EEPE3009 POWER SYSTEM PROTECTION (3-0-0)

Course Learning Objectives: This course will enable students to:
1.   To understand the significance of protection, protection schemes and role of earthing.
2.   To study the characteristics, functions and application areas of various relays.
3.   To acquire practical knowledge about common faults in power system apparatus and applying suitable protective schemes.
4.   To understand the functioning of static relays and Numerical protection concepts.
5.   To understand the problems associated with circuit breaking and to discuss about various circuit breakers.

Module I (5 Hours)
Protection Schemes: Significance and need for protective schemes – nature and causes of faults – types of faults Effects of faults - Zones of protection and essential qualities of protection – Types of Protection schemes - Power system Grounding and Methods of Grounding.

Module II (8 Hours)
Basics of Relays: Operating Principles and Relay Construction: Relay design and construction, Relay classification, Types of Electromagnetic relays, Theory of Induction relay torque, General Equations of Comparators and Electromagnetic Relays, Over Current relays, Directional relays, Distance relays, Differential relays. Feeder Protection: Over current, Distance and Pilot Protection. Static Relays: (Comparators and different relays) Amplitude comparator, Phase Comparator, Coincidence type phase comparator, Basic elements of a static relay, Over Current Relays, Differential Protection, Static distance Protection.

Module III (5 Hours)
Apparatus Protection: Transformer Protection, Generator Protection, Motor Protection, Bus bar protection schemes.

Module IV (6 Hours)
Numerical relays: Block Diagram of Numerical Relay, Signal Sampling & Processing, Numerical Over-current protection, Numerical Transformer differential Protection, Numerical distance Protection of Transmission Line.

Module V (6 Hours)
Circuit Breaker: Physics of arcing phenomenon and arc interruption – DC and AC circuit breaking – re-striking voltage and recovery voltage - rate of rise of recovery voltage - current chopping - interruption of capacitive current - resistance switching - Types of circuit breakers – air blast, oil, SF6 and vacuum circuit breakers – comparison of different circuit breakers – HVDC Breaker.

Course Outcomes (CO): On completion of this course, students are able to:
CO1   Understand and select proper protective scheme and type of earthing.
CO2   Explain the operating principles of various relays.
CO3   Suggest suitable protective scheme for the protection of various power system apparatus.
CO4   Analyze the importance of static relays and numerical relays in power system protection.
CO5   Summarize the merits and demerits and application areas of various circuit breakers.

Text Book(s):
1.   Power System Protection and Switchgear – B.Ravindranath & M.Chander–New Age International Publishers (Second Edition)
2.   Fundamentals of Power System Protection – Y.G.Paithankar and S.R.Bhide, PHI Publication.(Second Edition)
3.   Electrical Power System - C.L.Wadhwa New Age International Publishers. (Sixth Edition).
4.   Power System Engineering - M.L.Soni, P.V.Gupta, U.S.Bhatnagar, A.Chakrabarti, Dhanpat Rai & Co. (P) Ltd.
5.   Protection and Switchgear - B.Bhalja, R.P.Maheshwari, N.G. Chothani, OXFORD University Press.
6.   Power System Protection and Switchgear - Badri Ram, Vishwakarma, Tata McGraw hill.
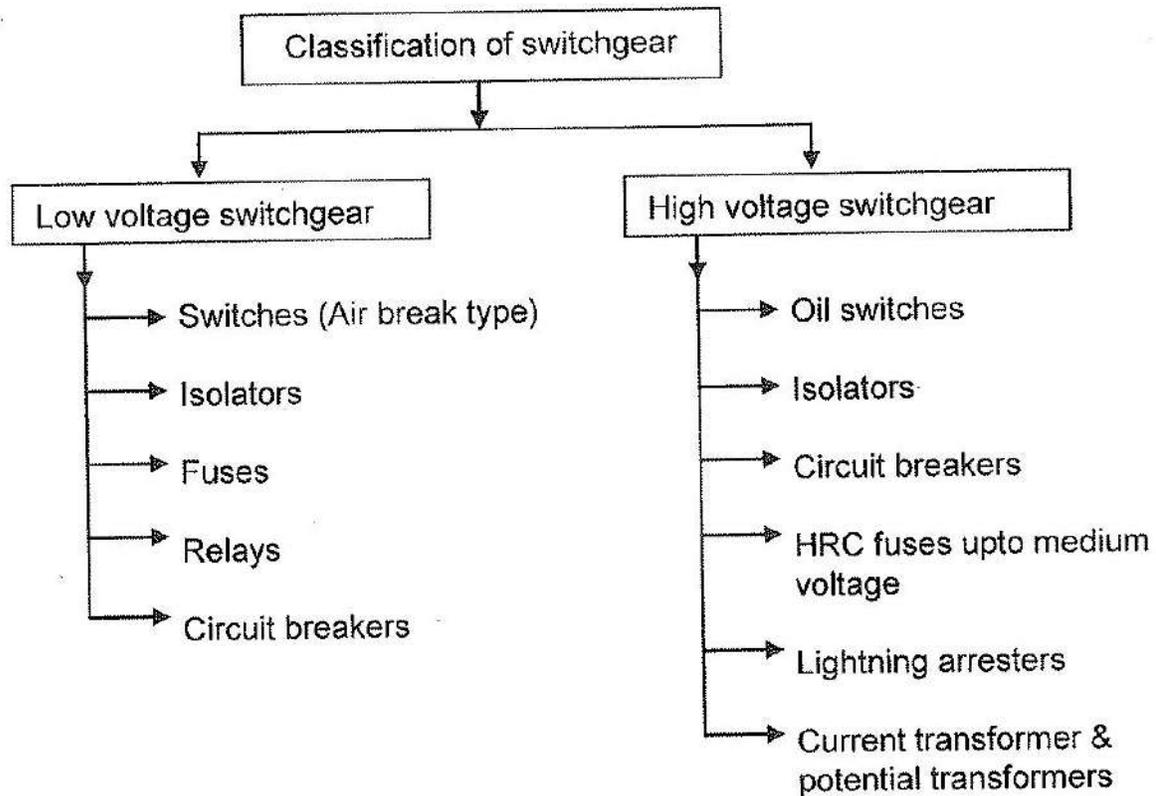
Reference Book(s):
1.   Power System relaying by Horwitz, Phadke, Research Press.
2.   Arun Ingole, 'Switch Gear and Protection' Pearson Education, 2018.
3.   Sunil S.Rao, 'Switchgear and Protection', Khanna Publishers, New Delhi, Four Edition,2010.
4.   NPTEL - https://nptel.ac.in/courses/108/105/108105167/

Module -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.

Classification of switchgear

Low voltage switchgear
→ Switches (Air break type)
→ Isolators
→ Fuses
→ Relays
→ Circuit breakers

High voltage switchgear
→ Oil switches
→ Isolators
→ Circuit breakers
→ HRC fuses upto medium voltage
→ Lightning arresters
→ Current transformer & potential transformers

1.1   Basic ideas of Relay Protection

A good electric power system should ensure the availability of electrical power without any interruption to every load connected to it. Generally power is transmitted through high voltage transmission line and lines are exposed, there may be chances of their breakdown due to storms, falling of external objects, and damage to the insulators etc. These can result not only mechanical damage but also in an electrical fault.

Protective relays and relaying systems detect abnormal conditions like faults in electrical circuits and automatically operate the switchgear to isolate faulty equipment from the system as quick as possible. This limits the damage at the fault location and prevents the effects of the fault spreading into the system. The switch gear must be capable of interrupting both normal currents as well as

fault current. The ==protective relay on the other hand must be able to recognize an abnormal condition in the power system and take suitable steps== so that there will be least possible disturbance to normal operation.

==Relay does not prevent the appearance of faults. It can take action only after the fault has occurred==. However, there are some devices which can anticipate and prevent major faults. For example, Buchholz relay is capable of detecting the gas accumulation produced by an incipient fault in a transformer.

1.2 Nature and causes of faults

The nature of fault simply implies ==any abnormal condition which causes a reduction in the basic insulation strength== between phase conductors, between phase conductor and earth or any earth screen surrounding the conductors.

==The reduction of the insulation is not considered as a fault until it produces some effect on the system i.e. until it results either in an excess current or in the reduction of the impedance== between the conductors, between the conductor and earth to a value below the lowest load impedance normal to the circuit.

Power systems mainly consist of generator, switch gear, transformer and distribution system.

The probability of failure is more on the power system due to their greater length and exposure to atmosphere.

(a) Breakdown at normal voltage may occur on account of:

(i) The deterioration of insulation

(ii) Damage due to unpredictable causes such as perching of birds, accidental short

circuiting by snakes, falling of tree branches, etc.

(b) Breakdown may occur because of abnormal voltages: This may happen because of (i) switching surges (ii) surges caused by lightning

Insulation may be subjected to transient over voltages because of switching operation.The voltage which rises at a rapid rate may achieve a peak value which approaches three times phase to neutral voltages.

 Lightning produces very high voltage surges in the power system in the order of million volts. These surges travel with the velocity of light in the power circuit. The limiting factors are the surge impedance and the line resistance.

1.3 Consequences of Faults

Serious results of the uncleared fault, is fire which may not only destroy the equipment of its origin but also may spread in the system and cause total failure.

The several Consequences of faults are;

1. A great reduction of the line voltages.

2. Damage caused to the element of the system by the electrical arc.

3. Damage to other parts in the system due to overheating.

4. Disturbance to the stability of the electrical system and this may even lead to a

   complete shutdown of the power system.

5. Reduction in the voltage may fail the pressure coil of the relay.

6. Considerable reduction in the voltage on healthy feeder connected to the system having fault. This may cause either an abnormally high current being drawn by the motor or the operation of no volt coils of the motors. (Considerable loss of industrial production as the motors will have to be restarted).

Frequency of fault occurrence in different links of a power system are:-

Equipments	% of total faults
OH line	50
Cables	10
Switchgear	15
Transformer	12
CTs & PTs	2
Control Equipment	3
Miscellaneous	8

Faults are of two types:

1. Short circuit fault- current

2. 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

1. Three phase faults (with or without earth connection)

2. Two phase faults (with or without earth connection)

3. Single phase to earth faults

Classification of Open Circuit Faults

1. Single Phase open Circuit

2. Two phase open circuit

3. Three phase open circuit

Consequences

L-L-L fault or three phase fault are called symmetrical 3-φ fault generally occurs due to carelessness of operating personnel. Usually the three phase lines are tied up together a bare conductor in order to protect the lineman working on the line against inadvertent-charging of the line. After work is over, if the linesman forgets to remove the tie-up and CB is closed, a symmetrical fault occurs.

Line to ground fault occurs most commonly in overhead line. A large no of these faults are transitory in nature and may vanish within a few cycles (if twig falls across a line and cross arm and burns itself out or just falls down).

(i) Damage to the equipment due to abnormally large and unbalanced currents and low voltages produced by the short circuits

(ii) 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.

(iii) 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.

(iv) 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
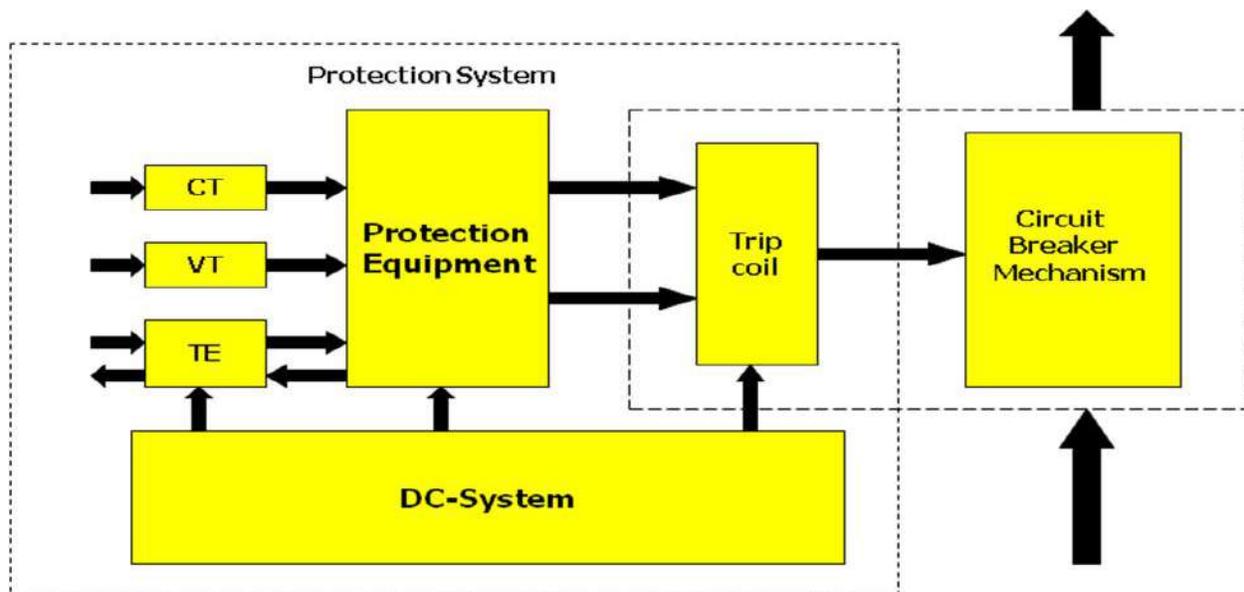
Zones and types of Protection system

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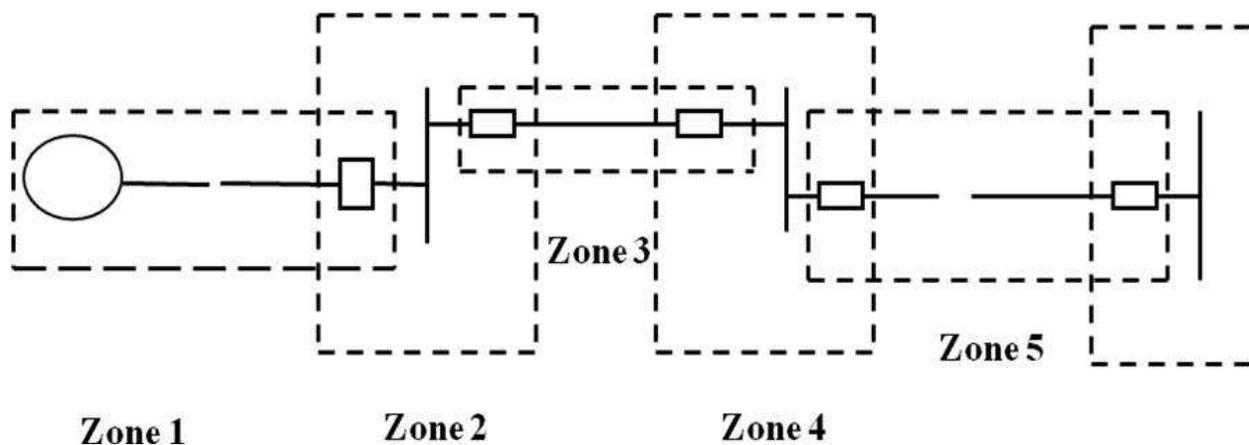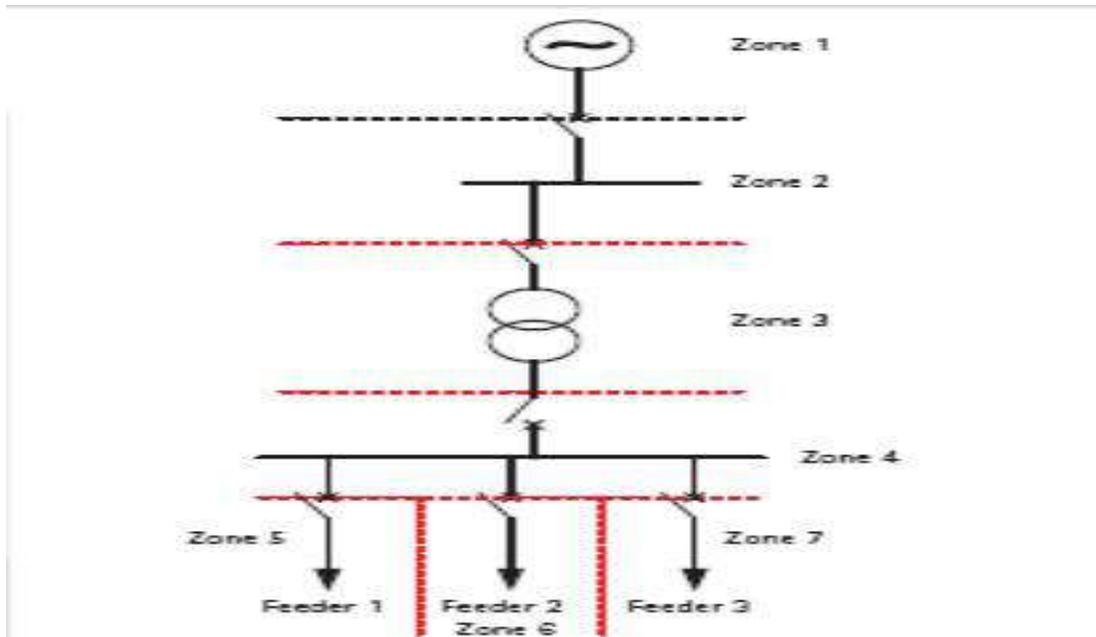
Types of Protection (Primary and Back-up Protection)

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.

a. Current or voltage supply to the relay.

b. D.C. tripping voltage supply

c. Protective relays

d. Tripping circuit

e. Circuit Breaker

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.

Protection System Requirements and some basic terminologies used

Every protective system which isolates a faulty element must satisfy four basic

requirements:1. Reliability 2. Selectivity 3. Fastness of operation 4. Discrimination

Reliability

Reliability is a qualitative term. It can be expressed as a probability of failure.

• Quality of personnel i.e. mistakes by personnel are most likely causes of failure.

• high contact pressure

• dust free enclosures

Records show that the order of likelihood of failure is relays, breakers, wiring, current transformers, voltage transformers and battery.

When relays using transistors are considered, the failure rate goes up still further.

Selectivity :

The property by which only the faulty element of the system is isolated and the remaining healthy sections are left intact.

Selectivity is absolute if the protection responds only to faults within its own zone and relative if it is obtained by grading the setting of protections of several zones which may respond to a given fault. The systems of protection which in principle are absolutely selective are known as unit system. The systems which selectivity is relative are non unit system.

Fastness of Operation

Protective relays are required to be quick acting due to the following reasons:

(a) Critical clearing time should not be exceeded.

(b) Electrical apparatus may be damaged, if they are made to carry fault currents for a long time.

(c) A persistent fault will lower the voltage resulting in crawling and overloading of industrial drives.

The figure below shows the typical values of power, which can be transmitted as a function of time. On the other hand, relays should not be extremely fast; otherwise the relay will operate for transient conditions.

Discrimination

• Protection must be sufficiently sensitive to operate reliably under minimum fault condition for a fault within its own zone while remaining stable under maximum load i.e. a relay should be able to distinguish between a fault and an overload.

• In the case of transformers, the inrush of magnetising current may be comparable to the full current, being 5 to 7 times the full load current. The relay should not operate for inrush current.

• In interconnected systems, there will be power swing, which should also be ignored by the relay.

The word discrimination is sometimes used to include selectivity.

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

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

2. **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.

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 over curent relay,

mathematically this can be defined as the ratio between the short circuit fault current (Is) and the relay operating current (Io). The value of Io , should not be too small or large so that the relay is either too sensitive or slow in responding.

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.

Adequacy: It is economically unavailable 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.

Some basic terminologies used in protection system

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

1. Measuring Relay

2. Fault Clearing Time

3. Auxilliary relay

4. Relay Time

5. Pick up value

6. Reset Value

7. Drop out

8. Reach (under and over reaches)

9. Relay Burden

10. Unit/ Non unit protection

11. All or Nothing relay

<u>Reference</u>

1) Introduction: https://youtu.be/mShiFjDPx0c

2) Zones of Protection : https://youtu.be/H0Q1KMJA5dw

Protective Relay. An electrical device designed to initiate isolation of a part of an electrical installation, or to operate an alarm signal, in the event of an abnormal condition or a fault.

Unit or Element. A self-contained relay unit which in conjunction with one or more other relay units performs a complex relay function, e.g. a directional unit combined with an overcurrent unit gives a directional overcurrent relay.

Energizing Quantity. The electrical quantity, i.e. current or voltage either alone or in combination with other electrical quantities required for the functioning of the relay.

Characteristic Quantity. The quantity to which the relay is designed to respond, e.g. current in an overcurrent relay, impedance in an impedance relay, phase angle in a directional relay, etc. Some relays have a calibrated response to one or more quantities, such quantities are called *characteristic quantities.*

Setting. The actual value of the energizing or characteristic quantity at which the relay is designed to operate under given conditions.

Power Consumption (Burden). The power consumed by the circuits of the relay at the rated current or voltage. It is expressed in volt-amperes for a.c. and watts for d.c.

Pickup. A relay is said to pickup when it moves from the *off* position

to the *on* position. The value of the characteristic quantity above which this change occurs is known as *pickup* value.

Dropout or Reset. A relay is said to dropout when it moves from the *on* position to the *off* position. The value of the characteristic quantity below which this change occurs is known as *dropout* or *reset* value.

Operating Time. The time which elapses between the instant of application of a characteristic quantity equal to the pickup value and the instant when the relay operates its contacts.

Resetting Time. The time which the operated relay takes to come back to its initial position as a result of a specified sudden change of the characteristic quantity, the time being measured from the instant at which the change occurs.

Overshoot Time. The time during which stored operating energy is dissipated after the characteristic quantity has been suddenly restored from a specified value to the value which it had at the initial position of the relay.

Characteristic Angle. The phase angle at which the performance of the relay is declared.

Characteristics (of a Relay in Steady State). The locus of the pickup or reset when drawn on a graph. In some relays the two curves are coincident and become the locus of balance or zero torque.

Reinforcing Relay. Relay which is energized by the contacts of the main relay and with its contacts in parallel with those of the main relay relieves them of their current carrying duty. The seal-in contacts are usually of higher current rating than those of the main relay.

Seal-in-Relay. Similar to the reinforcing relay described above except connected to stay until its coil circuit is interrupted by a switch on the circuit breaker.

Primary Relays. Those which are connected directly in the protected circuit.

Secondary Relays. Those connected to the protected circuit through current and potential transformers.

Auxiliary Relays. Relays which operate in response to the opening or closing

of its operating circuit to assist another relay in the performance of its function. The auxiliary relay may be instantaneous or may have a time lag and may operate within large limits of the characteristic quantity.

Backup Relay. A relay which operates usually after a slight time delay if the normal relay does not operate to trip its circuit breaker. A backup relay acts as a second line of defence.

Consistency. Accuracy with which the relay can repeat its electrical or time characteristics.

Flag or Target. A device used for indicating the operation of a relay, it is usually spring or gravity operated.

Reach. Remote limit of the zone of protection provided by the relay used mostly in connection with distance relays to indicate how far along a line the tripping zone of the relay extends.

Overreach or Underreach. Errors in relay measurement resulting in wrong operation or failure to operate respectively.

Blocking. Preventing the protective relay from tripping either due to its own characteristic or due to an additional relay.

Basic Principles and Components of Protection

There must be able to discriminate the appropriate disconnecting device. The method of discriminating the faults are two types.

(a) Those which discriminate as to the location of fault.

(b) Type of fault

Methods discriminate the type of faults are:

The main aim is that the fault section of the system be isolated and in the minimum time.

a) Discrimination by time

b) Discrimination by current magnitude

c) Discrimination by time and direction

d) Discrimination by distance measurement

e) Time as an addition to current magnitude or distance discrimination

f) current balance discrimination

g) Power direction comparison discrimination

h) Phase comparison discrimination

(a) Discrimination by time:

By adding time lag features to the controlling relay a number of CBs it is possible to trip the CB nearest to fault in prior to those which are farther from the part of fault.
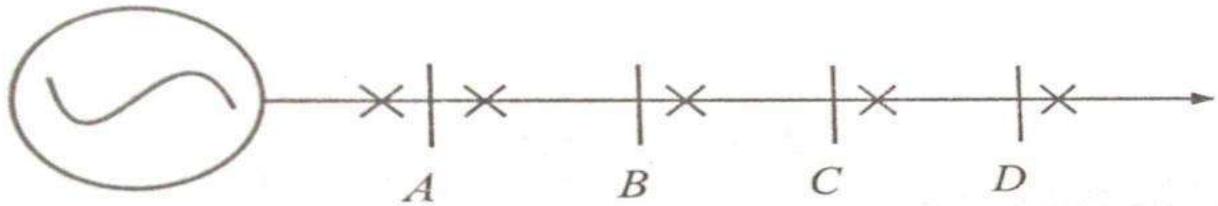
Figure 2.1: Radial feeder

Let in a radial feeder as shown, the circuit breakers at ABCD are identical and are set operate for a given value of current. For a fault at any section CD, if the fault current exceeds the set value the breakers at A,B and C will trip and whole feeder beyond A becomes dead.

For providing time lag to the circuit breakers at ABCD the tripping is delayed in the following manner.

D- no added time lag

C- .4 sec added time lag

B- .8 sec added time lag

A- 1.2 sec added time lag

Now if the fault occurs in the section CD the breaker at C will trip after a time of .4s and will clear the fault as a result feeder up to c will remain aline.

A .4s step time is necessary to account for the operation CB and its relay operation time.

(b) Discrimination by current magnitude (Also known as current gradded scheme)

This depends on the current magnitude. As the fault current will also very with location of fault.If the relays are set to pick up at a progressively higher current towards the source then a simple feeder system of above fig. can be protected.

(c) Discrimination by time and direction:
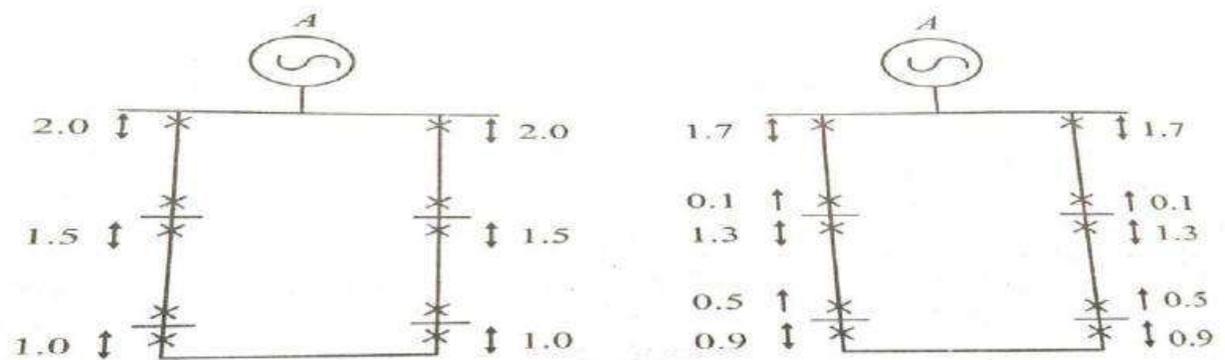
Ring main feeder with Non-directional relays : with same current setting but different time lag. Here proper discrimination cannot be obtained.

Ring main feeder with Directional relays: with same current setting and different time lag. Fault occurring on any section will be discriminating cleared without loss of supply.

(d) Discrimination by distance measurement:

Measurement of distance achieved in various way known as distance relay

(e) Time as an addition to current magnitude or distance discrimination:

1. time + current grading gives the most practical protection schemes

2. time + distance discrimination forms another practical protection scheme

(f) Current balance discrimination:

Another form of discrimination which is limited in its scope to one system element

which will cause isolation of this element only in the event of fault in this element and will not respond to any other fault external to this element, even through fault current passes through it. Such a protection is known as unit protection.

This form of protection is based on one of the following 2 principles.

1. Circulating current principle

2. Opposed voltage principle or balanced voltage principle.
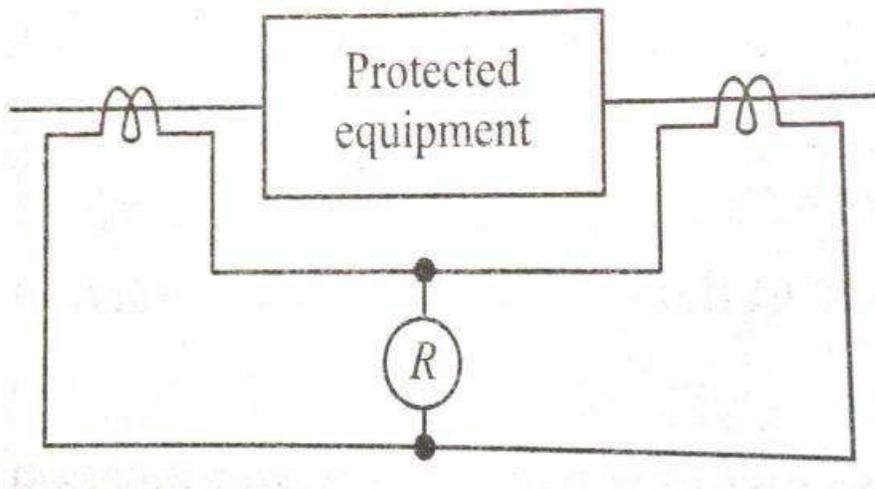
Circulating current principle

For an external fault the balanced current flow and there will be no current in the relay. So the apparatus will not be isolated.
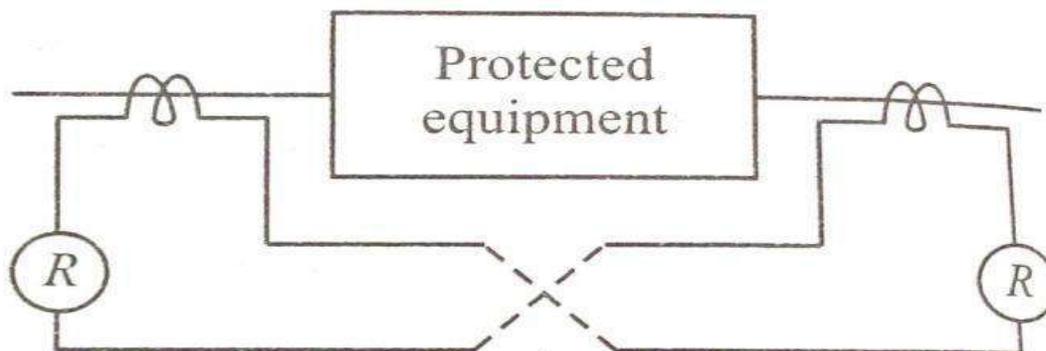
Balanced voltage protection

The relay time polarity of CTs at the two ends is such that there is no pilot current for the condition of load or external fault. For internal fault, the CTs voltage will no longer be balanced and current will be flow in the relay will trip.

(g) Power direction comparison discrimination:

i) Power flow out at both end

ii) Power flow in at both end.

iii)No power flow either in or out at the other end

Methods of discrimination to type of fault:

When fault currents may not be very high or may differ little in magnitude from loud currents as result the current magnitude detection fails to point out such a fault. Such a fault current has some peculiarity which distinguish itself from the normal load currents.

Ex- in a 3-ph system the currents and voltages can be resolved in to their phase sequence components which would ultimately give some idea about the nature of the current or voltages presents.

(a)Zero phase sequence networks:
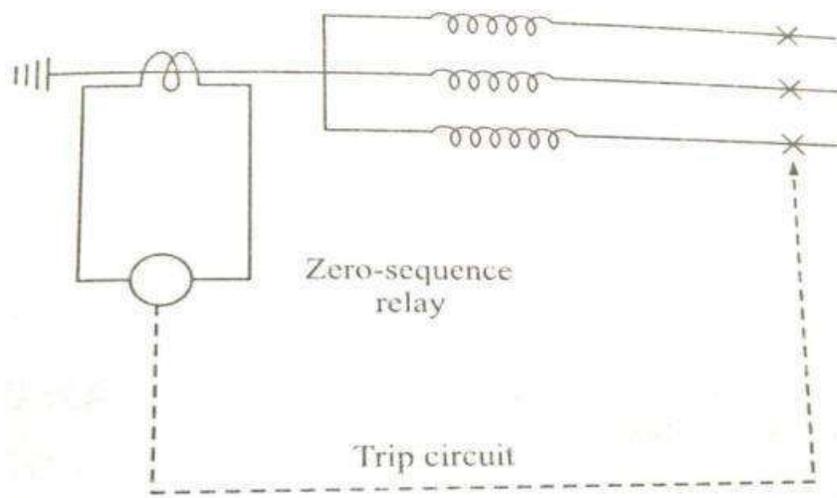
Zero phase sequence networks

Relay will be energized only by zero sequence current. This relay will ignore load currents or phase to phase short circuits.

(b) Negative-phase sequence networks:

Negative phase sequence current represents some form of unbalanced condition such as

• Phase to phase faults other than symmetrical three phase faults.

• Broken conductors
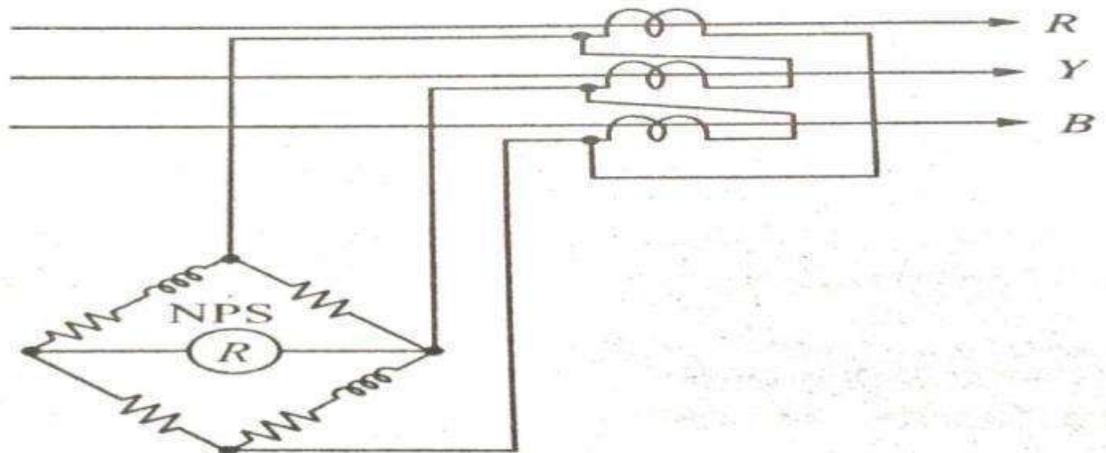
Negative-phase sequence networks

Derivation of a single phase quantity from a three phase quantities:

Auxiliary or pilot wires are used to transmit information from one end of the line to

the other end of the line. For normal 3ph system three pilot would ordinarily be required which would obviously be a very costly affair for longer system, particularly in transmission circuit.

It would naturally be preferable to have a mean of deriving a single phase quantities which under both normal and abnormal conditions will be representative of the three phase conditions.

Sometimes, it becomes necessary to the sequence current or voltages from correspond line currents or voltages in order to simplify the protection scheme by reducing the no of relay required.

There are two commonly used methods for deriving single phase quantities from a three phase system.

a. summation transformers

b. sequence transformers

(a) Summation transformers:
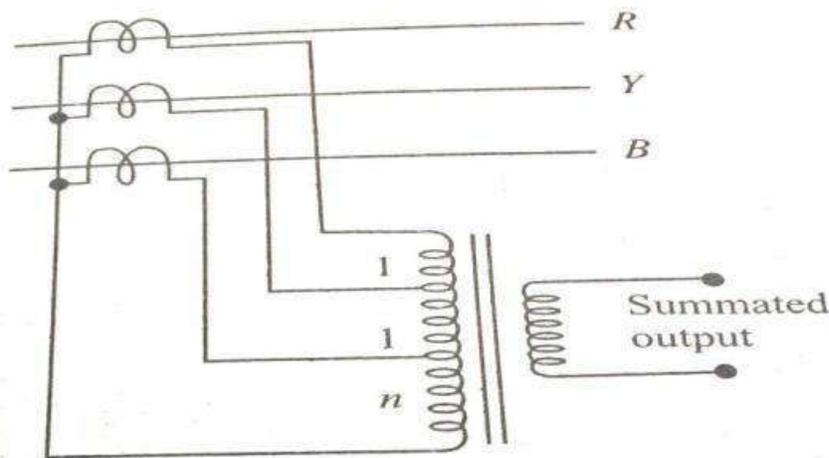
Summation transformers

Each CT energized a different number of turns as the primary with a resulting single phase output from the secondary. The output is seen to be proportional to the vector sum.

$$(n+2)IR + (n+1)IY + n\ IB$$

It is also possible to control independently the outputs for earth fault and phase faults.

The output on the earth faults is usually considerably more than that on phase faults is usually considerably more than that on phase faults so as to provide more sensitive action on earth faults.

Pick up setting can be expressed in term of combination of n and 1 for the various faults.

Zero output or a negligible small output may occur under through fault condition

when there is a phase to phase fault on the star side of the delta/star transformer giving 1:2:1 current distribution on the protected feeder.

(b) Sequence network:

In some cases it is desirable to make the protection respond to a particular phase

sequence component of the three phase system of currents and voltages.

Zero sequence and negative phase sequence networks are frequently used in power system protection.
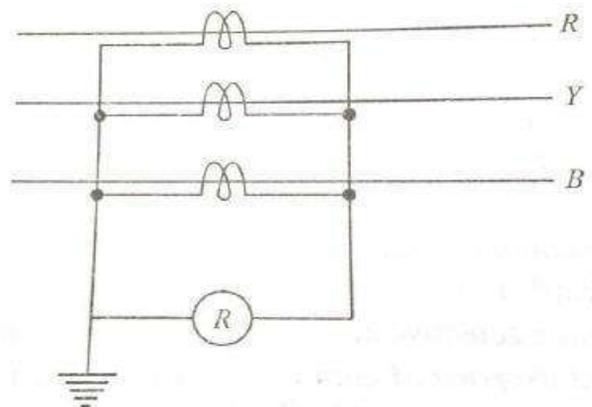
Zero sequence networks

Zero sequence networks are extensively used for earth fault protection. During the normal operation and for three phase and phase to phase faults the current passing through the relay is zero. When a single or double earth fault occurs, the zero sequence current flow through the relay.

For unbalanced condition or unsymmetrical faults:
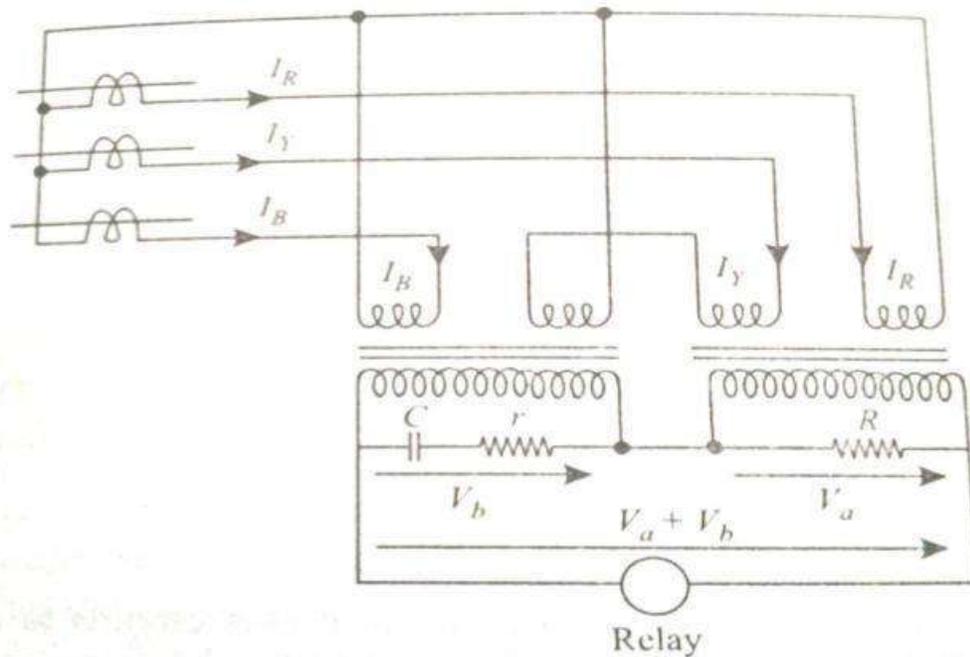
Negative phase sequence network

Negative phase sequence network

Negative phase sequence network are used. The values of r and c are there to give a phase sift of 60 degrees. It can be seen from the phasor diagram that for the +ve sequence currents the output voltage(Va+Vb) is zero where as for the negative sequence currents the output voltage is of considerable magnitude to operate the relay.

The protection responding to positive phase sequence components alone is not in relaying practice. Because under unsymmetrical faults, such a protection will have less sensitivity due to the fact that the positive phase is only a part of the fault current.
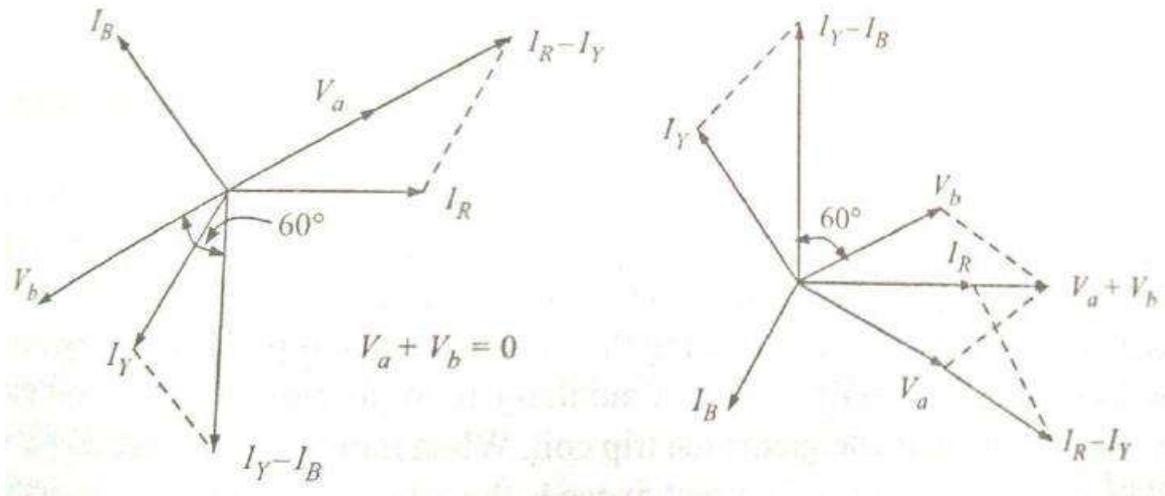
Positive sequence current   Negative sequence current

It is possible to use a combination of the positive sequence, negative sequence and zero sequence networks as a general rule. A combination of positive and negative sequence networks is wore common.

Components of Protection

Some of the commonly used components of the protective schemes are described here in brief. Those are

1. Relays

2. CB

3. Tripping and Auxiliary Supplies

4. CTs

Relays

When any abnormal condition develop, the main function of a protective relay is to isolate the faulty section with the least interruption to the service by controlling or operation the circuit breaker.

The relay may be designed to detect and to measure abnormal condition and close the contacts of the tripping circuit.

The two categories of relay are most commonly used in protective relay

a) Secondary indirect acting relays

Example: Current, Voltage, Power, Impedance, Reactance and frequency whether minimum or maximum

b) Secondary directing acting relay

A group of over current and under voltage relays designed to operate

immediately or with time lag.

These are relays of the electromagnetic type which are built into circuit breaker operating mechanism.

Circuit Breakers

It is desirable to switch on or off the various circuits like transmission line,

distributors generating plants under both normal and abnormal condition.

This can be done by a switch and a fuse but the limitations are

1. It take some time to replace

2. It cannot successfully interrupt heavy fault current.

So we use CB.

It can make or break a circuit either manually or automatically under all conditions (no load,

full load and fault) i.e.

a) It can make or break a circuit manually or by remote under normal condition

b) Break a circuit automatically under fault condition

c) Make a circuit either manually or by remote under fault condition

For operation of CB a relay is necessary. A protective relay is a device that detects the faults and initiate the operation of the circuit breaker to isolate the defective element from the rest of the system.

The electrical quantities which may change under fault condition are voltage, current, frequency and phase angle. Any changes in these quantities indicate presence of the fault.

Tripping and other Auxiliary Supplies For protective relay and automatic control scheme in power system use two kinds of

auxiliary supplies: DC and AC

DC auxiliary power supply is provided from batteries which is maintained continuously charged. The advantages of storage batteries are their high reliability and independent of power circuit conditions and of existence of fault.

Usually the voltage of the auxiliary supplies is maintained at 110 V

Mainly the auxiliary supplies power to protective relays, automatic control and the circuit breakers tripping circuit.Separate buses may also be provided for supplying power to relays, CB and other indicating circuit such as alarm and warning signals.
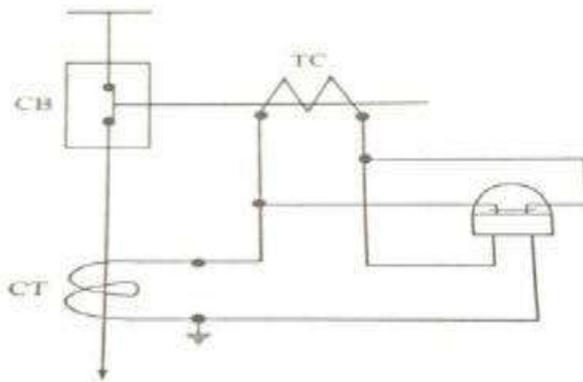
Relay with ac operative power from current transformer

In this scheme the relay has normally closed contacts. During normal operation the relay contacts continuously shut the circuit breakers trip coil and this keep the breaker closed.

When abnormal condition are approached the relays operates to open its contacts this put the trip.

Current Transformer (CT)

High magnitude primary current are reduce to a value suitable for relay operation to a value suitable for relay operation with the help of current transformers (CTs). (Then CTs provide current in the relay which are proportional to those in primary.)

The primary winding of the CTs is connected in series whit the load and carries the actual power system current (normal or fault). The secondary is connected to the measuring circuit or the relay.

The working range of a protective CT extends over the full range between the ankle and the knee points and beyond. Whereas the measuring CT usually operate in region of ankle point. Why?
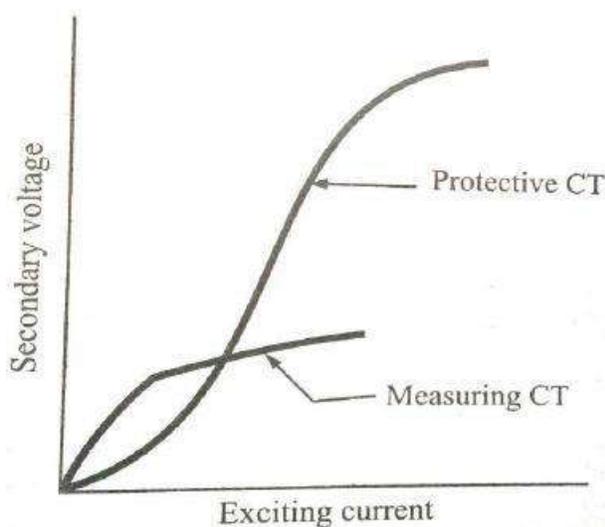
Measuring CTs require comparatively high accuracy over the range of 10% to 120% of rated.

Grain oriented steels having high saturation level are used As core materials for protective CTs and nickel iron alloys having low exciting ampere turn per unit length of the core use4d for measuring CTs.

It is common practice to use 1A secondary rating CTs.

The secondary of the bus bar primary CT is usually about 1500 secondary turn.

When rated primary currents much in excess of 1500 A are encountered then the main bar CTs with rated secondary current of 5A and 10A along with auxiliary CTs of 5/1 or 10/1 respectively are used.

Voltage Transformers

It is not possible to connect the voltage coils of the protective device directly to the system in case of high voltage systems. So it is necessary to step down the voltage, also to insulate the protective equipment from primary circuit. This is achieved by using a voltage transformers. Also known as potential transformer (PTs) which is similar to a power transformer. The voltage transformer is rated in terms of the maximum burden (VA) output it delivers without exceeding specified limits of errors. Whereas the power transformer is rated by the secondary output it delivers without exceeding a specified temperature rise.

The output of PTs is usually limited to a few hundred volt amperes and the secondary voltage is usually 110V between phases. Ideally a VT should produce a secondary voltage exactly proportion al to the primary voltage and exactly in phase opposition. This cannot obviously be achieved in practice owing to the voltage drops in the primary and secondary coil due to the magnitude and power factor of the secondary burden. Thus ratio errors and phase angle errors are introduced.

There are two types of Voltage devices

 a) The conventional wound type voltage transformers up to (132kV)

b) Capacitor Voltage Transformer (>132 kV)

When Appreciable current flows in the burden both ratio and phase are introduced because of the load current flowing through the capacitor C1.

The voltage drop on load due to reluctance of the capacitors can be compensated by inserting an inductance reactance in series with the load.

Linear Coupler

An iron core CT has limitation of saturation. Also owing to dc offset transient component present in the fault current, the stability on heavy through faults may be difficult to obtain.

With air cored CTs, also known as linear coupler, the problem of saturation and dc offset transient are overcome.

Two major difficulties with relay transient problem are

a) Differential saturation

b) Transference of DC through the iron cored CT

$$i_p = I_m \left(\cos \omega t - e^{-\frac{Rt}{L}} \right)$$

The secondary voltage is given by $M \frac{di}{dt}$

$$v_s = -\omega M \log \sin \omega t + \frac{R}{L} e^{-Rt/L}$$

$$v_s = -\omega M \log \left(\sin \omega t - \frac{R}{\omega L} e^{-Rt/L} \right)$$

It can be seen that the dc component voltage has been attenuated by a ratio R/X which may be 1/10 to 1/20 depending on the system.

References

3. B Ravindranath& M Chander, "Power system Protection and switchgear"New age International Publishers

4. Y.G Paithankar & S.R Bhide, "Fundamentals of powersystem Protection"PHI Publication

Operating principles and constructional features of relay

Relay classification

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

Protective relay can be classified as

- According to the function in protection scheme.

- According to the nature of actuating quantity.

- According to the connection of the sensing element

- According to the method by which the relay acts upon the circuit breaker

Generally the electrical protective relays can be broadly classified in two categories

(a) Electromagnetic relays

(b) Static relays

A relay in which the measurement or comparison of electrical quantities are done in a static network. The output signal operates a tripping device which may be electronic , semiconductor or electromagnetic.

The **static relays** are classified according to the types of measuring units or the comparator

1) Electronic relays

2) Transducer(magnetic amplifier relay)

3) Rectifier bridge relay

4) Transistor relay

5) Hall effect relay

6) Gauss effect relay

3.2 Principal types of electromagnetic relays

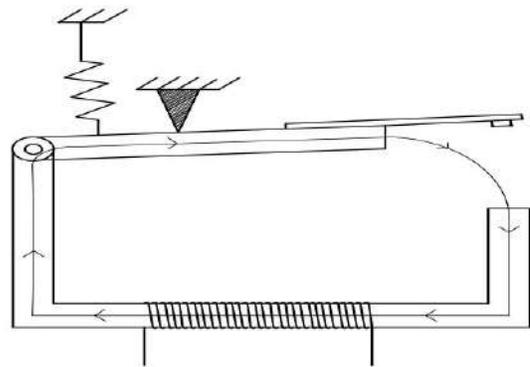There are two types of electromagnetic relays

a) Attracted armature type
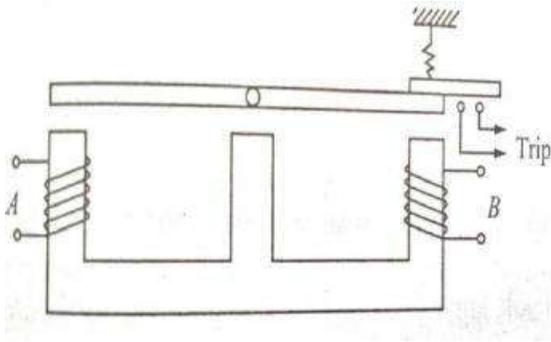
b) Induction type

Attracted armature type

• This includes plunger, hinged armature, balanced beam and moving iron polarised relay. These are simplified types which respond to A.C as well as D.C.
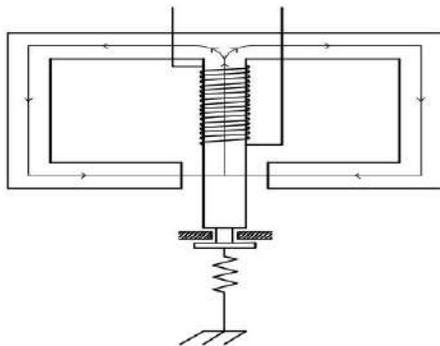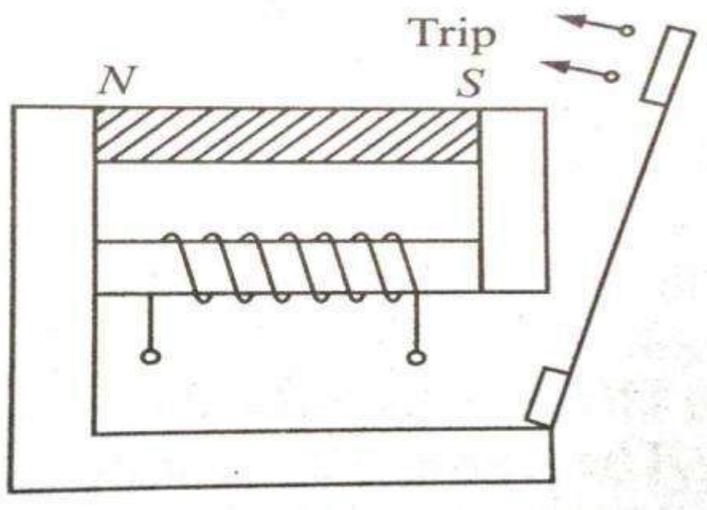

Plunger type)

Hinged armature type

Balanced beam type

Polarized moving iron type

In dc the electromagnetic force exerted on the moving element is proportional to the square of the flux or square of the current. In dc electromagnetic relay this force is constant. If this force exceeds the restraining force, the relay operates.

In ac electromagnetic relays the electromagnetic force is given by

$$Fe = kI^2$$
$$= k(I_{max}sinwt)^2$$
$$= \tfrac{1}{2}k\, I_{max}{}^2(1 - coswt)$$
$$= \tfrac{1}{2}k(\, I_{max}{}^2 - I_{max}{}^2cos\, 2wt\,)$$

This indicates that the electromagnetic force consists of two components (i) One constant(independent of time) and (ii)Another dependent on time and pulsating at double the frequency of the applied alternating quantities.
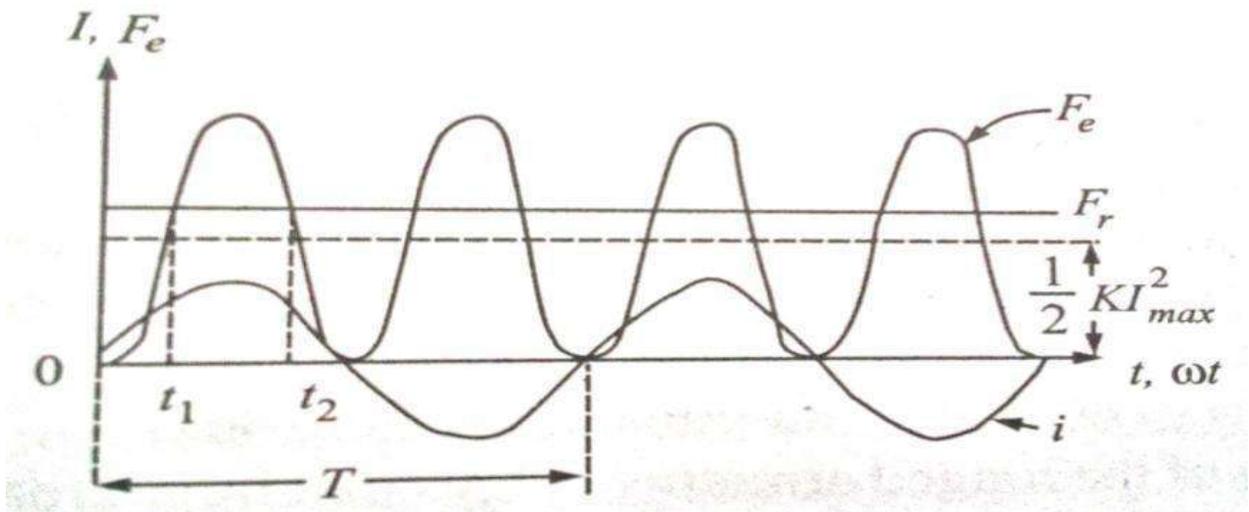
The total electromagnetic force pulsates at double the freq. the force is plotted graphically which shows that Fe =0 in every half period.

If Fr is produced with the help of a spring then it is constant.

Then the relay armature will be picked up at t1 and the armature drops off at t2.

Hence the armature vibrates at double the frequency. This causes the relay to hum and produces noise and also is a source of damage to relay contacts. This leads to sparking and unreliable operation of the relay operating circuit contacts due to make and break of the circuits.

To overcome this difficulties in ac electromagnetic relay the flux that produce electromagnetic force is divided into two fluxes among simultaneously but differing in time phase. So that the resultant electromagnetic force is always positive and this is always greater the restraining force so that the armature will not vibrate. This is achieved through shaded pole or by providing two winding having a phase shift.

The flux through the shaded pole lags behind the unshaded pole. In case of balanced beam type two quantities A and B are compared.Actually $|A|^2$ and $|B|^2$ are compared because the electromagnetic forces are proportional to (ampere turns)^2 .It has low ratio of reset by operating current.

Sensitivity of hinged armature relays can be increased for dc operation by the addition of a permanent magnet. This is known as a polarised moving iron relay.

Induction type relay

An induction relay essentially consists of aluminium disc placed in two alternating magnetic flux of same frequency but displaced in time and

space.The torque is produced in the disc by the interactions of one of the magnetic field with the currents induced in the disc by the other. Induction relays are widely used for protective relaying involving AC

quantities.High, low and adjustable speeds are possible and the various shapes of time/operating curve can be obtained.

Types of structure

a) Shaded pole

b) Wattmeter or double pole winding structure

c) Induction cup structure

(a) Shaded pole
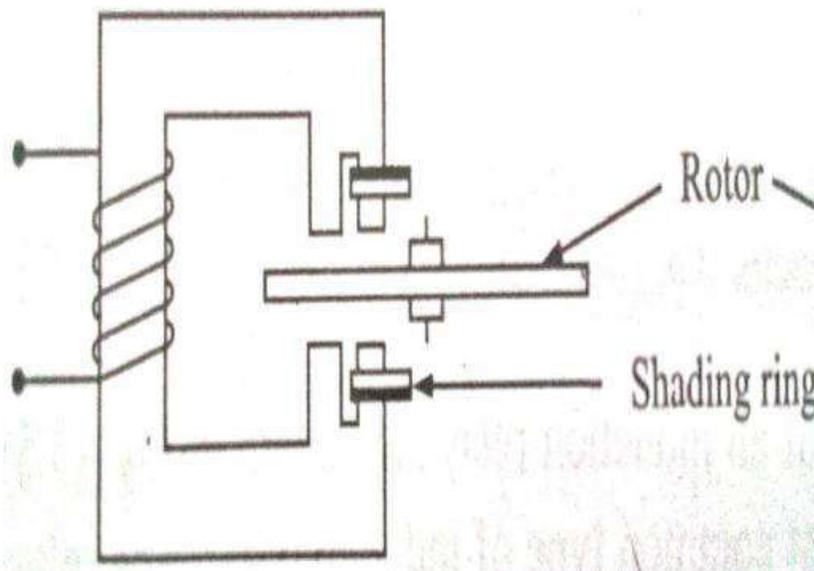
It consists of

1. 1. Pivoted aluminium disc free to rotate in the air gap of an electro magnet.

2. 2. One half is surrounded by copper band known as shaded ring.

The alternating flux in the shaded portion of the poles will lag behind the flux in the unshaded portion by an angle α due to the reaction of the current induced in the ring.

These two a.c fluxes differing in phase will produce the necessary torque to rotate the disc.

(b) Wattmeter structure or double winding structure
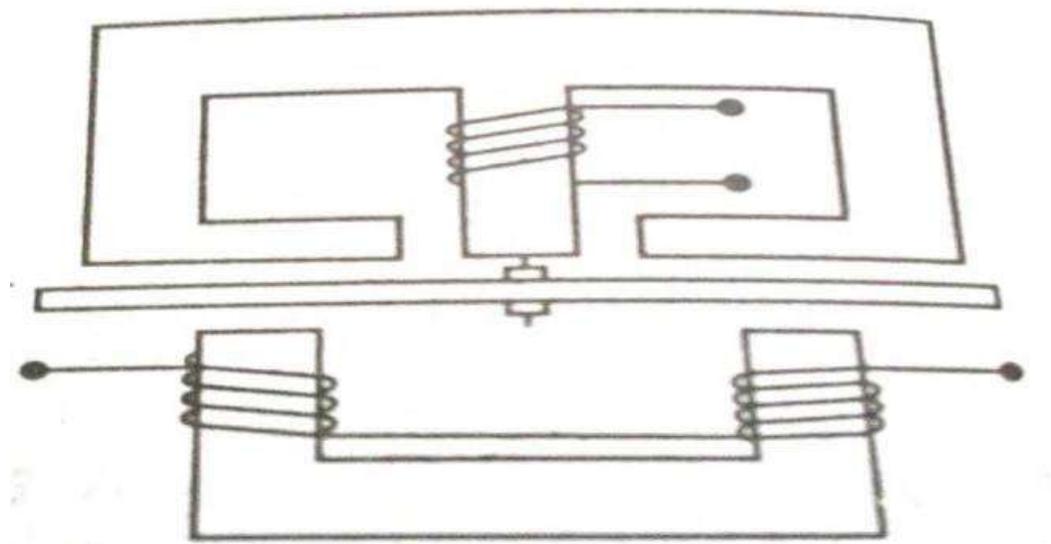
Wattmeter structure

In the wattmeter type these are two magnetic systems. A phase displacement between the fluxes is obtained either by having different inductance and resistance for the two circuits or energizing these from two different sources whose outputs are relatively displaced in phase as shown.

(c)Induction cup structure
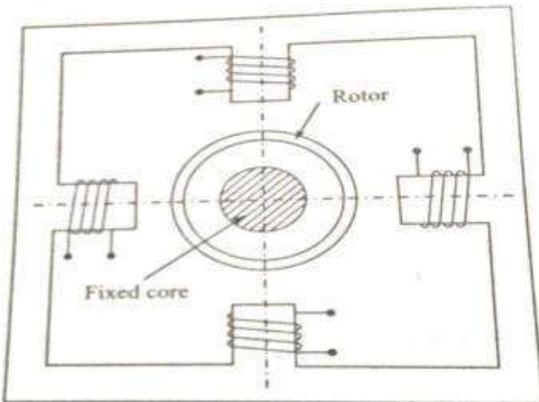
The rotating field is produced by two pairs of coils wound on four poles.The rotating field induced current in the cup to provide the necessary driving torque.

If Φ1 and Φ2 represent the fluxes produced by the respective pair of poles, then the torque produced is proportional to Φ1. Φ2 sinα
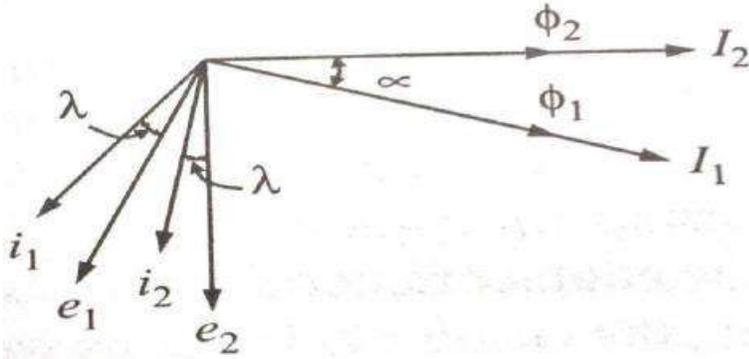
i.e T α Φ1.Φ2 sinα

A control spring and the back stop is provided for closing of the contacts that are attached to the spindle of the cup to prevent the continuous rotation.

Induction cup structure is more efficient torque producers than shaded pole and wattmeter type. So this type of relay has very high speed. The operating time is less than 1 second.

Theory of induction relay torque

Two magnetic fluxes Φ1 and Φ2 differing in time phase penetrate through a disc.

These alternating fluxes induce e.m.f.s e1 and e2 in the disc which lag their respective fluxes by 90 degrees.

$\Phi 1 = \Phi 1m \ \sin \omega t$

So $i_1 \, \alpha \, \dfrac{d\,\Phi 1}{dt} \propto \dfrac{d\Phi 1}{dt}(\Phi 1m \sin \omega t) \ \alpha \, \Phi_{1m} \cos \omega t$

$\Phi_2 = \Phi 2m \, \sin(\omega t + \alpha) \quad i_2 \, \alpha \, \dfrac{d\,\Phi 2}{dt} \quad \propto \dfrac{d\Phi 2}{dt}(\Phi_{2m} \sin(\omega t + \alpha)) \quad \alpha \, \Phi_{2m} \cos(\omega t + \alpha)$

$F_1 \, \alpha \, \Phi_1 \, i_2, \qquad F_2 \, \alpha \, \Phi_2 \, i_1$

Net force (F) $\alpha \ (F_2 - F_1)$

$\qquad \alpha \ (\Phi_2 \, i_1 - \Phi_1 \, i_2)$

$\qquad \alpha \ (\Phi_{2m} \, \Phi_{1m} \, (\sin(\omega t+\alpha)\cos\omega t - \sin \omega t \cos(\omega t + \alpha))$

$\qquad \alpha \ (\Phi_{2m} \, \Phi_{1m} \, (\sin(\omega t + \alpha - \omega t))$

$\qquad \alpha \ \Phi_{1m} \, \Phi_{2m} \sin \alpha$

$\qquad \alpha \ \Phi_1 \, \Phi_2 \sin \alpha$

where Φ_1 and Φ_2 are the rms values of the fluxes.

$\Phi 1 \, \alpha \, I_1$

$\Phi 2 \, \alpha \, I_2, \qquad$ For $T \, \alpha \, I_1 \, I_2 \sin(\alpha)$

The maximum torque is developed when α is 90 degree or 270 degree and zero torque when $\alpha=0$ or 180 degree.

Relay design and construction

The design of protective relay is normally divided into the following stages:

(a) Selection of the operating characteristics

(b) Selection of proper construction

(c) Design of the contact moment from the point of view of utmost reliability.

The relay operating characteristic must match with the abnormal operating characteristics of the system i.e. it should clearly show the conditions for tripping under various abnormal operating conditions.

The most important considerations in the design for construction are:

Reliability

Simplicity of construction

Circuitry

The construction of the relay is divided into the following:

i. Contacts

ii. Bearing

iii. Electromechanical design

iv. Termination and housing

Contacts

Contact performance is probably the most important item affecting reliability of the relay.

Corrosion or dust deposit can cause non-operation of relay.

Thus material and shape of relay are of considerable importance.

A good contact system design provides restricted contact resistance, reduced contact wear.

The contact material used are gold, gold alloy, platinum, pelledium and silver.

The selection of the contact material depends on a number of factors like:

- The voltage per contact break

- The current to break

- The type of atmospheric pollution under which the contacts are operate

The following factors are to be considered for selecting a suitable contact material:

1) The nature of the current to be interrupted (ac or dc)

2) Voltage at break and make operation

3) Value of current magnitude

4) Frequency of operation

5) The actual speed of contact at make or break

6) Contact shape

Some rules or points recommended in the design of contact system of a relay :

(a) The contacts should be bounce proof to avoid arcing at the contacts.

(b) There should be increased contact-pressure that leads to decrease in voltage drop or contact resistance.

(c) To promote accuracy and avoid sticking after a long period of inaction. So the relay should be designed to have maximum torque/friction ratio.

(d) The value of current that can be interrupted by a pair of contacts in ac circuit is 2 to 8 times than in a dc circuit.

Generally dome shaped contacts give best performances.

Bearing

(a) Single ball bearing

(b) Multi ball bearing

(c) Pivot and jewel bearing – This is the most common type for precision relay.

Electromechanical Design

It consists of the design of the magnetic circuit and the mechanical features of core,

yoke, and armature.The reluctance of the magnetic path is kept to a minimum by enlarging

the pole face which makes the magnetic circuit more efficient.AC electromagnets made from soft iron, low carbon steel core having a slot for mounting shaded rings are more common.

The relay coil current is usually limited to 5A and the coil voltage to 220 V but the insulation for the relay coil is designed to withstand at least 4kV.The relay coil is designed to carry about 15 times the normal current foe one second.

Termination and housing

Material used for springs are stainless steel, nickel steel, phosphorous bronze and Beryllium copper.

The spring is insulated from the armature by moulded blocks. For moulded blocks nylon is used.

References

1. B Ravindranath& M Chander, "Power system Protection and switchgear"New age International Publishers

2. Y.G Paithankar & S.R Bhide, "Fundamentals of powersystem Protection"PHI Publication

SYMMETRICAL COMPONENTS AND FAULT CALCULATIONS

Introduction

According to the method of symmetrical co-ordinates applied to a solution of polyphase network a system of n vectors or quantities may be resolved when n is prime, into n different symmetrical groups or systems, one of which consists of n equal vectors, and the rest (n-1) system consist of n equispaced vectors which with the first mentioned group of equal vectors forms an equal number of symmetrical n-phase systems.

3-Phase Systems

Any three coplanar vectors Va, Vb and Vc can be expressed in terms of three new vectors V1, V2 and V3 by three simultaneous equation with constant coefficients.

Thus

$$V_a = a_{11}V_1 + a_{12}V_2 + a_{13}V_3$$

$$V_b = a_{21}V_1 + a_{22}V_2 + a_{23}V_3$$

$$V_c = a_{31}V_1 + a_{32}V_2 + a_{33}V_3$$

Each of the vectors has been replaced by new vectors thereby making a new set of

nine vectors. The objective of making this transformation is done because

1. Calculations become simplified on the basis of this transformation.

2. The system of components chosen must have some physical significance.

According to the theorem, the three unbalanced vectors can be expressed by a set of three balanced system of vectors. A balanced system of three vectors is one in which the vectors are equal in magnitude and are equispaced. Hence the symmetrical components are:

1. Positive sequence components which have three vectors of equal magnitude and are displaced by 120° and has the same phase sequence as that of the original vectors.

2. Negative sequence components which have three vectors of equal magnitude and are displaced by 120° and has the opposite phase sequence as that of the original vectors.

3. Zero sequence components which have three vectors of equal magnitude and are also in phase with each other.

The subscripts 1, 2 and 0 represents positive, negative and zero sequence
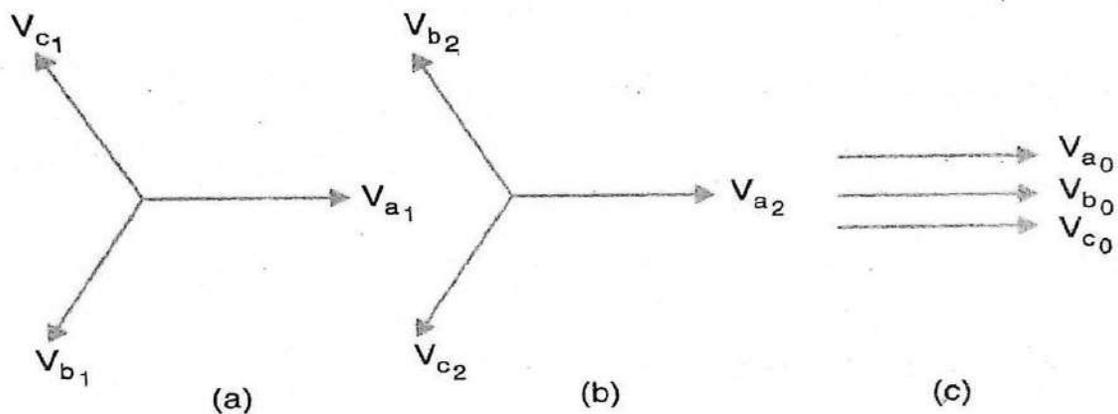
respectively.

Figure 1 (a) Positive sequence component (b) Negative sequence component (c) Zero sequence component

3. Significance of Positive, Negative and Zero sequence Components

The positive sequence system of vectors is meant that vectors are equal in magnitude and differs by 120° in phase with the same phase sequence. The real meaning is that if the stator winding of the alternator is supplied with a set of positive sequence voltages, the direction of rotation of the stator field is the same as the rotor. If the direction of rotation of the stator field is opposite to the direction of the rotor, the set of voltages are known as negative sequence voltages. The zero sequence voltages are the single phase voltages, and gives rise to the alternating field in the space.

From the above figure, it can be found out that the relation between the original set of unbalanced vectors and their corresponding symmetrical components is

$$V_a = V_{a_1} + V_{a_2} + V_{a_0}$$

$$V_b = V_{b_1} + V_{b_2} + V_{b_0}$$

$$V_c = V_{c_1} + V_{c_2} + V_{c_0}$$

Considering phase a as the reference vector, the relationship between the symmetrical components of phase b and c in terms of a can be written by the use of operator λ which has a magnitude of unity and a phase angle of 120° which rotates any vector by 120°. Thus

$$\lambda = 1\angle 120°$$

In the complex form

$$\lambda = \cos 120° + j\sin 120° = -0.5 + j\,0.866$$

Similarly

$$\lambda^2 = -0.5 - j\,0.866$$

$$\lambda^3 = 1.0 = 1\angle 360°$$

Or

$$\lambda^3 - 1 = 0$$

Or

$$(\lambda - 1)(\lambda^2 + \lambda + 1) = 0$$

Since $\lambda \neq 1$ as λ is a complex number

$$\lambda^2 + \lambda + 1 = 0$$

So for the positive sequence the symmetrical components of phase b and c in terms of symmetrical components of phase a can be written as

$$V_{b_1} = \lambda^2 V_{a_1}$$

$$V_{c_1} = \lambda V_{a_1}$$

For negative sequence vectors

$$V_{b_2} = \lambda V_{a_2}, \quad V_{c_2} = \lambda^2 V_{a_2}$$

For zero sequence vectors

$$V_{b_0} = V_{c_0} = V_{a_0}$$

Substituting these relations on to the above equations

$$V_a = V_{a_1} + V_{a_2} + V_{a_0}$$

$$V_b = \lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0}$$

$$V_c = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

Similar relations can be also derived for the phase currents in terms of symmetrical components of currents taking phase a as reference

$$I_a = I_{a_1} + I_{a_2} + I_{a_0}$$

$$I_b = \lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0}$$

$$I_c = \lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0}$$

From the above relation we can find the relation of symmetrical components in terms of phase components

$$V_{a_1} = \frac{1}{3}(V_a + \lambda V_b + \lambda^2 V_c)$$

Similarly

$$V_{a_2} = \frac{1}{3}(V_a + \lambda^2 V_b + \lambda V_c)$$

$$V_{a_0} = \frac{1}{3}(V_a + V_b + V_c)$$

4. Average Three Phase Power in terms of Symmetrical Components

The average power is given as

$$P = V_a I_a \cos\phi_a + V_b I_b \cos\phi_b + V_c I_c \cos\phi_c$$
$$P = V_a \cdot I_a + V_b \cdot I_b + V_c \cdot I_c$$
$$P = (V_{a_1} + V_{a_2} + V_{a_0}) \cdot (I_{a_1} + I_{a_2} + I_{a_0}) + (\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0}) \cdot (\lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0})$$
$$+ (\lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}) \cdot (\lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0})$$

Taking the first term on RHS

$$(V_{a_1} + V_{a_2} + V_{a_0}) \cdot (I_{a_1} + I_{a_2} + I_{a_0})$$
$$= V_{a_1} \cdot I_{a_1} + V_{a_2} \cdot I_{a_2} + V_{a_0} \cdot I_{a_0} + V_{a_1} \cdot I_{a_2} + V_{a_1} \cdot I_{a_0} + V_{a_2} \cdot I_{a_1} + V_{a_2} \cdot I_{a_0} + V_{a_0} \cdot I_{a_1}$$
$$+ V_{a_0} \cdot I_{a_2}$$

For second and the third term the dot product of two vectors doesn't change when both are rotated by the same angle.

For example,

$$\lambda^2 V_{a_1} \cdot \lambda^2 I_{a_1} = V_{a_1} \cdot I_{a_1}$$

$$\lambda^2 V_{a_1} \cdot \lambda I_{a_2} = \lambda V_{a_1} \cdot I_{a_2}$$

So the addition of the terms after expanding and rearranging,

$$P = 3V_{a_0} \cdot I_{a_0} + 3V_{a_2} \cdot I_{a_2} + 3V_{a_1} \cdot I_{a_1} + V_{a_1} \cdot I_{a_2}(1 + \lambda + \lambda^2) + V_{a_1} \cdot I_{a_0}(1 + \lambda + \lambda^2)$$
$$+ V_{a_2} \cdot I_{a_1}(1 + \lambda + \lambda^2) + V_{a_2} \cdot I_{a_0}(1 + \lambda + \lambda^2) + V_{a_0} \cdot I_{a_1}(1 + \lambda + \lambda^2)$$
$$+ V_{a_0} \cdot I_{a_2}(1 + \lambda + \lambda^2)$$

$$P = 3\left(V_{a_1} \cdot I_{a_1} + V_{a_2} \cdot I_{a_2} + V_{a_0} \cdot I_{a_0} \right)$$
$$P = 3\left[|V_{a_1}||I_{a_1}| \cos\theta_1 + |V_{a_2}||I_{a_2}| \cos\theta_2 + |V_{a_0}||I_{a_0}| \cos\theta_0 \right]$$

The same power expression can be very easily derived using matrix manipulation

$$P + jQ = V_a I_a^* + V_b I_b^* + V_c I_c^*$$

$$= [V_a \quad V_b \quad V_c] \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^* = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}^T \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^*$$

From previous equations

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \lambda \\ 1 & \lambda & \lambda^2 \end{bmatrix} \begin{bmatrix} V_{a_0} \\ V_{a_1} \\ V_{a_2} \end{bmatrix} = AV$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}^T = (AV)^T = V^T A^T$$

$$P + jQ = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}^T \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^* = [V_{a_0} \quad V_{a_1} \quad V_{a_2}] \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \lambda \\ 1 & \lambda & \lambda^2 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^*$$

Since λ and λ^2 are conjugates, so

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}^* = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \lambda \\ 1 & \lambda & \lambda^2 \end{bmatrix}^* \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^* = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda & \lambda^2 \\ 1 & \lambda^2 & \lambda \end{bmatrix} \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$P + jQ = [V_{a_0} \quad V_{a_1} \quad V_{a_2}] \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda^2 & \lambda \\ 1 & \lambda & \lambda^2 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \lambda & \lambda^2 \\ 1 & \lambda^2 & \lambda \end{bmatrix} \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$= [V_{a_0} \quad V_{a_1} \quad V_{a_2}] \begin{bmatrix} 3 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 3 \end{bmatrix} \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$= 3[V_{a_0} \quad V_{a_1} \quad V_{a_2}] \begin{bmatrix} I_{a_0} \\ I_{a_1} \\ I_{a_2} \end{bmatrix}^*$$

$$= 3[V_{a_0} I_{a_0}^* + V_{a_1} I_{a_1}^* + V_{a_2} I_{a_2}^*]$$

$$P = 3[|V_{a_0}||I_{a_0}| \cos \theta_0 + |V_{a_1}||I_{a_1}| \cos \theta_1 + |V_{a_2}||I_{a_2}| \cos \theta_2]$$

5. Sequence Impedances

Like the symmetrical components for the current, voltage and power, the impedances are also composed of symmetrical components known as the sequence impedances. These can be defined as follows:

The positive sequence impedance of equipment is the impedance offered by the equipment to the flow of positive sequence impedance. Similarly, the negative and zero sequence impedance of the equipment is the impedance offered by the equipment to the flow of corresponding sequence currents.

Measurement of Sequence Impedance of Rotating Machines

Measurement of positive sequence impedance: The positive sequence impedance depends upon the working of the machine, i.e. whether it is working under subtransient, transient or steady state condition. The impedance measured under steady state is known as synchronous impedance and is measured by the well known open circuit and short circuit test. The impedance is defined as

$$
\begin{aligned}
&\text{Synchronous impedance in p. u.}\\
&= \frac{\text{Normal open circuit voltage at the field current corresponding to the rated armature current}}{\text{Rated Armature current at that particular field current}}
\end{aligned}
$$

Method of test for synchronous Impedance: The machine here is run at a proper direction with the help of a prime mover. The shorting link switch is kept in off position to perform open circuit test and noted the readings of the voltmeter by varying the field current. Similarly, the short circuit test is done by putting the shorting switch on and noting the readings of armature current with the variation of the field current.
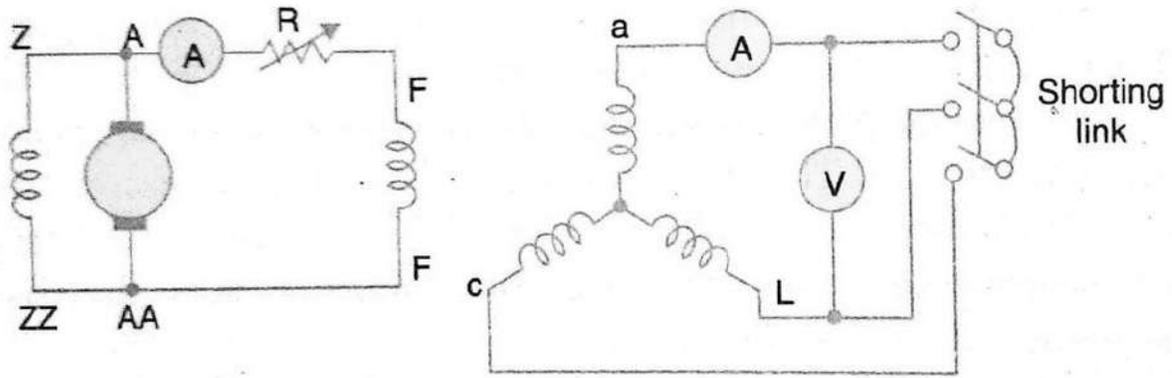
Figure 2 Connection Diagram for open circuit and short circuit test of an alternator

Measurement of Negative sequence Reactance: It is the impedance offered to the flow of negative sequence current.
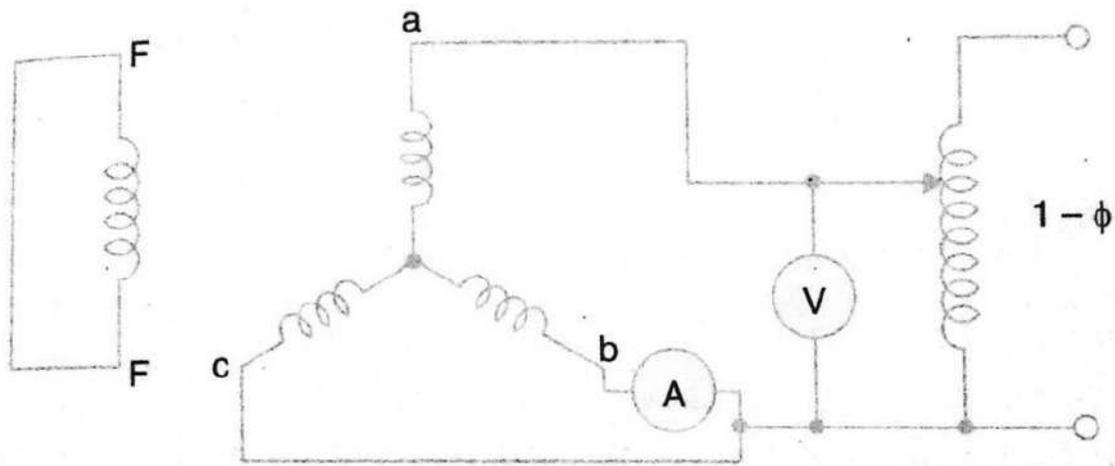

Figure 3 Measurement of negative sequence impedance

The machine here is driven at rated speed, and a reduced voltage is applied till the rated current flows in the armature. When there is a flow of negative sequence current there may be a possibility of hunting which would cause the pointer to deflect. This allows the mean reading to be taken. The negative sequence impedance is given by

$$Z_2 = \frac{V}{\sqrt{3}I}$$

Where V is the voltmeter and I is the ammeter reading.

This can be proved mathematically as follows

From the experiment, since it is similar to line-to-line fault with alternator unloaded,

$$I_a = 0, I_b = I, I_c = -I$$

Under these conditions, the positive sequence and negative sequence currents are opposite to each other and the positive and negative sequence voltages are equal.

$$V = V_a - V_b$$

$$V = V_{a_1} + V_{a_2} - (\lambda^2 V_{a_1} + \lambda V_{a_2}) = 2V_{a_2} + V_{a_2} = 3V_{a_2}$$

And the current in the ammeter

$$I = I_b = \lambda^2 I_{a_1} + \lambda I_{a_2} = (\lambda - \lambda^2)I_{a_2}$$

$$\lambda - \lambda^2 = -0.5 + j0.866 + 0.5 + j0.866 = \left|\sqrt{3}\right|\angle 90°$$

Current measured $= I = \sqrt{3}I_{a_2}$

$$\frac{V}{\sqrt{3}I} = \frac{V_a - V_b}{\sqrt{3}I_b} = \frac{3V_{a_2}}{\sqrt{3}.\sqrt{3}I_{a_2}} = \frac{V_{a_2}}{I_{a_2}} = Z_2$$

Measurement of zero sequence impedance: Zero sequence impedance is the impedance offered by the machine to the flow of zero sequence current. This impedance depends on the distribution of the windings on

the factors like pitch and breadth factors. The value is much smaller as compared to zero and negative sequences.
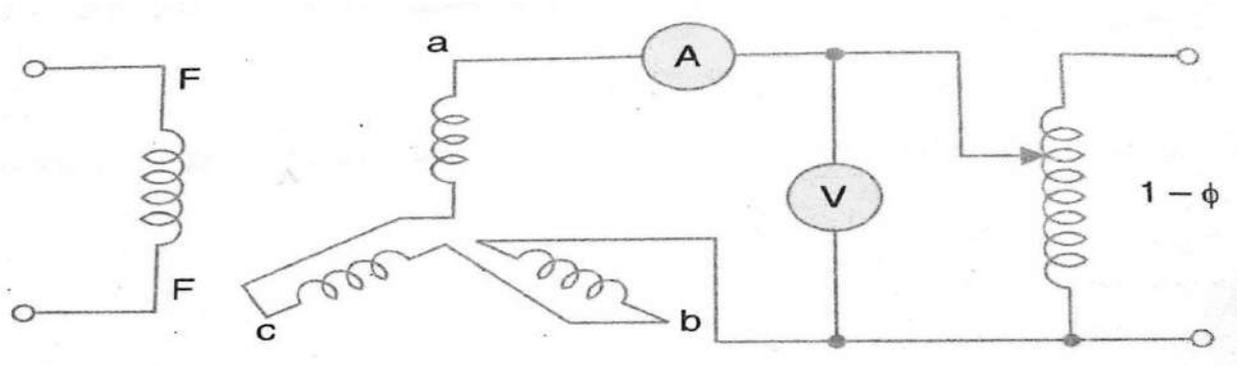

Figure 4 Measurement of Zero sequence impedance

The machine is at standstill and a reduced voltage is applied. The zero sequence impedance is $Z_0 = V/3I$.

6. Fault Calculation

The faults in a power system can be classified as:

1. Shunt Faults

2. Series Faults

Shunt type of faults involve power conductors or conductors-to-ground or short circuit between conductors. When the circuits are controlled by fuses and in which

one or two phases of the circuit gets opened while the other phase is closed, such

type of faults is known as series faults.

Shunt faults may be classified as (i) Line-to ground fault; (ii) Line-to-line fault; (iii) Double line to ground fault; and (iv) 3-phase fault. Of these, the first three are unsymmetrical faults as the symmetry is

distributed over one or two phases while the 3-phase fault is a balanced fault.

Series faults are classified as: (i) one open conductor; and (ii) two open conductors. These faults disturb the symmetry in one or two phases and are unbalanced faults.

We are mainly concerned with symmetrical faults.

Voltage of the neutral

The potential of the neutral when it is grounded through some impedance is not equal to the ground potential under unbalanced operation. The potential of the neutral is given as $V_n = -I_n Z_n$, where

Z_n is the neutral grounding impedance and the In is the neutral current. Here negative sign is given as the current flows from the ground to the neutral of the system and the potential of the neutral is lower than the ground

$$I_n = I_a + I_b + I_c$$
$$= \left(I_{a_1} + I_{a_2} + I_{a_0}\right) + \left(\lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0}\right) + \left(\lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0}\right)$$
$$= I_{a_1}(1 + \lambda + \lambda^2) + I_{a_2}(1 + \lambda + \lambda^2) + 3I_{a_0}$$
$$= 3I_{a_0}$$

$$V_n = -3I_{a_0} Z_n$$

Since the positive and negative sequence currents are absent through the neutral are absent, hence the drops due to these currents are also zero. Also for the balanced set of currents or voltages, the neutral is at the ground potential. Therefore for positive and negative sequence networks, neutral of the system will be taken as reference.

Reference of Voltages

The phase voltages at any point in a grounded system and their zero sequence components of voltage will be referred to the ground at that point. The positive and negative sequence components of voltage are referred to neutral. Therefore the voltage to ground and voltage to neutral is use alternatively but for the zero sequence system it is important to distinguish between the two terms.

7. Sequence network Equations

The equations will be derived for an unloaded transformer with neutral solidly grounded, assuming that the system is initially balanced, i.e. the generated voltages are of equal magnitude and displaced by $120°$.
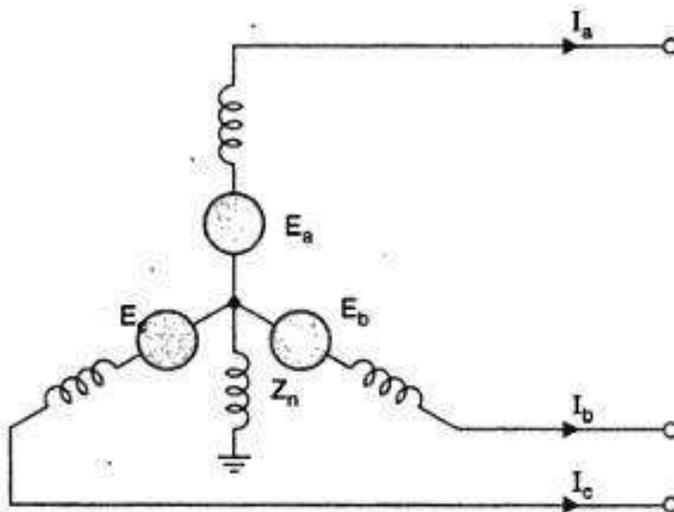
Figure 5 A balanced three phase system

Since the sequence impedances per phase are same for all three phase and we are considering initially a balanced system, the fault analysis will be done on single phase basis.

The positive sequence component of voltage at the fault point is the positive sequence generated voltage minus the drop due to the positive sequence current in the positive sequence impedance.

$$V_{a_1} = E_a - I_{a_1} Z_1$$

Similarly for the negative sequence component of voltage at the fault point is the negative sequence generated voltage minus the drop due to the negative sequence current in the negative sequence impedance.

$$V_{a_2} = E_{a_2} - I_{a_2} Z_2$$

Since the negative sequence voltage generated is zero, therefore

$$E_{a_2} = 0$$
$$V_{a_2} = -I_{a_2} Z_2$$

Similarly for zero sequence voltage

$$E_{a_0} = 0$$
$$V_{a_0} = V_n - I_{a_0} Z_{g_0} = -3I_{a_0} Z_n - I_{a_0} Z_{g_0} = -I_{a_0}(Z_{g_0} + 3Z_n)$$

Where Z_{g0} is the zero sequence impedance of the generator and Zn is the neutral impedance.

The three sequence network equations are therefore

$$V_{a_1} = E_a - I_{a_1}Z_1$$

$$V_{a_2} = -I_{a_2}Z_2$$

$$V_{a_0} = -I_{a_0}Z_0$$

Where $Z_0 = Z_{g0} + 3Z_n$ and the corresponding sequence networks for the unloaded alternator is shown in the figure below
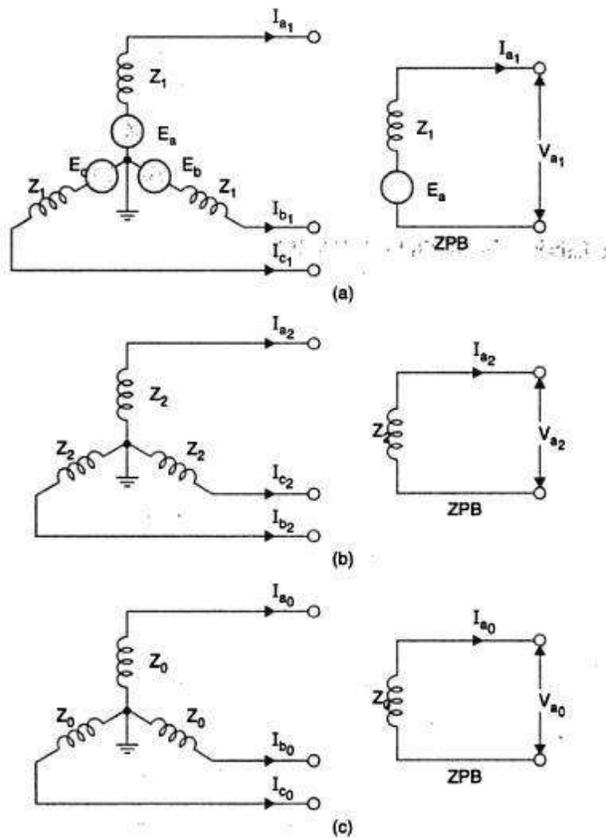

Figure 6 Sequence networks (a) Positive Sequence network (b) Negative sequence network (c) Zero Sequence network

8. Single Line-to-Ground Fault

The system to be analyzed is given below. If there is a line-to-ground fault at phase a, the boundary conditions are

$$V_a = 0$$

$$I_b = 0$$

$$I_c = 0$$
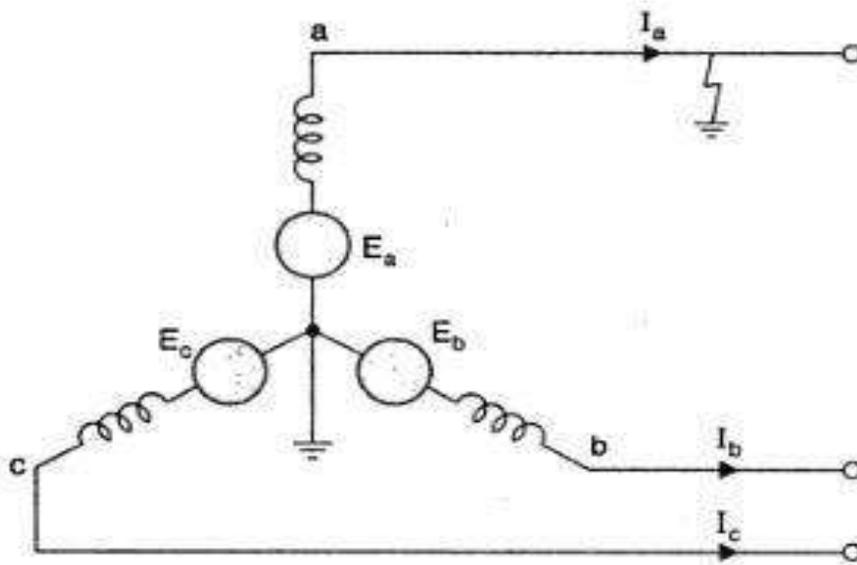
Figure 7 A solidly grounded, unloaded alternator: L-G fault on phase a

The sequence network equations are

$$V_{a_0} = -I_{a_0}Z_0$$

$$V_{a_1} = E_a - I_{a_1}Z_1$$

$$V_{a_2} = -I_{a_2}Z_2$$

The solution of these six equations will give all the six sequence components of voltage and current.

From the sequence current equations

$$I_{a_1} = \frac{1}{3}(I_a + \lambda I_b + \lambda^2 I_c)$$

$$I_{a_2} = \frac{1}{3}(I_a + \lambda^2 I_b + \lambda I_c)$$

$$I_{a_0} = \frac{1}{3}(I_a + I_b + I_c)$$

Substituting the values of I_b and I_c in the above equations

$$I_{a_1} = I_{a_2} = I_{a_0} = I_a/3$$

Similarly according to the symmetrical component of voltage

$$V_a = 0 = V_{a_1} + V_{a_2} + V_{a_0}$$

Substituting the values of sequence voltages from the sequence network equation,

$$E_a - I_{a_1} Z_1 - I_{a_2} Z_2 - I_{a_0} Z_0 = 0$$

Since,

$$I_{a_1} = I_{a_2} = I_{a_0}$$

The above equation becomes

$$E_a - I_{a_1} Z_1 - I_{a_1} Z_2 - I_{a_1} Z_0 = 0$$

$$I_{a_1} = \frac{E_a}{Z_1 + Z_2 + Z_0}$$

From the above equation it is evident that to simulate an L-G fault all the three sequence networks are required, and all these sequence networks are to be connected in series, as the sequence currents are equal in magnitude and phase. The interconnection is shown in the figure below
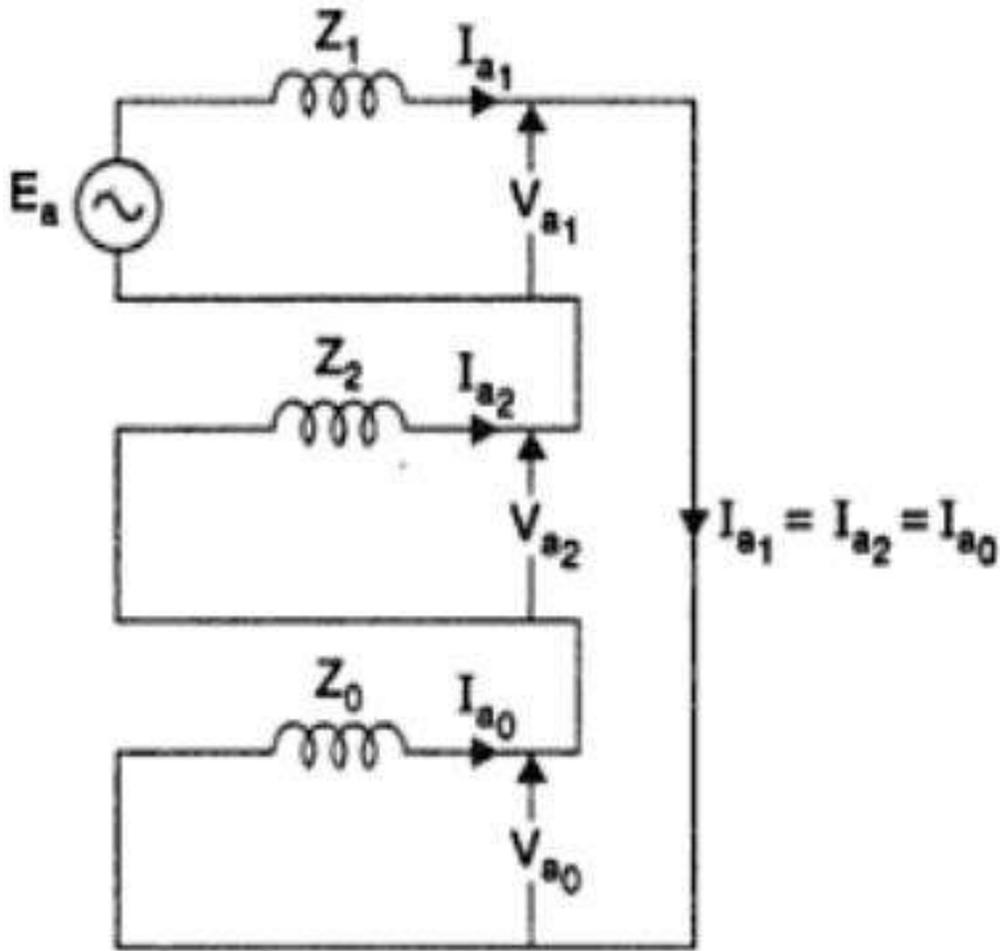
Figure 8 Interconnection of sequence networks for L-G fault

9. Line-to-Line Fault

As given in the figure below, the line-to-line fault takes place on phase b and c. The boundary conditions are

$$I_a = 0$$

$$I_b + I_c = 0$$

$$V_b = V_c$$

And the sequence network equations are same as above. The solution of these six equations will give the six unknowns.
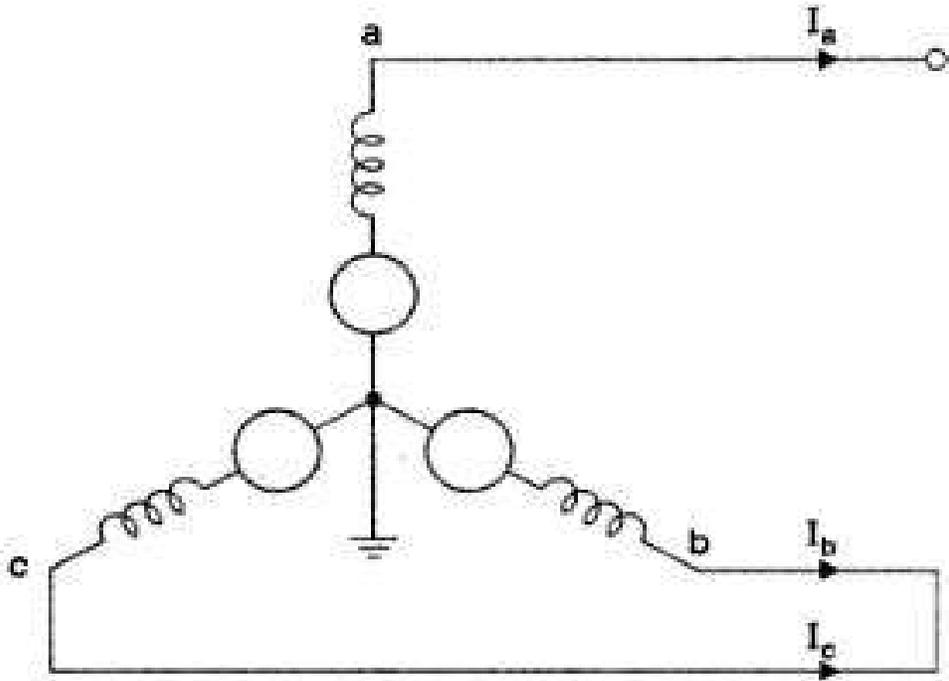

Figure 9 L-L fault on an unloaded and neutral grounded alternator

Using the relation

$$I_{a_1} = \frac{1}{3}(I_a + \lambda I_b + \lambda^2 I_c)$$

$$I_{a_2} = \frac{1}{3}(I_a + \lambda^2 I_b + \lambda I_c)$$

$$I_{a_0} = \frac{1}{3}(I_a + I_b + I_c)$$

And substituting for I_a, I_b and I_c

$$I_{a_1} = \frac{1}{3}(I_a + \lambda I_b + \lambda^2 I_c) = \frac{1}{3}(\lambda - \lambda^2)I_b$$

$$I_{a_2} = \frac{1}{3}(I_a + \lambda^2 I_b + \lambda I_c) = \frac{1}{3}(\lambda^2 - \lambda)I_b$$

$$I_{a_0} = \frac{1}{3}(I_a + I_b + I_c) = 0$$

So from the above relation, the zero sequence component of current is absent and the positive and negative sequence is equal in magnitude but opposite in phase.

$$I_{a_1} = -I_{a_2}$$

To simulate the L-L fault, the zero sequence network is not necessary and the positive and negative sequence networks must be connected in phase opposition.

From the voltage equation,

$$V_b = \lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0}$$

$$V_c = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

Substituting the voltage relation

$$V_b = V_c$$
$$\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0} = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

So, solving this we get

$$V_{a_1} = V_{a_2}$$

So the positive sequence component of voltage equals the negative sequence component of voltage.

$$V_{a_1} = V_{a_2}$$

$$E_a - I_{a_1}Z_1 = -I_{a_2}Z_2 = I_{a_1}Z_2$$

$$I_{a_1} = \frac{E_a}{Z_1 + Z_2}$$

The interconnection of the sequence network can be simulated as below
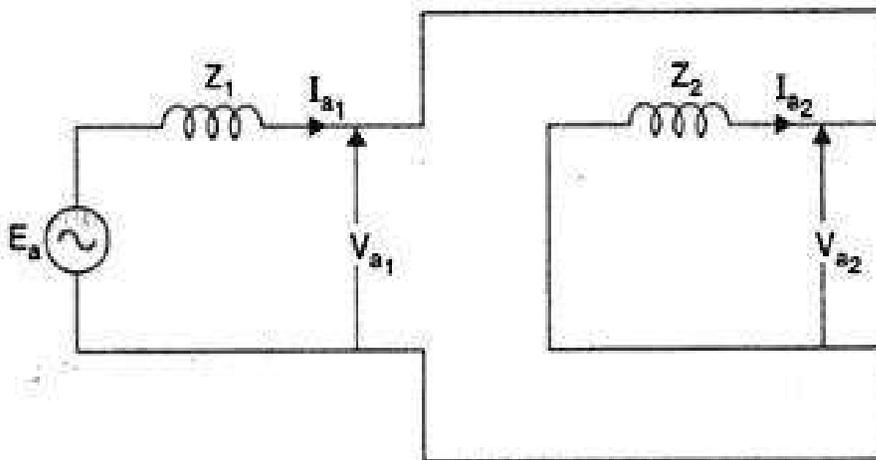
Figure 10 Interconnection of sequence networks for L-L fault

10. Double Line to Ground Fault

Assuming a double line to ground fault on phases b and c. The boundary conditions are

$$I_a = 0$$

$$V_b = 0$$
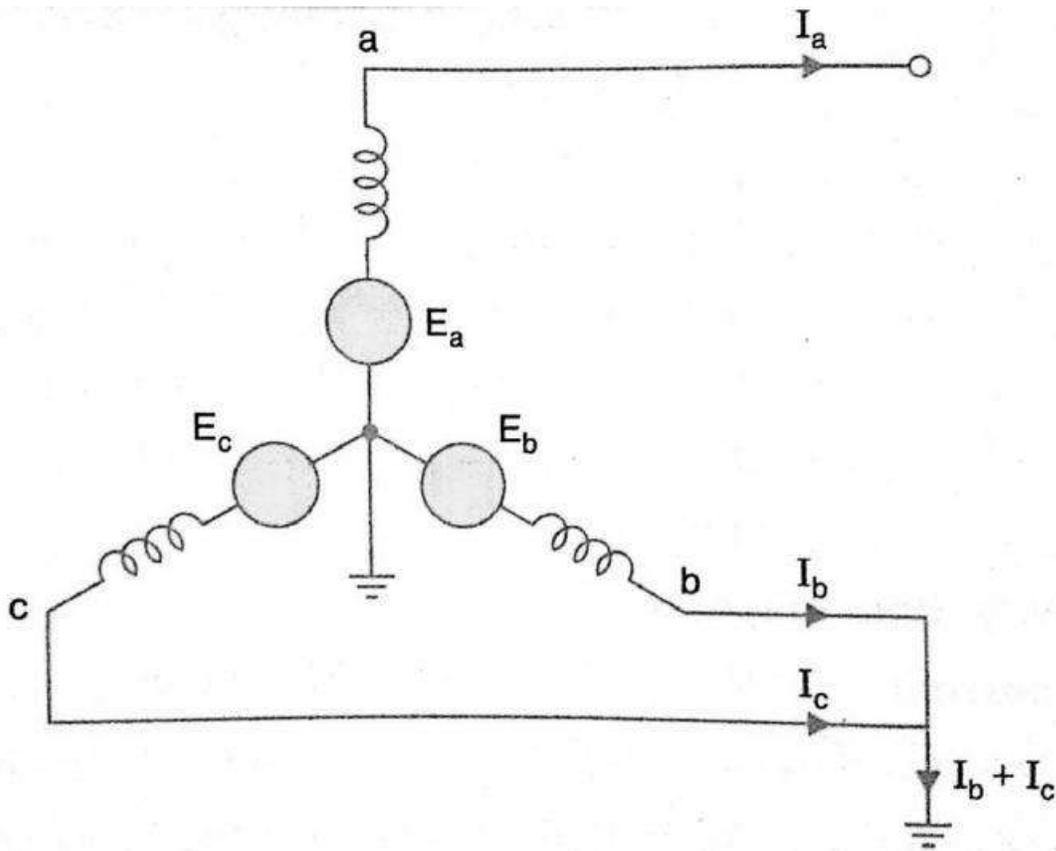
$$V_c = 0$$

And the sequence network equations are given.

Figure 11 A solidly grounded, unloaded alternator, L-L-G fault

The solution of these six equations will give six unknown symmetrical components. Using the symmetrical components of voltage

$$V_{a_0} = \frac{1}{3}(V_a + V_b + V_c) = \frac{V_a}{3}$$

$$V_{a_1} = \frac{1}{3}(V_a + \lambda V_b + \lambda^2 V_c) = \frac{V_a}{3}$$

$$V_{a_2} = \frac{1}{3}(V_a + \lambda^2 V_b + \lambda V_c) = \frac{V_a}{3}$$

$$V_{a_0} = V_{a_1} = V_{a_2}$$

Using the above relations,

$$V_{a_0} = V_{a_1}$$

$$-I_{a_0} Z_0 = E_a - I_{a_1} Z_1$$

$$I_{a_0} = -\left(\frac{E_a - I_{a_1} Z_1}{Z_0}\right)$$

Similarly,

$$V_{a_2} = V_{a_1}$$

$$-I_{a_2}Z_2 = E_a - I_{a_1}Z_1$$

$$I_{a_2} = -\frac{E_a - I_{a_1}Z_1}{Z_2}$$

Now from the boundary condition,

$$I_a = I_{a_1} + I_{a_2} + I_{a_0} = 0$$

Substituting the expression for sequence components of current

$$I_{a_1} - \frac{E_a - I_{a_1}}{Z_0} - \frac{E_a - I_{a_1}Z_1}{Z_2} = 0$$

Solving the above equation we get,

$$I_{a_1} = \frac{E_a}{Z_1 + \frac{Z_0 Z_2}{Z_0 + Z_2}}$$

From the above equation it is clear that all the three sequence networks are required to simulate L-L-G fault and also that the negative and zero sequence networks are connected in parallel. The interconnection of the network is shown below
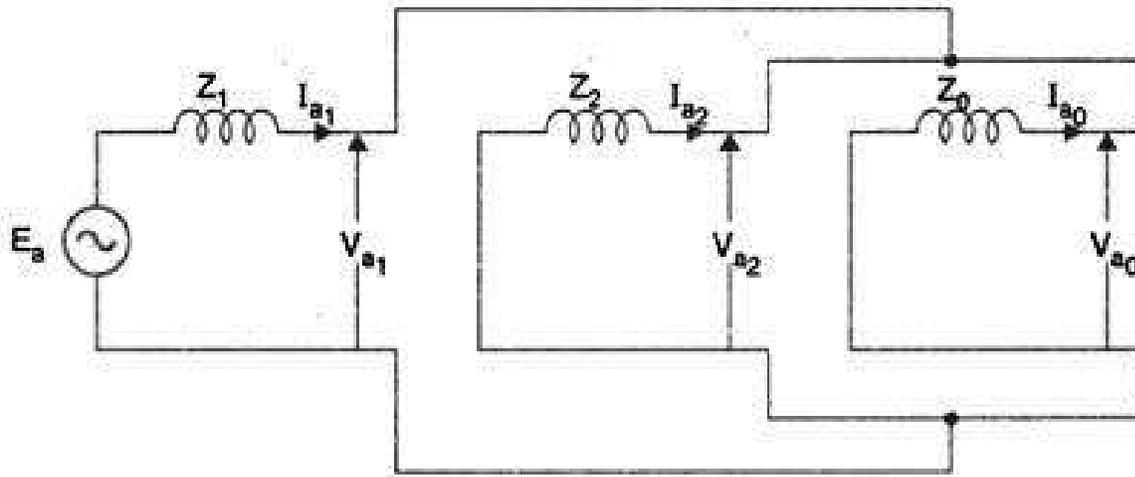
Figure 12 Interconnection of sequence networks for L-L-G fault

The neutral current

$$
\begin{aligned}
I_n &= I_b + I_c \\
&= \lambda^2 I_{a_1} + \lambda I_{a_2} + I_{a_0} + \lambda I_{a_1} + \lambda^2 I_{a_2} + I_{a_0} \\
&= (\lambda^2 + \lambda) I_{a_1} + (\lambda + \lambda^2) I_{a_2} + 2 I_{a_0} \\
&= -I_{a_1} - I_{a_2} + 2 I_{a_0} \\
&= I_{a_0} + 2 I_{a_0} = 3 I_{a_0}
\end{aligned}
$$

11. Three Phase Fault

As per the figure given below, the boundary conditions are

$$I_a + I_b + I_c = 0$$
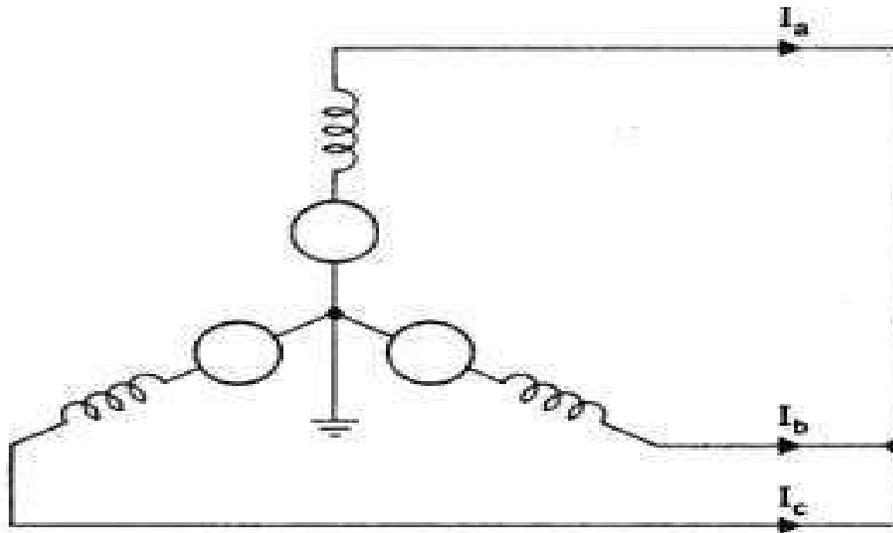
$$V_a = V_b = V_c$$

Figure 13 A 3-phase neutral grounded and unloaded alternator 3-phase shorted

Since the phase currents are equal in magnitude, taking Ia as the reference

$$I_b = \lambda^2 I_a \text{ and } I_c = \lambda I_a$$

Using this relation

$$I_{a_1} = I_a$$

$$I_{a_2} = 0$$

$$I_{a_0} = 0$$

Similarly, for the sequence voltages, it can be found out as according to the boundary condition

$$V_{a_1} = 0$$

$$V_{a_2} = 0$$

$$V_{a_0} = 0$$

Since,

$$V_{a_1} = 0$$

$$E_a - I_{a_1}Z_1 = 0$$

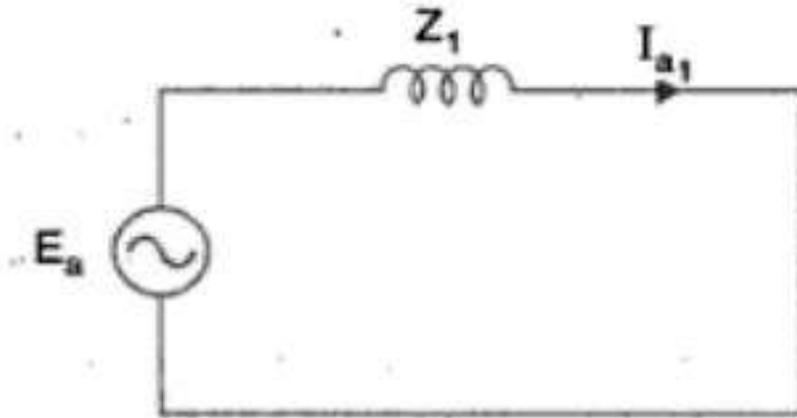$$I_{a_1} = \frac{E_a}{Z_1}$$

The sequence networks is shown as below

Figure 14 Interconnection of sequence network 3-phase fault

12. Line-to-ground fault with ZF

When the fault impedance and the neutral impedance are included, the analysis of the single line to ground fault can be analyzed as follows

The boundary conditions are

$$V_a = I_a Z_F$$

$$I_b = 0, I_c = 0$$

$$V_{a_0} = -I_{a_0}(Z_{g_0} + 3Z_n)$$

$$V_{a_1} = E_a - I_{a_1}Z_1, V_{a_2} = -I_{a_2}Z_2$$

From the above equations, the sequence components can be derived as

$$I_{a_1} = I_{a_2} = I_{a_0} = I_a/3$$

$$V_{a_1} + V_{a_2} + V_{a_0} = V_a = 3\, I_{a_1} Z_F$$

$$E_a - I_{a_1} Z_1 - I_{a_1} Z_2 - I_{a_1}(Z_0 + 3Z_n) = 3\, I_{a_1} Z_F$$

$$I_{a_1} = \frac{E_a}{Z_1 + Z_2 + (Z_0 + 3Z_n) + 3Z_F}$$

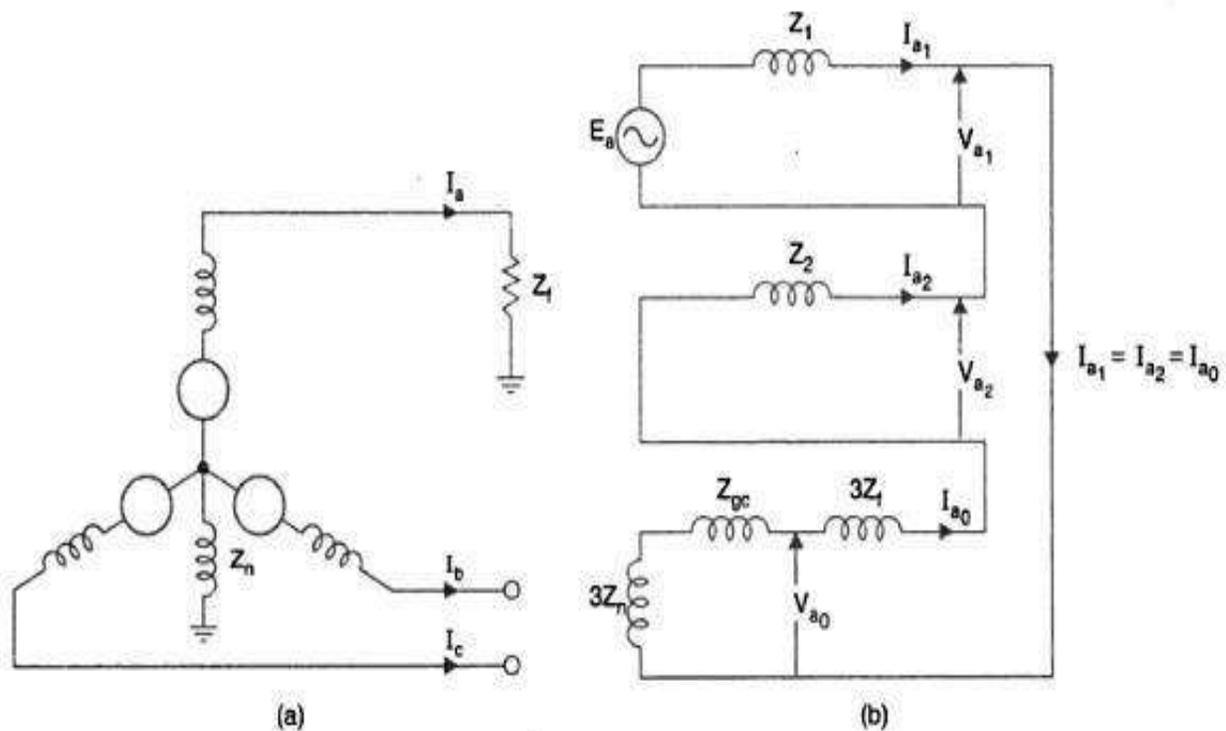The fault diagram and the interconnection is given below

Figure 15 (a) A 3 phase unloaded with neutral grounded through impedance Zn and fault impedance ZF, L-G fault (b) Interconnection of sequence network for L-G fault

13. Line-to-line fault with Z_F

The boundary conditions for the same are

$$I_a = 0$$

$$I_b + I_c = 0$$

$$V_b = V_c + I_b Z_F$$

And the sequence network equations

$$V_{a_0} = -I_{a_0} Z_0$$

$$V_{a_1} = E_a - I_{a_1} Z_1$$

$$V_{a_2} = -I_{a_2} Z_2$$

By using the symmetrical component analysis, we get

$$I_{a_1} = -I_{a_2} \text{ and } I_{a_0} = 0$$

Using the above boundary condition, we get

$$V_b = V_c + I_b Z_F$$

$$\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0} = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0} + (\lambda^2 I_{a_1} + \lambda I_{a_2}) Z_F$$

$$(\lambda^2 - \lambda) V_{a_1} = (\lambda^2 - \lambda) V_{a_2} + (\lambda^2 - \lambda) I_{a_1} Z_F$$

$$V_{a_1} = V_{a_2} + I_{a_1} Z_F$$

Substituting the values by sequence networks, we get

$$E_a - I_{a_1} Z_1 = -I_{a_2} Z_2 + I_{a_1} Z_F$$

$$I_{a_1} = \frac{E_a}{Z_1 + (Z_2 + Z_F)}$$

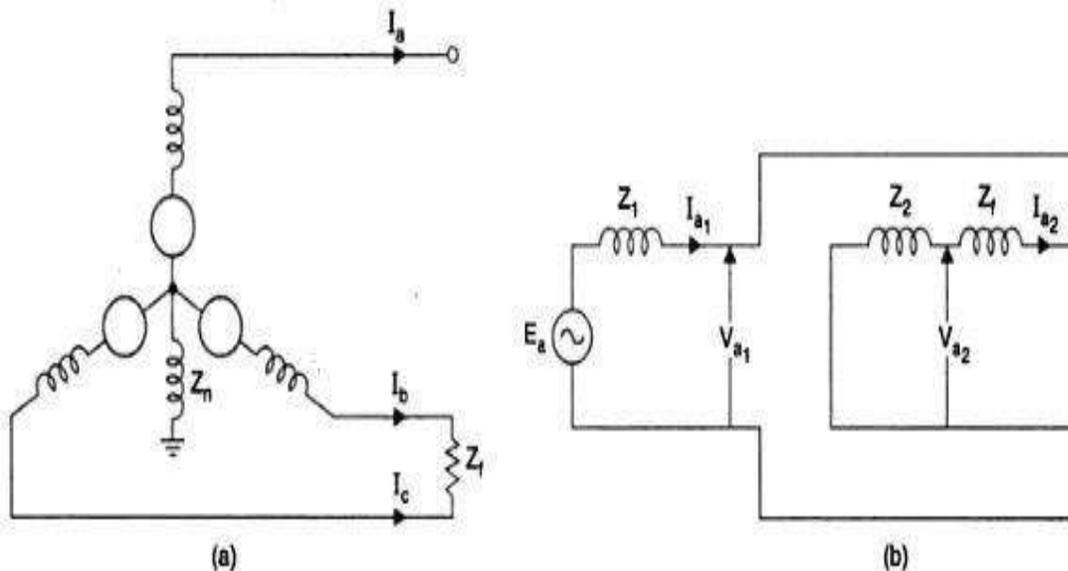The interconnection is shown in the figure below

Figure 16 (a) L-L fault; (b) Interconnection of sequence network, fault impedance Z$_F$, L-L fault

14. Double Line to Ground fault with Z$_F$

The boundary condition for this type of fault is

$$I_a = 0$$

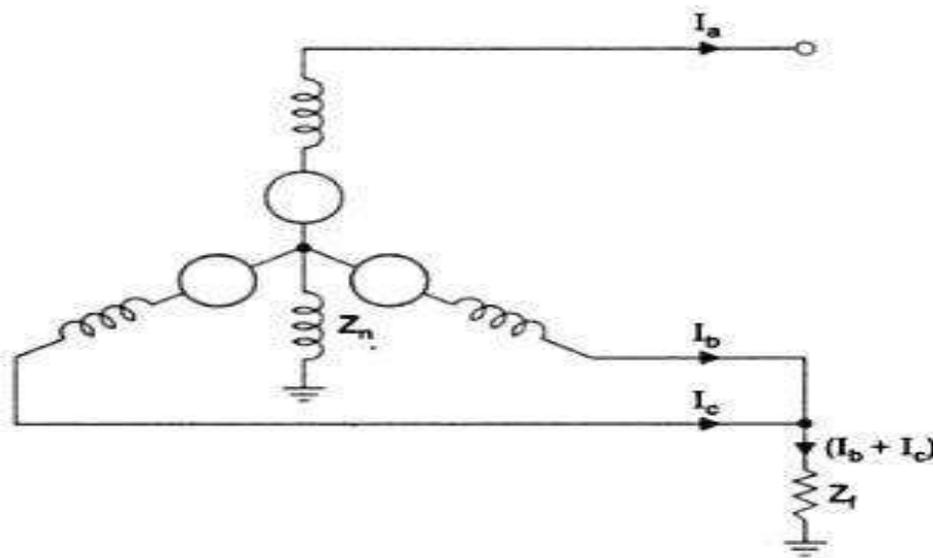$$V_b = V_c = (I_b + I_c)Z_F$$

Figure 17 L-L-G fault. Fault impedance Z$_F$ and neutral impedance Z$_n$.

And the sequence network equations

$$V_{a_0} = -I_{a_0}(Z_0 + 3Z_n)$$

$$V_{a_1} = E_a - I_{a_1}Z_1$$

$$V_{a_2} = -I_{a_2}Z_2$$

We know that

$$I_b + I_c = 3I_{a_0}$$

According to the boundary condition

$$V_b = V_c$$

$$\lambda^2 V_{a_1} + \lambda V_{a_2} + V_{a_0} = \lambda V_{a_1} + \lambda^2 V_{a_2} + V_{a_0}$$

$$V_{a_1} = V_{a_2}$$

Using the relation

$$V_b = 3I_{a_0}Z_F$$

$$\lambda^2 V_{a_1} + \lambda V_{a_1} + V_{a_0} = 3I_{a_0}Z_F$$

$$-V_{a_1} + V_{a_0} = 3I_{a_0}Z_F$$

$$V_{a_1} = V_{a_0} - 3I_{a_0}Z_F$$

Substituting the network sequence equations

$$E_a - I_{a_1}Z_1 = -I_{a_0}(Z_0 + 3Z_n) - 3I_{a_0}Z_F$$

$$I_{a_0} = -\frac{E_a - I_{a_1}Z_1}{Z_0 + 3Z_n + 3Z_F}$$

Similarly,

$$E_a - I_{a_1} Z_1 = -I_{a_2} Z_2$$

$$I_{a_2} = -\frac{E_a - I_{a_1} Z_1}{Z_2}$$

And

$$I_a = I_{a_1} + I_{a_2} + I_{a_0} = 0$$

$$I_{a_1} - \frac{E_a - I_{a_1} Z_1}{Z_2} - \frac{E_a - I_{a_1} Z_1}{Z_0 + 3Z_n + 3Z_F} = 0$$

$$I_{a_1} = \frac{E_a}{Z_1 + \frac{Z_2(Z_0 + 3Z_n + 3Z_F)}{Z_2 + Z_0 + 3Z_n + 3Z_F}}$$

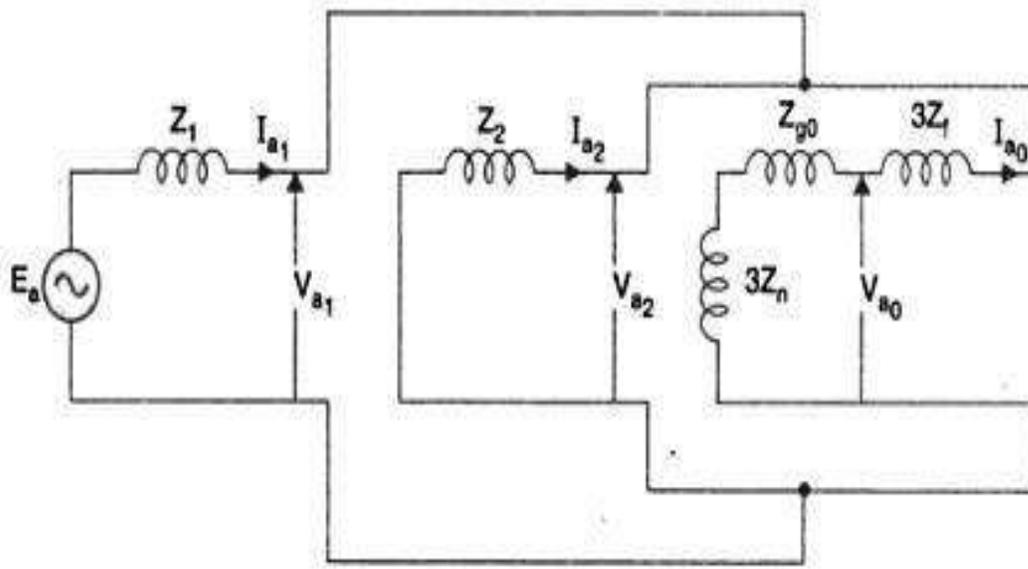The sequence network for the same is given by the figure below

Figure 18 Interconnection of sequence network

15. Faults in Power Systems

The faults in the power system are analyzed by making use of Thevenin's theorem about the point of fault location. The theorem is important as it can determine the changes in currents and voltages of a linear network when additional impedance is added between two nodes of the network.

To determine the distribution in current and voltage in the system, the distribution in each of the sequence networks must be determined. The Thevenin's equivalents of positive, negative and zero sequence networks are equivalent to those of the networks for a single generator.

Considering the system given below, it is needed to find the Thevenin equivalent network for determining the positive, negative and zero sequence networks about the point P.
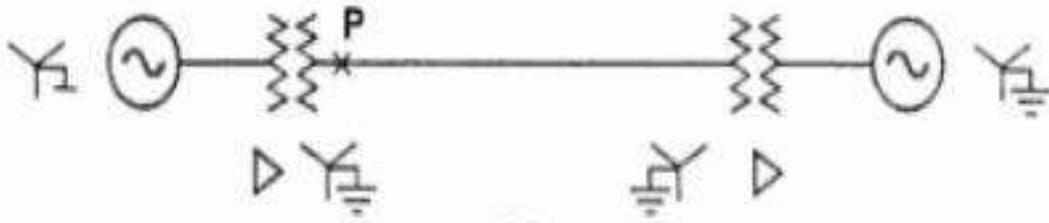
Figure 19 Single line diagram of a balanced 3-phase system

The Thevenin equivalent of the positive sequence network is obtained from the positive sequence network. The Thevenin equivalent voltage source is the prefault voltage at the fault point P and the equivalent impedance Z1eq is the impedance as seen between the fault point and the zero potential bus shorting the voltage sources.

Similarly, the Thevenin equivalent negative and zero sequence networks are obtained from the negative and zero sequence networks respectively. Since the system is balanced, no negative or zero sequence currents are flowing before the fault occurs. Hence the prefault voltage of both negative and zero sequence are equal to zero.

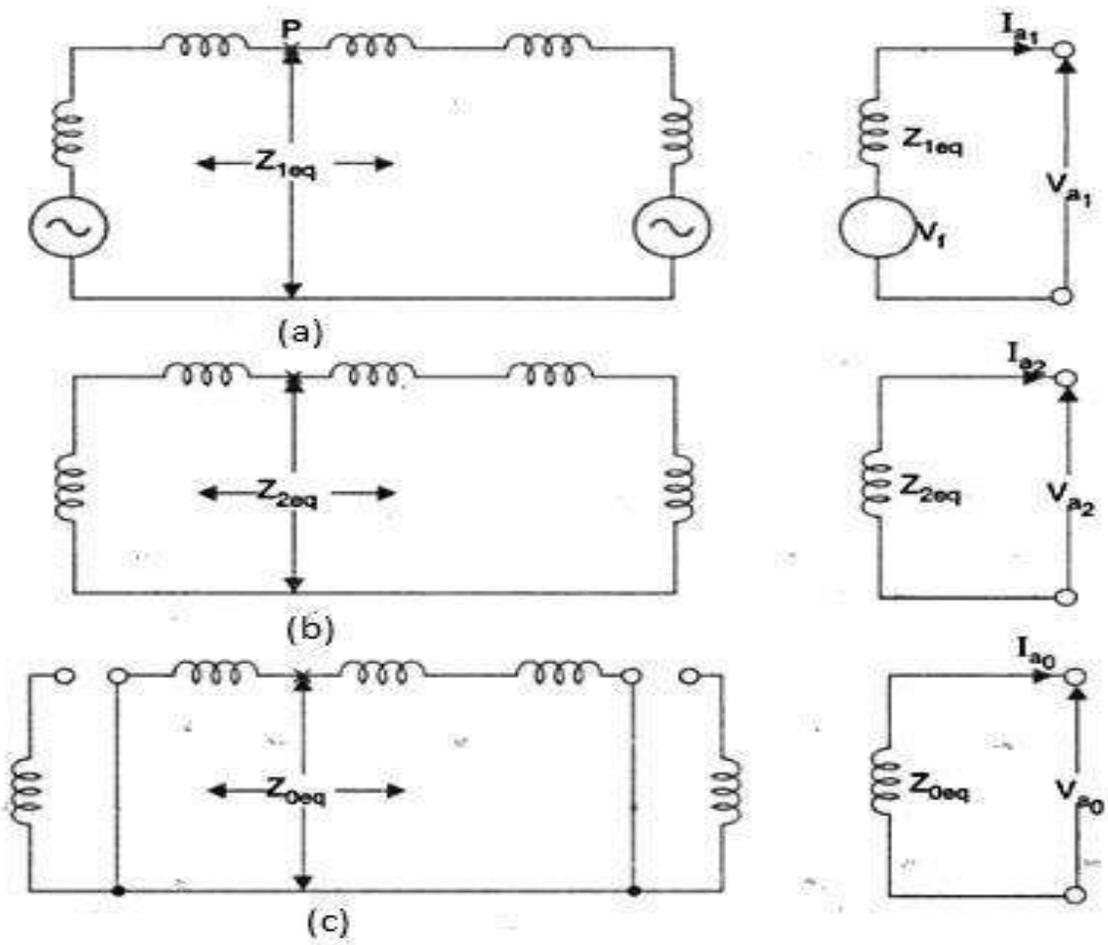The Thevenin Equivalent Network can be given as below

Figure 20 Thevenin's equivalent network of (a) Positive network (b) Negative sequence network (c) Zero sequence network

According to the actuating signals

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

a. Current

b. Voltage

c. Power

d. Frequency

e. Temperature

f. Pressure

Others Function

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

1.7 Basic Principle of Operation of Protective relay

Each relay in a protection scheme performs a certain function and responds in a given manner to a certain type of change in the circuit quantities.

Example:

• One type of relay may operate when the current increases above a certain magnitude known as over current relay

• While another may compare current & voltage and operate when the ratio V/I is less than a given value. It is known as under-impedance relay

Similarly various combinations of these electrical quantities could be worked out according to the requirements at a particular situation.

1.8 Economic Considerations

The cost of protection is linked with cost of the plant to be protected and increases

with cost of the plant. Usually, the protective gear should not cost more than 5% of the total cost. However, when the apparatus to be protected is of paramount importance like the generator or the main transmission line, the economic consideration are subordinated.

Average Costs in units per circuit ;

	Indoor 33 kV	132 kV	275 kV	400 kV
Total Avg. ckt cost	10	50.0	100	230
Relay	0.7	2.5	2.4	4.6
Relay Panel	0.4	0.6	1.5	2.3
Wiring	0.9	2.0	0.8	0.9
Relay Room	0.32	0.5	0.5	1.0
CTs	0.4	4.7	12.0	25.7
PTs	1.0	3.4	7.0	9.0

References

1. B Ravindranath& M Chander, "Power system Protection and switchgear"New age International Publishers

2. Y.G Paithankar & S.R Bhide, "Fundamentals of powersystem Protection"PHI Publication

MODULE-II

APPARATUS PROTECTION

1. Introduction

The two major equipments in a power system are the generators and the transformers. Even though the occurrences of faults in these are very less as compared to that of the lines, the damage due to these faults is severe in lieu of time and money as compared to that of the lines. Rapid reclosing of circuit breakers can clear the fault in case of lines and it helps in saving the amount of damage. But in case of these apparatus, it needs the aid of some attention or supervisory staff. Therefore fast clearing of the faults is necessary to minimize the damage and reduces the interruption to power services from reduced voltage and instability.

2. Transformer Protection

Nature of Transformer Faults

Power Transformers generally develop rare faults as it is static, totally enclosed and oil immersed but if these faults sustain the results may be serious unless the transformer is disconnected. The faults that generally occur in the transformer can be divided as:

1. Faults in auxiliary equipment which is a part of the transformer

2. Faults in the transformer winding and connections

3. Overloads and external short circuits.

Faults in Auxiliary Equipment

The detection of faults in auxiliary equipment is necessary to prevent ultimate failure of the main transformer windings. In these the components are

(i) Transformer oil: Oil is used as an insulator in transformer. So when low oil is present the live parts and the bushing leads gets exposed which are supposed to be beneath the oil. Oil level can be determined by the means of alarm indicators for immediate attention.

(ii) Gas cushion: The presence of oxygen or moisture may lead to deterioration of the transformer oil. Hence exclusion of this presence is necessary. Since the operating pressure varies within the tank, hence sealing of the tank is not an option. Pressure indicators and conservators are used to counter the expansion and contraction of oil. Whereas silica gel is provided in the breathing vent to absorb the moisture content. Sometimes a nitrogen cylinder is provided to provide an inert atmosphere maintaining the pressure between 0.5 and 0.8 atm.

(iii) Oil pumps and forced air fans: The top oil temperature normally gives the indication of the load on the transformer. A rise in temperature would indicate an overloading situation or due to the fault in cooling system. A hermometer with alarm contacts will indicate the temperature rise in oil

due to any of these faults.

(iv) Core and winding insulations: These faults can turn into major faults if not taken care of. Insulation failures may develop if

(a) The insulation of the laminations and core bolts may be of poor quality.

(b) Poor quality of insulation between windings or between winding and the core.

(c) Badly made joints or connections.

Winding Faults

Electrical Faults that can cause immediate serious damage and are determined by

the presence of unbalanced current or voltage may be divided into following classes:

(i) Faults between adjacent turns or parts of coils such as phase-to-phase faults on the HV and LV external terminals or on the winding itself or short circuits between turns of HV and LV windings.

(ii) Faults to ground or across complete windings such as phase-to-earth faults on either HV or LV side.

A short circuit between turns can start with a point contact resulting from mechanical forces or insulation deterioration due to excessive overload. The puncture of the turn insulation would cause a path through which the normal frequency voltage can maintain an arc. But if the voltage is insufficient to maintain the arc, it would be quenched by the oil present.

In the second case the ground faults are easy to detect as they are characterized by emission of large amount of gas due to decomposition of oil as well as in large values of fault currents. Rapid clearance is necessary to avoid excessive damage and to maintain stability.

Overload and External Short Circuits

Overloads can be persistent in the system provided the temperature rise in the windings is within the limits. Excessive overloading can cause deterioration in insulation and subsequent failure. An alarm indication can be initiated when the temperature limits exceed. External short circuits may only be limited by the transformer reactance, so a low value would result in excessive fault currents.

Differential Protection of Transformers

The best way of protection of any apparatus against an internal fault is by the method of differential protection scheme since it covers the apparatus' zone of protection. So for a transformer having ratings of 5 MVA and above, the differential scheme serves as an important

protection against internal phase-to-phase and phase-to-earth faults. Any fault in the protected part would result in the deviation Power System Protection of the current intensities at the input and output. So the result of this unbalance current can be employed for the tripping of the relay. For this reason the differential scheme combines the characteristics of selectivity and highest tripping time of the relay. A particular differential scheme is given below for a three-phase star delta transformer.
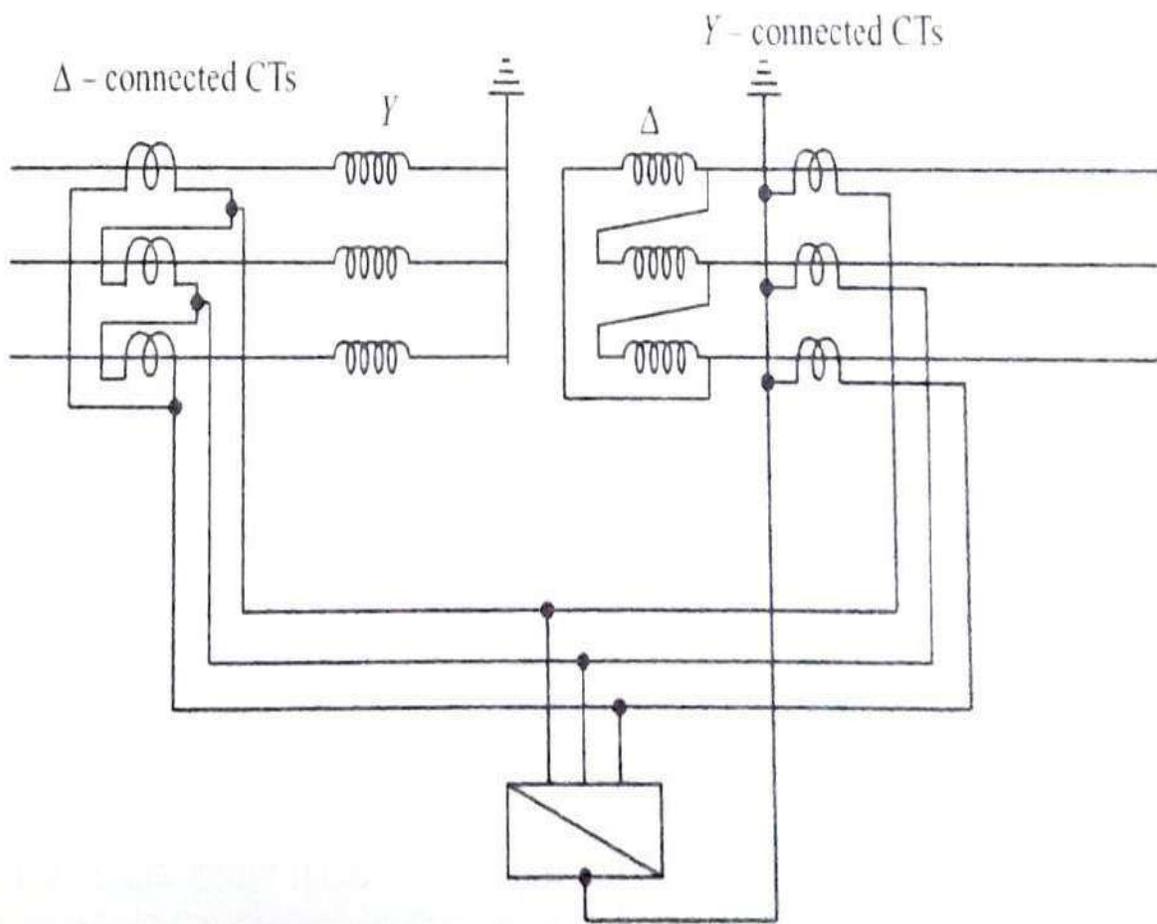

Figure 21 Differential Protection Scheme of star-delta transformer

For the relay to detect 0 spill current in normal operation, the currents incoming from both the CTs should be in direct opposition. Since in a star delta transformer the line currents have a displacement of 30˚, so the CTs have to be connected in delta on the star side of the transformer and in star for the delta side to avoid any spill current through relay in normal operation. Another advantage of this connection is the avoiding of triplet harmonics to appear on the line currents due to delta windings.

Problems Encountered in Differential Protection of Transformer

Even though setting of the ratios are done the scheme also suffers from drawbacks in it like

(i) Unmatched characteristics of CTs: The differential scheme employed for protection fails in the case of different CT ratio characteristics. Since the saturation characteristics are different, if they are not avoided would result in appreciable amount of spill current flowing through the relay.

(ii) Ratio change as a result of tapping: Most of the power transformers are provided with a tap changing equipment used for altering the turns ratio. It is impracticable to change the CT ratio for compensating this effect of tap changers. Biased relay can be employed for the overall protection of variable-ratio transformers.

(iii) Magnetizing Inrush current: When the transformer is re-energized, the transient inrush of the magnetizing current flowing is as high as ten

times the full load current as it depends on the flux trapped in the core of the transformer and the instant of the voltage cycle at which it is switched. Even though it's not a faulty condition, but depending on the magnitude of the current the differential scheme would trip.

Percentage or Biased Differential Relays

Since there is a mal-operation of the normal differential scheme and their associated drawbacks in the through fault and variable tap changing conditions,the scheme is modified by providing a restraining winding which is energized by the through current. This makes the operating winding biased or in other words it is made to operate by some percentage of the through current. This makes the relay more sensitive at low current without tripping for external fault.

If the ratio of restraining and operating coils is given as T, i.e.

$$\frac{N_r}{N_o} = T$$

Then the criterion for operation for a static comparator is:

$$\left|\frac{I_1 - I_2}{T}\right| > \left|\frac{I_1 + I_2}{2}\right|$$

Or for an electromagnetic comparator

$$\left|\frac{I_1 - I_2}{T}\right|^2 > \left|\frac{I_1 + I_2}{2}\right|^2$$

The value of this turns ratio T is generally 0.05 for generators and between 0.1-0.4 for transformers. Higher values are used if the transformer ratio is varied by tap changing equipment.
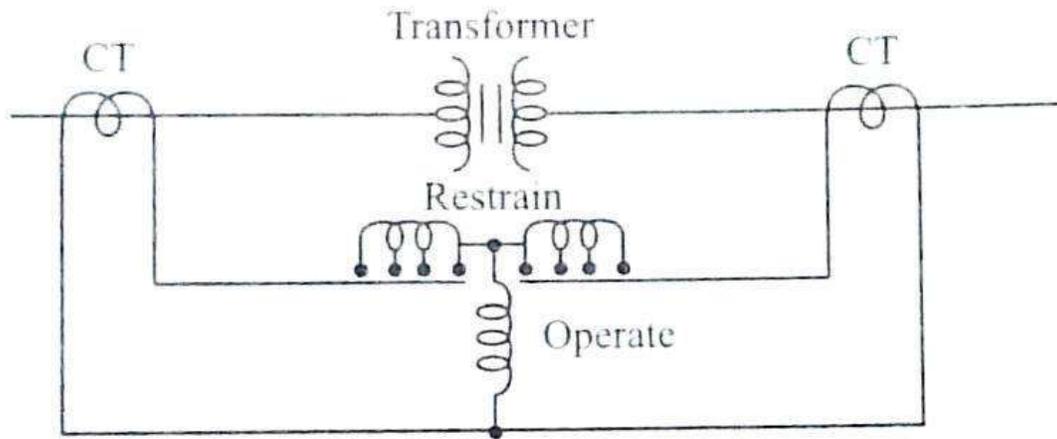

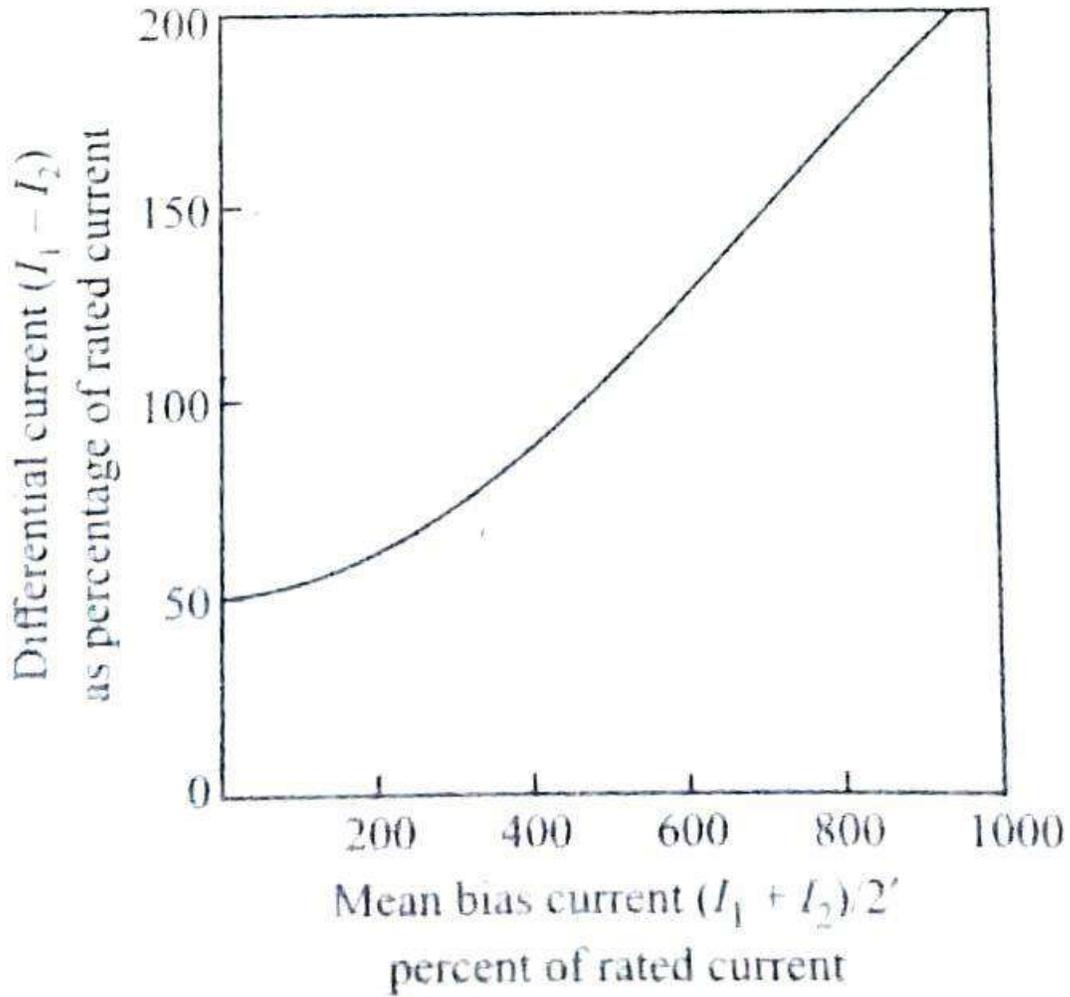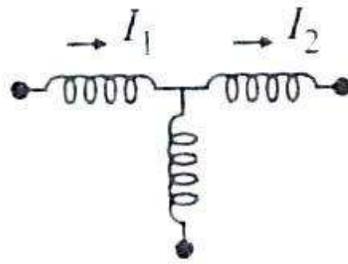**Figure 22 Biased Differential Protection for a transformer**

Figure 23 Biased Characteristics of biased differential relay for transformer protection. Setting 50% and bias 20%

Figure 2 shows the single line diagram for the biased differential schem

Methods for Preventing Operation on Inrush Currents

Magnetizing inrush currents is rich in harmonics unlike that in internal faults where the current is sinusoidal. So modifications are made in the construction of the relay. Since, the inrush current is rich in harmonics; the operating current is made to filter out these harmonics before being fed to the operating coil. This helps in the high speed and low operating current condition. Some of the methods are:

(i) Even Harmonic cancellation: For a typical inrush current waveform the harmonics as a percentage of fundamental is given as

Component	Fundamental	HARMONICS						
		D.C.	2nd	3rd	4th	5th	6th	7th
Typical Value percent	100	55	63	26.8	5.1	4.1	3.5	2.5

In this the 3rd harmonics and its multiples are removed since the

connections are made in delta on the transformer for star connected CTs

and CTs in delta for the star side of the transformer. The dc components

and even harmonics can be cancelled out in the operating circuit of the

rectifier bridge relay and can be diverted on to the restraining circuit.

Since the magnitudes of the 5th and 7th are small so they can be ignored.

(ii) Harmonic restraint: This is the most extensively used methods for making the relays immune to harmonics caused by inrush. The restraint coils is energized by the dc equivalent of bias winding current as well as the harmonics. Harmonic restraint circuit is formed by tuning XCXL which would permit only currents of only fundamental frequency to enter the operating circuit while the dc and higher harmonics are diverted onto the restraining winding. But this circuit may prove to be failure if the internal faults are also rich in harmonics which may be caused due to an arc or if the CT saturates and produce harmonics. For this purpose an instantaneous over current relay is provided in the differential circuit which is set above the maximum inrush current but will operate in less than one cycle on internal faults. The circuit for the same can be given as below
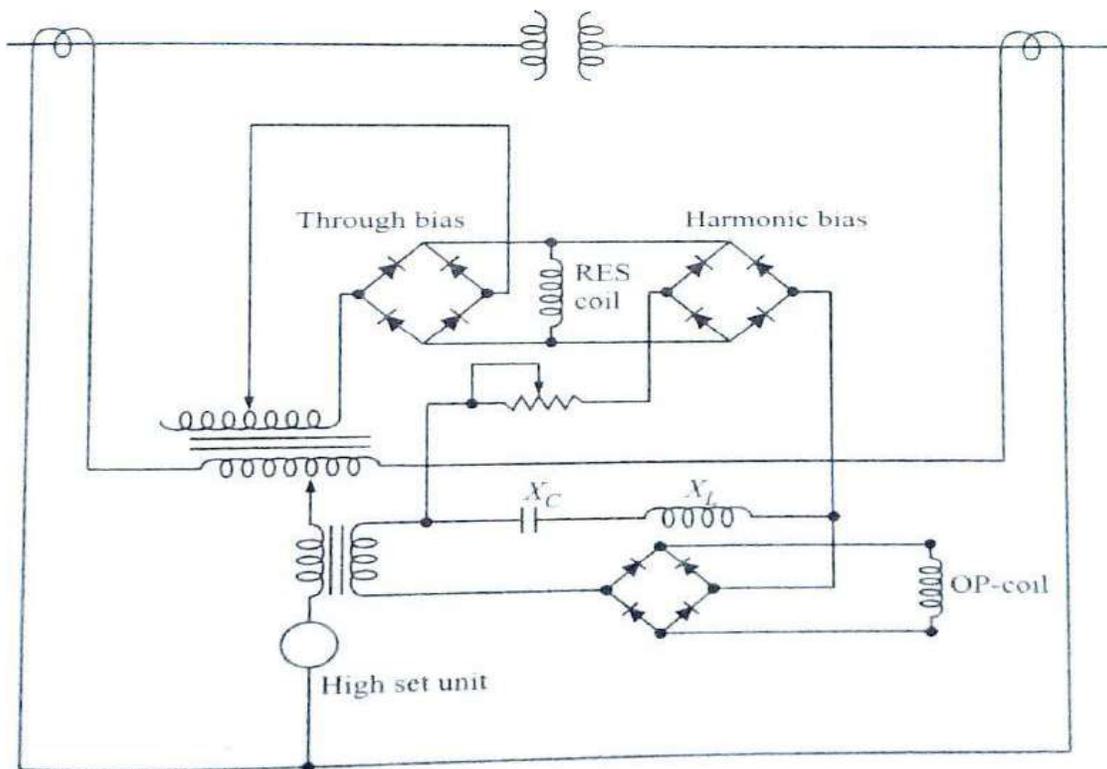

Figure 24 Basic Circuit of harmonic restraint relay

Influence of Winding connections and Earthing on Earth fault Current

The intensity of the earth fault current depends on the point in the winding where the fault has occurred and also on the winding connection and the method of neutral earthing. The conditions required for the flow of earth fault current from winding to earth are:

(i) A path must be there for the flow of current in and out of the winding.

(ii) The ampere-turns balance must be maintained between the windings.

From the first condition it is not necessary for the windings to be earthed for the current to flow as in case of star grounded side of the ransformers. For the delta side windings, the earthing is done by the use of earthing transformers.

In the case of resistance earthed neutral on the star side the magnitude of fault current depends on the value of earthing resistance and is proportional to the distance from the neutral end of the winding where the fault has occurred. If we consider a delta star transformer, having a neutral earthed resistor of 1:1 voltage ratio or the turns ratio on the primary to secondary side is $\sqrt{3}:1$. So for an earth fault current IF at 100% of the winding on the secondary side the primary current corresponding to the same would be $1/\sqrt{3}$ times the fault current on the secondary, i.e., $(1/\sqrt{3})$IF. Now as the fault position on the secondary varies, the magnitude of the fault current as well as the effective turns ratio between the primary and the secondary varies. For example, if the earth fault occurs at x% of the winding, the current on the secondary side would be $(x/100)$ IF. Hence the effective turns ratio would be $\sqrt{3}$: x/100, since x% of the winding would be active through which the current flows. This results in primary current having a value $(x/100)2IF/\sqrt{3}$. Thus the primary current is proportional to square of the

percentage of winding that is short circuited. The variation is shown in the figure below.
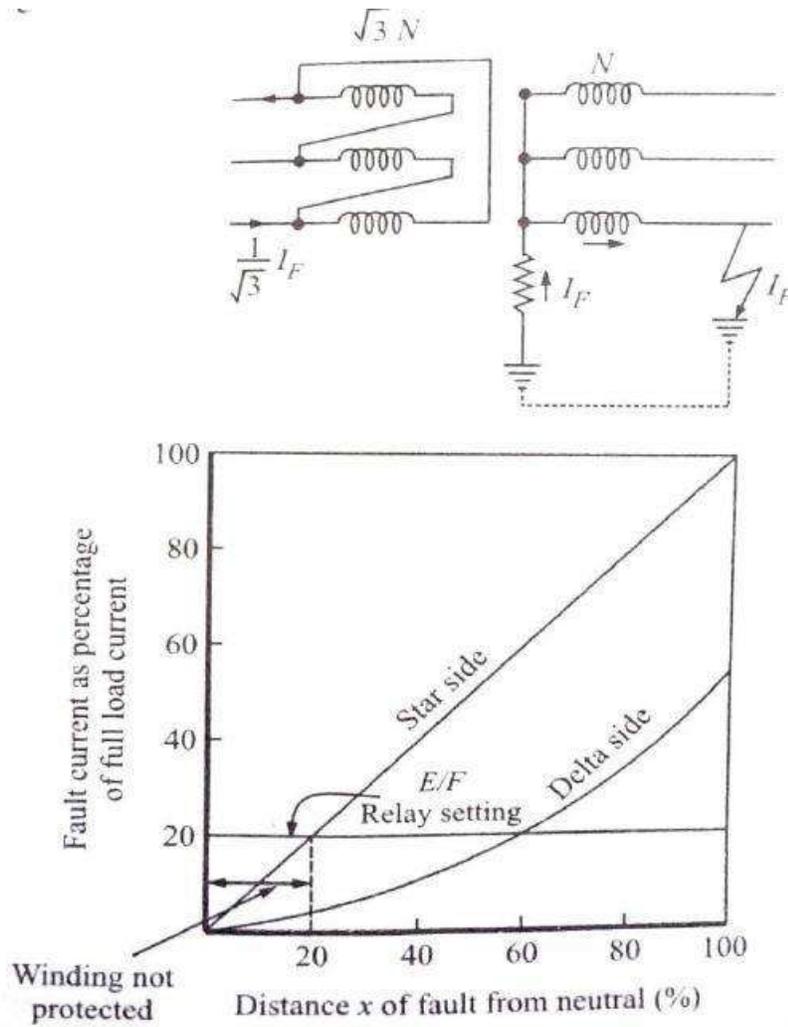

Figure 25 Transformer earth fault for resistance-earthed star winding

Star Winding with Neutral Solidly Grounded

The earth fault current unlike is resistance earthed is limited only by the impedance of the winding itself, and since the impedance is a variable quantity depending on the amount of winding that is faulted, the current no longer bears a linear relationship. The reason is that the leakage reactance of the faulted winding is more near to the star point, but the reactance of the other windings are reduced owing to the change in the transformation ratio. So the minimum fault occurs close to the middle of the winding.

Distance x of fault from neutral (%)
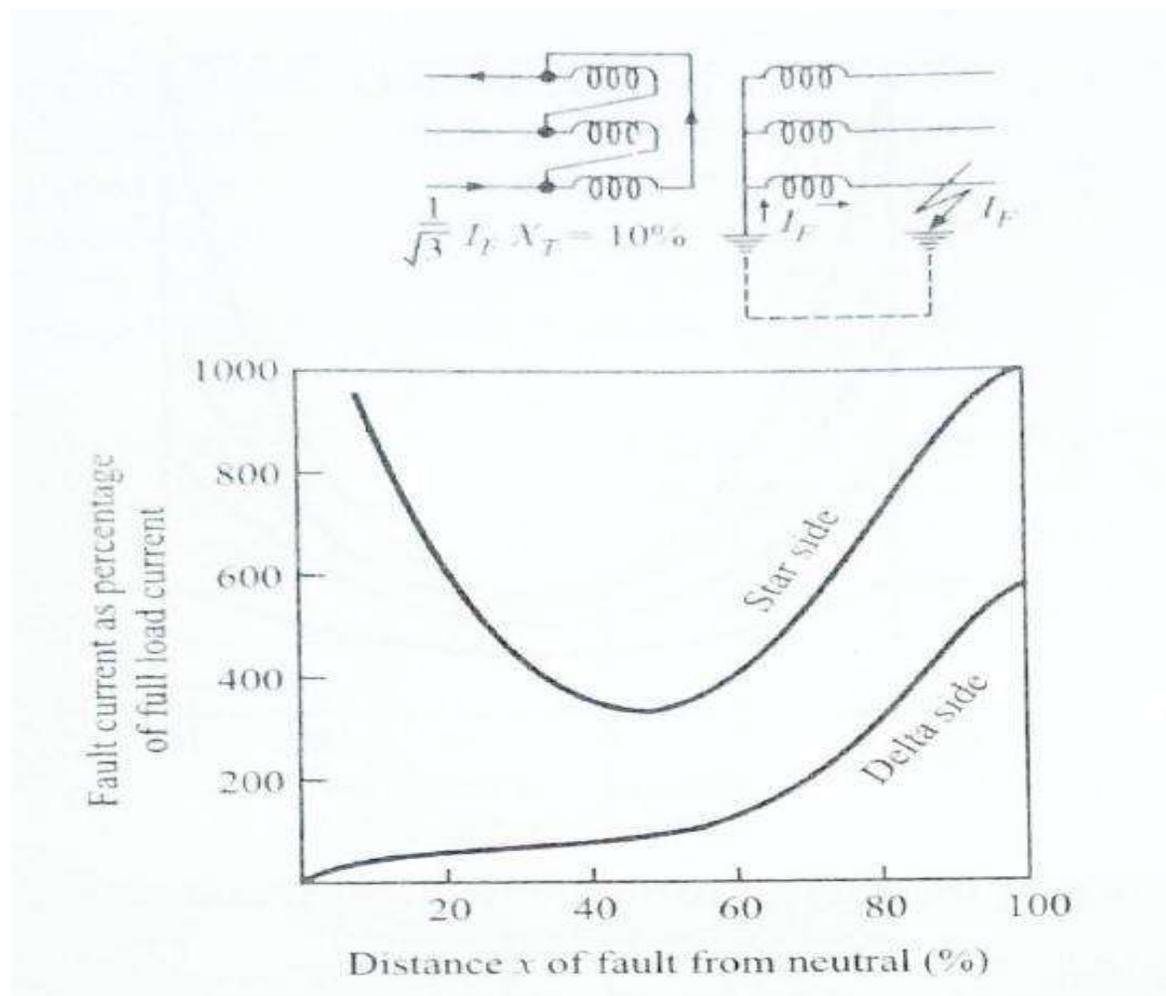
Delta Winding

The minimum voltage that can appear in the delta winding is only half the phase voltage and occurs at the midpoint of the winding. If the windings are not resistance earthed, depending on the leakage reactance the current may rise to about 200% of the full load current. If resistance earthing is employed the net impedance rises by the vector addition of resistance with the net reactance. But if the resistance is made to counter the orders of full load current, the minimum current that can flow would be V/2R.
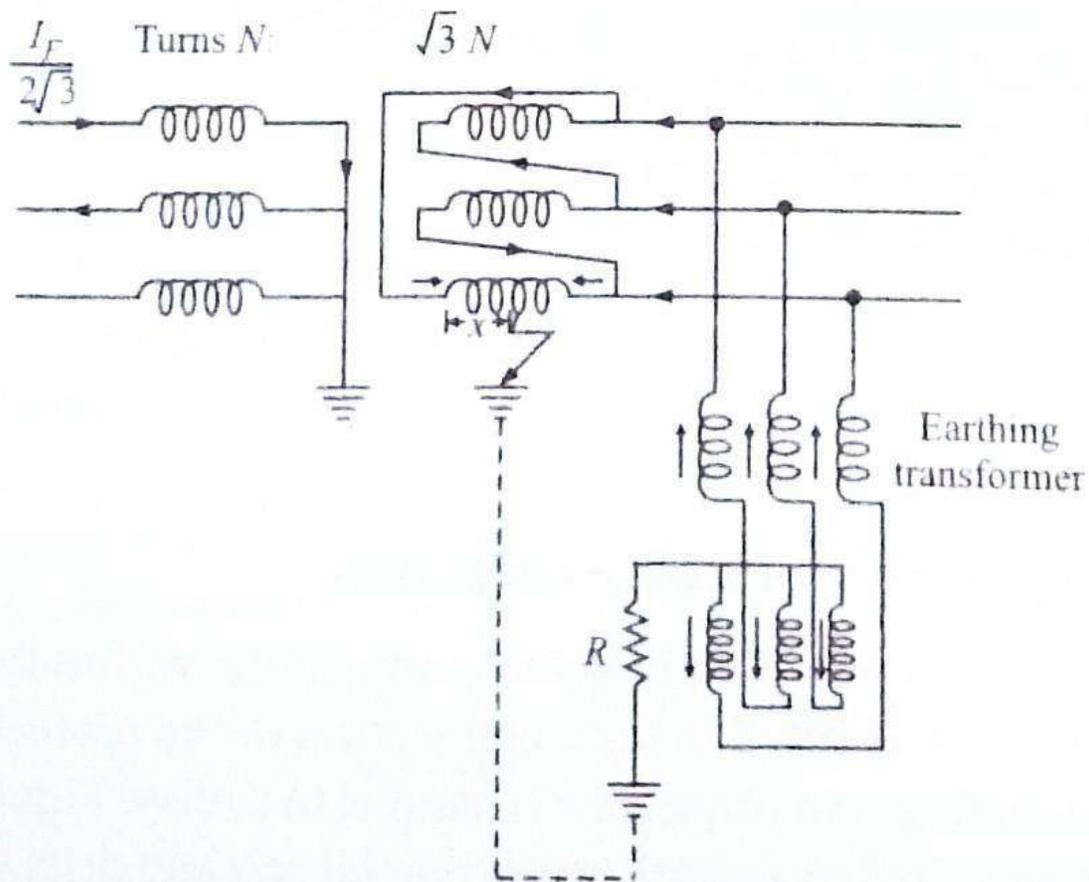

Figure 27 Transformer earth fault for a delta winding system, resistance earthed

Overcurrent and Earth Fault (Unrestricted)

The Overcurrent protection can be done by the use of IDMT relays for protection against excessive overloads and external short circuits. This protection scheme acts as a backup protection for the transformer. The current setting is so chosen that it would cater for above the permitted overload allowance and below the minimum short circuit current. This types of relay is kept on the supply side and would operate for both the LV and HV side breakers.

Tank Leakage Protection

If the tank is not highly insulated or where the insulation resistance is of 10 ohms, there might exist a chance of insulation breakdown between the transformer tank and earth. So an earth fault protection scheme can be employed by connecting a relay to the CT secondary whose primary is connected between the tank and the ground.

Restricted Earth Fault Protection

This type of protection if there is an earth fault within the internal zone of protection of the transformer. In this CTs are connected in each phase and the secondary of each CT is connected in parallel. The connections are made so because this leads to the addition of currents which is proportional to the zero sequence currents, which exists if and only if there is an earth or ground fault.

When it is an internal fault the current adds up to twice the fault current. But in case of external faults this sum is zero. A typical connection in restricted earth fault protection for transformer is given as below
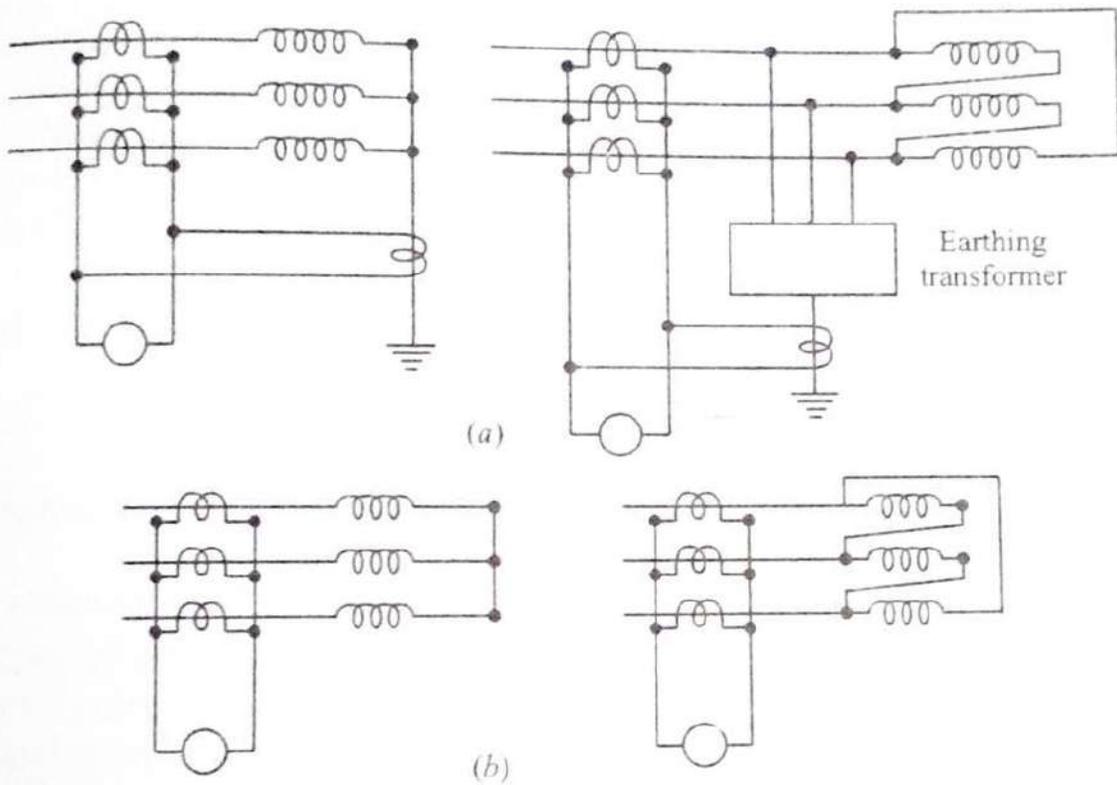
Figure 28 Restricted Earth Fault Protection: *(a)* **neutral earthed within the protected zone;** *(b)* **neutral not earthed within the protected zone**
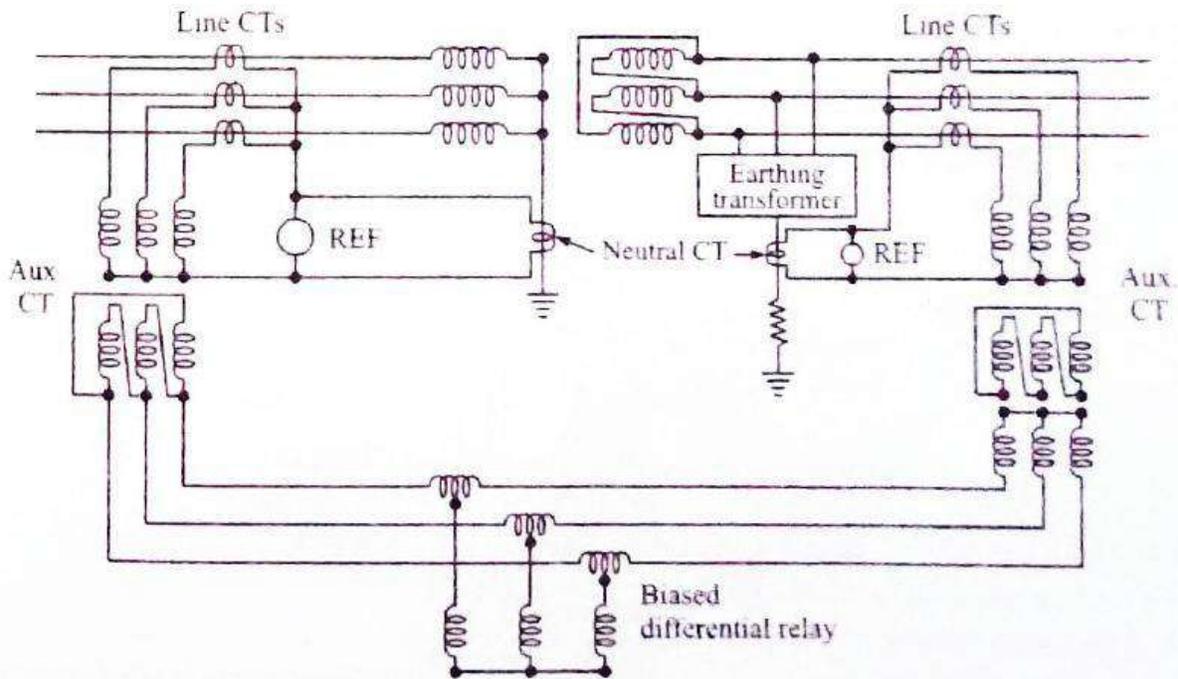
Figure 29 Differential and restricted earth-fault protection of a star-delta transformer

Gas Actuated Relays

When there is a fault in the transformer tank, it leads to the gas formation in the tank itself, which is slow for the incipient faults and violently for heavy faults. The gas which is formed due to ecomposition of the oil which is caused by the high amount of heat produced by the local currents can be made use of for detecting the faults. One of the famous relays in this context is the Buchholz Relay. It is the simplest type of relay consisting of a chamber connected between the conservator and the transformer main tank. Within the chamber, it consists of two

cylindrical floats, one at the top of the chamber and the other opposite orifice of the pipe to the transformer. In the normal conditions the floats are up, but when there is an incipient fault like an inter turn fault, the gas which is formed due to it moves up in the direction of conservator. On

moving up they are trapped inside the relay chamber and thereby reducing the oil level. This results in upper float to fall down which was initially kept up by the oil level. When this float reaches a predetermined

distance, it closes the contact and gives an alarming signal to the personnel.

But when the fault is heavy, the surge of gas and oil engages the lower float also to be pushed down which in turn trips the circuit breaker.
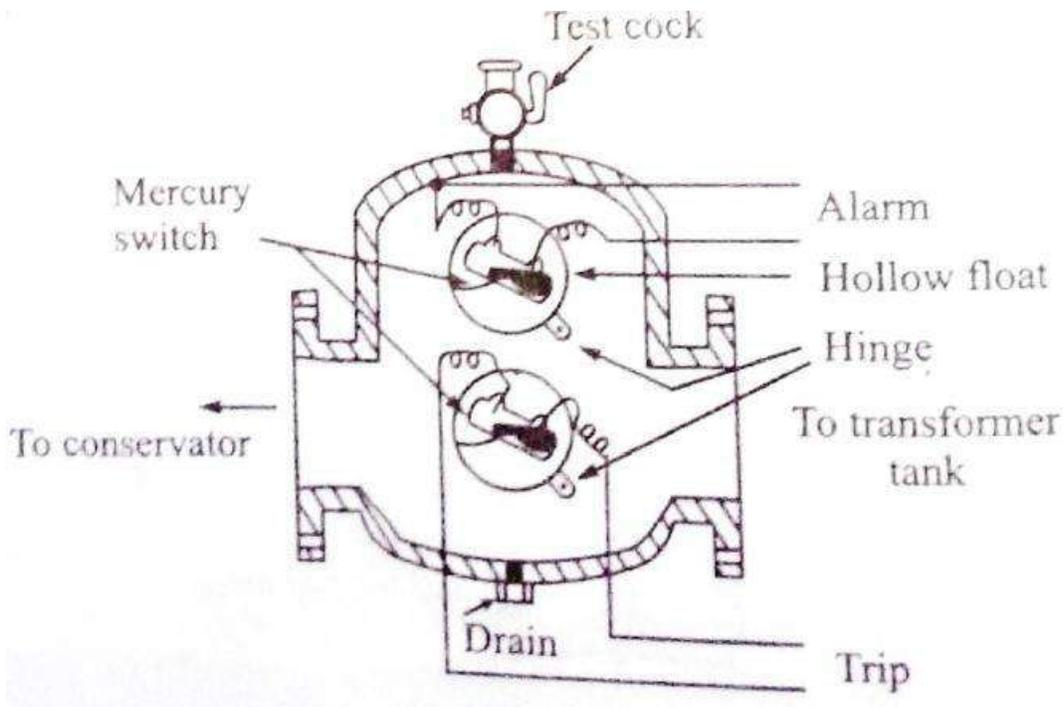

Figure 30 Buchholz Relay

Transformer Feeder Protection

In a method to supply bulk power from a major switching station, sometimes the transformer is connected directly without any provision of switchgear. Even though it is cost effective, but it would require

adequate protection schemes. In addition to the protection provided for transformer and feeder when considered separately, the need for some means of inter-tripping between the HV and LV circuit breakers becomes essential.

For countering this, two basic systems of protection can be done: unit and non-unit systems. In unit systems, the differential scheme can be applied separately for the transformer and feeder or considering both the transformer and feeder as an overall unit. In both the cases pilot wire is required. In non-unit systems, it provides back up protection for both the faults occurring outside the protected zone as well as that in the zone faults.
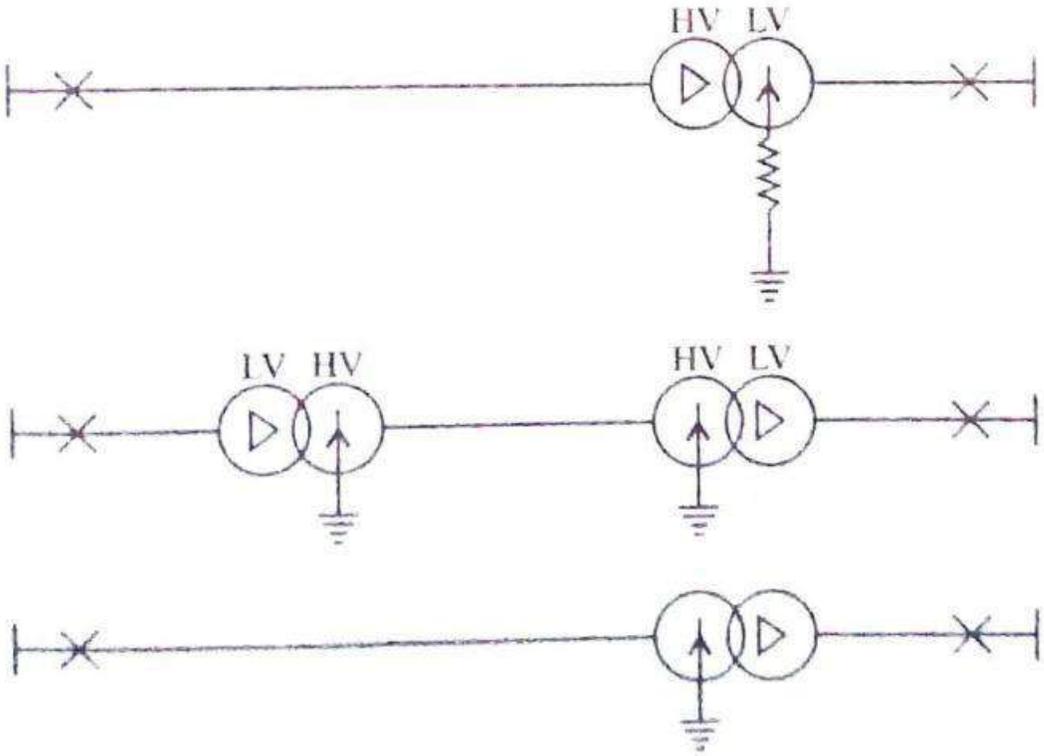

Figure 31 Typical transformer feeder circuit

3. Generator Protection

The generator is the prime equipment in the power system. The increased size of the generators and even greater increase in their capacity makes the imperative to protect them against fault. Unlike other apparatus only isolating the circuit breaker is not enough to prevent further damage as the generator would still supply power to its stator windings until the excitation is suppressed. So for isolation it is needed to open the field to avoid any excitation, and to stop the fuel supply to the prime mover.

Generator faults

Generator faults can be considered as follows.

(a) Stator faults: These include the following

(i) Phase to earth faults.

(ii) Phase to phase faults

(iii) Inter turn faults

The stator is prone to maximum amount of faults in the system with phase to earth fault being the most common. The inter turn faults and phase faults are less common but develop into an earth fault in the long run.

(b) Rotor faults: The faults that exist in the rotor can be either earth fault or an inter turn fault. These faults are mainly caused by the mechanical and thermal stress acting upon the winding insulation. The existence of such fault may be taken care of as the incidence of second fault may short circuit some part of the field winding which would result in the asymmetrical air gap flux which may cause vibrations and result in damage to the bearings.

In the modern era, the practice is to operate the field winding isolated from the earth so that a single fault between field winding and rotor body due to insulation breakdown can be tolerated.

(c) Abnormal running conditions: The abnormal running conditions that can occur are: (i) loss of excitation, (ii) unbalance loading, (iii) overloading, (iv) failure of prime mover, (v) over speeding, and (vi) over-voltage.

Field failure may occur due to a faulty field breaker. When a generator loses its excitation, the amount of reactive power supplied to the system is lost. Instead it would draw excitation from the system while delivering real power at leading power factor. This leads to an operation of an induction generator where the speed is slightly increased. Also due to loss of excitation there would be a voltage fall which would lead to loss of synchronism. The situation may also lead to overheating in rotor and damper windings.

If there is any unbalance in the system due to a phase fault or due to the

unbalance loading, it gives rise to negative sequence currents. It roduces an armature reaction field which rotates in a direction opposite to that of the rotor and hence produces a flux which is twice the frequency. These currents are linked to the rotor and damper windings which produces heating in the windings.

When there is an overloading in the generator, it would draw more current and as a result would produce more heating loss in the stator which may damage the insulation.

When there is a failure of prime mover, the real power delivering capacity is lost and instead it would draw power from the system making

it to run as a motor. This affects the drive of the system due to opposite torque being applied on to the shaft.

When a sudden load is removed then according to the AGC control, the machine is going to over speed. This happens mainly in the hydraulic generators since the water flow cannot be immediately stopped for the inertia in water motion.

Over voltages may occur due to the failure in the AVR control in the excitation or may be due to over speeding.

Stator Protection

As discussed, the most common fault that happens in stator is the earth faults.

Since an earth fault near the generator is very critical as the magnitude of the current is very high, so the current is limited by either a resistance connected in the neutral circuit. Depending on this value the current can be limited to either 200 to 250 A which is done by resistor earthing or 4 to 10 A by distribution transformer earthing. Even though the second method has an advantage of reducing the damage on to the stator core, the practicability of this method is limited if the transformer is connected in delta.

In the resistor earthing, the resistance is connected between the neutral and the ground and the CT is mounted on the neutral with an IDMT or an instantaneous attracted armature type relay. The maximum value of resistance is given by

$$R_n = \frac{10^6}{6\pi f C} \; ohms$$

Where C is the capacitance of the stator circuit to earth per phase in microfarad and f is the system frequency.
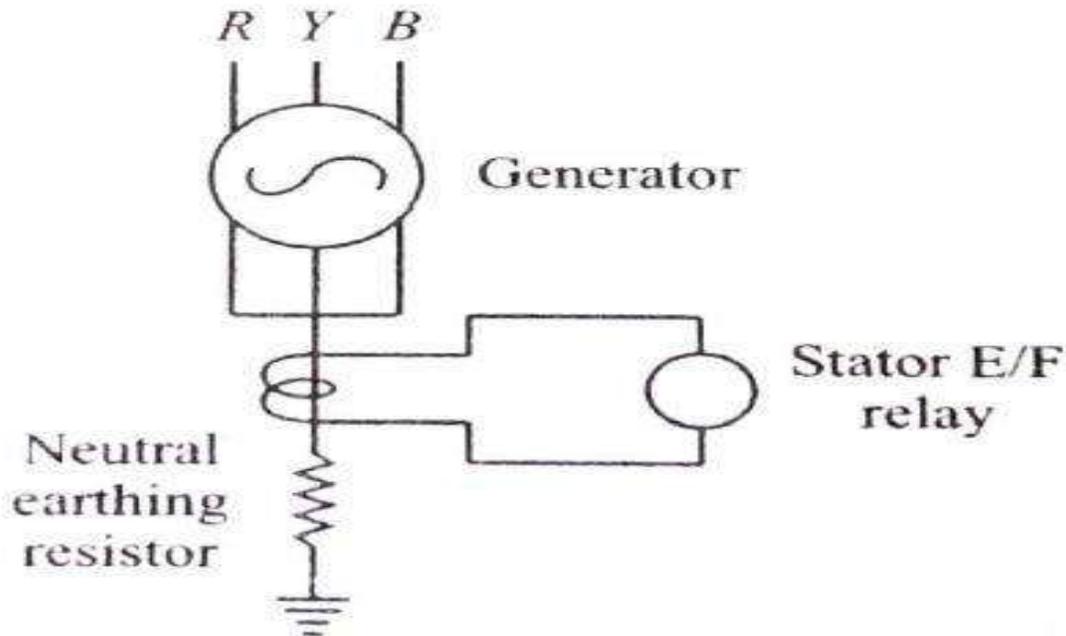

Figure 32 Location of E/F relay in a resistance earthed generator

If the neutral is earthed through the primary winding of a distribution transformer, earth-fault protection is provided by connecting an over-voltage relay across its secondary, then the maximum value of resistance is equal to

$$R_n = \frac{10^6}{6\pi f N^2 C} \ ohms$$

Where N is the turn ratio of the transformer.

Generator differential protection: The best form of protection for the stator windings against all the internal faults is by the use of differential

protection. The relay recommended for this application is instantaneous attracted armature type which is immune to ac transients and has the high speed feature if the CTs are reasonably matched. But when the CTs have dissimilar characteristics, biased differential relay can be applied as it would result in high amount of spill current flowing through the relay.

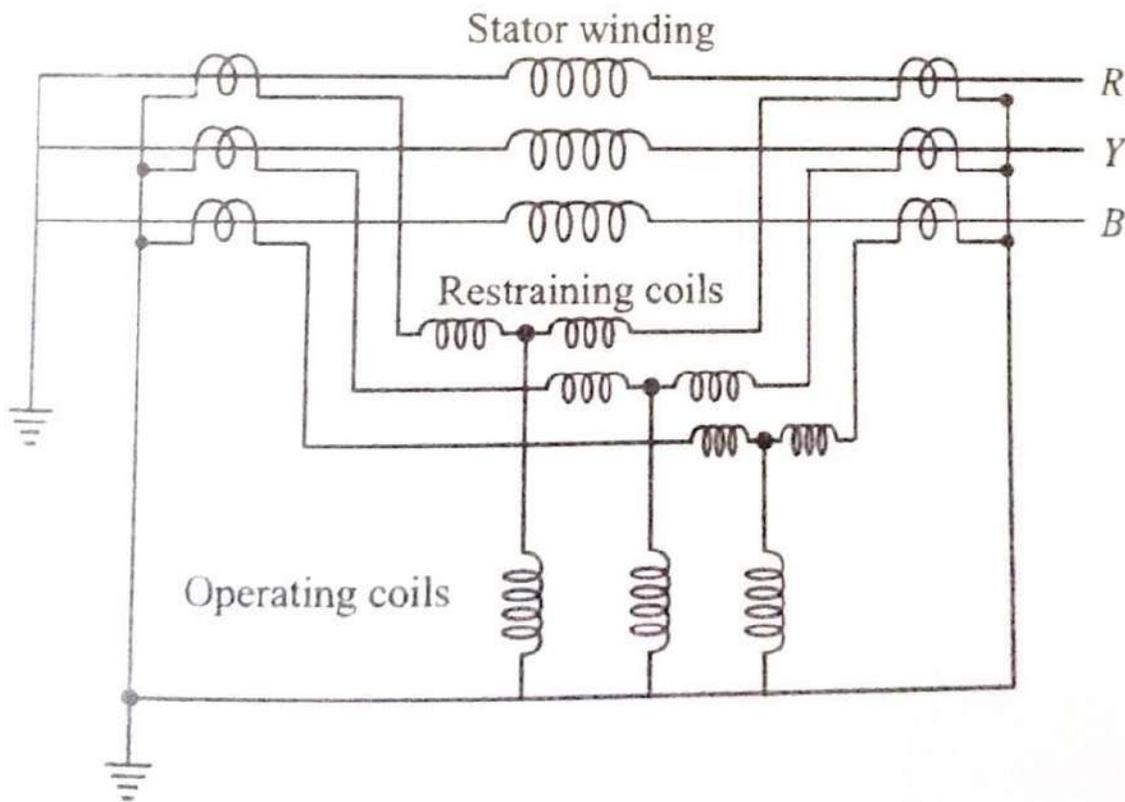A particular longitudinal biased differential relay protection scheme for the generator is given as below

Figure 33 Percentage Biased differential relay

Stator Inter turn fault protection: An inter-turn fault occurring on the same phase of the stator winding do not disturb the neutral current,

hence by the use of longitudinal differential relay it is not possible to detect such type of fault. This results to another modification in the protection designing whereby we make the transverse differential relay in case of the generators where the stators have two windings per phase. The protection scheme is given as
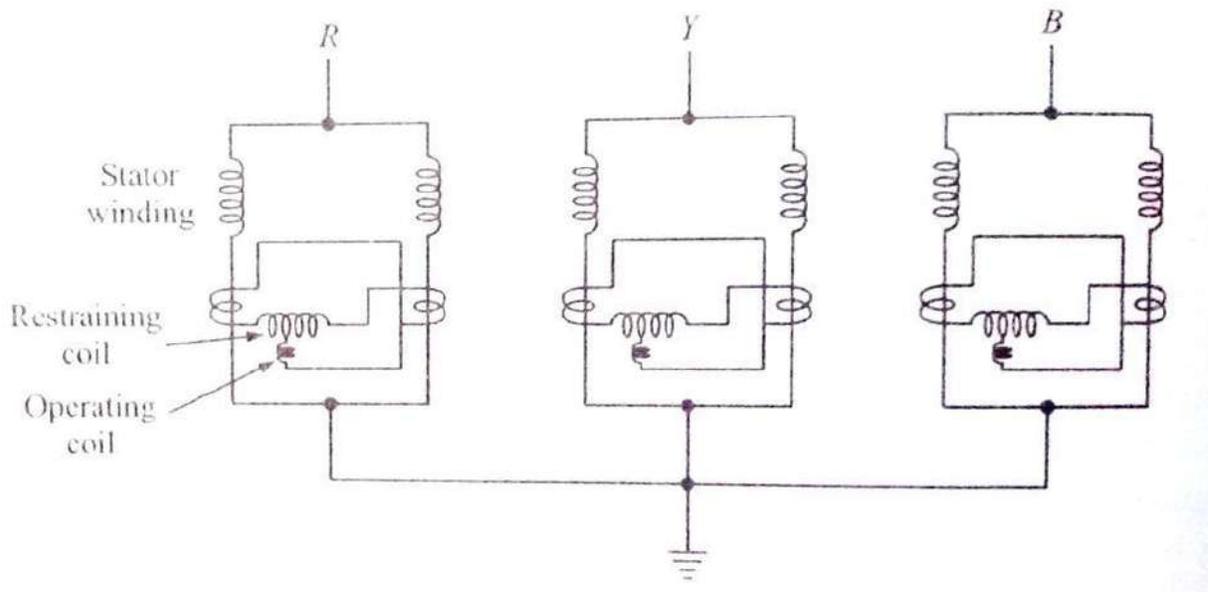

Figure 34 Biased Transverse differential protection for inter turn fault protection for 2 winding stator

Wherever single winding is present the protection of generators against inter turn fault is done by using zero sequence voltage caused by the reduction of emf in the faulted phase. One of the connections is given as
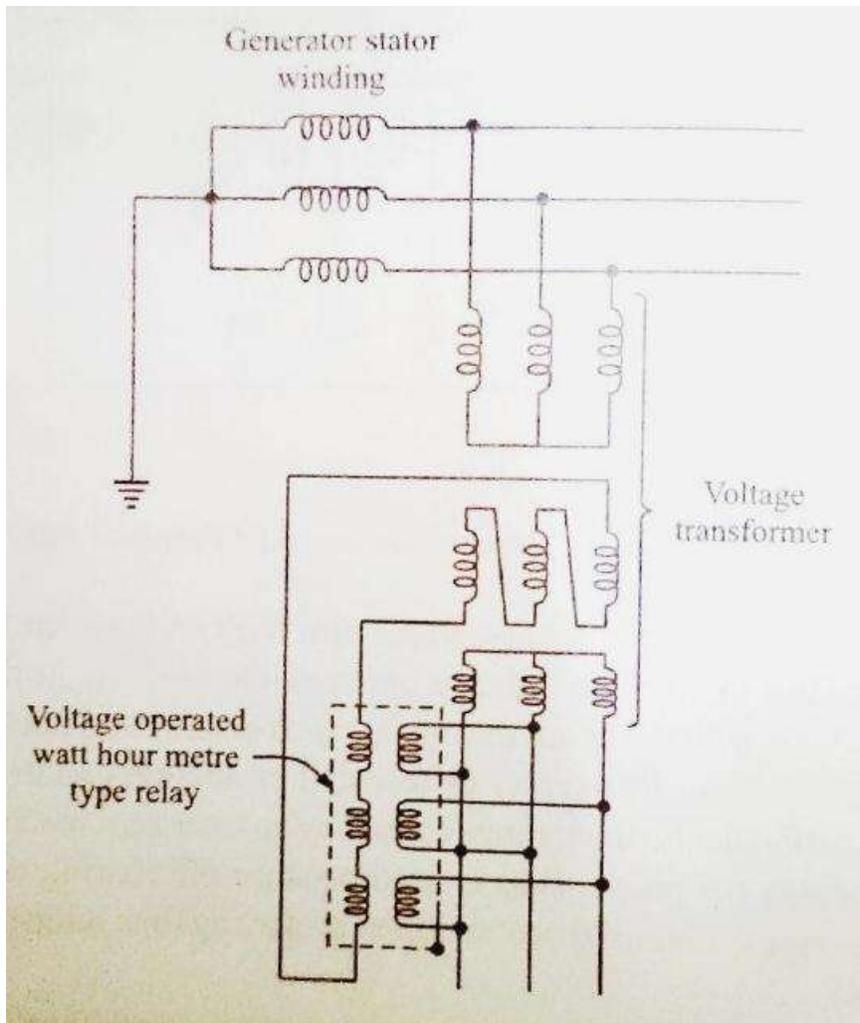
Figure 35 Inter Turn fault detection

Rotor Protection

The rotor windings as discussed earlier may be due to earth faults or open circuits.

The figure shows a modern method of rotor earth fault detection. The field is biased by a dc voltage which causes current to flow through R for an earth fault.
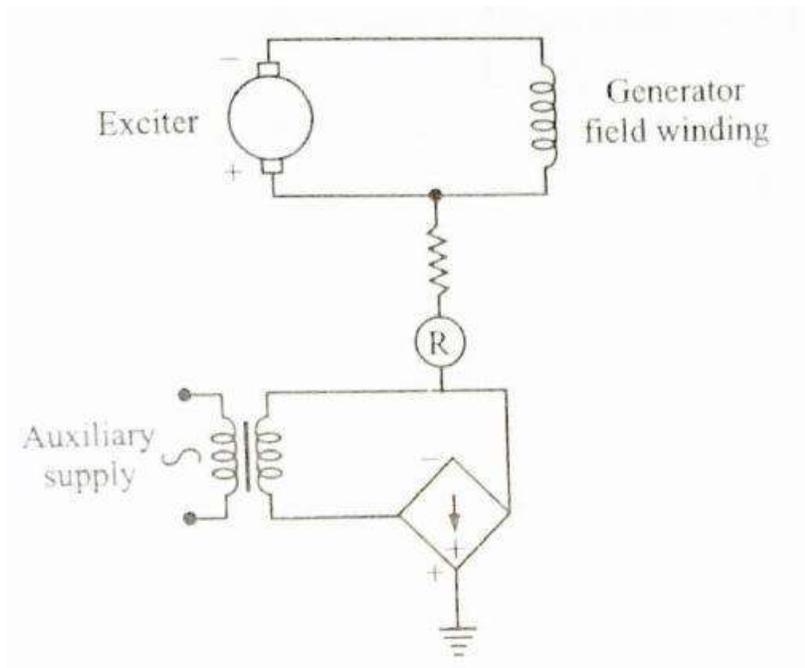
Figure 36 Rotor Earth Fault Detection

Loss of Excitation (Field Failure) Protection

As discussed, the loss of field circuit imposes the circuit to draw reactive VAR from the system. This results in machine being operated as an induction generator. This causes overheating in the circuit.

Loss of excitation is detected by the import of VAR indicating either actual or prospective loss of synchronism. So the transients in such phenomena can be allowed for 1 to 5 seconds in tripping sequence of the relay.

Due to the loss of excitation, there would be a drop in voltage and resulting in the drop of current. This can be detected by an undercurrent moving coil relay in the field circuit. Even this method is not suitable for generators having wide range of operation in the field excitation.

The alternative solution that can be implemented is to apply an offset impedance or mho relay. Its operating characteristics are arranged so that during conditions of low excitation the effective generator impedance falls in the tripping zone.
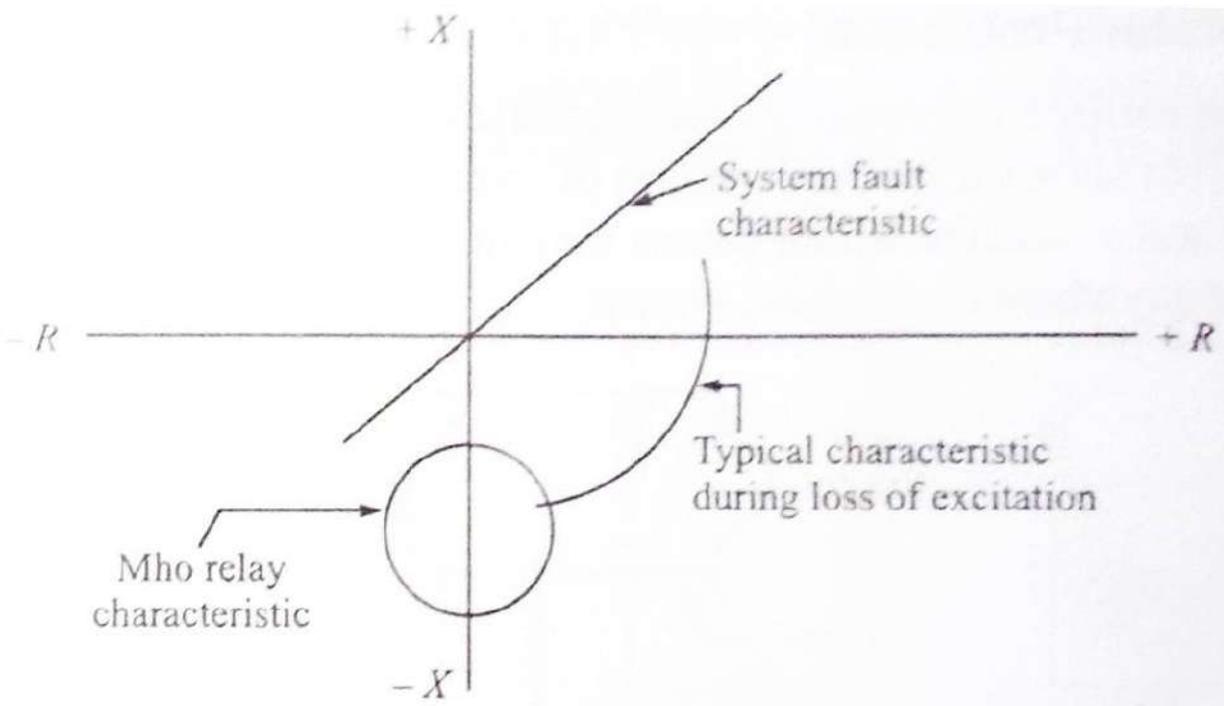

Figure 37 Loss of excitation characteristic

Unbalance Loading Protection

An unbalance loading situation gives rise to negative sequence currents in the rotor circuit which causes the heating in the circuit. The negative sequence currents move at twice the supply frequency and follow a normal resistance law. In case of high speed turbo generators this value is about 10 to 15% of the positive sequence currents. The heating time constant is expressed by a rating equation

$$I_2^2 t = K$$

Where I2 is the negative sequence current based on per unit basis of continuous maximum rating, t is the time in seconds and K is a constant usually varying between 3 and 20.

An IDMT relay almost matches the heating characteristic of the negative sequence current and can be detected by using an NPS filter as given below
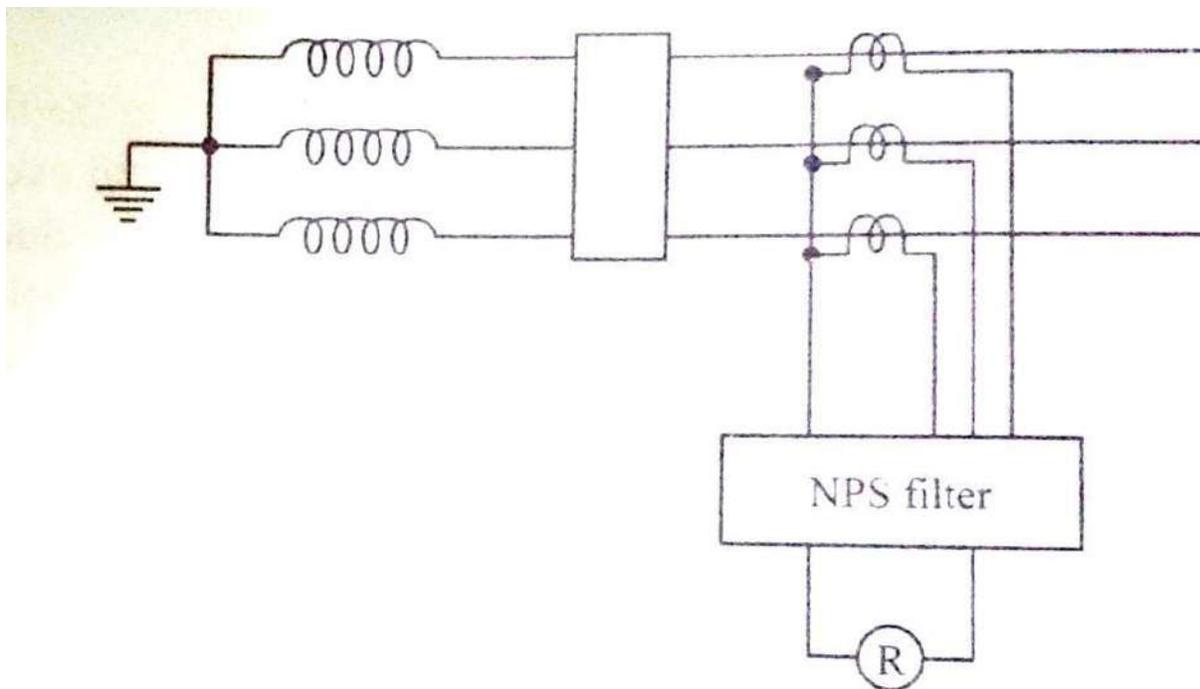

Figure 38 Protection against unbalanced load using negative sequence filter

Overload Protection

Overloading in the generator causes the stator windings to overheat. A provision of overcurrent relay is not an obvious solution as it wouldn't be able to discriminate on the basis of time. The relay must be so chosen so as to counter for the slowest relay on the system the generator is feeding. The simplest way is to detect the overloading condition by the means of temperature detection coil connected in a Wheatstone bridge.
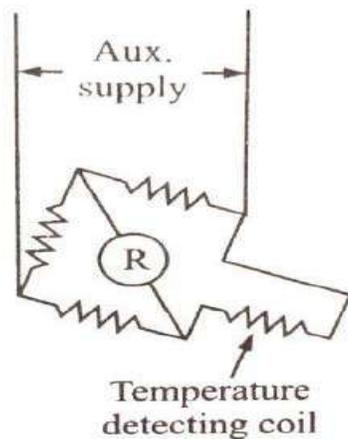

Figure 39 Stator overheating protection using temperature detector coils

Prime mover protection

When there is a failure of prime mover, the machine starts to act as a motor drawing real power from the system and thereby driving the prime mover. This condition imposes a balanced load on the system. A reverse power relay can be used to detect the tripping characteristics in this type situation since there is a change in the direction of flow of power working over the full power factor range. Under such conditions, the load coming on the machine is very low of the order of 1% of the machine rating. Even though it is a small amount, the condition can be harmful sometimes in case of steam turbines where the steam acts as coolant, maintaining the turbine blades at a constant temperature and the failure of steam results in overheating along with distortion of blades.
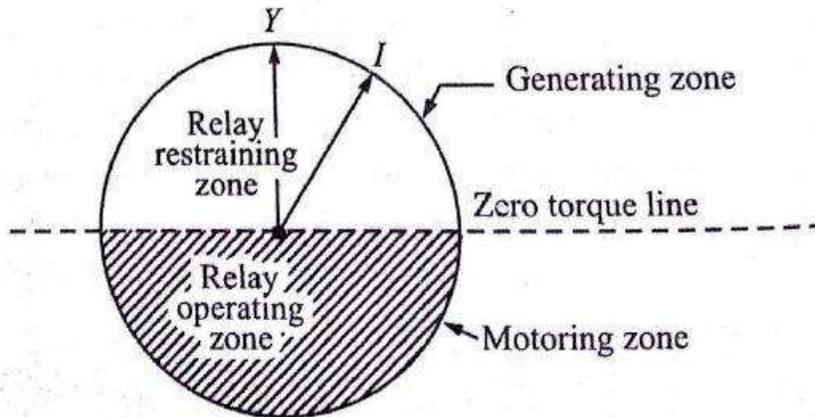
Figure 40 Reverse Power Relay operating characteristics

Over-speed Protection

Over speed protection is the most necessary protection in case of hydraulic generator sets unlike the case in steam sets which as fast acting governors. A provision of reverse or under power interlock relay is provided to prevent the main generator CB from tripping in non emergency situations. A provision of centrifugal switch is provided at the shaft which flies out and closes the valve when speed exceeds 10%.

Overvoltage Protection

Overvoltage protection is provided on machines which are subjected to over speed on loss of load. The relay is energized from a single phase voltage transformer, having the characteristics similar to IDMT characteristics.

Protected Scheme for a Direct Connected Generator

Direct Connected generators normally of smaller ratings consists of the following protections

(i) Unbiased differential protection

(ii) Back up overcurrent protection

(iii) Negative phase sequence protection

(iv) Standby earth fault

In addition to these protections the following may also be provided

(i) Field failure protection

(ii) Rotor earth-fault protection
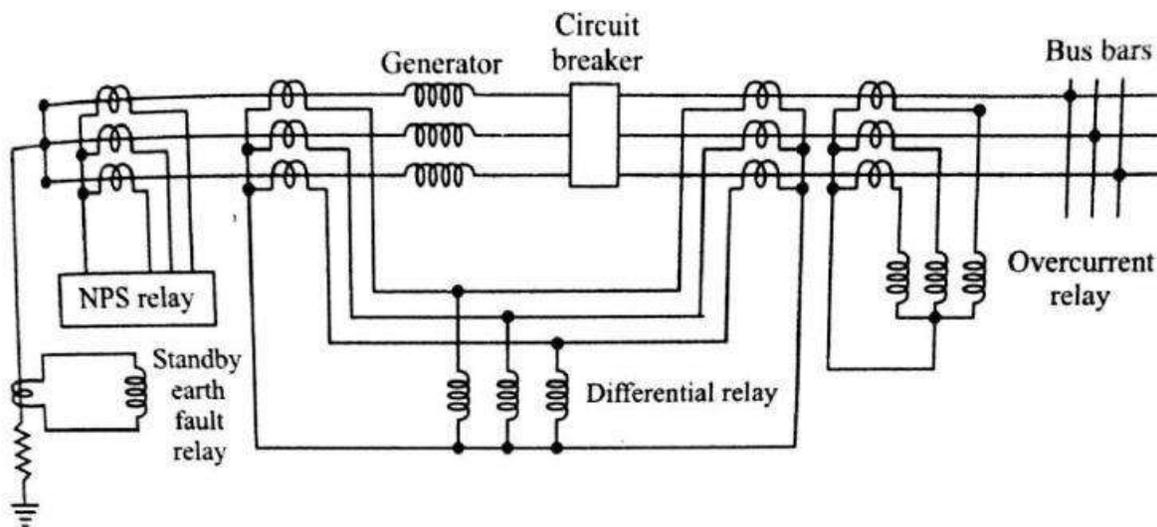
(iii) Reverse power protection

Figure 41 Typical Protective scheme for a 30 MW direct connected generator

4. Motor Protection

The motor acts as the important loads in the power system as they compose mostly 90% of the loads. The protection of these apparatus becomes very important. The motors that are taken into consideration are synchronous and induction motors.

Types of Faults

The faults that occur mostly in the motor are almost similar to that of the generators. The faults can be classified as:

(a) Stator Faults

(b) Rotor Faults

(c) Overloads

(d) Unbalanced supply voltages including single phasing.

(e) Under voltage

(f) Reverse or open phase starting

(g) Loss of synchronism

Stator Protection

The faults that occur in the stator can be either between phases or to the earth.

The protection of the motors against these faults can be done by the help of overcurrent tripping device which would give an inverse time-current

characteristics.

Phase fault protections are provided by two high-set instantaneous relay elements; the current setting is chosen above the maximum starting current.

Earth fault protection is provided in a motor operating on an earthed neutral system by using a simple instantaneous relay having a setting of approximately 30% of the full load current. Since the earth fault relay shouldn't trip at the initial switching due to CT saturation of high

starting current, so the voltage setting of the relay is increased by inserting a stabilizing resistance in series with it. The scheme

can be described as below
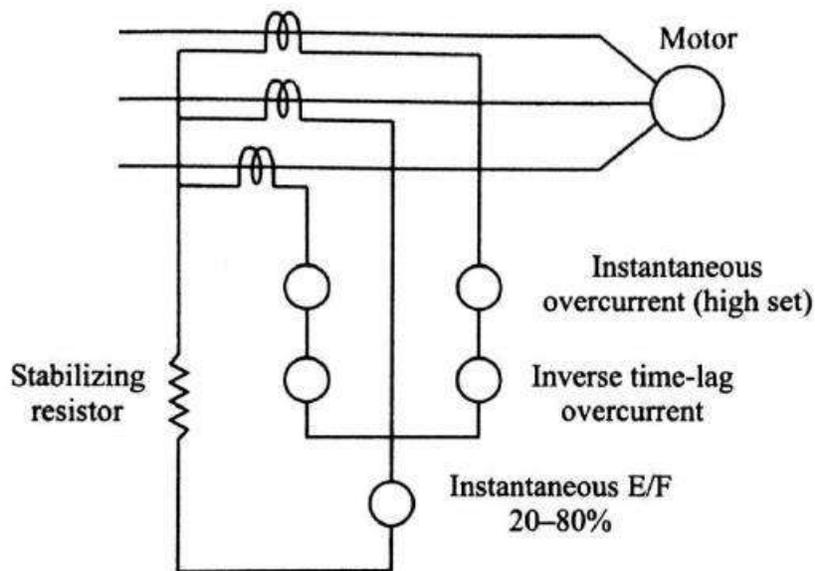
Figure 42 Induction motor-protection relay

Rotor Protection

Any unbalance in the supply or in the loading pattern will cause high amount of negative sequence current in the stator. This induces high frequency currents in the rotor circuit also. The frequency of this current is (2-s) times the normal frequency. The heating value of the negative sequence current is high as compared to positive sequence current, which is proportional to *(2-s) f* (approximately 100 Hz) a.c. resistance value. Hence motor protection must be taken into account the allowable voltage unbalance without overheating.

Overload Protection

The overload protection of the motor is designed so as to match the heating curve of the motor. The motor must not be allowed for most of the time for heating. For this reason the characteristics of the relay must not be more than the heating characteristics of the motor for protection. The protection must also have the capability to adjust its characteristics and should not allow the motor to restart until the motor winding temperature is high. For this reason the IDMT relay is best suited for this purpose.
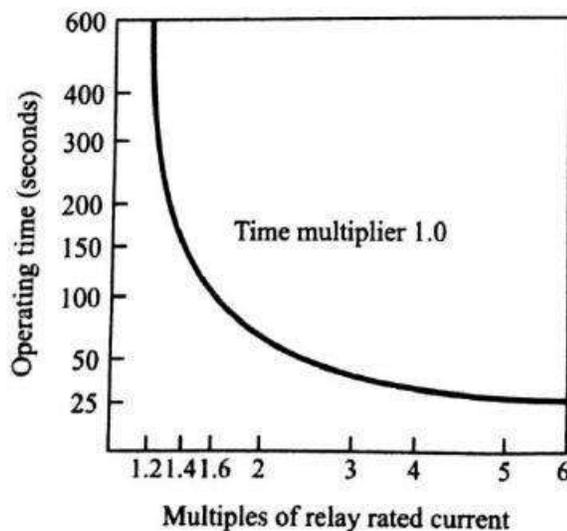
Figure 43 Operating time characteristic of IDMT relay induction type

Unbalance and Single Phasing Protection

An unbalance in the system causes the negative sequence currents to flow in the

motor. This would result in overheating of the machine windings. Unbalanced loads or accidental opening of one phase of the supply (single phasing) depending on the load still keeps the motor running with the induction of negative sequence in the motor.

For star connected motors the unbalance can be protected by two overload

elements. For delta connected motors such arrangement is satisfactory when the motor is running for more than 70% of the full load. A better scheme for detecting unbalance in motors is by the way of using bimetal strips as explained below:

In this arrangement, the bimetal relay has two slides S1 and S2 such that the slider S1 is moved by the deflection of the bimetal strips, whereas the slider S2 is kept in position due to non-bending of the bimetal strips. On symmetrical loading all the three bimetallic strips bend equally and both sliders move equally in the same direction by distance d thereby initiating the tripping. When there is a single phasing in the system, so that phase remains cold while the other two phases gets overloaded. This results in bending of these two phases while the other remains fixed. Hence the slider S1 moves accordingly while the slider S2 is held by bimetal strip of the cold phase. This bending initiates the tripping of the relay. Thus, the bimetal relay responds accordingly in case of single phasing.
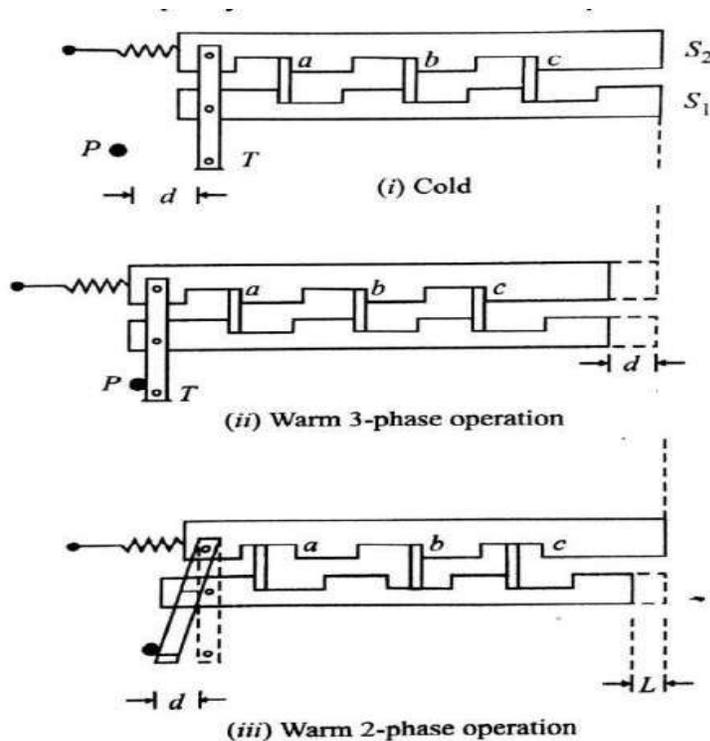

Figure 44 Bimetal relay with single phasing trip feature

In case of large motors the use of bimetal relay becomes sluggish because of the level of fault current being high. In this case we make the use of thermistors which causes the tripping action due to the change in resistance. The figure below illustrates the use of an over temperature protective scheme for a three phase over DOL starting type induction motor which has the NTC type thermistors connected in it.
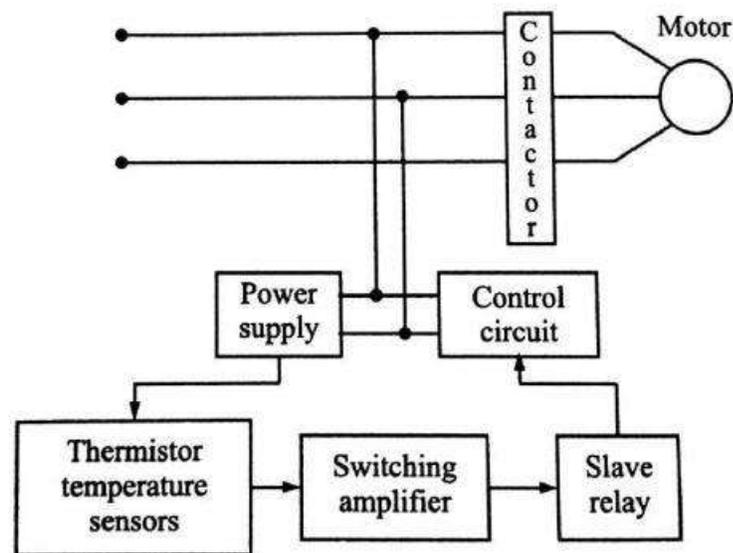
Figure 45 Temperature operated scheme

Under voltage Protection

A motor working in over voltage situation would generally be associated with overcurrent and thus can be protected by overload devices. A time delay is generally given to avoid transient behaviour of the voltage drop.

Reverse Phase Protection

The direction of rotation of the motor changes if the phase sequence is changed. In some motors this becomes very important. In order to ensure the direction of rotation an induction disc, poly phase voltage relay is used to protect the motor from starting when there is a mismatch of the

sequence. Such a connection is shown in the figure below, where the torque is proportional to the sine product of two voltages. So when there is a mismatch of sequence, there would be no torque and restrains the motor from operating.

Figure: Open and reversed phase relay

Loss of synchronism

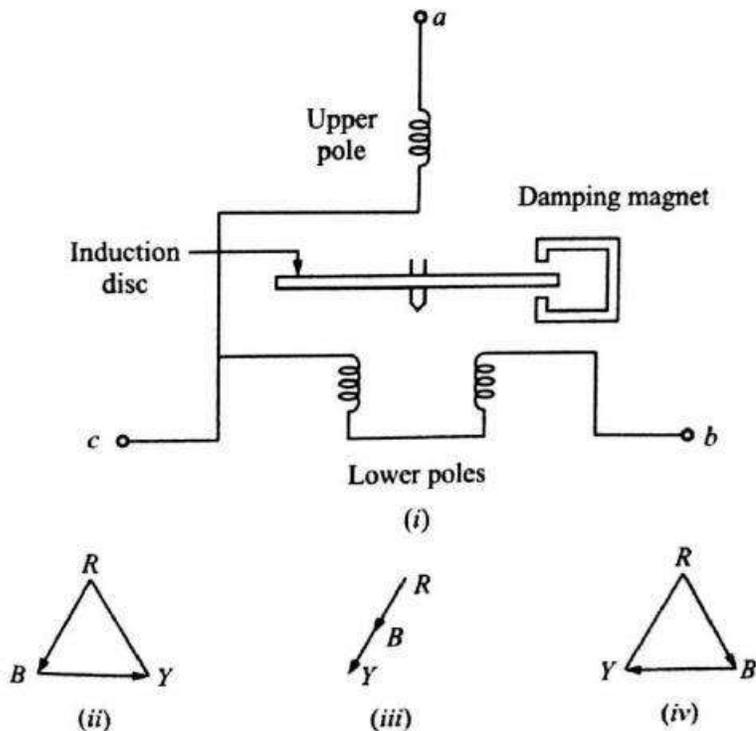A synchronous motor becomes out of synchronism when there is a severe overload or a reduction in the voltage. Such a condition would result in change in power factor due to pole slipping and is detected by the relay. Such circuit is given below where the voltage between two phases is measured and the current in third phase is measured.
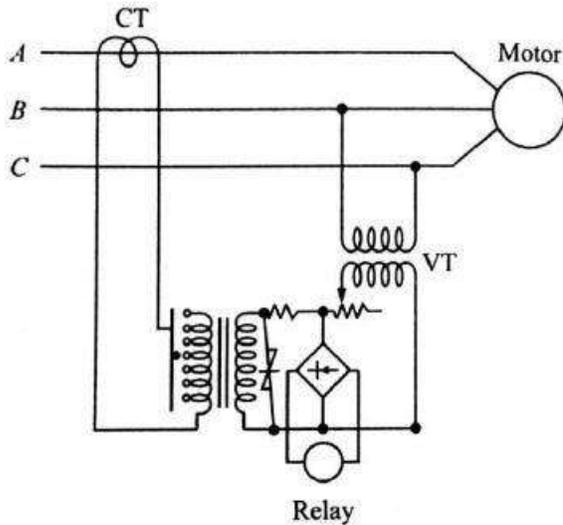
Figure: Out-of-step protection relay

5. Bus Faults

Bus zone protection includes the bus itself as well as circuit breakers, disconnecting switches, instrument transformers and bus sectionalizing reactors. These faults occurs rarely in the system but the provision of bus bar protection is necessary at the large and important station as the bus zone fault would result in interruption of high amount of power.

Bus Zone Faults

The faults in the bus zone can be divided as follows:

(i) Failure of circuit breaker to interrupt fault current or failure to clear under through fault conditions.

(ii) Insulation failure due to material deterioration.

(iii) Flashover causes by prolonged and excessive over voltages.

(iv) Errors in the operation and maintenance of switchgears.

(v) Foreign objects accidentally falling across bus bars.

Bus Backup Protection

When no separate protection is provided for the bus bars but there is a provision of distance protection, so any fault that is occurring at the bus zone protection would come under the zone 2 protection of the distance relay where it covers the bus bar and the next line also. This is satisfactory for the small switchgear case but not in the case of prime installations. Therefore a separate bus zone protection may be provided for the same.

Differential Scheme of Bus Bar Protection

It is based on the simple circulating current principle that during the normal condition or external fault condition, the incoming current must be equal to the leaving current. Since the bus in a power system acts as a node in an electrical circuit, if the summation of currents is not equal to zero, it means that there is a short circuit due to ground fault or phase to phase fault. The differential scheme can be given as below, whose CT ratio are given according to the highest current that is flowing in the feeder circuits.

Figure 48 Differential Protection of a bus
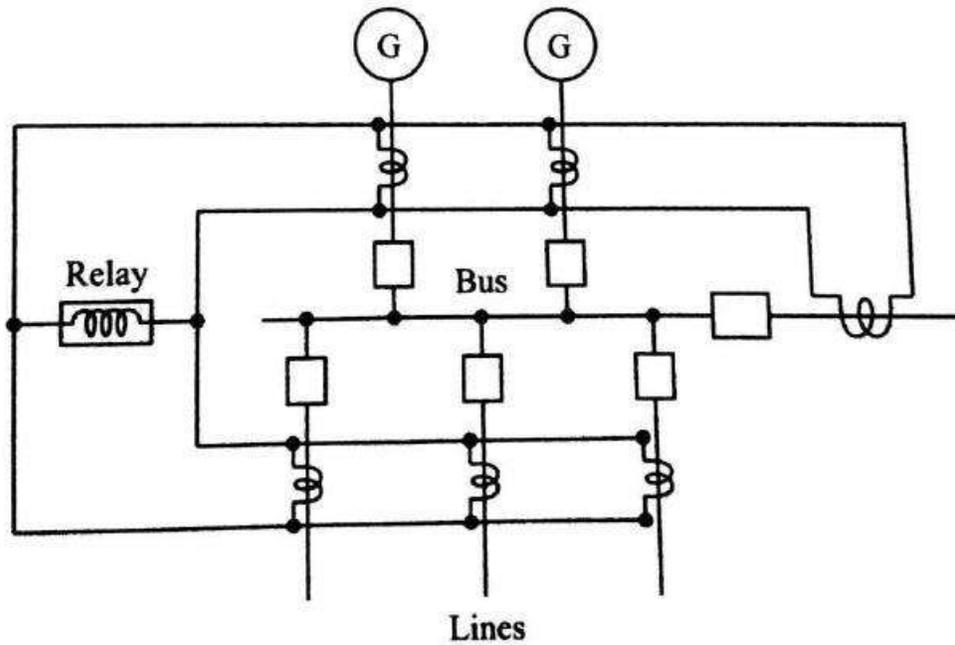
Figure: Differential Protection of a bus section

Since the CTs used here are of the same ratio, when there is a through fault condition, the magnetic conditions of the iron cored CTs would result in false operation due to saturation. Even with biasing of the relay, the improvement is not satisfactory.

An improvement can be done by the use of non iron cored CT also known as linear coupler to overcome the difficulties of iron cored CTs. In this the secondary voltage is proportional to the primary current. So when there is an external fault, the addition of the voltages won't result to zero since the current is still balanced, but when there is an internal fault there is an unbalance in current and hence results to some voltage in the linear coupler scheme.
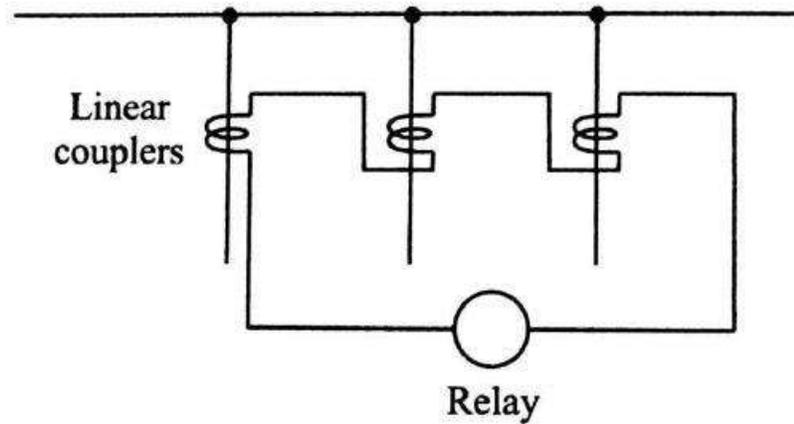
Figure: Linear Coupler scheme

Frame Leakage Protection

It is possible to design a station so that the faults which develop are mostly earth faults, by providing earthed metal barrier surrounding each conductor in the bus structure. With this arrangement every fault that might occur must involve a connection between the conductor and an earthed metal part.

The figure below shows the metal supporting structure also known as a fault bus earthed through a CT. Sometimes, the structure is earthed by the means of impedance connected in the neutral.
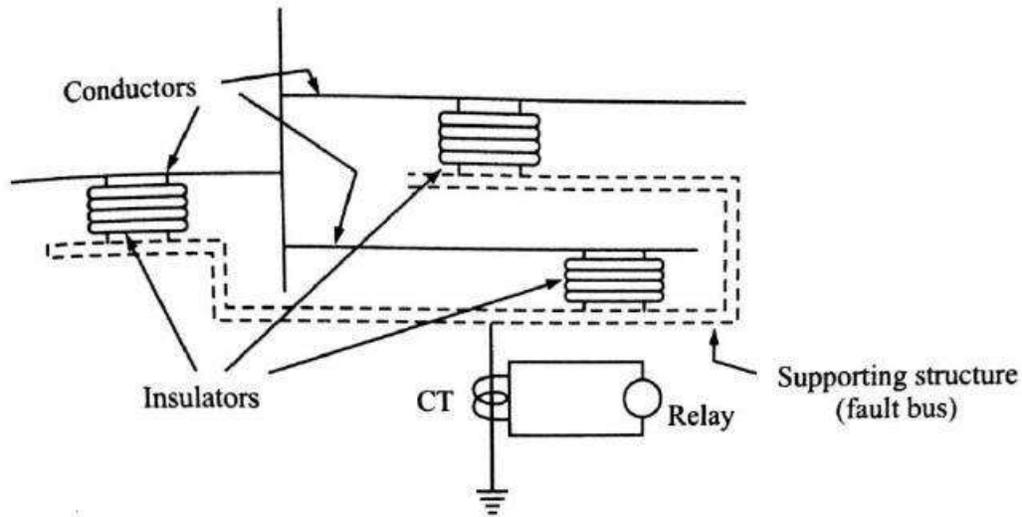
Figure: Frame leakage protection

In the resistance earthed neutral, the advantage is that besides limiting the value of current it is also used to protect certain part of the generator or transformer windings which are connected in the feeder circuits. The earth fault current for protecting $x\%$ of the winding is given as

$$I_F = (1-x)\frac{V}{R}$$

This must be also the primary fault setting of the differential protection *IS* for minimum operating current.
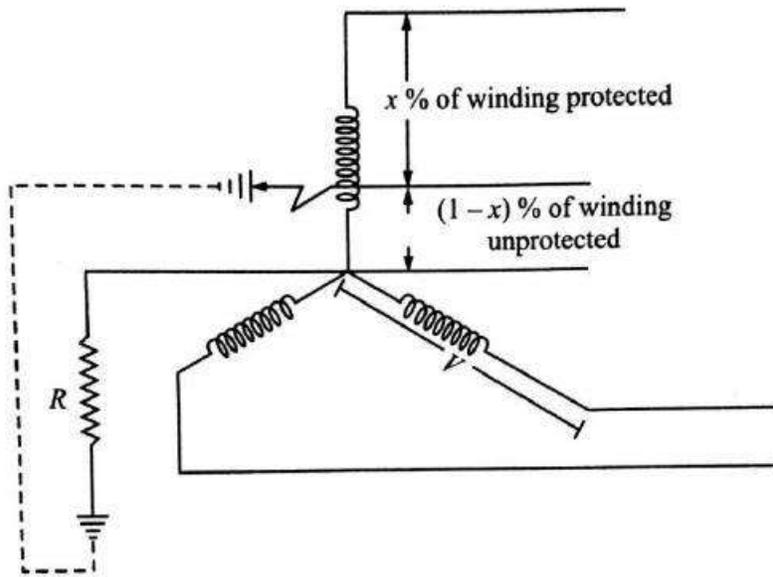
Figure 51 Percentage of unprotected winding against phase to earth fault

$$I_S = (1 - x)\frac{V}{R}$$

Or % of winding unprotected is

$$(1 - x) = \frac{I_S . R}{V} \times 100$$

CIRCUIT BREAKER

During the operation of power system, it is often desirable and necessary to switch on or off the various circuits (e.g., transmission lines, distributors, generating plants etc.) under both normal and abnormal conditions. In earlier days, this function used to be performed by a switch and a fuse placed in series with the circuit.

However, such a means of control presents two disadvantages.

1. Firstly, when a fuse blows out, it takes quite some time to replace it and restore supply to the customers.

2. Secondly, a fuse cannot successfully interrupt heavy fault currents that result from faults on modern high-voltage and large capacity circuits.

3. Due to these disadvantages, the use of switches and fuses is limited to low voltage and small capacity circuits where frequent operations are not expected e.g., for switching and protection of distribution transformers,lighting circuits, branch circuits of distribution

lines etc.

4. With the advancement of power system, the lines and other equipment operate at very high voltages and carry large currents. The arrangement of switches along with fuses cannot serve the desired function of switchgearin such high capacity circuits. This necessitates employing a more dependable means of control such as is obtained by the use of circuit breakers.

5. A circuit breaker can make or break a circuit either manually or automatically under all conditions viz., no-load, full-load and short-circuit conditions.

6. This characteristic of the circuit breaker has made it very useful equipment for switching and protection of various parts of the power system.

7. Thus a circuit breaker incorporates manual (or remote control) as well as automatic control for switching functions. The latter control employs relays and operates only under fault conditions

Operating principle:

A circuit breaker essentially consists of fixed and moving contacts, called Electrodes.Under normal operating conditions, these contacts remain closed and will not open automatically until and unless the system becomes faulty. Of course, the contacts can be opened manually or by remote control whenever desired. When a fault occurs on any part of the system, the trip coils of the circuit breaker get energized and the moving contacts are pulled apart by some mechanism, thus opening the circuit.

Arc Phenomenon:

When a short circuit occurs, a heavy current flows through the contacts of the circuit breaker before they are opened by the protective system. At the instant when the contacts begin to separate, the contact area decreases rapidly and large fault current causes increased current density

and hence rise in temperature. The heat produced in the medium between contacts (usually the medium is oil or air) Is sufficient to ionize the air or vaporize and ionize the oil. The ionized air or vapor acts as conductor and an arc is struck between the contacts.

The arc resistance depends upon the following factors:

1. **Degree of ionization**- the arc resistance increases with the decrease in the number of ionized particles between the contacts.

2. **Length of the arc**— the arc resistance increases with the length of the arc i.e., separation of contacts.

3. **Cross-section of arc**— the arc resistance increases with the decrease in area of X-section of the arc.

Principles of Arc Extinction:

Before discussing the methods of arc extinction, it is necessary to examine the factors responsible for the maintenance of arc between the contacts.

Methods of Arc Extinction (or) Interruption:

There are two methods of extinguishing the arc in circuit breakers viz.

1. High resistance method.

2. Low resistance or current zero method

High resistance method:

In this method, arc resistance is made to increase with time so that current is reduced to a value insufficient to maintain the arc. Consequently, the current is interrupted or the arc is extinguished.The principal disadvantage of this method is that enormous energy is dissipated in the arc. Therefore, it is employed only in D.C. circuit breakers and low-capacity a.c. circuit breakers.

The resistance of the arc may be increased by:

1. Lengthening the arc: The resistance of the arc is directly proportional to its length. The length of the arc can be increased by increasing the gap between contacts.

2. Cooling the arc: Cooling helps in the deionization of the medium between the contacts. This increases the arc resistance. Efficient cooling may be obtained by a gas blast directed along the arc.

3. Reducing X-section of the arc: If the area of X-section of the arc is reduced, the voltage necessary to maintain the arc is increased. In other words, the resistance of the arc path is increased. The cross-section of the arc can be reduced by letting the arc pass through a narrow opening or by having smaller area of contacts.

4. Splitting the arc: The resistance of the arc can be increased by splitting the arc into a number of smaller arcs in series. Each one of these arcs experiences the effect of lengthening and cooling. The arc may be split by introducing some conducting plates between the contacts.

Low resistance or Current zero method:

In this method is employed for arc extinction in a.c. circuits only. In this method, arc resistance is kept low until current is zero where the arc extinguishes naturally and is prevented from restriking in spite of the rising voltage across the contacts. All Modern high power a.c.

circuit breakers employ this method for arc extinction.In an a.c. system, current drops to zero after every half-cycle. At every current zero, the arc extinguishes for a brief moment.Now the medium between the contacts contains ions and electrons so that it has small dielectric strength and can be easily broken down by the rising contact voltage known as restriking voltage.If such a breakdown does occur, the arc will persist for another half cycle.If immediately after current zero, the dielectric strength of the medium between contacts is built up more rapidly than the voltage across the contacts, the arc fails to restrike and the current will be interrupted.

The rapid increase of dielectric strength of the medium near current zero can be achieved by:

1. Causing the ionized particles in the space between contacts to recombine into neutral molecules.

2. Sweeping the ionized particles away and replacing them by un ionized particles.Therefore, the real problem in a.c. arc interruption is to rapidly de ionize the medium between contacts as soon as the current becomes zero so that the rising contact voltage or restriking voltage cannot breakdown the space between contacts.

The de-ionization of the medium can be achieved by:

1. **Lengthening of the gap:** The dielectric strength of the medium is proportional to the length of the gap between contacts. Therefore, by opening the contacts rapidly, higher dielectric strength of the medium can be achieved.

2. **High pressure:** If the pressure in the vicinity of the arc is increased, the density of the particles constituting the discharge also increases. The increased density of particles causes higher rate of de-ionization and consequently the dielectric strength of the medium between contacts is increased.

3. **Cooling:** Natural combination of ionized particles takes place more rapidly if they are allowed to cool. Therefore, dielectric strength of the medium between the contacts can be increased by cooling the arc.

4. **Blast effect:** If the ionized particles between the contacts are swept away and replaced by UN ionized particles, the dielectric strength of the medium can be increased considerably. This may be achieved by a gas blast directed along the discharge or by forcing oil into the contact space.
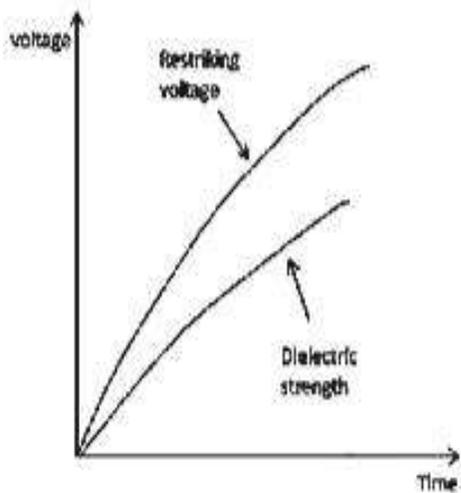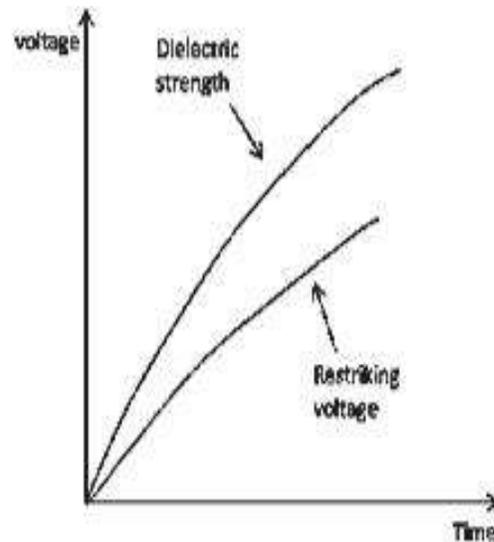
(a) Arc Extinguishes   (b) Arc Persists

There are two theories to explain the Zero current interruption of the Arc:

1. Recovery rate theory (Slepain's Theory)

2. Energy balance theory (Cassie's Theory)

<u>Recovery rate theory (Slepain's Theory):</u>

The arc is a column of ionized gases. To extinguish the arc, the electrons and ions are to be removed from the gap immediately after the current reaches a natural zero. Ions and electrons can be removed either by recombining them in to neutral molecules or by sweeping them away by

inserting insulating medium (gas or liquid) into the gap. The arc is interrupted if ions are removed from the gap recovers its dielectric strength is compared with the rate at which the restriking voltage (transient voltage) across the gap rises. If the dielectric strength increases more rapidly than the restriking voltage, the arc is extinguished. If the restriking voltage rises more rapidly than the dielectric strength,

the ionization persists and breakdown of the gap occurs, resulting in an arc for another half cycle.
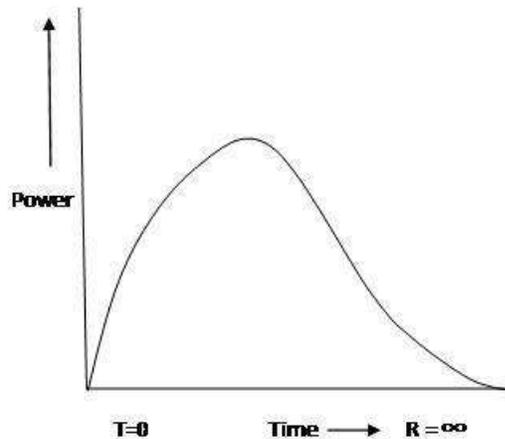
Energy balance theory (Cassie's Theory):

The space between the contacts contains some ionized gas immediately after current zero and hence, it has a finite post –zero moment, power is zero because restriking voltage is zero.

When the arc is finally extinguished, the power gain becomes zero, the gap is fully de-ionized and its resistance is infinitely high. In between these two limits, first the power increases, reaches a maximum value, then decreases and finitely reaches zero value as shown in figure. Due to the rise of restriking voltage and associated current, energy is generated in the space between the contacts. The energy appears in the form of heat. The circuit breaker is designed to remove this generated heat as early as possible by cooling the gap, giving a blast air or flow of oil at high velocity and pressure. If the rate of removal of heat is faster than the rate of heat generation the arc is extinguished. If the rate of heat generation is more than the rate of heat dissipation, the space breaks down again resulting in an arc for another half cycle.
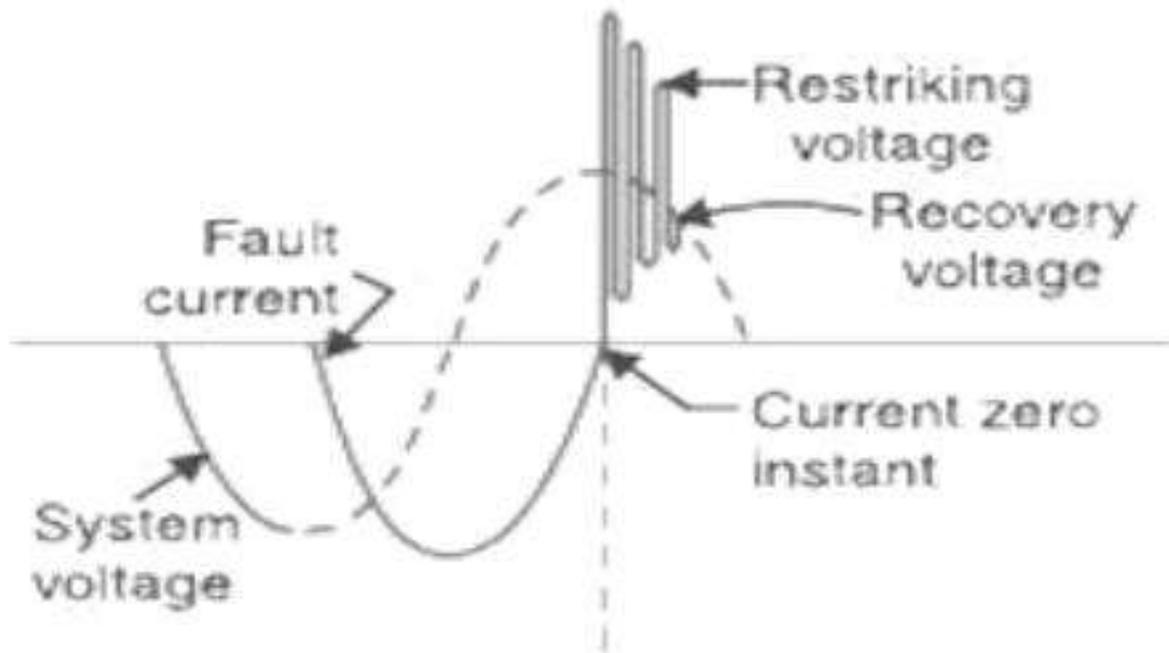
Important Terms:

The following are the important terms much used in the circuit breaker analysis:

1. Arc Voltage:

It is the voltage that appears across the contacts of the circuit breaker during the arcing period. As soon as the contacts of the circuit breaker separate, an arc is formed. The voltage that appears across the contacts during arcing period is called the arc voltage. Its value is low except for the period the fault current is at or near zero current point. At current zero, the arc voltage rises rapidly to peak value and this peak voltage tends to maintain the current flow in the form of arc.

2. Restriking voltage:
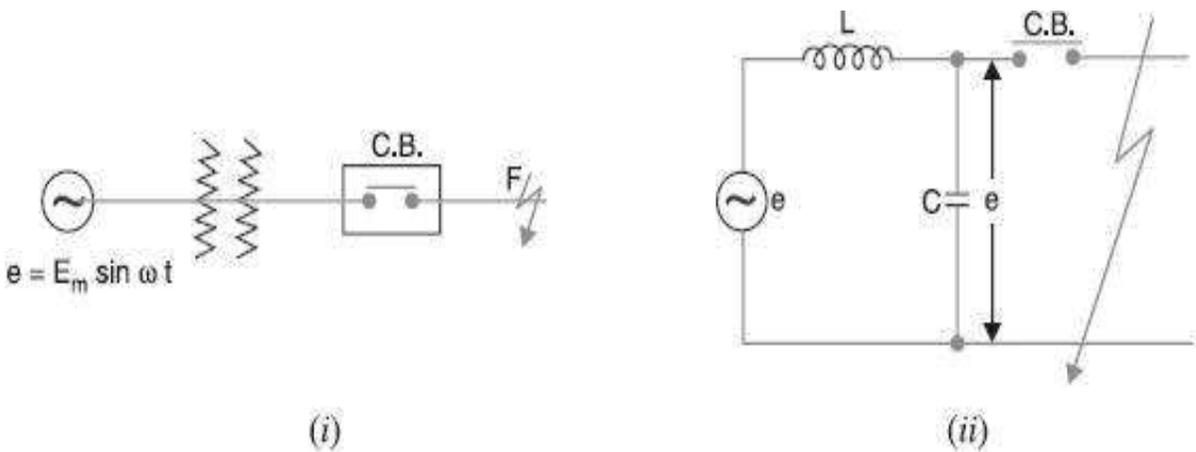
Fig. 1 Restriking voltage

It is the transient voltage that appears across the contacts at or near current zero during arcing period. At current zero, a high-frequency transient voltage appears across the contacts and is caused by the rapid distribution of energy between the magnetic and electric fields associated with the plant and transmission lines of the system. This transient voltage is known as restriking voltage (Fig. 1).

The current interruption in the circuit depends upon this voltage. If the restriking voltage rises more rapidly than the dielectric strength of the medium between the contacts, the arc will persist for another half-cycle. On the other hand, if the dielectric strength of the medium builds up more rapidly than the restriking voltage, the arc fails to restrike and the current will be interrupted.

3. **Recovery voltage:**

It is the normal frequency (50 Hz) R.M.S. voltage that appears across the contacts of the circuit breaker after final arc extinction. It is approximately equal to the system voltage. When contacts of circuit breaker are opened, current drops to zero after every half cycle.

At some current zero, the contacts are separated sufficiently apart and dielectric strength of the medium between the contacts attains a high value due to the removal of ionized particles. At such an instant, the medium between the contacts is strong enough to prevent the breakdown by the restriking voltage. Consequently, the final arc extinction takes place and circuit current is interrupted. Immediately after final current interruption, the voltage that appears across the contacts has a transient part (See Fig.1). However, these transient oscillations subside rapidly

due to the damping effect of system resistance and normal circuit voltage appears across the contacts. The voltage across the contacts is of normal frequency and is known as recovery voltage.

Expression for Restriking voltage and RRRV:

The power system contains an appreciable amount of inductance and some capacitance. When a fault occurs, the energy stored in the system can be considerable. Interruption of fault current by a circuit breaker will result in most of the stored energy dissipated within the circuit breaker, the remainder being dissipated during oscillatory surges in the system. The oscillatory surges are undesirable and, therefore, the circuit breaker must be designed to dissipate as much of the stored energy as possible.

Fig. 1 (i) shows a short-circuit occurring on the transmission line. Fig. 1 (ii) shows its equivalent circuit where L is the inductance per phase of the system up to the point of fault and C is the capacitance per phase of the system. The resistance of the system is neglected as it is

generally small.

Rate of rise of re-striking voltage:

It is the rate of increase of re-striking voltage and is abbreviated by R.R.R.V. usually; the voltage is in kV and time in microseconds so that R.R.R.V. is in kV/μ sec.

Consider the opening of a circuit breaker under fault conditions Shown in simplified form in Fig. 1 (ii) above. Before current interruption, the capacitance C is short-circuited by the fault and the short-circuit current through the breaker is limited by Inductance L of the system only. Consequently, the short-circuit current will lag the voltage by 90º as shown in Fig. 2, where I Represents the short-circuit current and ea represents the arc voltage. It may be seen that in this condition, the *entire generator voltage appears across inductance L.
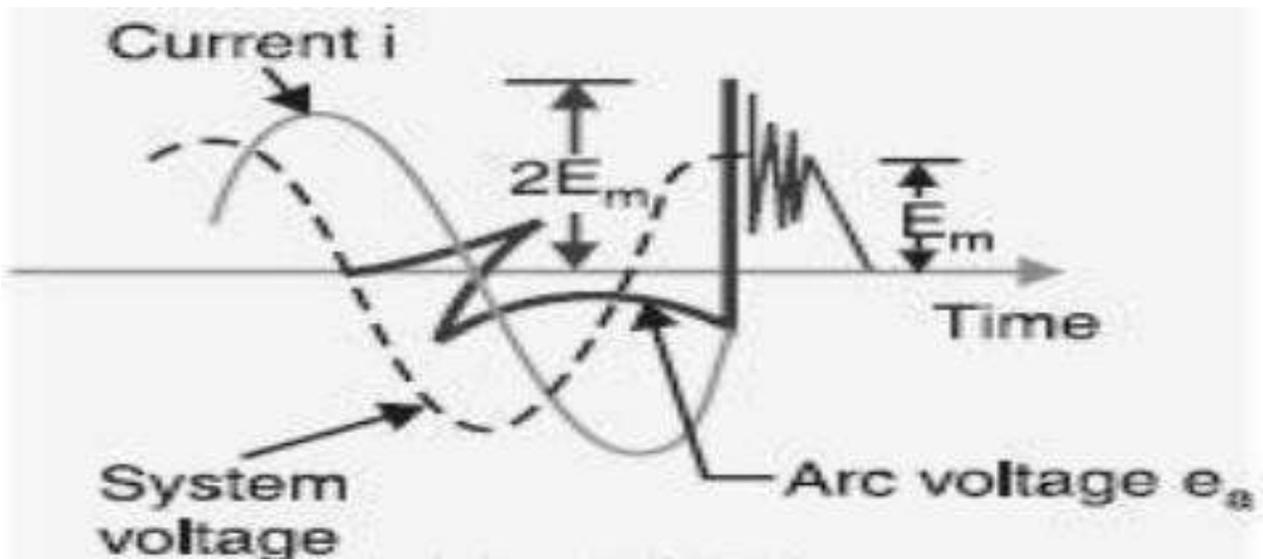

Fig. 2

When the contacts are opened and the arc finally extinguishes at some current zero, the generator voltage e is suddenly applied to the inductance and capacitance in series. Which appears across the capacitor C and hence across the contacts of the circuit breaker.

This transient voltage, as already noted, is known as re-striking voltage and may reach an instantaneous peak value twice the peak phase-neutral voltage i.e. 2 Em . The system losses cause the oscillations to decay fairly rapidly but the initial overshoot increases the possibility of restriking the arc.

It is the rate of rise of re-striking voltage (R.R.R.V.) which decides whether the arc will restrike or not. If R.R.R.V. is greater than the rate of rise of dielectric strength between the contacts, the arc will re-strike. However, the arc will fail to re-strike if R.R.R.V. is less than the rate of

increase of dielectric strength between the contacts of the breaker.

The value of R.R.R.V. depends up on:

1. Recovery voltage

2. Natural frequency of oscillations

For a short-circuit occurring near the power station bus-bars, C being small, the natural frequency **fn** will be high. Consequently, R.R.R.V. will attain a large value. Thus the worst condition for a circuit breaker would be that when the fault takes place near the bus-bars.

Current chopping:

It is the phenomenon of current interruption before the natural current zero is reached.

Current chopping mainly occurs in air-blast circuit breakers because they retain the same extinguishing power irrespective of the magnitude of the current to be interrupted. When breaking low currents (e.g., transformer magnetizing current) with such breakers, the powerful de-ionizing effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached. This phenomenon is known as

current chopping and results in the production of high voltage transient across the contacts of the circuit breaker as discussed below:

Consider again Fig. 1 (ii) repeated as Fig. 3 (i). Suppose the arc current is i when it is chopped down to zero value as shown by point a in Fig. 3 (ii). As the chop occurs at current i, therefore, the energy stored in inductance is L i2 /2.

This energy will be transferred to the capacitance C, charging the latter to a prospective voltage e given by:

The prospective voltage e is very high as compared to the dielectric strength gained by the gap so that the breaker restrike. As the de-ionizing force is still in action, therefore, chop occurs again but the arc current this time is smaller than the previous case. This induces a lower prospective voltage to re-ignite the arc. In fact, several chops may occur until a low enough current is interrupted which produces insufficient induced voltage to re-strike across the breaker gap. Consequently, the final interruption of current takes place.Excessive voltage surges due to current chopping are prevented by shunting the contacts of the breaker with a resistor (resistance switching) such that re ignition is unlikely to occur. This is explained in Fig. 3.
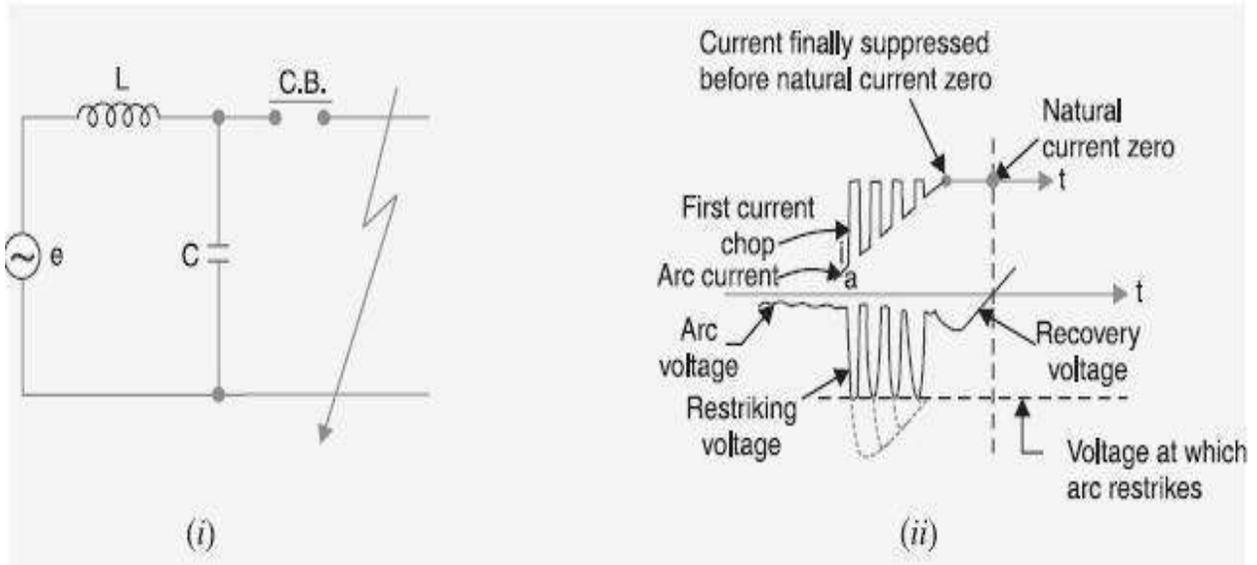
Fig. 3

Capacitive current breaking:

Another cause of excessive voltage surges in the circuit breakers is the interruption of capacitive currents. Examples of such instances are opening of an unloaded long transmission line, disconnecting a capacitor bank used for power factor improvement etc. Consider the simple equivalent circuit of an unloaded transmission line shown in Fig.4. Such a line, although unloaded in the normal sense, will actually carry a capacitive current I on account of appreciable amount of capacitance C between the line and the earth.

Let us suppose that the line is opened by the circuit breaker at the instant when line capacitive current is zero [point 1 in Fig.5. At this instant, the generator voltage V g will be maximum (i.e. V gm) lagging behind the current by 90º. The opening of the line leaves a standing charge on it (i.e., end B of the line) and the capacitor C1 is charged to V gm. However, the generator end of the line (i.e., end A of the line) continues its normal sinusoidal variations. The voltage V r across the circuit breaker will be the difference between the voltages on the respective

sides. Its initial value is zero (point 1) and increases slowly in the beginning. But half a cycle later [point R in Fig. 5], the potential of the circuit breaker contact _A ' becomes maximum negative which causes the voltage across the breaker (V r) to become 2 V gm. This voltage may be sufficient to restrike the arc. The two previously separated parts of the circuit will now be joined by an arc of very low resistance. The line capacitance discharges at once to reduce the voltage across the circuit breaker, thus setting up high frequency transient. The peak value of the initial transient will be twice the voltage at that instant i.e., −4 V gm. This will cause the transmission voltage to swing to −4V gm to + V gm i.e., −3V gm.
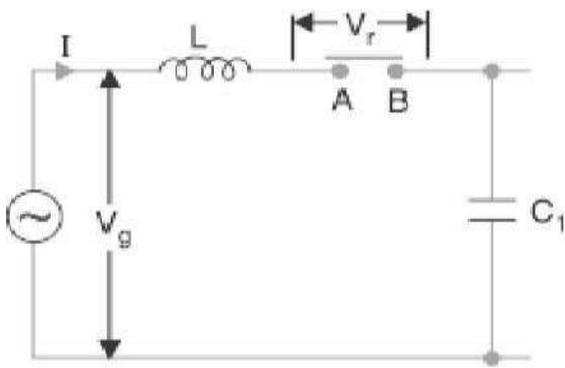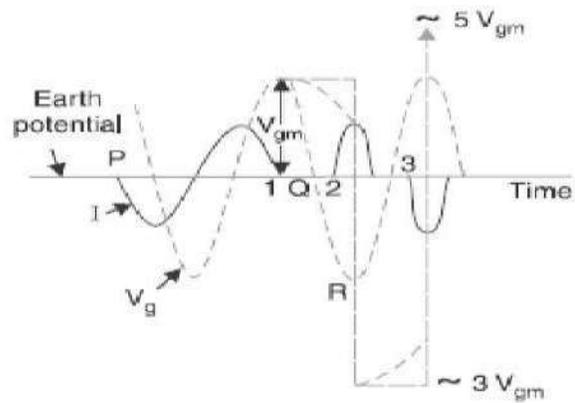
Fig. 4   Fig. 5

The re-strike arc current quickly reaches its first zero as it varies at natural frequency. The voltage on the line is now −3 Vgm and once again the two halves of the circuit are separated and the line is isolated at this potential. After about half a cycle further, the aforesaid events are repeated even on more formidable scale and the line may be left with a potential of 5V gm above earth potential. Theoretically, this phenomenon may proceed infinitely increasing the voltage by successive increment of 2 times V gm.

While the above description relates to the worst possible conditions, it is obvious that if the gap breakdown strength does not increase rapidly enough, successive re-strikes can build up a dangerous voltage in the open circuit line. However, due to leakage and corona loss, the maximum voltage on the line in such cases is limited to 5 V gm.

Resistance Switching:

It has been discussed above that current chopping, capacitive current breaking etc. give rise to severe voltage oscillations. These excessive voltage surges during circuit interruption can be prevented by the use of shunt resistance R connected across the circuit breaker contacts as shown in the equivalent circuit in Fig. 6. This is known as resistance switching.
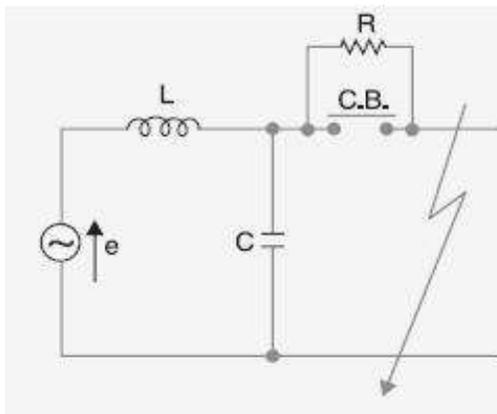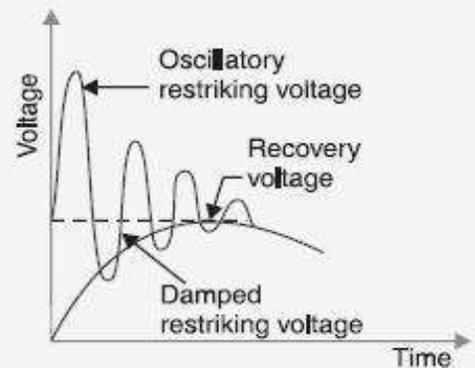
Fig. 6   Fig. 7

Referring to Fig. 6, when a fault occurs, the contacts of the circuit breaker are opened and an arc is struck between the contacts. Since the contacts are shunted by resistance R, a part of arc current flows through this resistance. This results in the decrease of arc current and an increase in the rate of de-ionization of the arc path. Consequently, the arc resistance is increased. The increased arc resistance leads to a further increase in current through shunt resistance. This process continues until the arc current becomes so small that it fails to maintain the arc. Now,

the arc is extinguished and circuit current is interrupted The shunt resistor also helps in limiting the oscillatory growth of re-striking voltage. It can be proved mathematically that natural frequency of oscillations (or) the frequency of damped oscillation of the circuit shown in Fig. 6 is given by: The effect of shunt resistance R is to prevent the oscillatory growth of re-striking voltage and cause it to grow exponentially up to recovery voltage. This is being most effective when the value of R is so chosen that the circuit is critically damped. The value of R required for critical damping is 0.5 . Fig. 7 shows the oscillatory growth and exponential growth when the circuit is critically damped.

To sum up, resistors across breaker contacts may be used to perform one or more of the following functions:

1. To reduce the rate of rise of re-striking voltage and the peak value of re-striking voltage.

2. To reduce the voltage surges due to current chopping and capacitive current breaking.

3. To ensure even sharing of re-striking voltage transient across the various breaks in multi break circuit breakers.

It may be noted that value of resistance required to perform each function is usually different. However, it is often necessary to compromise and make one resistor do more than one of these functions.

Switchgear Components:

The following are some important components common to most of the circuit breakers:

1. Bushings

2. Circuit breaker contacts

3. Instrument transformers

4. Bus-bars and conductors
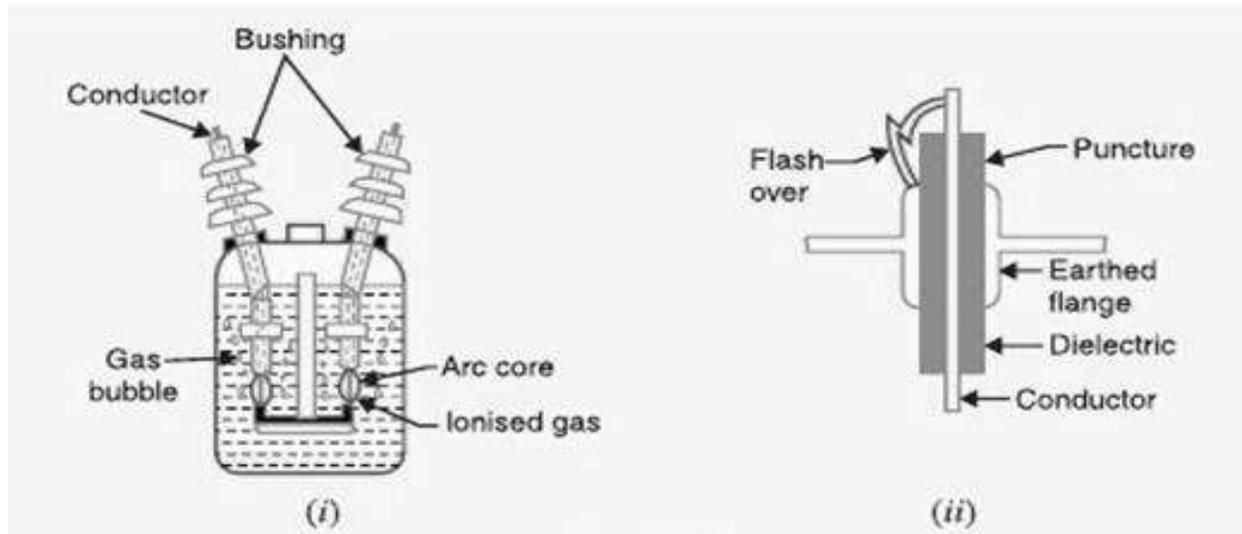
Fig. 8

Bushings:

When a high voltage conductor passes through a metal sheet or frame which is at earth potential, the necessary insulation is provided in the form of bushing. The primary function of the bushing is to prevent electrical breakdown between the enclosed conductor and the surrounding earthed metal work. Fig. 8 (i) shows the use of bushing for a plain-break oil circuit breaker.

The high voltage conductor passes through the bushing made of some insulating material (e.g., porcelain, steatite). Although there are several types of bushing (e.g., condenser type, oil filled etc.), they perform the same function of insulating the conductor from earthed tank. The failure of the bushing can occur in two ways. Firstly, the breakdown may be caused by puncture i.e., dielectric failure of the insulating material of the

bushing. Secondly, the breakdown may occur in the form of a flash-over between the exposed conductor at either end of the bushing and the

earthed metal. Fig. 8 (ii) illustrates these two possibilities. The bushings are so designed that flash-over takes place before they get punctured. It is because the puncture generally renders the bushing insulation unserviceable and incapable of withstanding the normal voltage. On the other hand, a flash-over may result in comparatively harmless burning of the surface of the bushing which can then continue to give adequate service pending replacement.

Circuit breaker contacts:

The circuit breaker contacts are required to carry normal as well as short-circuit current. In carrying the normal current, it is desirable that the temperature should not rise above the specified limits and that there should be low voltage drop at the point of contact. In carrying breaking and making short-circuit currents, the chief effects to be dealt with are melting and Vaporization by the heat of the arc and those due to electromagnetic forces. Therefore, the design of contacts is of considerable importance for satisfactory operation of the circuit breakers. There are three types of circuit breaker contacts viz.
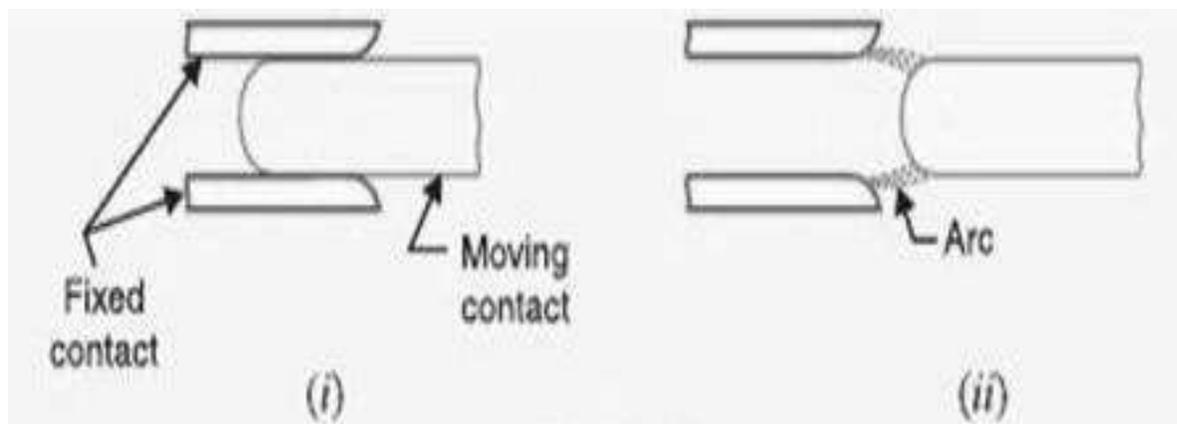
Fig. 9

a. Tulip type contacts: Fig. 9 (i) shows the Tulip type contact. It consists of moving contact which moves inside the fixed contacts. At contact separation, the arc is generally established between the tips of the fixed contacts and the tip of the moving contact as shown in Fig. 9 (ii). The advantage of this type of contact is that arcing is confined to the regions which are not in contact in the fully engaged position.

(i)   *(ii)*
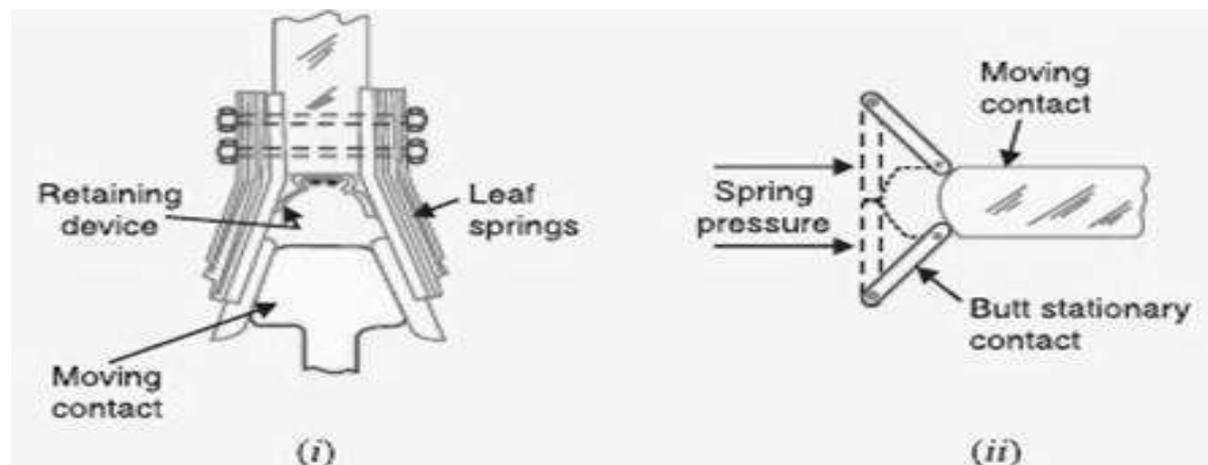
Fig. 10

b. Finger and wedge contacts: Fig. 10 (i) shows the finger and wedge type contact. This type of contact iis largely used for low-voltage oil circuit breakers owing to the general unsuitability for use with arc control devices.

c. Butt contacts: Fig. 10 (ii) shows the butt type contact and is formed by the springs and the moving contact. It possesses two advantages. Firstly, spring pressure is available to assist contact separation. This is useful in single-break oil circuit breakers and air-blast circuit breakers where relatively small —loop‖ forces are available to assist in opening. Secondly, there is no grip force so that this type of contact is especially suitable for higher short circuit rating.

Instrument transformers:

In a modern power system, the circuits operate at very high voltages and carry current of thousands of amperes. The measuring instruments and protective devices cannot work satisfactorily if mounted directly on the power lines. This difficulty is overcome by installing instrument transformers on the power lines. The function of these instrument transformers is to transform voltages or currents in the power lines to values which are convenient for the operation of measuring instruments and relays.

Fig. 11

There are two types of instrument transformers viz.

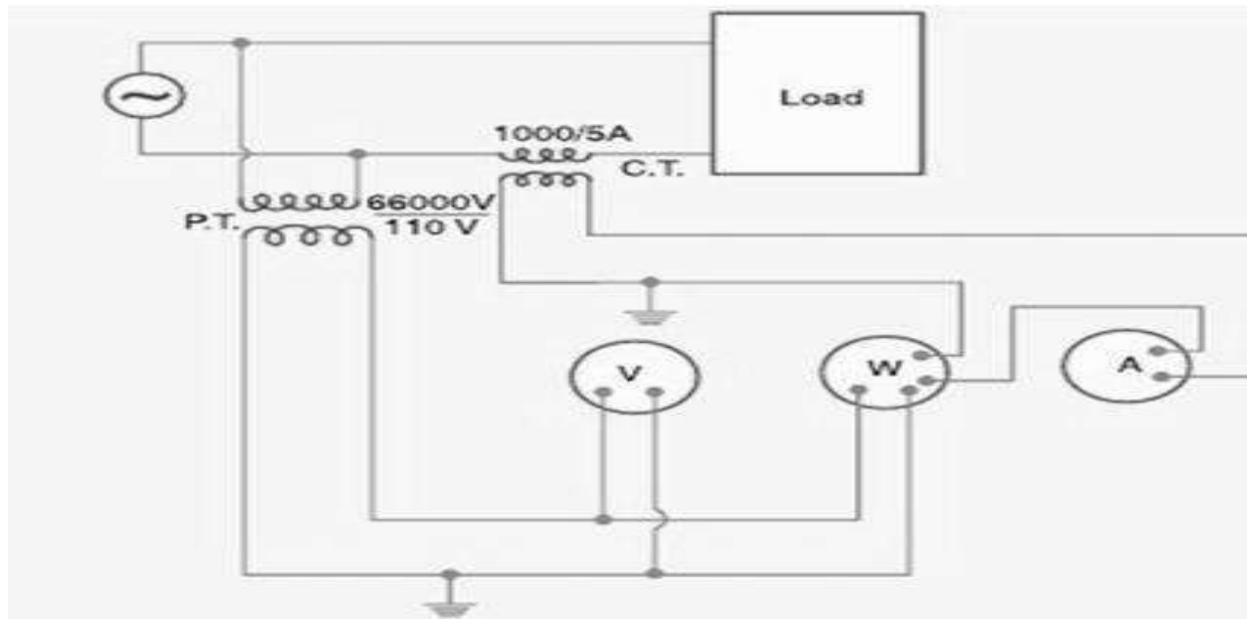1. Current transformer (C.T.)

2. Potential transformer (P.T.)

The primary of current transformer is connected in the power line. The secondary winding provides for the instruments and relays a current which is a constant fraction of the current in the line similarly, a

potential transformer is connected with its primary in the power line. The secondary provides for the instruments and relays a voltage which is a known fraction of the line voltage. Fig. 11 shows the use of instrument transformers. The *potential transformer rated 66,000/110V provides a voltage supply for the potential coils of voltmeter and wattmeter. The current transformer rated 1000/5 A supplies current to the current coils of wattmeter and ammeter.

The use of instrument transformers permits the following advantages:

a. They isolate the measuring instruments and relays from high-voltage power circuits.

b. The leads in the secondary circuits carry relatively small voltages and currents. This permits to use wires of smaller size with minimum insulation.

Bus-bars and conductors: The current carrying members in a circuit breaker consist of fixed and moving contacts and the conductors connecting these to the points external to the breaker. If the switchgear is of outdoor type, these connections are connected directly to the overhead lines. In case of indoor switchgear, the incoming conductors to the circuit breaker are connected to the bus bars.

Circuit Breaker Ratings:

A circuit breaker may be called upon to operate under all conditions. However, major duties are imposed on the circuit breaker when there is a fault on the system in which it is connected. Under fault conditions, a circuit breaker is required to perform the following three duties:

i.It must be capable of opening the faulty circuit and breaking the fault current.

ii. It must be capable of being closed on to a fault.

iii. It must be capable of carrying fault current for a short time while another circuit breaker (in series) is clearing the fault.

Corresponding to the above mentioned duties, the circuit breakers have three ratings viz.

1. Breaking capacity

2. Making capacity and

3. Short-time capacity.

Breaking capacity: It is current (r.m.s.) that a circuit breaker is capable of breaking at given recovery voltage and under specified conditions (e.g., power factor, rate of rise of restriking voltage).

The breaking capacity is always stated at the r.m.s. value of fault Current at the instant of contact separation. When a fault occurs, there is considerable asymmetry in the fault current due to the Presence of a d.c. component. The d.c. component dies away rapidly, a typical decrement

factor being 0·8 per cycle. Referring to Fig. 12, the contacts are separated at DD′ At this instant, the fault current has
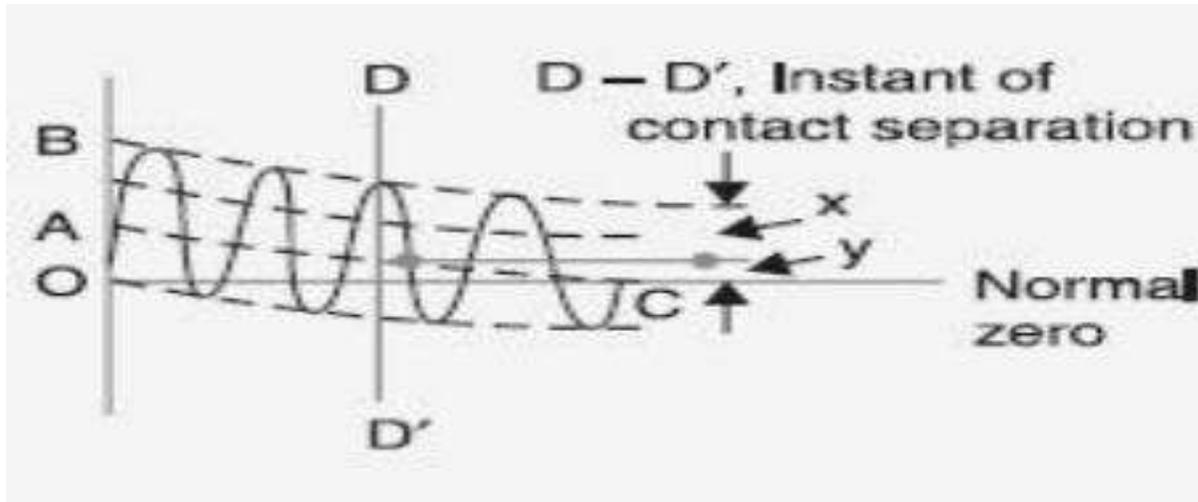
Fig. 12

 x = maximum value of a.c. component y = d.c. component

Symmetrical breaking current = r.m.s. value of a.c. component

Asymmetrical breaking current = r.m.s. value of total current

It is a common practice to express the breaking capacity in MVA by taking into account the rated breaking current and rated service voltage. Thus, if I is the rated breaking current in amperes and V is the rated service line voltage in volts, then for a 3-phase circuit,

In India (or Britain), it is a usual practice to take breaking current equal to the symmetrical breaking current. However, American practice is to take breaking current equal to asymmetrical breaking current. Thus the American rating given to a circuit breaker is higher than the Indian or British rating.

It seems to be illogical to give breaking capacity in MVA since it is obtained from the product of Short-circuit current and rated service voltage. When the short-circuit current is flowing, there is only a small voltage across the breaker contacts, while the service voltage appears across the contacts only after the current has been interrupted. Thus

MVA rating is the product of two quantities which do not exist simultaneously in the circuit.

Therefore, the *agreed international standard of specifying breaking capacity is defined as the rated symmetrical breaking current at a rated voltage.

Making capacity:

There is always a possibility of closing or making the circuit under short circuit conditions. The capacity of a breaker to ―make‖ current depends upon its ability to withstand and close successfully against the effects of electromagnetic forces. These forces are proportional to the square of maximum instantaneous current on closing. Therefore, making capacity is stated in terms of a peak value of current instead of r.m.s. value.

The peak value of current (including d.c. component) during the first cycle of current wave after the closure of circuit breaker is known as making capacity.

It may be noted that the definition is concerned with the first cycle of current wave on closing the circuit breaker. This is because the maximum value of fault current possibly occurs in the first cycle only when maximum asymmetry occurs in any phase of the breaker. In other words, the making current is equal to the maximum value of asymmetrical current. To find this value, we must multiply symmetrical breaking current by $\sqrt{2}$ to convert this from r.m.s. to peak, and then by

1·8 to include the ―doubling effect‖ of maximum asymmetry. The total multiplication factor becomes $\sqrt{2} \times 1·8 = 2·55$.

Making capacity = 2·55 X Symmetrical breaking capacity.

Short-time rating:

It is the period for which the circuit breaker is able to carry fault current while remaining closed. Sometimes a fault on the system is of very temporary nature and persists for 1 or 2 seconds after which the fault is automatically cleared. In the interest of continuity of supply, the breaker should not trip in such situations. This means that circuit breakers should be able to carry high current safely for some specified period while remaining closed i.e., they should have proven short-time rating. How ever, if the fault persists for duration longer than the specified time limit,

the circuit breaker will trip, disconnecting the faulty section.

The short-time rating of a circuit breaker depends upon its ability to withstand The electromagnetic force effects and The temperature rise.

The oil circuit breakers have a specified limit of 3 seconds when the ratio of symmetrical breaking current to the rated normal current does not exceed 40. However, if this ratio is more than 40, then the specified limit is 1 second.

Circuit Breaker

Classification of Circuit Breakers:

There are several ways of classifying the circuit breakers. However, the most general way of classification is on the basis of medium used for arc extinction. The medium used for arc extinction is usually oil, air, sulphur hexafluoride (SF6) or vacuum. Accordingly, circuit breakers may be classified into:

Fig.13

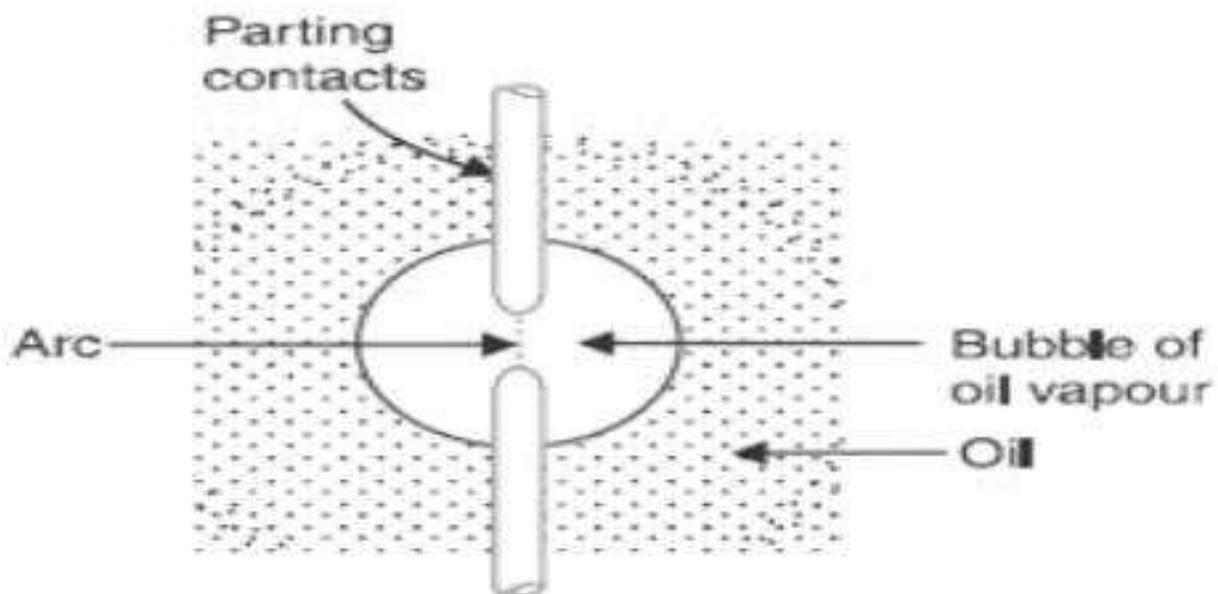1. **Oil circuit breakers:** which employ some insulating oil (e.g., transformer oil) for arc extinction?

2. **Air-blast circuit breakers:** in which high pressure air-blast is used for extinguishing the arc.

3. **Sulphur hexafluoride circuit breakers:** in which sulphur hexafluoride (SF6) gas is used for arc extinction.

4. **Vacuum circuit breakers:** in which vacuum is used for arc extinction.

Each type of circuit breaker has its own advantages and disadvantages. In the following sections, we shall discuss the construction and working of these circuit breakers with special emphasis on the way the arc extinction is facilitated.

Oil Circuit Breakers:

In such circuit breakers, some insulating oil (e.g., transformer oil) is used as an arc quenching medium. The contacts are opened under oil and an arc is struck between them. The heat of the arc evaporates the surrounding oil and dissociates it into a substantial volume of gaseous hydrogen at high pressure. The hydrogen gas occupies a volume about one thousand times that of the oil decomposed. The oil is, therefore, pushed away from the arc and an expanding hydrogen gas bubble surrounds the arc region and adjacent portions of the contacts (See Fig. 13). The arc extinction is facilitated mainly by two processes. Firstly, the hydrogen gas has high heat conductivity and cools the arc, thus aiding the de-ionization of the medium between the contacts. Secondly, the gas sets up turbulence in the oil and forces it into the space between

contacts, thus eliminating the arcing products from the arc path. The result is that arc is extinguished and circuit current †interrupted.

The advantages of oil as an arc quenching medium are:

i. It absorbs the arc energy to decompose the oil into gases which have excellent cooling properties.

ii. It acts as an insulator and permits smaller clearance between live conductors and earthed components.

iii. The surrounding oil presents cooling surface in close proximity to the arc.

The disadvantages of oil as an arc quenching medium are:

i.It is inflammable and there is a risk of a fire.

ii. It may form an explosive mixture with air

iii. The arcing products (e.g., carbon) remain in the oil and its quality deteriorates with successive operations. This necessitates periodic checking and replacement of oil.

Types of Oil Circuit Breakers:

The oil circuit breakers find extensive use in the power system. These can be classified into the following types

1. Bulk oil circuit breakers

2. Low oil circuit breakers

Bulk oil circuit breakers:

Which use a large quantity of oil. The oil has to serve two purposes. Firstly, it extinguishes the arc during opening of contacts and secondly, it insulates the current conducting parts from one another and from the earthed tank. Such circuit breakers may be classified into:

1. Plain break oil circuit breakers

2. Arc control oil circuit breakers.

In the former type, no special means is available for controlling the arc and the contacts are directly exposed to the whole of the oil in the tank. However, in the latter type, special arc control devices are employed to get the beneficial action of the arc as efficiently as possible.

Plain Break Oil Circuit Breakers:

A plain-break oil circuit breaker involves the simple process of separating the contacts under the whole of the oil in the tank. There is no special system for arc control other than the increase in length caused by the separation of contacts. The arc extinction occurs when a certain critical gap between the contacts is reached. The plain- break oil circuit breaker is the earliest type from which all other circuit breakers have developed. It has a very simple construction. It consists of fixed and moving contacts enclosed in a strong weather-tight earthed tank containing oil up to a certain level and an air cushion above the oil level. The air cushion provides sufficient room to allow for the reception of the arc gases without the generation of unsafe pressure in the dome of the circuit breaker. It also absorbs the mechanical shock of the upward oil movement. Fig. 14 shows a double break plain oil circuit breaker. It is called a double break because it provides two breaks in series.
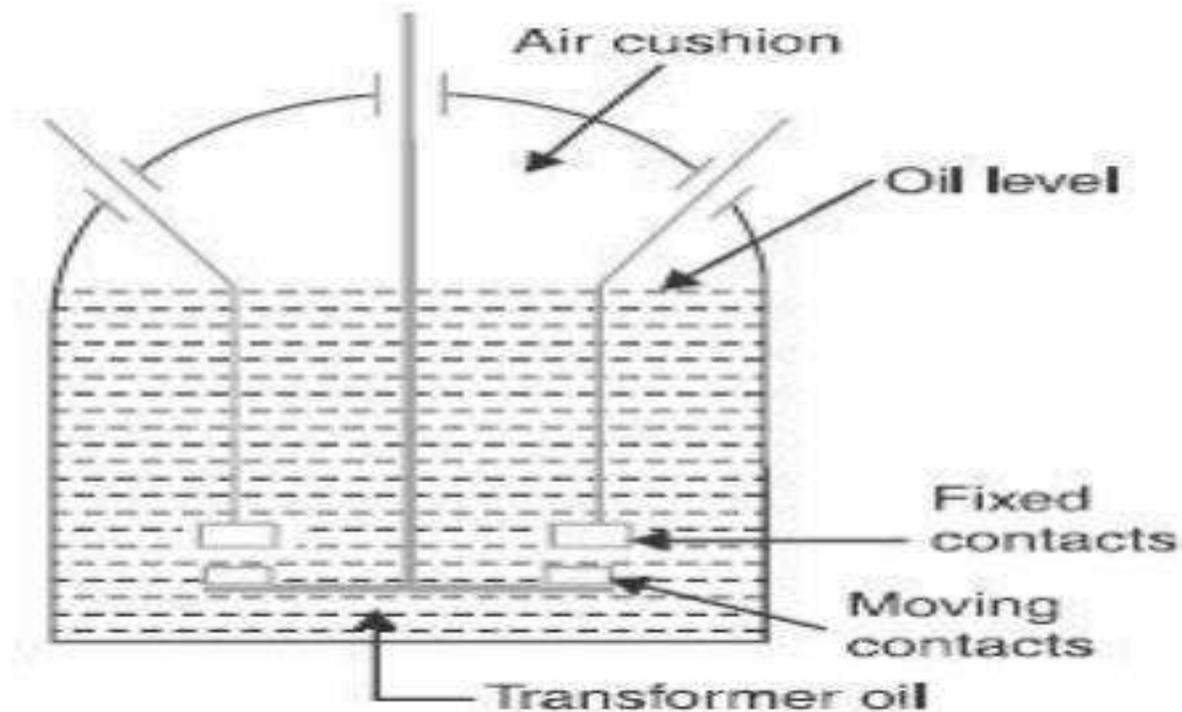

Fig. 14

Under normal operating conditions, the fixed and moving contacts remain closed and the breaker carries the normal circuit Current. When a fault occurs, the moving contacts are pulled down by the protective system and an arc is struck which vaporizes the oil mainly into hydrogen gas.The arc extinction is facilitated by the following processes:

i.The hydrogen gas bubble generated around the arc cools the arc column and aids the deionization of the medium between the contacts

ii. The gas sets up turbulence in the oil and helps in eliminating the arcing products from the arc path.

iii. As the arc lengthens due to the separating contacts, the dielectric strength of the medium is increased.

iv. The result of these actions is that at some critical gap length, the arc is extinguished and the circuit current

Disadvantages:

i. There is no special control over the arc other than the increase in length by separating the moving contacts. Therefore, for successful Interruption, Long arc length is necessary.

ii. The breakers have long and inconsistent arcing times

iii. The breakers do not permit high speed interruption

Due to these disadvantages, plain-break oil circuit breakers are used only for low voltage applications where high breaking-capacities are not important. It is a usual practice to use such breakers for low capacity installations for Voltages not exceeding 11 kV.

Arc Control Oil Circuit Breakers:

In case of plain-break oil circuit breaker discussed above, there is very little artificial control over the arc. Therefore, comparatively long arc length is essential in order that turbulence in the oil caused by the gas may assist in quenching it. However, it is necessary and desirable that

final arc extinction should occur while the contact gap is still short. For this purpose, some arc control is incorporated and the breakers are then called arc control circuit breakers.

There are two types of such breakers, namely:

1. **Self-blast oil circuit breakers**— in which arc control is provided by internal means i.e. the arc itself is employed for its own extinction efficiently.

2. **Forced-blast oil circuit breakers**— in which arc control is provided by mechanical means external to the circuit breaker.

Self-blast oil circuit breakers:

In this type of circuit breaker, the gases produced during arcing are confined to a small volume by the use of an insulating rigid pressure chamber or pot surrounding the contacts. Since the space available for the arc gases is restricted by the chamber, a very high pressure is

developed to force the oil and gas through or around the arc to extinguish it. The magnitude of pressure developed depends upon the value of fault current to be interrupted. As the pressure is generated by the arc itself, therefore, such breakers are some times called self-generated pressure oil circuit breakers.

The pressure chamber is relatively cheap to make and gives reduced final arc extinction gap length and arcing time as against the plain-break

oil circuit breaker. Several designs of pressure chambers (sometimes called explosion pots) have been developed and a few of them are described below:

1. Plain explosion pot:

It is a rigid cylinder of insulating material and encloses the fixed and moving contacts (See Fig. 15). The moving contact is a cylindrical rod passing through a restricted opening (called throat) at the bottom. When a fault occurs, the contacts get separated and an arc is struck between them. The heat of the arc decomposes oil into a gas at very high pressure in the pot. This high pressure forces the oil and gas through and round the arc to extinguish it. If the final arc extinction does not take place while the moving contact is still within the pot, it occurs immediately after the moving contact leaves the pot. It is because emergence of the moving contact from the pot is followed by a violent rush of gas and oil through the throat producing rapid extinction.
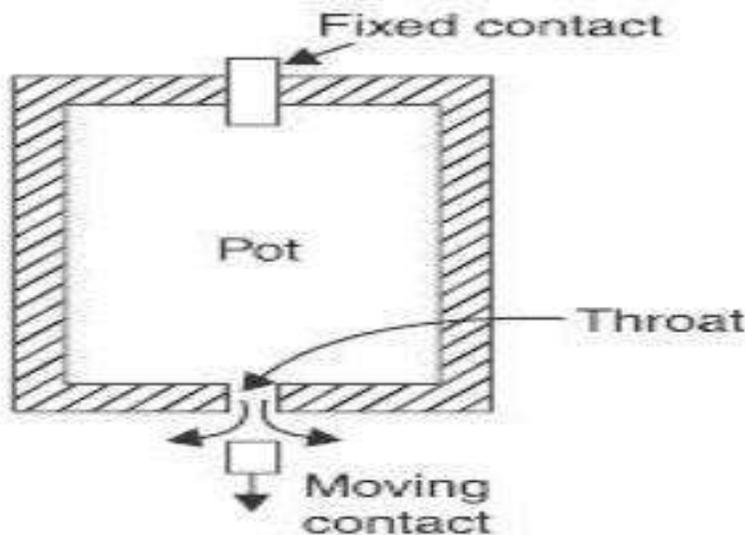

Fig. 15

The principal limitation of this type of pot is that it cannot be used for very low or for very high fault currents. With low fault currents, the

pressure developed is small, thereby increasing the arcing time. On the other hand, with high fault currents, the gas is produced so rapidly that explosion pot is liable to burst due to high pressure. For this reason, plain explosion pot operates well on moderate short-circuit currents only where the rate of gas evolution is moderate

2. Cross jet explosion pot:

This type of pot is just a modification of plain explosion pot and is illustrated in Fig. 16. It is made of insulating material and has channels on one side which act as arc splitters.

The arc splitters help in increasing the arc length, thus facilitating arc extinction. When a fault occurs, the moving contact of the circuit breaker begins to separate. As the moving contact is withdrawn, the arc is initially struck in the top of the pot. The gas generated by the arc exerts pressure on the oil in the back passage. When the moving contact uncovers the arc splitter ducts, fresh oil is forced *across the arc path. The arc is, therefore, driven sideways into the —arc splitters which increase the arc length, causing arc extinction.

The cross-jet explosion pot is quite efficient for interrupting heavy fault currents.However, for low fault currents, the gas pressure is †small and consequently the pot does not give a satisfactory operation.

3. Self-compensated explosion pot:

This type of pot is essentially a combination of plain explosion pot and cross jet explosion pot. Therefore, it can interrupt low as well as heavy short circuit currents with reasonable accuracy. Fig. 17 shows the schematic diagram of self-compensated explosion pot. It consists of two chambers; the upper chamber is the cross-jet explosion pot with two arc splitter ducts while the lower one is the plain explosion pot. When the

short-circuit current is heavy, the rate of generation of gas is very high and the device behaves as a cross-jet explosion pot. The arc extinction takes place when the moving contact uncovers the first or second arc splitter duct. However, on low short-circuit currents, the rate of gas generation is small and the tip of the moving contact has the time to reach the lower chamber. During this time, the gas builds up sufficient pressure as there is very little leakage through arc splitter ducts due to the obstruction offered by the arc path and right angle bends. When the moving contact comes out of the throat, the arc is extinguished by plain pot action.It may be noted that as the severity of the short circuit current increases, the device operates less and less as a plain explosion pot and more and more as a cross-jet explosion pot. Thus the tendency is to make the control self-compensating over the full range of fault currents to be interrupted.
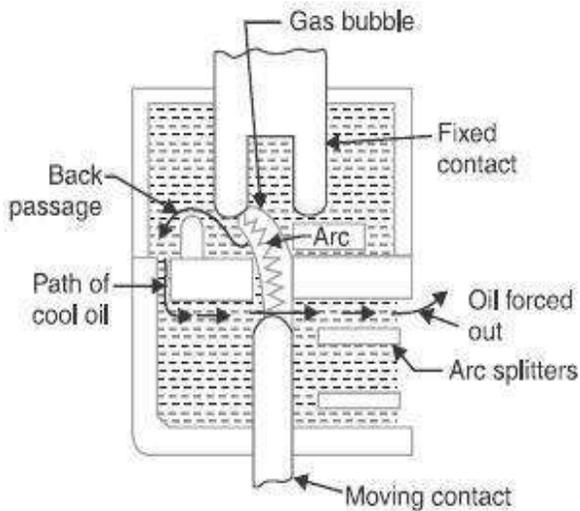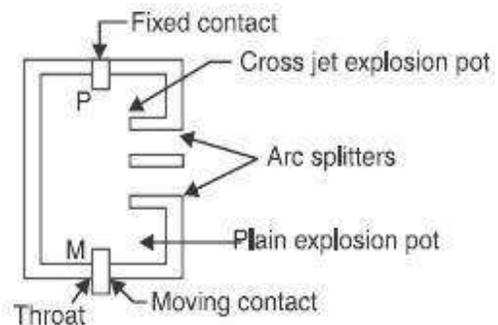

Fig. 16   **Fig. 17**

Forced-blast oil circuit breakers:

In the self-blast oil circuit breakers discussed above, the arc itself generates the necessary pressure to force the oil across the arc path. The major limitation of such breakers is that arcing times tend to be long and

inconsistent when operating against currents considerably less than the rated currents. It is because the gas generated is much reduced at low values of fault currents. This difficulty is overcome in forced-blast oil circuit breakers in which the necessary pressure is generated by external mechanical means independent of the fault currents to be broken.

In a forced -blast oil circuit breaker, oil pressure is created by the piston-cylinder arrangement. The movement of the piston is mechanically coupled to the moving contact. When a fault occurs, the contacts get separated by the protective system and an arc is struck between the contacts. The piston forces a jet of oil towards the contact gap to extinguish the arc. It may be noted that necessary oil pressure produced does not in any way depend upon the fault current to be broken.

Advantages:

i. Since oil pressure developed is independent of the fault current to be interrupted, the performance at low currents is more consistent than with self-blast oil circuit breakers.

ii. The quantity of oil required is reduced considerably.

Low Oil Circuit Breakers:

In the bulk oil circuit breakers discussed so far, the oil has to perform two functions.

Firstly, it acts as an arc quenching medium and secondly, it insulates the live parts from earth. It has been found that only a small percentage of oil is actually used for arc extinction while the major part is utilized for insulation purposes. For this reason, the quantity of oil in bulk oil circuit breakers reaches a very high figure as the system voltage increases. This not only increases the expenses, tank size and weight of the breaker but it also increase the fire risk and maintenance problems.
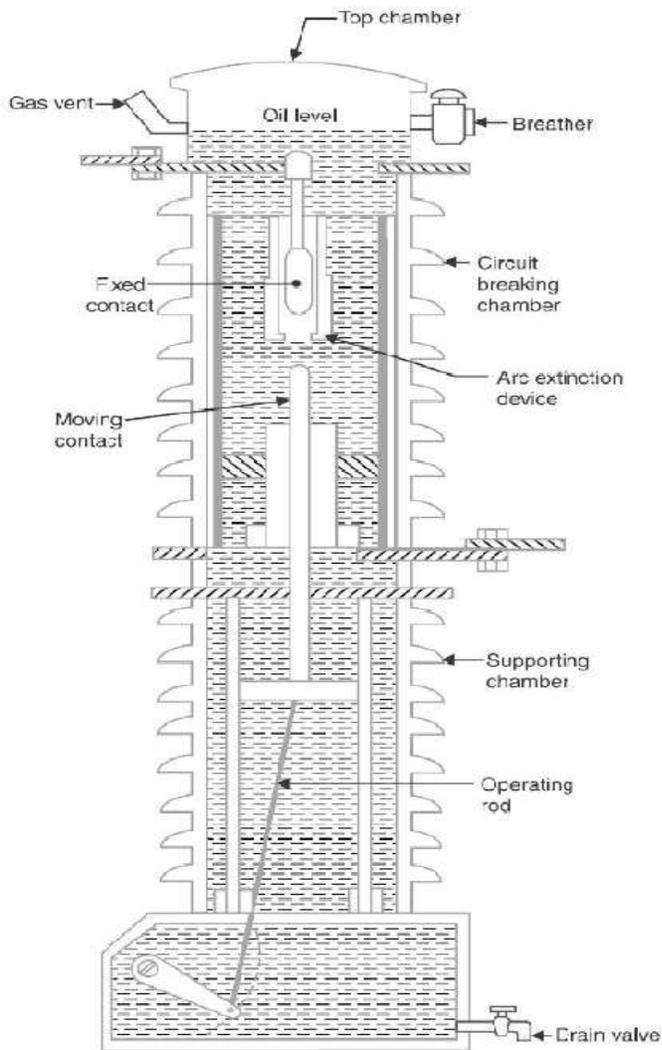
Fig. 18 Low-Oil Circuit Breaker

The fact that only a small percentage of oil (about 10% of total) in the bulk oil circuit breaker is actually used for arc extinction leads to the question as to why the remainder of the oil, that is not immediately surrounding the device, should not be omitted with consequent saving in bulk, weight and fire risk. This led to the development of low-oil circuit breaker. A low oil circuit breaker employs solid materials for insulation purposes and uses a small quantity of oil which is just sufficient for arc extinction. As regards quenching the arc, the oil behaves identically in bulk as well as low oil circuit breaker. By using suitable arc control

devices, the arc extinction can be further facilitated in a low oil circuit breaker.

Construction:

Fig 18 shows the cross section of a single phase low oil circuit breaker. There are two compartments separated from each other but both filled with oil. The upper chamber is the circuit breaking chamber while the lower one is the supporting chamber. The two chambers are separated by a partition and oil from one chamber is prevented from mixing with the other chamber. This arrangement permits two advantages. Firstly, the circuit breaking chamber requires a small volume of oil which is just enough for arc extinction. Secondly, the amount of oil to be replaced is reduced as the oil in the supporting chamber does not get contaminated by the arc.

Supporting chamber:

It is a porcelain chamber mounted on a metal chamber. It is filled with oil which is physically separated from the oil in the circuit breaking compartment. The oil inside the supporting chamber and the annular space formed between the porcelain insulation and bakelised paper is employed for insulation purposes only.

Circuit-breaking chamber:

It is a porcelain enclosure mounted on the top of the supporting compartment. It is filled with oil and has the following parts:

1. upper and lower fixed contacts

2. Moving contact

3. Turbulator

The moving contact is hollow and includes a cylinder which moves down over a fixed piston. The turbulator is an arc control device and has both axial and radial vents. The axial venting ensures the interruption of low currents whereas radial venting helps in the interruption of heavy currents.

Top chamber:

It is a metal chamber and is mounted on the circuit-breaking chamber. It provides expansion space for the oil in the circuit breaking compartment. The top chamber is also provided with a separator which prevents any loss of oil by centrifugal action caused by circuit breaker operation during fault conditions.

Operation:

Under normal operating conditions, the moving contact remains engaged with the upper fixed contact. When a fault occurs, the moving contact is pulled down by the tripping springs and an arc is struck. The arc energy vaporizes the oil and produces gases under high pressure. This action constrains the oil to pass through a central hole in the moving contact and results in forcing series of oil through the respective passages of the tabulator. The process of tabulation is orderly one, in which the sections of the arc are successively quenched by the effect of separate streams of oil moving across each section in turn and bearing away its gases.

A low oil circuit breaker has the following advantages over a bulk oil circuit breaker:

1. It requires lesser quantity of oil.

2. It requires smaller space.

3. There is reduced risk of fire.

4. Maintenance problems are reduced.

A low oil circuit breaker has the following disadvantages as compared to a bulk oil circuit breaker:

1. Due to smaller quantity of oil, the degree of carbonization is increased.

2. There is a difficulty of removing the gases from the contact space in time.

3. The dielectric strength of the oil deteriorates rapidly due to high degree of carbonization.

Maintenance of Oil Circuit Breakers:

The maintenance of oil circuit breaker is generally concerned with the checking of contacts and dielectric strength of oil. After a circuit breaker has interrupted fault currents a few times or load currents several times, its contacts may get burnt by arcing and the oil may lose some of its dielectric strength due to carbonization. This results in the reduced rupturing capacity of the breaker. There fore, it is a good practice to inspect the circuit breaker at regular intervals of 3 or 6 months.

During inspection of the breaker, the following points should be kept in view:

i. Check the current carrying parts and arcing contacts. If the burning is severe, the contacts should be replaced

ii. Check the dielectric strength of the oil. If the oil is badly discolored, it should be changed or reconditioned. The oil in good condition should withstand 30 kV for one minute in a standard oil testing cup with 4 mm gap between electrodes

iii. Check the insulation for possible damage. Clean the surface and remove carbon deposits

iv. with a strong

v. Check the insulation for possible damage. Clean the surface and remove carbon deposits and dry fabric

vi. Check the oil level.

vii. Check closing and tripping mechanism

Air-Blast Circuit Breakers:

These breakers employ a high pressure *air-blast as an arc quenching medium. The contacts are opened in a flow of air-blast established by the opening of blast valve. The air-blast cools the arc and sweeps away the arcing products to the atmosphere. This rapidly increases the dielectric strength of the medium between contacts and prevents from re-establishing the arc. Consequently, the arc is extinguished and flow of current is interrupted.

An air-blast circuit breaker has the following advantages over an oil circuit breaker:

1. The risk of fire is eliminated.

2. The arcing products are completely removed by the blast whereas the oil deteriorates with successive operations; the expense of regular oil replacement is avoided.

3. The growth of dielectric strength is so rapid that final contact gap needed for arc extinction is very small. This reduces the size of the device.

4. The arcing time is very small due to the rapid build up of dielectric strength between contacts. Therefore, the arc energy is only a fraction of that in oil circuit breakers, thus resulting in less burning of contacts.

5. Due to lesser arc energy, air-blast circuit breakers are very suitable for conditions where frequent operation is required.

6. The energy supplied for arc extinction is obtained from high pressure air and is independent of the current to be interrupted.

The use of air as the arc quenching medium offers the following disadvantages:

1. The air has relatively inferior arc extinguishing properties.

2. The air-blast circuit breakers are very sensitive to the variations in the rate of rise of restriking voltage.

3. Considerable maintenance is required for the compressor plant which supplies the airblast.

4. The air blast circuit breakers are finding wide applications in high voltage installations.

5. Majority of the circuit breakers for voltages beyond 110 kV are of this type.

Types of Air-Blast Circuit Breakers:

Depending upon the direction of air-blast in relation to the arc, air-blast circuit breakers are

classified into:

1. **Axial-blast type** in which the air-blast is directed along the arc path as shown in Fig.19(i).

2. **Cross-blast type** in which the air-blast is directed at right angles to the arc path as shown in Fig.19(ii).

3. **Radial-blast type** in which the air-blast is directed radially as shown in Fig.19(iii).
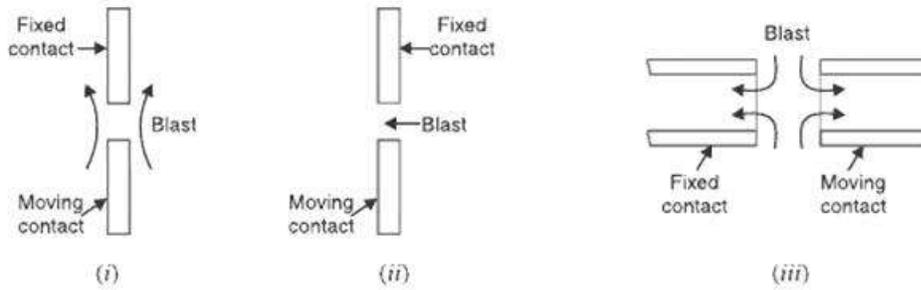

Fig. 19

Axial-blast air circuit breaker:

Fig. 20 shows the essential components of a typical axial blast air circuit breaker. The fixed and moving contacts are held in the closed position by spring pressure under normal conditions. The air reservoir is connected to the arcing chamber through an air valve. This valve remains closed under normal conditions but opens automatically by the tripping impulse when a fault occurs on the system.
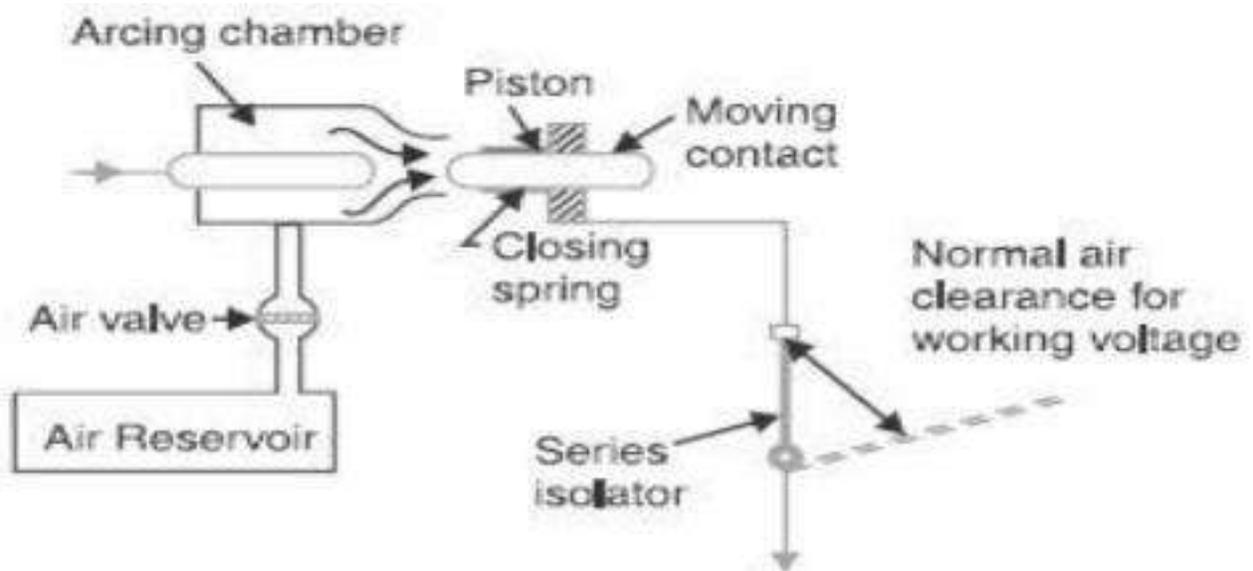

Fig. 20

When a fault occurs, the tripping impulse causes opening of the air valve which connects the circuit breaker reservoir to the arcing chamber. The high pressure air entering the arcing chamber pushes away the moving contact against spring pressure. The moving contact is separated and an arc is struck. At the same time, high pressure air blast flows along the arc and takes away the ionized gases along with it. Consequently, the arc is extinguished and current flow is interrupted.

It may be noted that in such circuit breakers, the contact separation required for interruption is generally small (1·75 cm or so). Such a small gap may constitute inadequate clearance for the normal service voltage. Therefore, an isolating switch is incorporated as a part of this type of circuit breaker. This switch opens immediately after fault interruption to provide the necessary clearance for insulation.

Cross-blast air breaker:

In this type of circuit breaker, an air-blast is directed at right angles to the arc. The cross-blast lengthens and forces the arc into a suitable chute for arc extinction. Fig. 21 shows the essential parts of a typical cross-blast Air circuit breaker. When the moving contact is withdrawn,

an arc is struck between the fixed and moving contacts. The high pressure cross-blast Forces the arc into a chute consisting of arc splitters and baffles. The splitters serve to increase the length of the arc and baffles give improved cooling. The result is that arc is extinguished and flow of Current is interrupted. Since blast pressure is same for all currents, the inefficiency at low currents is eliminated. The final gap for interruption is great enough to give normal insulation clearance so that a series isolating switch is not necessary.
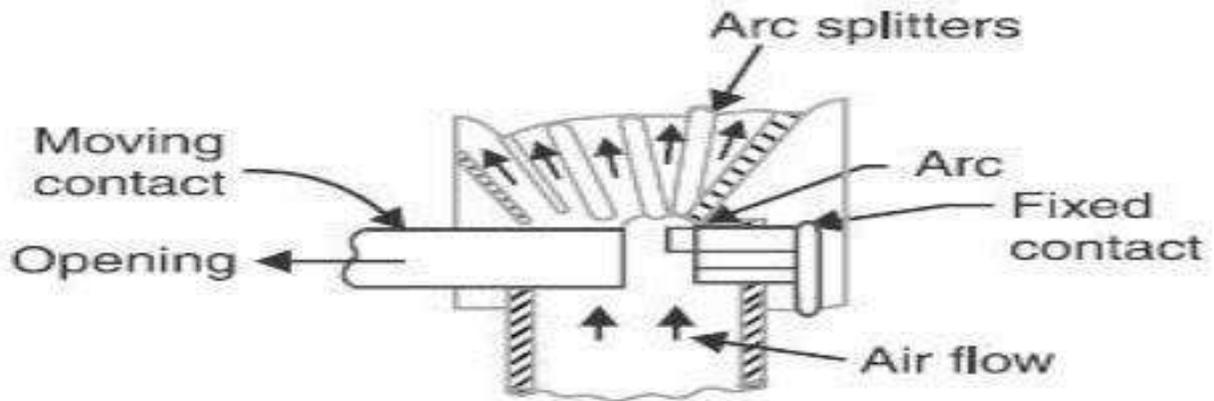
Fig. 21

Sulphur Hexafluoride (SF6) Circuit reakers:

In such circuit breakers, sulphur hexafluoride (SF6) gas is used as the arc quenching medium. The SF6 is an electro-negative gas and has a strong tendency to absorb free electrons. The contacts of the breaker are opened in a high pressure flow of SF6 gas and an arc is struck between them. The conducting free electrons in the arc are rapidly captured by the gas to form relatively immobile negative ions. This loss of conducting electrons in the arc quickly builds up enough insulation strength to extinguish the arc. The SF6 circuit breakers have been found to be very effective for high power and high voltage service.

Construction:

Fig. 22 shows the parts of a typical SF6 circuit breaker. It consists of fixed and moving contacts enclosed in a chamber (called arc interruption chamber) containing SF6 gas. This chamber is connected to SF6 gas reservoir. When the contacts of breaker are opened, the valve mechanism permits a high pressure SF6 gas from the reservoir to flow towards the arc interruption chamber. The fixed contact is a hollow cylindrical current carrying contact fitted with an arc horn. The moving contact is also a hollow cylinder with rectangular holes in the sides to

permit the SF6 gas to let out through these holes after flowing along and across the arc. The tips of fixed contact, moving contact and arcing horn are coated with copper-tungsten arc resistant material. Since SF6 gas is Costly, it is reconditioned and reclaimed by suitable auxiliary system after each operation of the breaker.
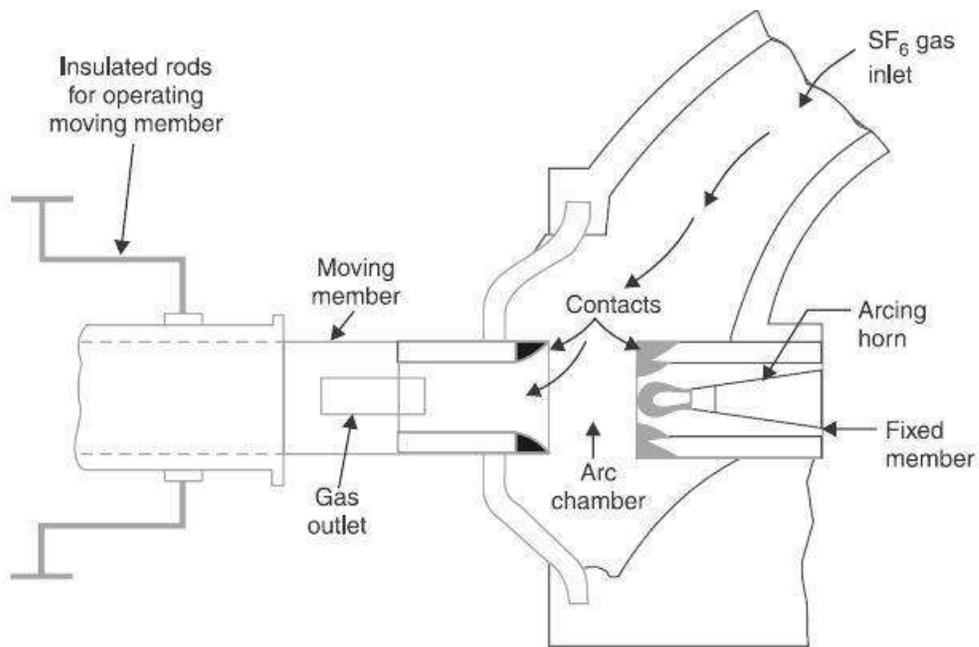

Fig. 22

Working:

In the closed position of the breaker, the contacts remain surrounded by SF6 gas at a pressure of about 2·8kg/cm. When the breaker operates, the moving contact is pulled apart and an arc is struck between the contacts. The movement of the moving contact is synchronized with the,opening of a valve which permits SF6 gas at 14 kg/cm pressure from the reservoir to the arc interruption chamber. The high pressure flow of SF6 rapidly absorbs the free electrons in the arc path to form immobile negative ions which are ineffective as charge carriers. The result is that the medium between the contacts quickly builds up high dielectric

strength and causes the extinction of the arc. After the breaker operation (i.e., after arc extinction), the valve is closed by the action of a set of springs.

Advantages:

Due to the superior arc quenching properties of SF6 gas, the SF6 circuit breakers have

many advantages over oil or air circuit breakers. Some of them are listed below:

1. Due to the superior arc quenching property of SF6, such circuit breakers have very short arcing time.

2. Since the dielectric strength of SF6 gas is 2 to 3 times that of air, such breakers can interrupt much larger currents.

3. The SF6 circuit breaker gives noiseless operation due to its closed gas circuit and no exhaust to atmosphere unlike the air blast circuit breaker

4. The closed gas enclosure keeps the interior dry so that there is no moisture problem.

5. There is no risk of fire in such breakers because SF6 gas is non-inflammable.

6. There are no carbon deposits so that tracking and insulation problems are eliminated.

7. The SF6 breakers have low maintenance cost, light foundation requirements and

minimum auxiliary equipment.

8. Since SF6 breakers are totally enclosed and sealed from atmosphere, they are particularly suitable where explosion hazard exists e.g., coal mines.

Disadvantages:

i. SF6 breakers are costly due to the high cost of SF6.

ii.Since SF6 gas has to be reconditioned after every operation of the breaker, additional equipment is required for this purpose.

Applications:

A typical SF6 circuit breaker consists of interrupter units each capable of dealing with currents up to 60 kA and voltages in the range of 50—80 kV. A number of units are connected in series according to the systemvoltage. SF6 circuit breakers have been developed for voltages 115 kV to 230 kV, power ratings 10 MVA to 20 MVA and interrupting time less than 3 cycles.

Vacuum Circuit Breakers (VC B):

In such breakers, vacuum (degree of vacuum being in the range from 10 to 10 torr) is used as the arc quenching medium. Since vacuum offers the highest insulating strength, it has far superior arc quenching properties than any other medium. For example, when contacts of a breaker are opened in vacuum, the interruption occurs at first current zero with dielectric strength between the contacts building up at a rate thousands of times higher than that obtained with other circuit breakers.

Principle:

The production of arc in a vacuum circuit breaker and its extinction can be explained as follows:

When the contacts of the breaker are opened in vacuum (10 to 10 torr), an arc is produced between the contacts by the ionization of metal vapours of contacts. However, the arc is quickly extinguished because the metallic vapours, electrons and ions produced during arc rapidly condense on the surfaces of the circuit breaker contacts, resulting in quick recovery of dielectric strength. The reader may note the salient feature of vacuum as an arc quenching medium. As soon as the arc is produced in vacuum, it is quickly extinguished due to the fast rate of recovery of dielectric strength in vacuum.

Construction:

Fig. 23 shows the parts of a typical vacuum circuit breaker. It consists of fixed contact, moving contact and arc shield mounted inside a vacuum chamber. The movable member is connected to the control mechanism by stainless steel bellows. This enables the permanent sealing of the vacuum chamber so as to eliminate the possibility of leak. A glass vessel or ceramic vessel is used as the outer insulating body. The arc shield prevents the deterioration of the internal dielectric strength by preventing metallic vapours falling on the inside surface of the outer insulating cover.
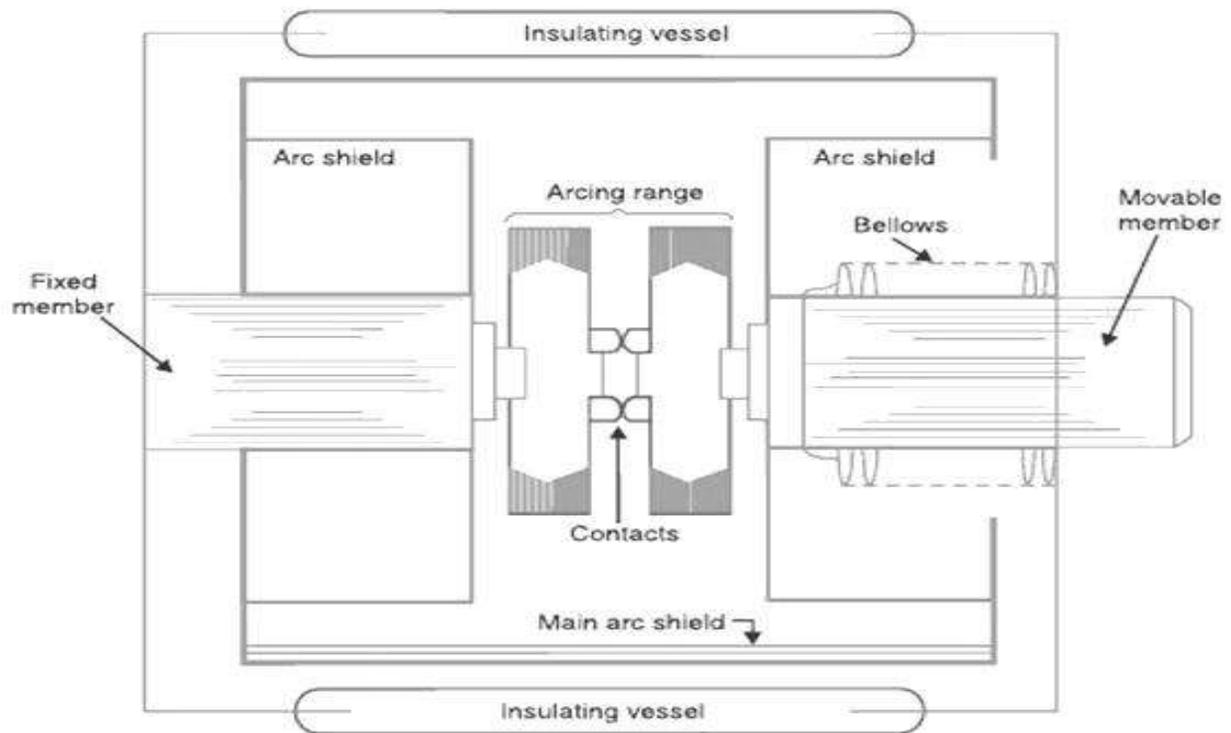
Fig. 23

Working:

When the breaker operates, the moving contact separates from the fixed contact and an arc is struck between the contacts. The production of arc is due to the ionization of metal ions and depends very much upon the material of contacts. The arc is quickly extinguished because the metallic vapours, electrons and ions produced during arc are diffused in a short time and seized by the surfaces of moving and fixed members and shields. Since vacuum has very fast rate of recovery of dielectric strength, the arc extinction in a vacuum breaker occurs with a short contact separation (say 0.625 cm).

Vacuum circuit breakers have the following advantages:

1. They are compact, reliable and have longer life.

2. There is no generation of gas during and after operation.

3. They can interrupt any fault current. The outstanding feature of a V C B is that it can break any heavy fault current perfectly just before the contacts reach the definite open position.

4. They require little maintenance and are quiet in operation.

5. They have low arc energy.

6. They have low inertia and hence require smaller power for control mechanism.

Applications:

For a country like India, where distances are quite large and accessibility to remote areas difficult, the installation of such outdoor, maintenance free circuit breakers should prove a definite advantage. Vacuum circuit breakers are being employed for outdoor applications ranging from 22 kV to 66 kV. Even with limited rating of say 60 to 100 MVA, they are suitable for a majority of applications in rural areas.