LECTURE NOTES

ON

POWER SYSTEM PROTECTION

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UNIT - I
CIRCUIT BREAKER

Introduction:

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.

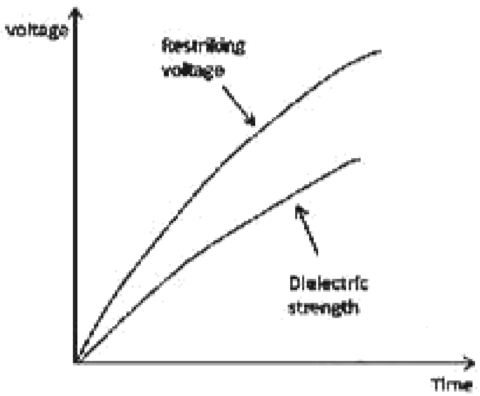
The rapid increase of dielectric strength of the medium near current zero can be achieved by:

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.

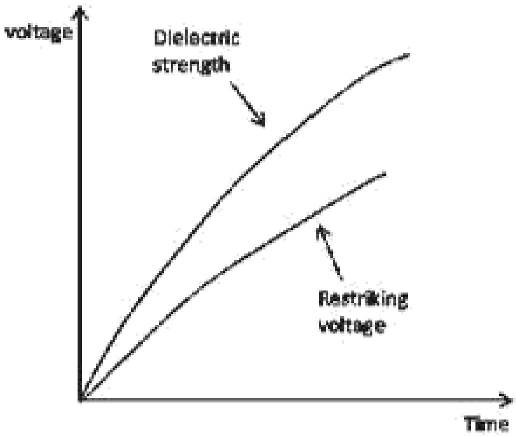
Therefore, the real problem in a.c. arc interruption is to rapidly de ionize the medium between contacts as soon as the current becomes zero so that the rising contact voltage or restriking voltage cannot breakdown the space between contacts.

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:

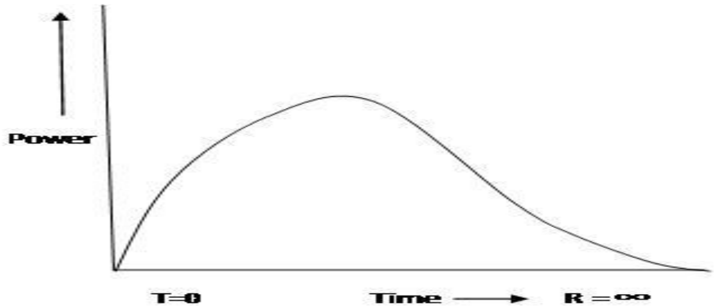
1. Recovery rate theory (Slepain‘s Theory)
2. Energy balance theory (Cassie‘s Theory)

Recovery rate theory (Slepain’s Theory):

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.

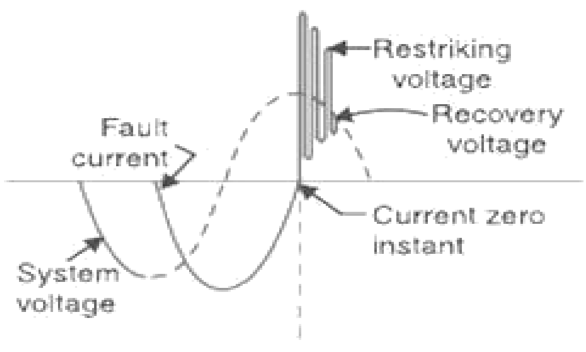
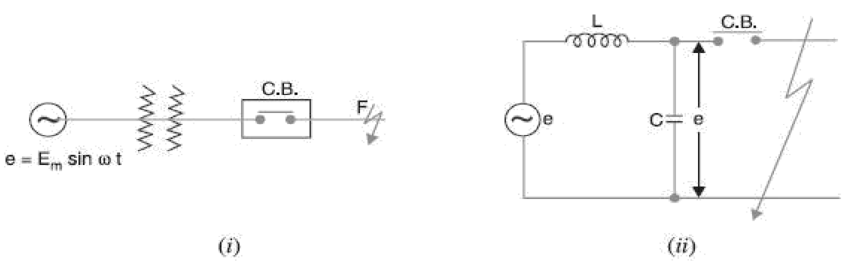


Fig. 19.1

2. Restriking voltage:



(*i*) (*ii*)

Fig. 19.17

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. 19.1).

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.19.1). 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. 19.17 (i) shows a short-circuit occurring on the transmission line. Fig 19.17 (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. 19.17 (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. 19.18, 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.

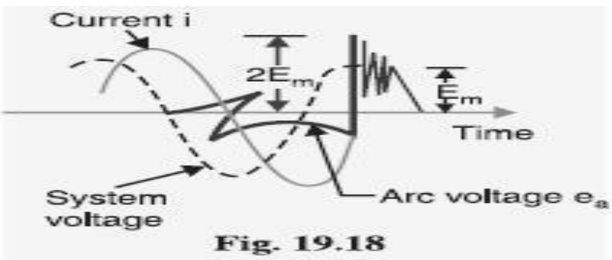


Fig. 19.18

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 E_m . The system losses cause the oscillations to decay fairly rapidly but the initial overshoot increases the possibility of re-striking the arc.

It is the rate of rise of re-striking voltage (R.R.R.V.) which decides whether the arc will re-strike 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 $\mathbf{f_n}$ 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. 19.17 (ii) repeated as Fig. 19.19 (i). Suppose the arc current is i when it is chopped down to zero value as shown by point a in Fig. 19.19 (ii). As the chop occurs at current i, therefore, the energy stored in inductance is L i^2 /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.

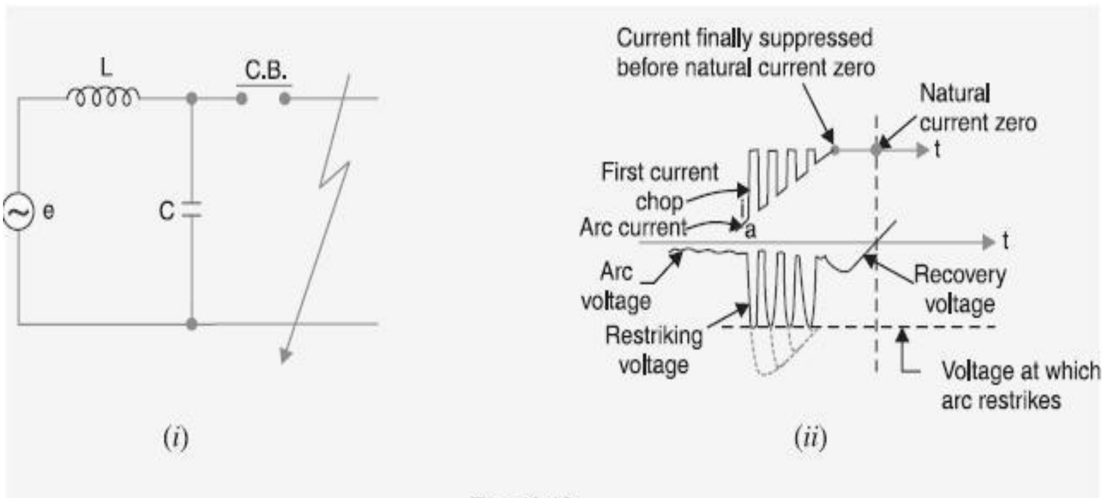


Fig. 19.19

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 Art 19.19.

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.19.20. 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. 19.21. 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. 19.21], 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.

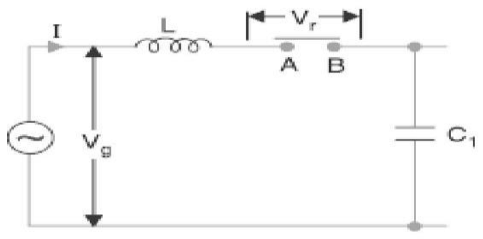


Fig. 19.20

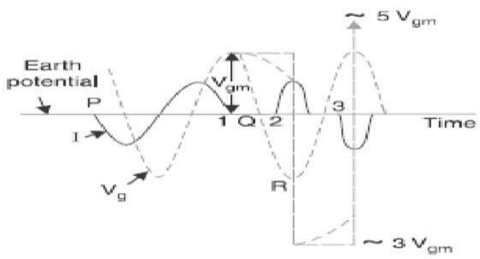


Fig. 19.21

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. 19.22. This is known as resistance switching.

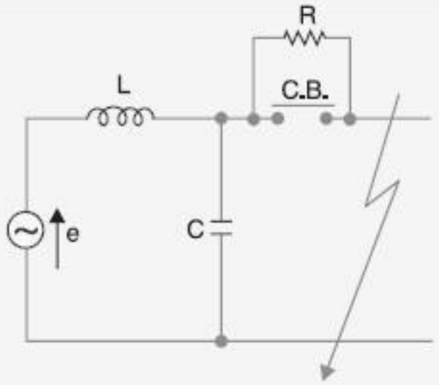


Fig. 19.22

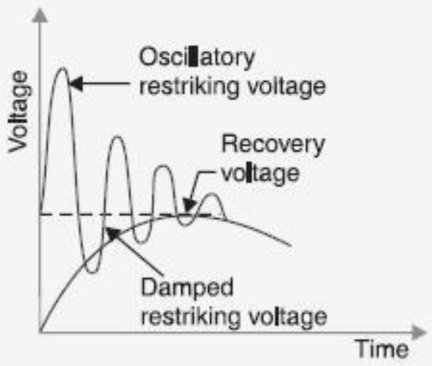


Fig. 19.23

Referring to Fig. 19.22, 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. 19.22 is given by:

$$f_n = \frac{1}{2\Pi}\sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}} \qquad —$$

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. 19.23 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

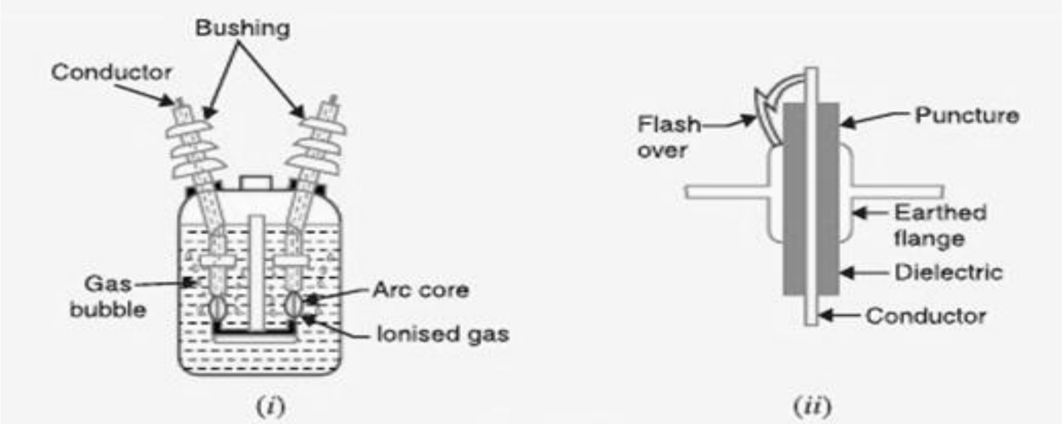


Fig. 19.13

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. 19.13 (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. 19.13 (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.

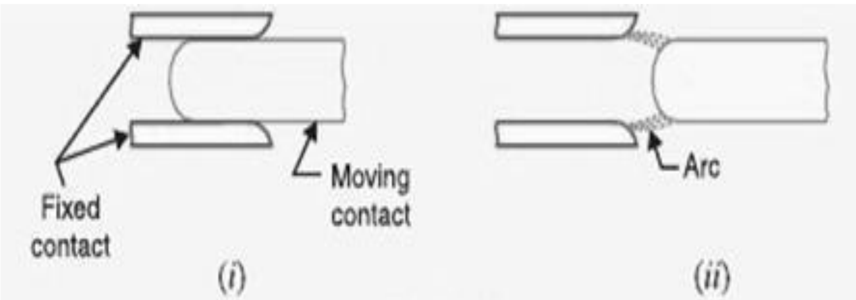


Fig. 19.14

a. **Tulip type contacts:** Fig. 19.14 (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. 19.14 (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.

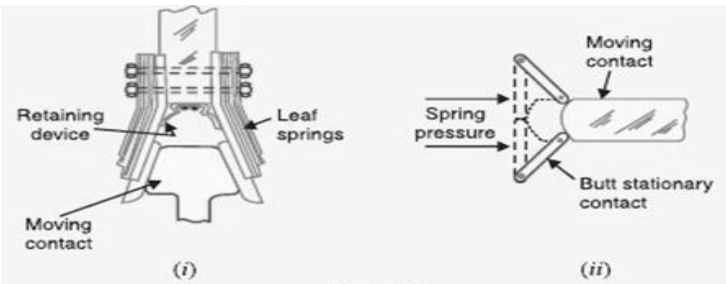


Fig. 19.15

b. **Finger and wedge contacts:** Fig. 19.15 (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. 19.15 (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.

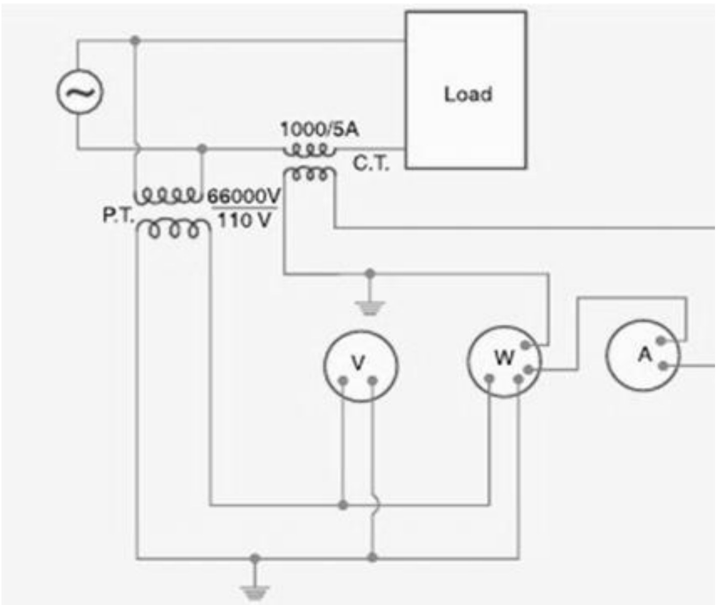


Fig. 19.16

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. 19.16 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. 19.24, the contacts are separated at DD´ At this instant, the fault current has

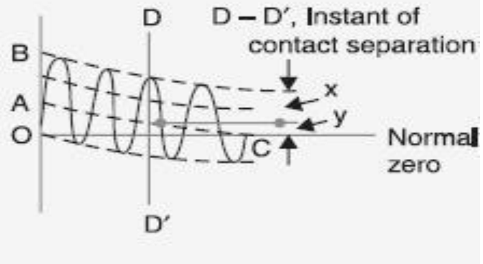


Fig. 19.24

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 √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 √2 X 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:

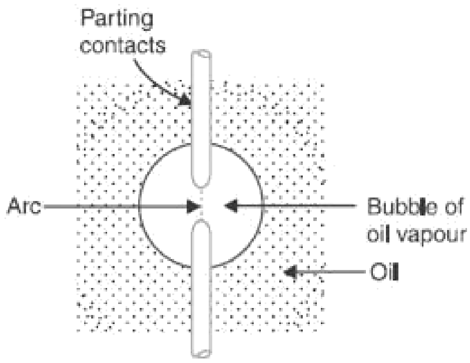


Fig. 19.2

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. 19.2). 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. 19.3 shows a double break plain oil circuit breaker. It is called a double break because it provides two breaks in series.

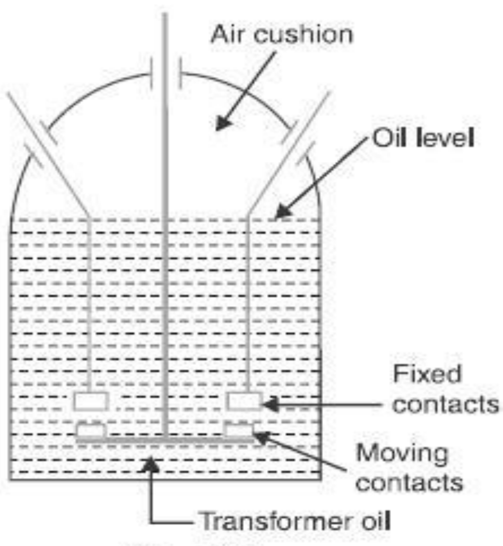


Fig. 19.3

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. 19.4). 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.

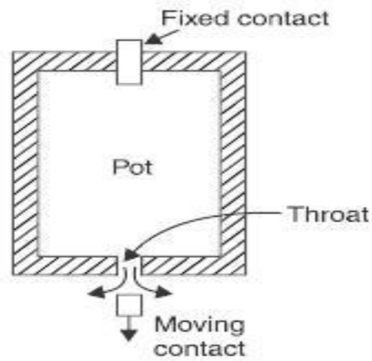
   

   Fig. 19.4

   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. 19.5. 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.

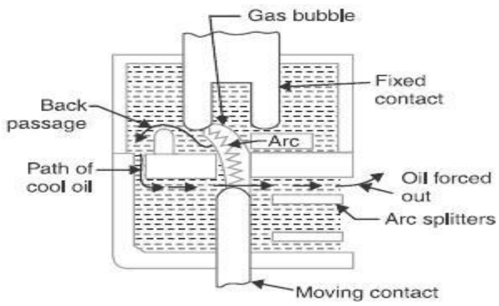


Fig. 19.5

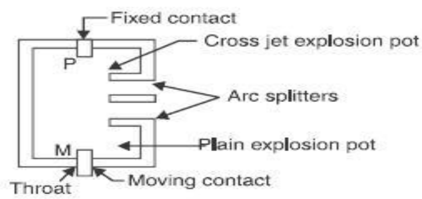


Fig. 19.6

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. 19.6 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.

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.

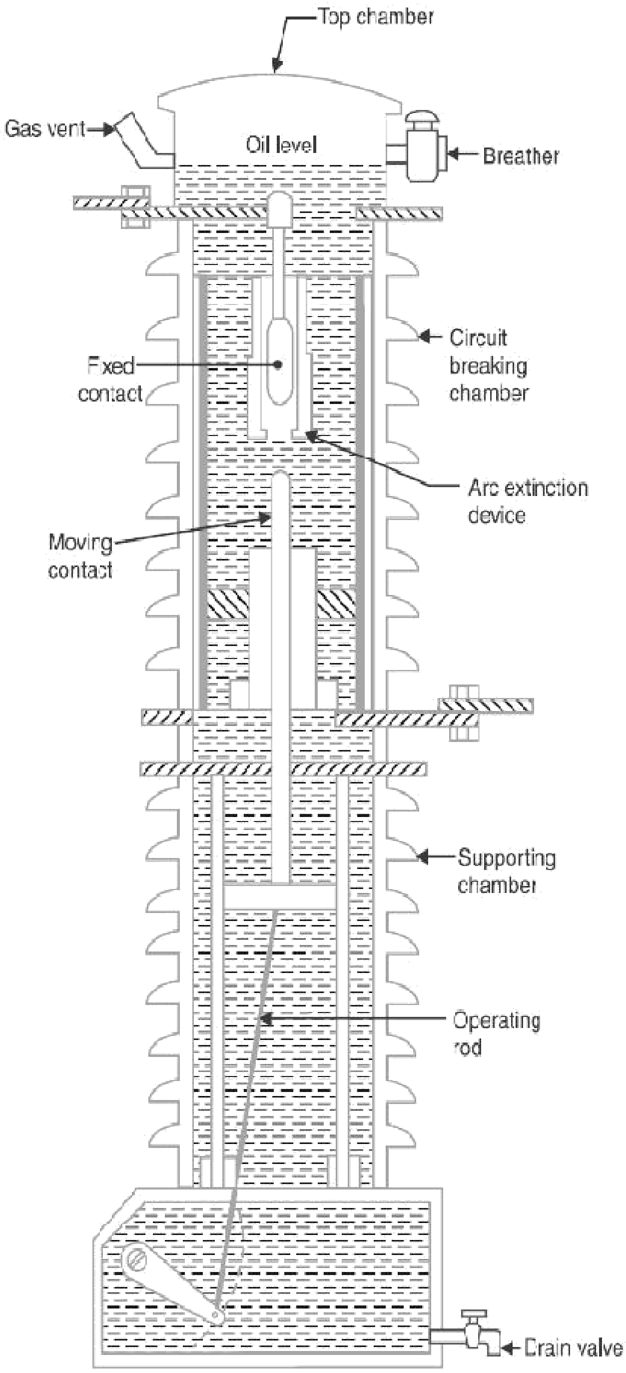


Fig. 19.7 Low-oil Circuit Breaker

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 19.7 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 re striking voltage.
3. Considerable maintenance is required for the compressor plant which supplies the air-blast.
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. 19.8(i).
2. **Cross-blast type** in which the air-blast is directed at right angles to the arc path as shown in Fig. 19.8 (ii).
3. **Radial-blast type** in which the air-blast is directed radially as shown in Fig. 19.8 (iii).

Axial-blast air circuit breaker:

Fig 19.9 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.

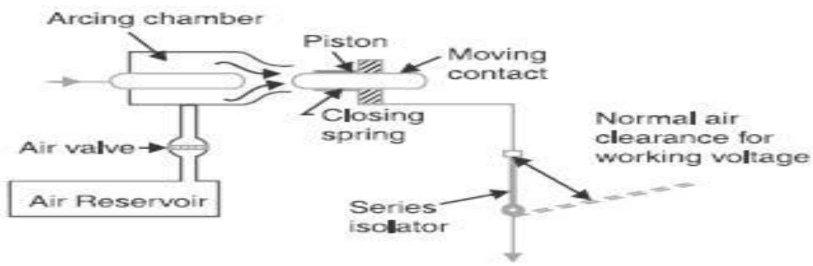


Fig. 19.9

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.

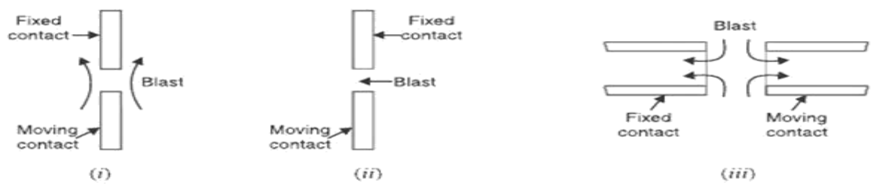


Fig. 19.8

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. 19.10 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.

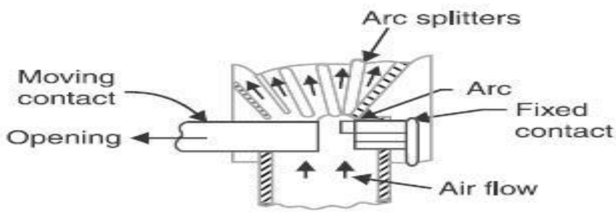


Fig. 19.10

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

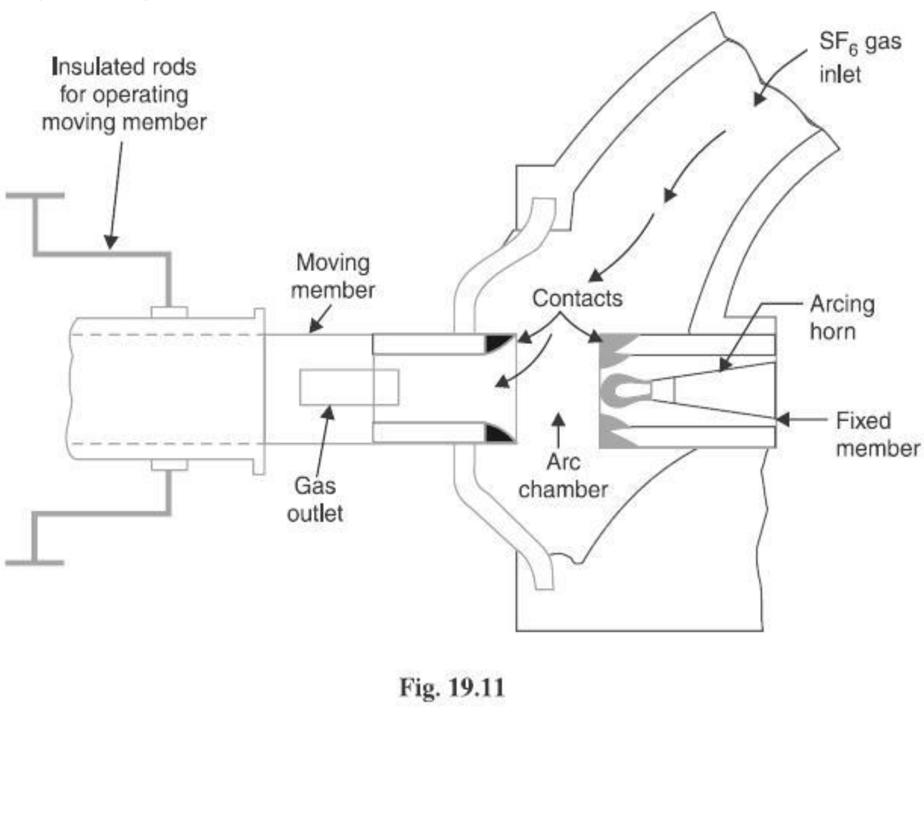


Fig. 19.11

Construction:

Fig. 19.11 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

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 system voltage. 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.

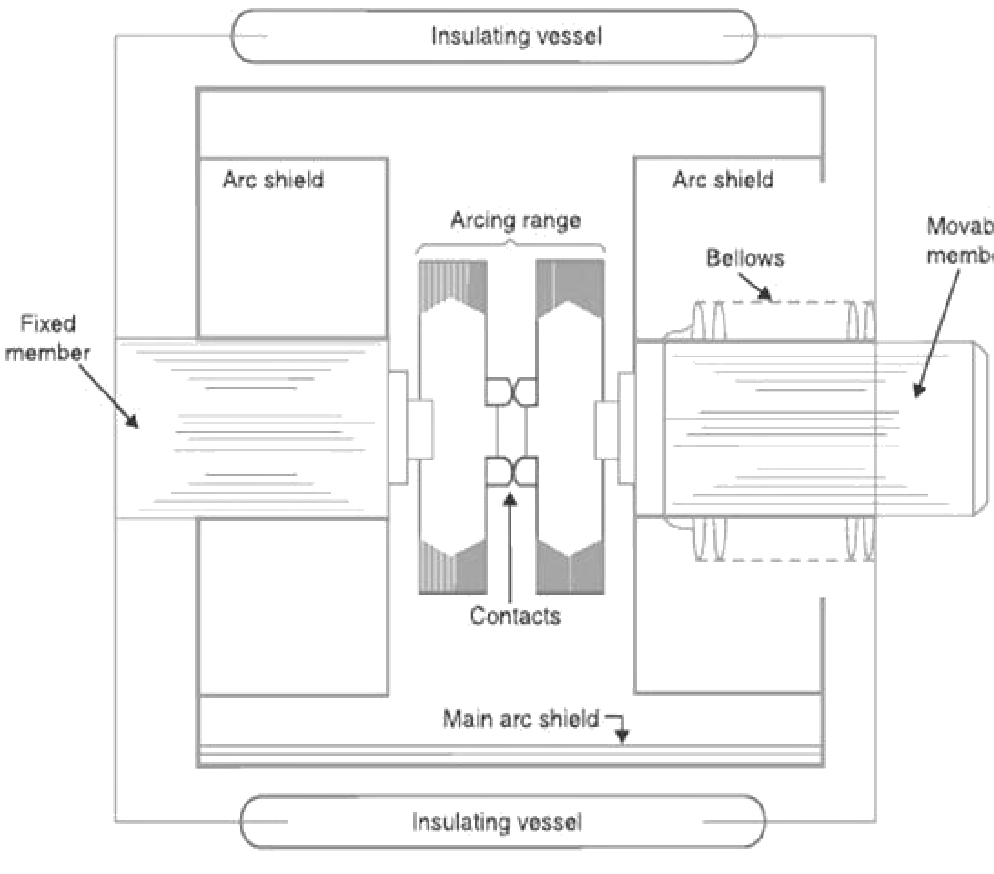


Fig. 19.12

Construction:

Fig. 19.12 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.

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:

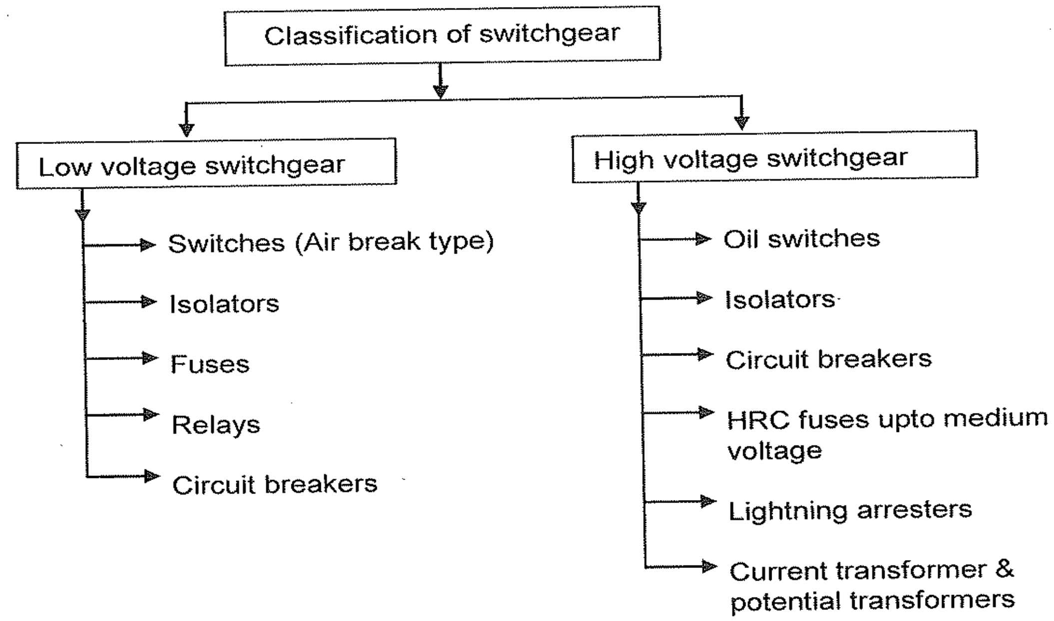
For a country like India, where distances are quite large and accessibility to remote areas difficult, the installation of such outdoor, maintenance free circuit breakers should prove a definite advantage. Vacuum circuit breakers are being employed for outdoor applications ranging from 22 kV to 66 kV. Even with limited rating of say 60 to 100 MVA, they are suitable for a majority of applications in rural areas.

UNIT-II

ELECTROMAGNETIC, STATIC AND NUMERICAL RELAYS

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.



Consequences of occurrence of Faults

Faults are of two type

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

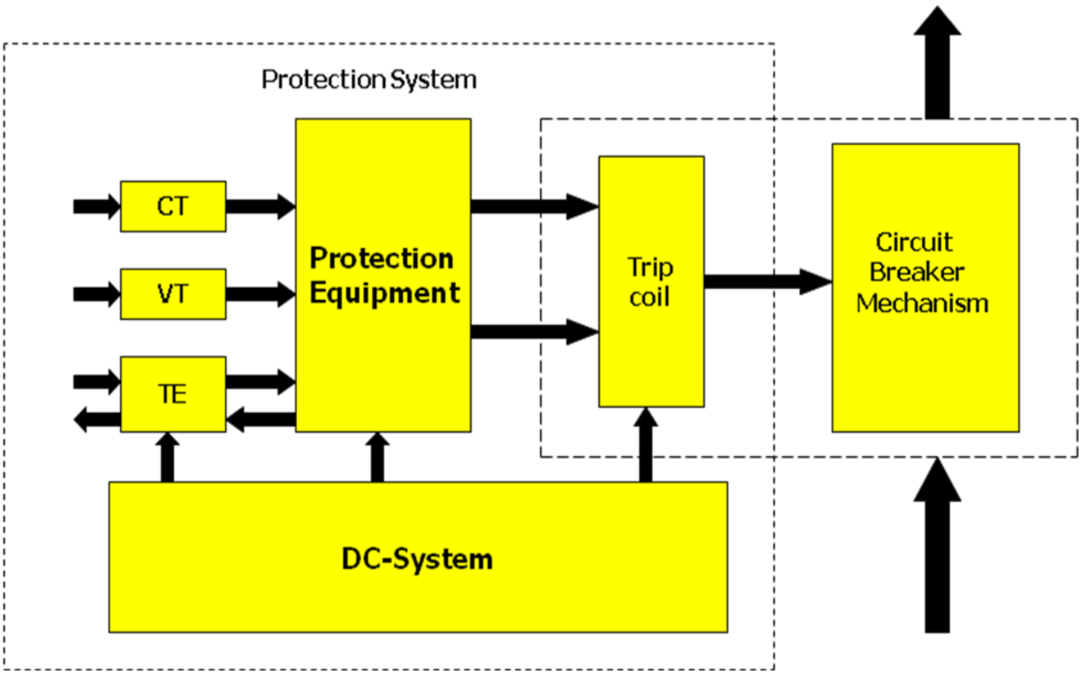
Classification of short circuited Faults

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
4. Single Phase open Circuit
5. Two phase open circuit
6. Three phase open circuit
7. Consequences

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

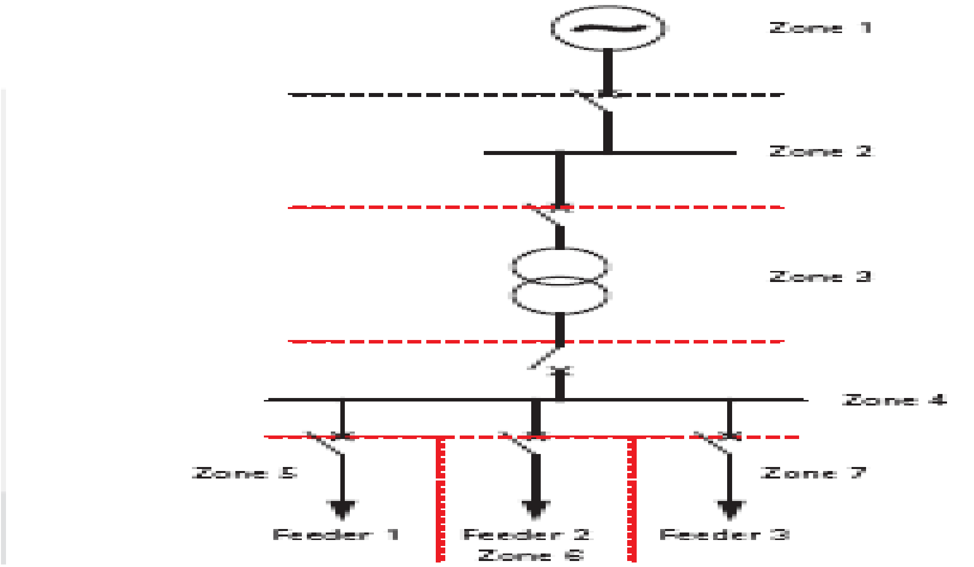


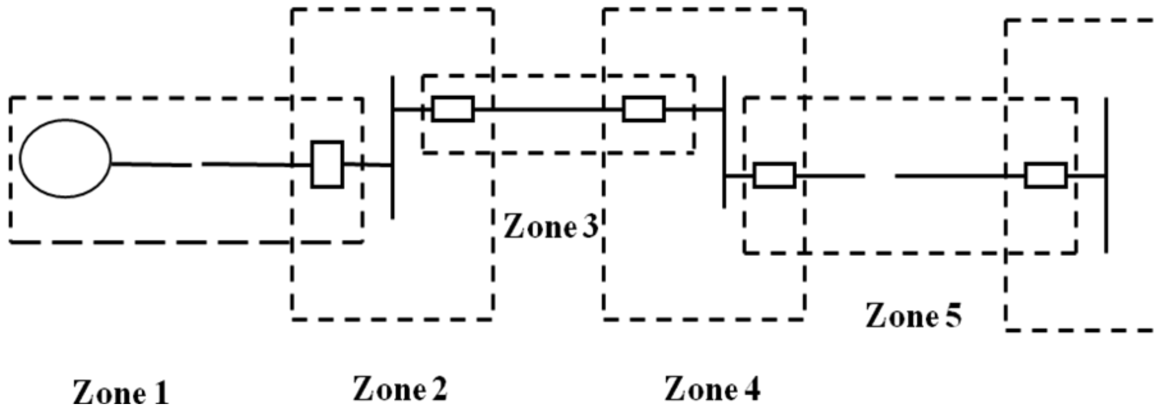
Zones and types of Protection system

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.

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





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

The fundamental requirements for a protection system are as follows:

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

i. Quality of Component used
ii. Maintenance schedule
iii. The supply and availability of spare parts and stocks
iv. The design principle
v. Electrical and mechanical stress to which the protected part of the system is subjected to.

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.

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

i) Time graded systems
ii) Unit systems

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

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 unviable to have a 100% protection of the entire system in concern. Therefore, the cost of the designed protection system varies with the criticality and importance of the protected zone.

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

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

Classification and construction of relays

Classification

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

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

a. Electromechanical
b. Solid State
c. Microprocessor
d. Numerical

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

- **OthersFunction**

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

- Directional Over current
- Distance
- Over voltage
- Differential
- Reverse Power
- Others

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

Electromechanical relays

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

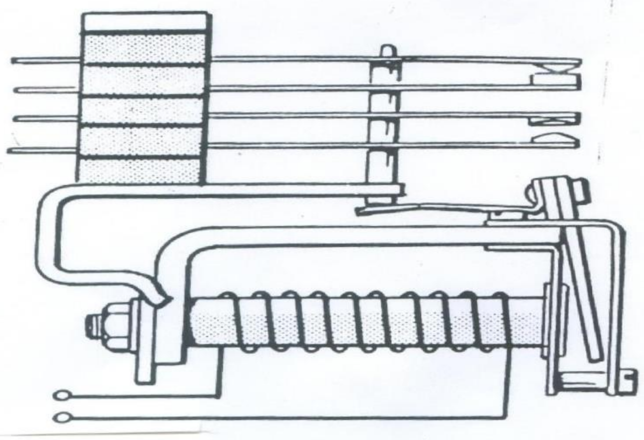
Attraction relays

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

1. The attracted armature type
2. Solenoid type relay

Attracted armature relays

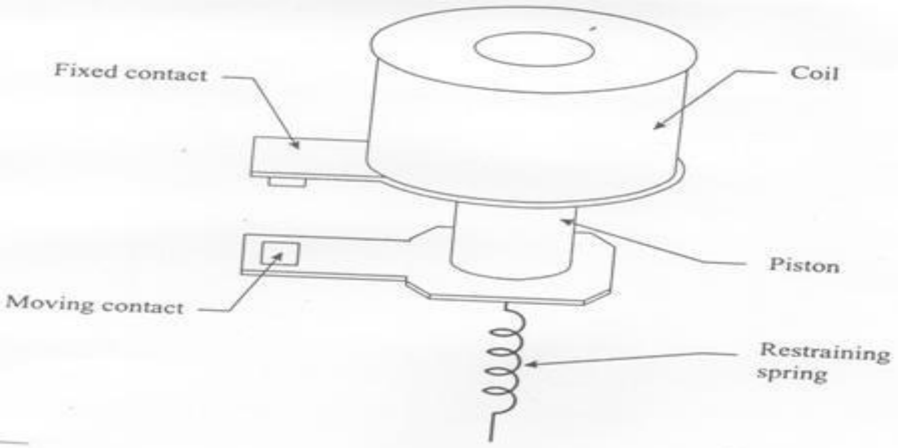
- Consists of a bar or plate (made of iron) that pivots when it is attracted towards the coil.
- The armature carries the moving part of the contact ,which is closed or opened, according to the design, when the armature is attracted to the coil.



· Hinged armature relay

Solenoid type relays

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



Solenoid-type relay

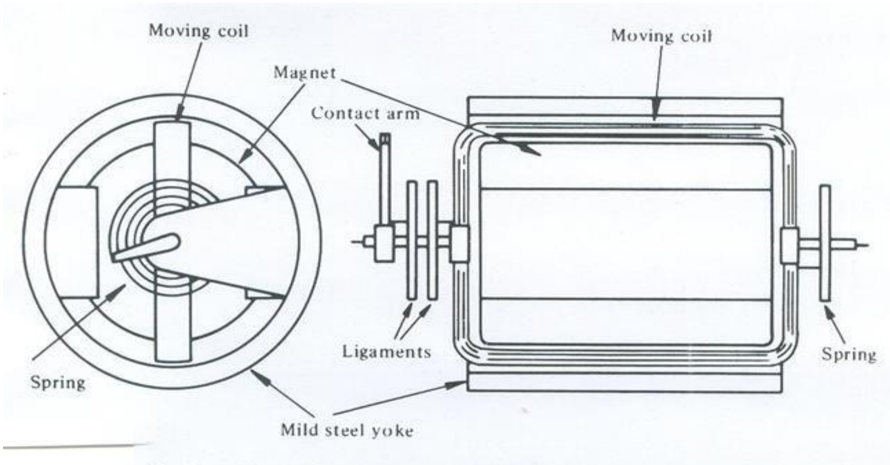
- The number of turns of the coil
- The air gap
- The effective area
- The reluctance of the magnetic circuit

K_2 is the restraining force, usually produced by spring For threshold or balanced condition, the resultant force is zero.

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

Relays with movable coils

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



Moving-coil relay for protection schemes

The torque produced in the coil is

Where, T= Torque B= flux density
l= length of the coil

a= distance between the two sides of the coil i=current flowing through the coil N=number of turns in the coil

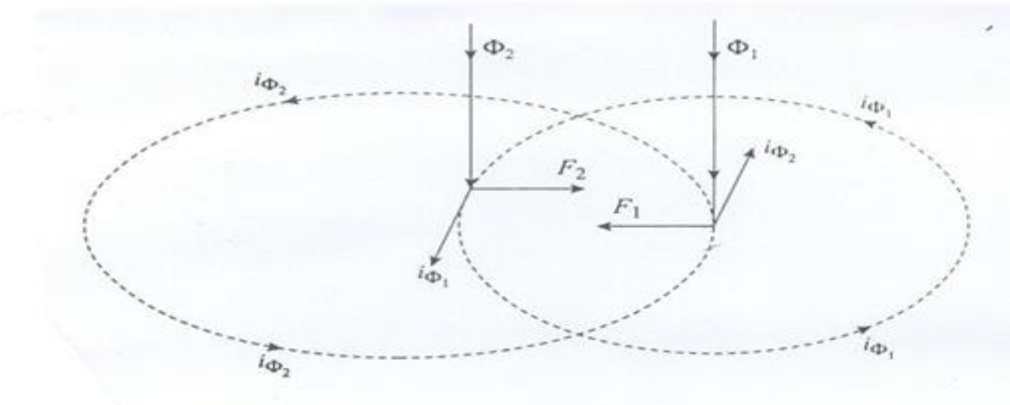
- The relay has inverse type characteristic

Induction relays

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

form of a DISC or CUP

Production of actuating torque



Electromagnetic forces in induction relays

Various quantities are shown at instant when

- Both fluxes are directed downward
- Are increasing in magnitude Let

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

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

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

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

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

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

- It may be noted that the net force is same at every instant.
- The net force is directed from the point where the leading flux process the rotor towards the point

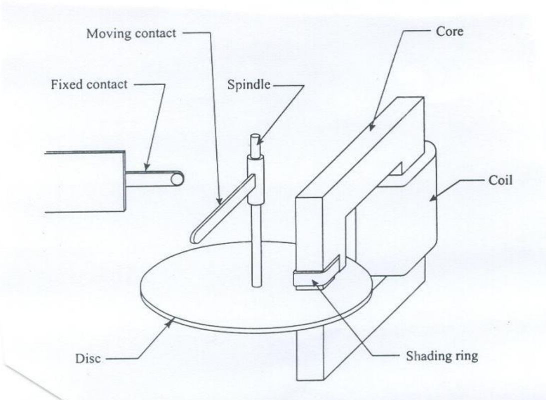
where the lagging flux pierces the rotor.

- Actuating force is produced in the presence of out of phase fluxes.
- Maximum force is produced when $\theta=90^o$

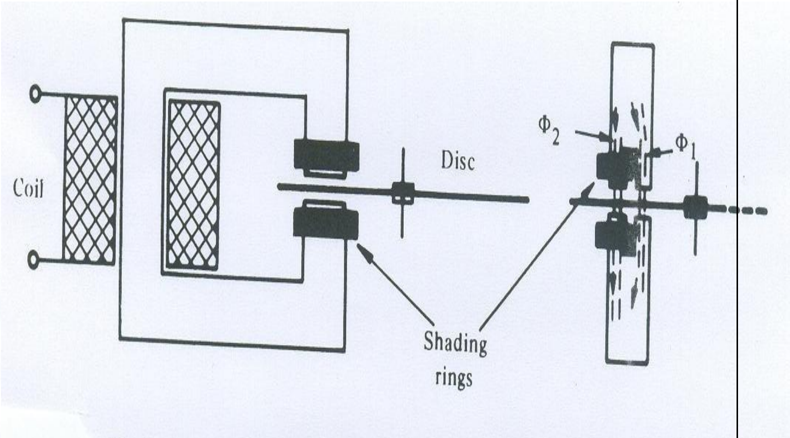
Classification of induction relays

- Shaded pole relay
- Watthour- meter type relay
- Cup type relay

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



Shaded-pole relay



Shaded-pole induction-disc relay

- The shading ring may be replaced by coils if control of operation of the shaded pole relay is desired.
- The inertia of the disc provides the time delay characteristics.

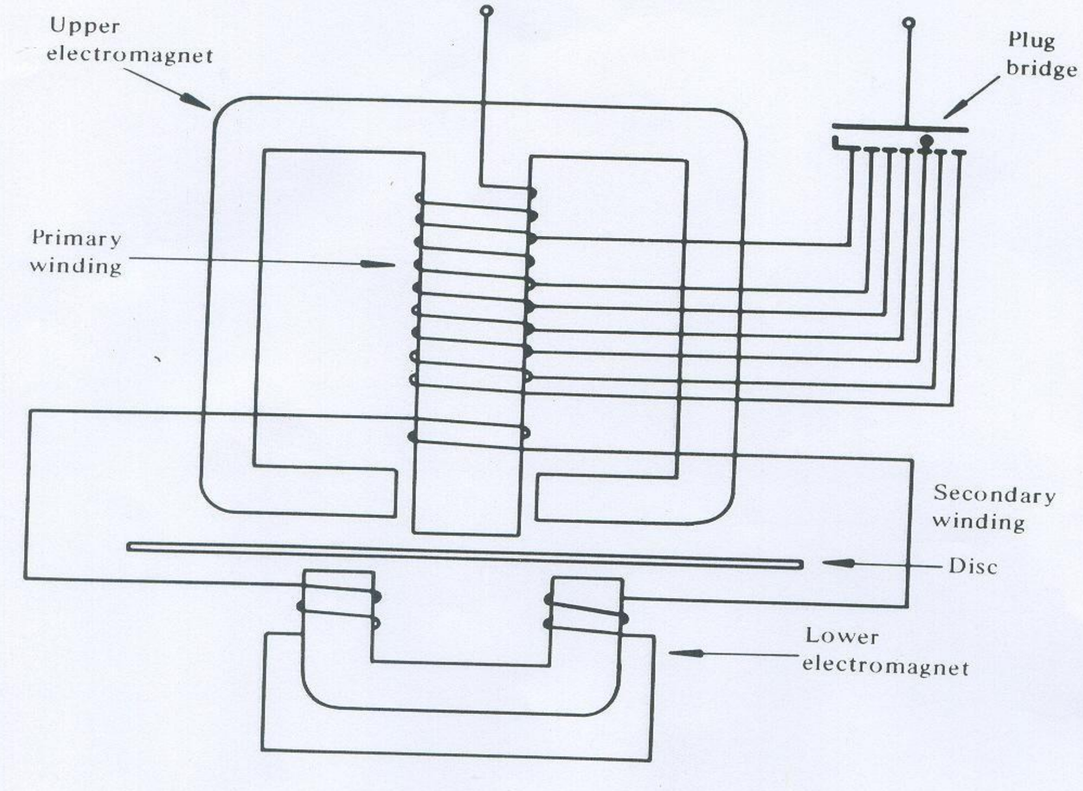
Watt hour –meter structure

- This structure gets its name from the fact that it is used in watt hour meters.

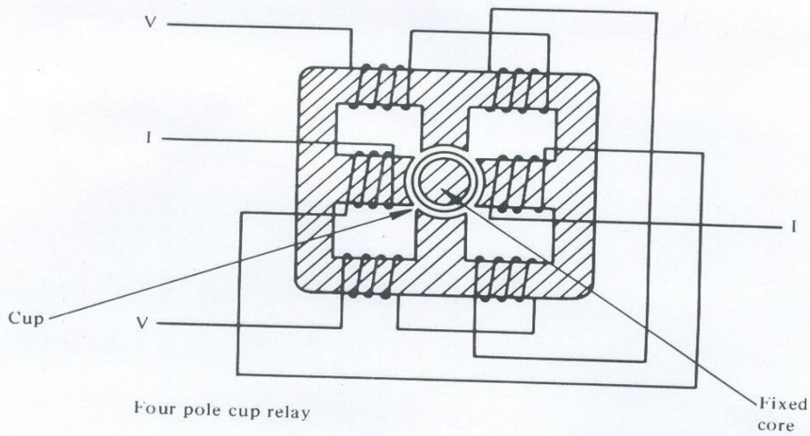
- As shown in the top figure below, it contains two separate coils on two different magnetic circuit, each of which produces one of two necessary fluxes for driving the rotor, which is also a disc

Induction-cup

- This type of relay has a cylinder similar to a cup which can rotate in the annular air gap between the poles & the fixed central core. The figure is shown above.
- The operation of this relay is similar to that of an induction motor with salient poles for the



Winding arrangement



Four pole cup relay

windings of the stator.

- The movement of the cup is limited to a small amount by the contact & the stops.
- A special spring provides restraining torque.
- The cup type of relay has a small inertia & is therefore principally used when high speed operation is required, for example in instantaneous units.

General Torque equation of Relay

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

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

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

Overcurrent Relays

- Protection against excess current was naturally the earliest protection systems to evolve
- From this basic principle has been evolved the graded over current system, a discriminate fault protection.
- "over current" protection is different from "over load protection".
- Overload protection makes use of relays that operate in a time related in some degree to the thermal capability of the plant to be protected.
- Over current protection, on the other hand, is directed entirely to the clearance of the faults, although with the settings usually adopted some measure of overload protection is obtained.
- In terms of the general torque equation the over current relay has both constants K_2 and

  K_3 equal to zero. Therefore, the equation becomes

- Based on the relay operating characteristics , overcurrent relays can be classified into three groups

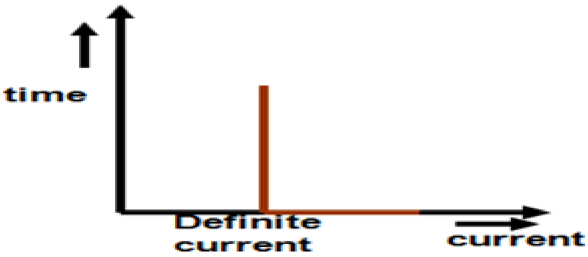
– Definite current or instantaneous

– Definite time

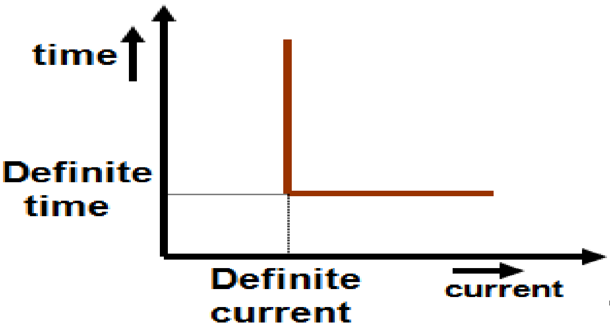
– Inverse time

DEFINITE-CURRENT RELAYS

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



DEFINITE TIME CURRENT RELAYS

- 

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

INVERSE TIME RELAYS

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

SETTING THE PARAMETERS OF TIME DELAY OVERCURRENT RELAY

Pick-up setting

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

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

Pick-up setting = (OLF x I_{nom}) / CTR

Where, OLF = Overload factor that depends on the element being protected. I_{nom} = Nominal circuit current rating, and CTR = CT Ratio

Time dial setting

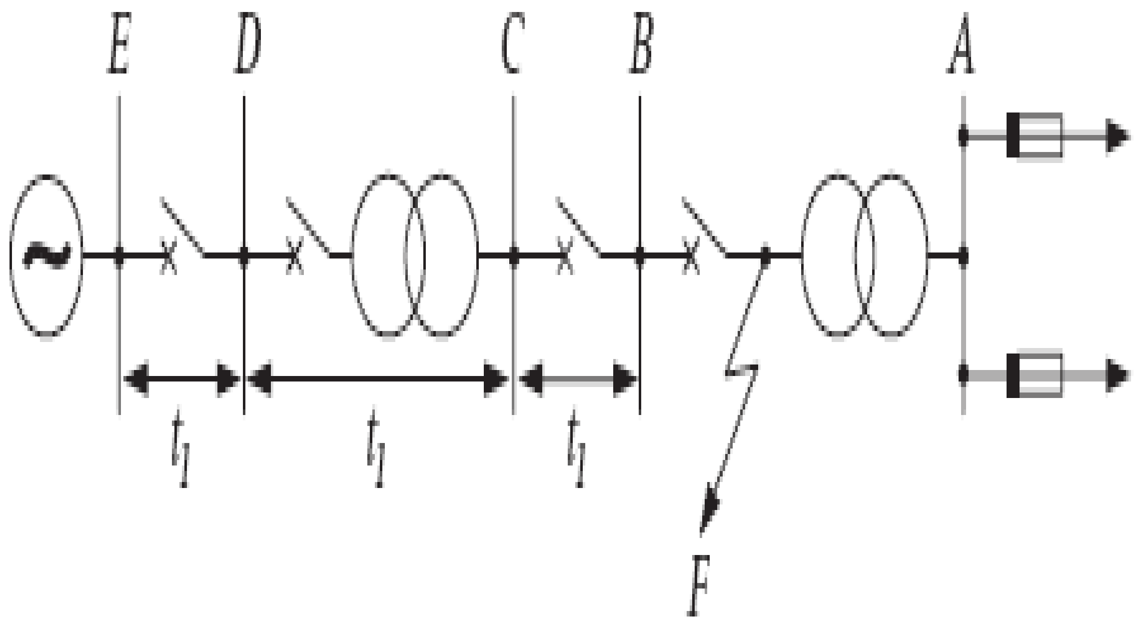
- The time-dial setting adjusts the time –delay before the relay operates whenever the fault current reaches a value equal to, or greater than the relay setting.
- The time-dial setting is also referred to as time multiplier setting (TMS)

DISCRIMINATION BY TIME

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

A simple radial distribution system is considered to illustrate this principle

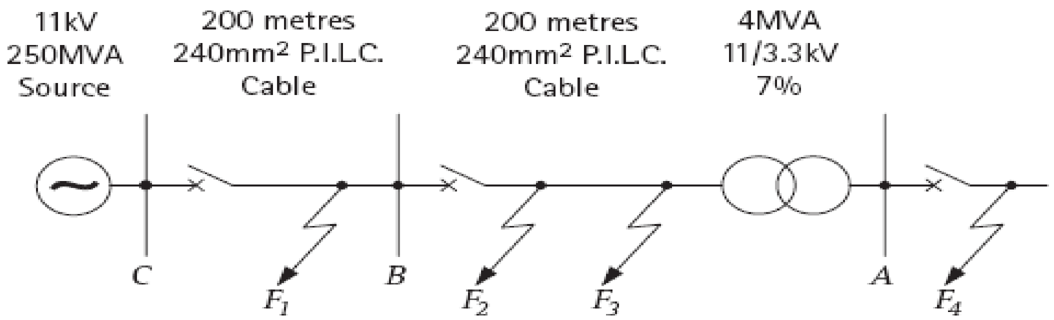
A radial distribution system with time-discrimination



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

DISCRIMINATION BY CURRENT

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



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

There are two types of torques

1. Restraining torque

2. Operating torque

The constant K depends on the design of the electromagnets.

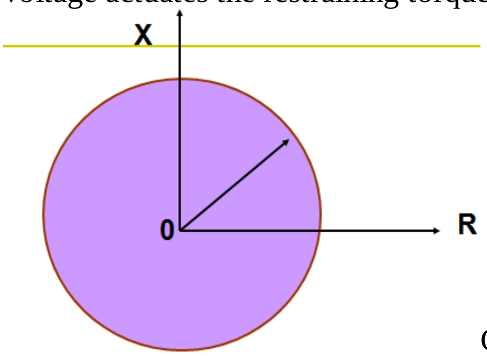
Types of distance relay

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

- Impedance Relay
- Mho Relay
- Reactance Relay

IMPEDANCE RELAY:

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

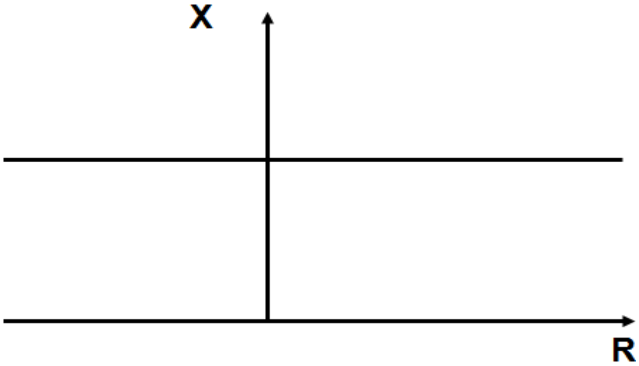


Considering K_2 to be negative (as it produces the restraining torque) and neglecting the torque component due to spring, the equation represents a circle in the R-X plane.

DISADVANTAGE OF IMPEDANCE RELAY

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

REACTANCE RELAY



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

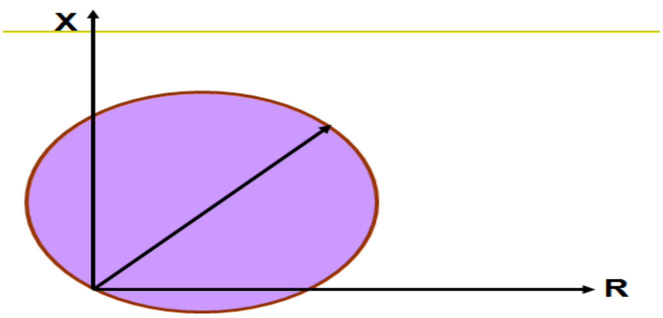
In the above equation, constant K_1 is positive as the current produces operating torque and K_3 is negative as the power direction produces restraining torque. In the above equation the angle τ is considered as 90^0. So the equation derives to

The portion below the line gives the operating zone of the relay.

MHO RELAY

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

The characteristics is shown below.

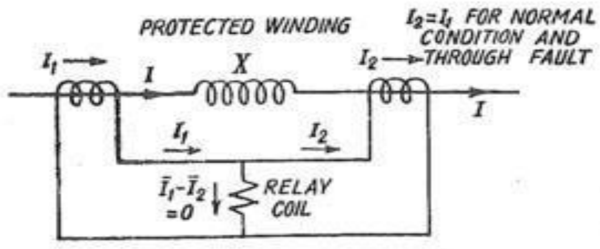


Differential Relay

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

Principle of circulating current differential (MERZ-PRIZE) protection

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



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

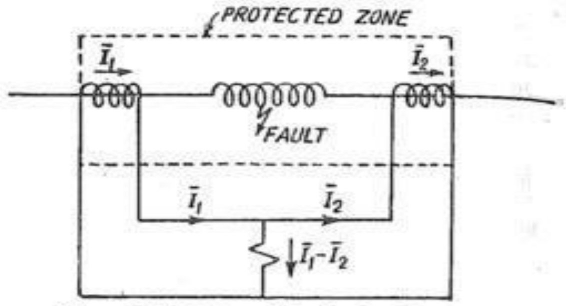
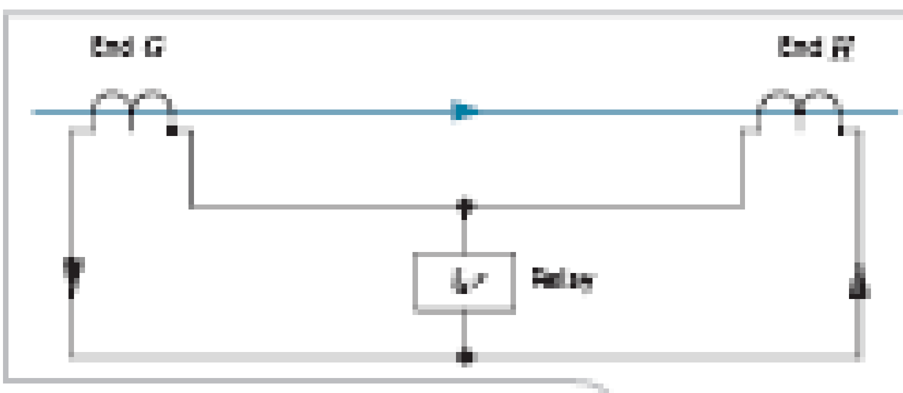


Fig. 1 (b). Internal Fault : $I_1 - I_2 \neq 0$.

During normal condition and external fault the protection system is balanced and the CT's ratios are such that secondary currents are equal. These current circulate in pilot wires. The vector differential current I_1- I_2 which flow through the relay coil is zero.
I_1-I_2 = 0 (normal condition or external faults)

This balance is disturbed for internal faults. When fault occurs in the protected zone, the current entering the protected winding is no more equal to the leaving the winding because some current flows to the fault. The differential I_1-I_2 flows through the relay operating coil and the relay operates if the operating torque is more than the restraining torque.
The current I_1 and I_2 circulate in the secondary circuit. Hence CT's does not get damaged. Polarities of CT's should be proper, otherwise the currents I_1 and I_2 would add up even for normal condition and mal operate the relay.



Differential Protection current balance

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

  The CTs at both ends of the protected circuit connected so that for through load or through fault conditions current circulates between the interconnected CTs. The over-current relay is normally connected across equipotential points and therefore doesn‟t operate.
- Circulating current balance methods are widely used for apparatus protection where CTs are within the same substation area and interconnecting leads between CTs are short (e.g. generator stator windings, Transformer, Bus bars etc.)
- The circulating current balance method is also called longitudinal differential protection or Merz-Price differential protection system.
- The current in the differential relay would be proportional to the phasor difference between the currents that enter and leave the protected circuit. If the current through the relay exceeds the pick-up value, then the relay will operate.

UNIT-III

SUBSTATIONS AND PROTECTION OF FEEDER / BUS BAR

Power Substation Types:
Power Substation:
An Electrical Power Substation receives electric power from generating station via transmission lines and delivers power via the outgoing transmission lines. Substations are integral parts of a power system and form important links between the generating stations, transmission systems, distribution systems and the load points. Various power substations located in generating stations, transmission and distribution systems have similar layout and similar electrical components. Electrical power substation basically consists of number of incoming circuit connections and number of outgoing circuit connections connected to the busbars. Busbars are conducting bars to which number of circuit connections is connected. Each circuit has certain number of electrical components such as circuit breakers, Isolators, earth switches, current transformers, voltage transformers, etc.

Functions of Electrical Power Substations are:

- Supply electric power to the consumers continuously
- Supply of electric power within specified voltage limits and frequency limits
- Shortest possible fault duration.
- Optimum efficiency of plants and the network
- Supply of electrical energy to the consumers at lowest cost

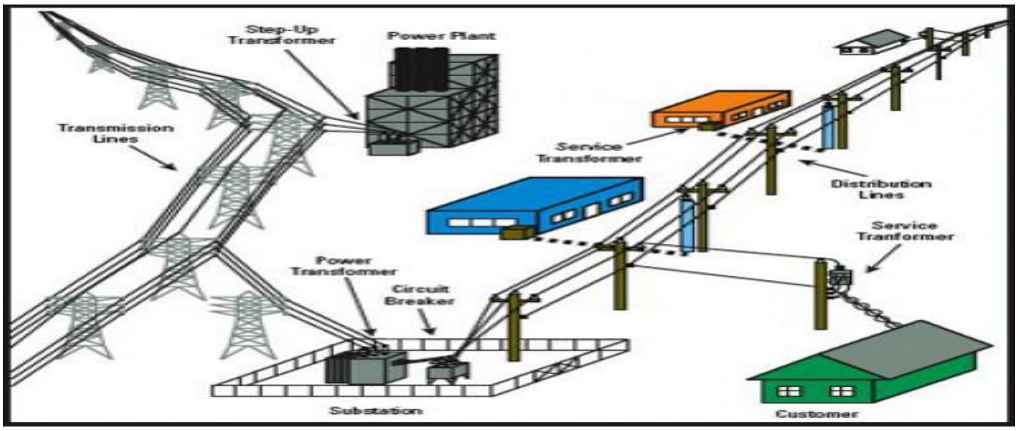
Types Of Electrical Power Substations:
Based ON Nature Of Duties:
Step up or primary Electrical Power substation:
Primary substations are associated with the power generating plants where the voltage is stepped up from low voltage (3.3, 6.6, 11, 33kV) to 220kV or 400kV for transmitting the power so that huge amount of power can be transmitted over a large distance to load centers.

Primary Grid Electrical Power Substation:

Such substations are located at suitable load centers along with the primary transmission lines. At primary Grid Power Substations the primary transmission voltage (220kV or 400kV) is stepped down to secondary transmission voltages (110kV) . This Secondary transmission lines are carried over to Secondary Power Substations situated at the load centers where the voltage is further stepped down to Sub transmission Voltage or Primary Distribution Voltages (11kV or 33kV).

Step Down or Distribution Electrical Power Substations:

Such Power Substations are located at the load centers. Here the Sub transmission Voltages of Distribution Voltages (11kV or 33kV) are stepped down to Secondary Distribution Voltages (400kV or 230kV). From these Substations power will be fed to the consumers to their terminals.



Transformer Substation:

Transformers are installed on such Substations to transform the power from one voltage level to other voltage level.

Switching Substation:
Switching substations are meant for switching operation of power lines without transforming the voltages. At these Substations different connections are made between various transmission lines. Different Switching Schemes are employed depends on the application to transmit the power in more reliable manner in a network.

Converting Substation:
Such Substations are located where AC to DC conversion is required. In HVDC transmission Converting Substations are employed on both sides of HVDC link for converting AC to DC and again converting back from DC to AC. Converting Power Substations are also employed where frequency is to be converted from higher to lower and lower to higher. This type of frequency conversion is required in connecting to Grid Systems.

Based on Operation Voltage:

High Voltage Electrical Power Substation:

This type of Substation associated with operating voltages between 11kV and 66kV.

Extra High Voltage Electrical Power Substation:

This type of Substation is associated where the operating voltage is between 132kV and 400kV.

Ultra High Voltage Electrical Power Substation:

Substations where Operating Voltages are above 400kV is called Ultra High Voltage Substati

Based On Substation Design:

Outdoor Electrical Power Substations:

In Outdoor Power Substations , the various electrical equipments are installed in the switchyard below the sky. Electrical equipment are mounted on support structures to obtain sufficient ground clearance.

Indoor Electrical Power Substation:

In Indoor Power Substations the apparatus is installed within the substation building. Such substations are usually for the rating of 66kV. Indoor Substations are preferred in heavily polluted areas and Power Substations situated near the seas (saline atmosphere causes Insulator Failures results in Flashovers)

Indoor Substation

Based on Design Configuration:

Air Insulated Electrical Power Substation:

In Air Insulated Power Substations busbars and connectors are visibe. In this Power Substations Circuit Breakers and Isolators, Transformers, Current Transformers, Potential Transformers etc are installed in the outdoor. Busbars are supported on the post Insulators or Strain Insulators. Substations have galvanized Steel Structures for Supporting the equipment, insulators and incoming and outgoing lines. Clearances are the primary criteria for these substations and occupy a large area for installation.

Gas Insulated Electrical Power Substation:

In Gas Insulated Substation Various Power Substation equipments like Circuit Breakers, Current Transformers, Voltage Transformers, Busbars, Earth Switches, Surge Arresters, Isolators etc are in the form of metal enclosed SF6 gas modules. The modules are assembled in accordance with the required Configuration. The various Live parts are enclosed in the metal enclosures (modules) containing SF6 gas at high pressure. Thus the size of Power Substation reduces to 8% to 10% of the Air Insulated Power Substation.

Hybrid Electrical Power Substation:

Hybrid Substations are the combination of both Conventional Substation and Gas Insulated Substation. Some bays in a Power Substation are Gas Insulated Type and some are Air Insulated Type. The design is based on convenience, Local Conditions available, area available and Cost.

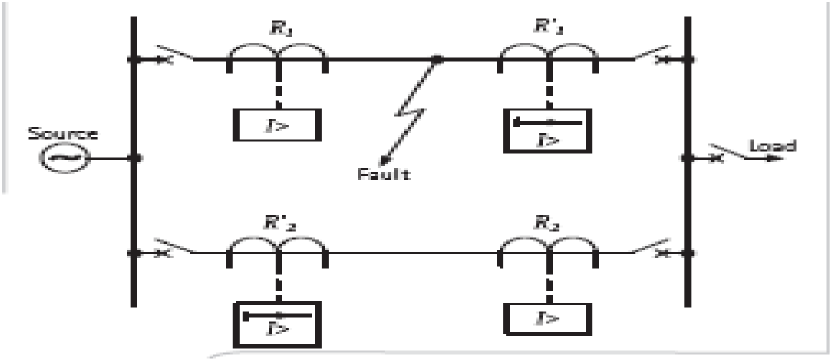
Gas Insulated Substation

PROTECTION OF FEEDERS

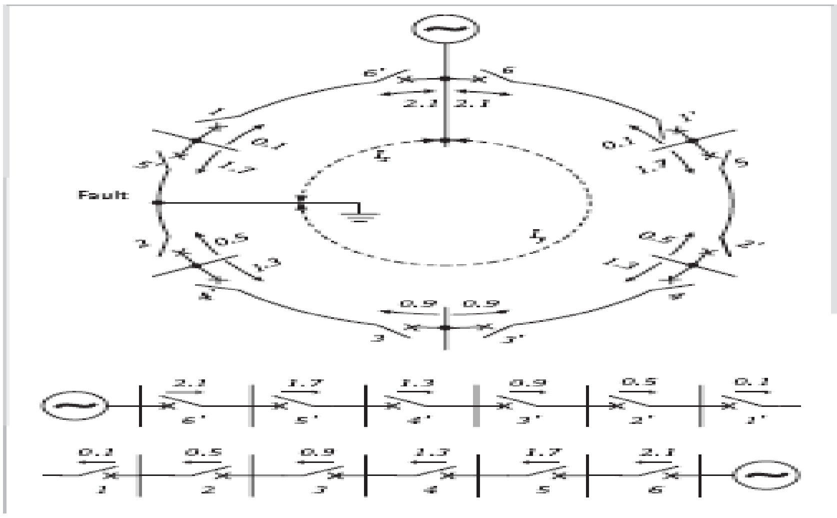
Over current and earth fault protection

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

Application of directional relays to parallel feeders

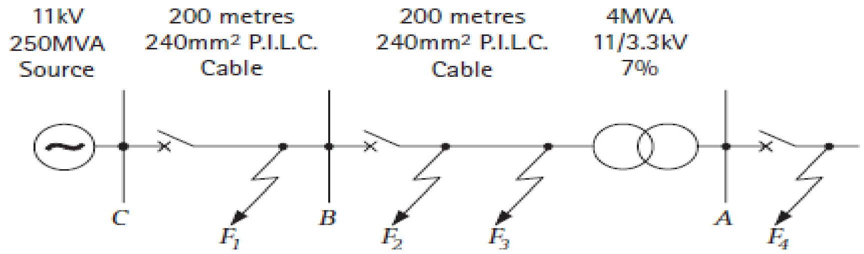


It may be seen from the below given parallel feeders that the relays placed at the load side of both the lines use directional element which respond to a direction away from the bus bars. Similarly, the relays placed at the source side do not require any directional element.



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

Over current protection radial system



other sections.

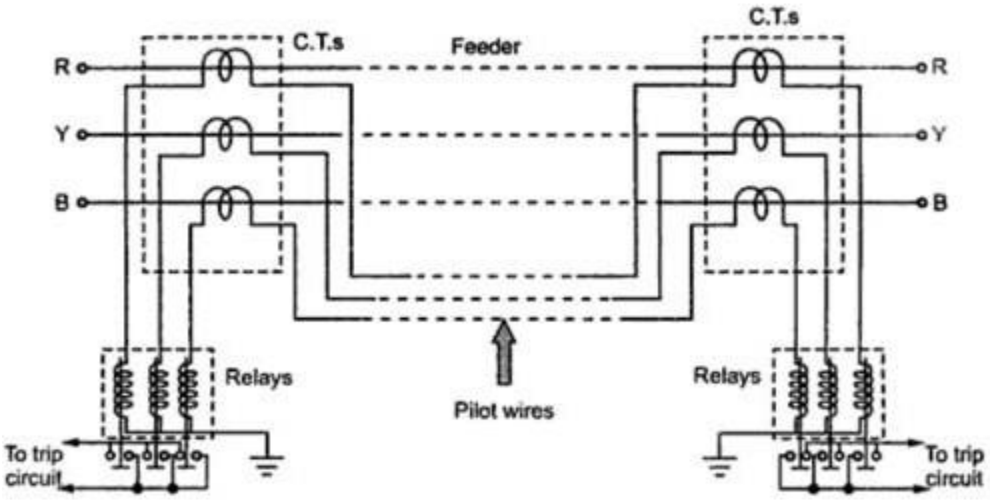
Pilot wire schemes for feeder protection

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

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

Merz-Price Voltage Balance System

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



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

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

i. It can be used for parallel as well as ring main system.

ii. It provides instantaneous protection to ground faults. The **limitations** of this method are as follows

iii. The C.T.s used must match accurately.

iv. The pilot wires must be healthy without discontinuity.

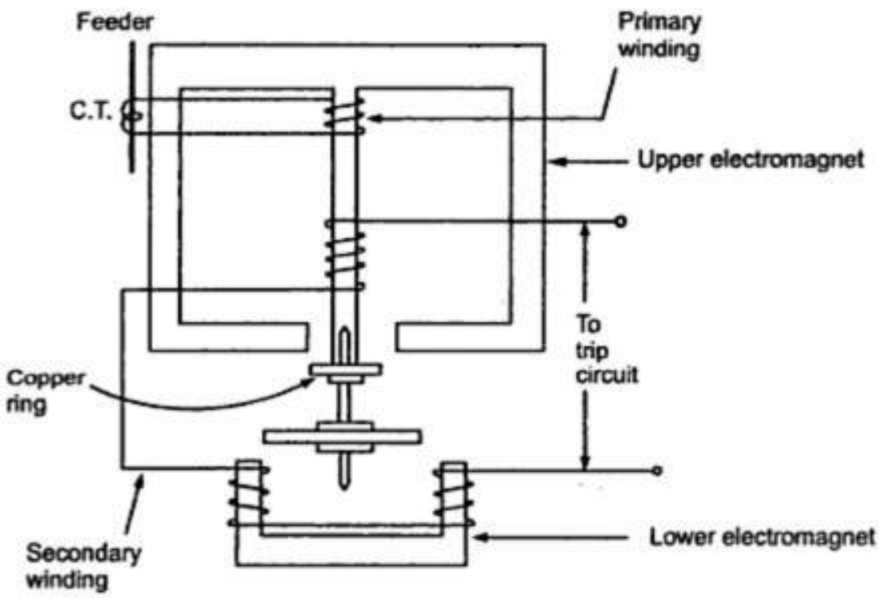
v. Economically not suitable as the cost is high due to long pilot wires.

vi. Due to long pilot wires, capacitive effects adversely bias the operation of the relays.

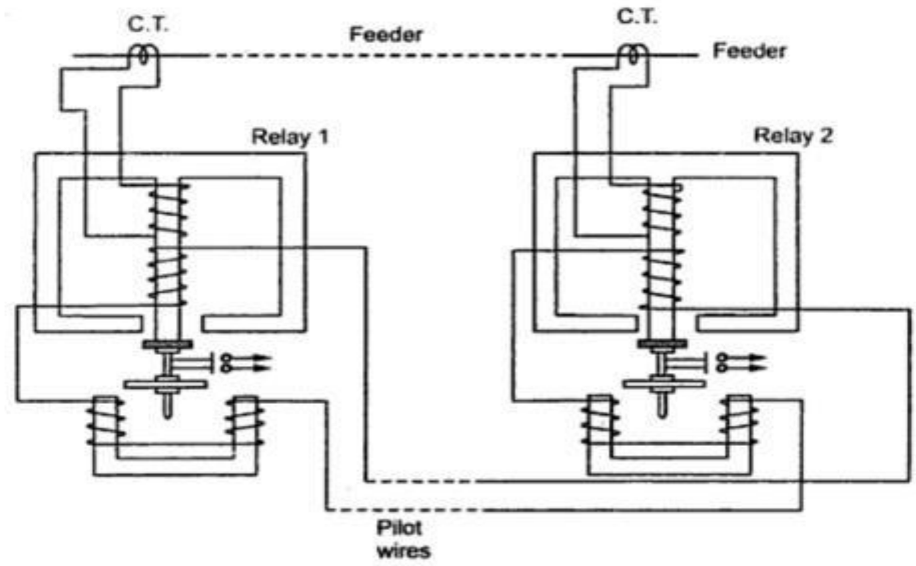
vii. The large voltage drop in the pilot wires requiring better insulation.

Translay Scheme

The translay relay is another type of differential relay. The arrangement is similar to overcurrent relay but the secondary winding is not closed on itself. Additionally copper ring or copper shading bands are provided on the central limb as shown in the figure below. In this scheme, two such relays are employed at the two ends of feeder as shown in the figure below



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



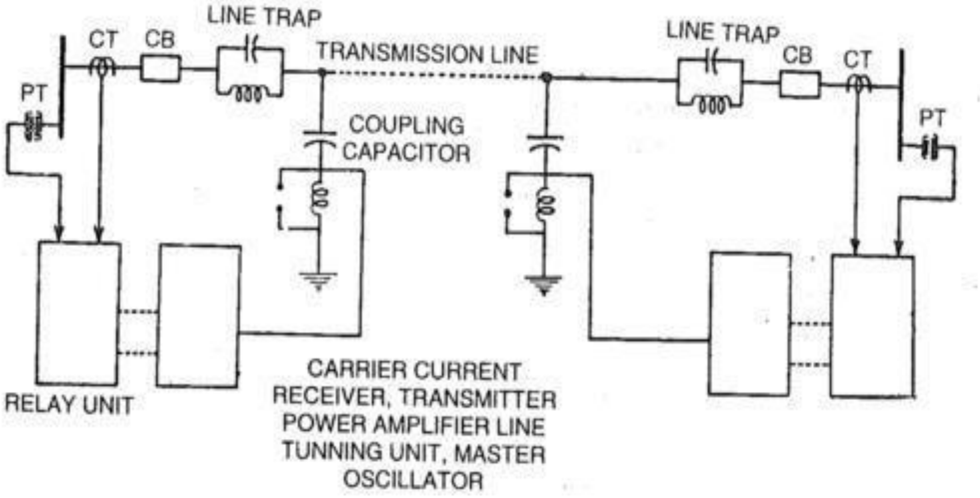
The secondaries of the two relays are connected to each other using pilot wires. The connection is such that the voltages induced in the two secondaries oppose each other. The copper coils are used to compensate the effect of pilot wire capacitance currents and unbalance between two currents transformers.

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

The **advantages** of this scheme are,

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

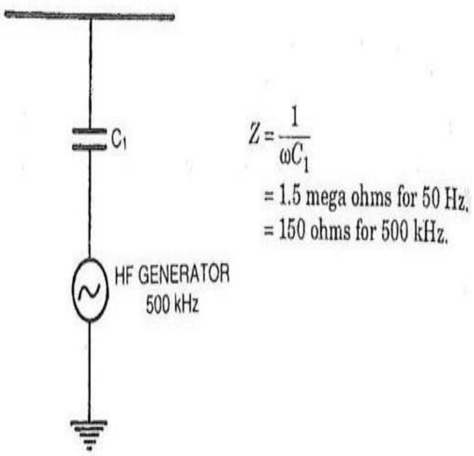
Carrier Current unit protection system

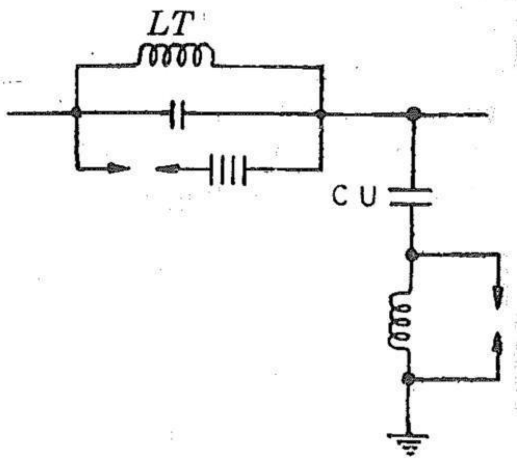


Schematic diagram of the carrier current scheme is shown below. Different basic components of the same are discussed below.

The Coupling capacitor

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





Wave Traps

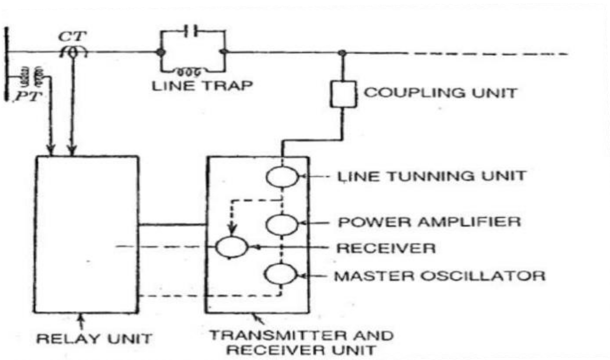
The Wave traps (also known as Line Trap) are inserted between the busbar and the connection of the CU. These traps are L and C elements connected in parallel, and they are tuned in such a manner that they offer low reactance to the power frequency signals and high reactance to the carrier waves. They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

Frequency spacing

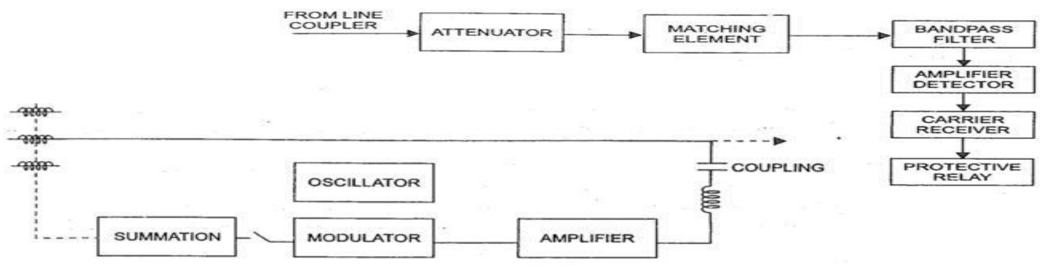
Different frequencies are used in adjacent lines and the wave traps ensure that carrier signals of other lines do not enter a particular line section. Therefore, proper choice of frequency bands for different lines are adopted.

Transmitter Unit

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



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



Static relays

Advantages of static relays

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

Basic circuits employed

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

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

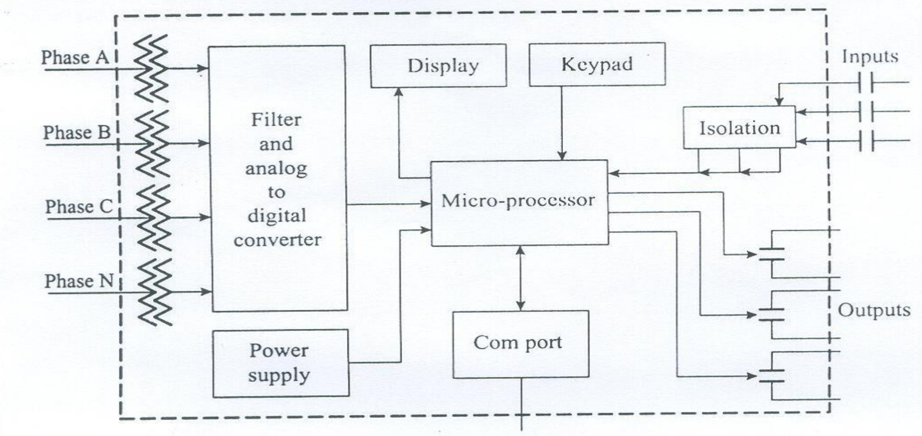
Numerical protection

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

- Reliability
- Self diagnosis
- Event and disturbance records
- Adaptive Protection
- Integration of Digital Systems

Typical architecture of numerical relays

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



General arrangement of numerical relays

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

1. State the relaying problem.

i) Model the relaying problem mathematically

ii) Write the algorithm.

iii) Convert the algorithm to a high level language.

iv) Test with a simulated data and modify the algorithm if required.

v) Generate the machine language code for the Micro processor/ Digital controller

vi) Download it for the numerical relay

vii) Test with a relay test bench.If found o.k. install it in parallel with the existing relay. Otherwise go back to step 3 to modify the algorithm and repaeat the process.

viii) Evaluate with various testing for longer period and launch it commercially if found o.k in its operation after operation of 2 years independently.

BUSBAR PROTECTION

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

BUSBAR FAULTS

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

TYPES OF PROTECTION SCHEMES

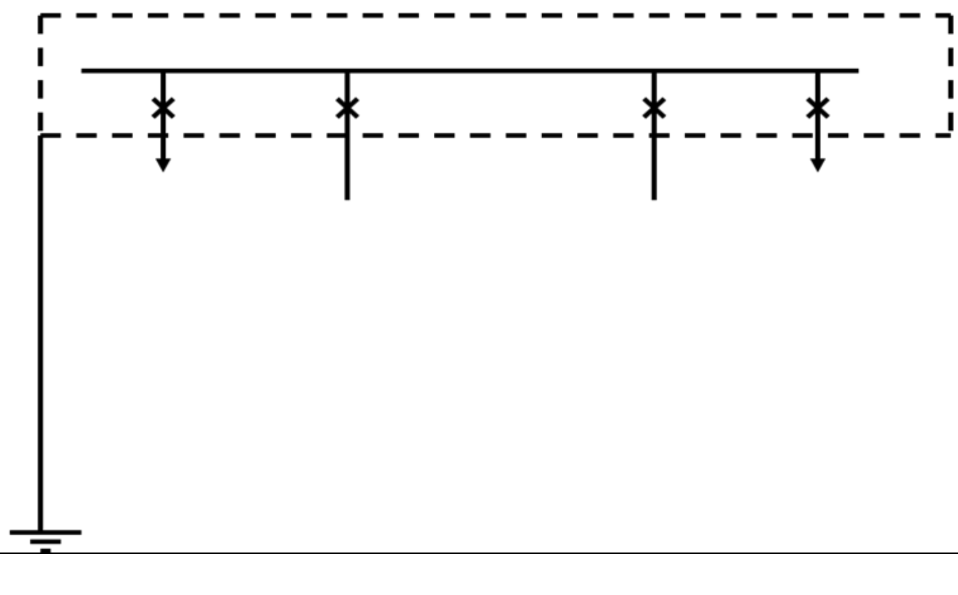
- o System protection used to cover bus bars
- o Frame –earth protection
- o Differential protection

SYSTEM PROTECTION

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

Frame-earth Protection

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



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

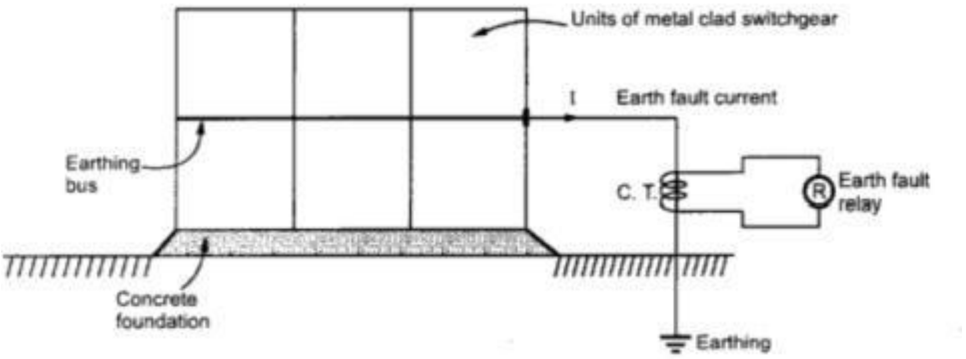
The concrete foundation of switchgear and the other equipments are lightly insulated from the ground. The resistance of these equipments with earth is about 12 ohms. When there is an earth fault, then fault current leaks from the frame and passes through the earth connection provided. Thus the primary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

UNIT-IV
GENERATOR AND TRANSFORMER PROTECTION

GENERATOR PROTECTION

INTRODUCTION

- The range of size of generators extends from a few hundred KVA to more than 500MVA



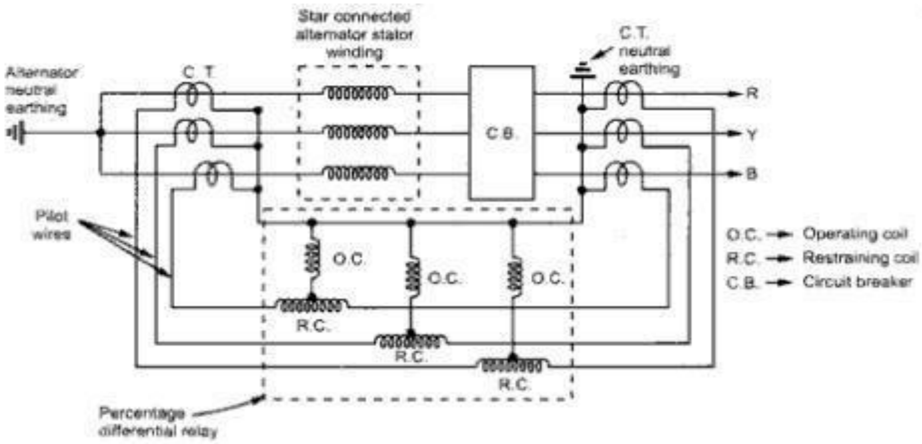
- Small and Medium sized sets may be directly connected to the distribution system

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

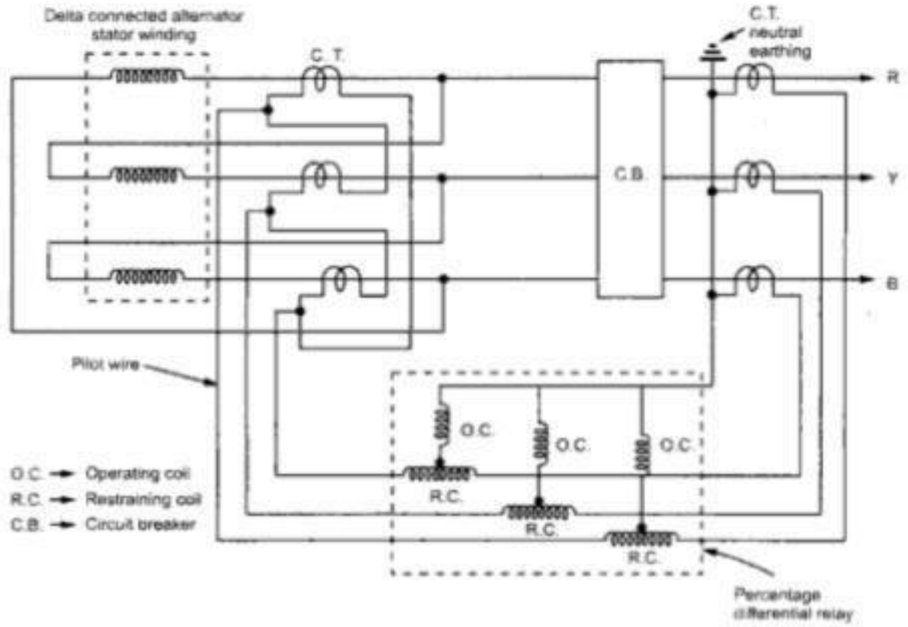
Biased Differential scheme (Merz-Price Scheme) for protection of Generators.

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

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



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



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

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

Earth fault protection of Generators.

The neutral point of the generator is usually earthed, so as to facilitate the protection of the stator winding and associated system. Impedance is inserted in the earthing lead to limit the magnitude of the earth fault current. Generators which are directly connected to the transmission or distribution system are usually earthed through a resistance which will pass approximately rated current to a terminal earth fault. In case of generator-transformer unit, the generator

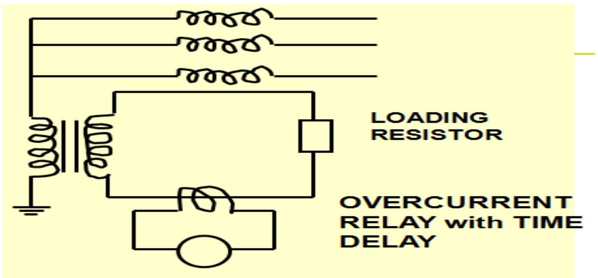
winding and primary winding of a transformer can be treated as an isolated system that is not

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

EARTH FAULT PROTECTION

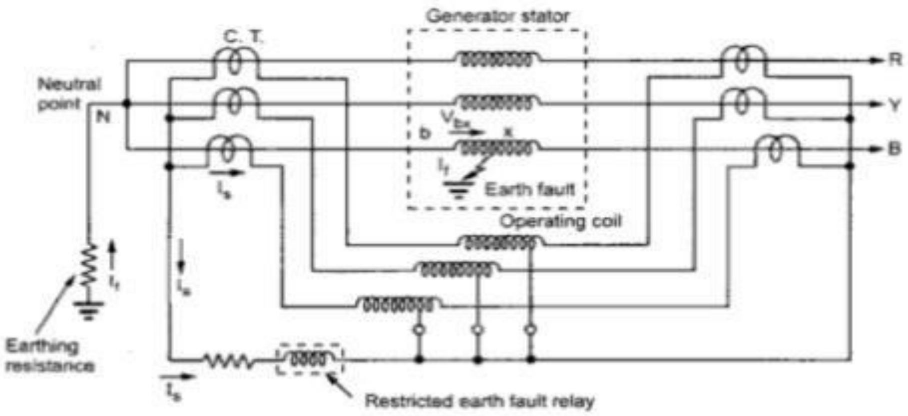
- Earth fault protection can be obtained by applying a relay to measure the transformer secondary current by connecting a voltage measuring relay in parallel with the load Resistor

earth faults. But for large costly generators, an additional protection scheme called restricted earth fault protection is provided.



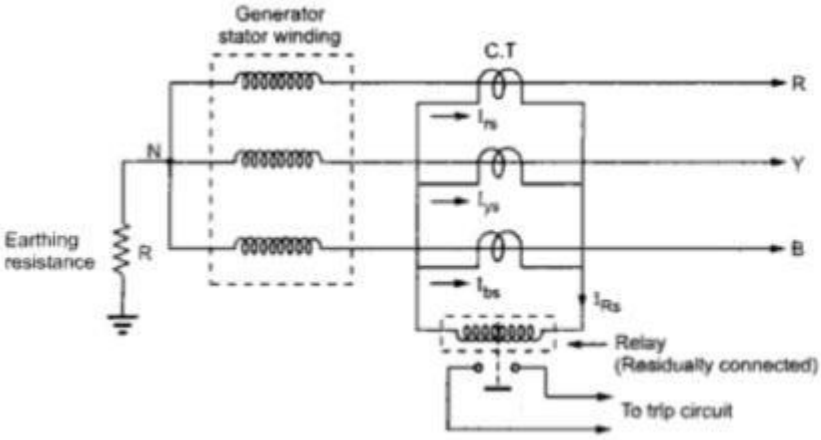
Restricted earth fault protection

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



The unrestricted earth fault protection uses a residually connected earth fault relay. It consists of three C.T.s, one in each phase. The secondary windings of three C.T.s are connected in parallel. The earth fault relay is connected across the secondaries which carries a residual current. The scheme is shown in the figure below.
Where there is no fault, under normal conditions, vector sum of the three line currents is

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

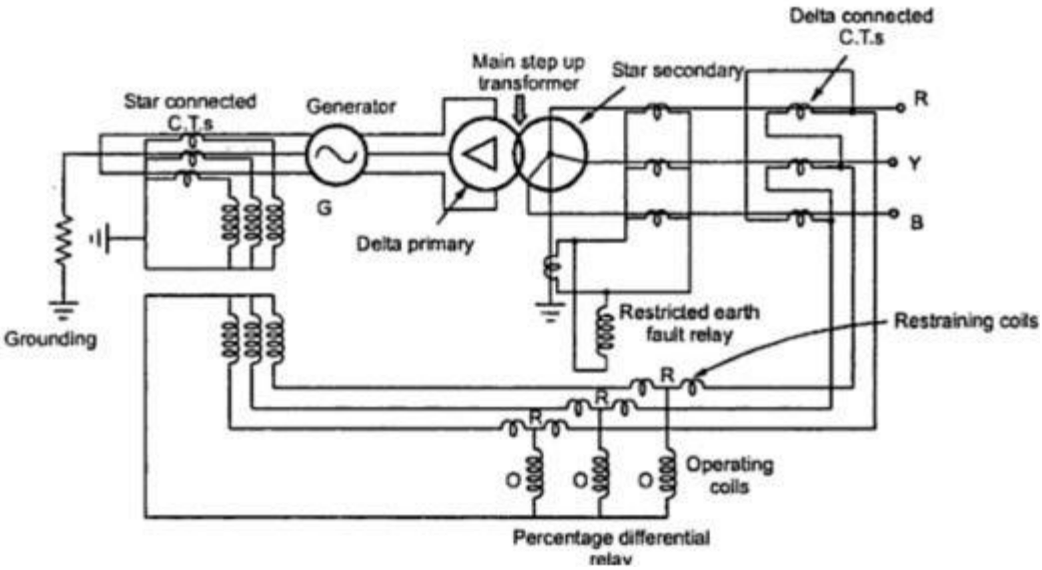


$\bar{I}_{rs} + \bar{I}_{ys} + \bar{I}_{bs} = 0$

Generator and Transformer Unit Biased Differential Protection

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

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



PHASE FAULT

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

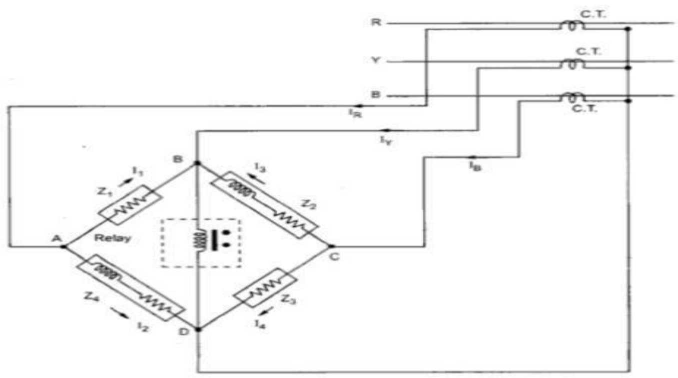
INTERTURN FAULTS

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

Negative sequence protection

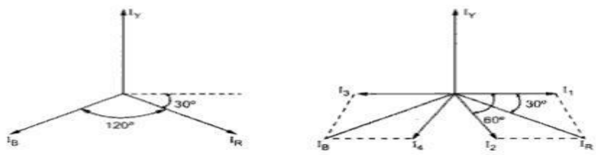
The negative sequence component can be detected by the use of a filter network. Many negative sequence filter circuits have been evolved.

One typical negative sequence filter circuit is as follows



Positive

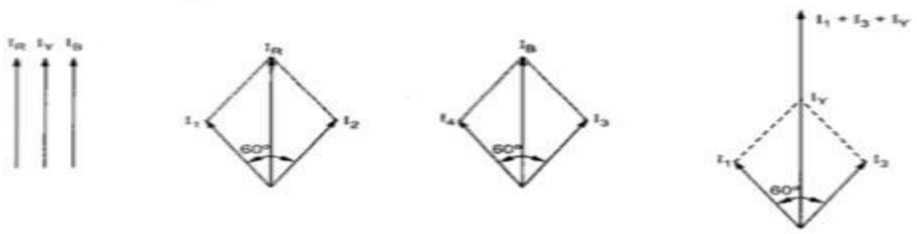
Negative



(a) C.T. secondary currents

(b) Vector sum

Zero



(a) (b) (c) (d)

POSITIVE SEQUENCE OPERATION

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

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

Let $\qquad I_1 = I_2 = I$

NEGATIVE SEQUENCE OPERATION

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

Zero Sequence operation

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

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

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

NEGATIVE SEQUENCE OPERATION

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

Zero Sequence operation

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

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

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

UNIT-V
PROTECTION AGAINST OVER VOLTAGES

Surge Protection

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

i. Internal overvoltage

ii. External overvoltage condition

Internal Overvoltage:

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

External Overvoltage:

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

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

The Concept of Surge:

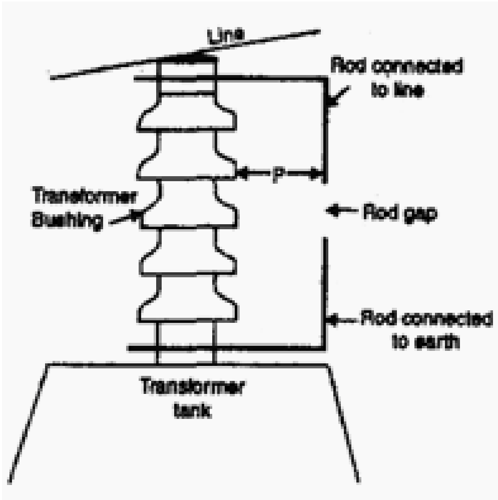
When a lightening surge or internal overvoltage condition strikes the end point of a transmission line it releases charge on the line and depending upon the inductance of the transmission line a voltage wave that is proportional to the charge density and a current wave travel over the line.
Depending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

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

1. Earthing Screens: This is the first line of defense provided, and they are like ground wires, sheets, provided over transmission line, substation buses, and other switchgears particularly those located outdoors. They can be copper conductors connected to ground.
2. Surge Diverters or Arrestors: The surge diverters better known as arrestors basically safe guards the insulation of the terminal apparatus and it ceases to carry current after a discharge.
3. Surge Modifiers: Surge capacitors and air cooled surge reactors modify the steepness of the wave front.

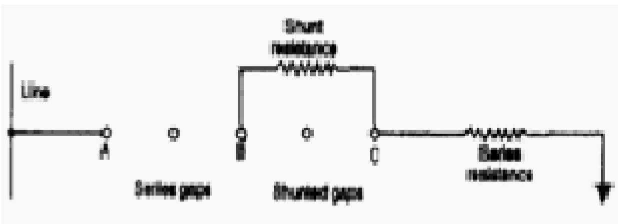
4. Surge Absorbers: Inductor metal shields absorb low energy surges. This device is appropriate for short duration surges as it can reduce only the steepness of the wave front. Such devices are not cost effective for higher transient surges.

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

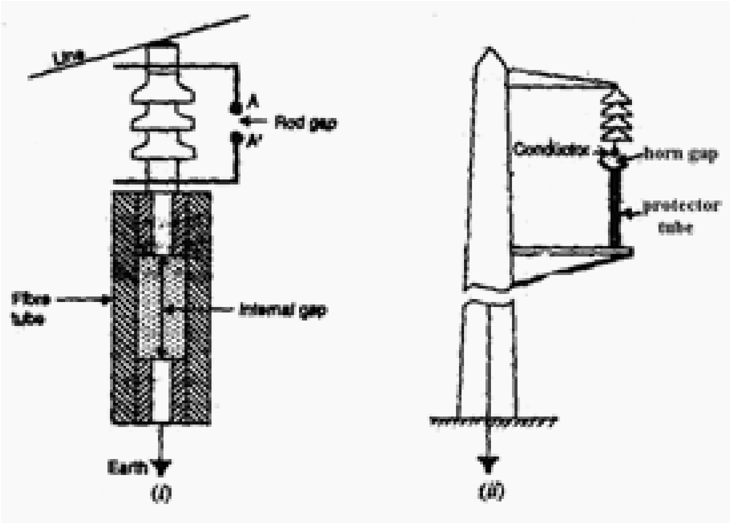


Rod Gap Arrester: This type of arrester is for lower voltage application. When the surge exceeds the designed value of the gap an arc is initiated. A small square rod of size 1 cm^2 bent at right angles and connected between the line and earth as shown in the figure above. The distance between the rod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

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

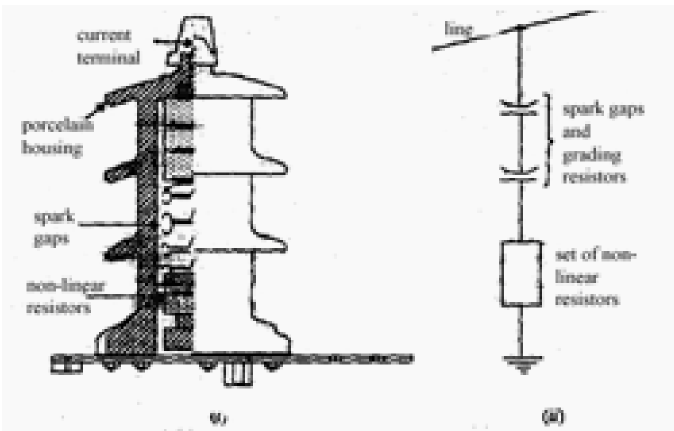


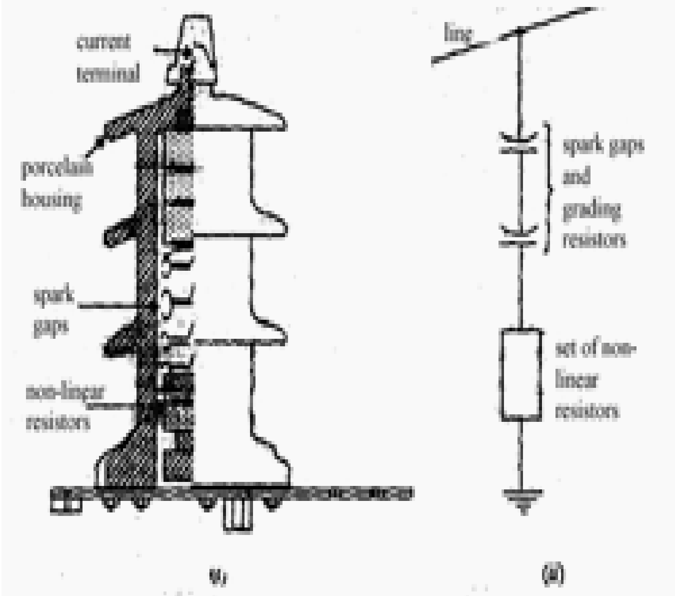
Multi gap arrestor: In this type of arrester, metallic cylinders of metal alloys of zinc, insulated from each other and separated by small multiple intervals of air gaps are connected in series as shown above. The first cylinder *A* in series is connected to the line and the others *B* and *C* to the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



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

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





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