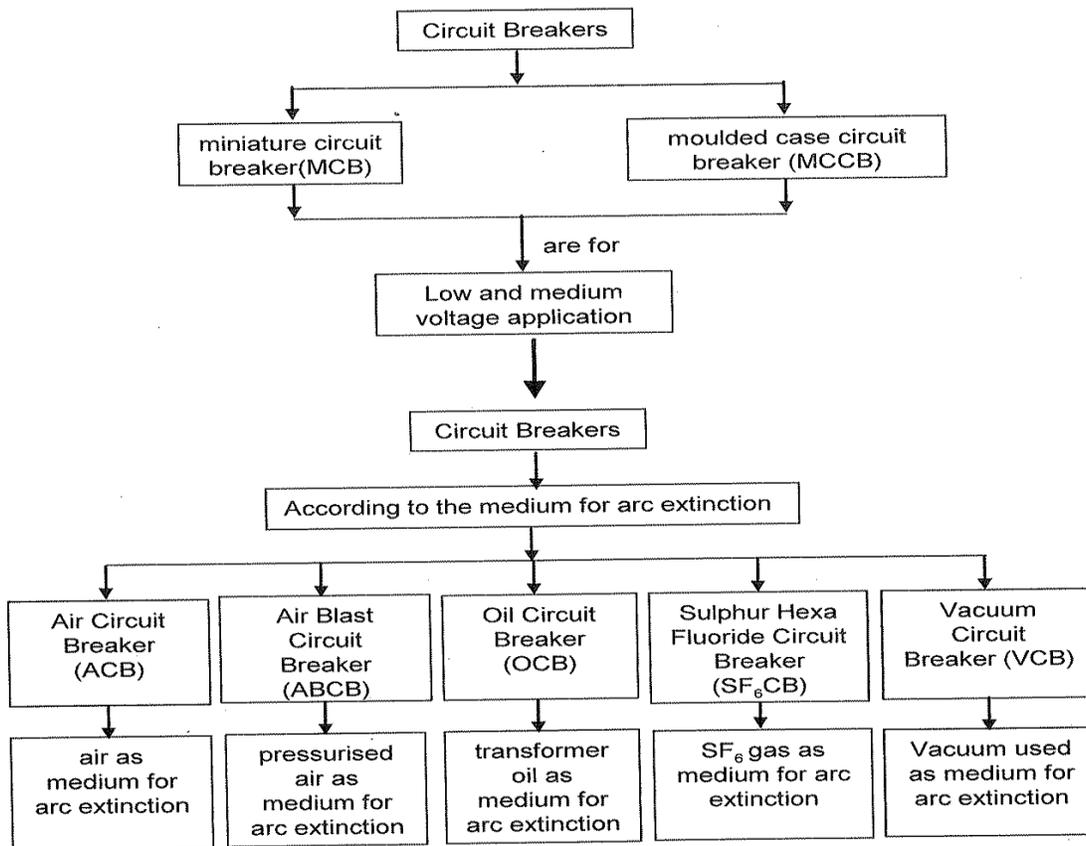
But a circuit breaker may have to withstand this power frequency over voltage, during its normal life span.

The Circuit Breaker must be rated for power frequencies withstand voltage for a specific time only. Generally the time is 60 seconds. Making power frequency withstand capacity, more than 60 second is not economical and not practically desired as all the abnormal situations of electrical power system are definitely cleared within much smaller period than 60 seconds.

2) Like other apparatuses connected to power system, a circuit breaker may have also to face lightening impulse and switching impulses during its life span.

The insulation system of CB has to withstand these impulse voltage waveform. So a circuit breaker is designed to withstand this impulse peaky voltage for microsecond range only.

NOMINAL SYSTEM VOLTAGE	HIGHEST SYSTEM VOLTAGE	POWER WITHSTAND	FREQUENCY VOLTAGE	IMPULSE VOLTAGE LEVEL
11 KV	12 KV	–	–	–
33 KV	36 KV	70 KV		170 KV
132 KV	145 KV	275 KV		650 KV
220 KV	245 KV	460 KV		1050 KV
400 KV	420 KV	–		–



3.5 Air Circuit Breaker and Air Blast Circuit Breaker

This type of circuit breakers, is those kind of circuit breaker which operates in air at atmospheric pressure. After development of oil circuit breaker, the medium voltage air circuit breaker (ACB) is replaced completely by oil circuit breaker in different countries. But in countries like France and Italy, ACBs are still preferable choice up to voltage 15 KV. It is also good choice to avoid the risk of oil fire, in case of oil circuit breaker. In America ACBs were exclusively used for the system up to 15 KV until the development of new vacuum and SF₆ circuit breakers.

3.5.1 Working principle of air circuit breaker(ACB)

The working principle of this breaker is rather different from those in any other types of circuit breakers. The main aim of all kind of circuit breaker is to prevent the reestablishment of arcing after current zero by creating a situation where in the contact gap will withstand the system recovery voltage. The air circuit breaker does the same but in different manner. For interrupting arc it creates an arc voltage in excess of the supply voltage. Arc voltage is defined as the minimum voltage required maintaining the arc. This circuit breaker increases the arc voltage by mainly three different ways,

1. It may increase the arc voltage by cooling the arc plasma. As the temperature of arc plasma is decreased, the mobility of the particle in arc plasma is reduced, hence more voltage gradient is required to maintain the arc.
2. It may increase the arc voltage by lengthening the arc path. As the length of arc path is increased, the resistance of the path is increased, and hence to maintain the same arc current more voltage is required to be applied across the arc path. That means arc voltage is increased.
3. Splitting up the arc into a number of series arcs also increases the arc voltage.

The *first objective* is usually achieved by forcing the arc into contact with as large an area as possible of insulating material. Every air circuit breaker is fitted with a chamber surrounding the contact. This chamber is called 'arc chute'. The arc is driven into it. If inside of the arc chute is suitably shaped, and if the arc can conform to the shape, the arc chute wall will help to achieve cooling. This type of arc chute should be made from some kind of refractory material. High temperature plastics reinforced with glass fiber and ceramics are preferable materials for making arc chute.

The *second objective* that is lengthening the arc path is achieved concurrently with the first objective. If the inner walls of the arc chute is shaped in such a way that the arc is not only forced into close proximity with it but also driven into a serpentine channel projected on the arc chute wall. The lengthening of the arc path increases the arc resistance.

The *third objective* is achieved by using metal arc splitter inside the arc chute. The main arc chute is divided into numbers of small compartments by using metallic separation plates. These metallic separation plates are actually the arc splitters and each of the small compartments behaves as individual mini arc chute. In this system the initial arc is split into a number of series

arcs, each of which will have its own mini arc chute. So, each of the arc splits has its own cooling and lengthening effect. This collectively, increases the overall arc voltage and helps in quenching.

3.5.2 Types of ACB

There are mainly two types of ACB are available.

1. Plain air circuit breaker.

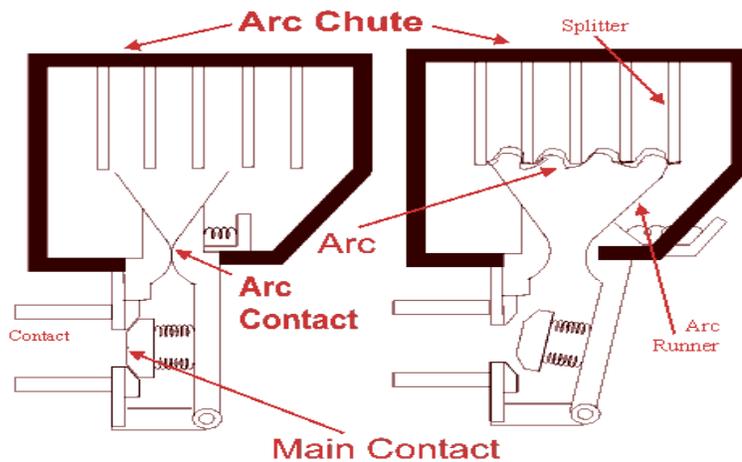
The above method explains the working principle of *plain break type* air circuit breakers.

2. Controlled Break Circuit breakers.

Operation of Controlled break ACB

The air circuit breaker, operated within the voltage level 1 KV, does not require any arc control device. Mainly for heavy fault current on low voltages (low voltage level above 1 KV) ABCs with appropriate arc control device, are good choice. These breakers normally have two pairs of contacts. The main pair of contacts carries the current at normal load and these contacts are made of copper. The additional pair is the arcing contact and is made of carbon. When circuit breaker is being opened, the main contacts open first and during opening of main contacts the arcing contacts are still in touch with each other. As the current gets, a parallel low resistive path through the arcing contact during opening of main contacts, there will not be any arcing in the main contact. The arcing is only initiated when finally the arcing contacts are separated. The arc contact is fitted with an arc runner which helps the arc discharge to move upward due to both thermal and electromagnetic effects as shown in the figure below. As the arc is driven upward it enters in the arc chute, consisting of splitters. The arc in chute will become colder, lengthen and split hence arc voltage becomes much larger than system voltage and therefore the arc is

quenched finally during the current zero.



Although this type of circuit breakers have become obsolete for medium voltage application, but they are still preferable choice for high current rating in low voltage application.

3.5.3 AIR BLAST CIRCUIT BREAKER

These types of air circuit breaker were used for the system voltage of 245 KV, 420 KV and even more, especially where faster breaker operation was required. Air blast circuit breaker has some specific *advantages* over oil circuit breaker which are listed as follows,

1. There is no chance of fire hazard caused by oil.
2. The breaking speed of circuit breaker is much higher during its operation.
3. Arc quenching is much faster.
4. The duration of arc is same for all values of small as well as high currents interruptions.
5. As the duration of arc is smaller, so lesser amount of heat is generated, which ensures longer service life of the contacts.
6. The stability of the system can be well maintained as it depends on the speed of operation.
7. Requires much less maintenance compared to oil circuit breaker.

Some of the *disadvantages* of using ABCB are as follows

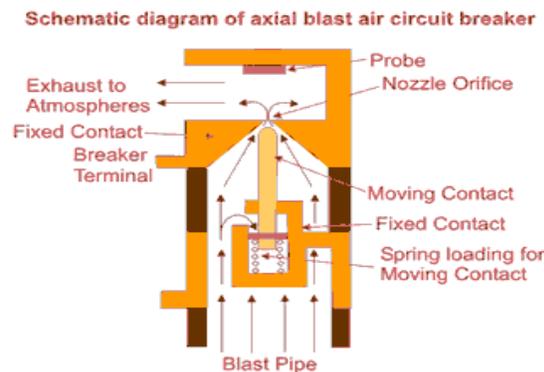
1. In order to have frequent operations, it is necessary to have sufficiently high capacity air compressor.

2. Frequent maintenance of compressor, associated air pipes and automatic control equipments is also required.
3. Due to high speed current interruption there is always a chance of high rate of rise of re-striking voltage and current chopping.
4. There also a chance of air pressure leakage from air pipes junctions.

As we said earlier that there are mainly two types of ACB, plain air circuit breaker and air blast circuit breaker. But the later can be sub divided further into three different categories.

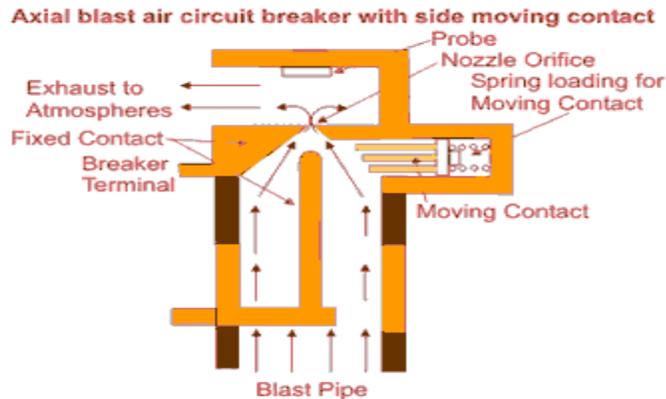
1. Axial Blast ACB.
2. Axial Blast ACB with side moving contact.
3. Cross Blast ACB.

1. AXIAL BLAST AIR CIRCUIT BREAKER



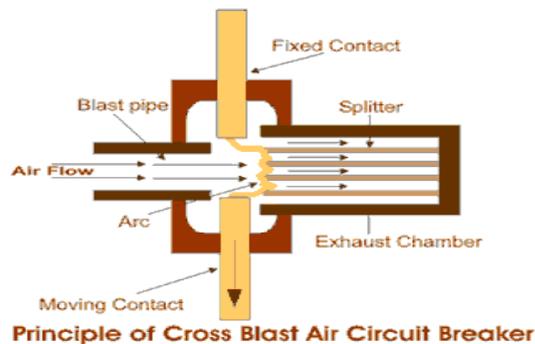
In axial blast ACB the moving contact is in contact with fixed contact with the help of a spring pressure as shown in the figure above. There is a nozzle orifice in the fixed contact which is blocked by tip of the moving contact at normal closed condition of the breaker. When fault occurs, the high pressure air is introduced into the arcing chamber. The air pressure will counter the spring pressure and deforms the spring hence the moving contact is withdrawn from the fixed contact and nozzle hole becomes open. At the same time the high pressure air starts flowing along the arc through the fixed contact nozzle orifice. This axial flow of air along the arc through the nozzle orifice will make the arc lengthen and colder hence arc voltage become much higher than system voltage that means system voltage is insufficient to sustain the arc consequently the arc is quenched.

2. AXIAL BLAST ACB WITH SIDE MOVING CONTACT



In this type of axial blast air circuit breaker, the moving contact is fitted over a piston supported over a spring. In order to open the circuit breaker the air is admitted into the arcing chamber when pressure reaches to a predetermined value, it presses down the moving contact. An arc is drawn between the fixed and moving contacts. The air blast immediately transfers the arc to the arcing electrode and is consequently quenched by the axial flow of air.

3. CROSS BLAST AIR CIRCUIT BREAKER



The working principle of cross blast air circuit breaker is quite simple. In this system, a pipe is fixed in perpendicular to the movement of moving contact in the arcing chamber and on the opposite side of the arcing chamber one exhaust chamber is also fitted at the same alignment of blast pipe, so that the air coming from blast pipe can straightly enter into exhaust chamber through the contact gap of the breaker. The exhaust chamber is split with arc splitters. When moving contact is withdrawn from fixed contact, an arc is established in between the contact, and at the same time high pressure air coming from blast pipe will pass through the contact gap

radially, and the high pressure air blast will forcefully take the arc into exhaust chamber where the arc is split with the help of arc splitters and ultimately arc is quenched.

3.6 Oil Circuit Breaker

Oil Circuit Breakers are generally of two types and they are

- i) Bulk Oil type or the Dead tank type (OCB)
- ii) Minimum Oil Circuit Breaker(MOCB)

3.6.1. Bulk Oil type or the Dead tank type (OCB)

The bulk oil circuit breakers are those which use large volumes of oil for two specific purposes. These oils need large tanks which solve the purpose of arc quenching chamber. The oil is used for

- a) Providing insulation from the live current carrying contacts
- b) Serving as a medium of arc quenching.

The tank, that houses the current carrying contacts, is at ground potential. When the moving contacts open to initiate the circuit breaking process, an arc is struck inside the oil medium. Due to oil heating, it vapourizes to produce hydrogen and other hydrocarbon gases. These gases generate high pressure in the vicinity of the arc and cool it. Subsequently, the arc can't sustain itself and gets quenched.

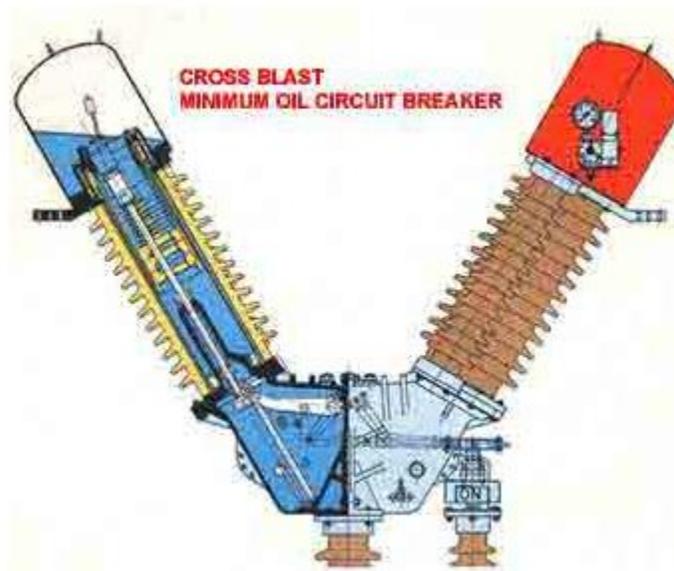
3.6.2. Minimum Oil Circuit Breaker (MOCB)

These types of circuit breakers utilize oil as the interrupting media. However, unlike bulk oil circuit breaker, a minimum oil circuit breaker places the interrupting unit in insulating chamber at live potential. The insulating oil is available only in interrupting chamber. The features of designing MOCB is to reduce requirement of oil, and hence these breaker are called minimum oil circuit breaker.

As the volume of the oil in bulk oil circuit breaker is huge, the chances of fire hazard in bulk oil system are more. For avoiding unwanted fire hazard in the system, one important development in the design of oil circuit breaker has been introduced where use of oil in the circuit breaker is much less than that of bulk oil circuit breaker. It has been decided that the oil in the circuit breaker should be used only as arc quenching medium, not as an insulating media. In this type of circuit breaker the arc interrupting device is enclosed in a tank of insulating material which as a whole is at live potential of system. This chamber is called arcing chamber or interrupting pot. The gas pressure developed in the arcing chamber depends upon the current to

be interrupted. Higher the current to be interrupted causes larger the gas pressure developed inside the chamber, hence better the arc quenching. But this puts a limit on the design of the arc chamber for mechanical stresses. With use of better insulating materials for the arcing chambers such as glass fiber, reinforced synthetic resin etc, the minimum oil circuit breaker are able to meet easily the increased fault levels of the system.

Working principle or arc quenching in minimum oil circuit breaker



Working Principle of minimum oil circuit breaker is described below. In a minimum oil circuit breaker, the arc is drawn across the current carrying contacts is contained inside the arcing chamber. Hence the hydrogen bubble formed by the vaporized oil is trapped inside the chamber. As the contacts continue to move, after its certain travel an exit vent becomes available for exhausting the trapped hydrogen gas. There are two different types of arcing chambers, available in terms of *venting*. One is axial venting and other is radial venting. In axial venting, gases (mostly Hydrogen), produced due to vaporization of oil and decomposition of oil during arc, will sweep the arc in axial or longitudinal direction.

Let's have a look on working principle Minimum Oil Circuit Breaker with axial venting arc chamber. The moving contact has just been separated and arc is initiated in MOCB.

The ionized gas around the arc sweeps away through upper vent and cold oil enters into the arcing chamber through the lower vent in axial direction as soon as the moving contact tip crosses the lower vent opening and final arc quenching in minimum oil circuit breaker occurs

The cold oil occupies the gap between fixed contact and moving contact and the minimum oil circuit breaker finally comes into open position.

Whereas in case of radial venting or cross blast, the gases sweeps the arc in radial or transverse direction. The axial venting generates high gas pressure and hence has high dielectric strength, so it is mainly used for interrupting low current at high voltage.

On the other hand radial venting produces relatively low gas pressure and hence low dielectric strength so it can be used for low voltage and high current interruption. Many times the combination of both is used in minimum oil circuit breaker so that the chamber is equally efficient to interrupt low current as well as high current. These types of circuit breaker are available up to 8000 MVA at 245 KV.

3.7 Vacuum Circuit Breaker or VCB

A vacuum circuit breaker is such kind of circuit breaker where the arc quenching takes place in vacuum. The technology is suitable for mainly medium voltage application. For higher voltage vacuum technology has been developed but not commercially viable. The operation of opening and closing of current carrying contacts and associated arc interruption take place in a vacuum chamber in the breaker which is called vacuum interrupter. The vacuum interrupter consists of a steel arc chamber in the centre symmetrically arranged ceramic insulators. The vacuum pressure inside a vacuum interrupter is normally maintained at 10^{-6} bar.



The material used for current carrying contacts plays an important role in the performance of the Vacuum circuit breaker. Cu-Cr is the most ideal material to make VCB

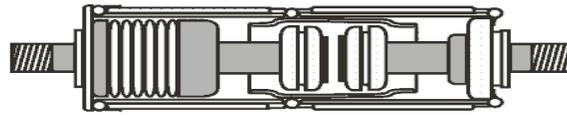
contacts. Vacuum interrupter technology was first introduced in the year of 1960. But still it is a developing technology. As time goes on, the size of the vacuum interrupter is being reduced from its early 1960's size due to different technical developments in this field of engineering. The contact geometry is also improving with time, from butt contact of early days it gradually changes to spiral shape, cup shape and axial magnetic field contact. The vacuum circuit breaker is today recognized as most reliable current interruption technology for medium voltage switchgear. It requires minimum maintenance compared to other circuit breaker technologies.

3.7.1. Advantages of vacuum circuit breaker or VCB

Service life of vacuum circuit breaker is much longer than other types of circuit breakers. There is no chance of fire hazard as oil circuit breaker. It is much environment friendly than SF₆ Circuit breaker. Besides, the contraction of VCB is much user friendly. Replacement of vacuum interrupter (VI) is much convenient.

3.7.2 Operation of vacuum circuit breaker

The main aim of any circuit breaker is to quench arc during current zero crossing, by establishing high dielectric strength in between the contacts so that reestablishment of arc after current zero becomes impossible. The dielectric strength of vacuum is eight times greater than that of air and four times greater than that of SF₆ gas. This high dielectric strength makes it possible to quench a vacuum arc within very small contact gap. For short contact gap, low contact mass and no compression of medium the drive energy required in vacuum circuit breaker is minimum. When two face to face contact areas are just being separated to each other, they are not done so instantly. Instead, as the contact area on the contact face is being reduced and ultimately comes to a point and then they are finally de-touched. This happens in a fraction of micro second. At this instant of de-touching of contacts in a vacuum, the current through the contacts concentrated on that last contact point on the contact surface and makes a hot spot there. As the medium is vacuum, the metal on the contact surface gets easily vaporized due to that hot spot and create a conducting media for arc path. Therefore, the material constituting the arc is very small and thus a feeble arc is established even with high current interruption. The arc will be initiated and continues until the onset of next current zero. Th figure below shows the cross section assembly of a VCB.



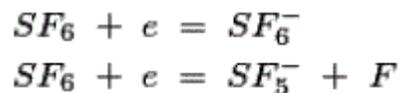
Cross section of Vacuum Interrupter

At current zero this vacuum arc is extinguished and the conducting metal vapor is re-condensed on the contact surface. At this point, the contacts are already separated hence there is no question of re-vaporization of contact surface, for next cycle of current. That means, the arc cannot be reestablished again. In this way vacuum circuit breaker prevents the reestablishment of arc by producing high dielectric strength in the contact gap after current zero.

There are two types of arc shapes. For interrupting current up to 10 kA, the arc remains diffused and the form of vapor discharge and cover the entire contact surface. Above 10 kA the diffused arc is constricted considerably by its own magnetic field and the contracts. The phenomenon gives rise to over heating of contacts at its center. In order to prevent this, the design of the contacts should be such that the arc does not remain stationary but keeps travelling by its own magnetic field. Specially designed contact shape of vacuum circuit breaker makes the constricted stationary arc travel along the surface of the contacts, thereby causing minimum and uniform contact erosion.

3.8 SF₆ Circuit Breaker

A circuit breaker in which the current carrying contacts operate in sulphur hexafluoride or SF₆ gas is known as an *SF₆ circuit breaker*. SF₆ has excellent insulating property and it has a high electro-negativity. Therefore, it has high affinity of absorbing free electrons. Whenever a free electron collides with the SF₆ gas molecule, it is absorbed by that gas molecule and forms a negative ion with the following processes.



These negative ions are much heavier than a free electron and therefore the over all mobility of the negatively charged particle in the medium is considerably reduced compared to

other gases. As the mobility of charged particle is reduced, therefore the severity of arcing shall also be affected and reduced.



Hence, for heavier and less mobile charged particles in SF₆ gas, it acquires very high dielectric strength. Not only the gas has a good dielectric strength but also it has the unique property of fast recombination after the process of arcing is completed. The gas also has a very good heat transfer property. Due to its low gaseous viscosity (because of less molecular mobility) SF₆ gas can efficiently transfer heat by convection. So due to its high dielectric strength and high cooling effect SF₆ gas is approximately 100 times more effective arc quenching medium compared to air. Due to these unique properties of this gas, SF₆ circuit breaker is used in complete range of medium voltage and high voltage electrical power system. These circuit breakers are available for the voltage ranges from 33KV to 800KV and even more.

3.8.1 Disadvantages of SF₆ CB

The SF₆ gas is identified as a greenhouse gas, safety regulation are being introduced in many countries in order to prevent its release into atmosphere.

Puffer type design of SF₆ CB needs a high mechanical energy which is almost five times greater than that of oil circuit breaker.

3.8.2 Types of sf₆ circuit breaker

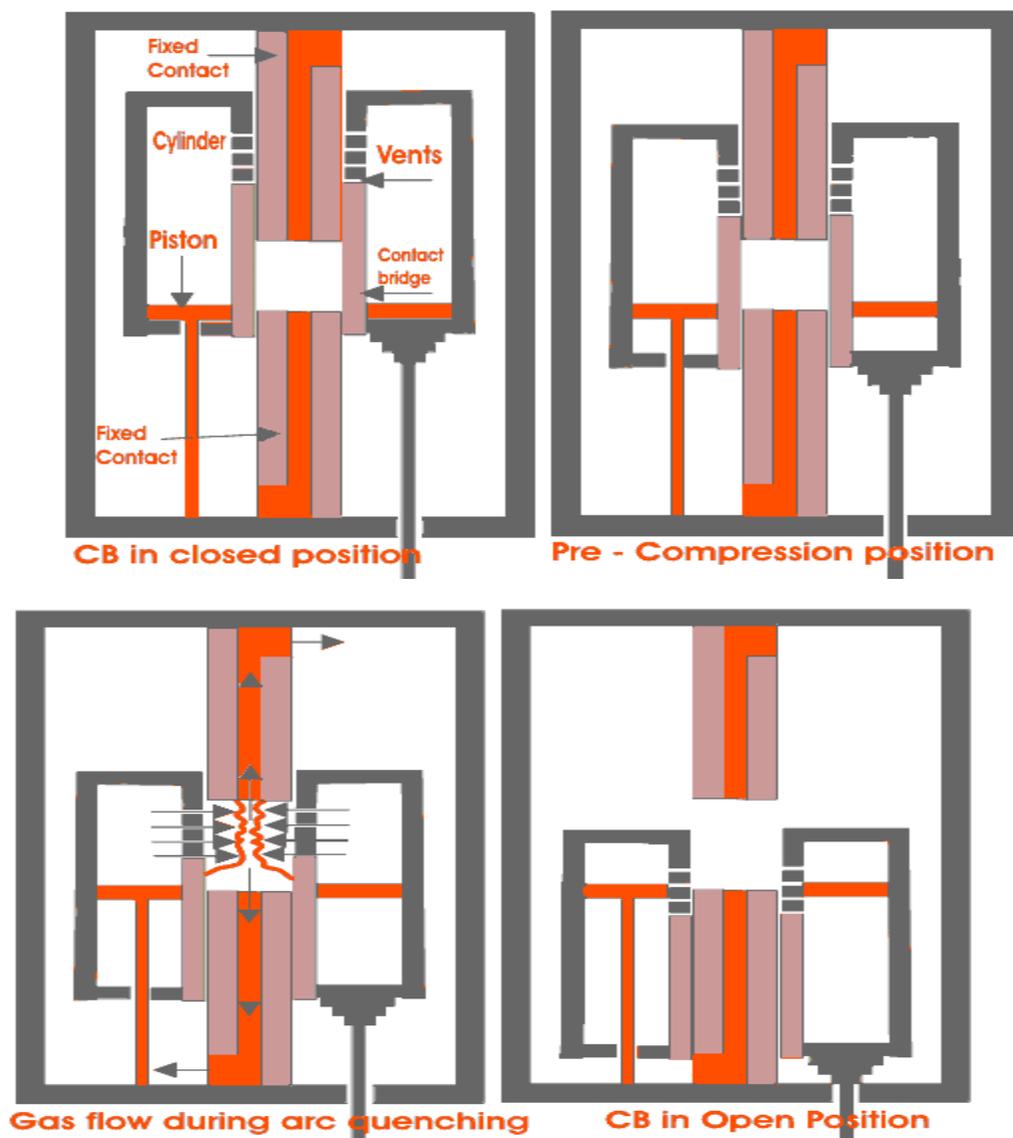
There are mainly three types of SF₆ CB depending upon the voltage level of application-

1. Single interrupter SF₆ CB applied for up to 245 KV(220 KV) system.
2. Two interrupter SF₆ CB applied for up to 420 KV(400 KV) system.

3. Four interrupter SF₆ CB applied for up to 800 KV(715 KV) system.

3.8.3 Working of SF₆ circuit breaker

The working of SF₆ CB of first generation was quite simple it is some extent similar to air blast circuit breaker. Here SF₆ gas was compressed and stored in a high pressure reservoir. During operation of SF₆ circuit breaker this highly compressed gas is released through the arc in breaker and collected to relatively low pressure reservoir and then it pumped back to the high pressure reservoir for re utilize.



The working of SF₆ circuit breaker is little bit different in modern time. Innovation of

Puffer type design makes operation of SF₆ CB much easier. In *Puffer* type design, the arc energy is utilized to develop pressure in the arcing chamber for arc quenching.

Here the breaker is filled with SF₆ gas at rated pressure. There are two fixed contact fitted with a specific contact gap. A sliding cylinder bridges these to fixed contacts. The cylinder can axially slide upward and downward along the contacts. There is one stationary piston inside the cylinder which is fixed with other stationary parts of the SF₆ circuit breaker, in such a way that it cannot change its position during the movement of the cylinder. As the piston is fixed and cylinder is movable or sliding, the internal volume of the cylinder changes when the cylinder slides.

During opening of the breaker the cylinder moves downwards against position of the fixed piston hence the volume inside the cylinder is reduced which produces compressed SF₆ gas inside the cylinder. The cylinder has numbers of side vents which were blocked by upper fixed contact body during closed position. As the cylinder move further downwards, these vent openings cross the upper fixed contact, and become unblocked and then compressed SF₆ gas inside the cylinder will come out through this vents in high speed towards the arc and passes through the axial hole of the both fixed contacts. The arc is quenched during this flow of SF₆ gas.

During closing of the circuit breaker, the sliding cylinder moves upwards and as the position of piston remains at fixed height, the volume of the cylinder increases which introduces low pressure inside the cylinder compared to the surrounding. Due to this pressure difference SF₆ gas from surrounding will try to enter in the cylinder. The higher pressure gas will come through the axial hole of both fixed contact and enters into cylinder via vent and during this flow; the gas will quench the arc.

3.9 D.C circuit breakers

It is well known that DC has no natural current zero. Therefore, the current either needs to reduced, by lengthening of the arc or cooling or by forced reduction of the current to zero. For lower voltage cases, a simple resistance and inductive coil connected across a switch forces the current to reduce to zero. Such a scheme is particularly being successful when the current magnitude is small. For higher voltage and current cases, a method that combines forced current reduction and grid control mechanism is applied.

Forced reduction of current zero: In this method an oscillatory LC network is utilized to let an oscillatory current flow in opposite direction to that of the direct current (DC). The moment the oscillatory current magnitude exceeds the DC value, the breaker current falls to zero temporarily. This helps in quenching the arc. The peak oscillatory current of the LC circuit should be more than the DC value through the breaker. The scheme operation can be understood from the figure given below. A normally open (NO) and a Normally Closed (NC) auxiliary breakers are utilized to discharge and charge the capacitor of the LC unit. The capacitor first is charged to line voltage through the L and R through the NC breaker. At the desired instant of main C.B opening, the capacitor discharges through the L when, the NO breaker becomes closed and NC becoming open.

In this scheme, the value of C is so chosen that, the rise time constant of the line voltage is smaller than the charging time constant of C, which ensures that the voltage across the C is maintained for longer time. Similarly the value of L is so chosen that, the rise time constant of the line current should be more than the changing time constant of the oscillatory current, which ensures that the oscillatory current reaches the load current quickly.

Method of Grid Control: All transient faults which die out immediately, can be controlled by method of grid control. In this method the faults can be switched out gradually in an artificial manner by forcing the whole system voltage to reduce to zero temporarily, with the help of converter grid control. Fast acting isolating switches are then used to isolate the faults. With this method also the short circuit current magnitude can be reduced considerably to levels much below the full, load levels so that severity of the fault can be reduced. This partial current reduction method is sufficient in the case of unsustained faults.

3.9.1 Miniature circuit breaker or MCB

Nowadays we use more commonly miniature circuit breaker or *MCB* in low voltage electrical network instead of fuse. The MCB has some advantages compared to the fuse.

1. It automatically switches off the electrical circuit during abnormal condition of the network means in over load condition as well as faulty condition. The fuse does not sense but miniature circuit breaker does it in more reliable way. MCB is much more sensitive to over current than fuse.

2. Another advantage is, as the switch operating knob comes at its off position during tripping, the faulty zone of the electrical circuit can easily be identified. But in case of fuse, fuse wire should be checked by opening fuse grip or cutout from fuse base, for confirming the blow of fuse wire.
3. Quick restoration of supply cannot be possible in case of fuse as because fuses have to be rewired or replaced for restoring the supply. But in the case of MCB, quick restoration is possible by just switching on operation.
4. Handling MCB is more electrically safe than fuse.

Because of many advantages of MCB over fuse units, in modern low voltage electrical network, miniature circuit breaker is mostly used instead of backdated fuse unit.

Only one disadvantage of MCB over fuse is that this system is more costlier than fuse unit system.



Miniature Circuit Breaker

Working principle MCB

There are two arrangement of operation of miniature circuit breaker. One due to thermal effect of over current and other due to electromagnetic effect of over current. The thermal operation of miniature circuit breaker is achieved with a bimetallic strip whenever continuous over current flows through MCB, the bimetallic strip is heated and deflects by bending. This deflection of bimetallic strip releases mechanical latch. As this mechanical latch is attached with operating mechanism, it causes to open the miniature circuit breaker contacts. But during short circuit condition, sudden rising of current, causes electromechanical displacement of plunger associated with tripping coil or solenoid of MCB. The plunger strikes the trip lever

causing immediate release of latch mechanism consequently open the circuit breaker contacts. This was a simple explanation of miniature circuit breaker working principle.

Miniature circuit breaker construction

Miniature circuit breaker construction is very simple, robust and maintenance free. Generally a MCB is not repaired or maintained, it just replaced by new one when required. A miniature circuit breaker has normally three main constructional parts. The primary one is its frame and the other two parts are as follows

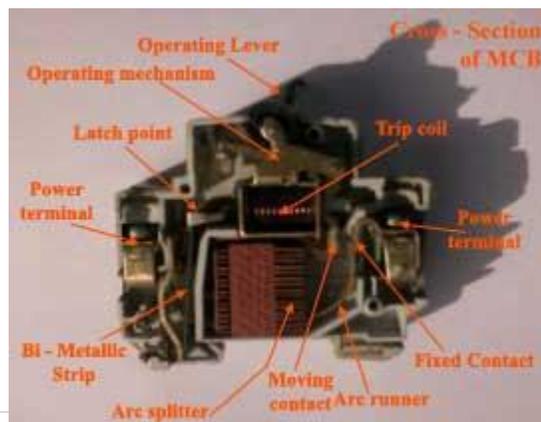
Operating mechanism of miniature circuit breaker

The operating mechanism of miniature circuit breaker provides the means of manual opening and closing operation of miniature circuit breaker. It has three-positions “ON,” “OFF,” and “TRIPPED”. The external switching latch can be in the “TRIPPED” position, if the MCB is tripped due to over-current. When manually switch off the MCB, the switching latch will be in “OFF” position. In close condition of MCB, the switch is positioned at “ON”. By observing the positions of the switching latch one can determine the condition of MCB whether it is closed, tripped or manually switched off.

The TRIP Unit of the MCB

The trip unit is the main part, responsible for proper working of miniature circuit breaker. Two main types of trip mechanism are provided in MCB. A bimetal provides protection against over load current and an electromagnet provides protection against short-circuit current.

OPERATION OF MINIATURE CIRCUIT BREAKER



There are three mechanisms provided in a single miniature circuit breaker to make it switched off. If we carefully observe the picture beside, we will find there are mainly one bi – metallic strip, one trip coil and one hand operated on – off lever. Electric current carrying path of a miniature circuit breaker shown in the picture is like follows. First left hand side power terminal – then bimetallic strip – then current coil or trip coil – then moving contact – then fixed contact and – lastly right had side power terminal. All are arranged in series.

Miniature Circuit Breaker

If circuit is overloaded for long time, the bi – metallic strip becomes over heated and deformed. This deformation of bi metallic strip causes, displacement of latch point. The moving contact of the MCB is so arranged by means of spring pressure, with this latch point, that a little displacement of latch causes, release of spring and makes the moving contact to move for opening the MCB. The current coil or trip coil is placed such a manner that during short circuit fault the *mmf* of that coil causes its plunger to hit the same latch point and make the latch to be displaced. Hence the MCB will open in same manner. Again when operating lever of the miniature circuit breaker is operated by hand, that means when we make the MCB at off position manually, the same latch point is displaced as a result moving contact separated from fixed contact in same manner. So, whatever may be the operating mechanism from either of the three possibilities, such as deformation of bi – metallic strip, increased *mmf* of trip coil and/or manual operation, the same latch point is displaced and the deformed spring is released, which ultimately responsible for movement of the moving contact. When the moving contact separated from fixed contact, there may be a high chance of arc. This arc then goes up through the arc runner and enters into arc splitters and is finally quenched. When we switch on an MCB, we actually reset the displaced operating latch to its previous on position and make the MCB ready for another switch off or trip operation.

3.10 HRC Fuse or High Rupturing Capacity Fuse

HRC fuse or high rupturing capacity fuse is a type of fuse whose wire or element can carry short circuit heavy current for a known time period. During this time if the fault is removed, then it does not blow off otherwise it blows off or melts.

The enclosure of HRC fuse is either of glass or some other chemical compound. This enclosure is fully air tight to avoid the effect of atmosphere on the fuse materials. The ceramic enclosure having metal end cap at both heads, to which fusible silver wire is welded. The space within the enclosure, surrounding the fuse wire or fuse element is completely packed with a filling powder. This type of fuse is reliable and has inverse time characteristic, that means if the fault current is high then rupture time is less and if fault current is not so high then rupture time is long.

3.10.1 Operation of HRC fuse

When the over rated current flows through the fuse element of high rupturing capacity fuse the element is melted and vaporized. The filling powder is of such a quantity that the chemical reaction between the silver vapour and the filling powder forms a high electrical resistance substance which very much help in quenching the arc.

MODULE-IV

OUTLINE OF LESSON

- 4.1 Static relays**
- 4.2 Numerical protection**
- 4.3 Digital Relay**
- 4.4 Testing and Maintenance of Protective grears**
- 4.5 Protection against Surges**

4.1 Static relays

4.1.1 Advantages of static relays

- Due to the amplification of energizing signals obtainable, the sources need only provide low power. Therefore the size of the associated current and voltage transformers could be reduced.
- Improved accuracy and selectivity.
- Fast operation of relays and hence fast clearance of faults.
- Flexibility of circuitry would allow new and improved characteristics.
- The relays would be unaffected by the number of operations.

4.1.2 Basic circuits employed

- Timers
- Phase comparators
- Amplitude Comparator
- Level detectors
- Integrators
- Polarity detectors

High reliability operational amplifiers are used for realizing the basic components of static relays.

4.2 Numerical protection

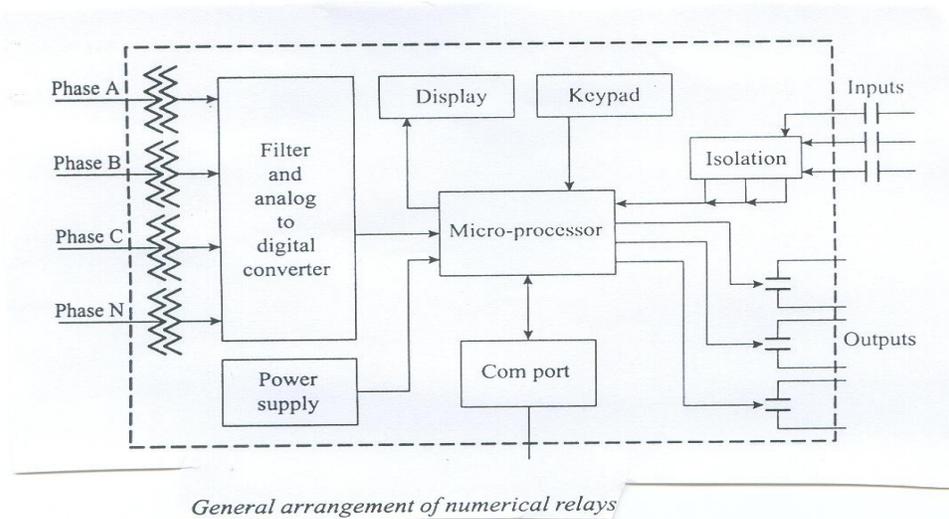
Numerical relays are technically superior to the conventional type relays. Their general characteristics are :

- Reliability
- Self diagnosis
- Event and disturbance records
- Adaptive Protection

- Integration of Digital Systems

4.2.1 Typical architecture of numerical relays

Numerical relays are made up from modules with well defined functions.



The use of algorithm of fault diagnosis, with the help of numerical relays can be understood clearly from the following development steps.

1. State the relaying problem.
2. Model the relaying problem mathematically
3. Write the algorithm.
4. Convert the algorithm to a high level language.
5. Test with a simulated data and modify the algorithm if required.
6. Generate the machine language code for the Micro processor/ Digital controller
7. Download it for the numerical relay
8. Test with a relay test bench. If found o.k. install it in parallel with the existing relay. Otherwise go back to step 3 to modify the algorithm and repeat the process.
9. Evaluate with various testing for longer period and launch it commercially if found o.k in its operation after operation of 2 years independently.

4.3 Digital Relays

- The digital relay does not record the analog signal, but only samples of the signal, which are spread in time.
- the mathematics of discrete signal processing is used.
- The relay is programmed to apply various forms of digital signal processing algorithms to the observed samples and based on the results of these computations, the decision to trip is made.

4.3.1 *Different components of a digital relay*

- i) Isolation transformer and surge protection circuit
- ii) Multiplexor and S/H circuits
- iii) Anti Aliasing Filters
- iv) Digital Input and Output systems.
- v) Central Processing unit
- vi) Event Storage system
- vii) Signal conditioning circuit.
- viii) Communication Peripherals
- ix) Power Supply Block
- x) Sampling Clock

Isolation transformer and surge protection circuit:

Since the digital circuits are highly vulnerable to switching and lightning surge therefore, proper isolation of the circuits with isolation transformer and surge protection circuit is required.

Multiplexors and S/H Circuits:

Multiplexors and sample and hold (S/H) circuits are required for converting the analog signals to digital. The widely accepted Shannon's sampling theorem is used for sampling the analog signal.

Anti Aliasing Filter

The anti aliasing filters are basically low pass filters which block unwanted frequencies.

The Digital input output system

This system actually gathers data and status reports of C.B. contacts status, other relay states, reset signals etc. Also the output systems generate and provide the tripping, alarm and any other control signal.

Central Processing Unit

It is the core component of the system which performs all the logics and algorithms regarding different characteristics, maintains timing function and communicates with the external device. Therefore, this the most vital block of the numerical system.

Event Storage System, RAM, ROM, EPROM:

The RAM store the input sample data temporarily and buffer data permanently. It is processed during the execution of relay algorithm. The ROM stores the relay algorithm permanently. EPROM is used to store certain parameters such as the relay setting, or any other relevant data. The event storage system basically stores the historical data such as fault related data, transient data, event time data.

Communication Peripherals:

The relay setting, data uploading and event data recording are done through various communication peripherals following a protocol IEC61850, which increases inner coordination between the relays among the local and remote substation equipment.

Power Supply

It is powered by local station battery provided with charger.

4.4 Testing Commissioning and Maintenance of Protective Gears

Testing: There are three types of tests to be performed on protective gears and they are

- i) Type Test
- ii) Acceptance & Commissioning test
- iii) Maintenance Schedule

4.4.1 Type test: This test is meant for the manufacturers to guarantee quality and reliability of the protection system. Several tests come under this category and they are as follows

- a) Operating Value test

The operating quantities true relay operational value is tested. Quantities like Voltage , currents, frequency, preset & operating values are tested & compared. A $\pm 10\%$ difference may be allowed depending upon the imporatnce.

b) Operating Time test

It is time from which relay coil is energised to the time at which the contacts operate. Different range of errors from $\pm 5\%$ to $\pm 12\%$ may be allowed for different range of operating quantities. For example in an IDMT relay for higher PSM lesser allowable errors are allowed.

c) Reset Value/Time Test:

Reset value is defined as the percentage of the nominal set value. In this test the actuating quantity is first increased so that relay remains in ON state & then gradually the value is reduced & the mark at which the relay stops operating is noted down. For finding the *reset time* the actuating quantity is suddenly removed.

d) Temperature Rise Test: Checks the withstand capacities of insulation used in relays against temperature rise slightly above the operating value of the relay.

e) Contact Capacity Test : As the contacts of the relay actuate the tripping coil of the circuit breaker. So the making and breaking capacities of the same are determined using appropriate resistive and inductive loading at a low *p.f.* of 0.4.

f) Over Load Test: In this test above 10 to 20 times the maximum Pick up value of the relay is passed through the relay. For example in the case of an IDMT type over current relay 20 times the pick up value is passed with maximum possible TMS & continuous current carrying capacity of the relay is observed.

g) Mechanical Test: Several hundred to thousand operations are repeated under over setting of the relay and particularly the electro mechanical types of relay are tested for any damage & maloperation of parts.

4.4.2 Commissioning and Acceptance Test:

Such Tests are also done at the manufactureres site to verify the performance of the relay as per the declared and agrred customers' specifications along with relevent standards.

a) *Insulation Resistance Test:*

Initially all the earth resistances are removed. A 500 V megger is used to measure the insulation resistance to earth of the instrument transformers, which connect the higher rating power lines. The typical value should be 5 M Ω .

b) *Primary Injection Test:* This test ensures the correct installation of the entire protection system. This test however, is done after the Secondary injection tests are completed. This test involves testing of CT/PT, secondary winding, relay coil, trip and alarm circuit and all the intervening wiring circuits. A portable Injection transformer is used which contains several low voltage (10 to 20 V) high current windings, which can

be connected in series and parallel. A high current upto 1 KA from a 10 KVA injection kit is made to pass through various circuits for testing.

- c) *Secondary Injection Test:* This test is done before the primary injection test. This test ensures that the relay is properly calibrated when tested after injecting current. Separate testing contacts are provided in the relay.
- d) *Tripping Test:* After the secondary and primary injection tests are over, the proper sequence of operation of the system till the C.B contacts gets tripped are needed to be verified. All the flags & contacts are checked again for their correct sequence of operation. This is important, as during the injection tests the whole sequence of operation was not tested.
- e) *Impulse Test:* This test is more often required for Distance relays. As per the recommendations of the International Electrotechnical Commission (IEC), any transient wave of exponential nature with peak value of 1 to 5 KV & rise time of 1.2 ms & fall time of 60 μ sec is applied & it is tested that the components of the relay must withstand it.

4.4.3 Maintenance Schedule

The maintenance schedule is required to ensure that the protection system senses the fault accurately and operates immediately with desired speed. The need of routine maintenance is felt due to the following reasons.

1. Continuous vibration of the electromechanical types of relays.
2. Insulation resistance reduced after being affected by humidity.
3. Relay contacts, ligaments corrosion due to pollution and continuous operation.
4. Possibility of open circuiting of the coils due to contact electrolysis which causes green spots.

The frequency of routine maintenance varies and depends upon the fault history of the relay and its vulnerability. Some examples of different frequencies of maintenance schedule is given below.

- a) Continuous Checking : 1) Pilot Supervision 2) Trip Circuit 3) Relay Voltage 4) Battery Earth fault 5) CT and supervision of busbars.
- b) Daily: All the relay flags. If Carrier current protection is used, then daily tests are mandatory.
- c) Monthly: Water Level of liquid earthing resistance.
- d) Bimonthly: Channel Tests

- e) Half Yearly: All tripping tests
- f) Yearly: Operating level, Sensitivity, tripping angle, secondary Injection test, Insulation resistance test, Inspection of Gas and oil actuated relays, Battery biasing equipments etc.
- g) Records: It is extremely important to record all data related to test results and any operational data for referring in future.

4.5 Surge Protection

It is well known that surge voltage in a power system is caused due to 2 reasons

- i) Internal overvoltage
- ii) External overvoltage condition

Internal Overvoltage:

Stationary overvoltage may occur due to prolonged single phase to ground fault, with the neutral is either grounded through a arc suppression coil. It may also happen due to current chopping.

External Overvoltage:

Due to atmospheric discharge through static charge or lightening strokes this type of overvoltage may occur.

To protect the switch gear and protection system from this condition, some special precaution may be taken. Before discussing about the schemes of protection, it is important to understand the concept of surge first.

The Concept of Surge:

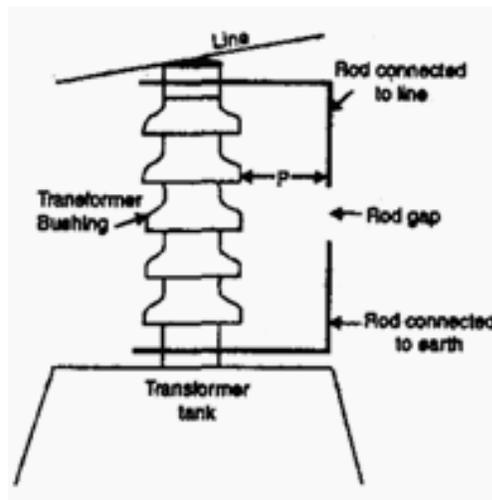
When a lightening surge or internal overvoltage condition strikes the end point of a transmission line it releases charge on the line and depending upon the inductance of the transmission line a voltage wave that is proportional to the charge density and a current wave travel over the line. Depending upon the L and C values of the line, the shape of the wave front of the voltage wave will be decided. So, more the L value, a steeper wave front will be available. The value of C of the line to ground impedance of the line, several bushings, insulators etc., decide the shape of the wave front. Moreover, when such an wave front strikes an open ended line, then the reflective wave front shall double up depending upon the amount of charge in the surge impedance.

To protect such surges, two stages of defense is provided. They are discussed below

- a) Earthing Screens: This is the first line of defense provided, and they are like ground wires, sheets, provided over transmission line, substation buses, and other switchgears particularly those located outdoors. They can be copper conductors connected to ground.

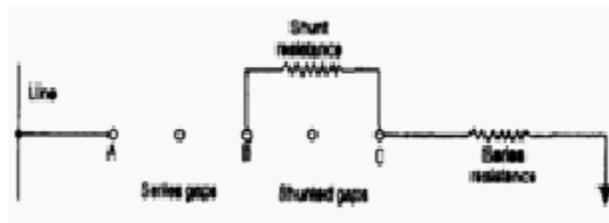
- b) **Surge Diverters or Arrestors:** The surge diverters better known as arrestors basically safeguard the insulation of the terminal apparatus and it ceases to carry current after a discharge.
- c) **Surge Modifiers:** Surge capacitors and air cooled surge reactors modify the steepness of the wave front.
- d) **Surge Absorbers:** Inductor metal shields absorb low energy surges. This device is appropriate for short duration surges as it can reduce only the steepness of the wave front. Such devices are not cost effective for higher transient surges.

Of the different protective equipments Lightning Arresters (LA) are more widely used. They are of different types as follows

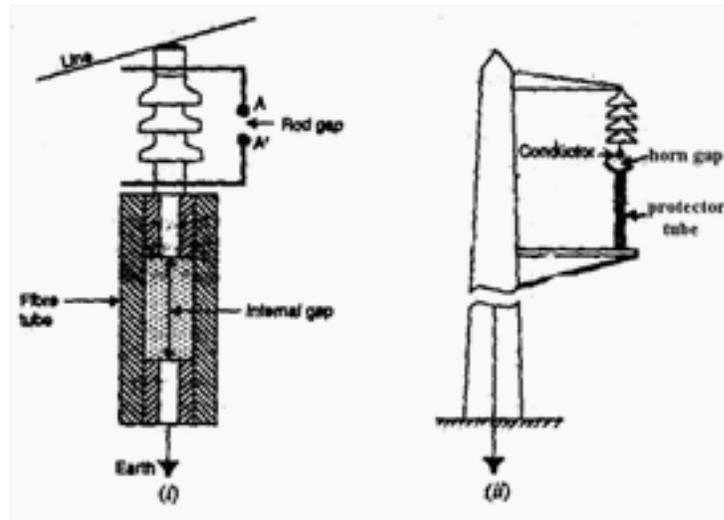


a) **Rod Gap Arrester:** This type of arrester is for lower voltage application. When the surge exceeds the designed value of the gap an arc is initiated. A small square rod of size 1 cm^2 bent at right angles and connected between the line and earth as shown in the figure above. The distance between the rod and the insulator should not be less than the gap length so that the arc could reach the insulator and damage it. When the surge voltage reaches the design value of the gap an arc appears in the gap providing an ionized path between it and ground.

b) **Horn Gap Arrestor:** It consists of horn shape metal rods separated by a small air gap. The horns are so constructed that the gap between them gradually increases towards the top as depicted in the figure below. The horns are mounted on insulators. One of the horns is connected to the line through a resistance R and a choke coil L . The other end of the horn is solidly grounded. The resistance helps in limiting the current flow to a small value. The choke coil is so designed that it offers small reactance to the power frequency but a high reactance during transient frequency. Thus it does not allow the transient to enter into the apparatus to be protected. The gap between the horns are so designed that the normal power frequency supply voltage is not sufficient to cause a spark across gaps.

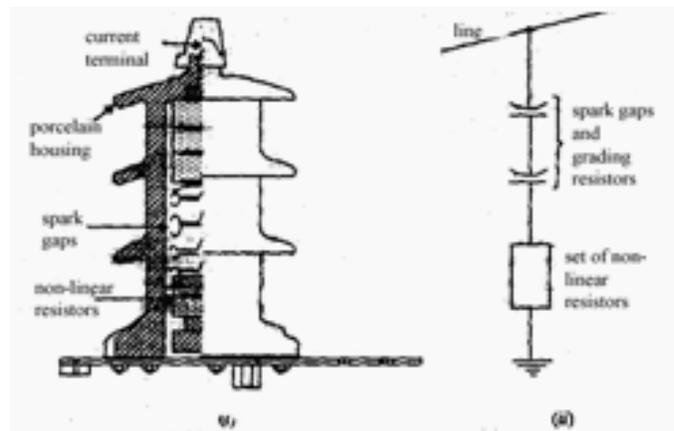


c) *Multi gap arrester*: In this type of arrester, metallic cylinders of metal alloys of zinc, insulated from each other and separated by small multiple intervals of air gaps are connected in series as shown above. The first cylinder *A* in series is connected to the line and the others *B* and *C* to the ground through a series resistance. The series resistance limits the power loss to the arc. The two cylinders *B* and *C* are also shunted through resistance. Under normal conditions, the mid cylinder *B* is at earth potential and the normal supply voltage is unable to break down the series gap. During, a transient overvoltage condition the first two series gaps break down first. Out of the two gaps between the three cylinders, the second gap is there for extra safety.

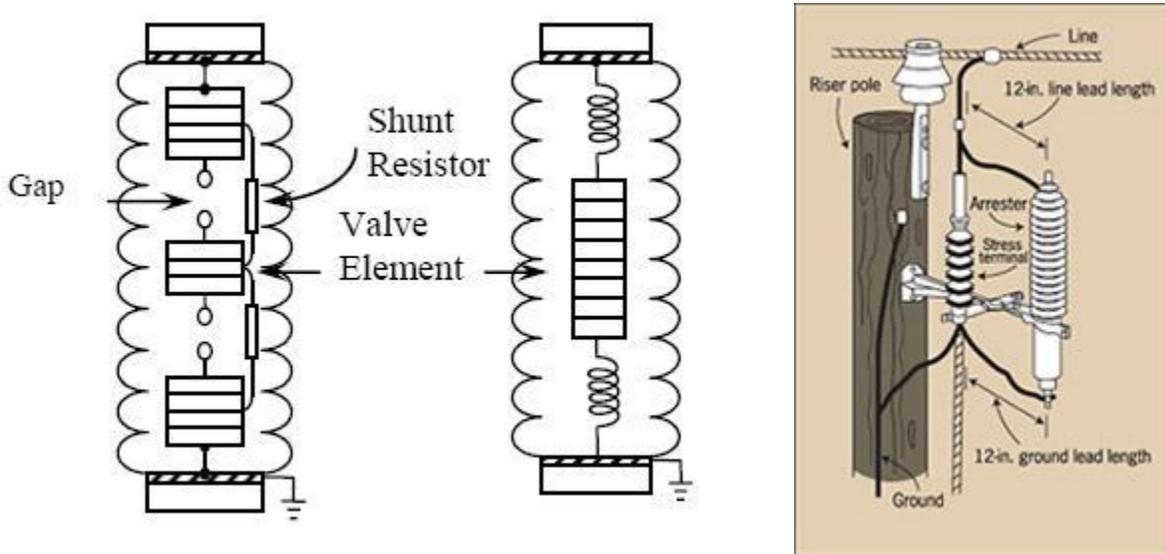


d) *Expulsion type arrester*: This type of arrester is also known as the protector tube, which is commonly used on systems operating at voltages upto 33 KV. As shown in the figure above, this type of arrester has two gaps. One of them is a normal rod gap and the other one is enclosed within a fiber tube. The second gap has two electrodes inside the fibre tube. The upper electrode is connected to the rod gap and the lower electrode to the earth. The entire expulsion tube is hung from a transmission line with the help of insulators. The series gap is set to arc over a specified voltage lower than the withstand capacity of the line or the equipment where it is mounted. This tube does not have long life and therefore not used these days.

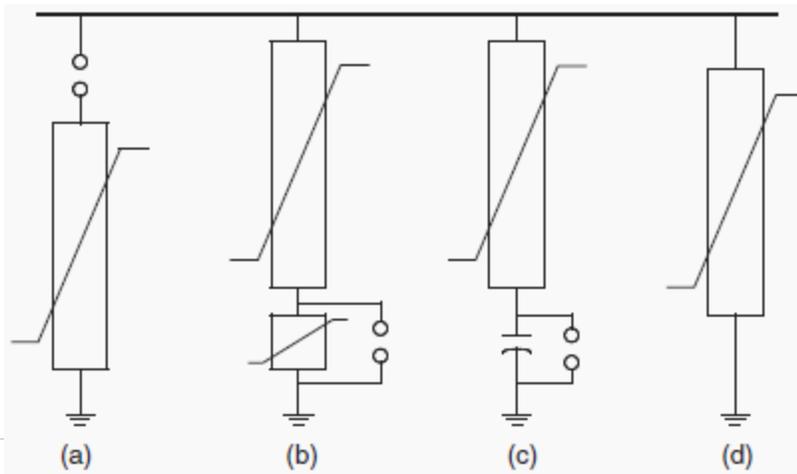
e) *Valve Type arrester*: This type of arrester has a non linear resistor in series with the spark gap as shown below. In traditional arresters, the characteristic of the gap spark over voltage versus the surge front time does not match well with the strength versus front characteristics of most of the insulators. Thus it is difficult to coordinate the protective device with the system voltage for which it is used. To resolve this non linear resistors are used in series with the gap to limit the power follow current after an arrester discharge operation. These arresters are used for higher voltage application. Both the assemblies of spark gap and non linear resistor are housed inside a tight porcelain container. There are two types of such arresters and they are discussed below.



f) *Silicon Carbide Lightning Arrester*: A non linear Silicon Carbide (SiC) material is connected in series with the spark gaps as shown below. The spark gaps provide high impedance during normal condition, where as the SiC disks restricts the flow of current through the spark gap. The non linear resistor of SiC is made by mixing the same by binding material and forming a moulded disk. The disk diameter depends on its energy rating and thickness on the operating voltage rating. The V-I characteristics of a SiC has a hysteresis type loop, the resistance being high during the rising part of the impulse wave and it has a lower value during the tail of the wave front. These type of arresters are used upto a voltage level of 220 KV.



Metal Oxide Lightning Arrester: The Metal Oxide (MO) arrester shown below, uses metal oxide varistors for manufacturing. The main component being ZnO powder, mixed with some other metal oxides to form a ceramic mould. The characteristic is robust enough to avoid any use of spark gaps in series. Due to higher levels of leakage current compared to SiC type of arresters during transient overvoltage conditions. However, they carry even lesser current during normal voltage condition, therefore, they have even more non linear characteristics so that spark gaps can be avoided unlike the SiC type of arresters. During surge expulsion when the surge current is very high in the range of 250-500 A, a shunt gap provided in series with the arrester safeguards by bypassing with a spark over. These types of arresters are used for even more voltage levels.



SAMPLE MODEL QUESTION PAPERS

F.M. 70

Time: 3 Hours

Answer any SIX including Q No. 1

Figures specified on the right side of margin denote Marks

Q1. Answer all the following questions: (2×10)

- (a) What is meant by 'sensitivity factor' of relay? How is it important?
- (b) Explain briefly, the main reason and consequences of current chopping.
- (c) What is the theory of Energy Balance?
- (d) What is meant by doubling effect in the theory of circuit breaking?
- (e) What is the fundamental difference in the operation of an isolator and a circuit breaker?
- (f) What is a hybrid comparator? Explain in brief.
- (g) Define 'Burden' of a relay? What is its unit?
- (h) Where does one use a *reactance* relay and what is its main limitation?
- (i) Differentiate between the roles of a *wave trap* and *coupling capacitors* in carrier current protection.
- (j) Explain the *duality* principle of amplitude and phase comparators.

Q.2

- (a) With neat diagram explain the principle of operation of an Induction disc type Over Current relay. How can a directional feature introduced in the same. (6)
- (b) An IDMT relay is used to protect an alternator of 33KV (Star) rating, through 500/1 Amp C.T. The relay has plug setting of 125% and TMS of 0.75. A three phase short circuit fault occurs near the alternator such that the impedance from alternator to the fault point is $j6$ Ohms. Find the fault current and the time of operation of the relay. The IDMT characteristic is given below, which is assumed to be linear between two consecutive points.

PSM	2	4	6	8	10	12	(4)
Time(s)	7	6	4.2	3.5	3.1	2.9	

- Q3. a) With proper scheme of time grading show the principle of distance protection known as three stepped protection. Where are they utilized? (5)
- b) With proper circuit connection and necessary phasor diagrams explain the relay meant for detecting Negative phase sequence in any three phase equipment. (5)
- Q.4 (a) What are the limitations of a Merz Price differential scheme and how can they be overcome? Discuss in detail. (4)
- (b) With neat sketch show the circuit connection diagram of biased differential relay along with the primary/ secondary winding connections for a 33/11 KV 3-Phase transformer connected in $yd11$ phasor group. Moreover choose suitable ratings of both end C.Ts, if it is required to design for 100 A of current in the star connected side of transformer. (6)
- Q.5 (a) Draw the circuit diagram of a 'Restricted Earth Fault' protection scheme of a 3-phase alternator? Why it is named as 'Restricted'? Also with proper circuit diagram explain the protection of rotor winding of the same alternator. (6)
- (b) The neutral point of a 3 phase 20 MVA, 11KV Star connected alternator is earthed through a resistance of 5 Ohms. The relay operates when the out of balance current is 1.5 Amp. The C.T. has a ratio of 1000/5. What is the percentage of winding that is protected? Moreover, calculate the resistance required to protect 90% of the winding. (4)
- Q.6
- (a) Explain the construction and working principle of a SF₆ Circuit breaker, discussing its merits and application. (6)
- (b) In a short circuit test on 3-pole 110 KV, the power factor of the fault, which involves earth was found out to be 0.4 and the recovery voltage was 0.95 times the full line value. The nature of breaker current was symmetrical and the frequency of oscillation of restriking voltage was 15 KHz. Determine the following. (4)
- a) The value of $RRRV_{Avg}$
- b) The value of $RRRV_{Max}$.
- Q.7
- (a) What is the principle with which a Carrier Current Protection system operates for protection of a long transmission line? With neat schematic diagram showing all important components, discuss about its operation. (6)
- (b) With proper illustrations explain the principle of operation of Vacuum Circuit breakers. (4)
- Q.8 Write short notes on any two (5×2)
- (a) DC Circuit breakers
- (b) Admittance Relay
- (c) Amplitude comparators

F.M. 70

Time: 3 Hours

Answer any SIX including Q No. 1

Figures specified on the right side of margin denote Marks

Q.1 (2×10)

- i) Write the general torque equation of a relay.
- ii) Enumerate four important attributes of a protection system.
- iii) Write two main disadvantages of using Merz Price differential scheme.
- iv) Define 'RRRV', and mention its importance.
- v) Write two main advantages of Vacuum Circuit breaker.
- vi) Why SF₆ is considered to be one of the best medium for breaker operation? Discuss
- vii) What is understood by 'Current Chopping'? Explain in brief.
- viii) What is the principle of arc extinction adopted in DC breakers?
- ix) How a 'Power Swing' condition in power system affects the operation of relay? Explain
- x) In feeder protection which type of over current relays are used and are they of similar types over the entire length?

Q2. i) With neat sketch, explain the principle of operation of 'Induction disc type' Over Current (O.C) relay. How the time delay mechanism is adjusted in the O.C. IDMT relay characteristics? Explain in brief. (5)

- i) An IDMT relay is used to protect an alternator of 11KV (Star) rating, through 500/1 Amp C.T. The relay has plug setting of 125% and TMS of 0.3. If the fault is created at a point near the alternator such that the impedance from alternator to the fault point is j5 Ohms. Find the fault current and the time of operation of the relay. The IDMT characteristics is given below.

PSM	2	4	6	8	10	12	(5)
Time(s)	7	6	4.2	3.5	3.1	2.9	

Q3. i) Discuss the process of arc extinction in the medium of oil and what characteristics it should have? Discuss various types of OCBs used in power network. (5)

- ii) Show a schematic diagram for a directional relay. Using the universal torque equation and R-X diagrams show how a directional element can be realized and used along with impedance relay to provide directional feature into it. (5)
- Q4.i) Discuss about the various schemes of Bus-Zone protection and specify their relative merits and demerits? (5)
- ii) In a short circuit test on a circuit breaker of 132 KV 3 phase the following results were obtained. Power Factor of the fault 0.4, recovery voltage is 0.9 times the full line voltage, the breaking current is symmetrical, and the frequency of oscillation of restriking voltage is 16 kHz. Determine the RRRV and its average values, assuming the fault involves ground. (5)
- Q5.i) What are the demerits of differential relay? With circuit diagram discuss how a biased differential connection helps in overcoming these demerits. (5)
- ii) With neat sketches, discuss in detail about the Carrier Current Protection scheme used in long transmission lines. What are its merits over pilot wire relaying schemes? (5)
- Q6.i) Draw the circuit diagram of a 'Restricted Earth Fault' protection scheme of a generator? Why it is named as 'Restricted'? (5)
- ii) A 50 MVA, 11KV, 50 Hz Y- connected alternator is protected by an earth fault relay which operates at 5% setting of CT primary level. Determine the value of ground resistance required to be connected with neutral, which could protect 95% of the generator winding. The CT used for this circuit is 3000/1. Also, determine the current flowing through the neutral in the event of above earth fault. (5)
- Q7.i) Discuss and establish the duality of Amplitude and Phase comparators. (5)
- ii) Discuss with neat circuit diagram as to how it is possible to realize a static Impedance Relay? Is it possible to use a phase comparator for realizing this relay? How, explain. (5)
- Q8. Write short notes on the following topics (5×2)
- i) SF₆ Circuit Breaker
- ii) Negative Phase sequence relay

BTech-7th

S.G.P.D.

F.M. 70

Time: 3 Hours

Answer any SIX including Q No. 1

Figures specified on the right side of margin denote Marks

- Q1. Answer all the following questions: [2×10]
- (a) What is meant by *Linear Couplers*? How they are different from normal CTs?
 - (b) What is the effect of opening the C.B connecting an unloaded transmission line? Explain briefly.
 - (c) Define the *Making Capacity* of a circuit breaker.
 - (d) Write the general torque equation of a relay, and from it find the equation of MHO relay.
 - (e) In the three stepped protection of feeders, specify the zones meant for primary and backup protection. Justify.
 - (f) What is the problem of magnetizing inrush current in protecting transformers with differential scheme?
 - (g) How the principle of arc formation in the medium of Vacuum is different from other mediums?
 - (h) What is the necessity of protecting 3-phase generators from *Loss of Excitation Systems*?
 - (i) What is the main advantage of using MOCB over bulk oil type of breakers?
 - (j) What is meant by *duality* of amplitude and phase comparators? Justify briefly
- Q.2 (10)
- A 30 MVA, 13.8 KV 3-phase alternator is supplying load to two motors at the receiving end. There are two numbers of transformers connected at the sending and receiving ends rated at 35 MVA, 13.2KV(grounded Star)/115KV(Delta) with 10% leakage reactance. The series and zero sequence reactances of the transmission line are 80 Ω and 200 Ω respectively. The motors are having 10 MVA and 20 MVA capacities at 12.5 KV. The sub-transient, negative sequence and zero sequence reactances of the alternator are 15%, 15% and 5% and those of motors are 20%, 20% and 5% respectively, at their respective own bases. The neutral point of Star connected alternator and one of the motors (Star connected) is grounded through reactors of 2 Ω . Draw the sequence network and determine the fault current for a LG fault near the secondary side of the sending end transformer, and determine the fault MVA also.
- Q.3 i) Define Active Recovery Voltage & discuss *three* important factors which affect the severity of it on circuit breakers. (4)

- ii) Two numbers of IDMT O.C. relays used with C.T ratio 200:1 placed at locations No.1 and 2 as shown in Fig.1. The fault current is 1800A near breaker No.1. Relay No.1 & 2 is set at 100% and 125% plug settings respectively and the first relay has TMS of 0.2. If the time grading margin between both the relays is 0.5 sec then determine the TMS setting of relay No.2. Both the relays have the following characteristics for unity TMS. Consider the portions of characteristics between two consecutive points as linear. (6)

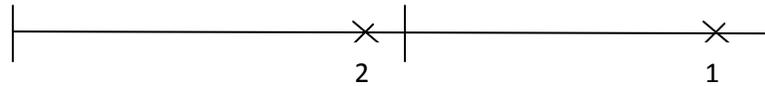


Fig.1

PSM	2	4	6	8	10	12
Time(s)	7	6	4.2	3.5	3.1	2.9

- Q.4 i) With proper schematic diagram explain the operating principle of SF₆ circuit breaker. (6)
- ii) A 50 HZ 3 Phase alternator with grounded neutral has an inductance of 1.6 mH/phase, and it is connected to the bus-bar through a C.B. The capacitance to earth between alternator and C.B. is 0.0032 μF/phase. Due to short circuit fault the C.B. opens when the r.m.s value of current is 8000 Amp. Determine the following. (4)
- a) The value of RRRV_{Avg} b)The value of RRRV_{Max}.
- Q.5 i) Enumerate two major reasons behind the use of biased differential protection scheme for the protection of power transformers. (3)
- ii)With neat sketch show the circuit connection diagram of biased differential relay along with the primary/ secondary winding connections for a 66/220 KV 3-Phase 100 MVA transformer connected in *yd11* phasor group. Moreover choose suitable ratings of both end C.T.s and interposing C.T.s if required. (7)
- Q.6 With detail schematic diagram of equipments used in carrier aided distance protection scheme explain the principle of operation of the same with carrier blocking scheme. (10)
- Q.7 i) What is understood by Power Swing Condition in power system? Explain in brief. Which type of distance relay is least affected by this condition? Justify (5)
- ii) Distinguish between the operation of Arcing Horn and Rod Gap for protection against overvoltage. (5)
- Q.8 Wrtie short notes on any *two* (5×2)
- (a) HRC Fuse
- (b) Integrating type amplitude comparator
- (c) Phase comparator based on principle

F.M. 70

Time: 3 Hours

Answer any SIX including Q No. 1

Figures specified on the right side of margin denote Marks

Q1. Answer all the following questions: (2×10)

- (a) What is meant by doubling effect in the theory of circuit breaking?
- (b) Explain briefly, the main reason and consequences of current chopping.
- (c) An 11KV, 500MVA circuit breaker suddenly closes on to a 3-phase short circuit fault. Determine the asymmetrical breaking current considering 50% of DC component.
- (d) How the directional property can be introduced in an over current relay? Explain the concept.
- (e) What is the fundamental difference in the operation of an isolator and a circuit breaker?
- (f) What is a hybrid comparator? Explain in brief.
- (g) What is meant by under-reach of an impedance relay? Why it happens, explain.
- (h) Where does one use a reactance relay and what is its main limitation?
- (i) Differentiate between the roles of a wave trap and coupling capacitors in carrier current protection.
- (j) What is the basic principle of operation of DC circuit breaker?

Q.2 A 3-phase generator is delivering load to a large Induction motor through a radial transmission line and two numbers of transformers connected at both the sending and receiving ends. The motor is drawing 15 MW of load current at 0.9 power factor leading at its terminal voltage of 3.1 KV. For the data given for each of the machines, transformers and line, determine the fault current delivered by both generator and motor if a 3-phase short circuit occurs at the generator bus. Use per unit method for calculation. Also, determine the breaker rating in MVA.

Generator: 25 MVA, 12.4 KV, $X_d''=10\%$, Motor: : 20 MVA, 3.8 KV, $X_d''=15\%$,
Transformers(sending end): : 25 MVA, 11/33 KV, X=8%, Transformers(receiving end): 20 MVA,
33/3.3 KV, X=10%, Transmission line: 20 ohm reactance. (10)

Q.3 i) With neat diagram explain the principle of operation of an Induction disc type Over Current relay. (5)

- ii) An IDMT relay is used to protect an alternator of 33KV (Star) rating, through 500/1 Amp C.T. The relay has plug setting of 110% and TMS of 0.6. If severest fault is assumed to be at a point near the alternator such that the impedance from alternator to the fault point is j5 Ohms. Find the

fault current and the time of operation of the relay. The IDMT characteristic is given below, which is assumed to be linear between two consecutive points. (5)

- Q.4 i) Draw the 3-Phase connection diagram of a star/star connected transformer along with the suitable C.T connection for biased differential protection of the same. (3)
- ii) How can the mal operation of differential protection scheme due to magnetizing inrush current be avoided in the protection of transformers (3)
- iii) A 3-Phase star/delta 33/6.6 KV transformer is protected with biased differential scheme. The ratio on its low voltage side is 400/5. Show the connection diagram of the scheme depicting also the rating of the high voltage side C.Ts. (4)
- Q.5 i) Draw the circuit diagram of a 'Restricted Earth Fault' protection scheme of a generator? Why it is named as 'Restricted'? (5)
- ii) A directional relay has a Voltage coil of $(210 + j400) \Omega$. What is the power factor at which the relay will develop maximum torque? Also, find the compensating impedance needed to be put in series with the voltage coil so that the relay shall develop maximum torque at lagging unity power factor. (5)
- Q.6 i) With proper schematic diagrams, explain the principle of operation of Vacuum Circuit breakers. (5)
- ii) Discuss the difference in operation between amplitude and phase comparators. Also with proper circuit diagram explain the operation of an Integrating type amplitude comparator. (5)
- Q.7 i) Discuss in brief about four important factors which affect transient stability of power system. (4)
- ii) A 50 HZ generator connected to an infinite bus is delivering 50% of maximum power which can be delivered. Due to a three phase short circuit fault the effective line reactance increases 5 times than what it was before fault. After the fault is cleared the generator is delivering power which is 75% of the maximum capacity. Determine the critical clearing angle for the above condition. (6)
- Q.8 Write short notes on any *two* of the following (5×2)
- Surge Arrestors
 - Mho Relay
 - MOCB

Acknowledgement

The committee members gratefully acknowledge *google*, *scribd*, *NPTEL*, *yourelectrichome*, *scilab* for myriad suggestions and help for preparing this lecture note. The committee members also want to express their gratitude to the persons who think knowledge should be freely accessible and distributable without any restrictions, so that every possibility of human endeavor, gets equal opportunity to explore, expand and become enlightened by the collective gifts of mankind. However apart from this lecture note students/readers are recommended to follow the below mentioned books in the references and above all confer with the faculties for better understanding of this authoritative subject of electrical engineering.

References

- [1]. Van C Warrington, "*Protective Relays*" Vol.-I & II
- [2]. Ravindranath, M.Chander, "*Power System Protection and SwitchGear*", Wiley Eastern Ltd.
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