UNIT I

CIRCUIT BREAKERS

Circuit Breakers: Elementary principles of arc interruption, Recovery, Restriking Voltage and Recovery voltages - Restriking Phenomenon, Average, Max. RRRV, Current Chopping and Resistance Switching - CB ratings and Specifications: Types and Numerical Problems. – Auto reclosures. Description and Operation of- Minimum Oil Circuit breakers, Air Blast Circuit Breakers, Vacuum and SF6 circuit breakers.

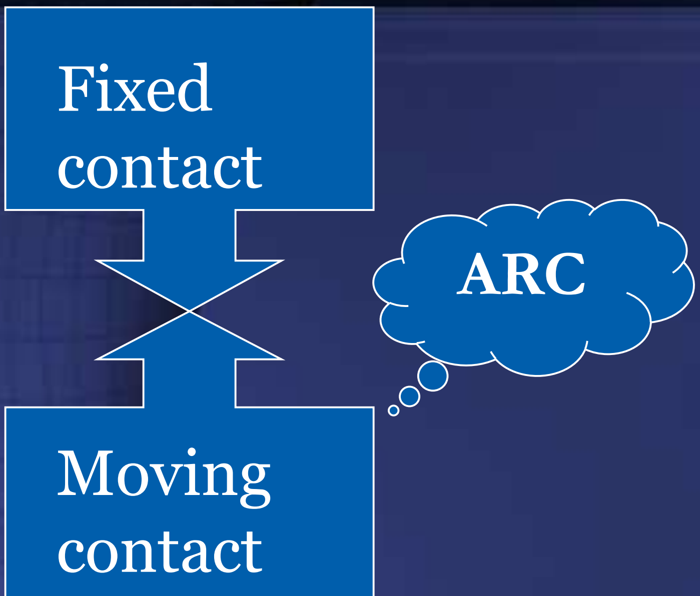
WHAT IS A CIRCUIT BREAKER?

A circuit breaker is an equipment which can

- **make or break a circuit either manually or by remote control under normal conditions**
- **break a circuit automatically under fault conditions**
- **make a circuit either manually or by remote control under fault conditions**

POINTS TO BE DISCUSSED:-

- PRINCIPLE
- ARCS
- METHODS OF ARC INTERRUPTION



IN A CIRCUIT BREAKER

OPERATING PRINCIPLE OF BREAKER

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 energised and the moving contacts are pulled apart by some mechanism, thus opening the circuit.

OVERVIEW OF ARCS IN BREAKERS-:

During the separation of contacts, due to large fault current and high current density at the contact region the surrounding medium ionises and thus a conducting medium is formed. This is called the ARC.

The production of arc not only delays the current interruption process but it also generates enormous heat which may cause damage to the system or to the circuit breaker itself.

Methods of Arc interruption

- High resistance method
- 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

Disadvantages

- Enormous energy is dissipated in the arc.

The resistance of the arc may be increased by

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.

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Cooling the arc

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

Reducing X-section of the arc

If the area of X-section of the arc is reduced, 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.

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.

Disadvantages

- It is not suitable for large current circuit breakers.
- It can be used for low power ac and dc circuit breakers

Low resistance or current zero method

- All modern high power AC Circuit Breakers employ this method for arc extinction.

- In this method, arc resistance is kept low until current zero where the arc extinguishes naturally and is prevented from restriking in spite of the rising voltage across the contacts.

- 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.

- The real problem in AC arc interruption is to rapidly deionise 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-ionisation of the medium can be achieved by :

- ✓lengthening of the gap
- ✓high pressure
- ✓cooling
- ✓blast effect

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.**

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-ionisation and consequently the dielectric strength of the medium between contacts is increased.**

- **Cooling:** Natural combination of ionised 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.

- **Blast effect:** If the ionised particles between the contacts are swept away and replaced by un-ionised 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

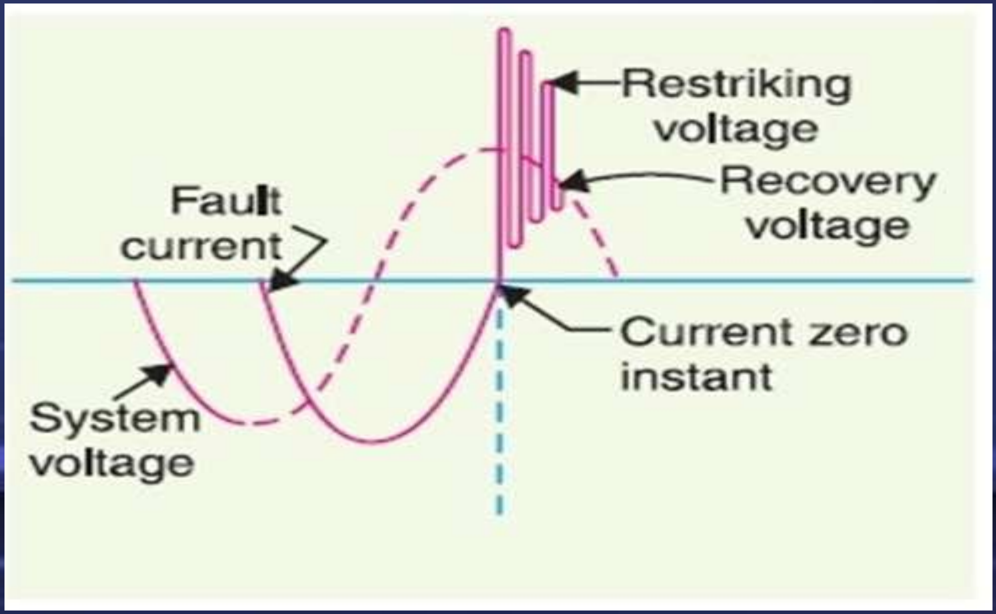
Important Terms

Arc Voltage:

It is the voltage that appears across the contacts of the circuit breaker during the arcing period

Restriking voltage:

It is the transient voltage that appears across the contacts at or near current zero during arcing period.



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

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.

Rate of rise of restriking voltage(RRRV):

It is the ratio of peak value of restriking voltage to Time to reach peak value.

$$\text{The average RRRV} = \frac{\text{Peak value of restriking voltage}}{\text{Time taken to reach to peak value}}$$

$$= \frac{2V_m}{\pi\sqrt{LC}}$$

The RRRV is given by

$$\frac{dv}{dt} = \frac{V_m}{\sqrt{LC}} \sin \frac{t}{\sqrt{LC}}$$

This is maximum when

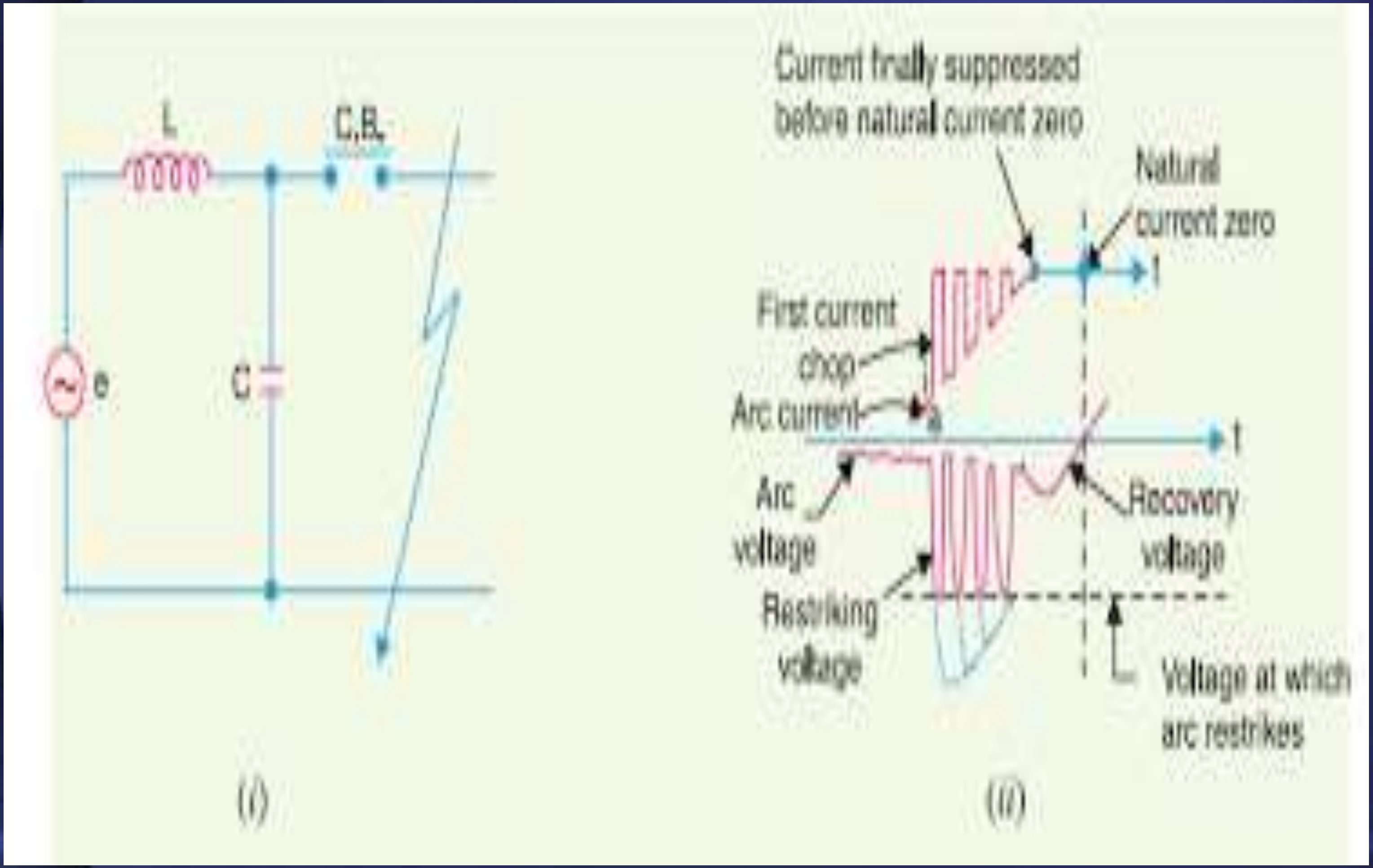
$$\frac{t}{\sqrt{LC}} = \frac{\pi}{2}$$

or

$$t = \frac{\pi}{2} \sqrt{LC}$$

and the value is $\frac{V_m}{\sqrt{LC}}$

Current chopping



Current chopping circuits and its wave forms

- **It is the phenomenon of current interruption before the natural current zero is reached.**
- **Current chopping mainly occurs in air-blast and vacuum 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-ionising effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached**

- **This results in the production of high voltage transient across the contacts of the circuit breaker.**
- **As the chop occurs at current i, therefore, the energy stored in inductance is $LI^2 / 2$. This energy will be transferred to the capacitance C, charging the latter to a prospective voltage V given by :**

$$LI^2 / 2 = CV^2 / 2$$

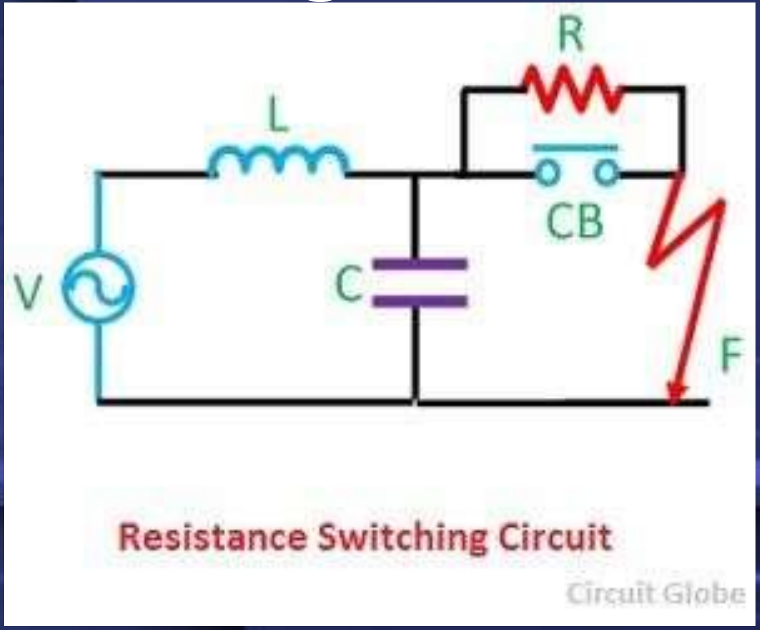
Here V = Voltage across the capacitor

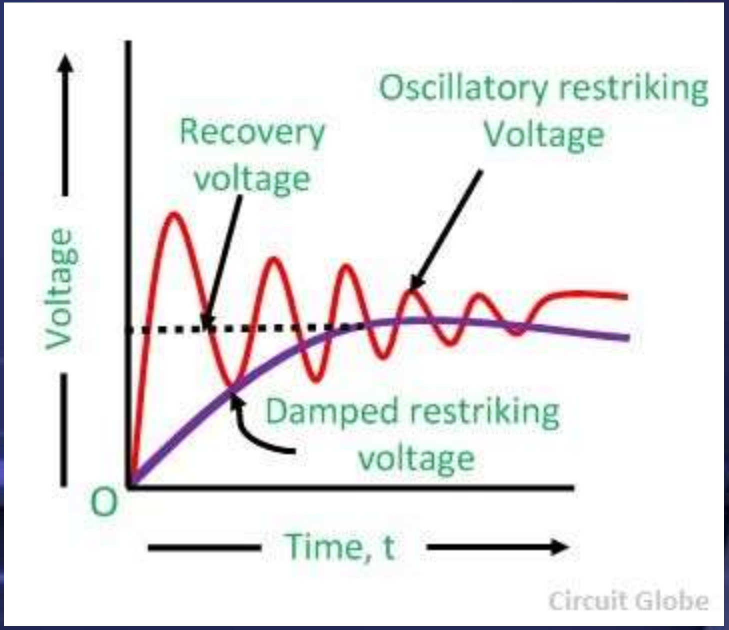
$$V = I \sqrt{(L/C)}$$

- **Excessive voltage surges due to current chopping are prevented by shunting the contacts of the breaker with a resistor (resistance switching).**

Resistance Switching

- The 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 This is known as resistance switching.





- 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-ionisation 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

Resistance $R = 0{\cdot}5\,\mathrm{sqrt}(L/C)$

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

To sum up, resistor across the circuit breaker contacts may be used to perform any one or more of the following functions.

- ✓**It reduces the RRRV (Rate of Rising of Restriking Voltage) and peak restriking voltage burden on the circuit breaker.**
- ✓**To reduce the voltage surges due to current chopping and capacitive current breaking.**
- ✓**In a multi-break circuit breaker, it helps in distributing the transient recovery voltage more uniformly across the contact gaps.**

Circuit Breaker Ratings

Duties of circuit breaker under fault conditions :

- **It must be capable of breaking the faulty circuit and breaking the fault current.**
- **It must be capable of being closed on to a fault.**
- **It must be capable of carrying fault current for a short time while another circuit breaker (in series) is clearing the fault**

RATINGS OF CIRCUIT BREAKER

- **Breaking capacity**
- **Making capacity**
- **Short-time capacity**

Breaking capacity

Definition

It is current 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 in 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.**
- **the contacts are separated at DD´. At this instant, the fault current has**

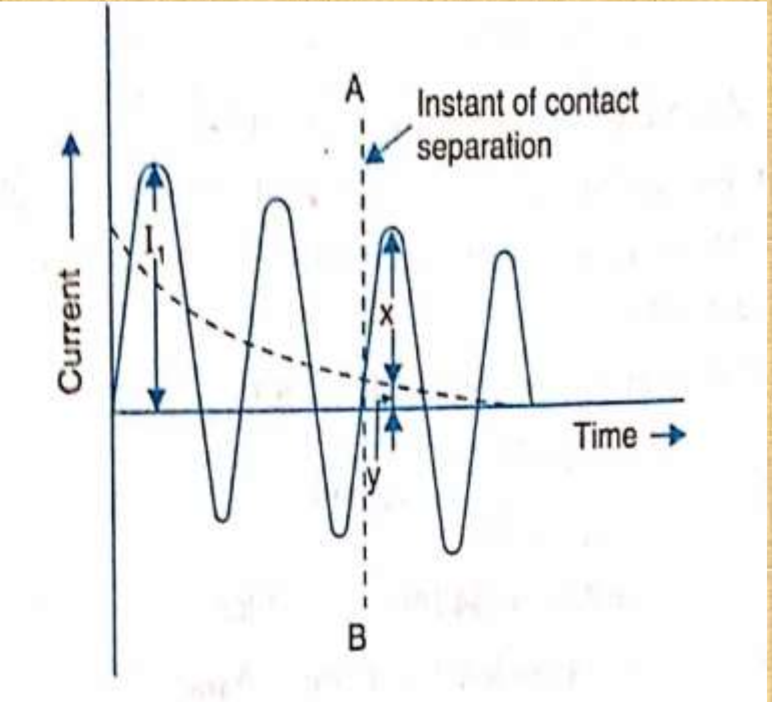


Fig. 15.13 Determination of breaking current at the instant of contact separation.

x = maximum value of a.c. component

y = d.c. component

∴ Symmetrical breaking current = r.m.s. value of a.c. component $= \frac{x}{\sqrt{2}}$

Asymmetrical breaking current = r.m.s. value of total current $= \sqrt{\left(\frac{x}{\sqrt{2}}\right)^2 + y^2}$

- It is a common practice to express the breaking capacity in MVA by taking into account the rated breaking current and rated service voltage.
- 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, Breaking capacity = √ 3 × V × I × 10−6 MVA

Making Capacity
Definition

The peak value of current during the first cycle of current wave after the closure of circuit breaker is known as making capacity.

- **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 × 1·8 = 2·55**

- **Asymmetrical breaking current=2.55 × symmetrical breaking current**

- **Making capacity =2·55 × Symmetrical breaking capacity**

Short-time rating

Definition: It is the period for which the circuit breaker is able to carry fault current while remaining closed

- **If the fault is temporary in 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.**
- **if the fault is permanent and persists for a 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**
  - **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**

Specifications of circuit breaker

- **Rated voltage**
- **Rated current**
- **Rated frequency**

- **Rated voltage** –The rated voltage of the circuit breaker is the highest RMS voltage, above nominal voltage for which the circuit breaker is designed and is the upper limits for operation. The rated voltage is depicted in KVrms and used phase to phase voltage for three phase circuit.

- **Rated current** – The rated normal current of the circuit breaker is the RMS value of the current with which the circuit breaker shall be able to carry at rated frequency and at rated voltage continuously, under specified conditions

- **Rated Frequency** – The rated frequency of a circuit breaker is the frequency at which it is designed to operate. Standard frequency is 50 Hz

TYPES CIRCUIT BREAKERS

Different Types Of Circuit Breaker

- **Oil Circuit Breaker** which employ some insulating oil (e.g., transformer oil) for arc extinction.

- **Air Blast Circuit Breaker** in which high pressure air-blast is used for extinguishing the arc.

- **Sulpher Hexafluroide Circuit Breakers** in which sulphur hexafluoride (SF6) gas is used for arc extinction

- **Vacuum Circuit Breakers** in which vacuum is used for arc extinctio

Types of Oil Circuit Breakers

1.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.
- secondly, it insulates the current conducting parts from one another and from the earthed tank.

2.Low oil circuit breakers which use minimum amount of oil.

- In such circuit breakers, oil is used only for arc extinction
- the current conducting parts are insulated by air or porcelain or organic insulating material

BULK OIL CIRCUIT BREAKER

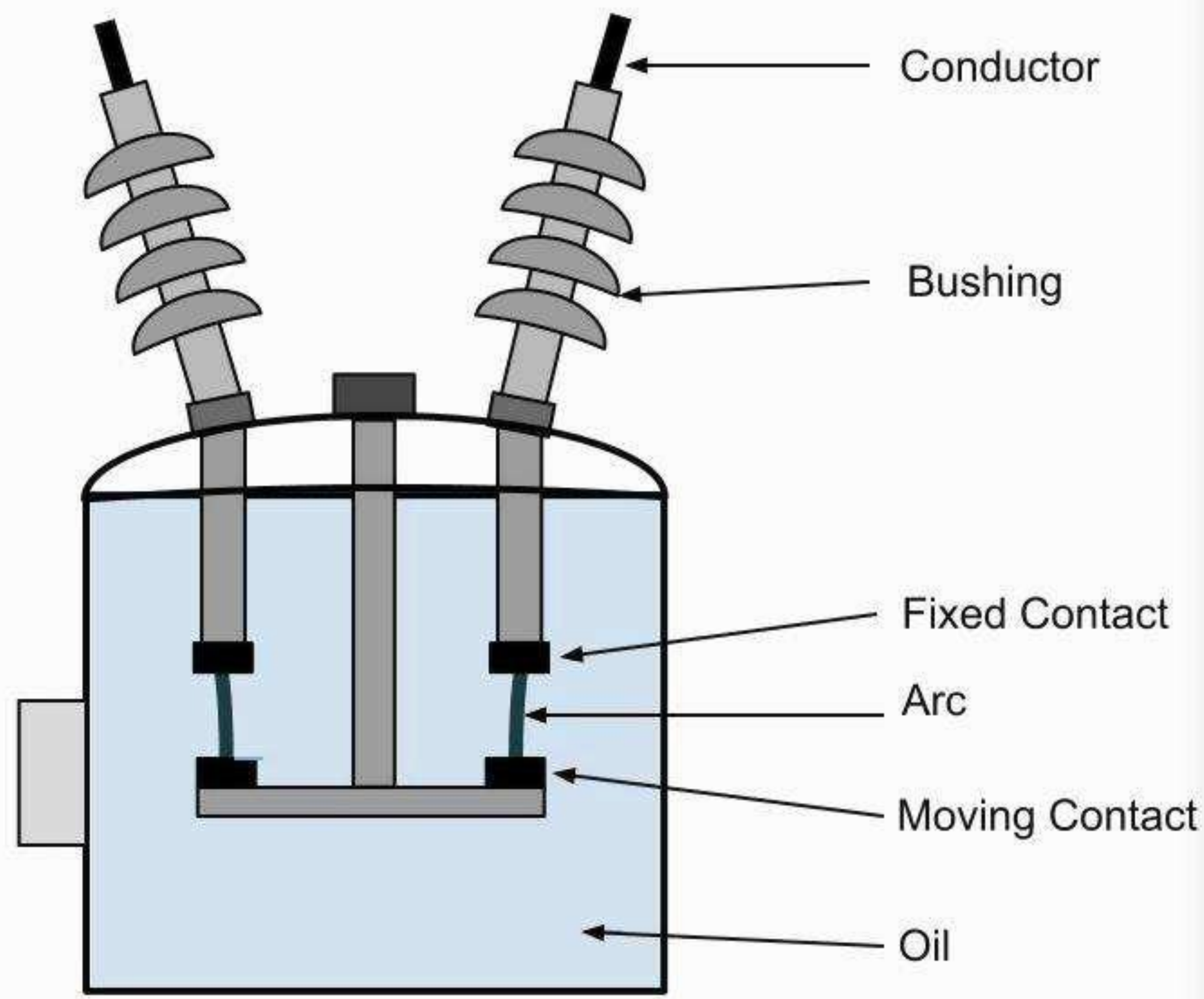


Fig-A: Bulk Oil Circuit Breaker (BOCB)

CONSTRUCTION

- 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 upto 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.

OPERATION

- 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 vapourises the oil mainly into hydrogen gas.

The arc extinction is facilitated by the following processes

- The hydrogen gas bubble generated around the arc cools the arc column and aids the de-ionisation of the medium between the contacts.
- The gas sets up turbulence in the oil and helps in eliminating the arcing products from the arc path.
- As the arc lengthens due to the separating contacts, the dielectric strength of the medium is increased

Advantages-

- By connecting several interrupting mechanism in series, the voltage rating of the breaker can be increased.
- By careful design the interrupting capacity rating can be increased up to 26000 MVA.
- Quiet operation.

Disadvantages-

- The breaker contains flammable oil , consequently it should located outdoor.
- Oil breakdown at high temperature forms carbon which gets dissolved in the oil, this increases the oil conductivity.
- Becomes an environmental hazard if spillage occurs.

LOW ORMINIMUM OIL CIRCUIT BREAKER

CONSTRUCTION

- The cross section of a single phase low oil circuit breaker as shown in fig.
- 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 has two advantages

✓the circuit breaking chamber requires a small volume of oil which is just enough for arc extinction.

✓the amount of oil to be replaced is reduced as the oil in the supporting chamber does not get contaminated by the arc.

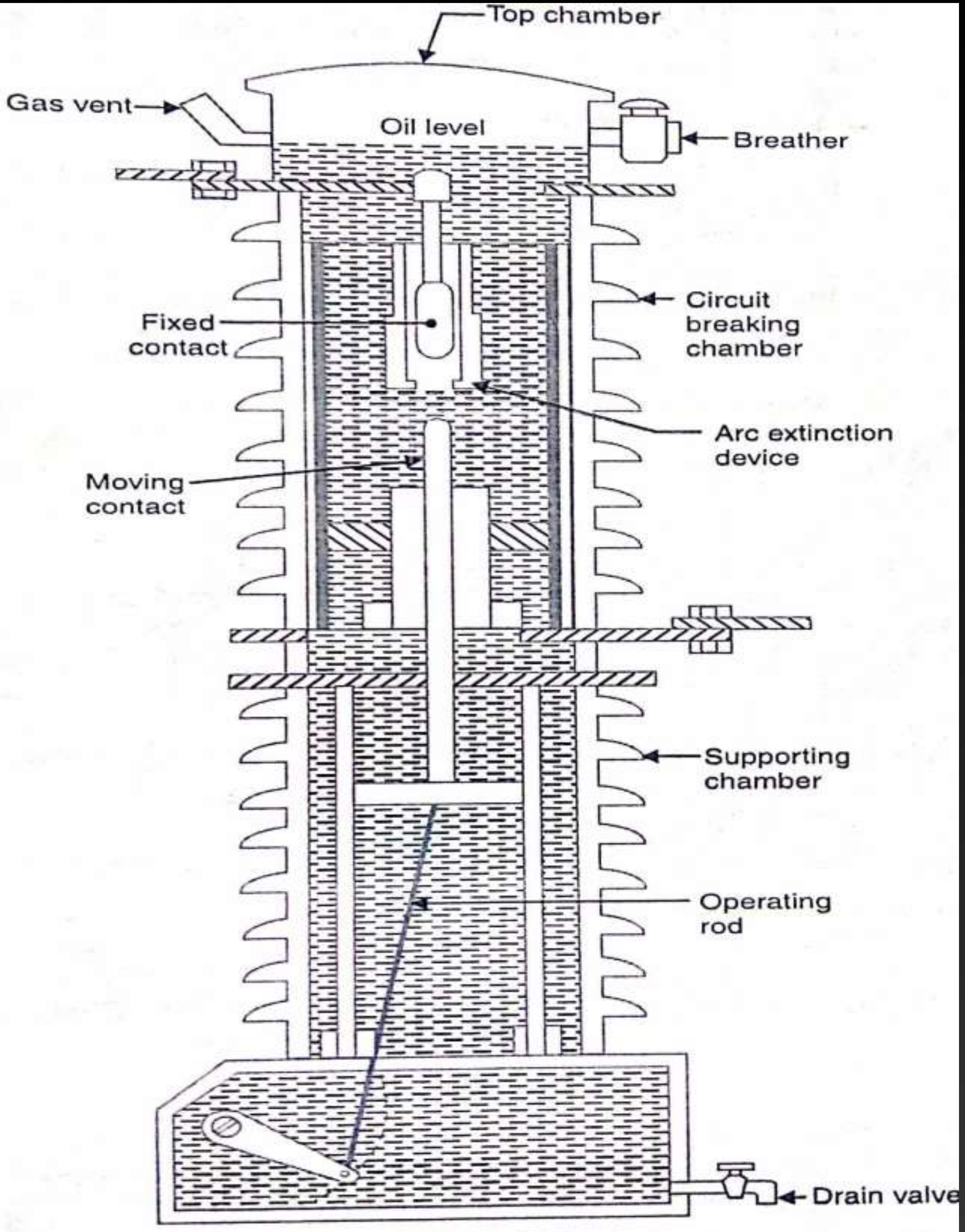


Fig. 19.7 Low-oil Circuit Breaker

1. **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.
2. **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 :

- upper and lower fixed contacts
- moving contact
- 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.

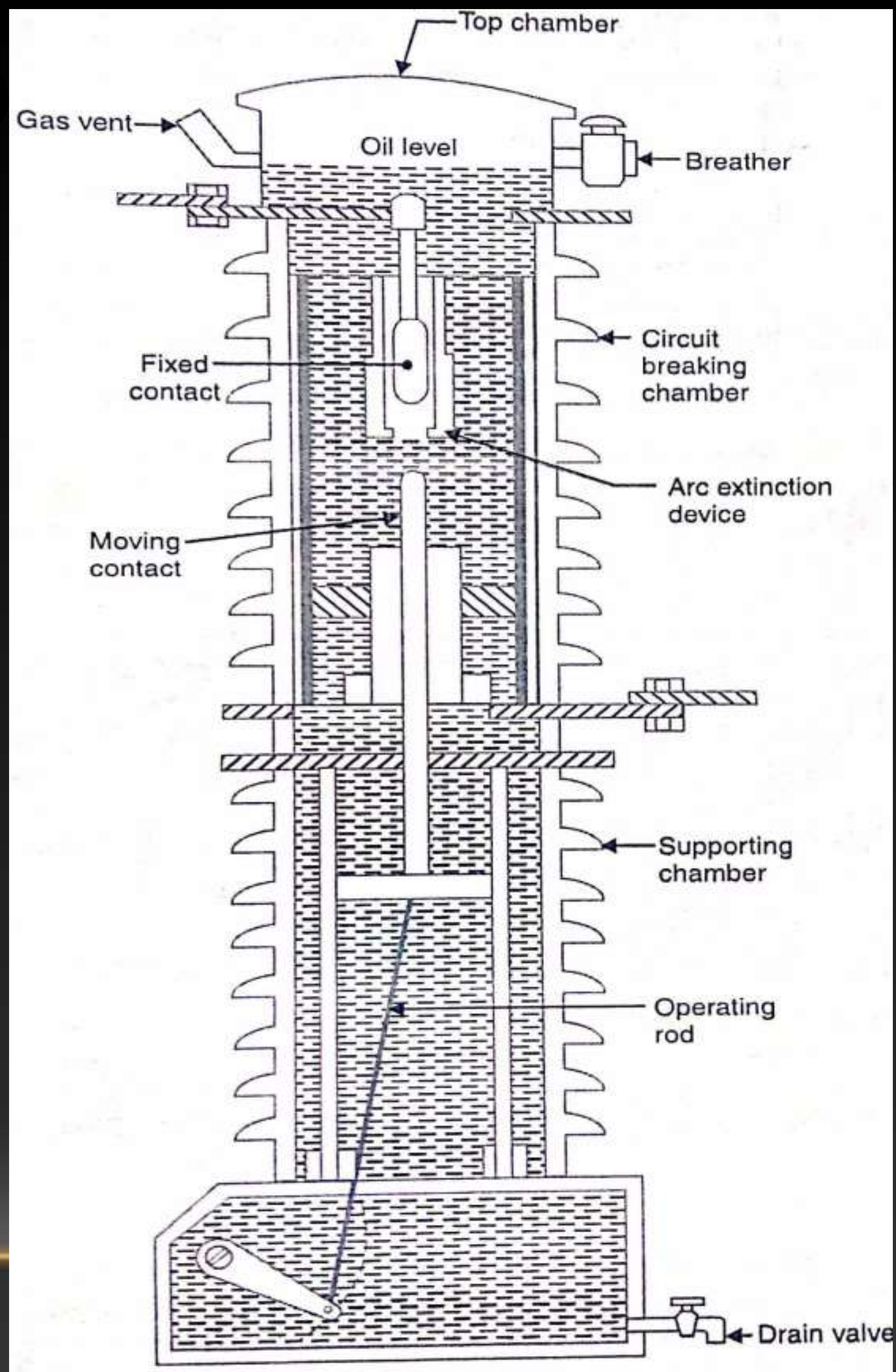


Fig. 19.7 Low-oil Circuit Breaker

CONCLUSION

3. **Top chamber:** It is a metal chamber and is mouted 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 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 vaporises the oil and produces gases(hydrozen) under high pressure.
- As oil between the contacts gets vaporized in this process some fresh oil is filled between the contacts. This fresh oil also gets vaporized and generates gases and again fresh oil is filled.
- The process of turbulation is orderly one, in which the arc is successively quenched and the flow of current is interrupted.

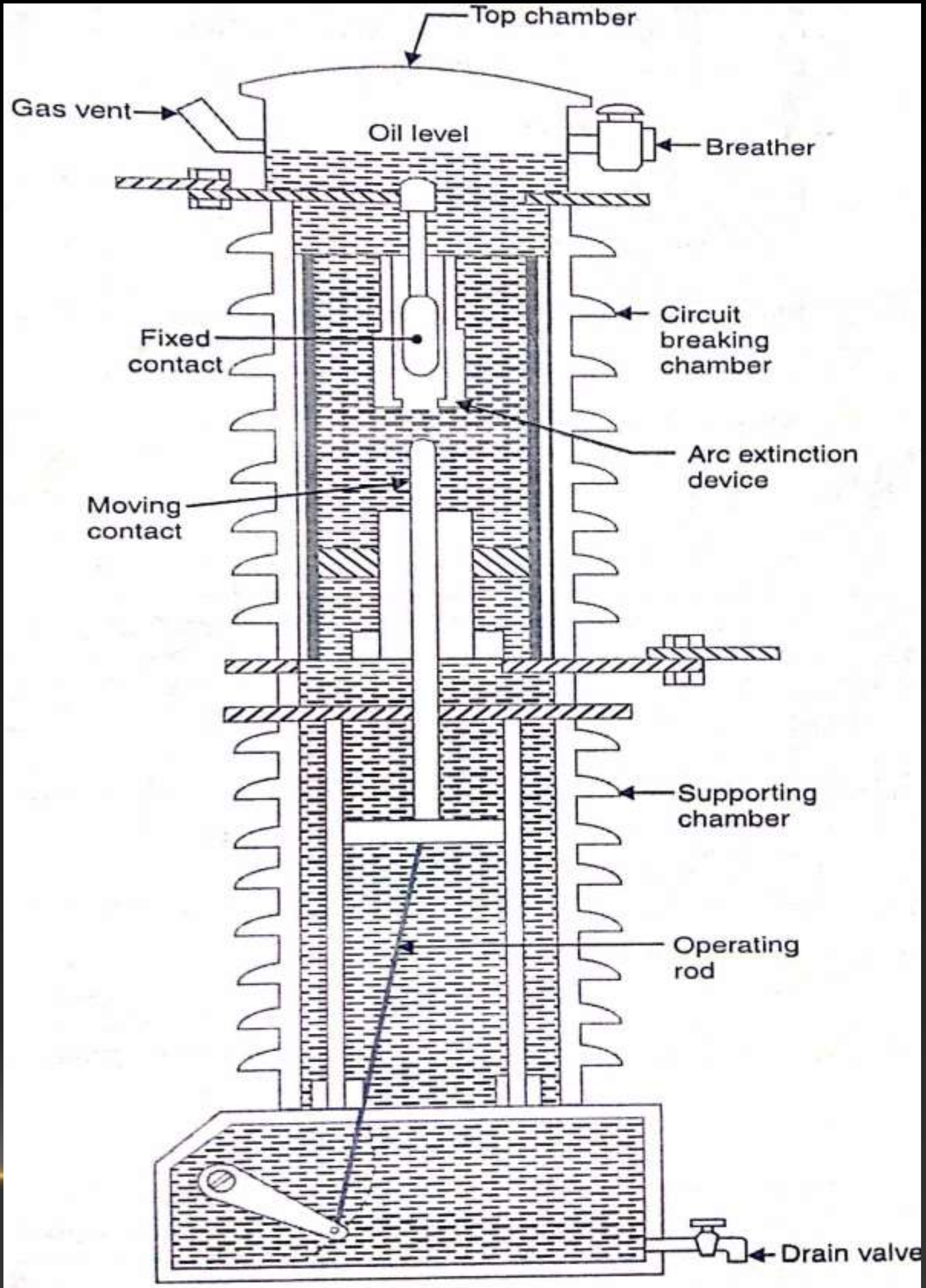


Fig. 19.7 Low-oil Circuit Breaker

Advantages:

- It requires lesser quantity of oil.
- It requires smaller space.
- There is reduced risk of fire.
- Maintenance problems are reduced.

Disadvantages:

- Due to smaller quantity of oil, the degree of carbonization is increased.
- There is a difficulty of removing the gases from the contact space in time.
- The dielectric strength of the oil deteriorates rapidly due to high degree of carbonization.

SULPHUR HEXAFLOURIDE (SF6) CIRCUIT BREAKERS

- In this circuit breakers, sulphur hexaflouride (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 dielectric strength to extinguish the arc.

Application

- The SF6 circuit breakers have been found to be very effective for high power and high voltage service

CINSTRUCTION

- It consists of fixed and moving contacts enclosed in a arc interruption chamber containing SF6 gas.

- This chamber is connected to SF6 gas reservoir.

- Under abnormal conditions the contacts of breaker 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.

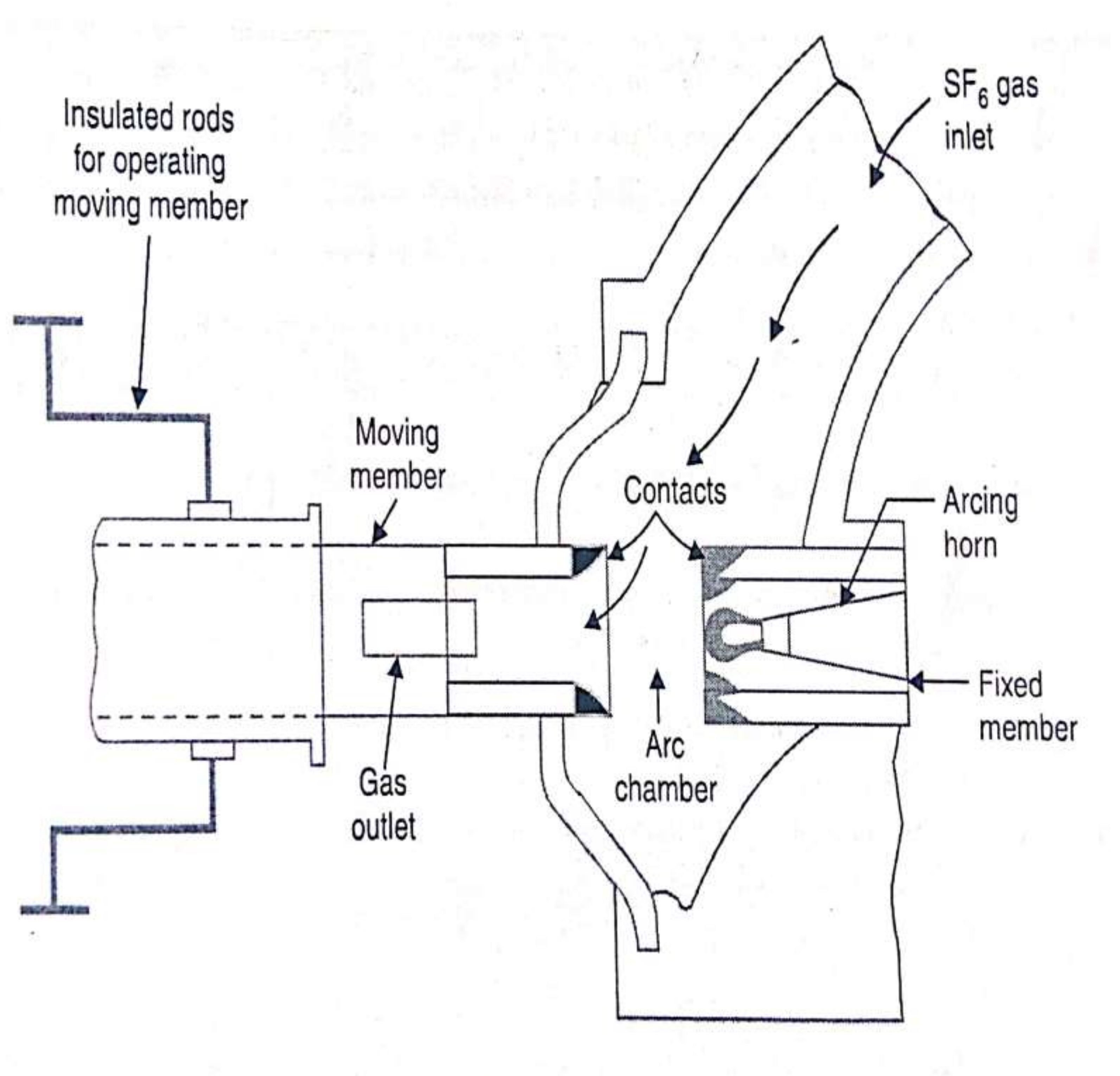


Fig. 19.11 typical SF6 circuit breaker

CINSTRUCTION

- 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 fixed contact, moving contact and arcing horn are coated with copper-tungsten arc resistant material.

- Since SF6 gas is costly, it is reconditioned and reclaimed by suitable auxiliary system after each operation of the breaker.

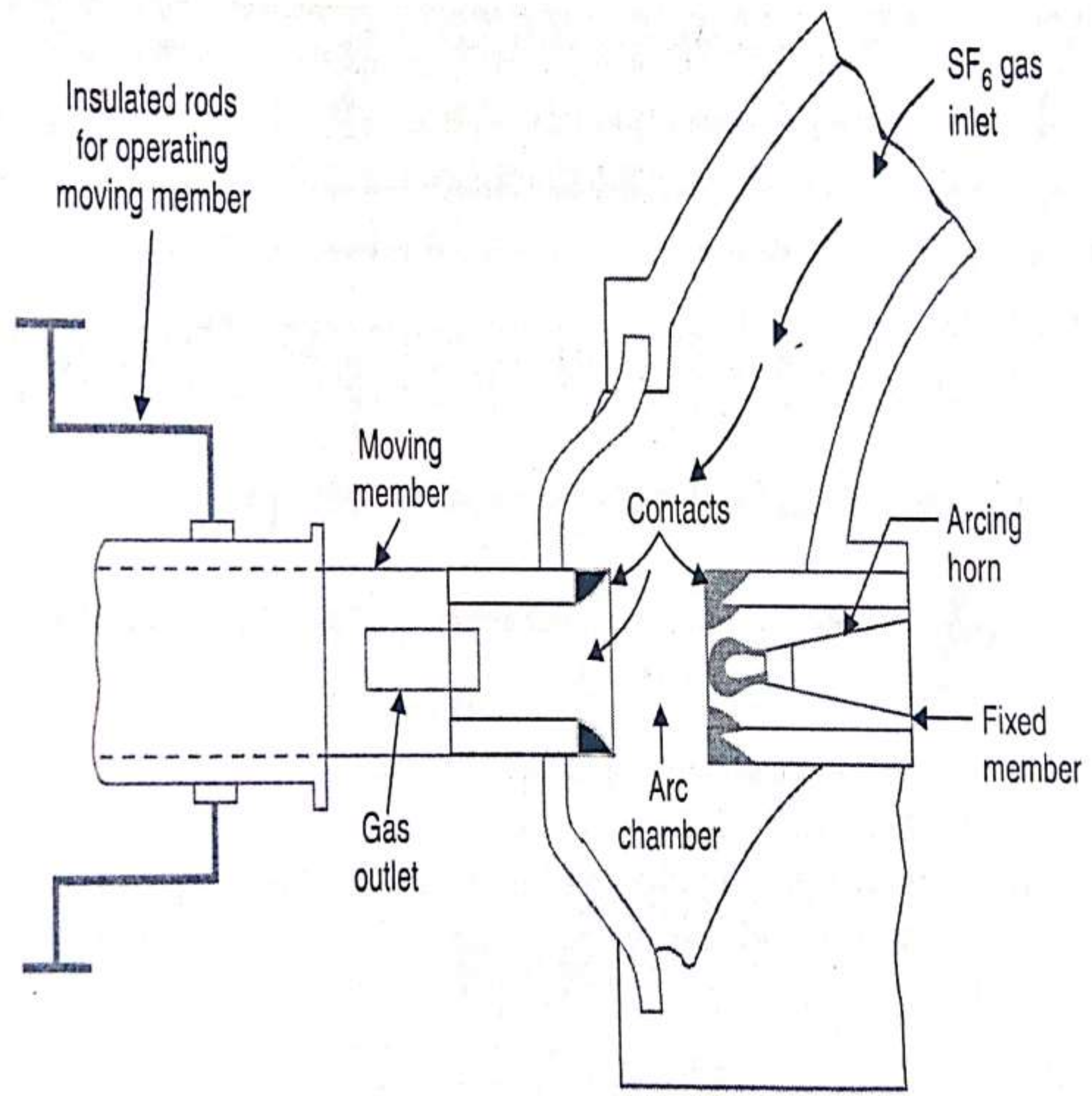


Fig. 19.11 typical SF6 circuit breaker

WORKING

- Under normal conditions the breaker contacts are in closed position, the contacts remain surrounded by SF6 gas at a pressure of about 2·8 kg/cm2 .

- Under abnormal conditions 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/cm2 pressure from the reservoir to the arc interruption chamber.

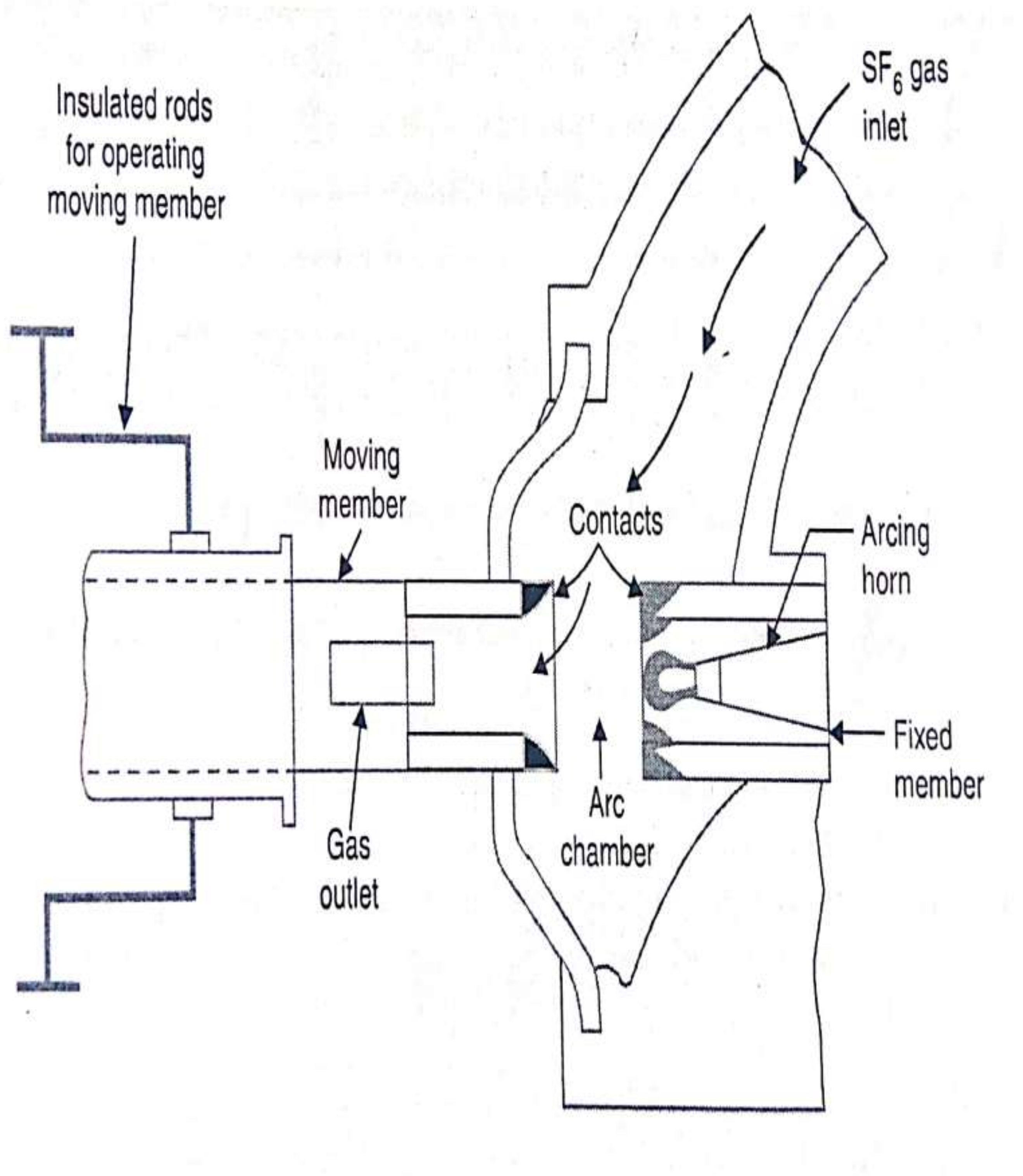


Fig. 19.11

WORKING

CONCLUSION

- The high pressure flow of SF6 rapidly absorbs the free electrons in the arc path to form immobile negative ions.
- 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 the valve is closed by the action of a set of springs

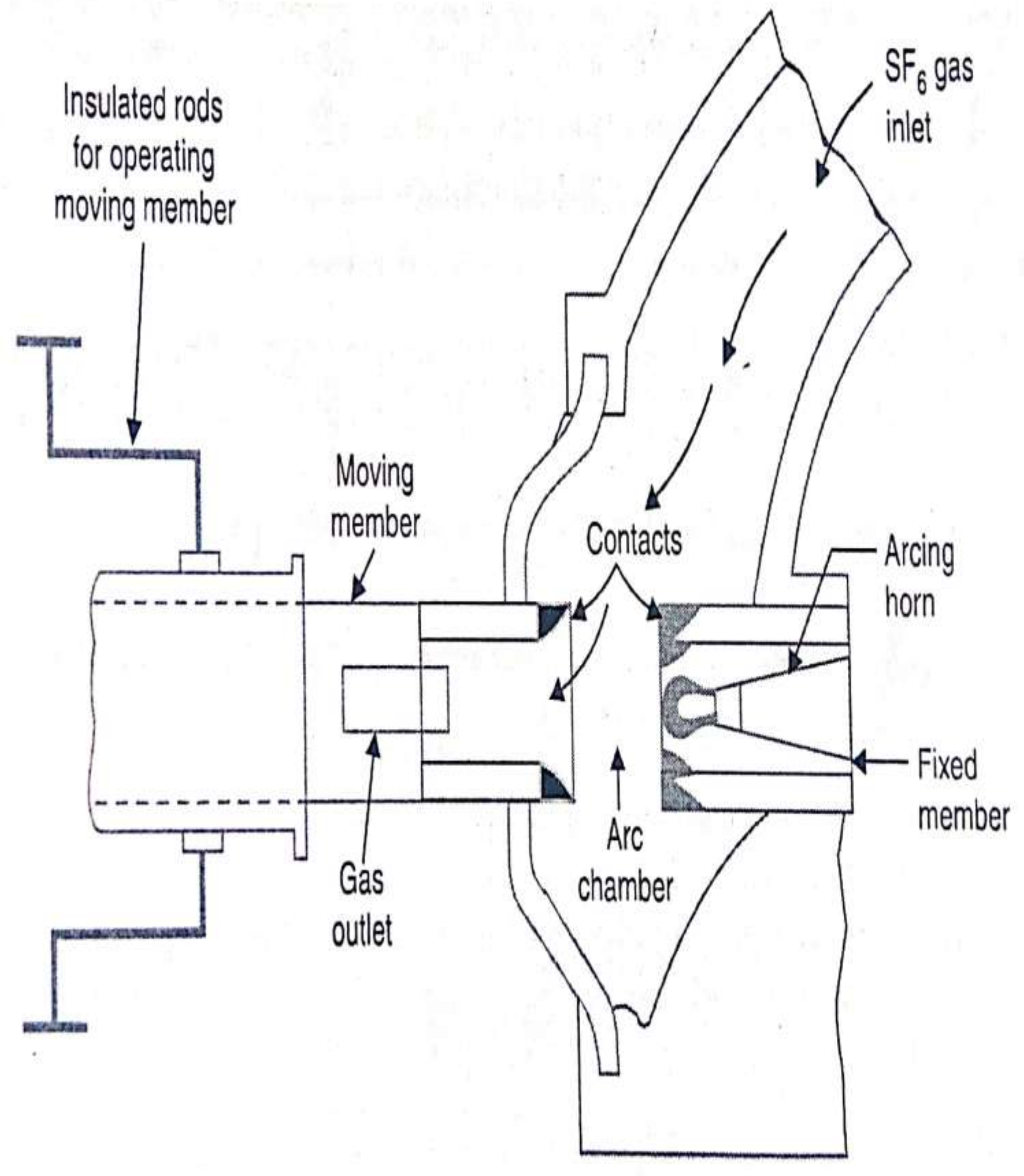


Fig. 19.11

Advantages:

- Due to the superior arc quenching property of SF6, such circuit breakers have very short arcing time.

- The dielectric strength of SF6 gas is 2 to 3 times that of air, such breakers can interrupt much larger currents.

- The SF6 circuit breaker gives noiseless operation due to its closed gas circuit and no exhaust to atmosphere unlike the air blast circuit breaker.

- There is no risk of fire in such breakers because SF6 gas is non-inflammable.

- There are no carbon deposits so that tracking and insulation problems are eliminated.

- The SF6 breakers have low maintenance cost, light foundation requirements and minimum auxiliary equipment.

CONCLUSION

Disadvantages:

(i) SF6 breakers are costly due to the high cost of SF6.

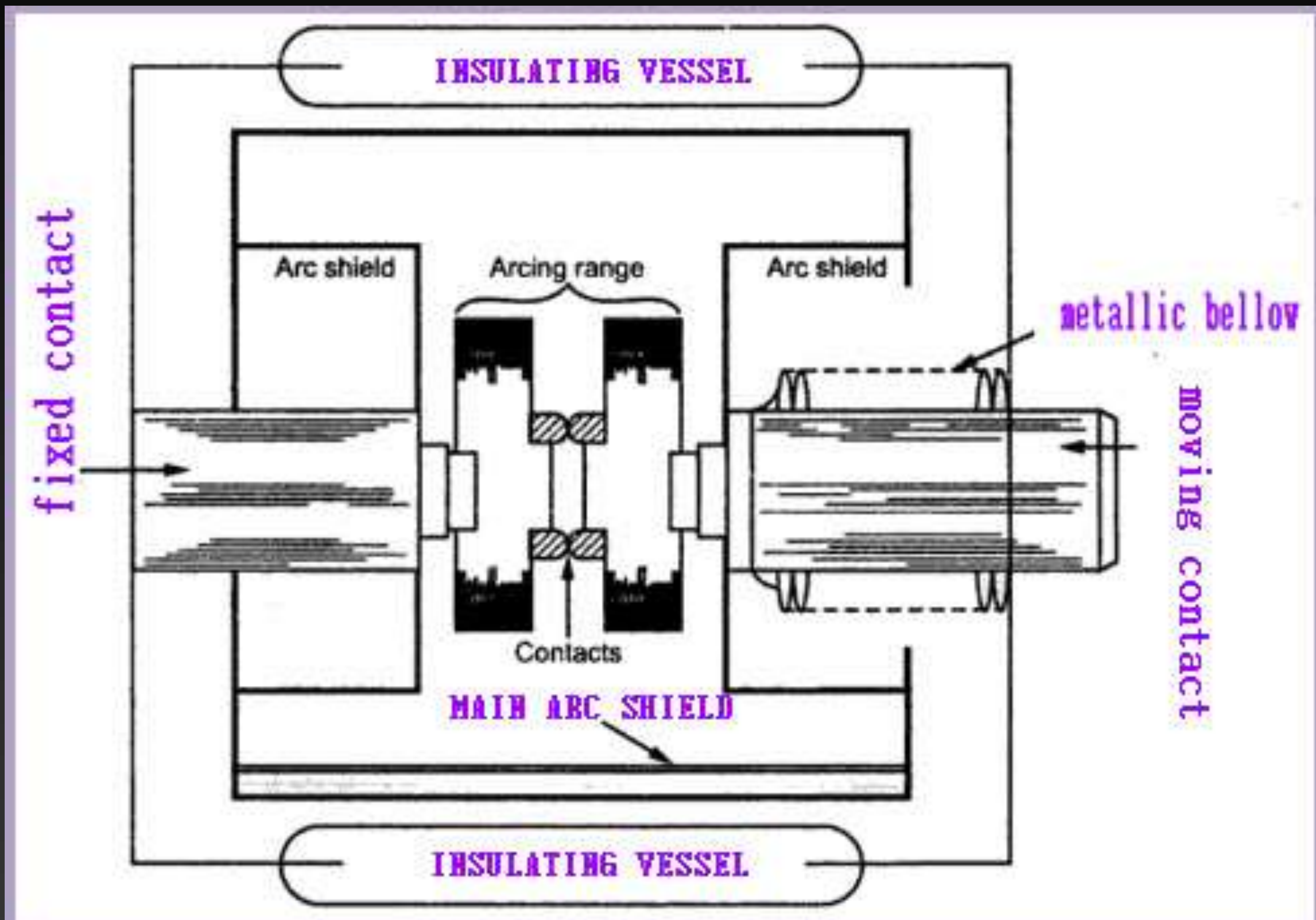
(ii) Since SF6 gas has to be reconditioned after every operation of the breaker, additional equipment is required for this purpose.

Applications

A typical SF6 circuit breaker consists of interrupter units each capable of dealing with currents upto 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 BREAKER(VCB)

- In this breakers, vacuum (degree of vacuum being in the range from 10−7 to 10−5 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.

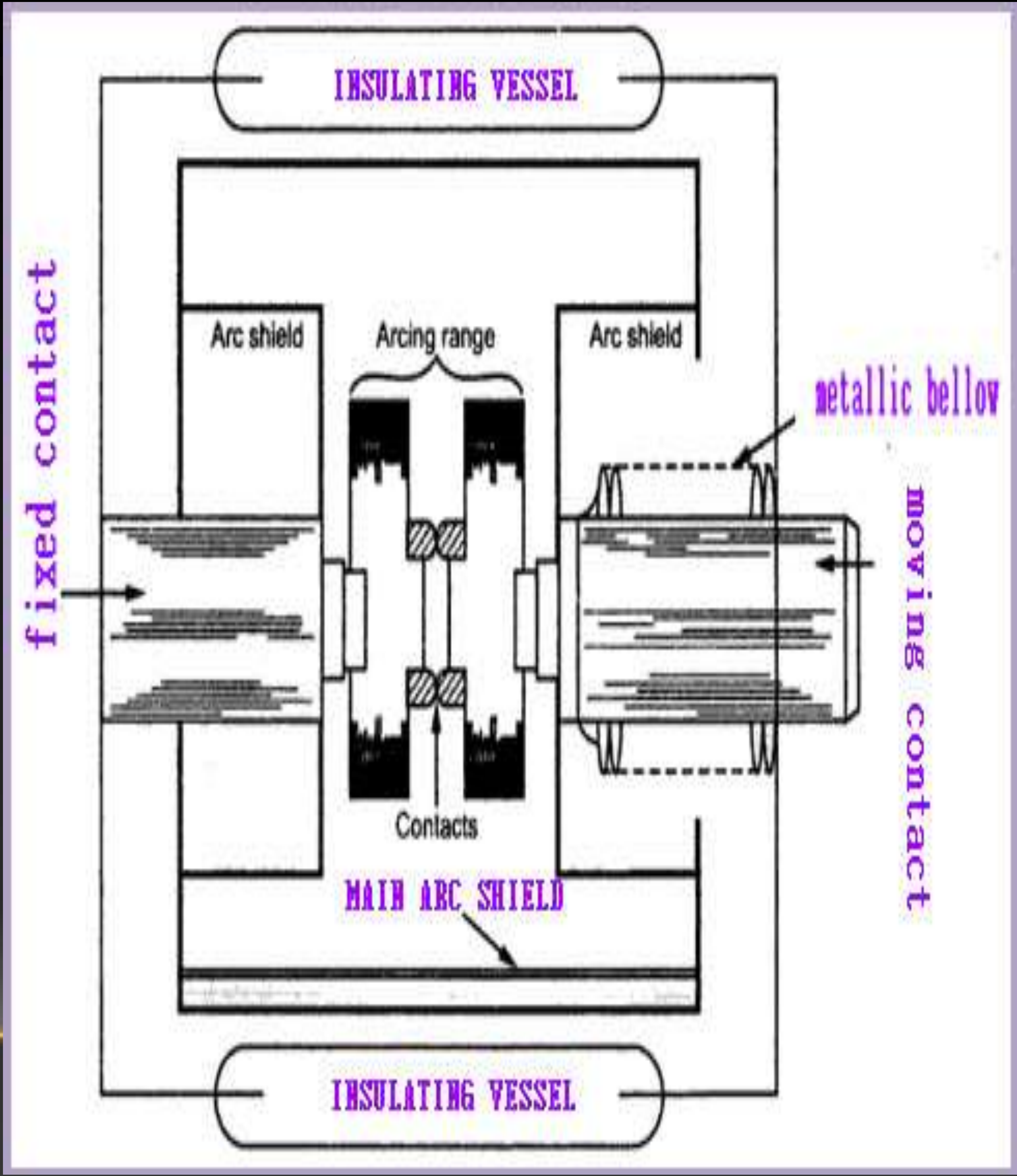


- When the contacts of breaker are opened in vacuum, the interruption occurs at first current zero with dielectric strength between the contacts building up at a rate thousands of times higher than that obtained with other circuit breakers.

VACUUM CIRCUIT BREAKER(VCB)

- The essential parts of a typical vacuum circuit breaker are as shown in fig.
- 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

CONSTRUCTION



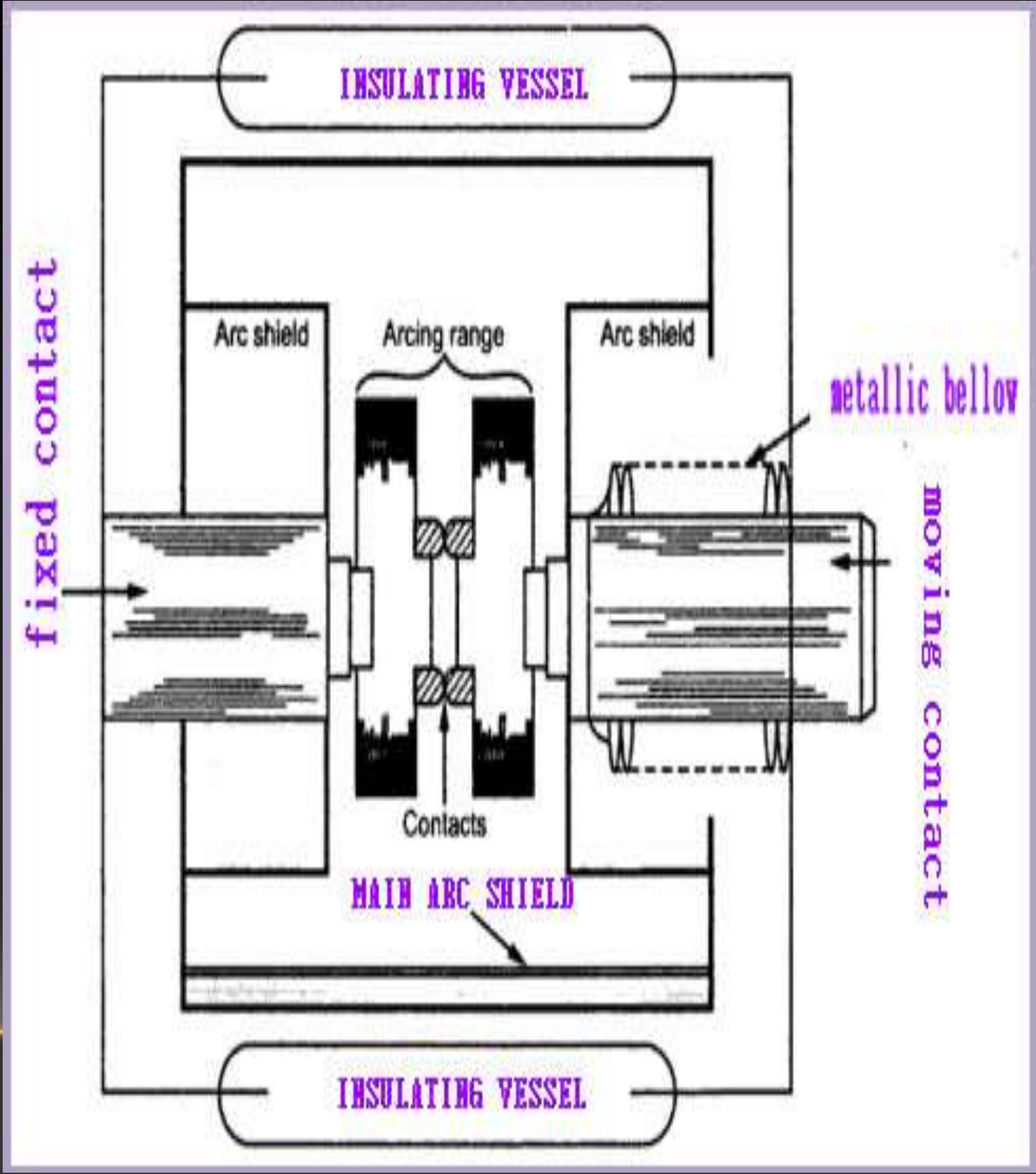
WORKING

✓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 ionisation 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).



ADVANTAGES

- They are compact, reliable and have longer life.
- There are no fire hazards.
- There is no generation of gas during and after operation.
- They can interrupt any fault current.
- They require little maintenance and are quiet in operation.
- They can successfully withstand lightning surges.
- They have low arc energy.

Applications

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.

CONSTRUCTION

- The essential components of a typical axial blast air circuit breaker are as shown in fig.
- 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.

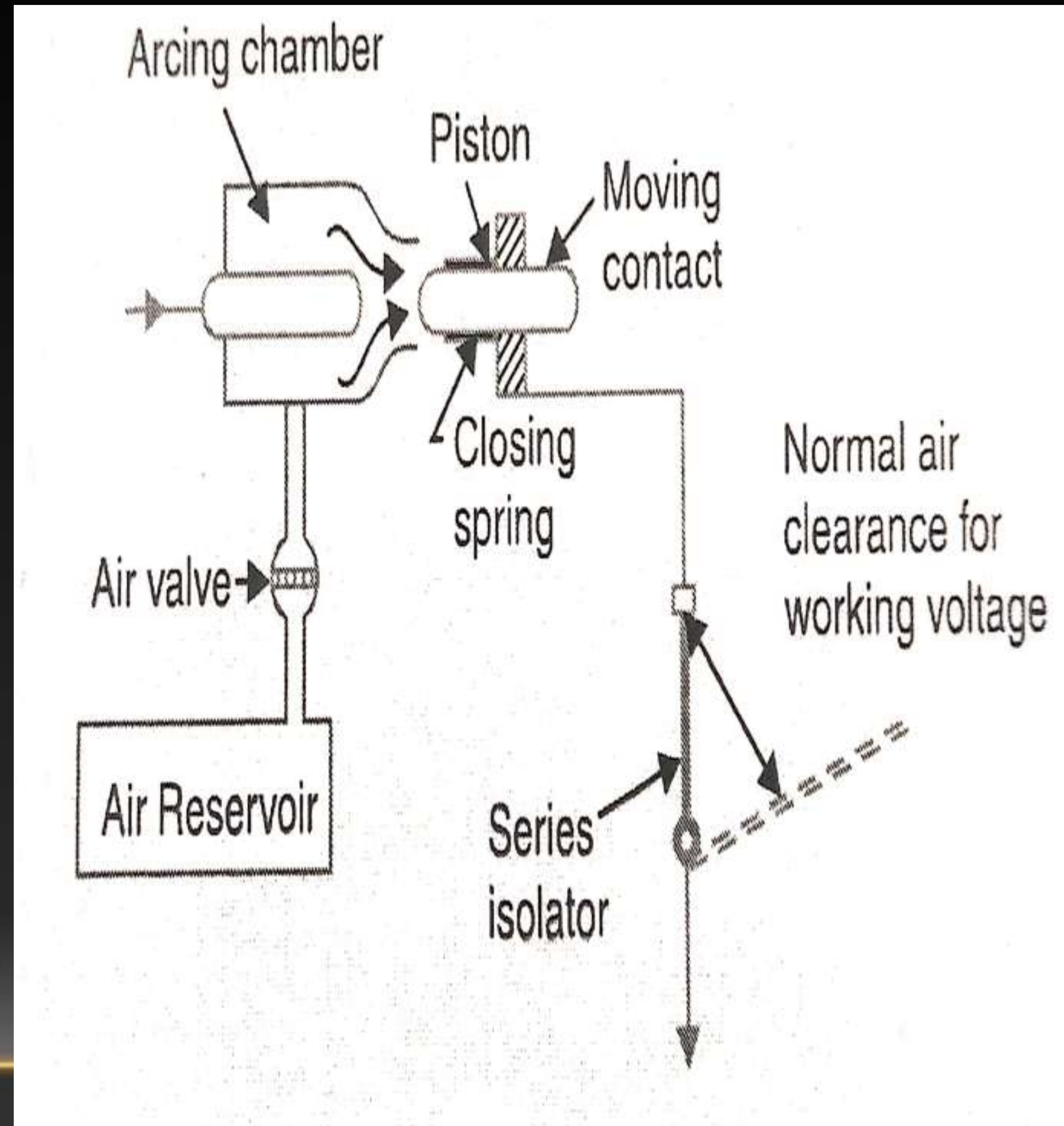


Fig. 19.9

OPERATION

✓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 ionised gases along with it. Consequently, the arc is extinguished and current flow is interrupted.

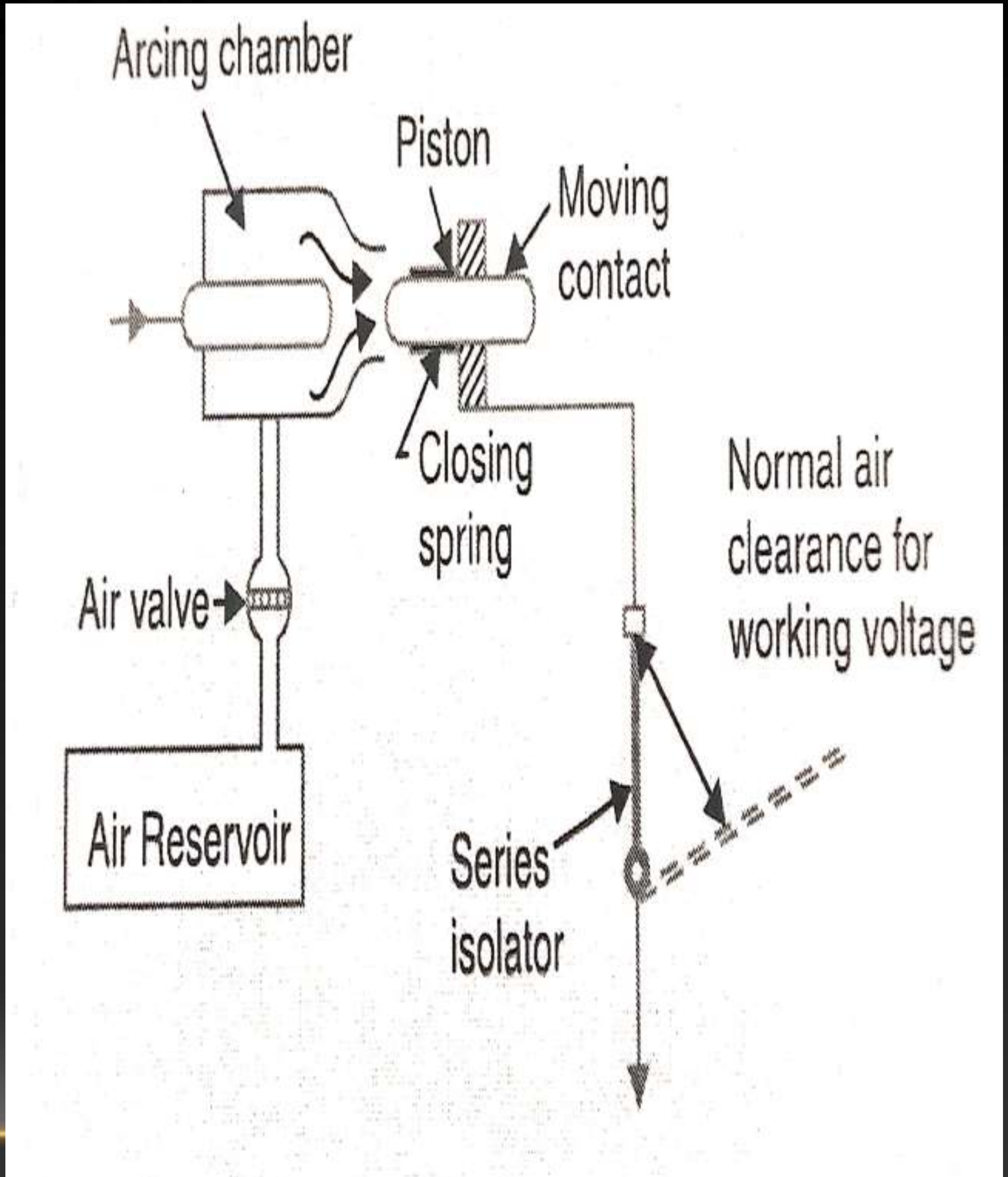


Fig. 19.9

2.CROSS-BLAST AIR CIRCUIT BREAKER

- The essential parts of a typical cross-blast air circuit breaker are as shown in fig.
- 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.
- 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

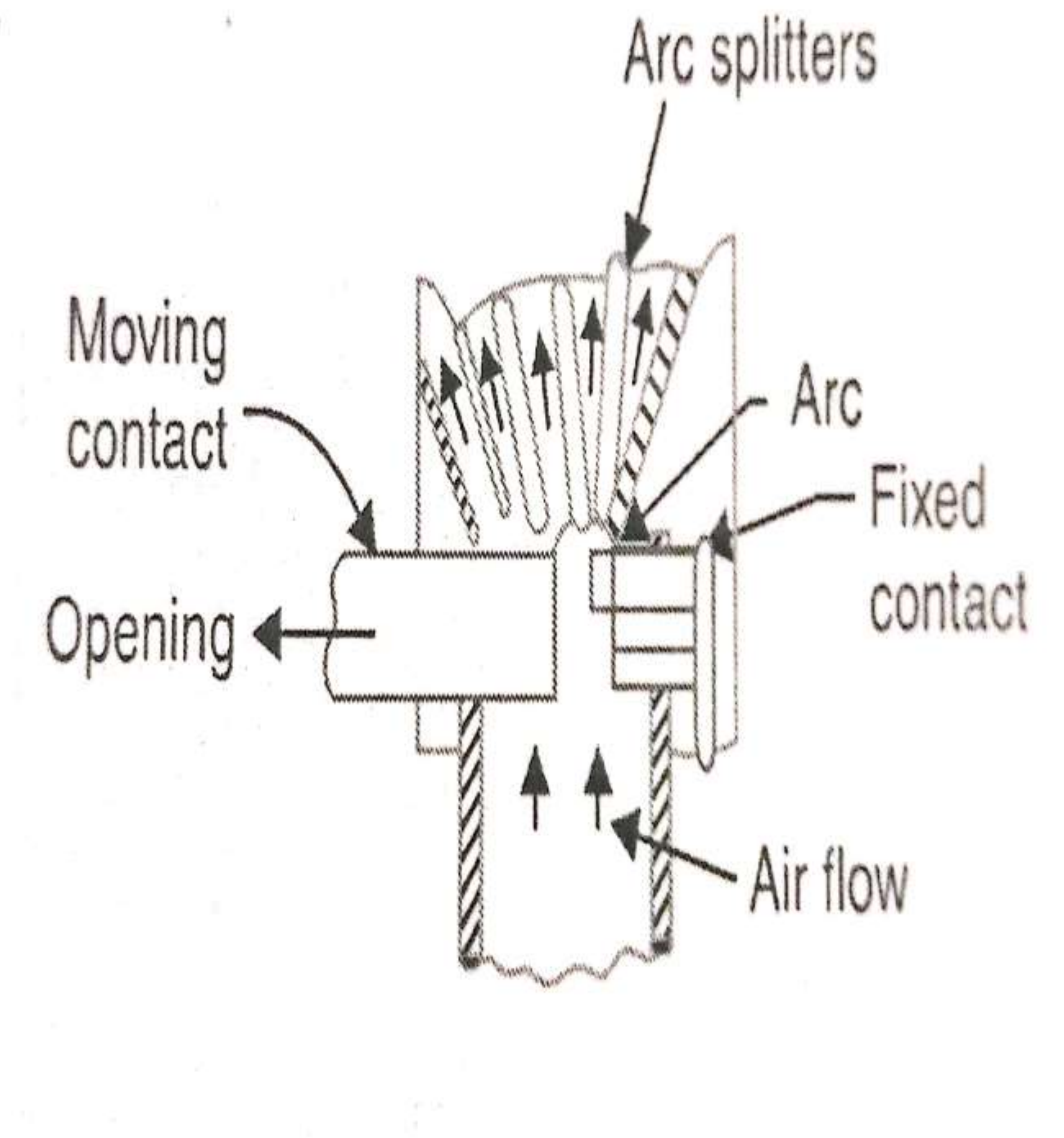


Fig. 19.10

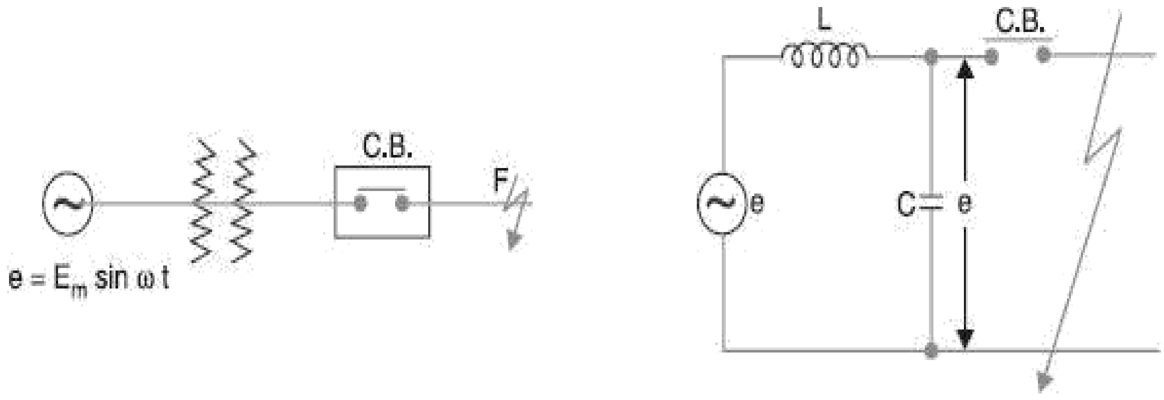
APPLICATION

The air blast circuit breakers are finding wide applications in high voltage installations. Majority of the circuit breakers for voltages beyond 110 kV are of this type.

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.



(i) (ii)

Fig. 19.17

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.

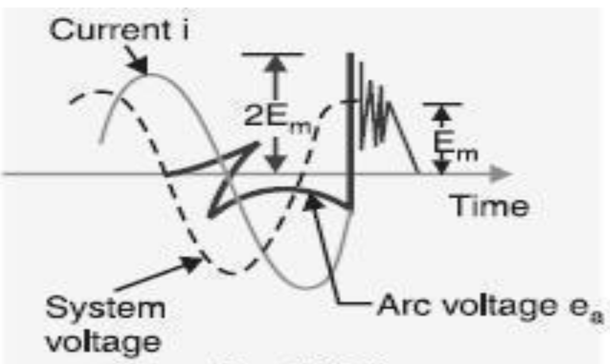


Fig. 19.18

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.

This LC combination form a series oscillatory circuit and voltage across capacitance which is restriking voltage rises and oscillates.

The natural frequency of oscillations is given by $f_n = 1/2\pi\sqrt{LC}$

The voltage across the capacitance which is the voltage across the contacts of the circuit breaker can be calculated in terms of L, C, f_n and system voltage. The mathematical expression for transient condition is as follows.

$E = L\,di/dt + 1/c\int i\,dt$

$i = dq/dt = d(CV_c)/dt$

$di/dt = d^2(CV_c)/dt^2 = Cd^2V_C/dt^2$

$E = LCd^2V_c/dt^2 + V_C$

$E/S = LCS^2V_C(S) + V_C(S)$

$E/S[LCS^2+1] = V_C(S)$

$V_C(S) = E/LCS[S^2+1/LC] = E\omega_n^2/S(S^2+\omega_n^2)$ where $\omega_n = 1/\sqrt{LC}$

Taking inverse laplace transform

$V_c(t) = E(1-\cos\omega_n t) = E(1-\cos 1/\sqrt{LC}\ t)$ = restriking voltage

The maximum value of restriking voltage = $dv_C(t)/dt=0$

$= 2E_{peak}$ = 2 X Peak value of system voltage

The rate of rise of restriking voltage (RRRV)

$= w_n E \sin w_n t$

The maximum value of RRRV= $w_n E = w_n E_{peak}$

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 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:

$$Li^2 = Cv^2 \Rightarrow v = i\sqrt{L/C}$$

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.

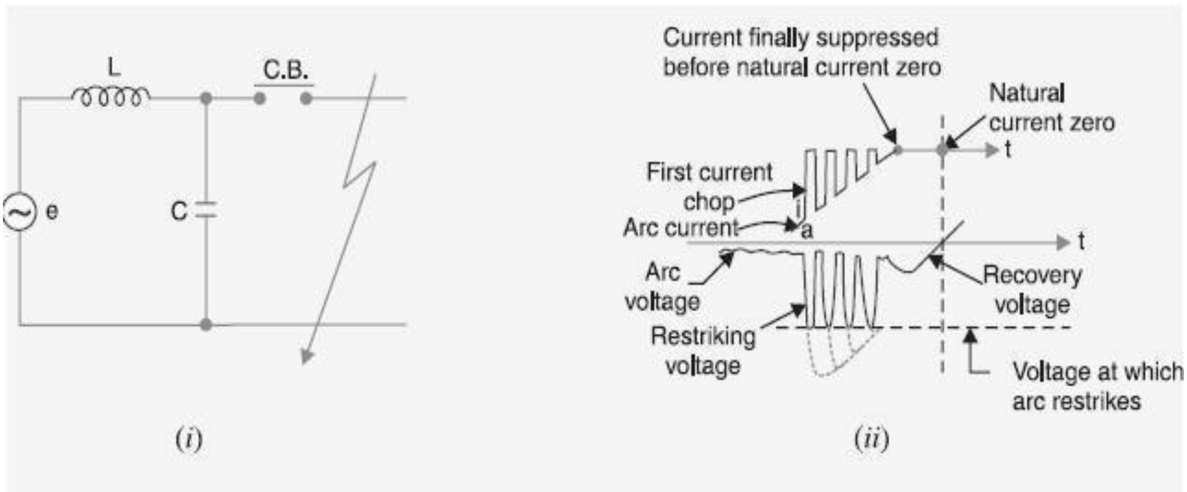


Fig. 19.19

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.

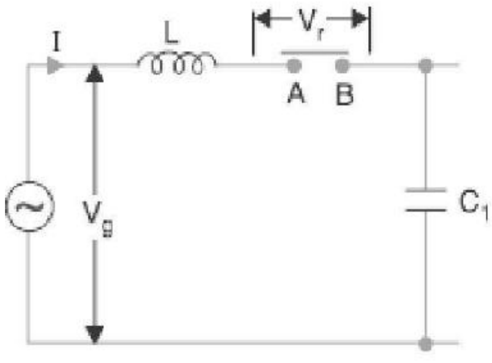


Fig. 19.20

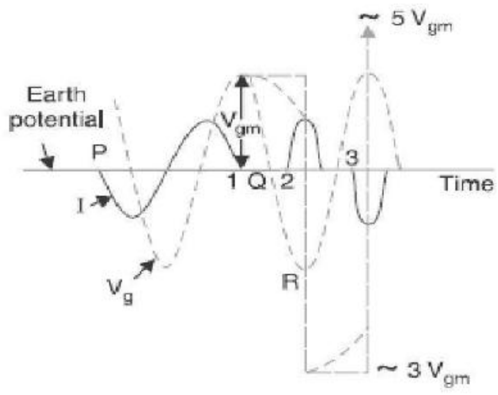


Fig. 19.21

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.

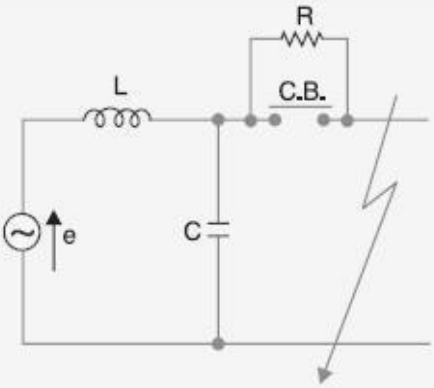


Fig. 19.22

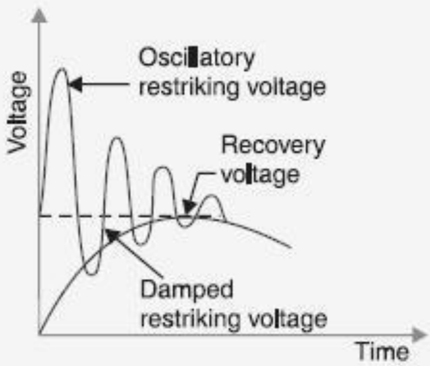


Fig. 19.23

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 voltage equation is given by

$$L\frac{di}{dt}+\frac{1}{C}\int i_C\,dt = E \quad \text{and} \quad i = i_c + i_R$$

Therefore, the above equation become

$$L\frac{d(i_c+i_R)}{dt}+v_c = E$$

or
$$L\frac{di_c}{dt}+L\frac{di_R}{dt}+v_c = E$$

$$i_c = \frac{dq}{dt} = \frac{d(Cv_c)}{dt}$$

Therefore,
$$\frac{di_c}{dt} = \frac{d^2(Cv_c)}{dt^2} = C\frac{d^2v_c}{dt^2}$$

$$\frac{di_R}{dt} = \frac{d(v_c/R)}{dt} = \frac{1}{R}\frac{dv_c}{dt}$$

Substituting these values in the main equation, we get

$$LC\frac{d^2v_c}{dt^2}+\frac{L}{R}\frac{dv_c}{dt}+v_c = E$$

Taking Laplace Transform, we get

$$LCS^2v_c(S)+\frac{L}{R}S\,v_c(S)+v_c(S) = \frac{E}{S}$$

Other terms are zero, as $v_c = 0$ at $t = 0$

or
$$LCv_c(S)\left[S^2+\frac{1}{RC}S+\frac{1}{LC}\right] = \frac{E}{S}$$

or
$$v_c(S) = \frac{E}{SLC\left[S^2+\frac{1}{RC}S+\frac{1}{LC}\right]}$$

For no transient oscillation, all the roots of the equation should be real. One root is zero, i.e. $S = 0$ which is real. For the other two roots to be real, the roots of the quadratic equation in the denominator should be real. For this, the following condition should be satisfied.

$$\left[\left(\frac{1}{2RC}\right)^2-\frac{1}{LC}\right] \geq 0 \quad \text{or} \quad \frac{1}{4R^2C^2} \geq \frac{1}{LC}$$

or
$$\frac{4}{LC} \leq \frac{1}{R^2C^2} \quad \text{or} \quad R^2 \leq \frac{LC}{4C^2}$$

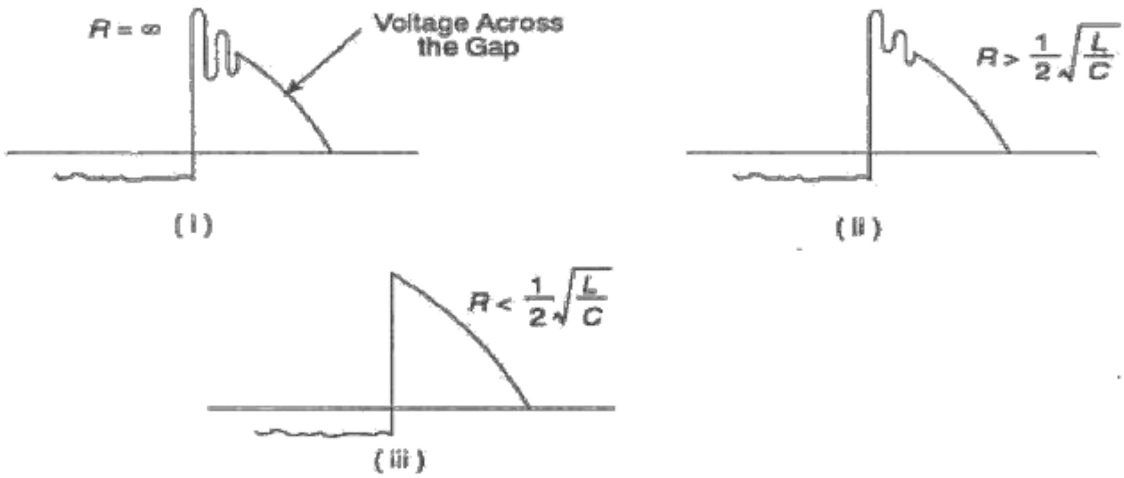


FIGURE 9.9 Transient oscillations for different values of R

or $$R^2 \leq \frac{1}{4} \cdot \frac{L}{C} \quad \text{or} \quad R \leq \frac{1}{2}\sqrt{\frac{L}{C}}$$

Therefore, if the value of the resistance connected across the contacts of the circuit breaker is equal to or less than $\frac{1}{2}\sqrt{L/C}$ there will be no transient oscillation. If $R > \frac{1}{2}\sqrt{L/C}$, there will be oscillation. $R = \frac{1}{2}\sqrt{L/C}$ is known as critical resistance. Figure 9.9 shows the transient conditions for three different values of R.

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:

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

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

UNIT II Electromagnetic, Static and Numerical Relays:

Basic Requirements of Relays – Primary and Backup protection - Construction details of – Attracted armature, balanced beam, inductor type and differential relays – Universal Torque equation – Characteristics of over current, Direction and distance relays. Static Relays – Advantages and Disadvantages – Definite time, Inverse and IDMT static relays – Comparators – Amplitude and Phase comparators. Microprocessor based relays – Advantages and Disadvantages – Block diagram for over current (Definite, Inverse and IDMT), Distance Relays, Impedance Relays and Reactance Relays with their Flow Charts.

Relay

Introduction :-

❖designed to trip a circuit breaker when a fault is detected.

❖ A relay may also be called an “electromagnetic switch”.

❖ Relays use a “low amperage circuit” to control a “high amperage circuit”.

RELAY

DEFINITION

A **protective relay** is a device that detects the fault and initiates the operation of the circuit breaker to isolate the defective element from the rest of the system.

- The relays detect the abnormal conditions in the electrical circuits by constantly measuring the electrical quantities which are different under normal and fault conditions.

- The electrical quantities which may change under fault conditions are voltage, current, frequency and phase angle.

- Through the changes in one or more of these quantities, the faults signal their presence, type and location to the protective relays.

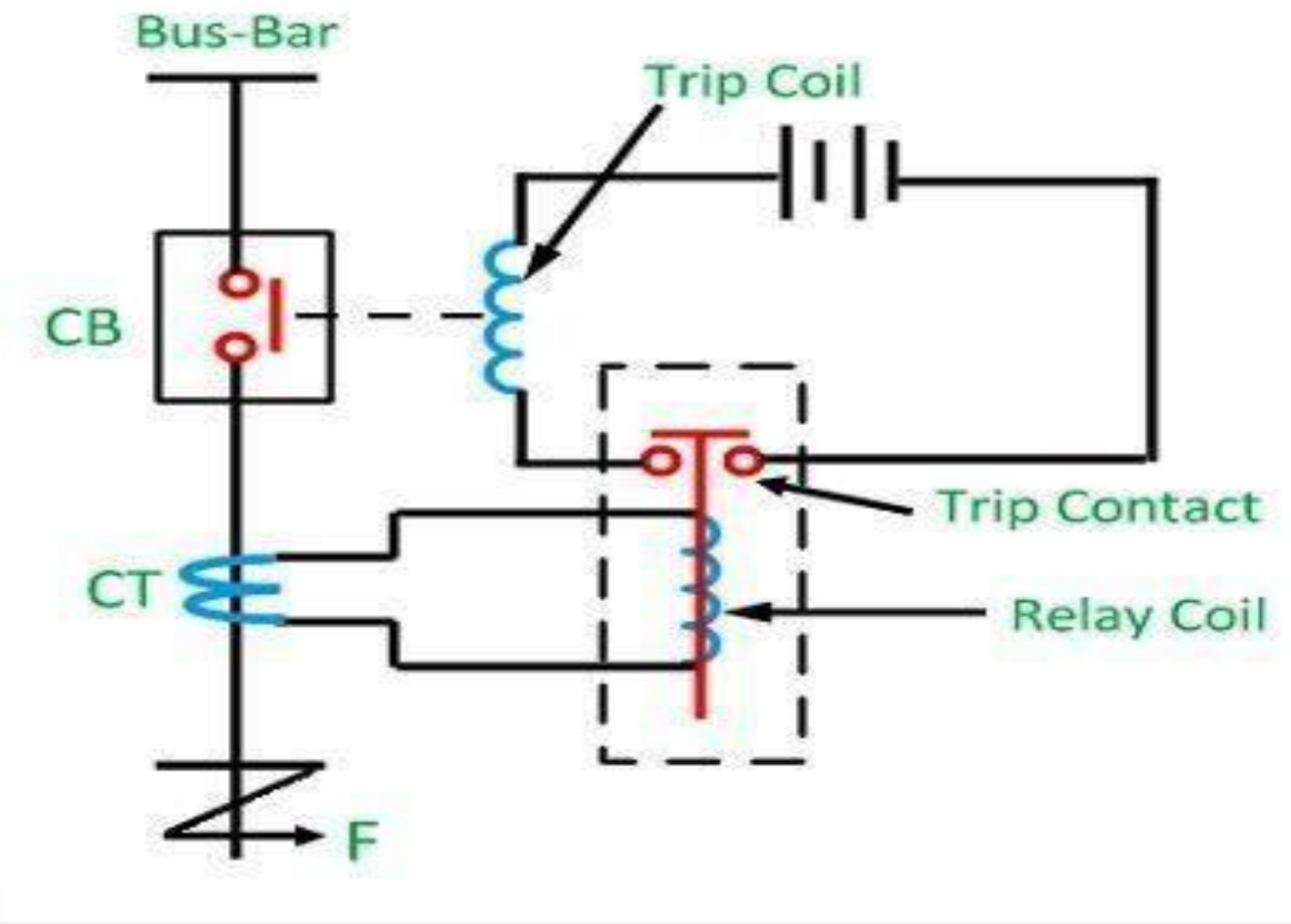


Fig: Typical relay circuit

The relay circuit can be divided into three parts :

- First part is the primary winding of a current transformer (C.T.) which is connected in series with the line to be protected.

- Second part consists of secondary winding of C.T. and the relay operating coil.

- Third part is the tripping circuit which may be either a.c or d.c. It consists of a source of supply, the trip coil of the circuit breaker and the relay stationary contacts.

OPERATION

- When a short circuit occurs at point F on the transmission line, the current flowing in the line increases to an enormous value.

- This results in a heavy current flow through the relay coil, causing the relay to operate by closing its contacts.

- This in turn closes the trip circuit of the breaker, making the circuit breaker open and isolating the faulty section from the rest of the system.

- In this way, the relay ensures the safety of the circuit equipment from damage and normal working of the healthy portion of the system.

Fundamental Requirements of Protective Relay

1. Selectivity
2. Speed
3. Sensitivity
4. Reliability
5. Simplicity
6. Economy

Selectivity: It is the ability of the protective system to select correctly that part of the system in trouble and disconnect the faulty part without disturbing the rest of the system.

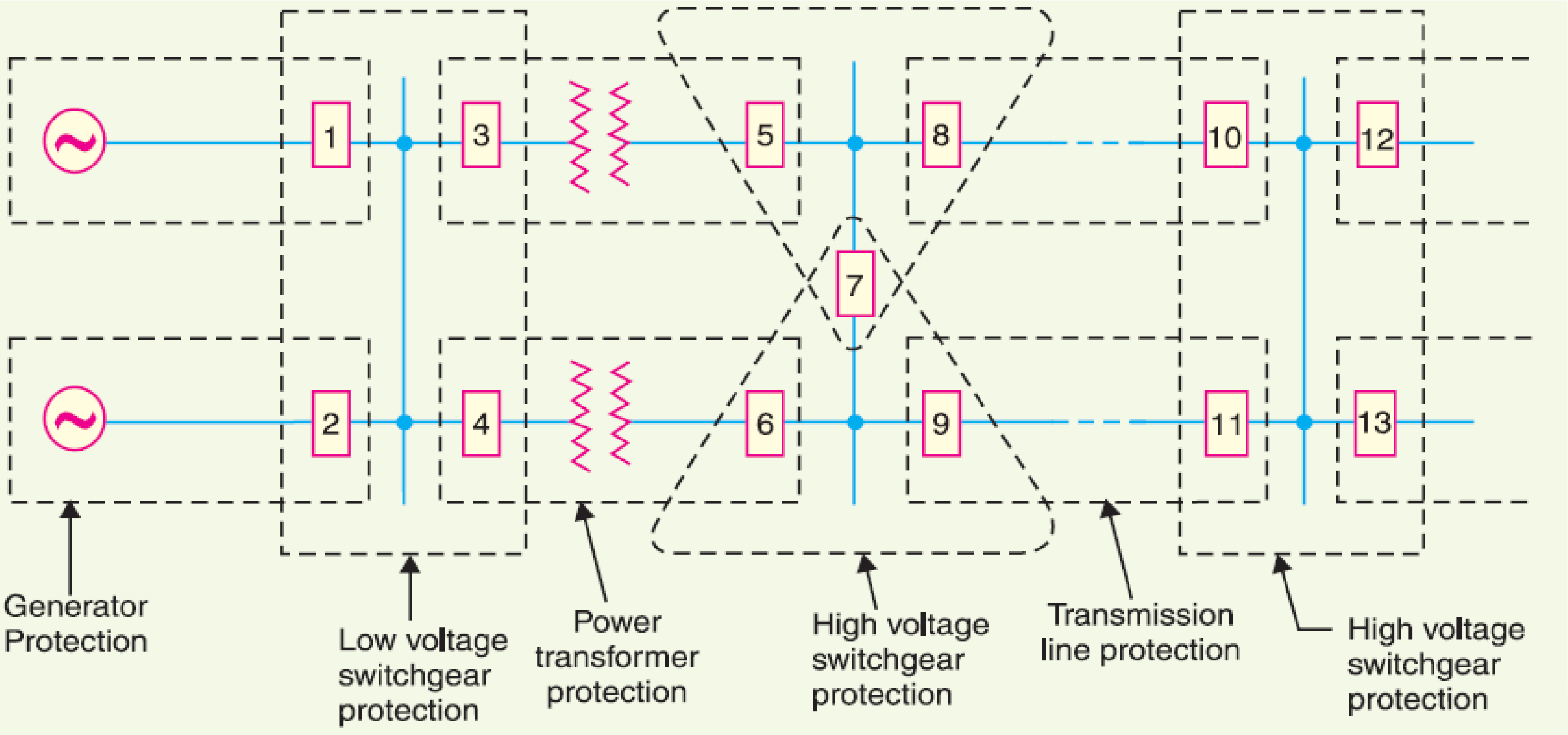


Fig. 21.2

Speed: The relay system should disconnect the faulty section as fast as possible for the following reasons

- ✓ Electrical apparatus may be damaged if they are made to carry the fault currents for a long time.

- ✓A failure on the system leads to a great reduction in the system voltage. If the faulty section is not disconnected quickly, then the low voltage created by the fault may shut down consumers motors and the generators on the system may become unstable.

- ✓The high speed relay system decreases the possibility of development of one type of fault into the other more severe type.

Sensitivity: It is the ability of the relay system to operate with low value of actuating quantity.

- Sensitivity of a relay is a function of the volt-amperes input to the coil of the relay necessary to cause its operation.

- The smaller the volt-ampere input required to cause relay operation, the more sensitive is the relay.

- A 1 VA relay is more sensitive than a 3 VA relay.

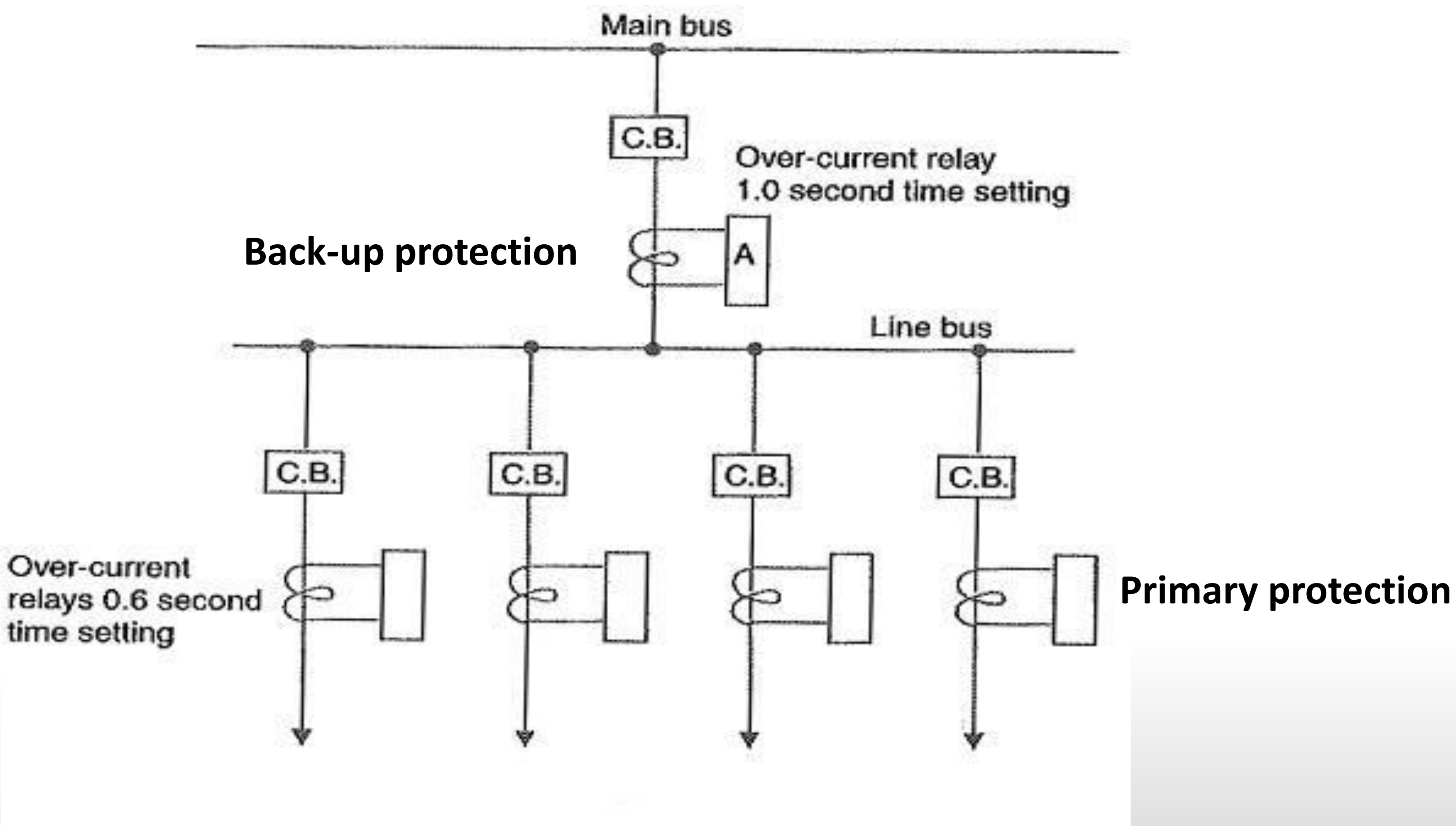
Reliability: It is the ability of the relay system to operate under the pre-determined conditions. Without reliability, the protection would be rendered largely ineffective and could even become a liability.

Simplicity: The relaying system should be simple so that it can be easily maintained.
Reliability is closely related to simplicity. The simpler the protection scheme, the greater will be its reliability.

Economy: The most important factor in the choice of a particular protection scheme is the economic aspect.
As a rule, the protective gear should not cost more than 5% of total cost. economic considerations are often subordinated to reliability.

TYPES OF PROTECTION

- Primary protection
- Back-up protection



Primary Protection

- The primary protection is also known as main protection and serves as the first line of defence.
- It is designed to protect the component parts of the power system.
- Each line has an over current relay and circuit breaker that protects the line.
- If a fault occurs on any line, it will be cleared by its relay and circuit breaker. This forms the primary or main protection and serves as the first line of defense.
- The service record of primary Relaying is very high with well over ninety percent of all operations being correct.
- Sometimes faults are not cleared by primary relay system because of trouble within the relay, wiring system or breaker. Under such conditions, back-up protection does the required job.

Back-up protection.

- It is the second line of defence in case of failure of the primary protection.
- It is designed to operate with sufficient time delay so that primary relaying will be given enough time to function if it is able to.
- Relay A provides back-up protection for each of the four lines.
- If a line fault is not cleared by its relay and breaker, the relay A on the group breaker will operate after a definite time delay and clear the entire group of lines.
- It is evident that when back-up relaying functions, a larger part is disconnected than when primary relaying functions correctly. Therefore, greater emphasis should be placed on the better maintenance of primary relaying.

Classifications :-

- According to ***Construction & Principle*** –

1. Electromagnetic Attraction relay
2. Electromagnetic Induction relay
3. Electro dynamic relay
4. Moving Coil relay
5. Thermal type relay
6. Static relay etc.

- According to ***Applications*** :-

1.Under V,Under I,Under P Relay

2.Over V, Over I,Over P Relay

3.Directional or Reverse Current Relay

4.Directional or Reverse Power Relay

5.Differential Relay

6.Distance Relay etc.

- According to ***Time of Operation*** :-

1.Instantaneous type Relay

2.Inverse type

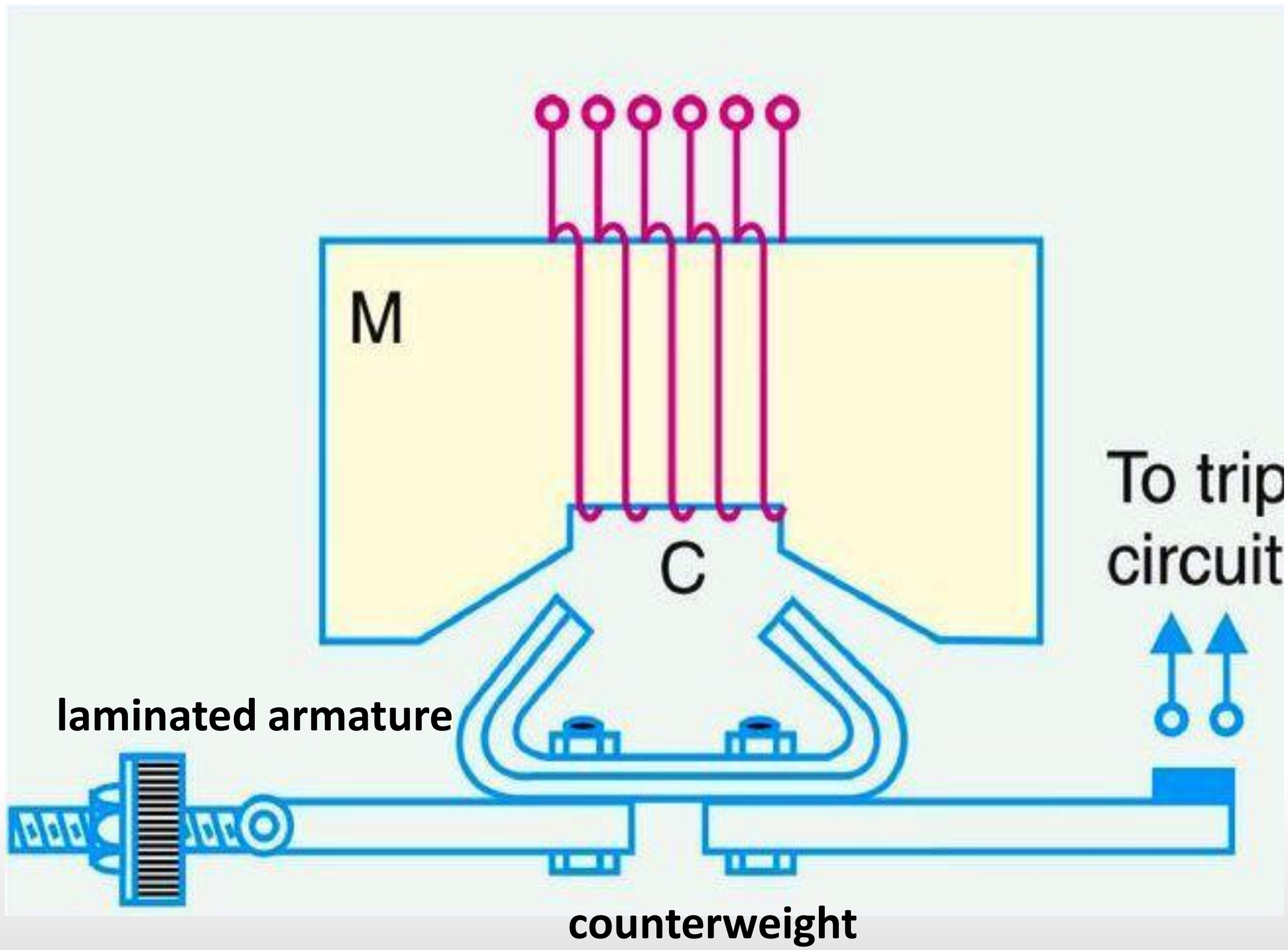
3.Very Inverse type Relay

4.IDMT Relay

5.Extremely inverse type Relay

Types Of Electromagnetic Attraction Relays

1.Electromagnetic attraction type relay



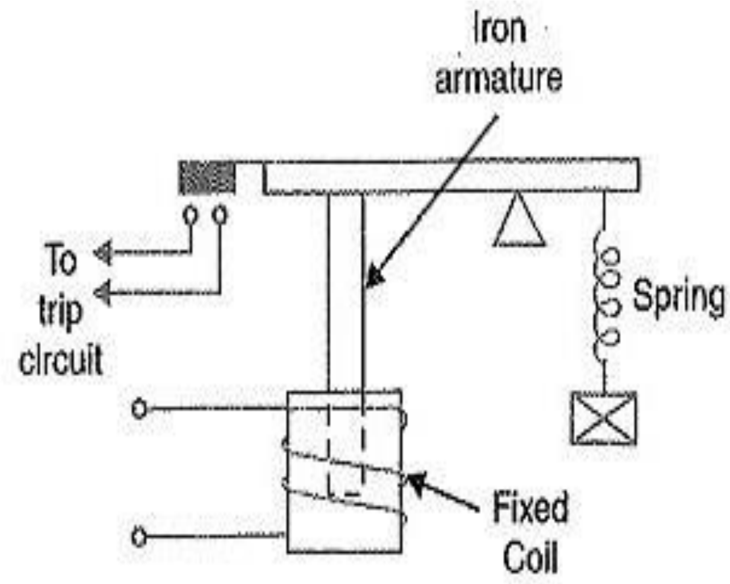
Construction: It consists of a laminated electromagnet M carrying a coil C and a pivoted laminated armature. The armature is balanced by a counterweight and carries a pair of spring contact fingers at its free end.

Operation: Under normal operating conditions, the current through the relay coil C is such that counterweight holds the armature in the position shown.

when a short-circuit occurs, the current through the relay coil increases sufficiently and the relay armature is attracted upwards. The contacts on the relay armature bridge a pair of stationary contacts attached to the relay frame. This completes the trip circuit which results in the opening of the circuit breaker and, therefore, in the disconnection of the faulty circuit.

Note: The minimum current at which the relay armature is attracted to close the trip circuit is called **pickup current**.

2.Balanced beam type relay

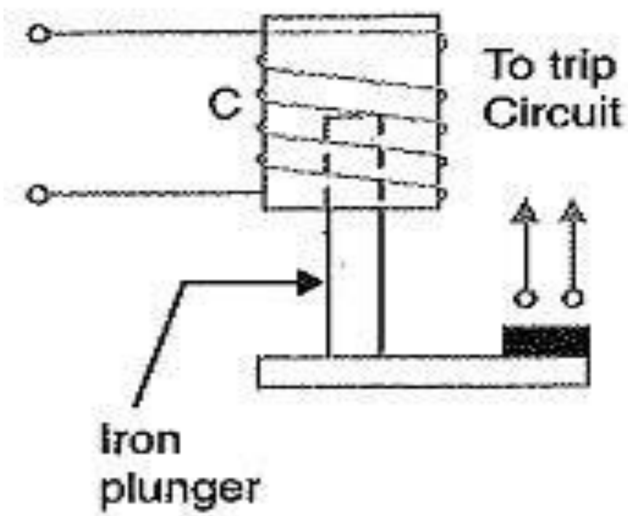


Construction: It consists of an iron armature fastened to a balance beam.

Operation: Under normal operating conditions, the current through the relay coil is such that the beam is held in the horizontal position by the spring.

However, when a fault occurs, the current through the relay coil becomes greater than the pickup value and the beam is attracted to close the trip circuit. This causes the opening of the circuit breaker to isolate the faulty circuit.

3.Solenoid type relay



Construction: It consists of a solenoid and movable iron plunger arranged as shown.

Operation: Under normal operating conditions, the current through the relay coil C is such that it holds the plunger by gravity or spring in the position shown.

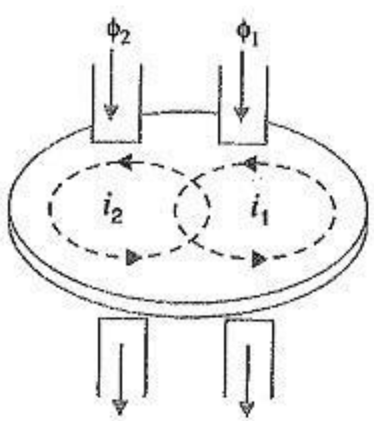
However, on the occurrence of a fault, the current through the relay coil becomes more than the pickup value, causing the plunger to be attracted to the solenoid. The upward movement of the plunger closes the trip circuit, thus opening the circuit breaker and disconnecting the faulty circuit.

2.ELECTROMAGNETIC INDUCTION RELAYS

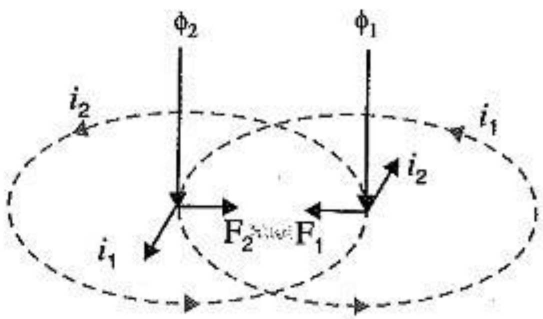
Construction: An induction relay essentially consists of a pivoted aluminium disc placed in two alternating magnetic fields of the same frequency but displaced in time and space.

Operation: Electromagnetic induction relays operate on the principle of induction motor. The torque is produced in the disc by the interaction of one of the magnetic fields with the currents induced in the disc by the other.

- These are used in a.c. circuits.



(i)



(ii)

Let

$$\phi_1 = \phi_{1max} \sin \omega t$$
$$\phi_2 = \phi_{2max} \sin (\omega t + \alpha)$$

where Ø1 and Ø2 are the instantaneous values of fluxes and Ø2leads Ø1by an angle α

$$i_1 \propto \frac{d\phi_1}{dt} \propto \frac{d}{dt}(\phi_{1max} \sin \omega t)$$
$$\propto \phi_{1max} \cos \omega t$$
$$i_2 \propto \frac{d\phi_2}{dt} \propto \phi_{2max} \cos (\omega t + \alpha)$$
$$F_1 \propto \phi_1 i_2 \quad \text{and} \quad F_2 \propto \phi_2 i_1$$

Fig (ii) shows that the two forces are in opposition.
∴ Net force F at the instant considered is

Fig (ii) shows that the two forces are in opposition.

∴ Net force F at the instant considered is

$$
\begin{aligned}
F &\propto F_2 - F_1 \\
&\propto \phi_2 i_1 - \phi_1 i_2 \\
&\propto \phi_{2max} \sin(\omega t + \alpha)\, \phi_{1max} \cos \omega t - \phi_{1max} \sin \omega t\, \phi_{2max} \cos(\omega t + \alpha) \\
&\propto \phi_{1max}\, \phi_{2max} [\sin(\omega t + \alpha) \cos \omega t - \sin \omega t \cos(\omega t + \alpha)] \\
&\propto \phi_{1max}\, \phi_{2max} \sin \alpha \\
&\propto \phi_1\, \phi_2 \sin \alpha \qquad \ldots(i)
\end{aligned}
$$

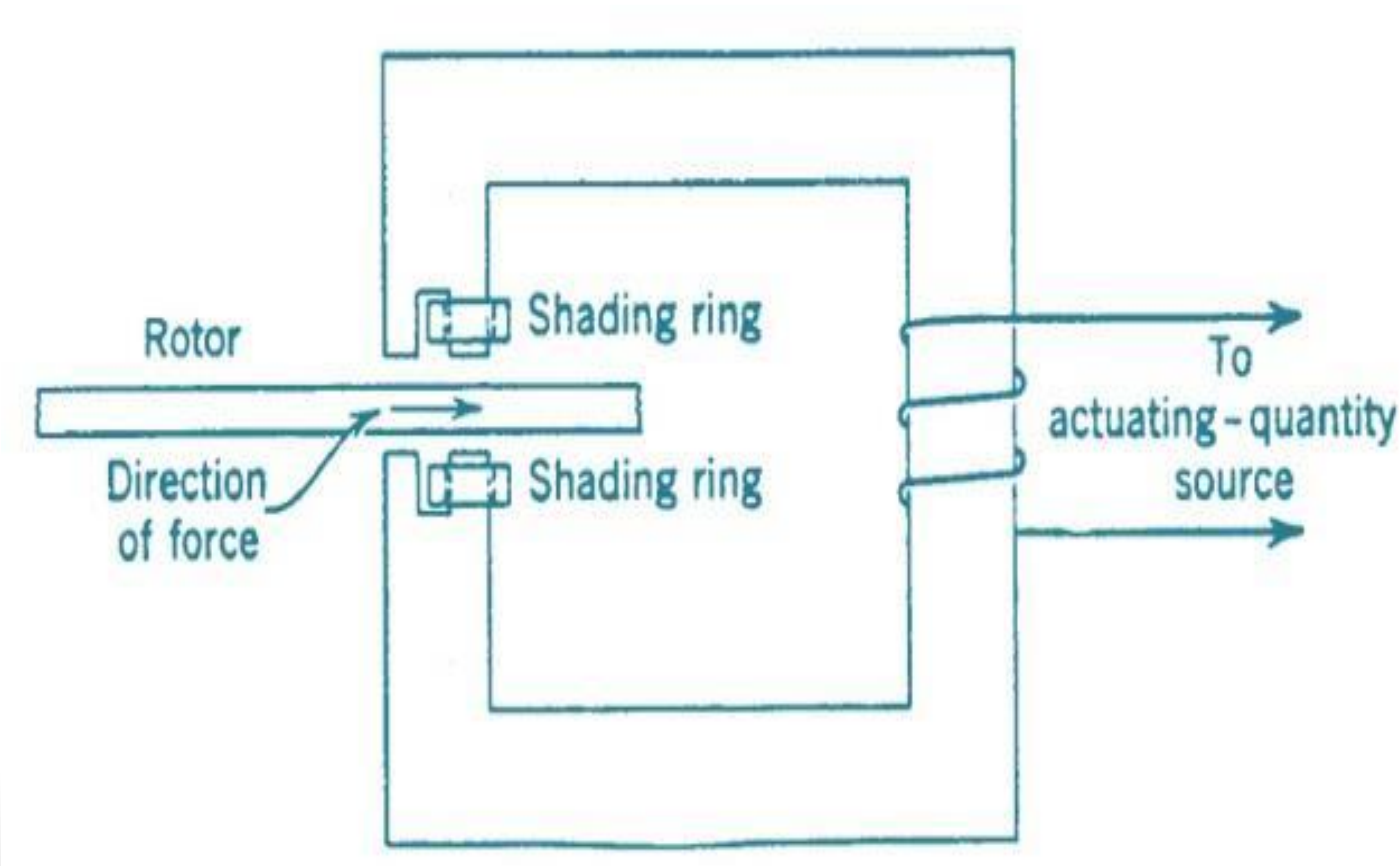
Conclusion:

- **The greater the phase angle α between the fluxes, the greater is the net force applied to the disc. Obviously, the maximum force will be produced when the two fluxes are 90 out of phase.**
- **The net force is the same at every instant.**
- **The direction of net force and hence the direction of motion of the disc depends upon which flux is leading.**

TYPES ELECTROMAGNETIC INDUCTION RELAYS

- Shaded-pole structure
- Watt-hour-meter or double winding structure
- Induction cup structure

1.Shaded-pole structure



Shaded pole structure Induction relay

- It consists of a pivoted aluminium disc free to rotate in the air-gap of an electromagnet.
- One half of each pole of the magnet is surrounded by a copper band known as shading ring.
- The alternating flux ϕs in the shaded portion of the poles will, owing to the reaction of the current induced in the ring, lag behind the flux ϕu in the unshaded portion by an angle α.
- These two a.c. fluxes differing in phase will produce the necessary torque to rotate the disc. As proved earlier, the driving torque T is given by

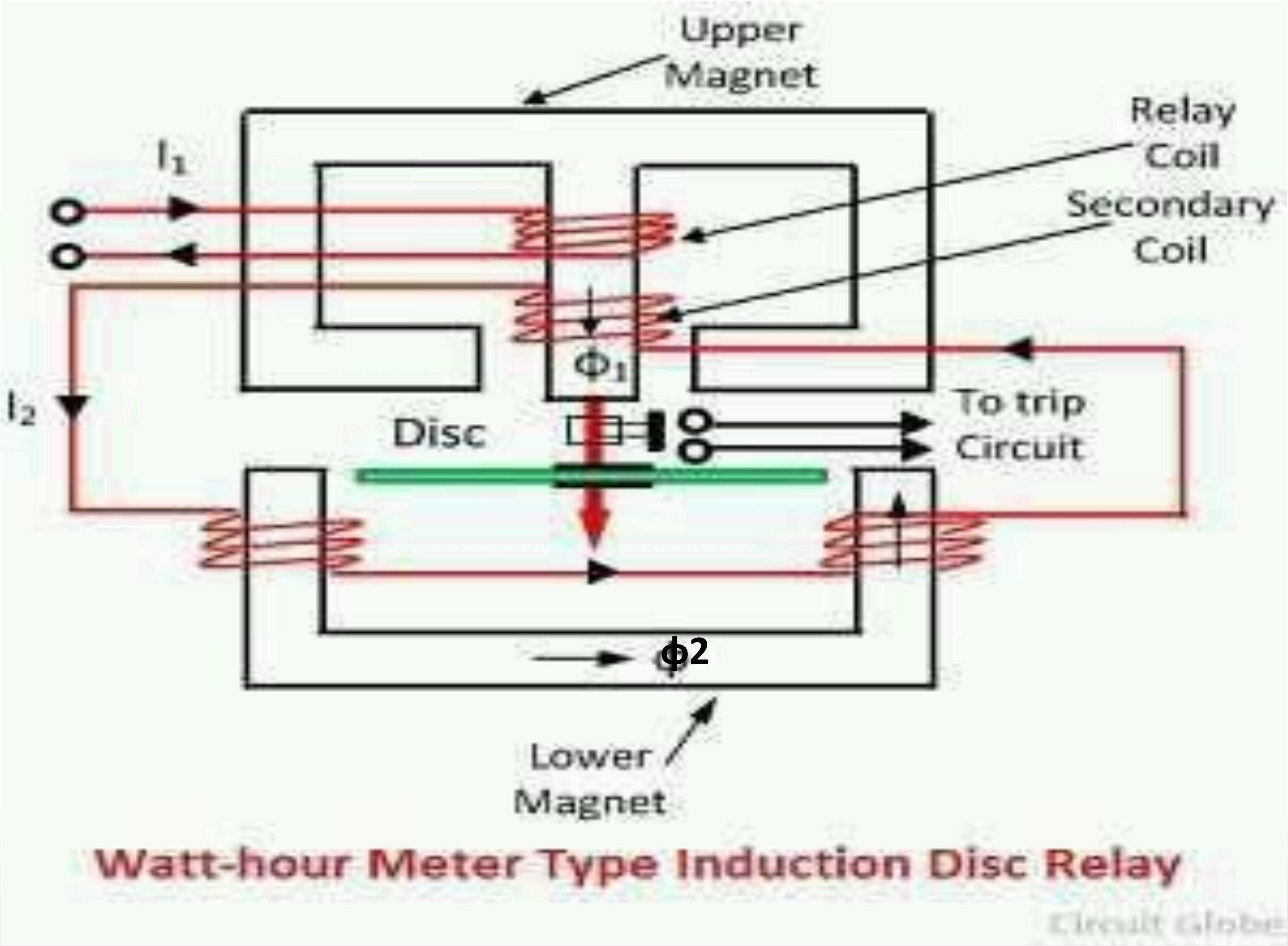
$$T \propto \phi_s \phi_u \sin \alpha$$

Assuming the fluxes ϕs and ϕu to be proportional to the current I in the relay coil,

$$T \propto I^2 \sin \alpha$$

- Driving torque is proportional to the square of current in the relay coil.

2.Watt-hour-meter or double winding structure



Construction: It consists of a pivoted aluminium disc arranged to rotate freely between the poles of two electromagnets.

The upper electromagnet carries two windings ; the primary and the secondary.

Lower electromagnet carries one winding which is connected in series with the secondary winding.

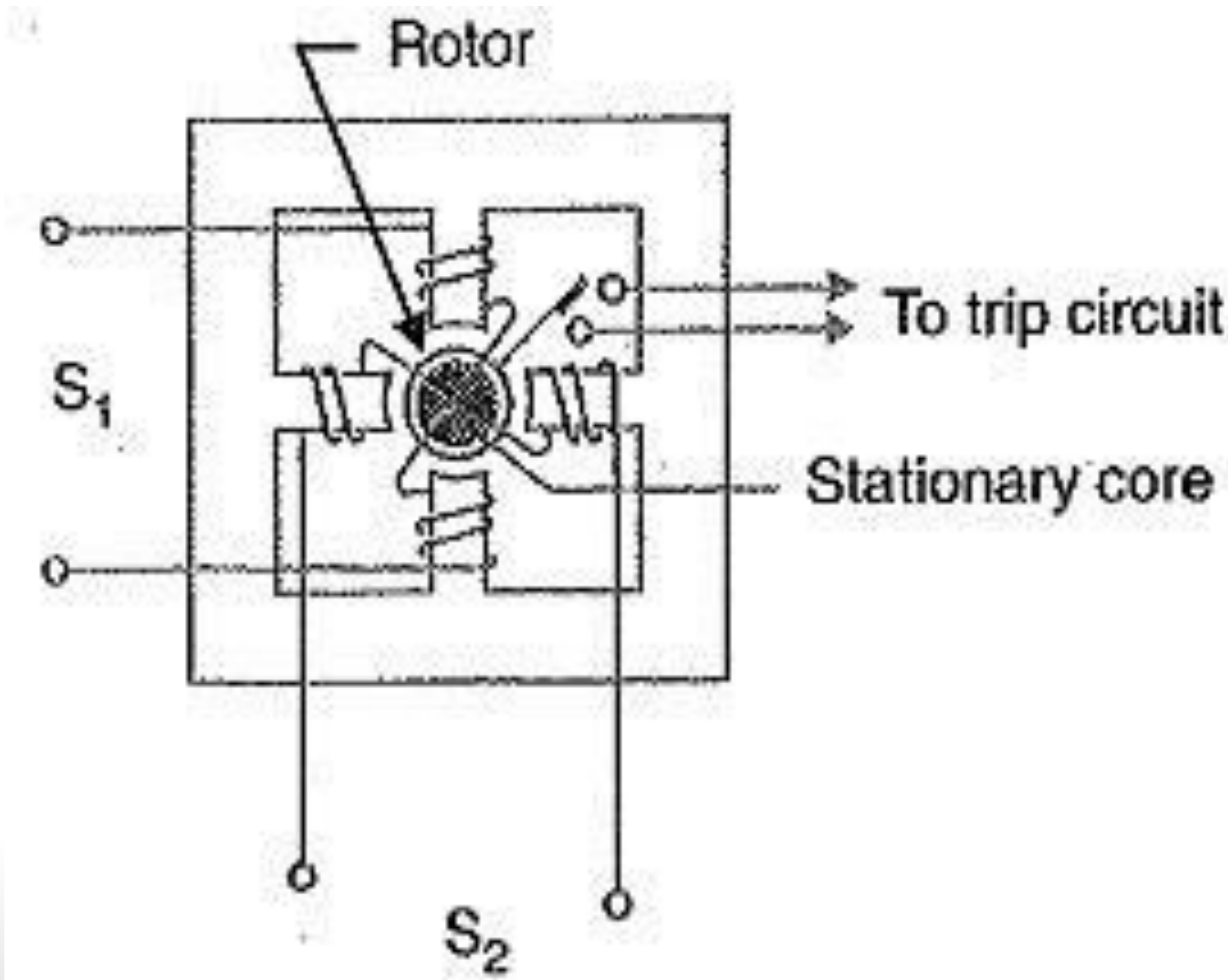
Operation: The primary winding carries the relay current I1 while the secondary winding is connected to the winding of the lower magnet.

The primary current induces e.m.f. in the secondary and so circulates a current I2 in it. The flux $\phi 2$ induced in the lower magnet by the current in the secondary winding of the upper magnet will lag behind $\phi 1$ by an angle α. The two fluxes $\phi 1$and $\phi 2$ differing in phase by α will produce a driving torque on the disc proportional to $\phi 1 \phi 2 \sin\alpha$.

$$T \alpha\ \phi 1 \phi 2 \sin\alpha$$

Important feature : Operation of relay can be controlled by opening or closing the secondary winding circuit. If this circuit is opened, no flux can be set by the lower magnet however great the value of current in the primary winding may be and consequently no torque will be produced. Therefore, the relay can be made inoperative by opening its secondary winding circuit.

3.Induction cup structure



Construction: It most closely resembles an induction motor, except that the rotor iron is stationary, only the rotor conductor portion being free to rotate. The moving element is a hollow cylindrical rotor which turns on its axis. The rotating field is produced by two pairs of coils wound on four poles as shown.

Operation: The rotating field induces currents in the cup to provide the necessary driving torque. If $\phi 1$ and $\phi 2$ represent the fluxes produced by the respective pairs of poles, then torque produced is proportional to $\phi 1 \phi 2 \sin \alpha$ where α is the phase difference between the two fluxes.

Important features :

- Induction cup structures are more efficient torque producers than either the shaded-pole or the watt-hour meter structures.
- Therefore, this type of relay has very high speed and may have an operating time less then 0·1 second.

Distance relay :-

1.IMPEDANCE RELAY

- +ve (operative)Torque by current element
- -ve(restraining)Torque by voltage element

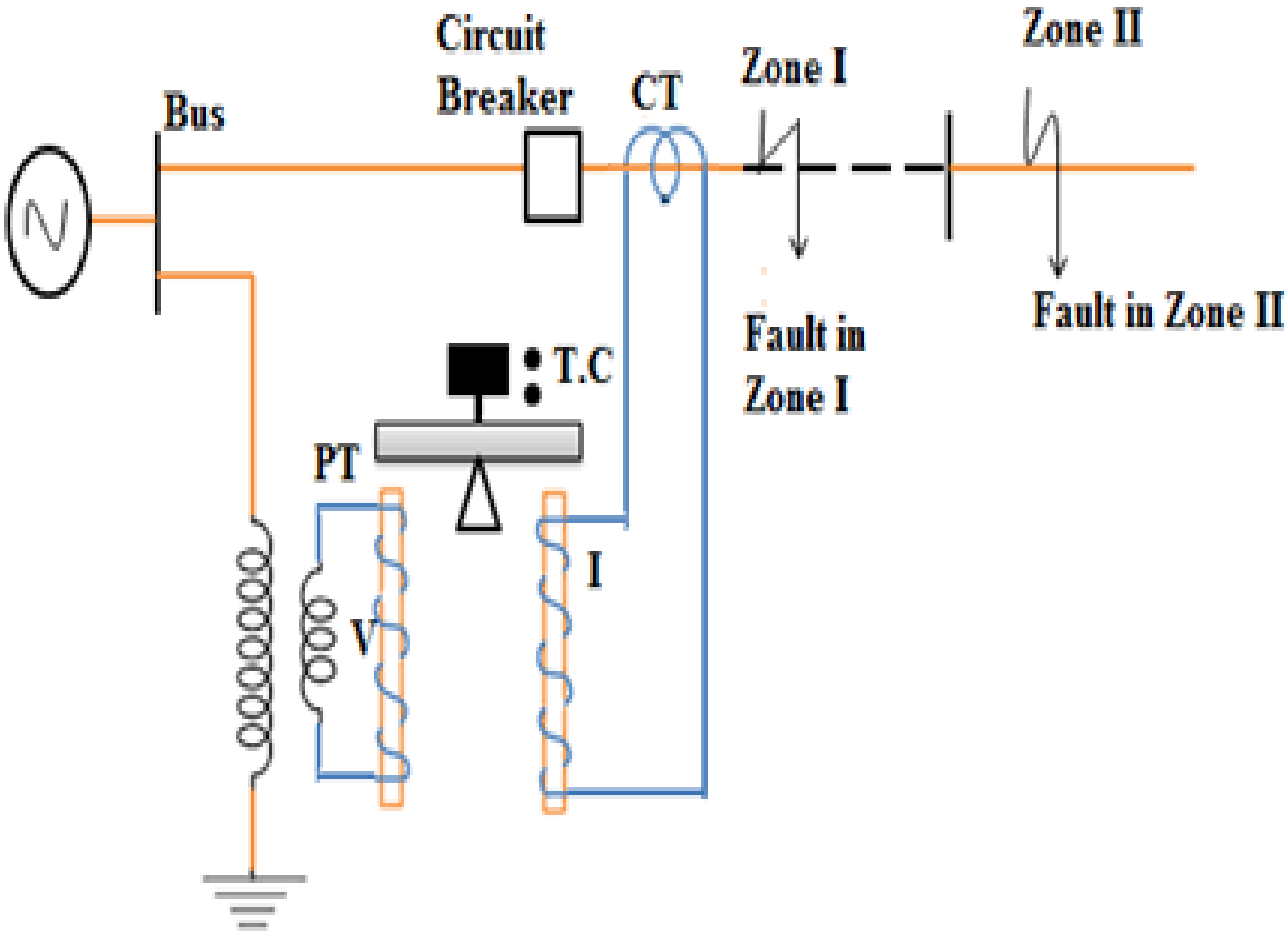
✓At normal condition

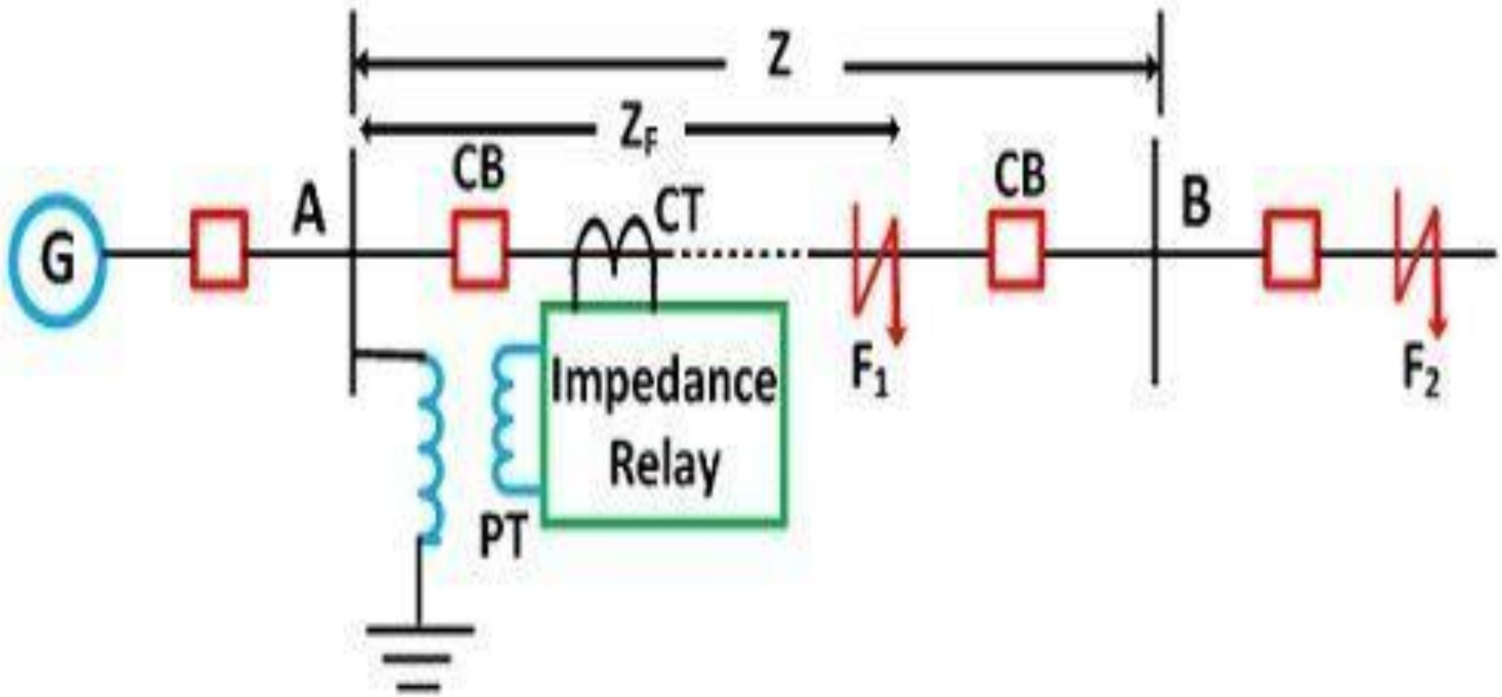
operative torque = restraining torque

✓At fault

operative torque > restraining torque

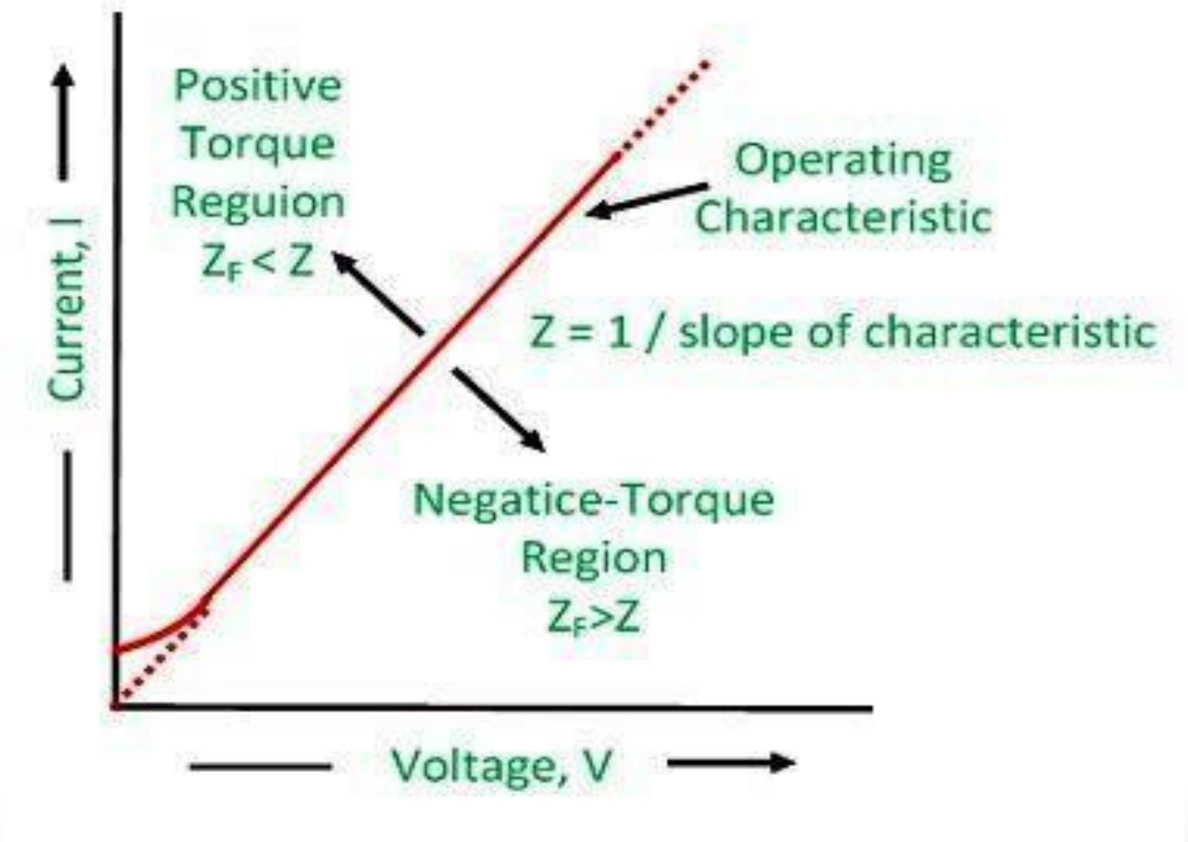
➢Also called voltage restrained over current relay.


Bus
Circuit
Breaker
CT
Zone I
Zone II
Fault in
Zone I
Fault in Zone II
T.C
PT
V
I

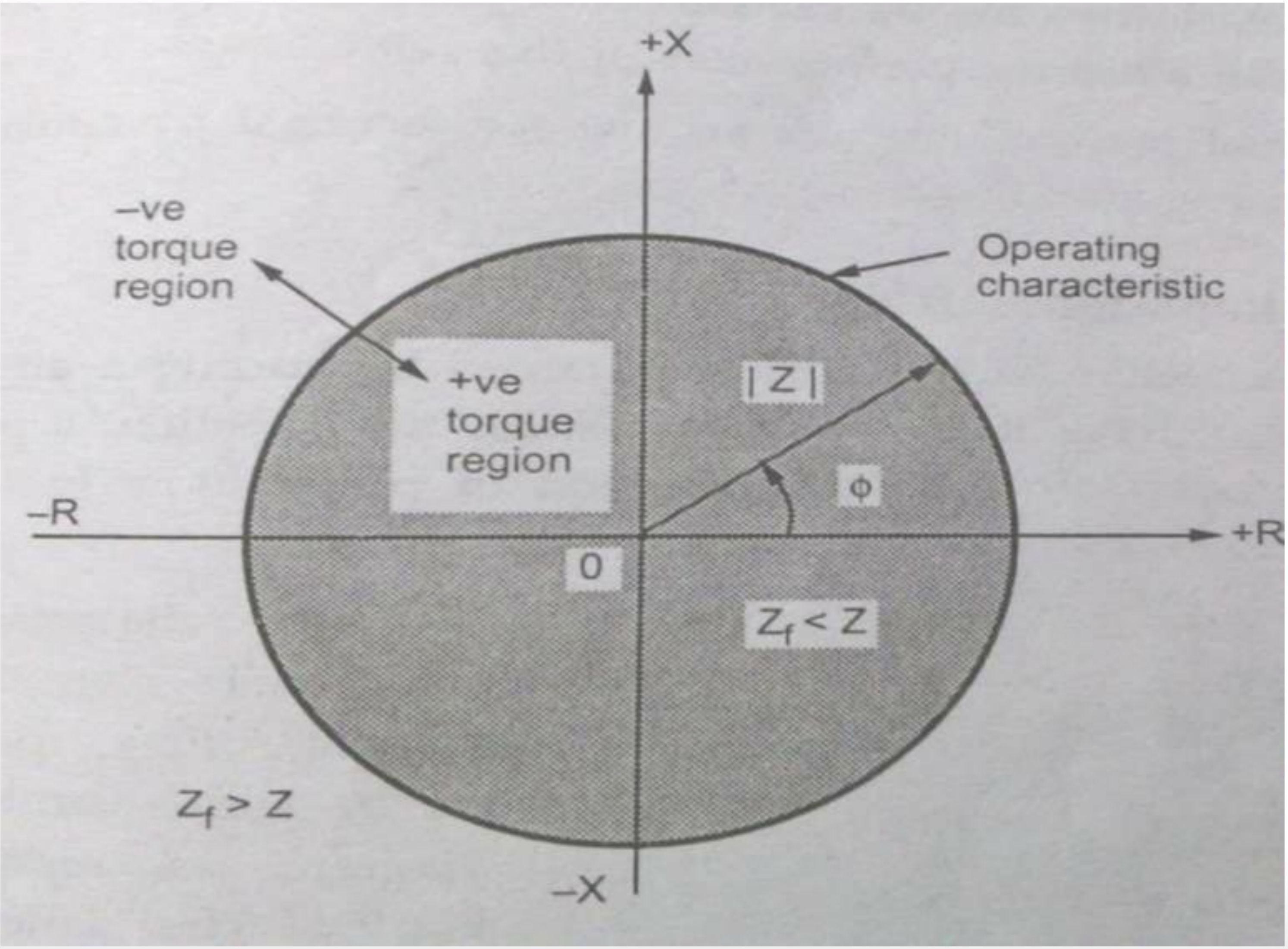


Principle of operation of an Impedance Relay

Circuit Globe



Operating characteristics of impedance relay



R-X Diagram Of Impedance Relay

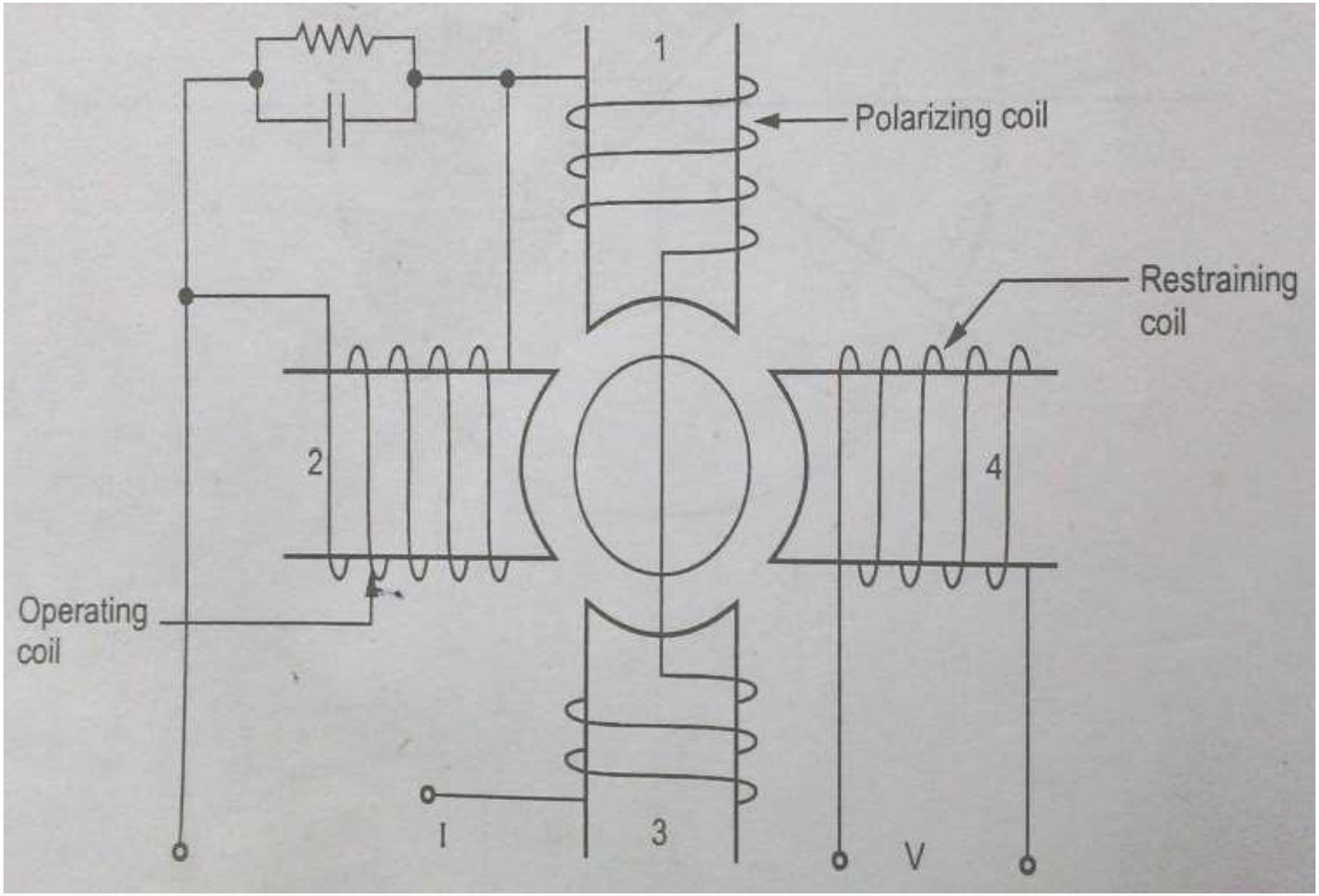
2.Reactance relay :-

- Operative Torque by current
- Restraining Torque by Current-Voltage Directional relay

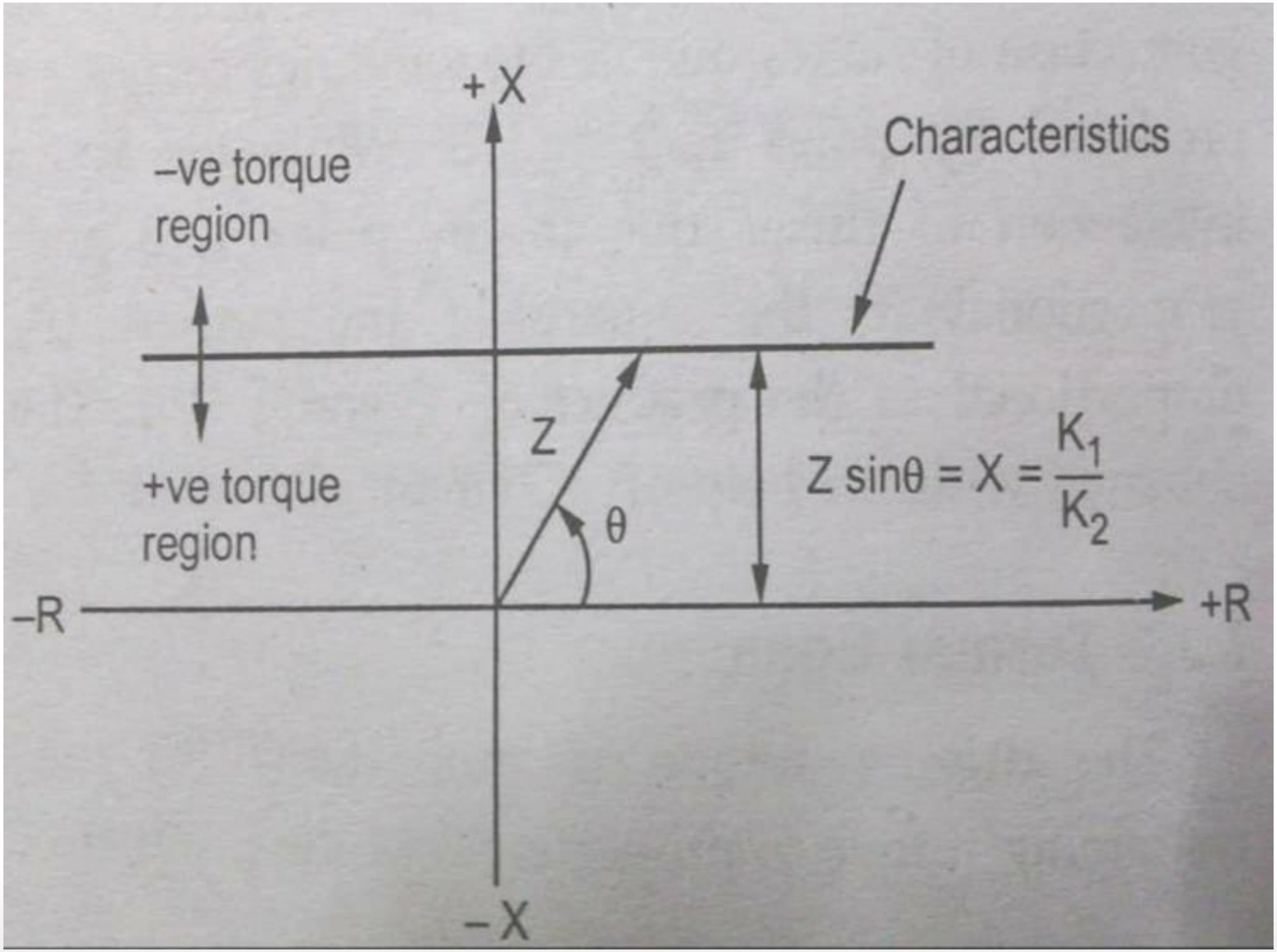
❖ +ve torque by over current element

❖ -ve torque by directional unit

✓Directional element designed for maxi. Torque angle = 90 degree



Block diagram

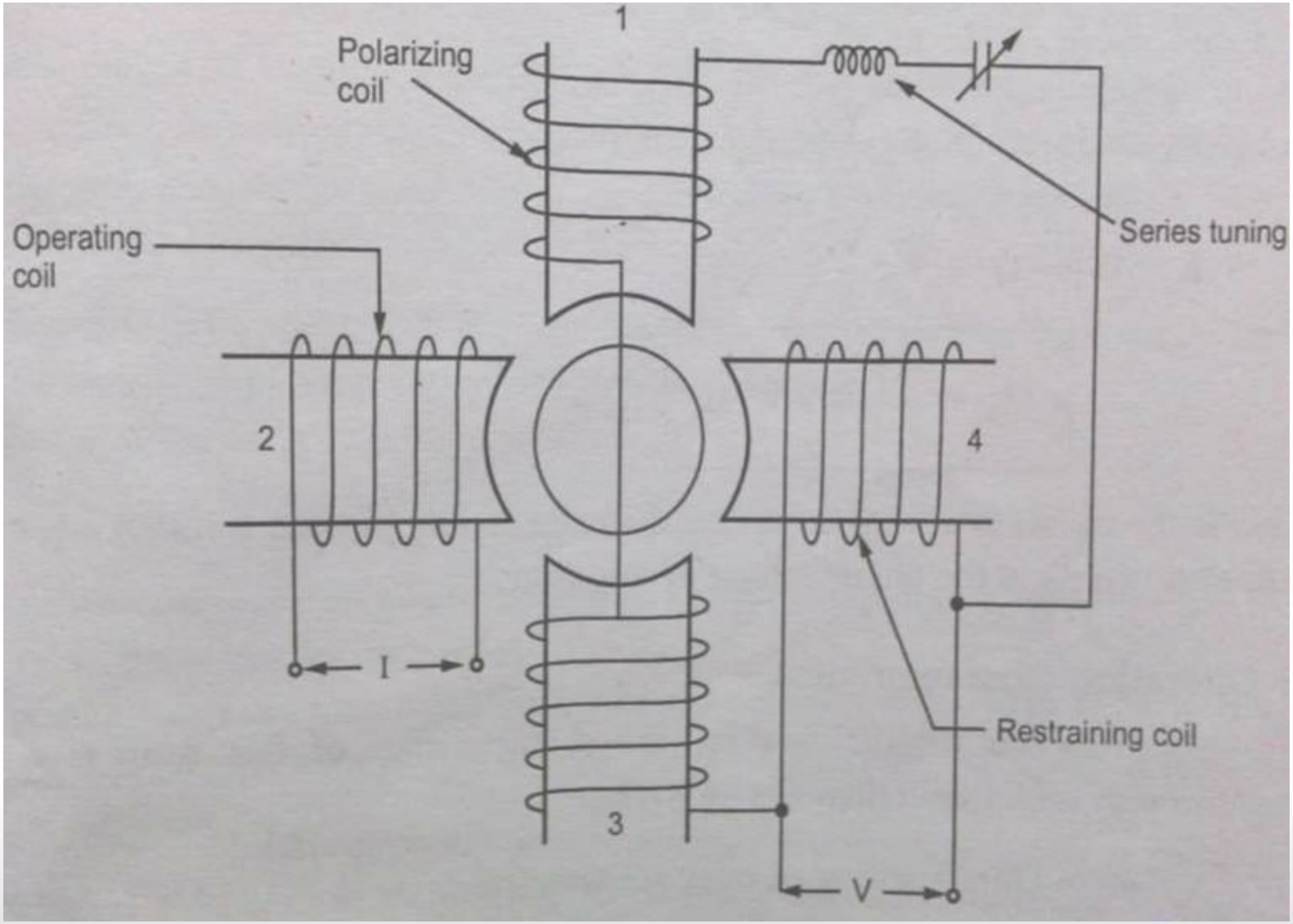


R-X Diagram Of Reactance Relay

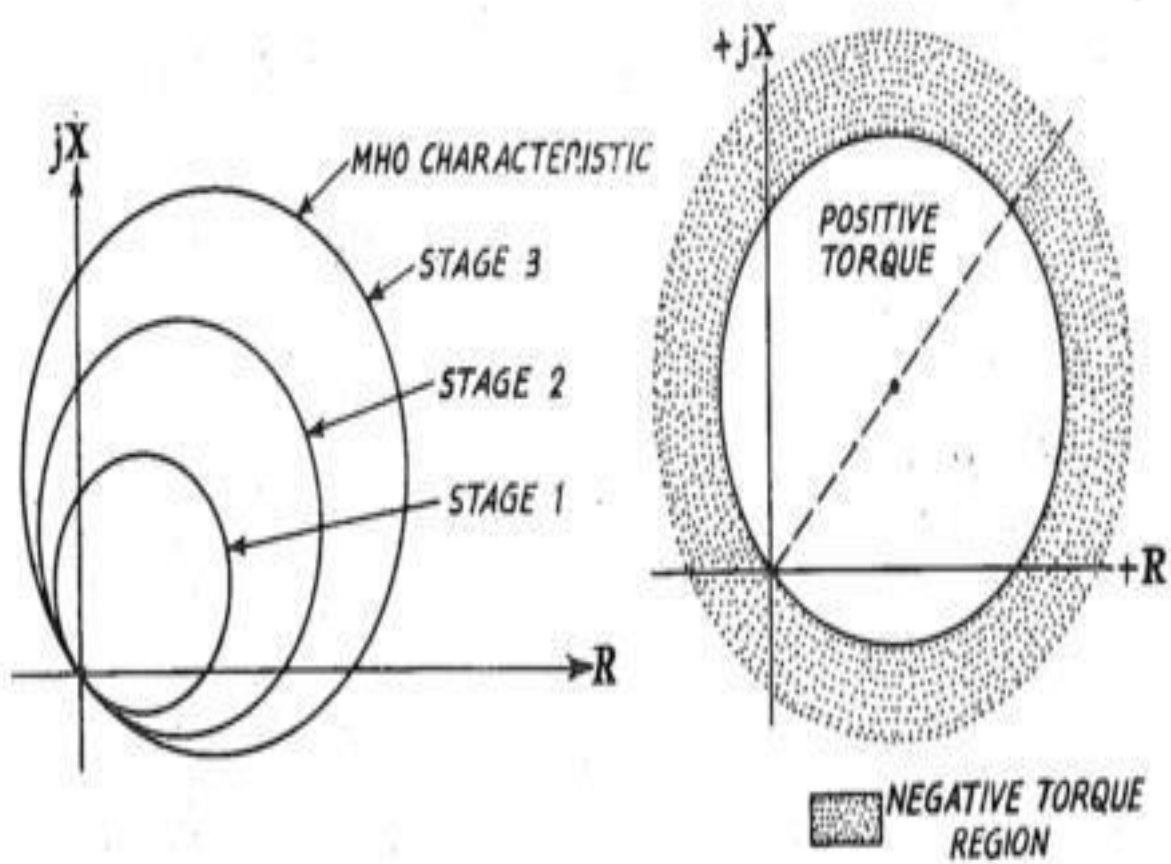
3.Mho relay :-

- Induction cup type structure.
  - Operative Torque produced by V & I element.
  - Restraining Torque by Voltage element.
- Also called ***Admittance relay.***

Application:Mho Relay is used for Protection of EHV/UHV transmission lines



Block diagram



(a) (b)

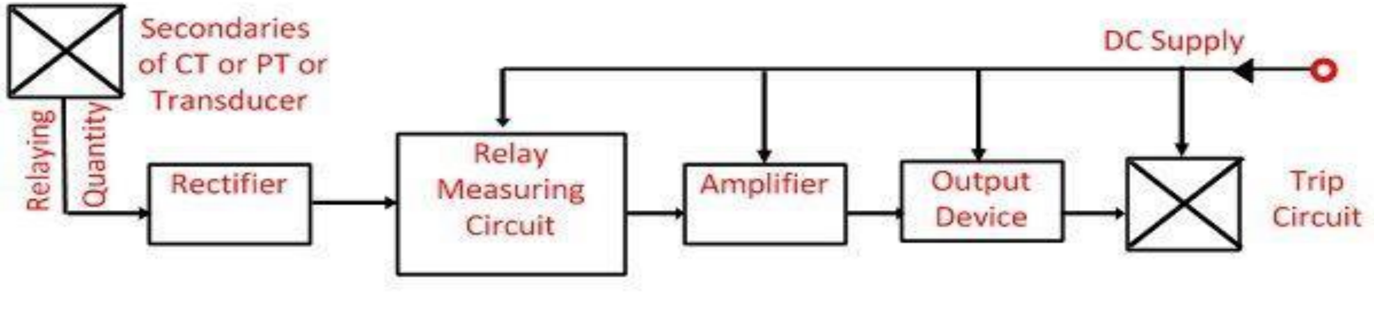
Fig. .14. Voltage Restrained Directional Characteristic (Ohm Characteristic).

STATIC RELAY

- The relay which does not contain any moving parts is known as the static relay

- The output is obtained by the static components like magnetic and electronic circuit etc

RELAY MEASURING CIRCUIT: Comparators, Level Detector and the Logic Circuit



Block Diagram of Static Relay

Operation Of Static Relay :

- **The input of the current transformer is connected to the transmission line, and their output is given to the rectifier.**

- **The rectifier was rectifying the input signal and pass it to the relaying measuring unit.**

- **The relaying measuring unit has the comparators, level detector and the logic circuit.**

- **The output signal from relaying unit obtains only when the signal reaches the threshold value.**

- **The output of the relaying measuring unit acts as an input to the amplifier.**

- **The amplifier amplifies the signal and gives the output to the output devices. The output device activates the trip coil and opens the circuit breaker.**

ADVANTAGES OF STATIC RELAY

- The static relay consumes very less power because of which the burden on the measuring instruments decreases.

- The static relay gives the
  - quick response
  - long life
  - high reliability
  - accuracy
  - high resistance to shock and vibration.

- **Less maintenance**
- **Compact size**

- **The reset time of the relay is very less.**
- **It does not have any thermal storage problems.**
- **The relay amplifies the input signal which increases their sensitivity.**

- ❑The chance of unwanted tripping is less in this relay.

- ❑The static relay can easily operate in earthquake-prone areas.

Disadvantages or Limitations of Static Relay

- Static relays are temperature sensitive.
- The relay is easily affected by the high voltage surges. Thus, precaution should be taken for avoiding the damages through voltage spikes.
- The working of the relay depends on the electrical components.
- The relay has less overloading capacity.

- **The static relay is more costly as compared to the electromagnetic relay.**
- **The construction of the relay is easily affected by the surrounding interference.**
- **Static relays are inflexible, inadaptable and complex**

Comparator

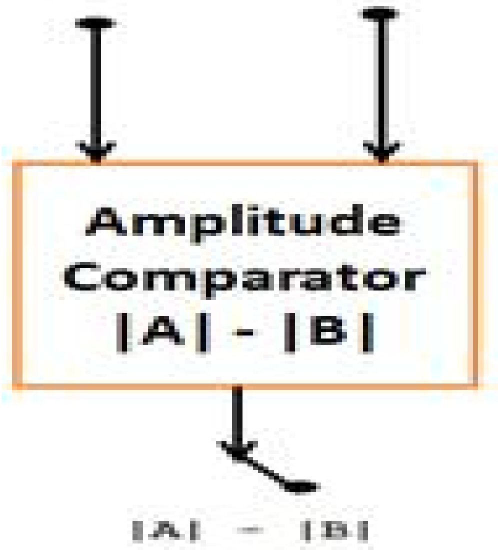
- The magnitude of voltage & current and phase angle between them may change when a fault occurs.
- Static relay senses the change in these parameters to differentiate between healthy and faulty conditions.
- This is achieved by comparing either the magnitudes of voltage & current or the phase angle between them.
- The circuitry which performs this function is called comparator.
- Two types – amplitude comparator and phase comparator

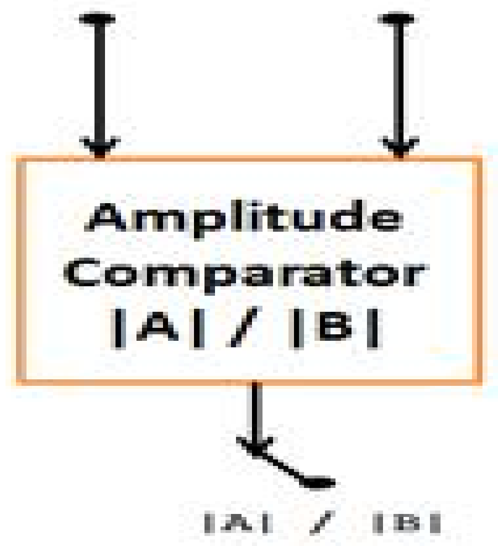
Amplitude Comparator

✓It compares the magnitude of two input quantities irrespective of the angle between them.

✓The two quantities are operating quantity and restraining quantity.

✓When the magnitude of the operating quantity is greater than the restraining quantity, the relay sends trip signal to C.B





Comparison by difference:

- Output is +ve, if |A| > |B|
- Output is –ve, if |A| < |B|
- Output is zero, if |A| = |B|

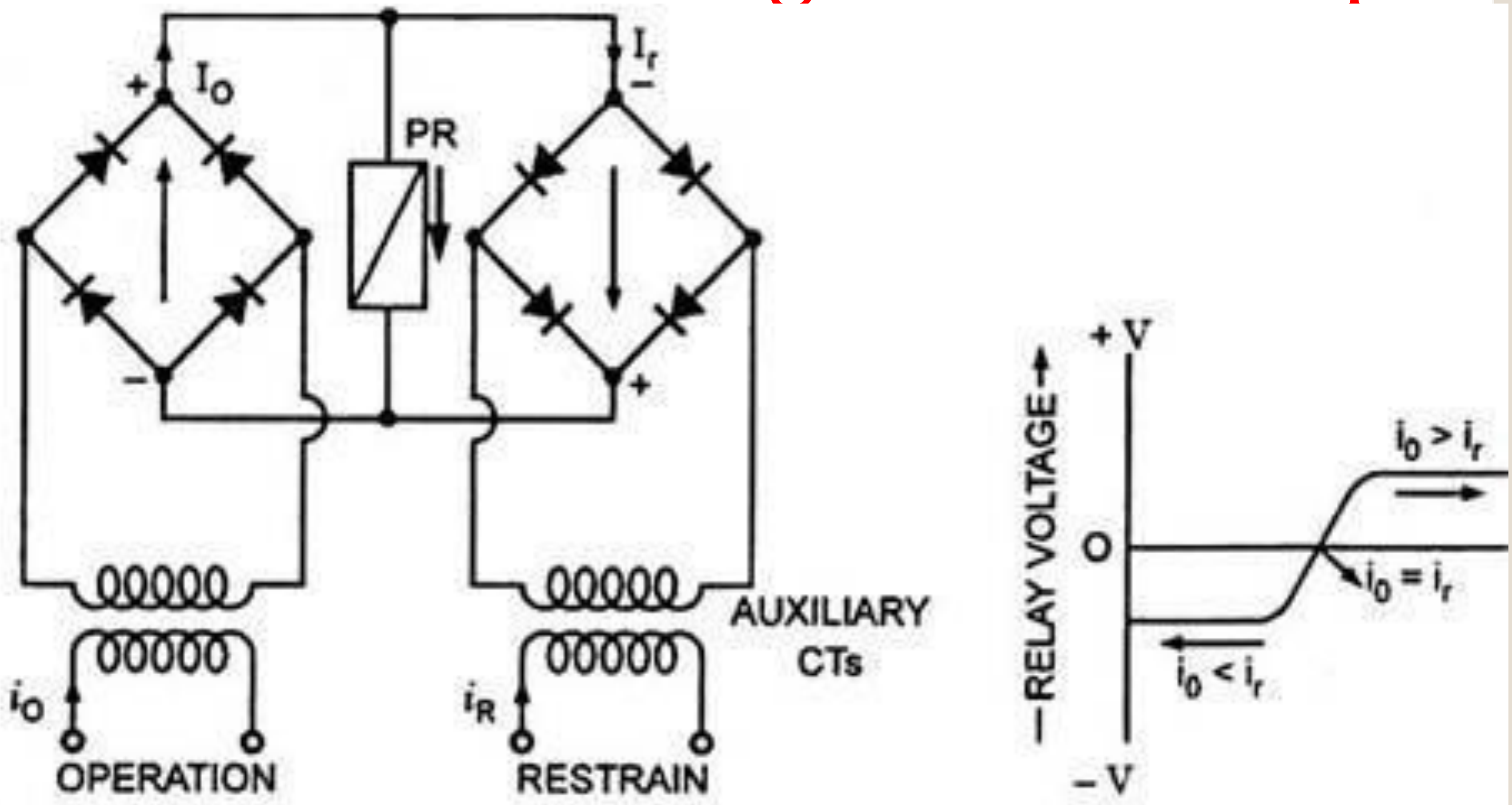
Comparison by ratio:

- Output is >1, if |A| > |B|
- Output <1, if |A| < |B|
- Output is Zero, if |A| is zero.

Types of amplitude comparators

- Circulating current comparator
- Opposed voltage comparator

Circulating current Comparato



(a) Basic Circuit (b) Output Voltage

Fig. 3.7. ***Circulating Current Type Rectifier Bridge Comparator***

- i_O and i_r are operating and restraining currents.
- Under no fault condition, i_r > i_O. The differential current flows through the relay in -ve direction.
- During a fault, i_o > i_r. Hence the differential current flows through the relay in +ve direction to trip C.B

Opposed Voltage Comparator

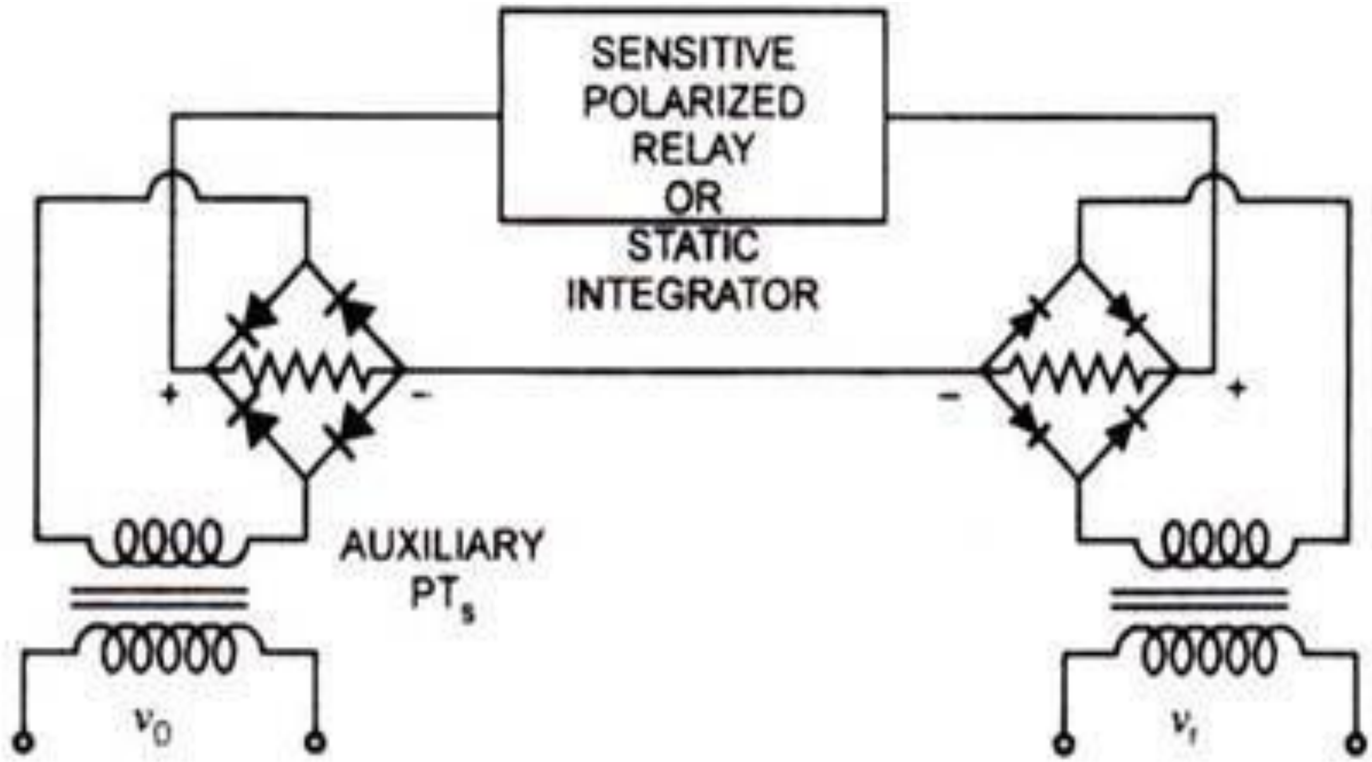
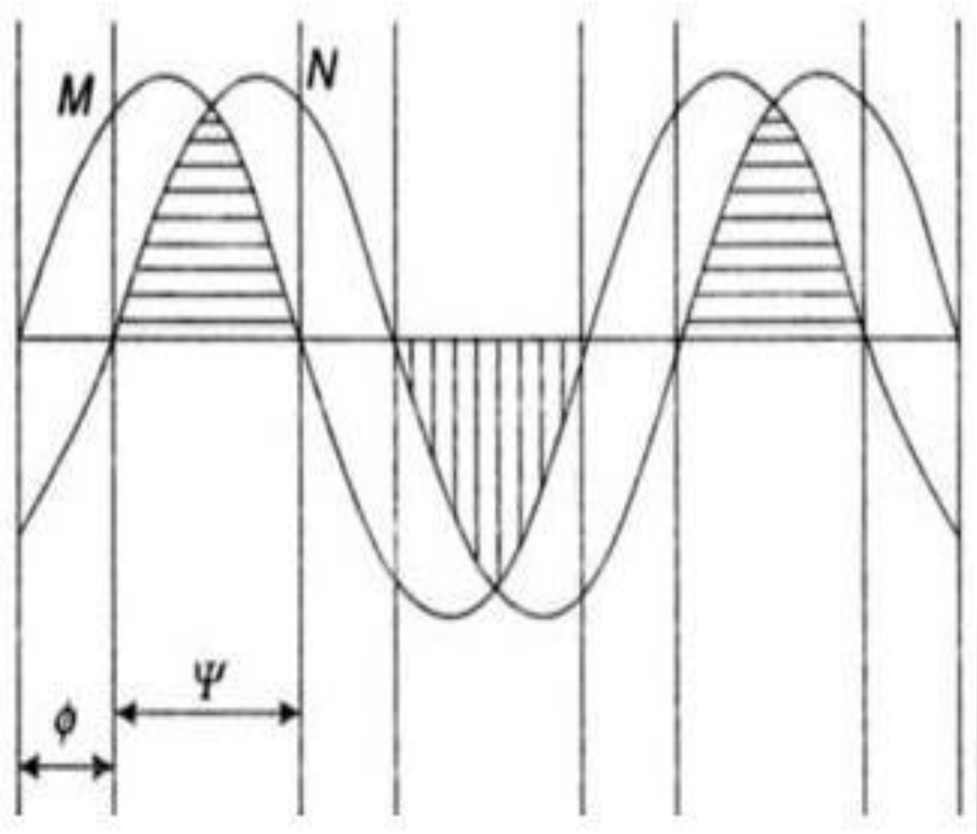


Fig. 3.10. ***Opposed Voltage Type Rectifier Bridge Comparator***

- V_O and V_r are operating and restraining voltages.
- Under no fault condition, $V_r > V_O$. The differential current flows through the relay in -ve direction.
- During a fault, $V_o > V_r$. Hence the differential current flows through the relay in +ve direction to trip C.B.

Phase Comparator

- It compares two input quantities in phase angle ,irrespective of their magnitudes and operates if the phase angle between them if less than or equal to 90



- If the 2 signals have a phase difference of ϕ, then the angle of coincidence $\psi = 180 - \phi$.
- If $\phi < 90^0$, then $\psi > 90^0$. The phase comparator may be designed to trip the C.B, when $\psi > 90^0$.
- If $\phi > 90^0$, then $\psi < 90^0$. The phase comparator will not send the trip signal to C.B, when $\psi < 90^0$.
- The period of coincidence is measured by different techniques.

Types of Phase Comparator

1..Coincidence type P.C

a) Block spike P.C

b) Phase-splitting type P.C

2.Vector product P.C

a) Hall effect P.C

b) Magneto-resistivity P.C

1.Coincidence Type Phase Comparator

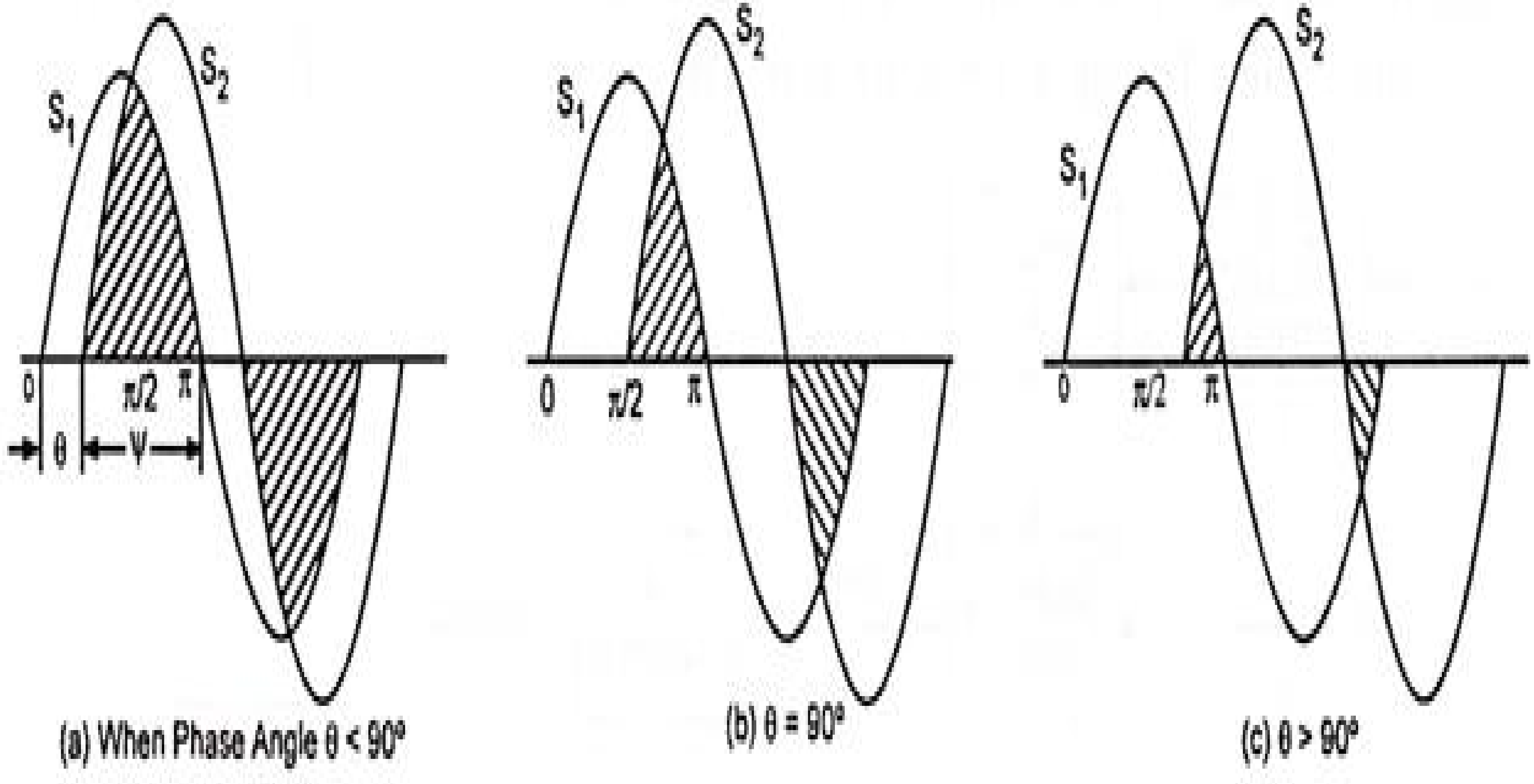
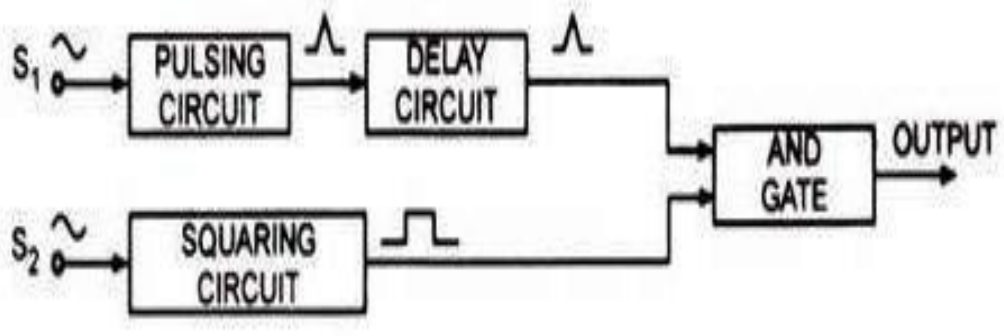
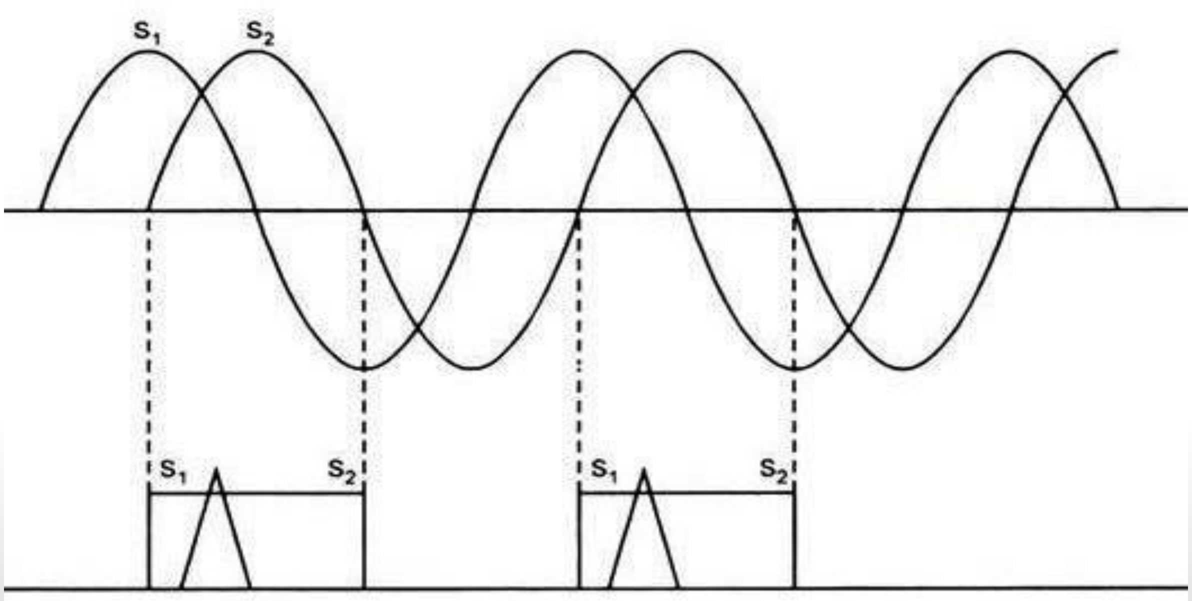


Fig. 3.17. *Coincidence of Signals S_1 and S_2*

a)Spikes and Block Coincidence Techniques in Phase Comparator



(a) Block Diagram

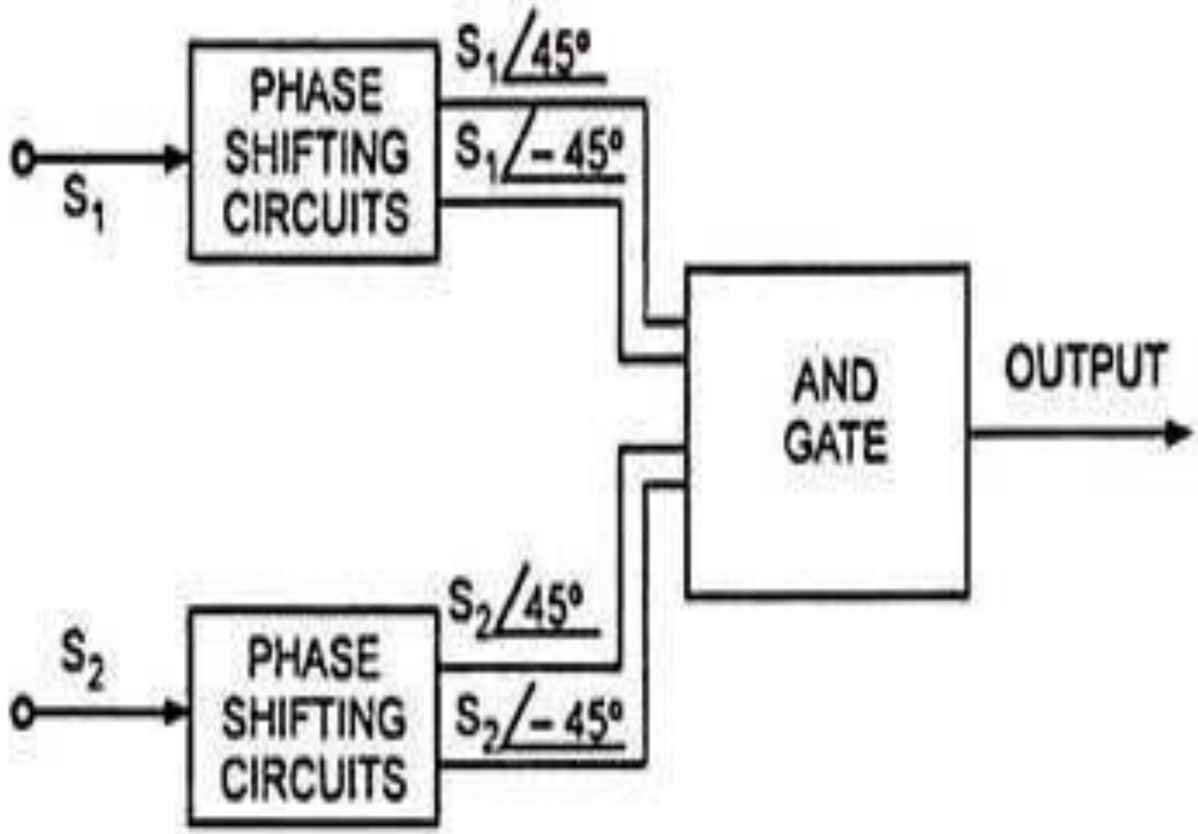


(b) Waveforms

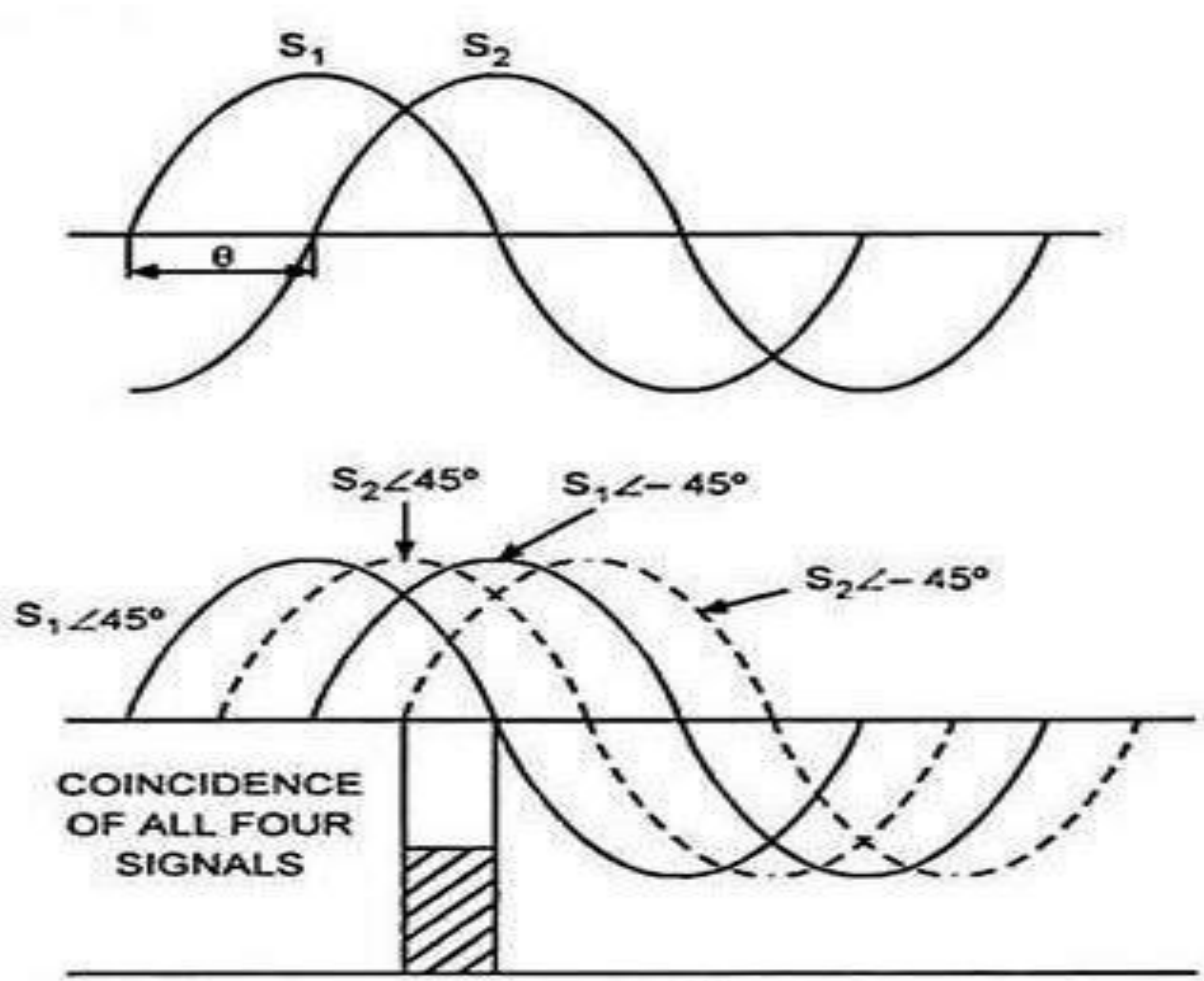
Operation :

One of the inputs is converted to square wave and the other into a pulse of short duration at the instant of its zero crossing, peak value or at any angle (preferably at the instant of its peak value). The squared and spike signals are fed through an AND gate. If these two signals coincide at any time, the output then only would be available from the AND gate.

b)Phase Comparator with Phase Splitting Technique



(a) Block Diagram



(b) Waveforms

2.Vector product Phase comparator

- Its output is proportional vector product to two input quintiles.

Types

a) Hall effect Phase comparator

b) Magneto-resistivity Phase comparator

a)Hall effect phase comparator

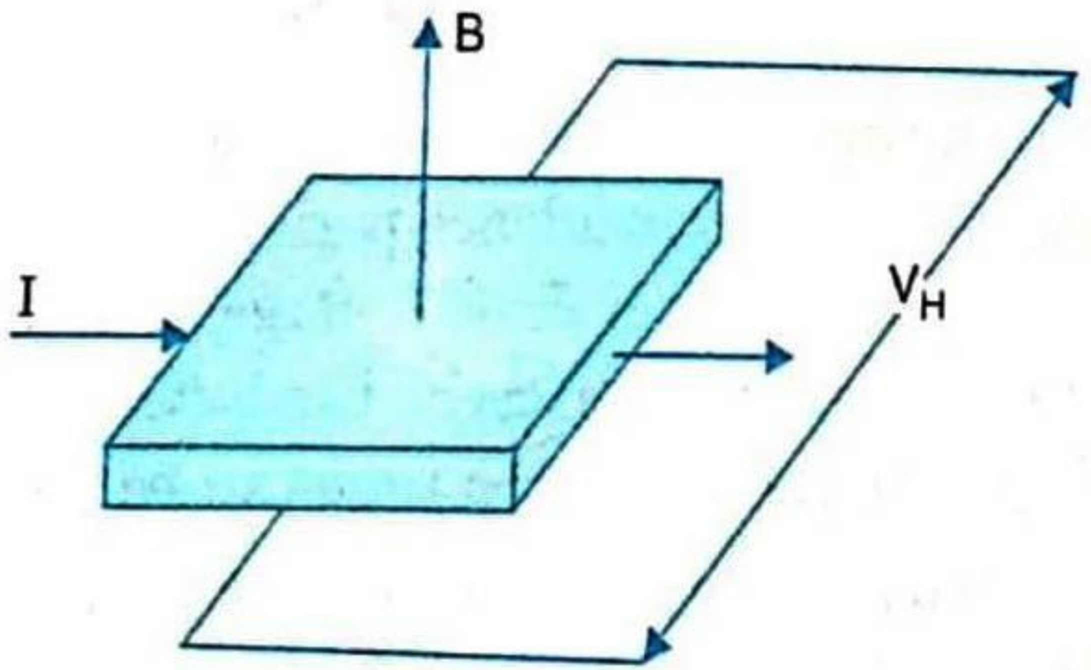


Fig. 14.83 Hall effect phase comparator.

If two inputs are flux and current I, and are sinusoidal

$$\phi = \phi_m \sin \omega t$$

$$I = I_m \sin (\omega t - \alpha)$$

The vector product of two vectors is given by

$$V_H = K\phi_m I_m \sin \omega t \sin (\omega t - \alpha)$$

$$V_H = \frac{K\phi_m I_m}{2} [\cos \alpha - \cos (2\omega t - \alpha)]$$

- It consists of both dc and double frequency ac components
- Double frequency component can be eliminated by cross connecting the hall elements

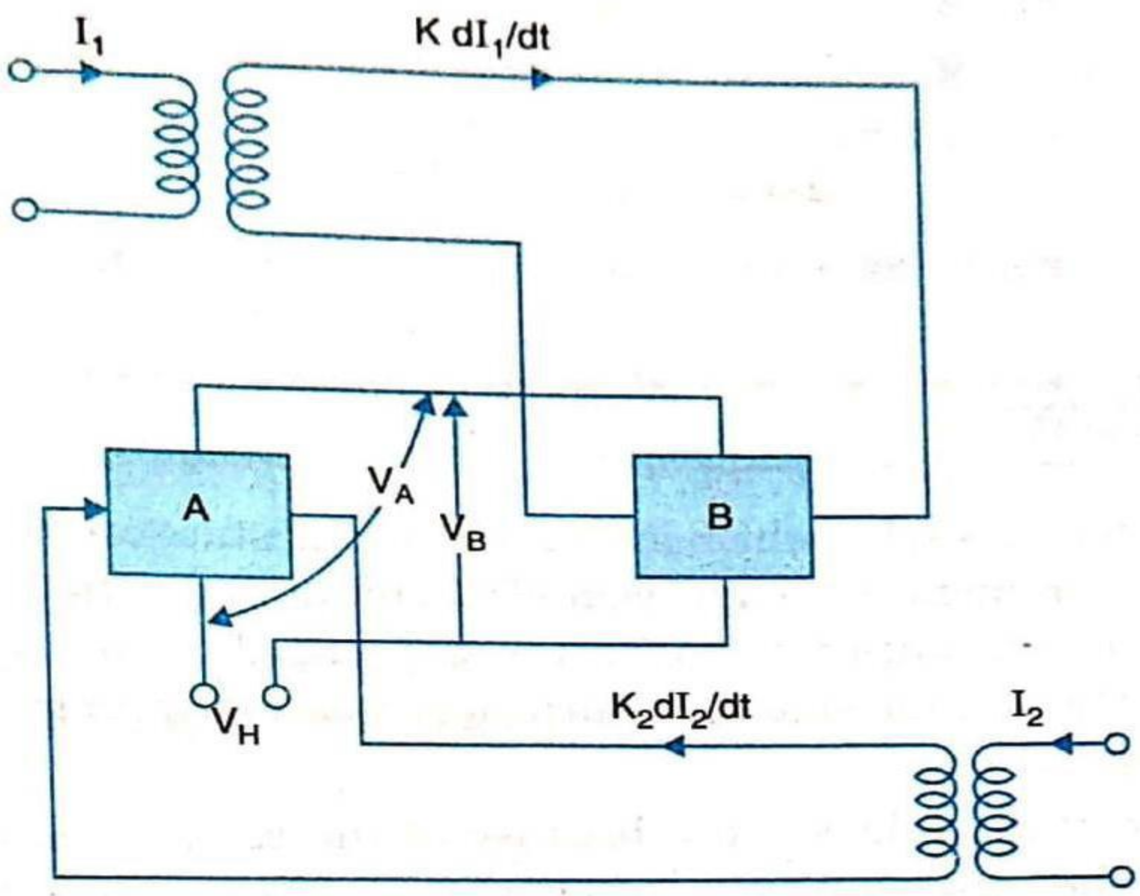


Fig. 14.84 Cross connection of two Hall elements.

Let
$$I_1 = I_{m_1} \sin \omega t$$
$$I_2 = I_{m_2} \sin (\omega t + \alpha)$$

The two fluxes ϕ_A and ϕ_B through the elements A and B are $\phi_A \propto I_1$ and $\phi_B \propto I_2$, and the currents through the elements are $I_A \propto \frac{dI_2}{dt}$ and $I_B \propto \frac{dI_1}{dt}$.

Since the two elements are so connected that the output voltages oppose each other, therefore, the resultant voltage is given by

$$V_H = V_A - V_B$$
$$\propto I_{m_1} . \sin \omega t . I_{m_2} \omega \cos (\omega t + \alpha) - I_{m_2} \sin (\omega t + \alpha) \omega I_{m_1} \cos \omega t$$

or
$$V_H \propto I_{m_1} I_{m_2} \sin \alpha$$

Disadvantages

- High cost of hall element
- Large temperature error
- Low output

b)Magneto-resistivity Phase comparator

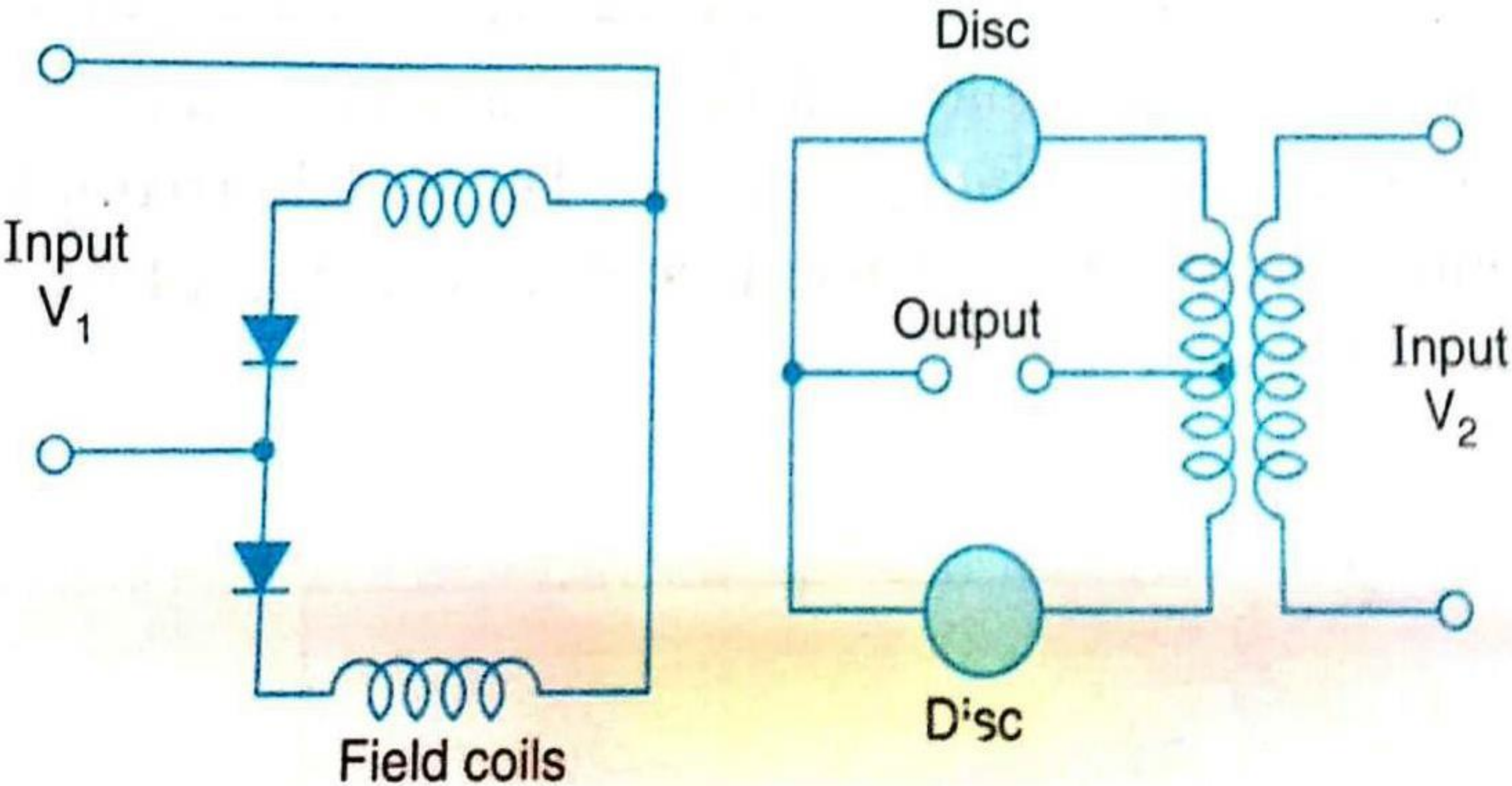


Fig. 14.85 Phase comparator magneto resistivity.

MICROPROCESSOR BASED RELAYS

- OVER CURRENT RELAYS
  - INSTANTANEOUS
  - INVERSE
  - IDMT
  - VERY INVERSE
  - EXTREAMLY INVERSE

- DISTANCE RELAYS
  - IMPEDANCE RELAY
  - REACTANCE RELAY
  - MHO RELAY

OVER CURRENT RELAYS

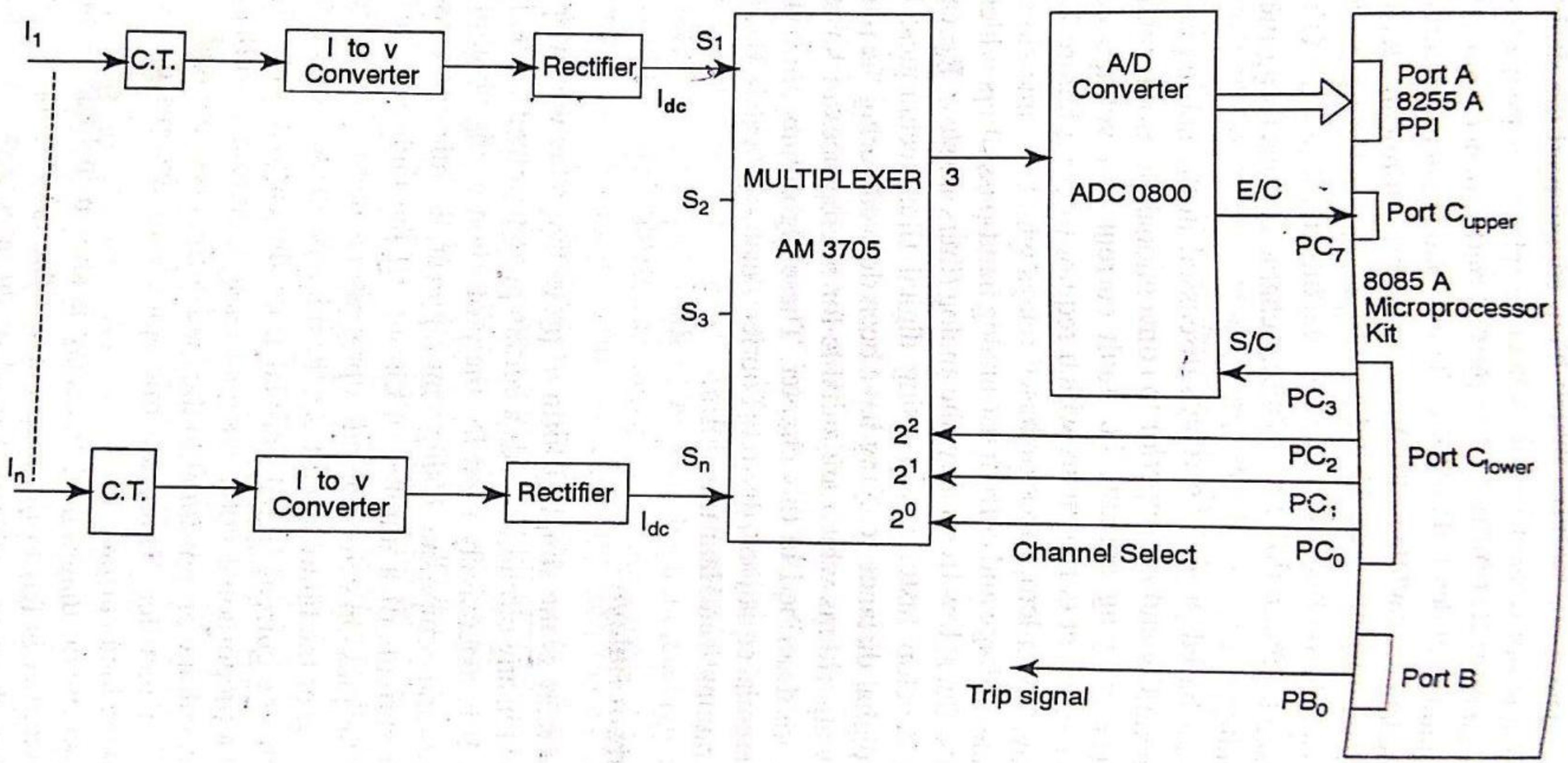


FIGURE 8.1(a) *Block schematic diagram of overcurrent relay*

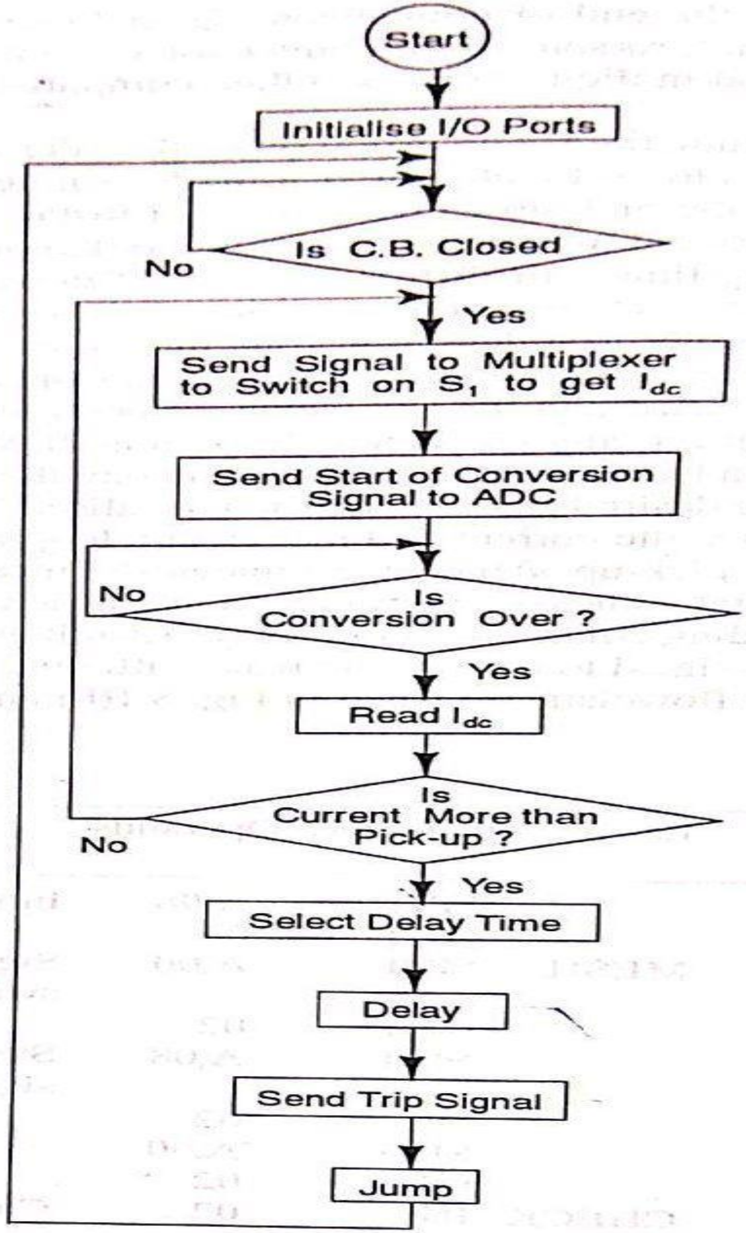


FIGURE 8.1(b) Program flowchart for overcurrent relay

IMPEDANCE RELAY

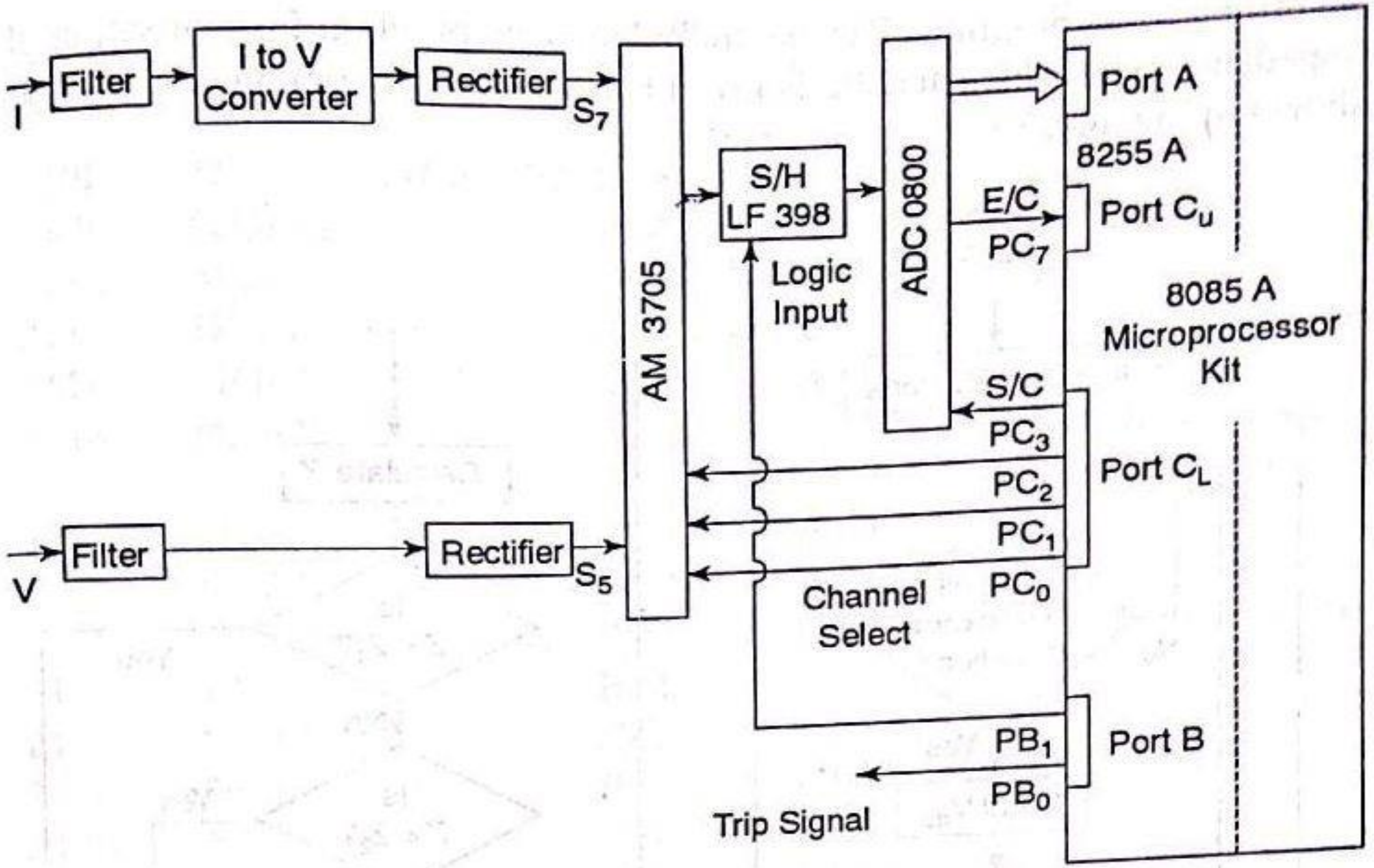


FIGURE 8.3 Block schematic diagram of interface for impedance relay

CONDITION OF IMPEDANCE RELAY

$$K_1 V_{dc} < K_2 I_{dc} \text{ or } \frac{V_{dc}}{I_{dc}} < \frac{K_2}{K_1}$$

or
$$\frac{V}{I} < K$$

or
$$Z < K$$

where K_1, K_2 and K are constants.

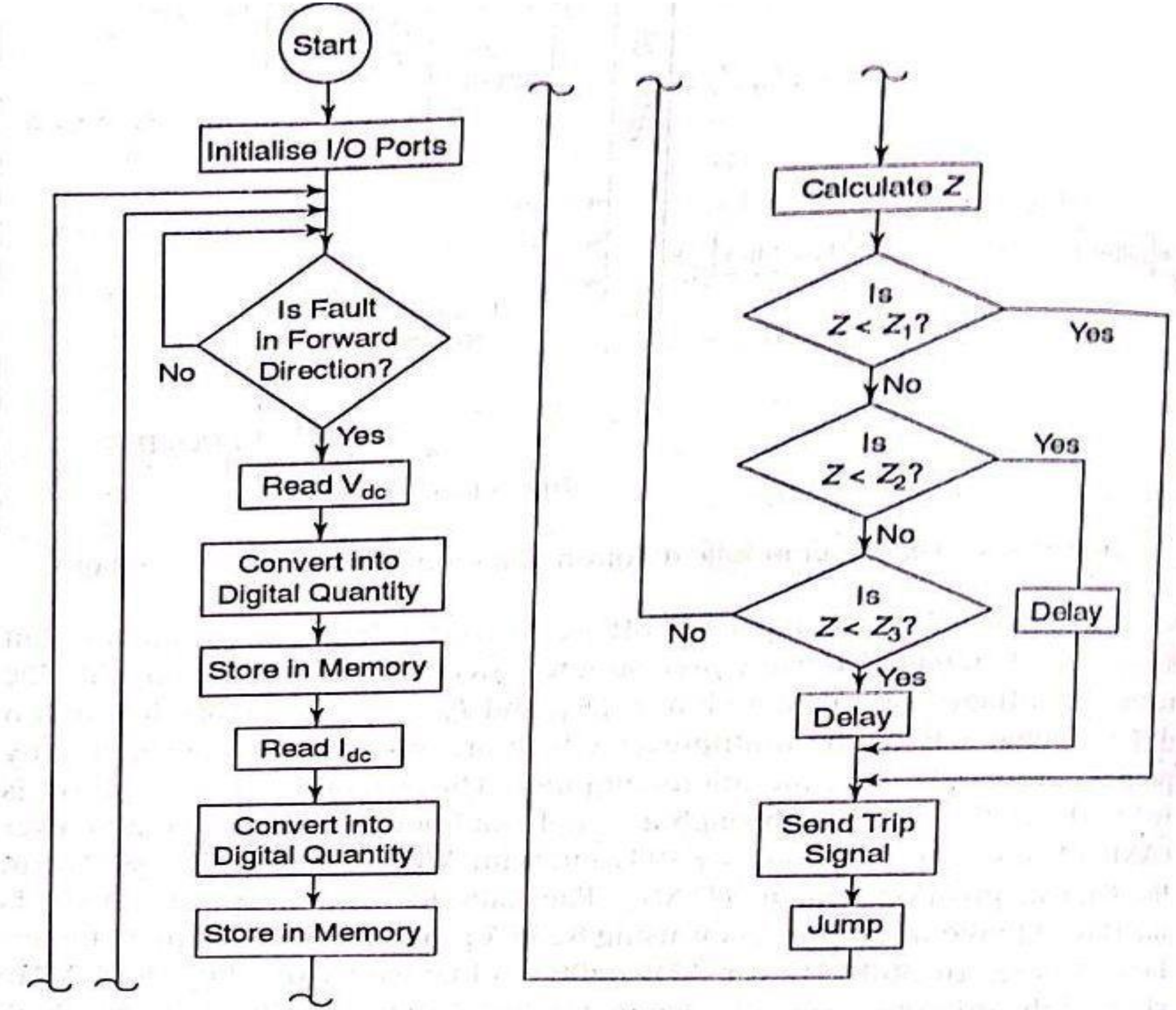


FIGURE 8.4 Program flowchart for impedance relay

REACTANCE RELAY

CONDITION:

$$V_m \sin\phi < K_1 I_{dc} \quad \text{or} \quad \frac{V_m \sin\phi}{I_{dc}} < K_1$$

$$\frac{V \sin\phi}{I} < K \quad \text{(as } V_m \text{ and } I_{dc} \text{ are proportional to rms values } V \text{ and } I\text{, respectively)}$$

$$Z \sin\phi < K$$

$$X < K \qquad (8.2)$$

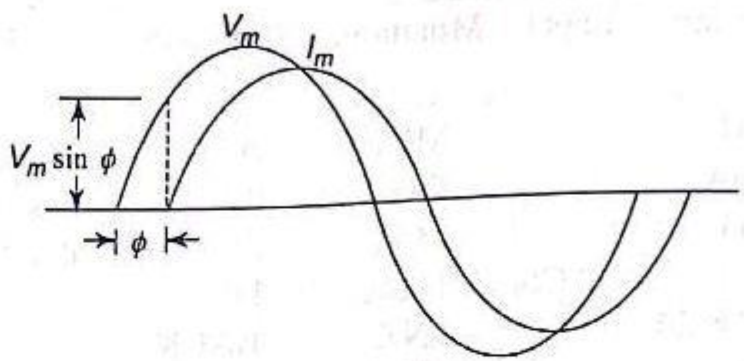


FIGURE 8.8 Instantaneous value of voltage at current zero

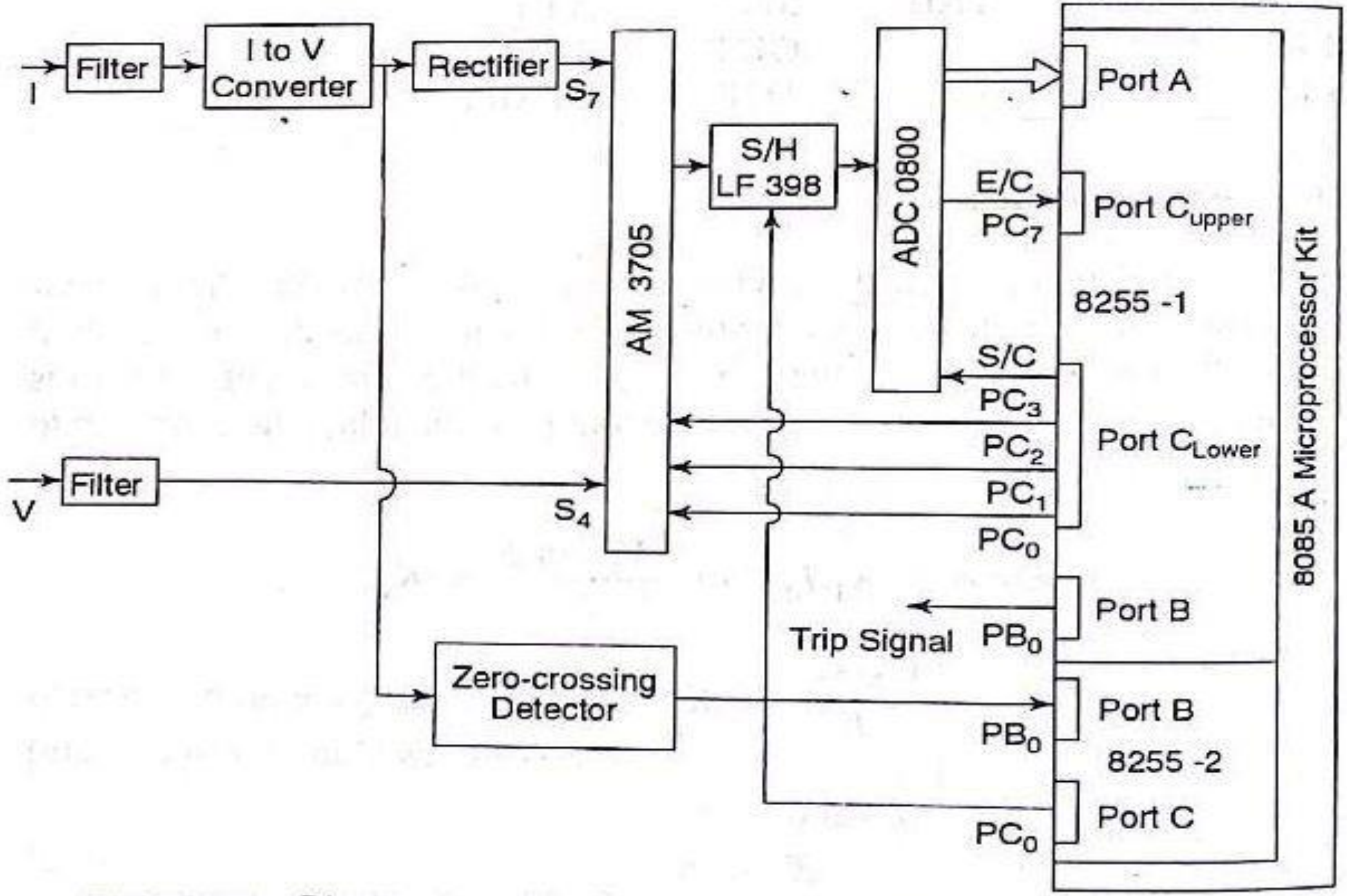
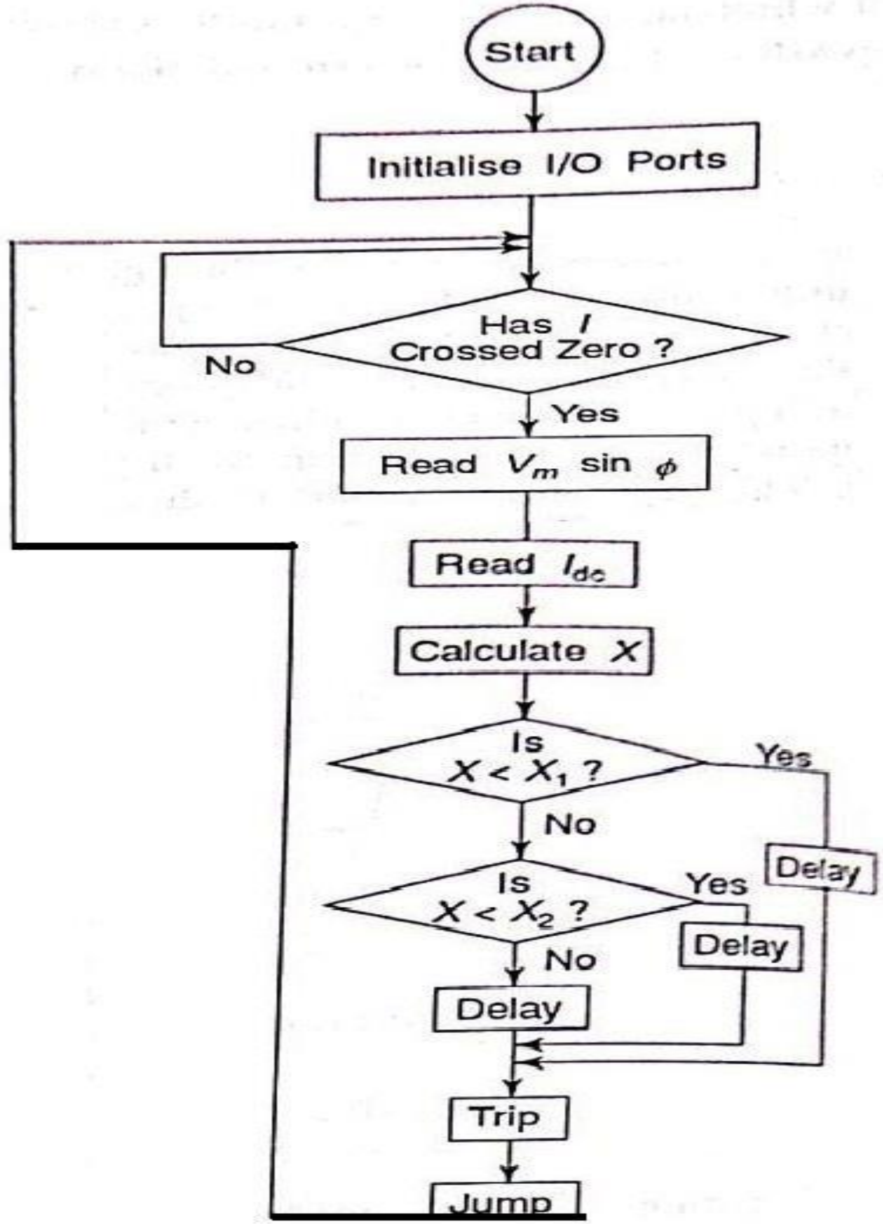


FIGURE 8.9 Block schematic diagram of interface for reactance relay



Start
Initialise I/O Ports
Has I Crossed Zero ?
No
Yes
Read V_m sin ϕ
Read I_{dc}
Calculate X
Is $X < X_1$?
Yes
No
Delay
Is $X < X_2$?
Yes
No
Delay
Delay
Trip
Jump

MHO RELAY

CONDITION:

$$I_m \cos\phi > K_1 V_{dc} \text{ or } \frac{I_m}{V_{dc}} \cos\phi > K_1$$

or $$\frac{I}{V}\cos\phi > K_2$$ (as I_m and V_{dc} are proportional to the rms values of I and V respectively)

or $$Y\cos\phi > K_2 \text{ or } \frac{1}{Y\cos\phi} < \frac{1}{K_2}$$

or $$M < K \tag{8.14}$$

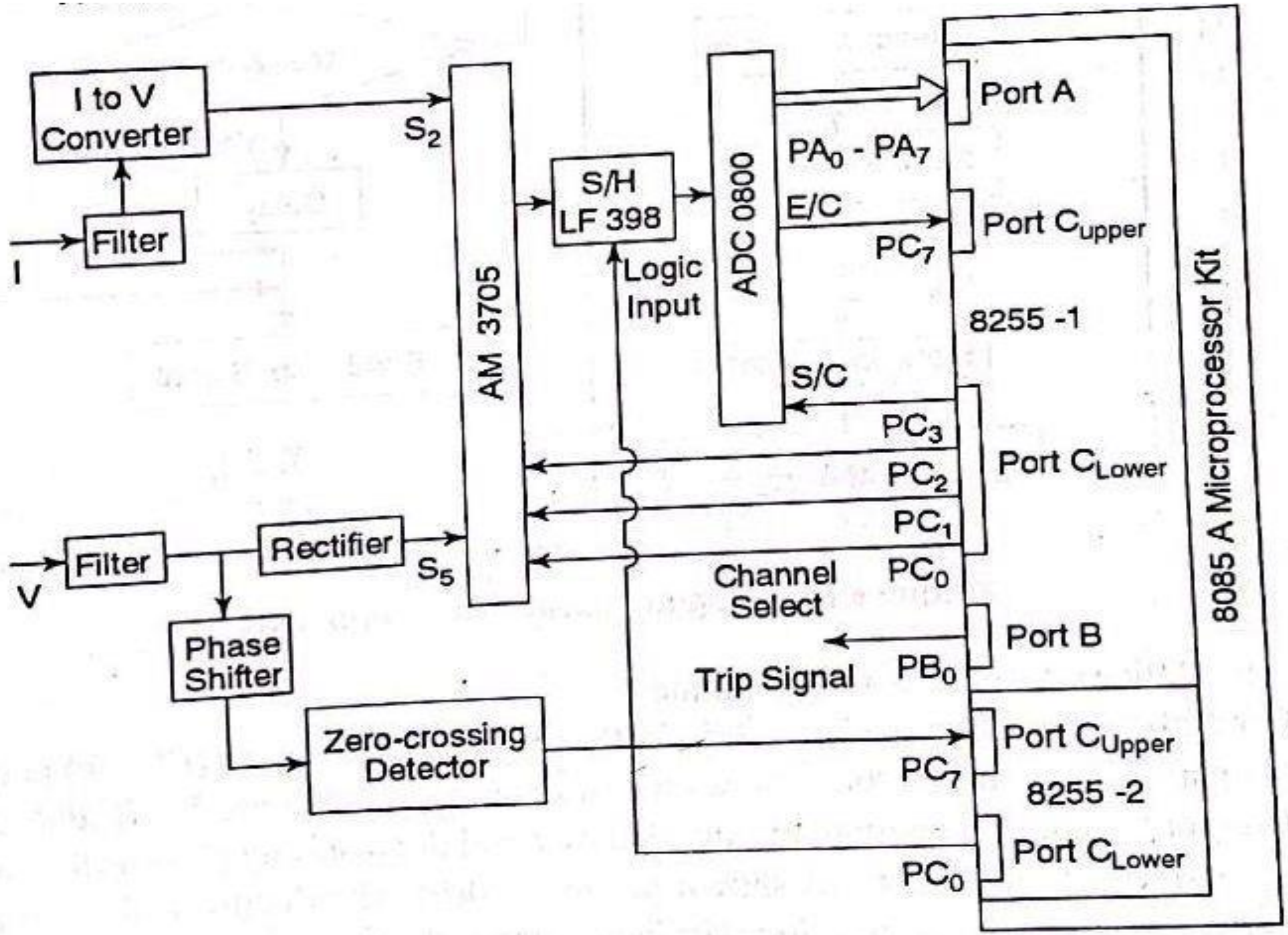


FIGURE 8.18 Block schematic diagram of interface for mho relay

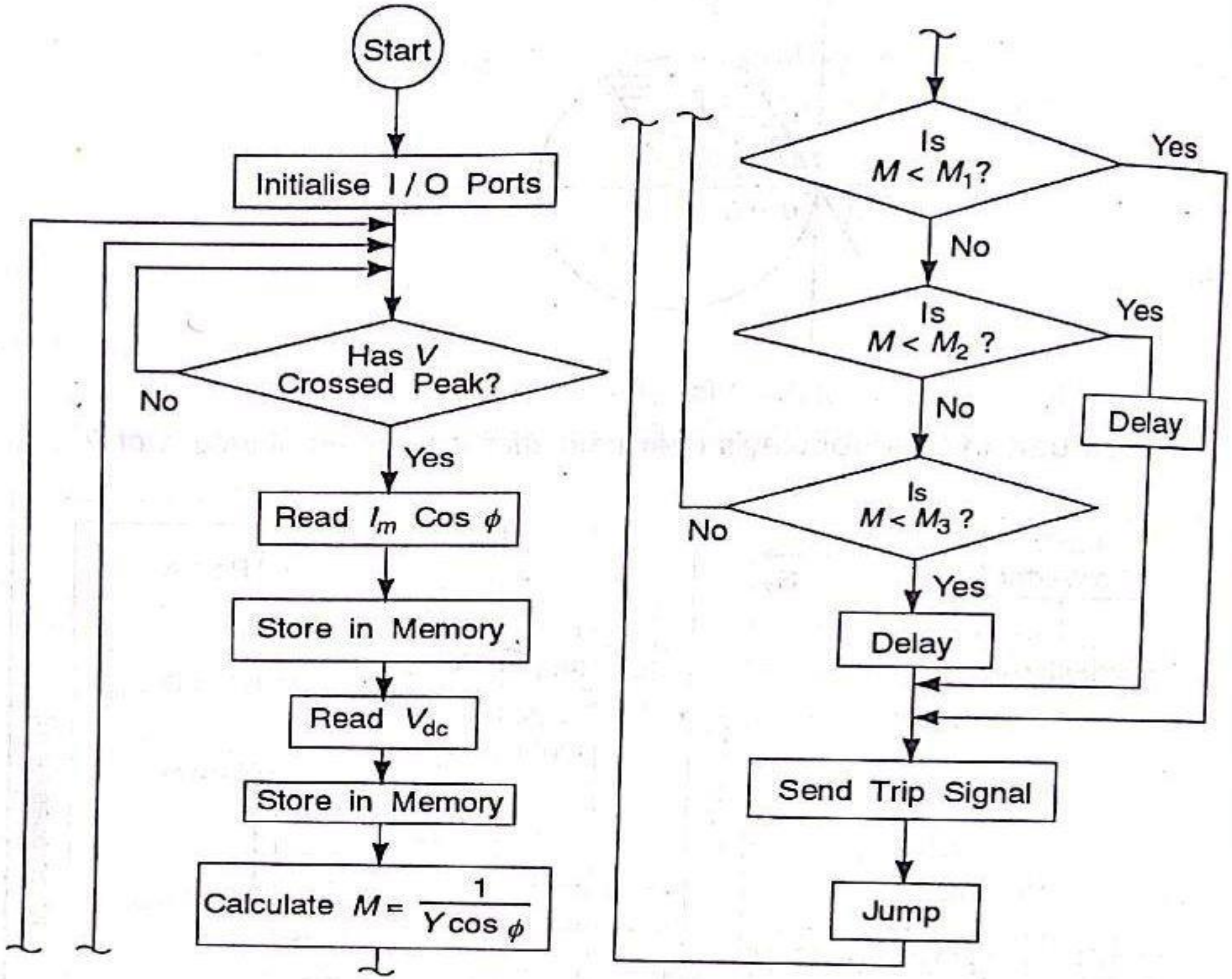


FIGURE 8.19 Program flowchart for mho relay

Advantages

- Compactness
- Speed
- Reliability
- Flexibility
- It can quickly move data between the various memory locations.

Disadvantages

- Most of the microprocessor does not support floating point operations.
- Costly(15 to 20times)
- The main disadvantage is it's over heating physically.
- It should not contact with the other external devices.

Important Terms

1.Pick-up current:

It is the minimum current in the relay coil at which the relay starts to operate.

So long as the current in the relay is less than the pick-up value, the relay does not operate and the breaker remains in the closed position.

However, when the relay coil current is equal to or greater than the pickup value, the relay operates to energise the trip coil which opens the circuit breaker

2.Current setting:

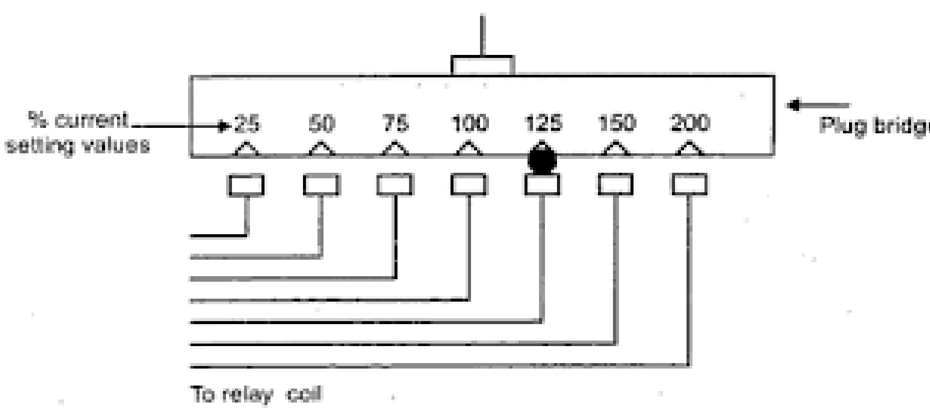
It is often desirable to adjust the pick-up current to any required value. This is known as **current setting** and is usually achieved by the use of tappings on the relay operating coil.

The taps are brought out to a plug bridge as shown in Fig.

The plug bridge permits to alter the number of turns on the relay coil.

This changes the torque on the disc and hence the time of operation of the relay.

∴ Pick-up current = Rated secondary current of C.T. × Current setting



For example, suppose that an overcurrent relay having current setting of 125% is connected to a supply circuit through a current transformer of 400/5.

The rated secondary current of C.T. is 5 amperes.

Therefore, the pick-up value will be 25% more than 5 A i.e. $5 \times 1{\cdot}25 = 6{\cdot}25$ A.

It means that with above current setting, the relay will actually operate for a relay coil current equal to or greater than 6·25 A.

The current plug settings usually range from 50% to 200% in steps of 25% for overcurrent relays and 10% to 70% in steps of 10% for earth leakage relays.

3.Plug-setting multiplier (P.S.M.):

It is the ratio of fault current in relay coil to the pick-up current i.e.

$$\text{P.S.M.} = \frac{\text{fault current in relay coil}}{\text{pickup value}}$$

$$= \frac{\text{fault current in relay coil}}{\text{\% current setting} \times \text{rated secondary current of C.T.}}$$

For example, suppose that a relay is connected to a 400/5 current transformer and set at 150%. With a primary fault current of 2400 A, the plug-setting multiplier can be calculated as under :

Pick-up value = Rated secondary current of CT × Current setting = $5 \times 1{\cdot}5 = 7{\cdot}5$ A

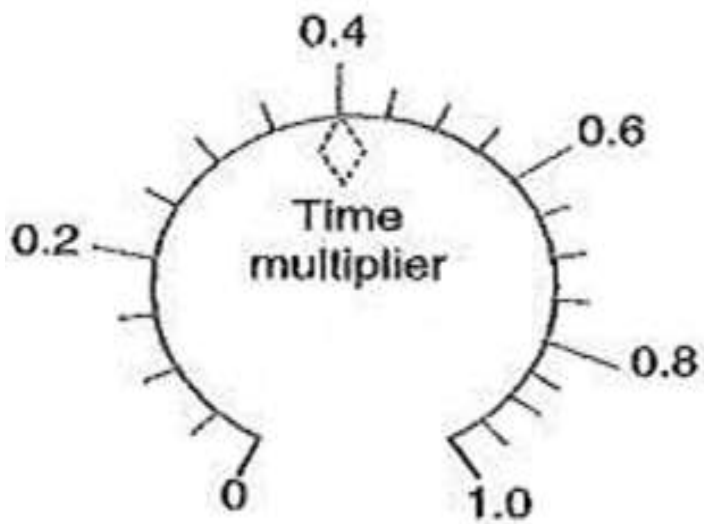
Fault current in relay coil = $2400 \times 5/400 = 30$ A

$$\therefore \text{P.S.M.} = 30/7{\cdot}5 = 4$$

4.Time-setting multiplier:

A relay is generally provided with control to adjust the time of operation. This adjustment is known as **time-setting multiplier.**

- The time-setting dial is calibrated from 0 to 1 in steps of 0.05 sec. These figures are multipliers to be used to convert the time derived from time/P.S.M. curve into the actual operating time.
- Thus if the time setting is 0·1 and the time obtained from the time/P.S.M. curve is 3 seconds, then actual relay operating time = 3 × 0·1 = 0·3 second.



Time/P.S.M. Curve:

- Fig.shows the curve between time of operation and plug setting multiplier of a typical relay.
- The horizontal scale is marked in terms of plug-setting multiplier.
- The vertical scale is marked in terms of the time required for relay operation.
- If the P.S.M. is 10, then the time of operation (from the curve) is 3 seconds. The actual time of operation is obtained by multiplying this time by the time-setting multiplier.

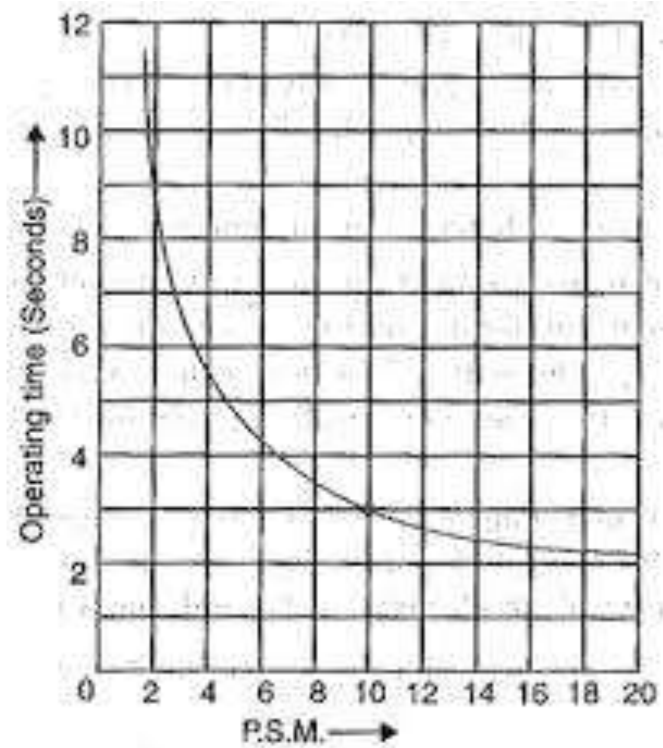
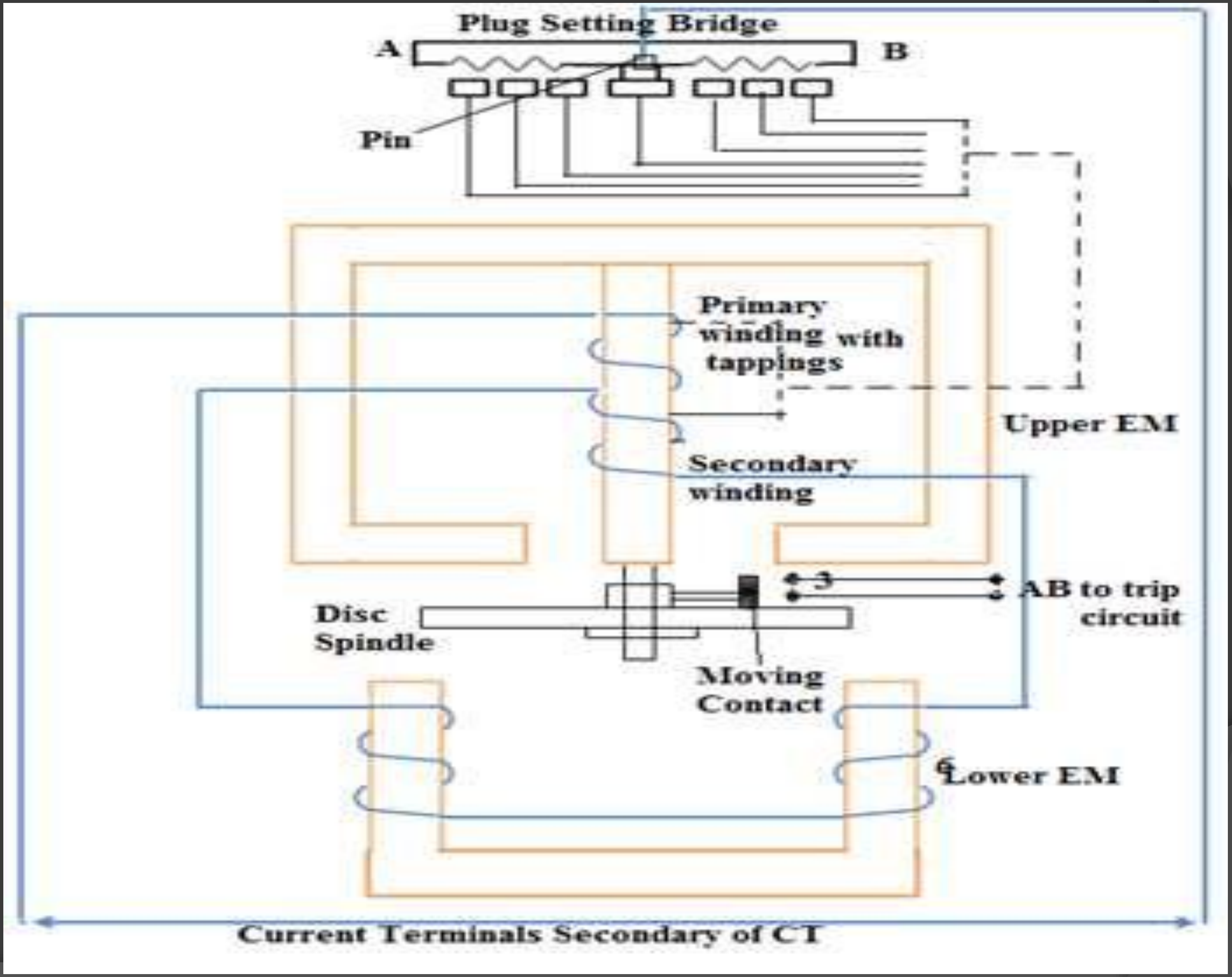


Fig. 21.16

Induction type Directional and Non-directional relays

Induction Type Over Current Relays(non-directional)



Induction Type Directional power relay(Reverse power relay)

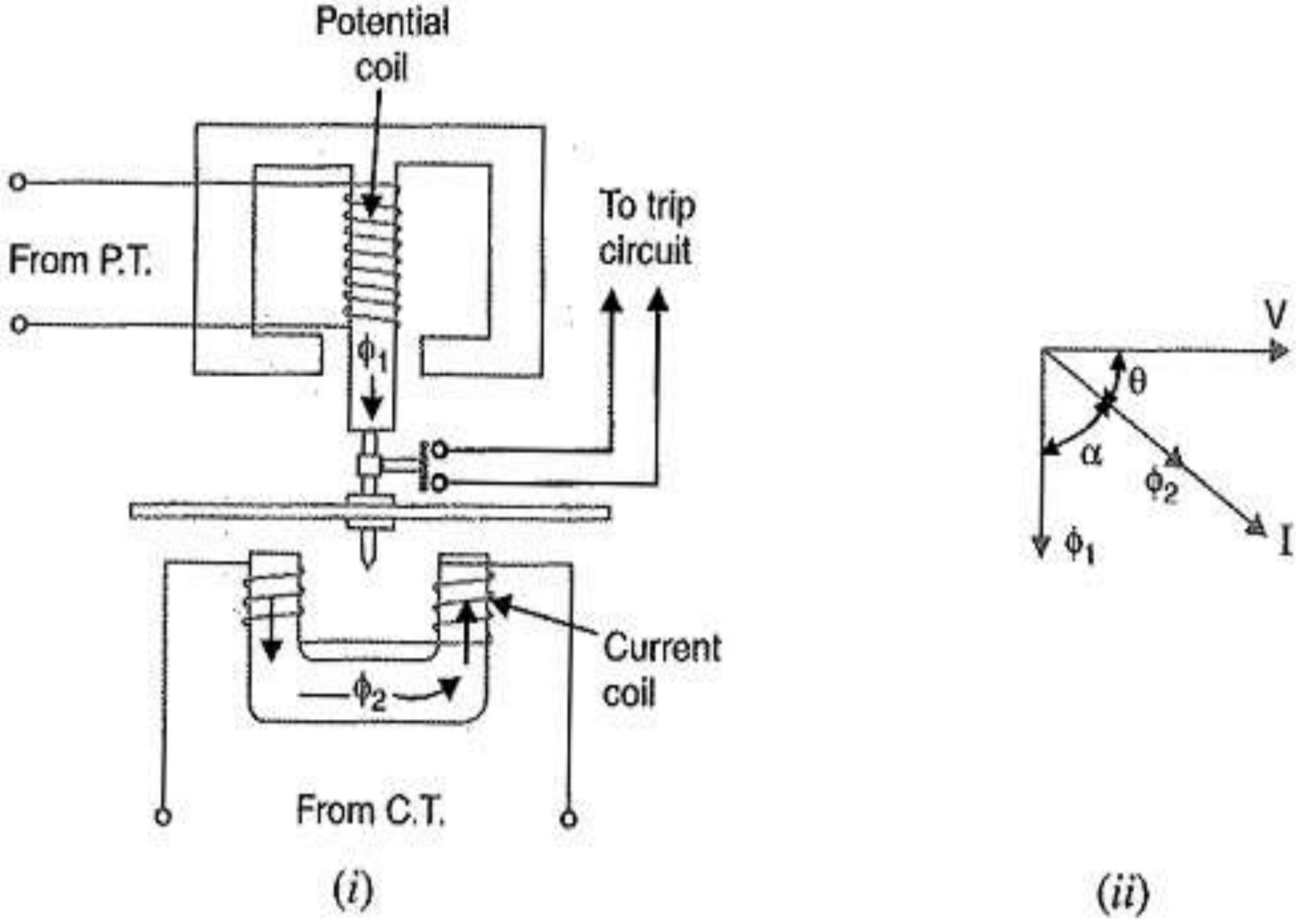


Fig. 21.18

Torque Equation

$T \propto \varphi 1\ \varphi 2 \sin \alpha$

Since φ1 ∝ V, $\varphi 2 \propto I$ and $\alpha = 90 - \theta$

$\therefore T \propto V I \sin (90 - \theta)$

$T \propto V I \cos \theta$

T ∝ power in the circuit

Induction Type Over Current Relay(directional)

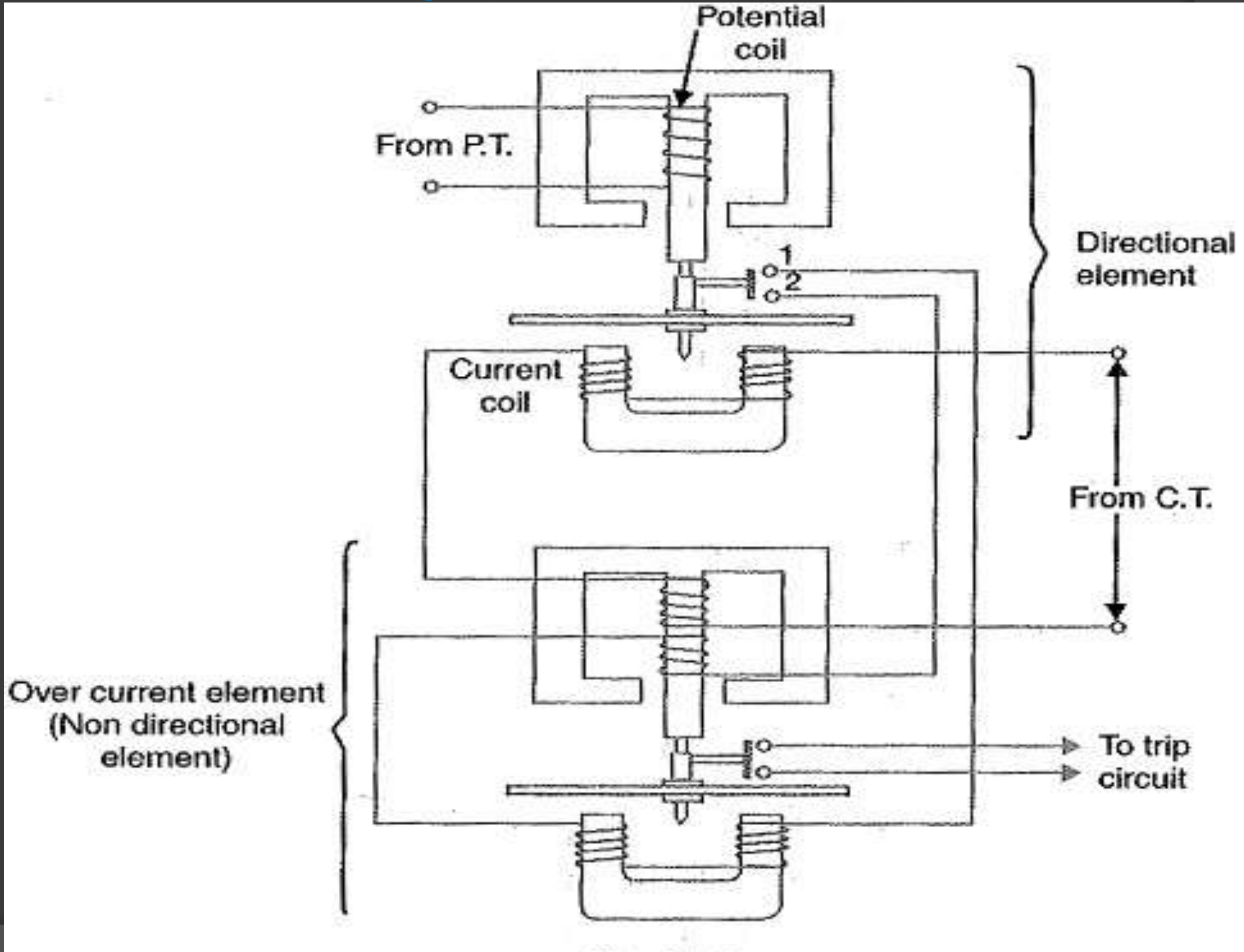


Fig. 21.19

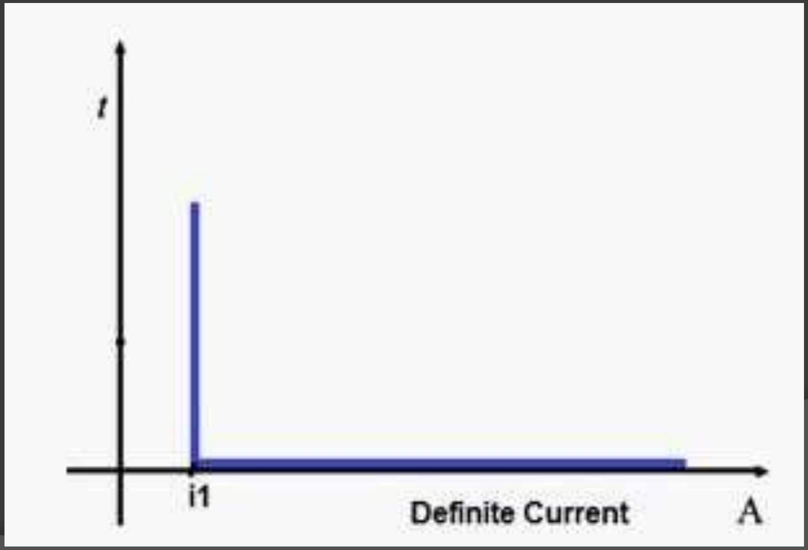
CHARACTERISTICS OF OVER CURRENT RELAYS

Depending on the time of operation of relay

- Instantaneous Over-current Relay
- Inverse time over current Relay
- Inverse definite minimum time (IDMT) over-current Relay
- Very Inverse Relay
- Extremely Inverse Relay

Instantaneous Over-current Relay

- **Instantaneous Over-current Relay is one in which no intentional time delay is provided for the operation.**
- **The time of operation of such Relay is approximately 100 ms.**
- **Instantaneous Over-current relay is employed where the impedance between the source and the Relay is small as compared with the impedance of the section to be provided.**



Important Features Of An Instantaneous Over-current Relay

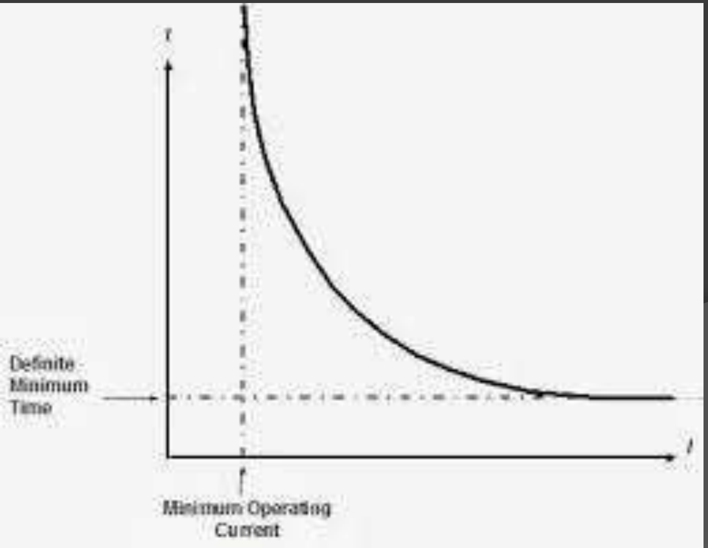
- Operates in a definite time when current exceeds its Pick-up value.
- Its operation criterion is only current magnitude.
- Operating time is constant.
- There is no intentional time delay.
- The relay located furthest from the source operate for a low current value
- The operating currents are progressively increased for the other relays when moving towards the source.

Inverse time over current Relay

- Inverse time over-current Relay is one in which the time of Operation of Relay decreases as the fault current increases.
- The more the fault current the lesser will be the time of operation of the Relay.
- Normally it has more inverse characteristic near the pick-up value which in turn means that if fault current is equal to pick-up value then the relay will take infinite time to operate.

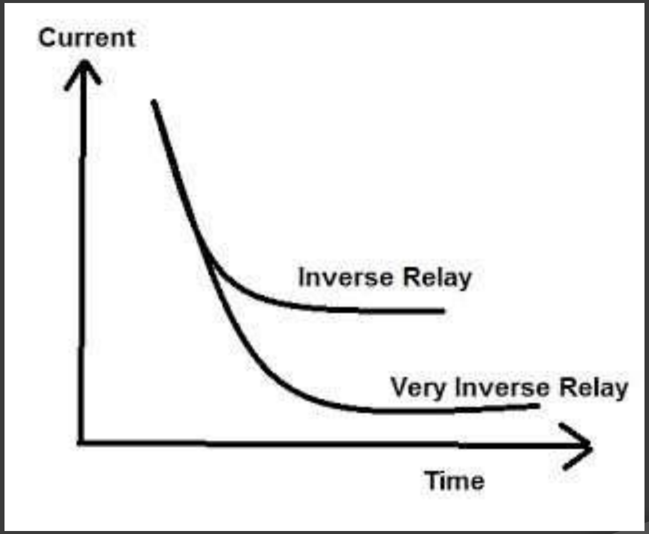
Inverse definite minimum time (IDMT) over-current Relay:

- **Inverse definite minimum time (IDMT) over-current Relay is one in which the operating time is approximately inversely proportional to the fault current near pick-up value and then becomes constant above the pick-up value of the relay.**
- **The time of operation at Pick-up value is nearly very high and as the fault current increases the time of operation decreases maintaining some definite time.**



Very Inverse Relay

- Very Inverse Relay is one in which the Time of operation is inverse with respect to fault current over a wide range



Extremely Inverse Relay

- Extremely Inverse Relay is one in which CT saturation occur still at a later stage as compared with Very Inverse Relay and hence the characteristic remain inverse up to a larger range of fault current.
- The equation describing the Extremely Inverse Relay is $I^2t = K$ where I is operating current and t is time of operation of the Relay.

$$k = \frac{\beta}{(I / I_o)^{\alpha} - 1}$$

K = Time of actuation

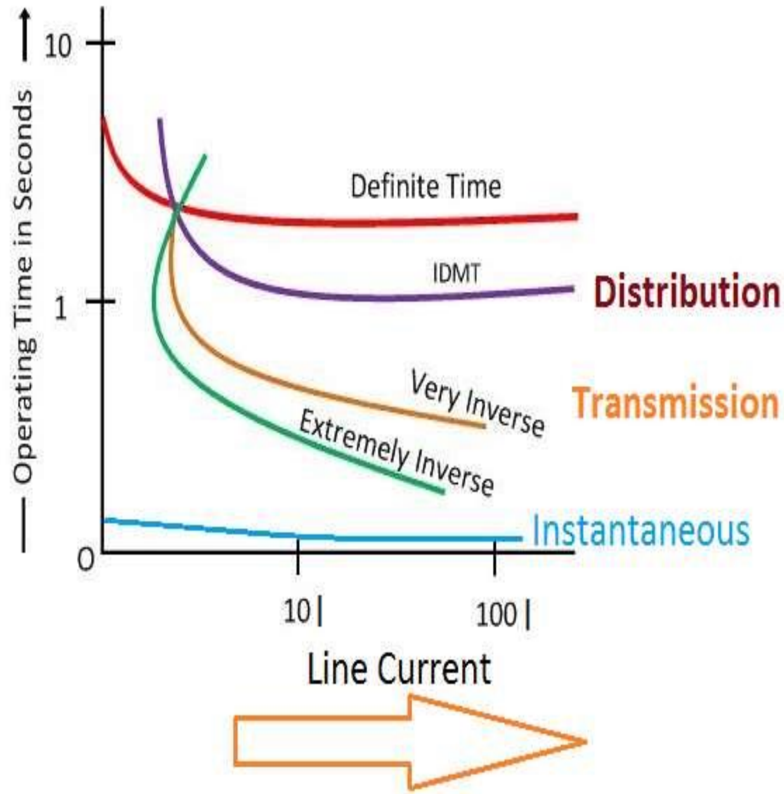
α, β = Constant which depends on the type of Relay

I = Fault Current

I_0 = Pick-up current

Value of α and β for different types of Relay

6 Tyes Over Current Relay



Characteristic of Various Overcurrent Relay

T=0 sec

I= Ipickup

Universal Relay Torque Equation

➢The universal torque equation explains the working of an electrical relay. The relay has some arrangement of electromagnetic.

➢These electromagnetic consist current and voltage windings. The current through the winding produces magnetic flux.

➢ And the torque is produced by the interaction of the flux of the same winding or between the flux of both the windings.

$$\text{Torque Developed by curent windings} = K_1 I^2$$

$$\text{Torque developed by voltage winding} = K_1 V^2$$

➢If both the current and voltage windings are used, the torque developed by the interaction between the fluxes is given by the equation

$$= K_3 VI cos(\theta - \tau)$$

Where θ is the angle between V and I and the τ is the relay maximum torque angle.

➢If the relay has current, voltage and the torque angle, the torque will be developed, and it will be given as

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

where K_1, K_2, K_3 are the tap setting or constant of V and I. The K_4 is the mechanical restraint due to spring

UNIT – III
PROTECTION OF GENERATORS & TRANSFORMERS

Protection of Generators against Stator Faults, Rotor Faults and Abnormal Conditions. Restricted Earth Fault and Inter-Turn Fault Protection – calculation of percentage winding unprotected. Protection of Transformers: Percentage Differential Protection, Numerical Problems on Design of CT Ratio, Buchholtz Relay Protection, Numerical Problems.

Introduction:

- In a generating station the generator and transformer are the most expensive equipments and hence it is desirable to employ a protective system to isolate the faulty equipment as quickly as possible to keep the healthy section in normal operation and to ensure uninterruptable power supply.
- The basic electrical quantities those are likely to change during abnormal fault conditions are current,voltage,phase angle and frequency . Protective relays utilizes one or more of these quantities to detect abnormal conditions in a power system.

Generator faults

- Stator Winding Faults

- Rotor Circuit Faults

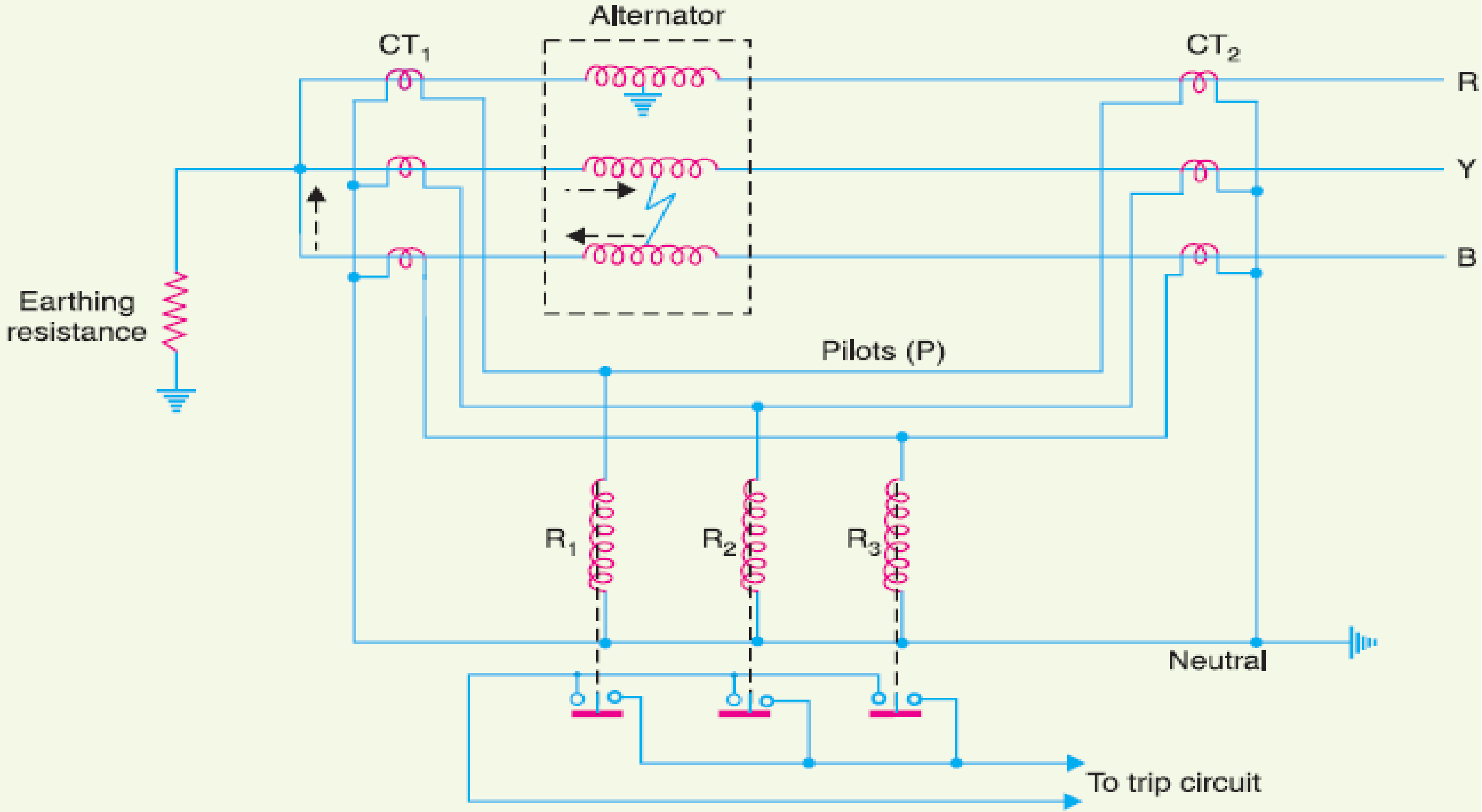
- Abnormal Conditions

Stator Winding Faults

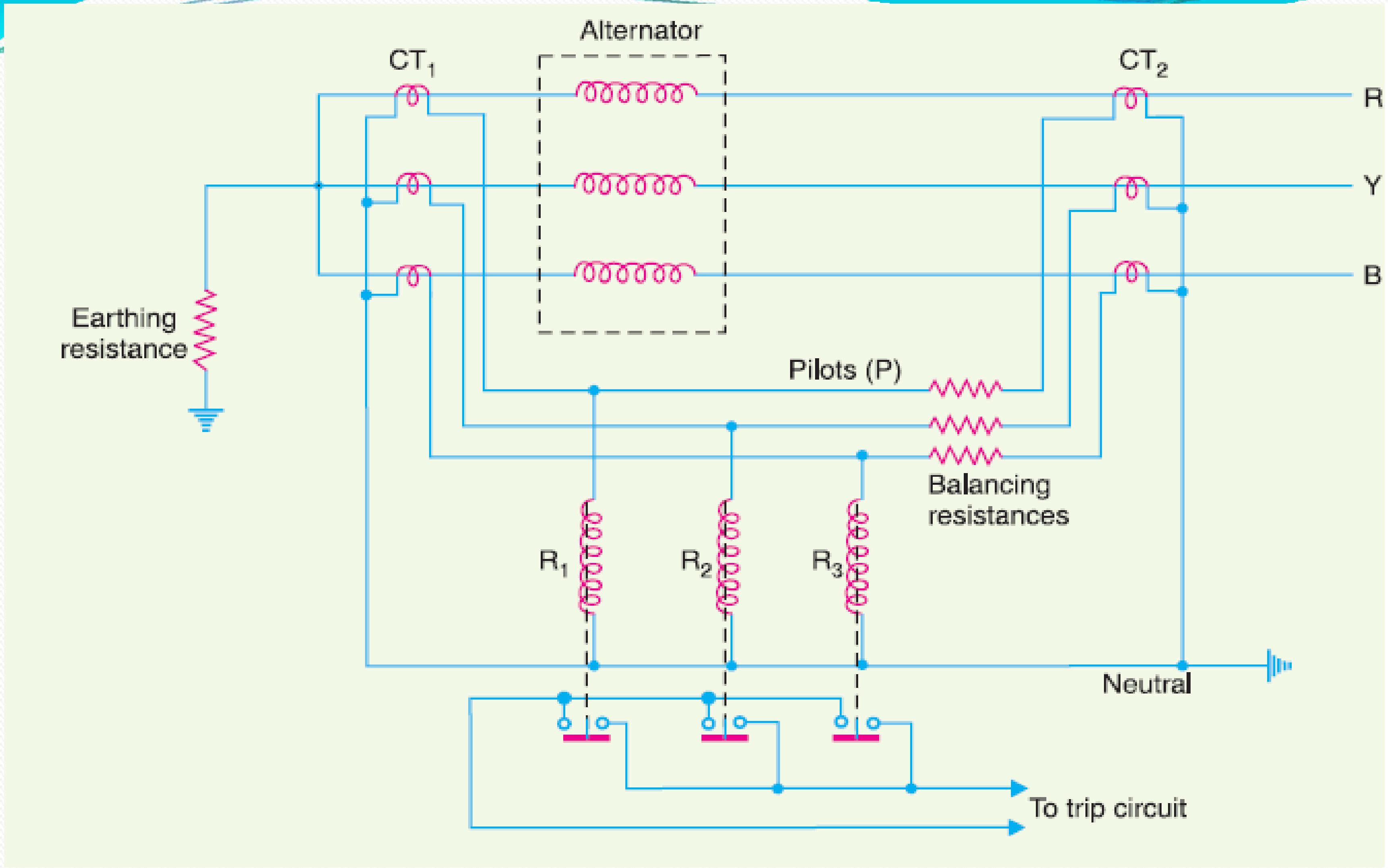
- Phase-to-earth Faults
- Phase-to-phase Faults
- Inter-turn Faults

Differential Protection or Merz-price Circulating Current Scheme

- CTs are provided at each end of the generator winding which is to be protected.(as shown in fig.)
- When there is no fault the differential current (I1-I2) through the relay is zero. So the relay will not operate.
- When the fault occurs the balance is disturbed and differential current (I1-I2) flows through the operating coil of the relay causing relay operation and the trip circuit of the circuit breaker is closed.



Differential protection of generator



Differential protection using balancing resistor

- In some cases, the alternator is located at a considerable distance from the switchgear.

- But relays are located close to the circuit breaker, therefore, it is not convenient to connect the relay coils to midpoints of the pilots.

- Under these circumstances, balancing resistances are inserted in the shorter lengths of the pilots so that the relay tapping points divide the whole secondary impedance of two sets of CTs into equal portions

Modified differential protection:

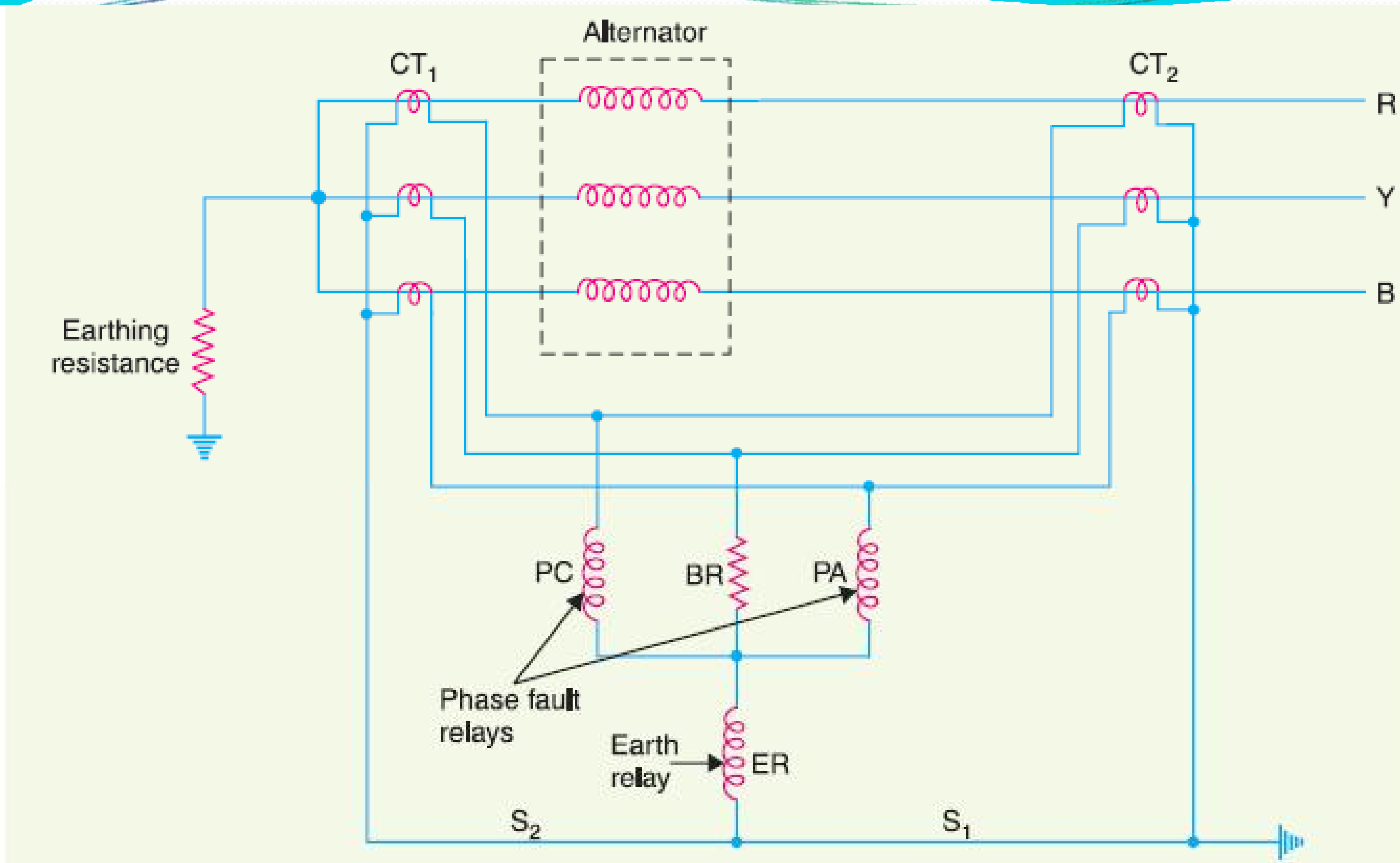
- Generally protection is made for 80 to 85% of the winding.
- If any fault occurs near the neutral point then the fault current is very small and relay does not operate.
- Modified differential protection scheme is used to over come this.
- Two phase elements (PC and PA) and balancing resistor(BR) is connected in star and the earth relay(ER) is connected between the star point and neutral pilot wire.

Operation

- Under normal operating conditions, currents at the two ends of each stator winding will be equal. Therefore, no current flows through the operating coils of the relays and the relays remain inoperative.

- If an earth-fault occurs on any one phase, the out-of-balance secondary current in CTs in that phase will flow through the earth relay ER and via pilot S1 or S2 to the neutral of the current transformers.

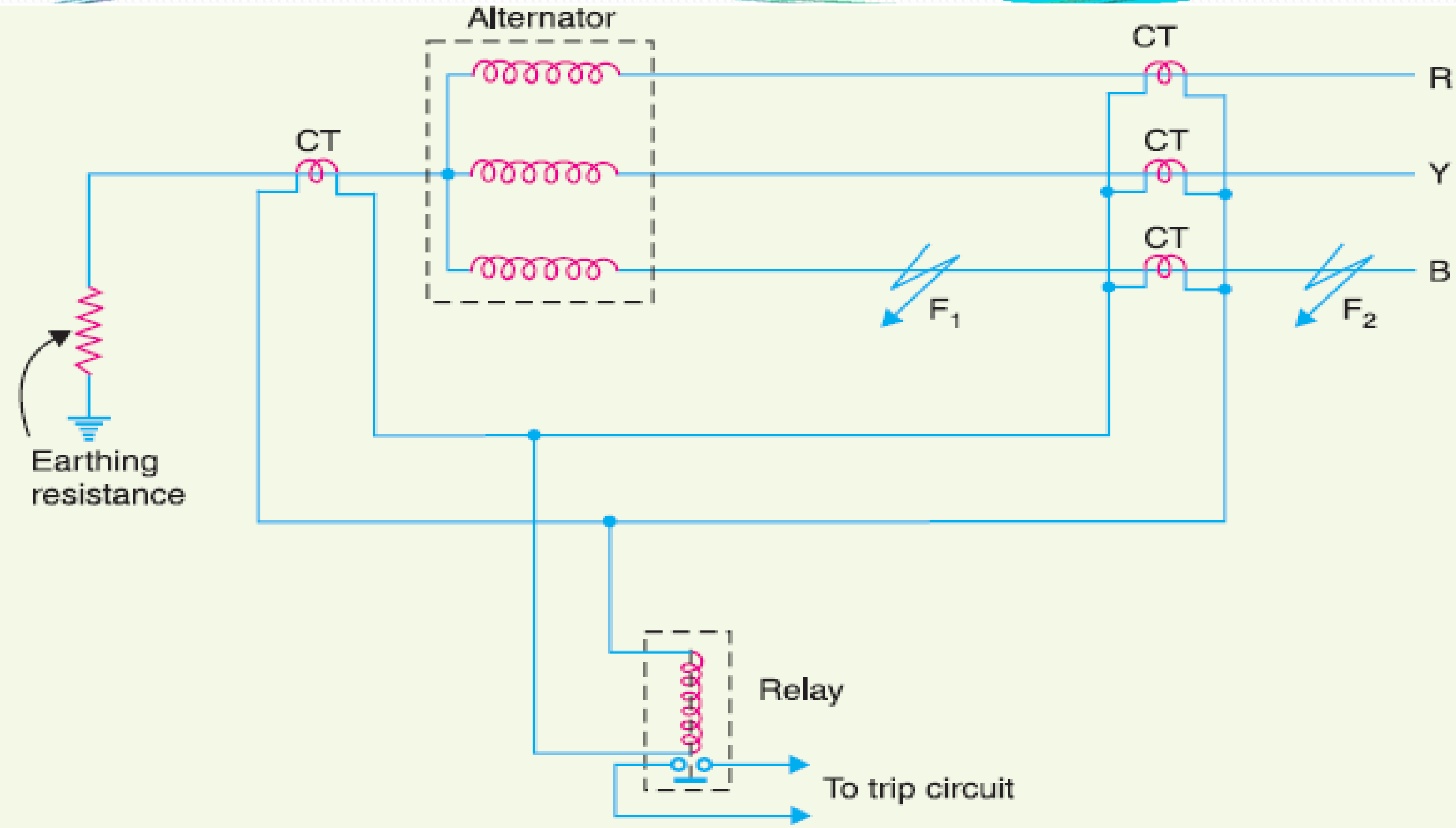
- If a fault occurs between two phases, the out-of-balance current will circulate round the two transformer secondaries via any two of the coils PA, BR, PC without passing through the earth relay ER. Therefore, only the phase-fault relays will operate.



Modified differential protection

Restricted or balanced earth fault protection:

- In case of small size generators star point is not available because it is made inside the generator and grounded through some low resistance then percentage differential relay for ground fault is provided and is known as restricted earth fault protection.
- This scheme can be used only for ground faults but not for phase faults.



Restricted or Balanced earth fault protection

Operation

- Under normal operating conditions, the currents flowing in the alternator leads and hence the currents flowing in secondaries of the line current transformers add to zero and no current flows through the relay.

- If an earth-fault develops at F2 external to the protected zone, the sum of the currents at the terminals of the alternator is exactly equal to the current in the neutral connection and hence no current flows through the relay.

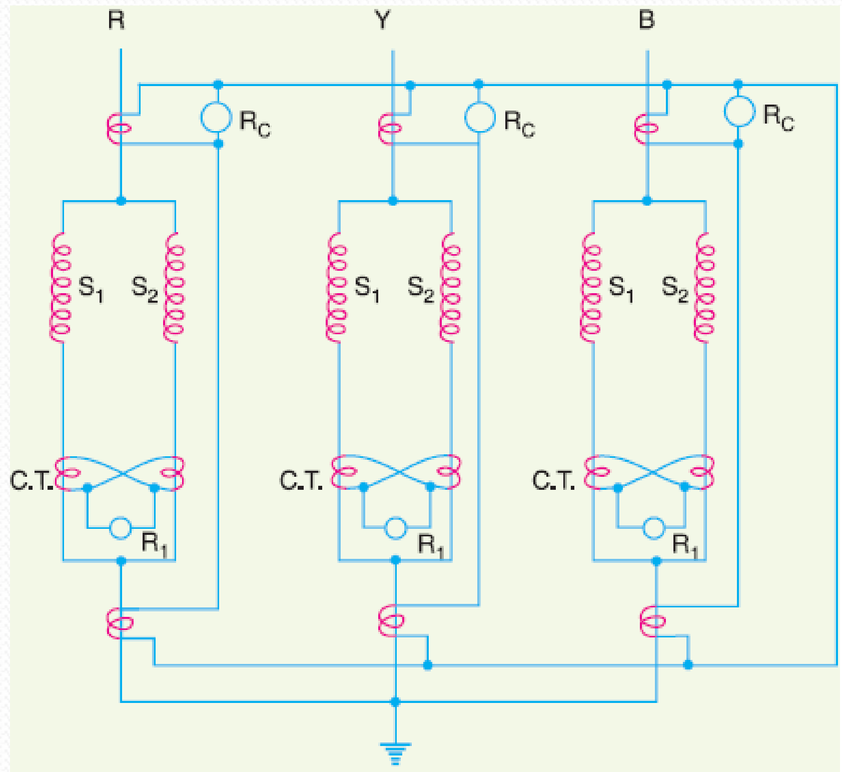
- When an earth-fault occurs at F1 or within the protected zone, these currents are no longer equal and the differential current flows through the operating coil of the relay. The relay then closes its contacts to disconnect the alternator from the system.

Stator inter-turn fault protection:

- Inter-turn fault on the same phase of the stator winding cannot be detected by transverse differential protection as it does not disturb the balance between the currents in neutral and high voltage CTs.

- Cross differential protection is used for inter-turn faults .

- Used in case of hydro-electric generator having double winding armature.
- As shown in figure relay Rc provides protection against phase to ground and phase to phase fault.
- The relay R1 provides protection against inter-turn faults.



ROTOR FAULTS & ITS PROTECTION

i. *Rotor Earth Fault*

ii. *Loss of Excitation*

iii. *Rotor Temperature*

❖ ***The Different Protection Schemes For Rotor :***

i. *Rotor Earth Fault Protection*

ii. *Loss of Excitation Protection*

iii. *Rotor Temperature Alarm*

ROTOR EARTH FAULT PROTECTION

ROTOR EARTH FAULT PROTECTION

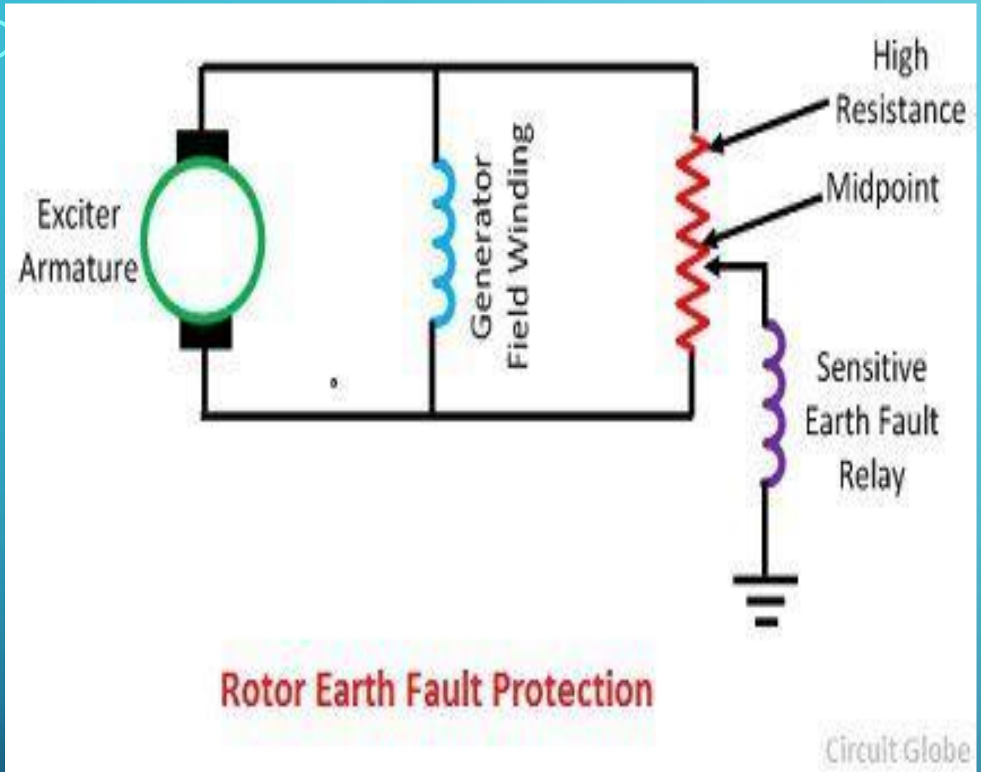
Methods of Earth fault protection

i. *Potentiometer method*

ii. *AC Injection method*

iii. *DC Injection methods*

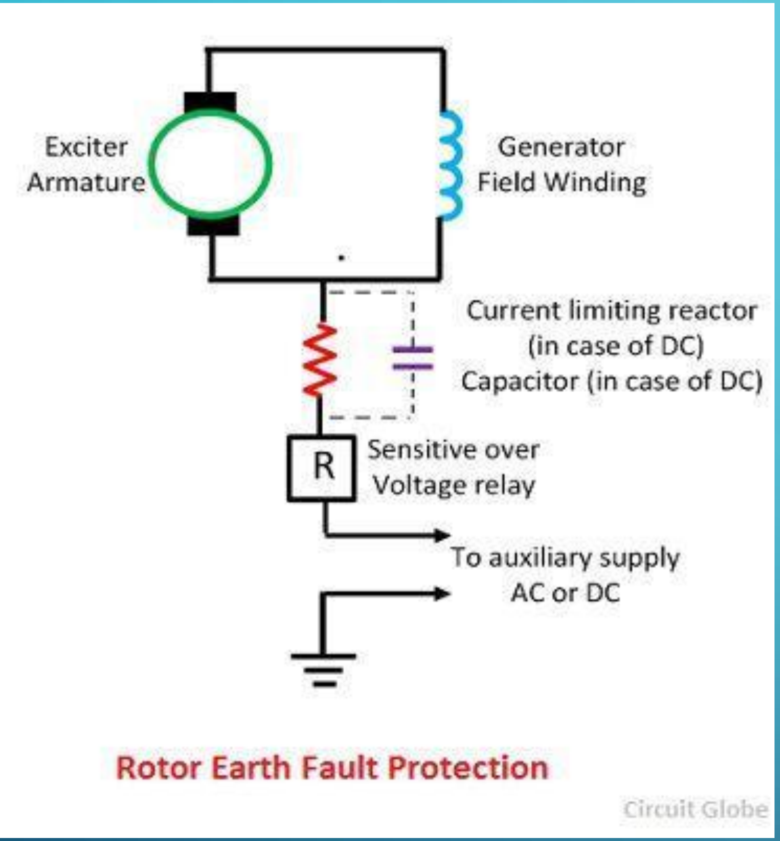
POTENTIOMETER METHOD



- a high resistance is connected across the field winding of the rotor.
- The midpoint of the resistor is grounded through a sensitive relay.
- When the fault occurs the relay detect the fault and send the tripping command to the breaker.

Disadvantage : It can detect the fault for most of the rotor circuit except the rotor centre point. This difficulty can be overcome by shifting the tap on the resistor from centre to somewhere else.

AC INJECTION METHOD



- *In this method, alternating current is injected into the field winding circuit and ground along with a sensitive overvoltage relay and a current limiting capacitor.*
- *A single earth fault in the rotor will complete the circuit comprises the alternating current source, sensitive relay and earth fault. Thus, the earth fault is sensed by the relay.*

Disadvantage : The major disadvantage of such type of system is the leakage current that flows through the capacitor.

DC INJECTION METHOD

- The problem of the AC injection system can be overcome by using the DC injection method.
- This method is simple and has no problem of leakage currents.
- The one terminal of the sensitive relay is connected to the exciter, and the other terminal is connected to the negative terminal of the DC source.
- The positive terminal of the DC source is grounded.
- When the earth fault occurs, the fault current will complete the circuit path, and the fault is sensed by the relay.

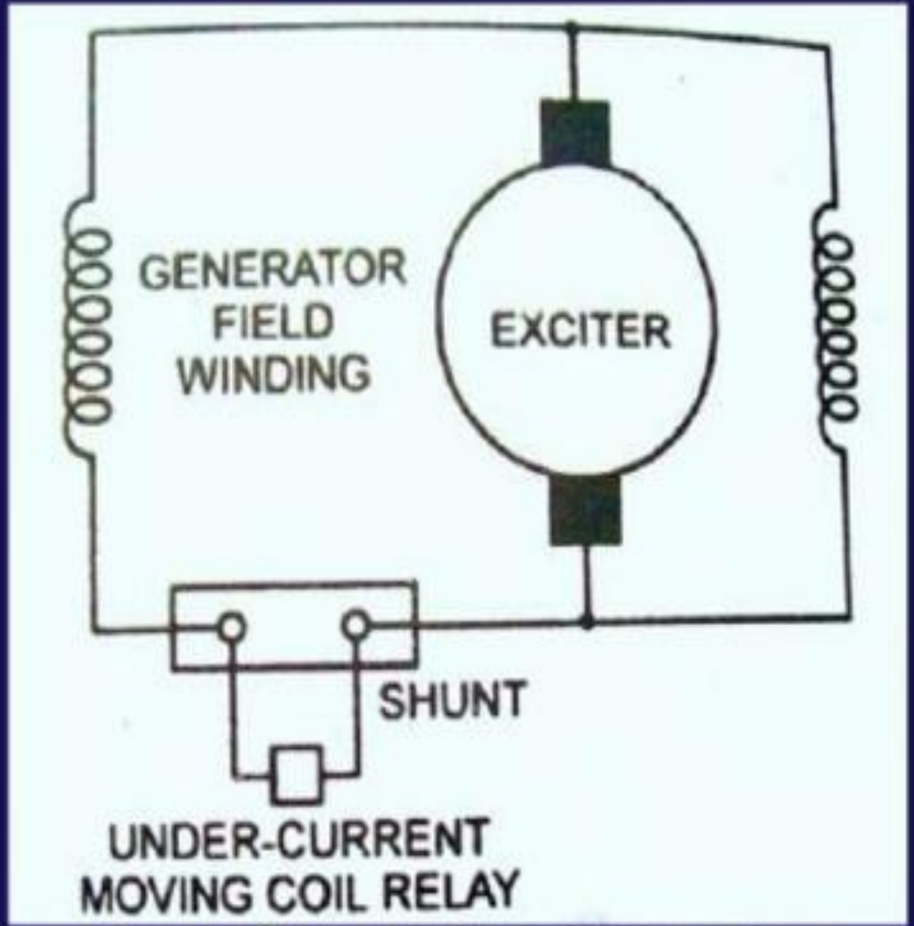
LOSS OF EXCITATION PROTECTION

- When the excitation of generator is lost it operates as an Induction generator. It derives excitation from the system and supply power at leading power factor which may cause-

i. A fall in voltage causes loss of synchronism and system instability.

ii. Over heating of rotor due to induction current on it.

- The relay mostly used for this type of protection is Directional distance type relay.

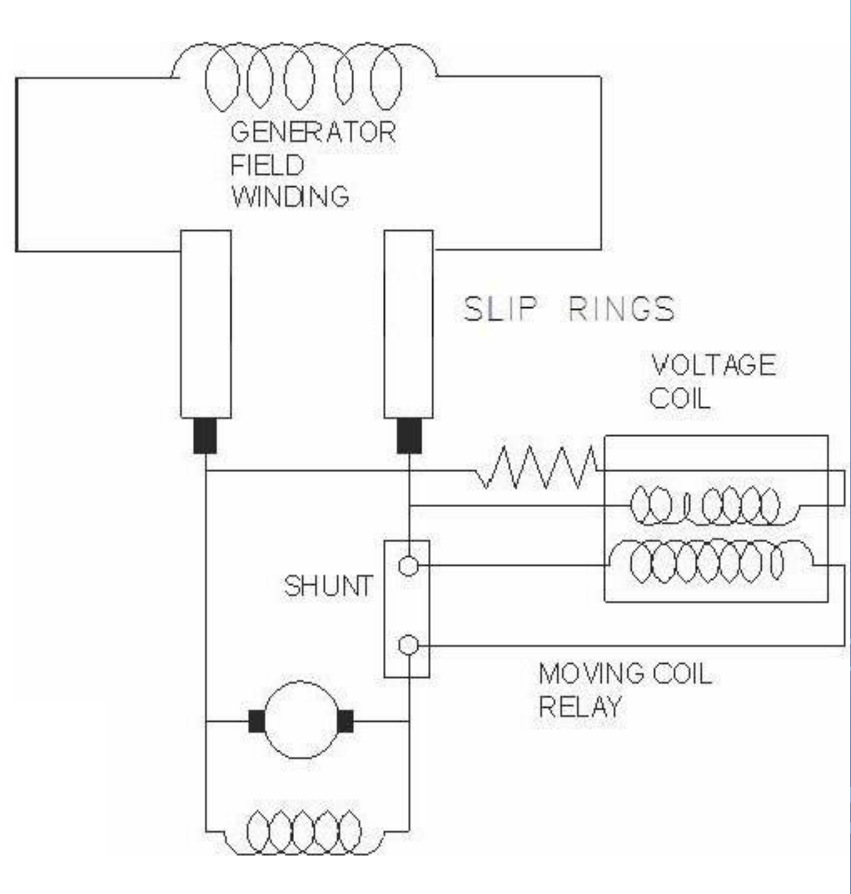


Loss of Excitation Protection

ROTOR TEMPERATURE ALARM

ROTOR TEMPERATURE ALARM

- *This type of protection scheme is installed generally in large alternators.*
- *It indicates the level of temperature but not the actual hot spot temperature.*
- *The relay measures the temperature by measuring the resistance(as shown in fig).*
- *The relay measures the ratio of voltage & current.*



Abnormal conditions of alternator

- **Failure Of Prime-mover**
- **Failure Of Field**
- **Over Current**
- **Over Speed**
- **Overvoltage**
- **Unbalanced Loading**
- **Stator Winding Faults**

1.Failure of prime-mover:

When input to the prime-mover fails, the alternator runs as a synchronous motor and draws some current from the supply system. This motoring conditions is known as “inverted running”.

- In case of turbo-alternator sets, failure of steam supply may cause inverted running.
- If the steam supply is gradually restored, the alternator will pick up load without disturbing the system.
- If the steam failure is likely to be prolonged, the machine can be safely isolated by the control room attendant since this condition is relatively harmless.

- In case of hydro-generator sets, protection against inverted running is achieved by providing mechanical devices on the water-wheel. When the water flow drops to an insufficient rate to maintain the electrical output, the alternator is disconnected from the system(manually).

- Diesel engine driven alternators, when running inverted, draw a considerable amount of power from the supply system and it is a usual practice to provide protection against motoring in order to avoid damage due to possible mechanical seizure. This is achieved by applying reverse power relays to the alternators which isolate the latter during their motoring action.

2.Failure of field

- The chances of field failure of alternators are undoubtedly very rare.
- Even if it does occur, no immediate damage will be caused by permitting the alternator to run without a field for a short-period.
- It is sufficient to rely on the control room attendant to disconnect the faulty alternator manually from the system bus-bars.

3.Over current

- It occurs mainly due to partial breakdown of winding insulation or due to overload on the supply system.
- On the occurrence of an overload, the alternators can be disconnected manually.

4.Over speed

- The chief cause of over speed is the sudden loss of all or the major part of load on the alternator.
- Modern alternators are usually provided with mechanical centrifugal devices mounted on their driving shafts to trip the main valve of the prime-mover when a dangerous over speed occurs.

5.Overvoltage

- overvoltage in an alternator occurs when speed of the prime-mover increases due to sudden loss of the alternator load.

❑In case of steam-turbine driven alternators, the control governors are very sensitive to speed variations. They exercise a continuous check on over speed and thus prevent the occurrence of overvoltage on the generating unit. Therefore, over-voltage protection is not provided on turbo-alternator sets.

❑In case of hydro-generator, the control governors are much less sensitive to rise in speed due to loss of load. The over-voltage relays are operated from a voltage supply derived from the generator terminals. The relays are so arranged that when the generated voltage rises 20% above the normal value.

6.Unbalanced loading

Unbalanced loading means that there are different phase currents in the alternator

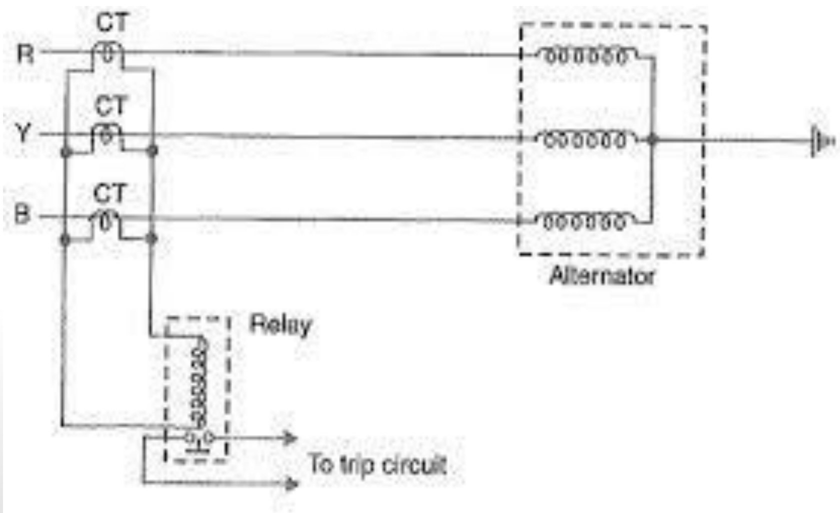


Fig. 22.1

4. It does not require current transformers with air gaps or special balancing features.

5.6 Restricted Earth Fault Protection of Generator

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

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

In this scheme, the value of earth resistance, relay setting, current rating of earth resistance must be carefully selected. The earth faults are rare near the neutral point as the voltage of neutral point with respect to earth is very less. But when earth fault occurs near the neutral point then the insufficient voltage across the fault drives very low fault current than the pick up current of relay coil. Hence the relay coil remains inoperative. Thus 15 to 20% winding from the neutral side remains unprotected in this scheme. Hence it is called restricted earth fault protection. It is usual practice to protect 85% of the winding.

The restricted earth fault protection scheme is shown in the Fig. 5.7.

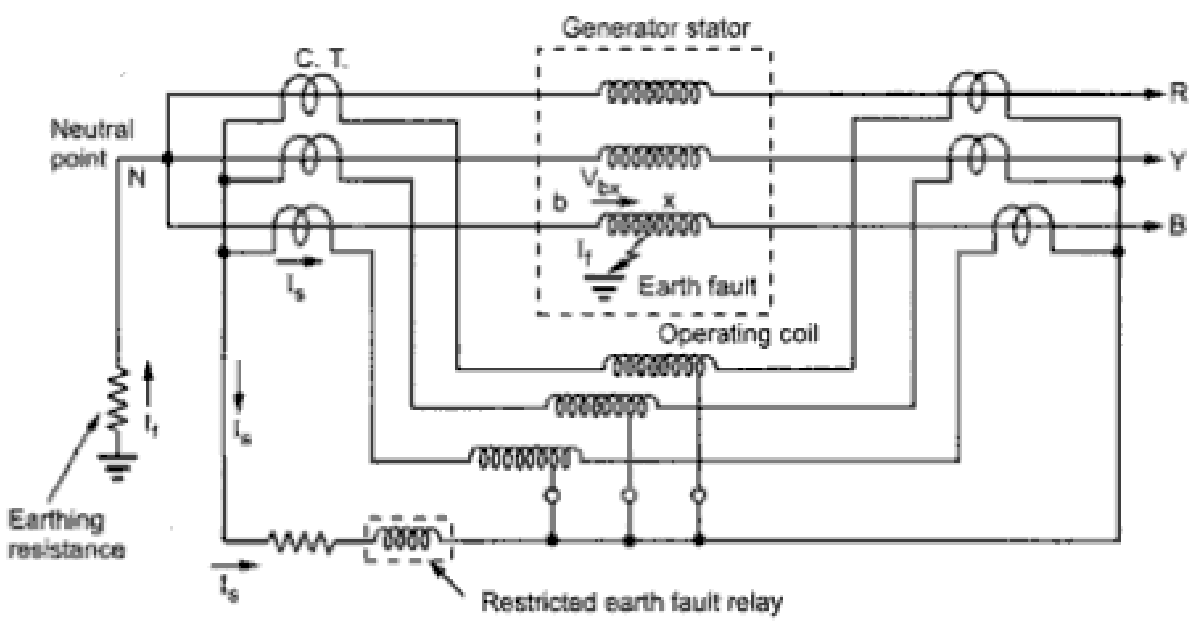


Fig. 5.7 Restricted earth fault protection

Consider that earth fault occurs on phase B due to breakdown of its insulation to earth, as shown in the Fig. 5.7. The fault current I_f will flow through the core, frame of machine to earth and complete the path through the earthing resistance. The C.T. secondary current I_s flows through the operating coil and the restricted earth fault relay coil of the differential protection. The setting of restricted earth fault relay and setting of overcurrent relay are independent of each other. Under this secondary current I_s, the relay operates to trip the circuit breaker. The voltage V_{bx} is sufficient to drive the enough fault current I_f when the fault point x is away from the neutral point.

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

5.6.1 Effect of Earth Resistance on % of Winding Unprotected

Let us see the effect of earth resistance on the % of the winding which remains unprotected.

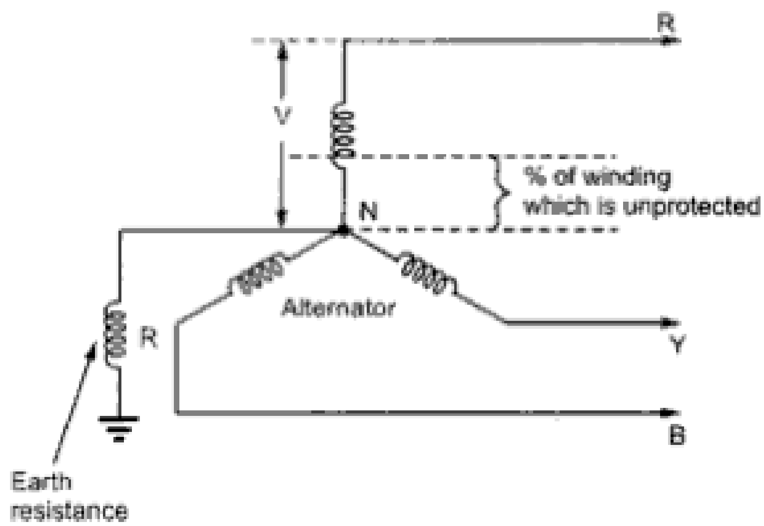


Fig. 5.8

Consider the earth resistance R used to limit earth fault current as shown in the Fig. 5.8.

The value of the resistance R limits the earth fault current.

If the resistance R is very small i.e. the neutral is almost solidly grounded, then the fault current is very high. But high fault currents are not desirable hence small R is not preferred for the large machines.

For low resistance R, the value of R is selected such that full load current passes through the neutral, for a full line to neutral voltage V.

In medium resistance R, the earth fault current is limited to about 200A for full line to neutral voltage V, for a 60 MW machine.

In high resistance R, the earth fault current is limited to about 10 A. This is used for distribution transformers and generator-transformer units.

Now higher the value of earth resistance R, less is the earth fault current and less percentage of winding gets protected. Large percentage of winding remains unprotected.

Let V = Full line to neutral voltage

I = Full load current of largest capacity generator

R = Earth resistance

Then the value of the resistance R is,

$$R = \frac{V}{I}$$

And the percentage of winding unprotected is given by,

$$\text{\% of winding } \mathbf{unprotected} = \frac{RI_o}{V} \times 100$$

where I_o = Minimum operating current in the primary of C.T.

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

Greater percentage of windings of small capacity machines running parallel get protected.

Example 5.1 : *A generator is protected by restricted earth fault protection. The generator ratings are 13.2 kV, 10 MVA. The percentage of winding protected against phase to ground fault is 85%. The relay setting is such that it trips for 20% out of balance. Calculate the resistance to be added in the neutral to ground connection.*

Solution : The given values,

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

From rating, calculate the full load current,

$$I = \frac{\text{Rating in VA}}{\sqrt{3}\, V_L} = \frac{10 \times 10^6}{\sqrt{3} \times 13.2 \times 10^3}$$

$$= 437.386 \text{ A}$$

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

$$\therefore \quad I_o = 4387.386 \times \frac{20}{100} = 87.477 \text{ A}$$

$$= \text{Minimum operating current}$$

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

$$= \frac{13.2\times10^3}{\sqrt{3}} = 7621.02 \text{ V}$$

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

$$\therefore \quad 15 = \frac{RI_0}{V}\times100$$

$$\therefore \quad 15 = \frac{R\times87.477}{7621.02}\times100$$

$$\therefore \quad R = 13.068\ \Omega$$

➡ **Example 5.2 :** *A star connected 3 phase, 12 MVA, 11 kV alternator has a phase reactance of 10%. It is protected by Merz-Price circulating current scheme which is set to operate for fault current not less than 200 A. Calculate the value of earthing resistance to be provided in order to ensure that only 15% of the alternator winding remains unprotected.*

Solution : The given values are,

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

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

$$\therefore \quad 12\times10^6 = \sqrt{3}\times11\times10^3\times I_L$$

$$\therefore \quad I_L = \frac{12\times10^6}{\sqrt{3}\times11\times10^3}$$

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

$$V = \frac{V_L}{\sqrt{3}} = \frac{11\times10^3}{\sqrt{3}} = 6350.8529 \text{ V}$$

$$\% \text{ Reactance} = \frac{IX}{V}\times100$$

where X = reactance per phase

and I = rated current

$$\therefore \quad 10 = \frac{629.8366\,X}{6350.8529}\times100$$

$$\therefore \quad X = 1.0083\ \Omega$$

∴ Reactance of unprotected winding

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

$$= \frac{15}{100} \times 1.0083$$

$$= 0.1512\ \Omega$$

$$v = \text{voltage induced in unprotected winding}$$

$$= \frac{15}{100} \times V = 0.15 \times 6350.8529$$

$$= 952.6279\ V$$

$$i = \text{Fault current}$$

$$= 200\ A$$

$$Z = \text{Impedance offered to the fault}$$

$$= \frac{v}{i} = \frac{952.6279}{200}$$

$$= 4.7631\ \Omega \qquad \ldots (1)$$

Now $$Z = r + j\,\text{(reactance of unprotected winding)}$$

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

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

Equating (1) and (2),

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

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

$$\therefore \quad r^2 = 22.6646$$

$$\therefore \quad r = 4.7607\ \Omega$$

This is the earthing resistance required.

5.7 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 these 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 Fig. 5.9.

When 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.

PROTECTION OF TRANSFORMER

Introduction

Transformers are static devices, totally enclosed and generally oil immersed. Therefore, chances of faults occurring on them are very rare. But when fault occurring , It is very harmful for power system and our environment. So there are many protection system keep in back-up protection of power system safety.

COMMON FAULTS IN TRANSFORMER

(i) Open circuits

(ii) Overheating

(iii) winding short-circuits (earth-faults, phase-to-phase faults and inter-turn faults)

TYPES PROTECTION

- Buchholz Relay Protection
- Earth-fault Relay Protection
- Over Current Protection
- Differential Protection

- Buchholz devices providing protection against all kinds of incipient faults i.e. slow-developing faults such as insulation failure of windings, core heating, fall of oil level due to leaky joints etc.

- Earth-fault relays providing protection against earth-faults only.

- Over current relays providing protection mainly against phase-to-phase faults and overloading.

- Differential system (or circulating-current system) providing protection against both earth and phase faults

Buchholz Relay

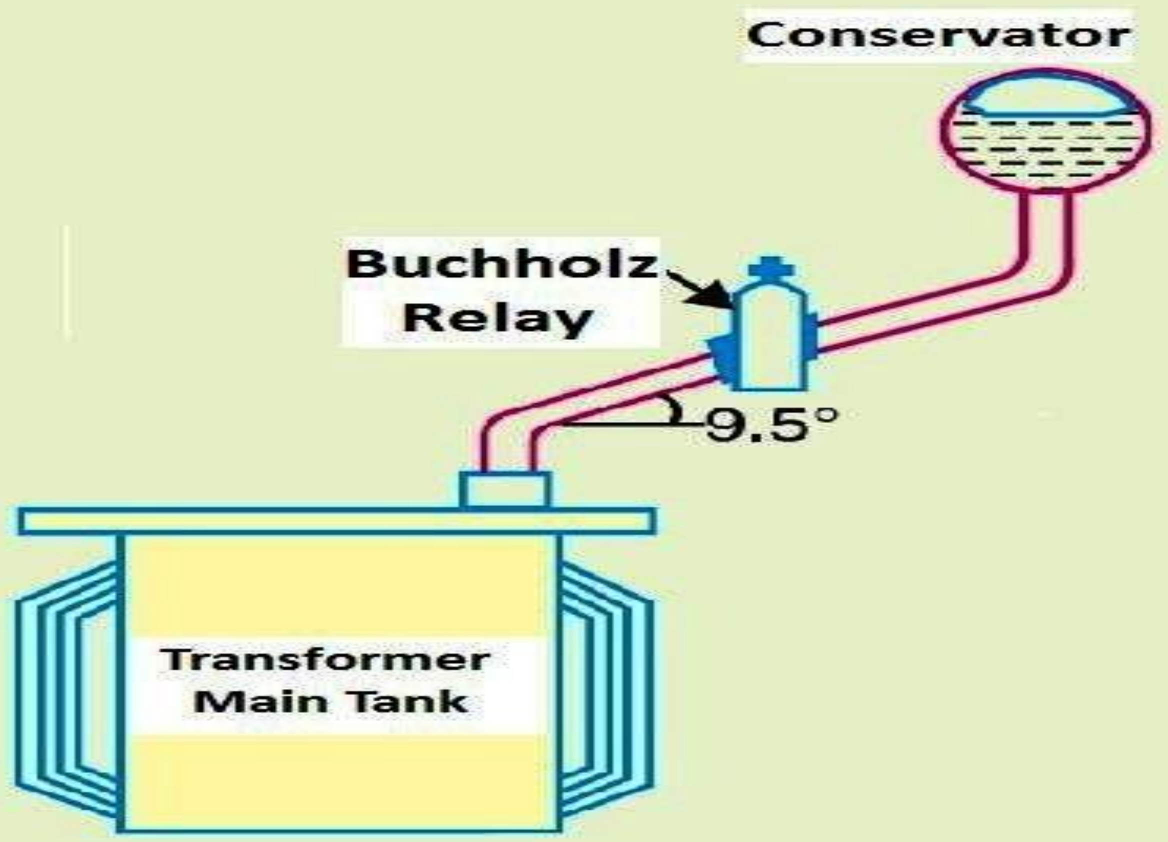
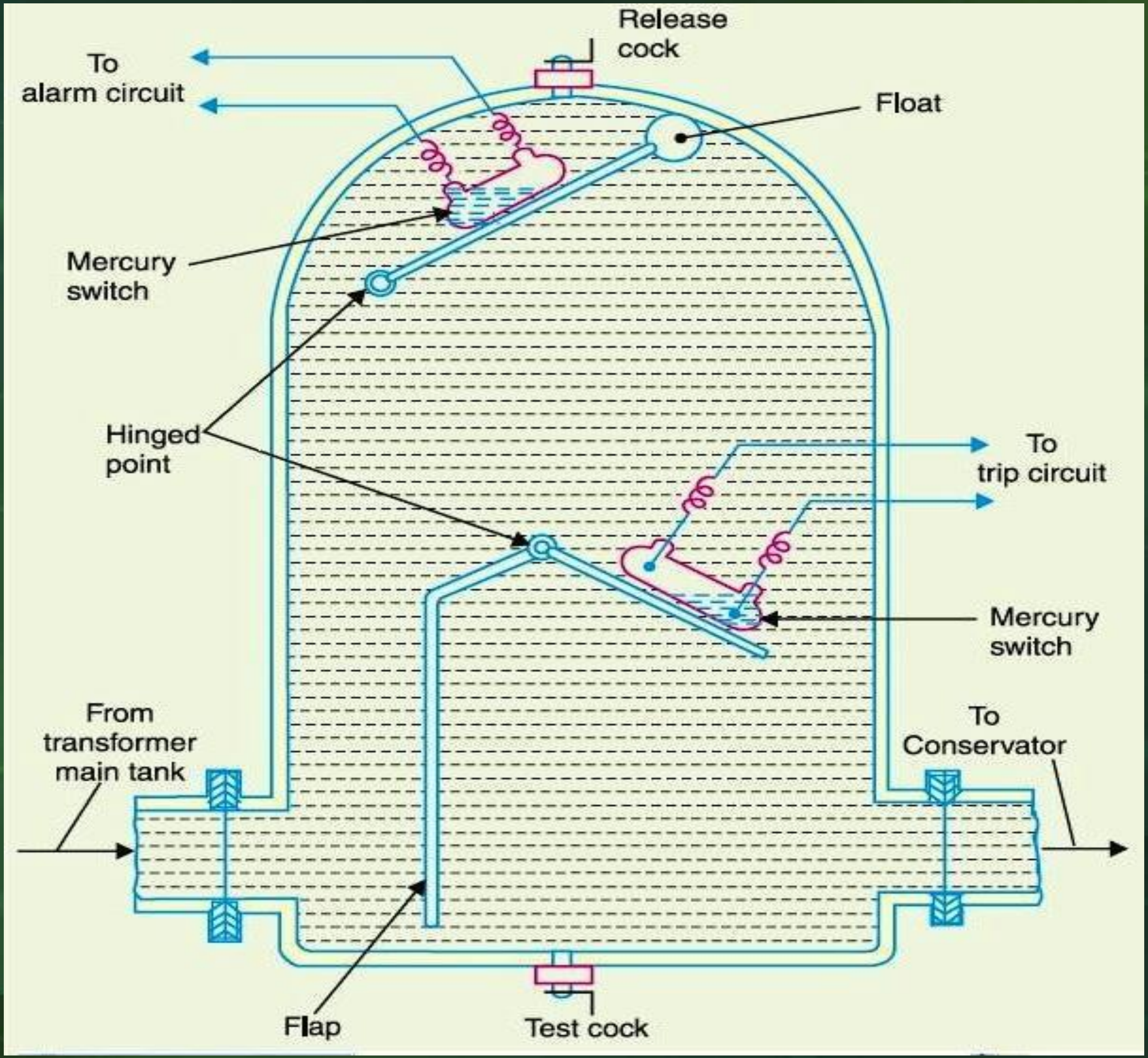


Fig: Buchholz Relay with Constructional Details

Buchholz Relay

- Buchholz relay is a gas-actuated relay installed in oil immersed transformers for protection against all kinds of faults.
- Named after its inventor, Buchholz, it is used to give an alarm in case of incipient (i.e. slow-developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults.
- It is usually installed in the pipe connecting the conservator to the main tank
- It is a universal practice to use Buchholz relays on all such oil immersed transformers having ratings in *excess of 750 kVA.

Buchholz Relay



CONSTRUCTION

- It takes the form of a domed vessel placed in the connecting pipe between the main tank and the conservator.

The device has two elements

- The upper element consists of a mercury type switch attached to a float.
- The lower element contains a mercury switch mounted on a hinged type flap located in the direct path of the flow of oil from the transformer to the conservator.
- The upper element closes an alarm circuit during incipient faults whereas the lower element is arranged to trip the circuit breaker in case of severe internal faults.

OPERATION

(i) In case of incipient faults within the transformer, the heat due to fault causes the decomposition of some transformer oil in the main tank. The products of decomposition contain more than 70% of hydrogen gas. The hydrogen gas being light tries to go into the conservator and in the process gets entrapped in the upper part of relay chamber. When a predetermined amount of gas gets accumulated, it exerts sufficient pressure on the float to cause it to tilt and close the contacts of mercury switch attached to it. This completes the alarm circuit to sound an *alarm.

(ii) If a serious fault occurs in the transformer, an enormous amount of gas is generated in the main tank. The oil in the main tank rushes towards the conservator via the Buchholz relay and in doing so tilts the flap to close the contacts of mercury switch. This completes the trip circuit to open the circuit breaker controlling the transformer.

Advantage

1.It is the simplest form of transformer protection.
2.It can be used high power application(up to 500Kva) It is the best protection system than any others.
3.It detects the incipient faults at a stage much earlier than is possible with other forms of protection.

Disadvantage

- It can only be used with oil immersed transformers equipped with conservator.

- The device can detect only faults below oil level in the transformer.

MERZ-PRICE CIRCULATING-CURRENT SCHEME
OR
DIFFERENTIAL PROTECTION

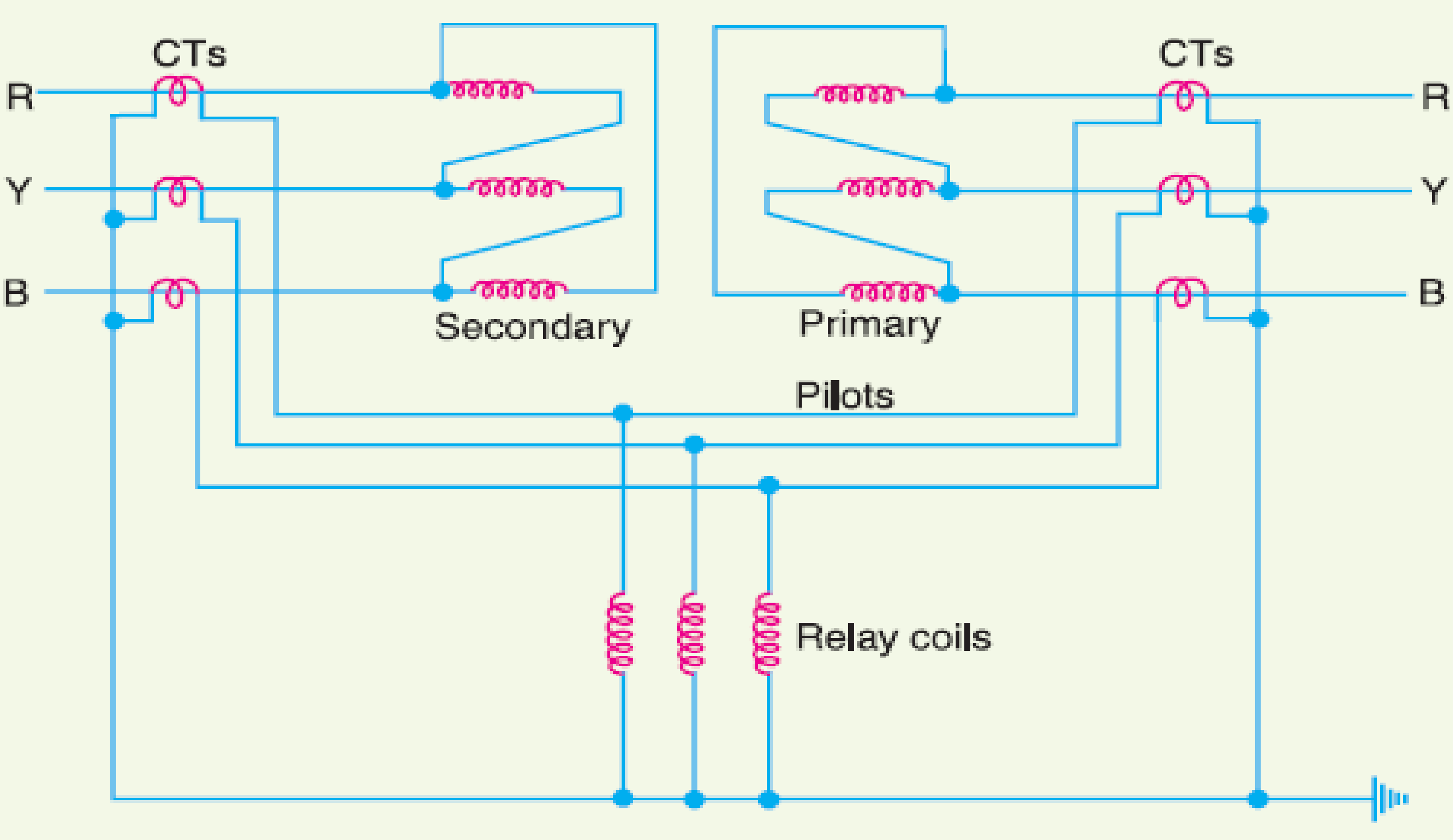


Fig. 22.15

CONSTRUCTION

- *CTs on the* two sides of the transformer are connected in star.

- This compensates for the phase difference between the power transformer primary and secondary.

- The *CTs on* the two sides are connected by pilot wires and one relay is used for each pair of *CTs.*

OPERATION

- During normal operating conditions, the secondaries of *CTs carry identical currents. Therefore, the currents entering and* leaving the pilot wires at both ends are the same and no current flows through the relays.

- If a ground or phase-to-phase fault occurs, the currents in the secondaries of *CTs will no longer be the same and* the differential current flowing through the relay circuit.

S. No.	Power transformer connections		Current transformer connections	
	Primary	Secondary	Primary	Secondary
1	Star with neutral earthed	Delta	Delta	Star
2	Delta	Delta	Star	Star
3	Star	Star with neutral earthed	Delta	Delta
4	Delta	Star with neutral earthed	Star	Delta

Example 7.1 : *A three phase power transformer having a line voltage ratio of 400 V to 33 kV is connected in star-delta. The C.T.s on 400 V side have current ratio as 1000/5. What must be the C.T. ratio on 33 kV side.*
Assume current on 400 V side of transformer to be 1000 A.

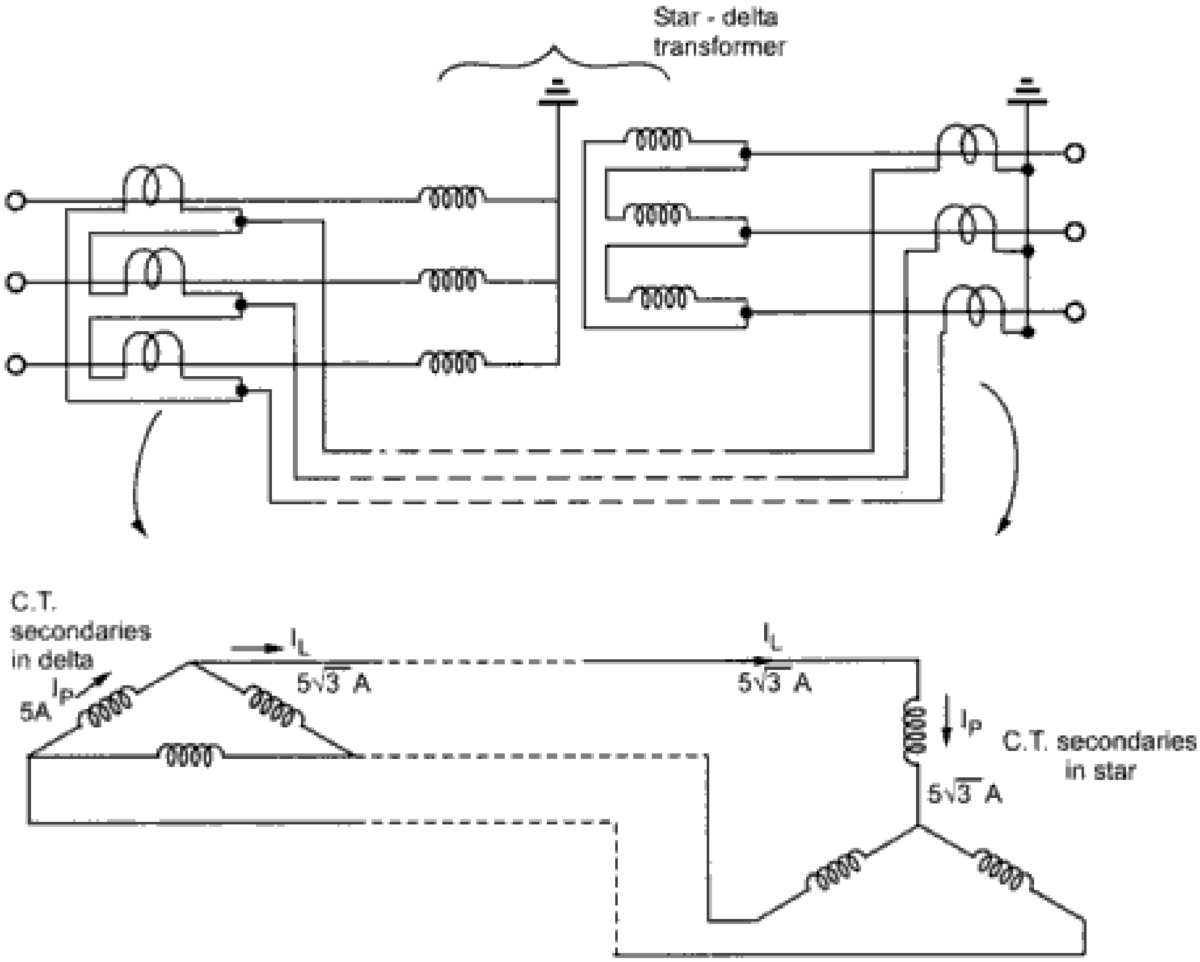


Fig. 7.4

Solution : The arrangement is shown in the Fig. 7.4.

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

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

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

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

$$I_P = 1000 \times \frac{5}{1000} = 5 \text{ A}$$

This is shown in the Fig. 7.4.

$$I_L = \sqrt{3}\, I_P = 5\sqrt{3} \quad \text{A}$$

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

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

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

$\therefore$ Primary apparent power = Secondary apparent power

$$\therefore \quad \sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2}$$

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

$$\therefore \quad I_{L2} = \frac{400\times 1000}{33000} = 12.12 \text{ A}$$

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

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

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

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

7.4 Problems Encountered in Differential Protection

The problems encountered in the simple differential protection are,

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

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

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

UNIT – IV
PROTECTION OF FEEDERS & LINES

Protection of Feeder (Radial & Ring Main) Using Over Current Relays. Protection of Transmission Line – 3 Zone Protection Using Distance Relays. Carrier Current Protection. Protection of Bus Bars.

UNIT-III

PROTECTION OF FEEDERS AND LINES

Transmission line: Transfer electrical power from generation station to distribution substation.

Feeder: To connect the consumer/load end with the substation. There are no tapping taken out of them.

The probability of faults occurring on the lines is much more due to their greater length and exposure to atmospheric conditions. This has called for many protective schemes as compared to alternators and transformers.

REQUIREMENTS OF LINE PROTECTION

- In the event of a short-circuit, the circuit breaker closest to the fault should open, all other circuit breakers remaining in a closed position.

- In case the nearest breaker to the fault fails to open, back-up protection should be provided by the adjacent circuit breakers.

- The relay operating time should be just as short as possible in order to maintain system stability, without unnecessary tripping of circuits.

COMMON METHODS OF LINE PROTECTION

- ❑ Time-graded over current protection
- ❑ Differential protection
- ❑ Distance protection

TYPES OF FEEDERS

- RADIAL FEEDERS
- RING MAIN FEEDERS
- PARALLEL FEEDERS

RADIAL FEEDER PROTECTION

- **A radial system is that power can flow only in one direction, from generator or supply end to the load.**

Disadvantage:-

Continuity of supply cannot be maintained at the receiving end in the event of fault.

TIME-GRADED OVER CURRENT PROTECTION

Time-graded protection of a radial feeder can be achieved by using

- **Definite Time Relays**
- **Inverse Time Relays.**

DEFINITE TIME RELAY

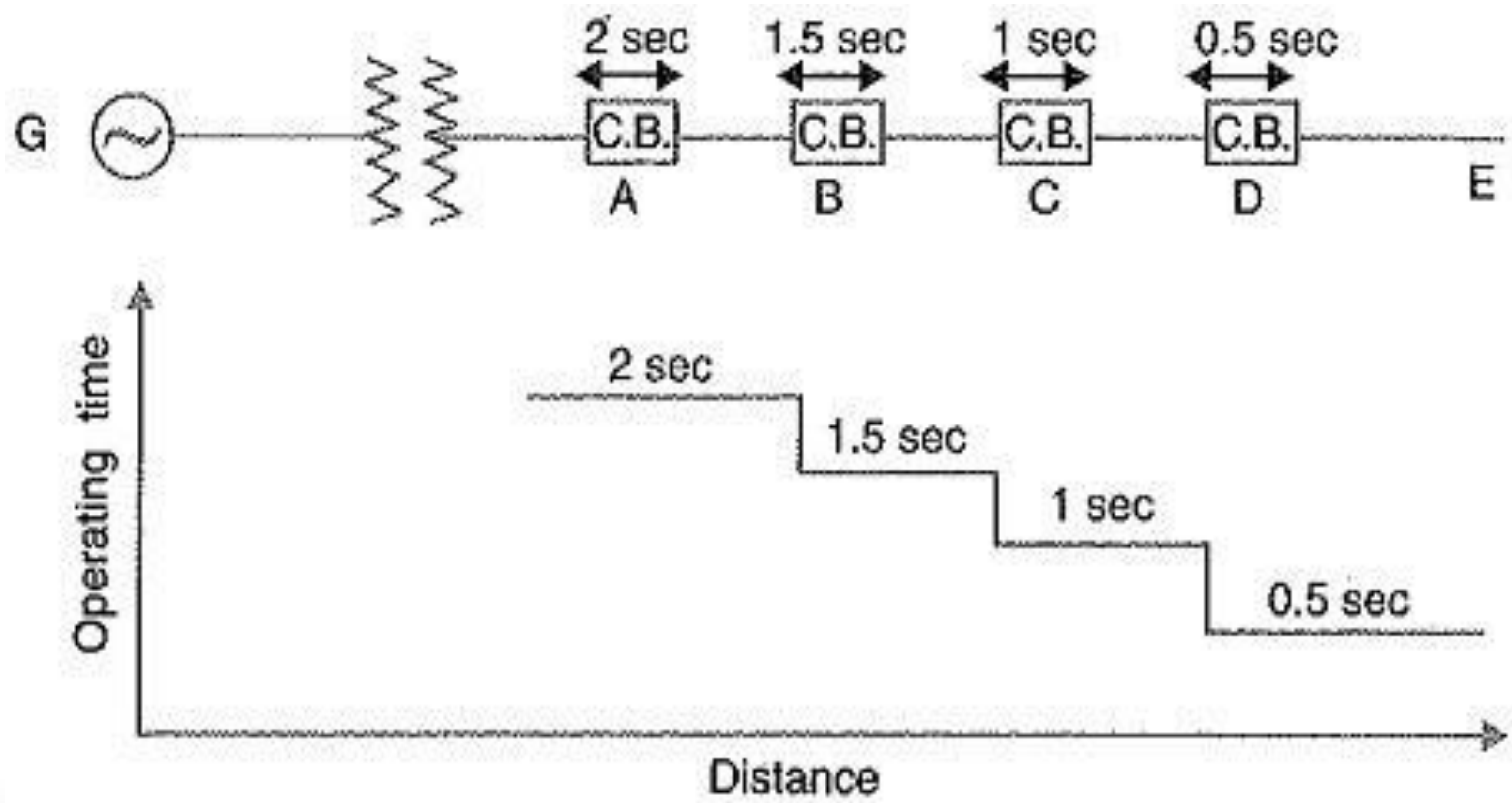


Fig. 23.4

OPERATION

- The time of operation of each relay is fixed and is independent of the operating current.

- The relay D has an operating time of 0·5 second while for other relays, time delay is successively increased by 0·5 second.

- If a fault occurs in the section DE, it will be cleared in 0·5 second by the relay and circuit breaker at D because all other relays have higher operating time.

- In this way only section DE of the system will be isolated. If the relay at D fails to trip, the relay at C will operate after a time delay of 0·5 second i.e. after 1 second from the occurrence of fault.

Disadvantage

- if there are a number of feeders in series, the tripping time for faults near the supply end becomes high

INVERSE TIME RELAY

- Inverse time relays the operating time is inversely proportional to the operating current.
- Farther the circuit breaker from the generating station, the shorter is its relay operating time.

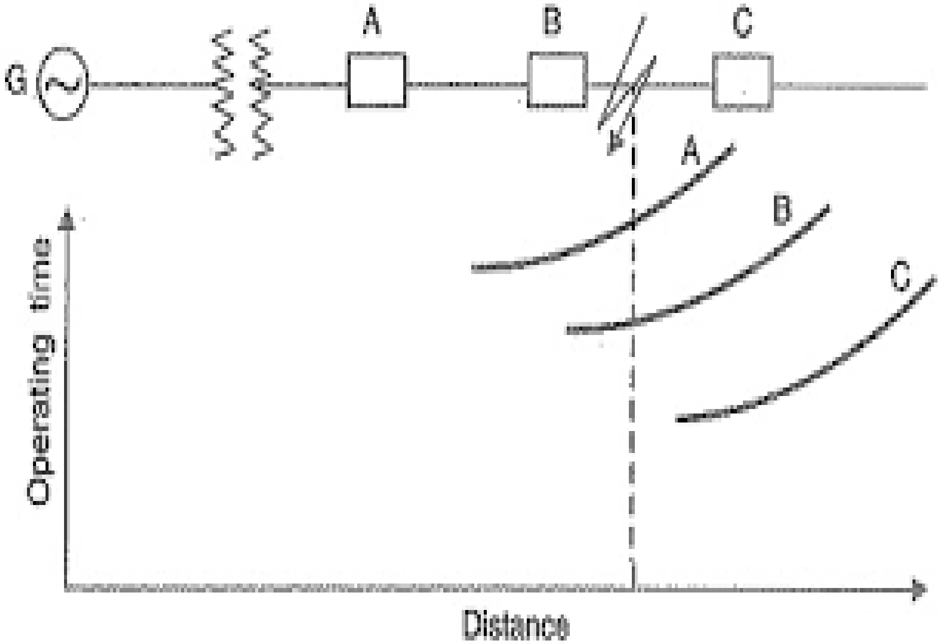


Fig. 23.5

OPERATION

- The three relays at A, B and C are assumed to have inverse-time characteristics.
- A fault in section BC will give relay times which will allow breaker at B to trip out before the breaker at A

RING MAIN FEEDER PROTECTION

- In this system various power stations or sub-stations are interconnected by alternate routes, thus forming a closed ring.

- In case of damage to any section of the ring, that section may be disconnected for repairs, and power will be supplied from both ends of the ring, thereby maintaining continuity of supply.

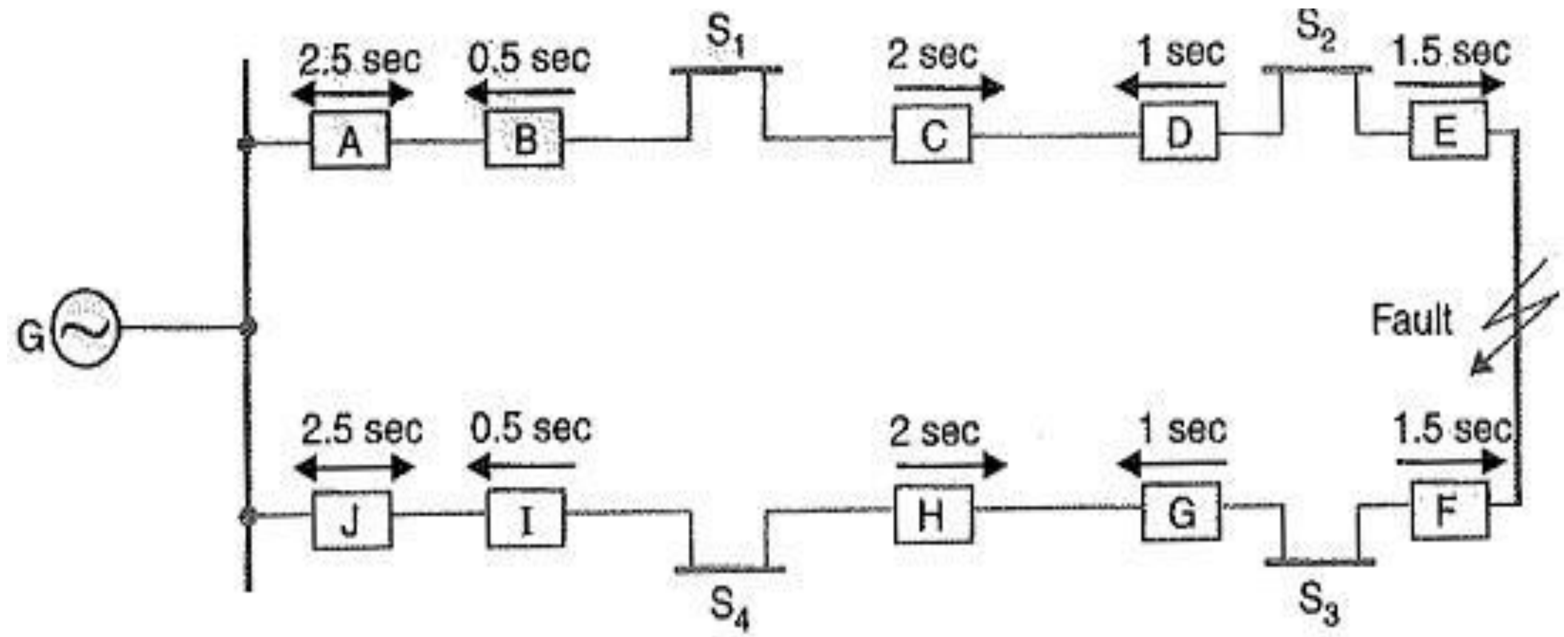


Fig. 23.7

Ring main feeder

- Ring main system consisting of one generator G supplying four sub-stations S1, S2, S3 and S4.
- In this feeder power can flow in both directions under fault conditions.
- Therefore, it is necessary to grade in both directions round the ring and also to use directional relays.
- Only faulty section of the ring is isolated under fault conditions

Types of relays and their time settings

- ❑The two lines leaving the generating station should be equipped with non-directional over current relays (A and J).
- ❑At each sub-station, reverse power or directional relays should be placed in both incoming and outgoing lines (B, C, D, E, F, G, H and I).
- ❑ There should be proper relative time-setting of the relays.

Example: In loop G S1 S2 S3 S4 G ; the outgoing relays (A, C, E, G and I) are set with decreasing time limits e.g. A = 2·5 sec, C = 2 sec, E = 1·5 sec G = 1 sec and I = 0·5 sec

Similarly in loop (opposite direction) G S4 S3 S2 S1 G, the outgoing relays (J, H, F, D and B) are also set with a decreasing time limit e.g. J = 2·5 sec, H = 2 sec, F = 1·5 sec, D = 1 sec, B = 0·5 sec.

OPERATION

- Suppose a fault occurs at the point between S2 and S3.

- only circuit breakers at E and F should open to clear the fault whereas other sections maintains the continuity of supply.

The power will be fed to the fault via two routes
(i)from G around S1 and S2 and
(ii) from G around S4 and S3.

It is clear that relays at A, B, C and D as well as J, I, H and G will not trip. Therefore, only relays at E and F will operate before any other relay operates because of their lower time-setting.

PARALLEL FEEDERS PROTECTION

- Where continuity of supply is particularly necessary, two parallel feeders may be installed.

- If a fault occurs on one feeder, it can be disconnected from the system and continuity of supply can be maintained from the other feeder.

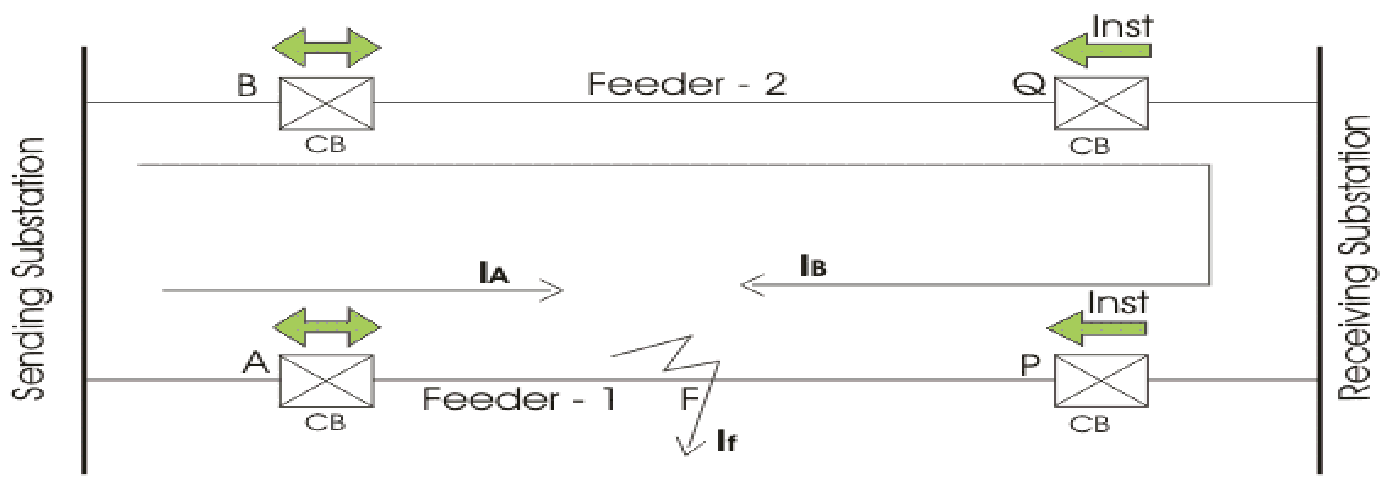
- The parallel feeders cannot be protected by non-directional over current relays only.

- It is necessary to use directional relays also and to grade the time setting of relays for selective trippings.

The protection of parallel feeder requires

- ❑Each feeder has a non-directional over current relay at the generator end. These relays should have inverse-time characteristic.

- ❑Each feeder has a reverse power or directional relay at the sub-station end. These relays should be instantaneous type and operate only when power flows in the reverse direction i.e. in the direction of arrow at P and Q.



OPERATION

- Suppose an earth fault occurs on feeder 1.
- only circuit breakers at A and P should open to clear the fault whereas feeder 2 should remain intact to maintain the continuity of supply.

The fault is fed via two routes

1.directly from feeder 1 via the relay A

2.from feeder 2 via B, Q, sub-station and P

DIFFERENTIAL PILOT-WIRE PROTECTION

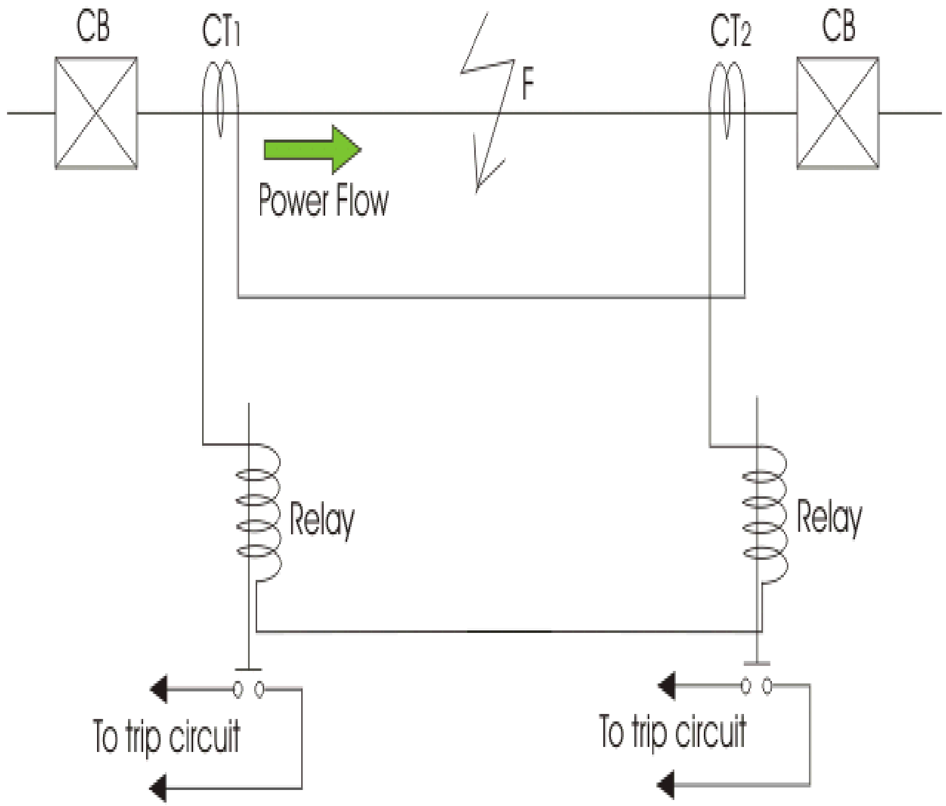
PRINCIPLE:

The differential pilot-wire protection is based on the principle that under normal conditions, the current entering one end of a line is equal to that leaving the other end. As soon as a fault occurs between the two ends, this condition no longer holds and the difference of incoming and outgoing currents is arranged to flow through a relay which operates the circuit breaker to isolate the faulty line.

The following are the differential protection schemes for the feeders

1. Merz-Price voltage balance system
2. Translay scheme

Merz-price voltage balance system



single line diagram of Merz-price voltage balance system

Construction:

Identical current transformers are placed in each phase at both ends of the line. The pair of CTs in each line is connected in series with a relay in such a way that under normal conditions, their secondary voltages are equal and in opposition

i.e. they balance each other.

OPERATION

- Under healthy conditions, current entering the line at one-end is equal to that leaving it at the other end. Therefore, equal and opposite voltages are induced in the secondaries of the CTs at the two ends of the line. The result is that no current flows through the relays.

- Suppose a fault occurs at point F on the line. This will cause a greater current to flow through CT1 than through CT2. Consequently, their secondary voltages become unequal and circulating current flows through the pilot wires and relays. The circuit breakers at both ends of the line will trip out and the faulty line will be isolated.

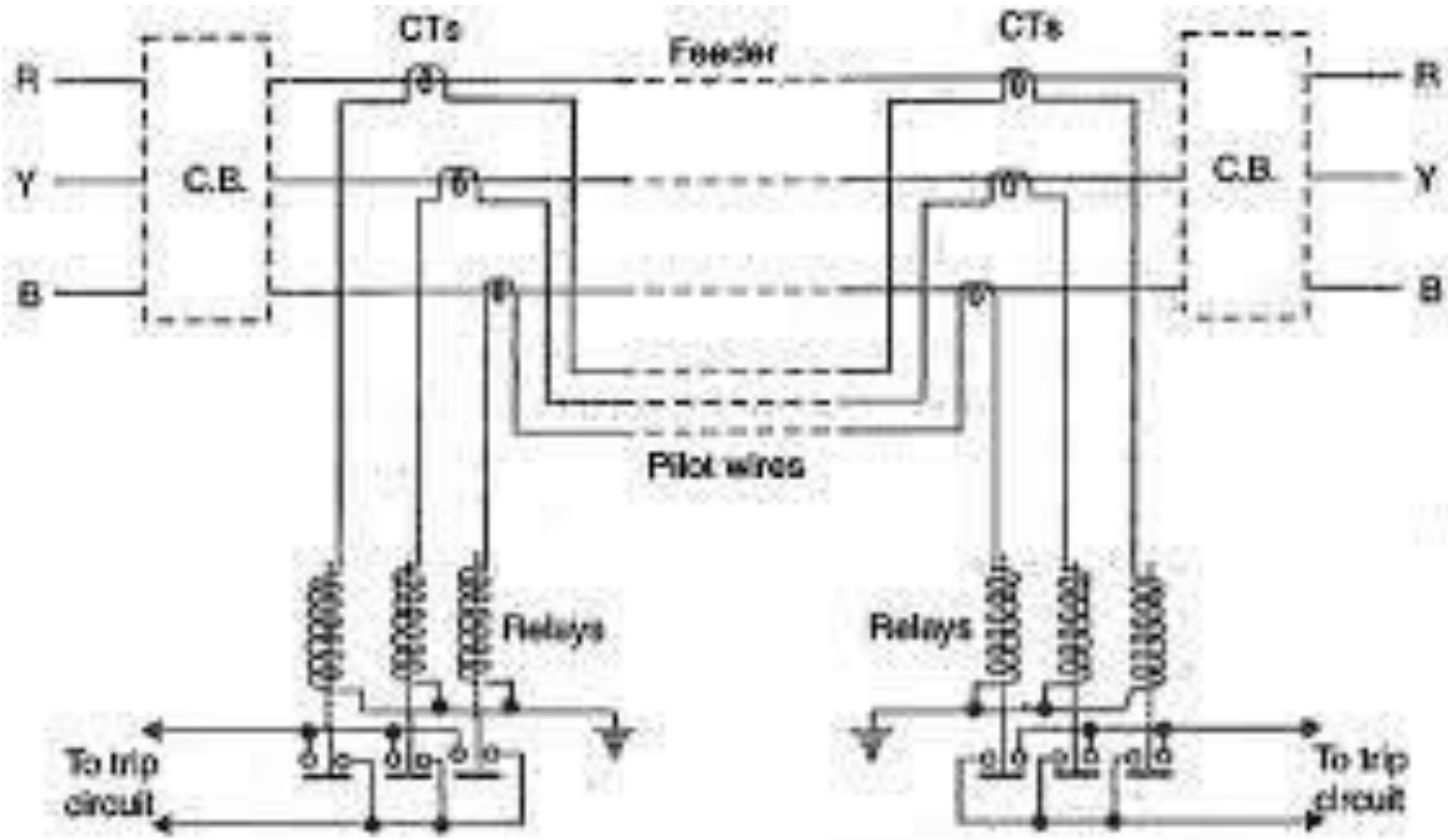


Fig. 23.9

3-phase Merz price voltage balance system

Advantages

- It can be used for ring mains as well as parallel feeders.
- It provides instantaneous protection for ground faults.
- This system provides instantaneous protection which reduces the amount of damage to overhead conductors.

Disadvantages

- Accurate matching of current transformers is very essential.
- If there is a break in the pilot-wire circuit, the system will not operate.
- It is very expensive because of greater length of pilot wires required.
- In case of long lines, charging current due to pilot-wire capacitance effects may be sufficient to cause relay operation even under normal conditions.
- It cannot be used for line voltages beyond 33 kV because of constructional difficulties.

Translay sheme

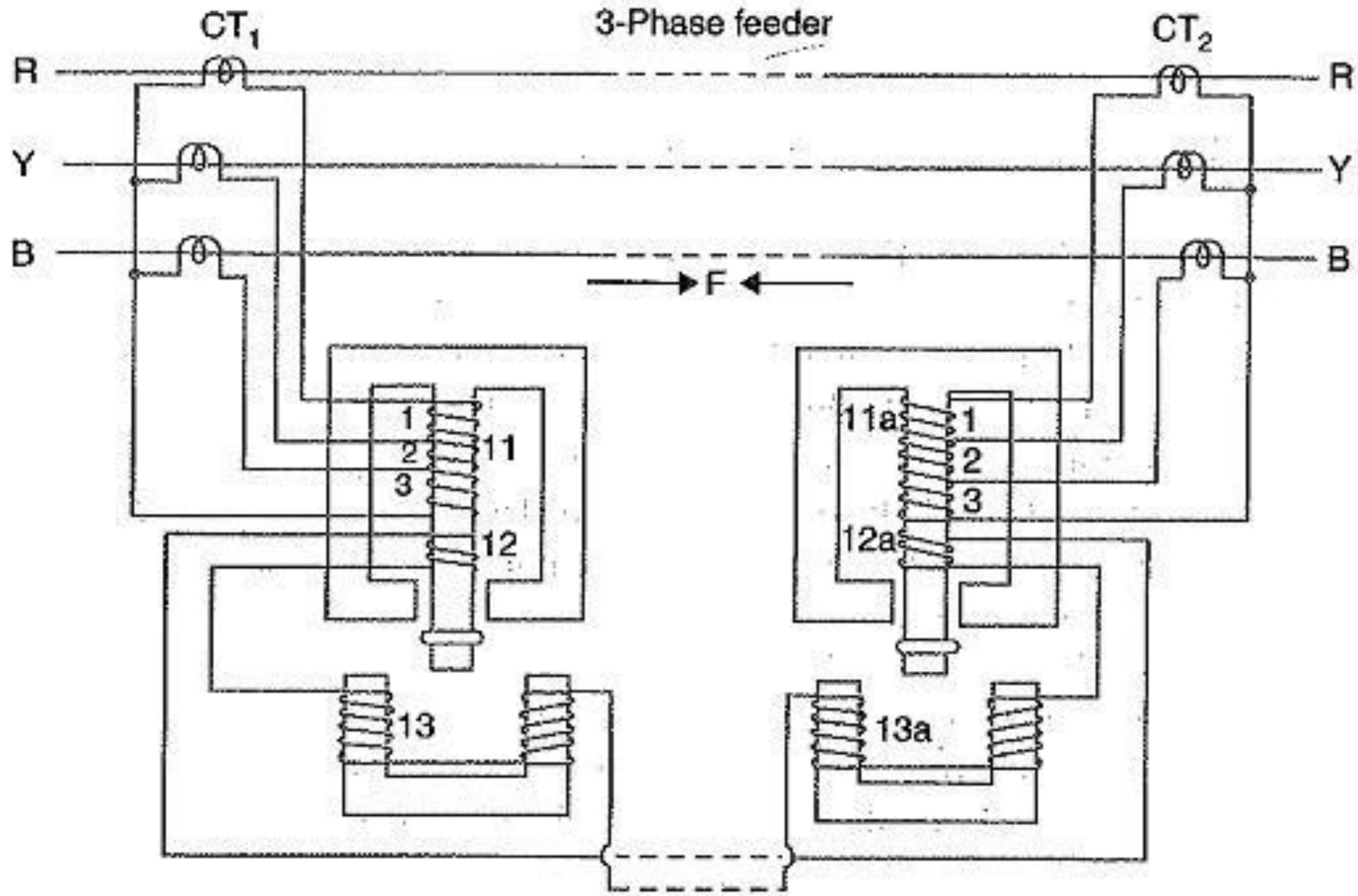


Fig. 23.11

Construction:

- The relays used in the scheme are essentially over current induction type relays.
- Each relay has two electromagnetic elements upper and lower elements.
- The upper element carries a winding (11 or 11 a) which is energized as a summation transformer from the secondaries of the line CTs connected in the phases of the line to be protected.
- The upper element also carries a secondary winding (12 or 12 a) which is connected is series with the operating winding (13 or 13 a) on the lower magnet.
- The secondary windings 12, 12 a and operating windings 13, 13 a are connected in series in such a way that voltages induced in them oppose each other.

Note :- relay discs and tripping circuits have been omitted in the diagram for clarity.

OPERATION

(i) Suppose a fault F occurs between phases R and Y. This will energise only section 1 of primary windings 11 and 11a and induce voltages in the secondary windings 12 and 12a. As these voltages are now additive, therefore, current will circulate through operating coils 13, 13a and the pilot circuit. This will cause the relay contacts to close and open the circuit breakers at both ends. A fault between phases Y and B energises section 2 of primary windings 11 and 11a whereas that between R and B will energise the sections 1 and 2.

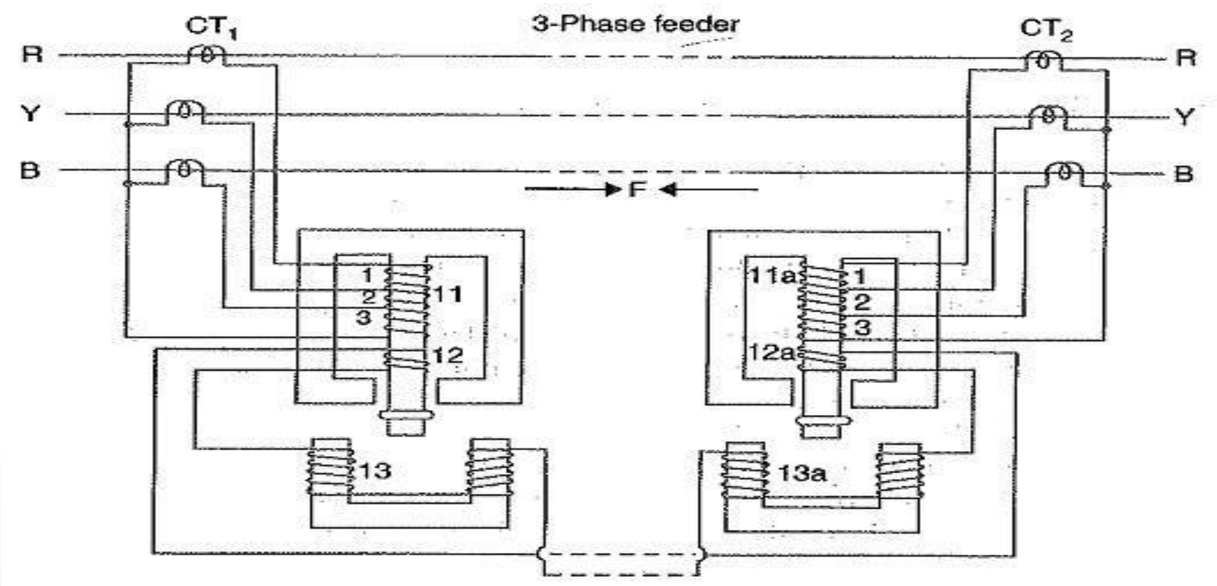


Fig. 23.11

Fig:Translay sheme of protection

(ii) Now imagine that an earth fault occurs on phase R. This will energise sections 1, 2 and 3 of the primary windings 11 and 11a. the voltages induced in the secondary windings 12 and 12a are additive and cause a current to flow through the operating coils 13, 13a. The relays, therefore, operate to open the circuit breakers at both ends of the line. In the event of earth fault on phase Y , sections 2 and 3 of primary winding 11 and 11a will be energised and cause the relays to operate. An earth fault on phase B will energise only section 3 of relay primary windings 11 and 11a

Advantages

- The system is economical as only two pilot wires are required for the protection of a 3-phase line.
- Current transformers of normal design can be used.
- The pilot wire capacitance currents do not affect the operation of relays.

DISTANCE PROTECTION

Both time-graded and pilot-wire system are not suitable for the protection of very long high voltage transmission lines.

Because

- **long time delay in fault clearance at the generating station end when there are more than four or five sections.**

- **the pilot-wire system becomes too expensive owing to the greater length of pilot wires required.**

DISTANCE RELAYS

- Fig shows a simple system consisting of lines in series such that power can flow only from left to right.
- The relays at A, B and C are set to operate for impedance less than Z1, Z2 and Z3 respectively.
- Suppose a fault occurs between sub-stations B and C, the fault impedance at power station A and sub-station B will be Z1 + Z and Z respectively.

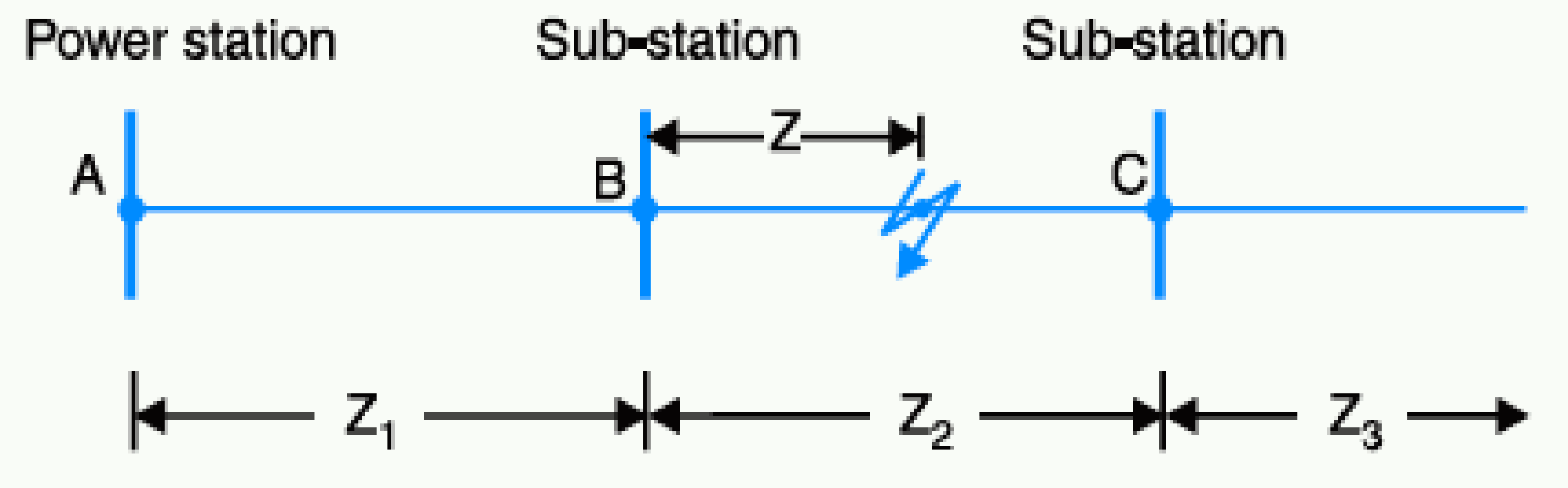


Fig. 23.12 (*i*)

- It is clear that for the portion shown, only relay at B will operate.

- Similarly, if a fault occurs within section AB, then only relay at A will operate.

DISADVANTAGES

- In actual practice, it is not possible to obtain instantaneous protection for complete length of the line due to inaccuracies in the relay elements and instrument transformers.

- It is not reliable.

3-ZONE PROTECTION

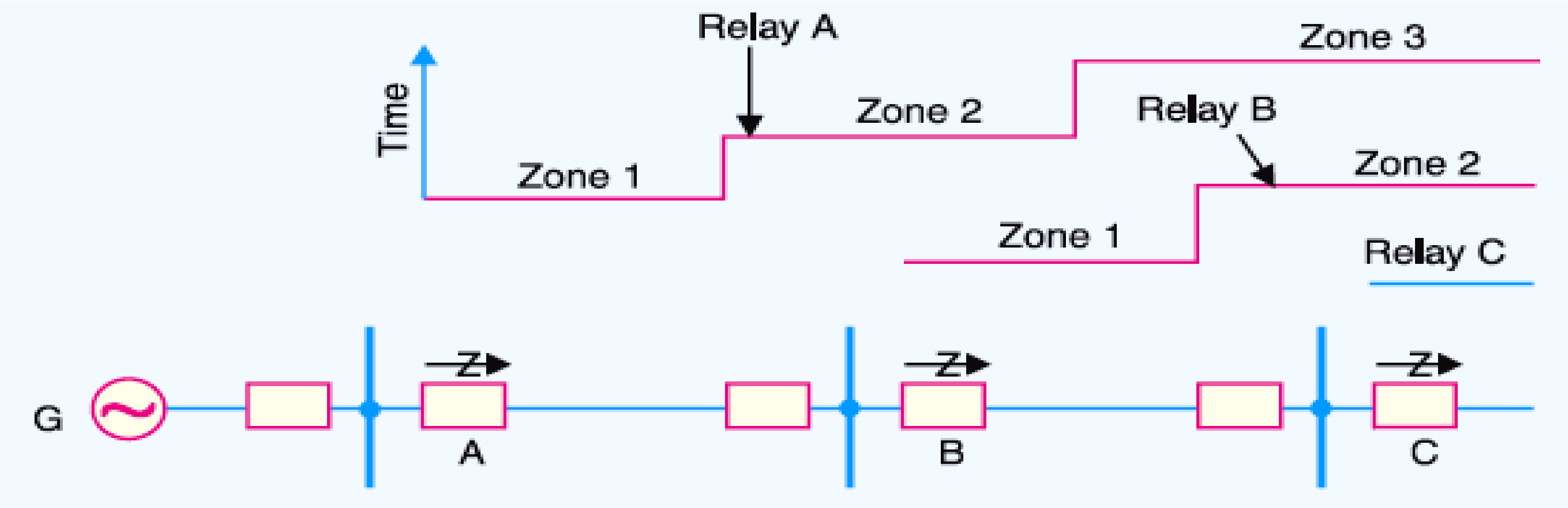


Fig. 23.12 (*ii*)

- In this scheme of protection, three distance elements are used at each terminal.
- The zone 1 element covers first 90% of the line and is arranged to trip instantaneously for faults in this portion.
- The zone 2 element trips for faults in the remaining 10% of the line and for faults in the next line section, but a time delay is introduced to prevent the line from being tripped if the fault is in the next section.
- The zone 3 element provides back-up protection in the event a fault in the next section is not cleared by its breaker.

BUSBAR PROTECTION

- Bus bars are used in generating stations and sub-stations to form link between the incoming and outgoing circuits.

- If a fault occurs on a bus bar, considerable damage and disruption of supply will occur unless some form of quick-acting automatic protection is provided to isolate the faulty bus bar.

The most commonly used schemes for bus bar protection are :

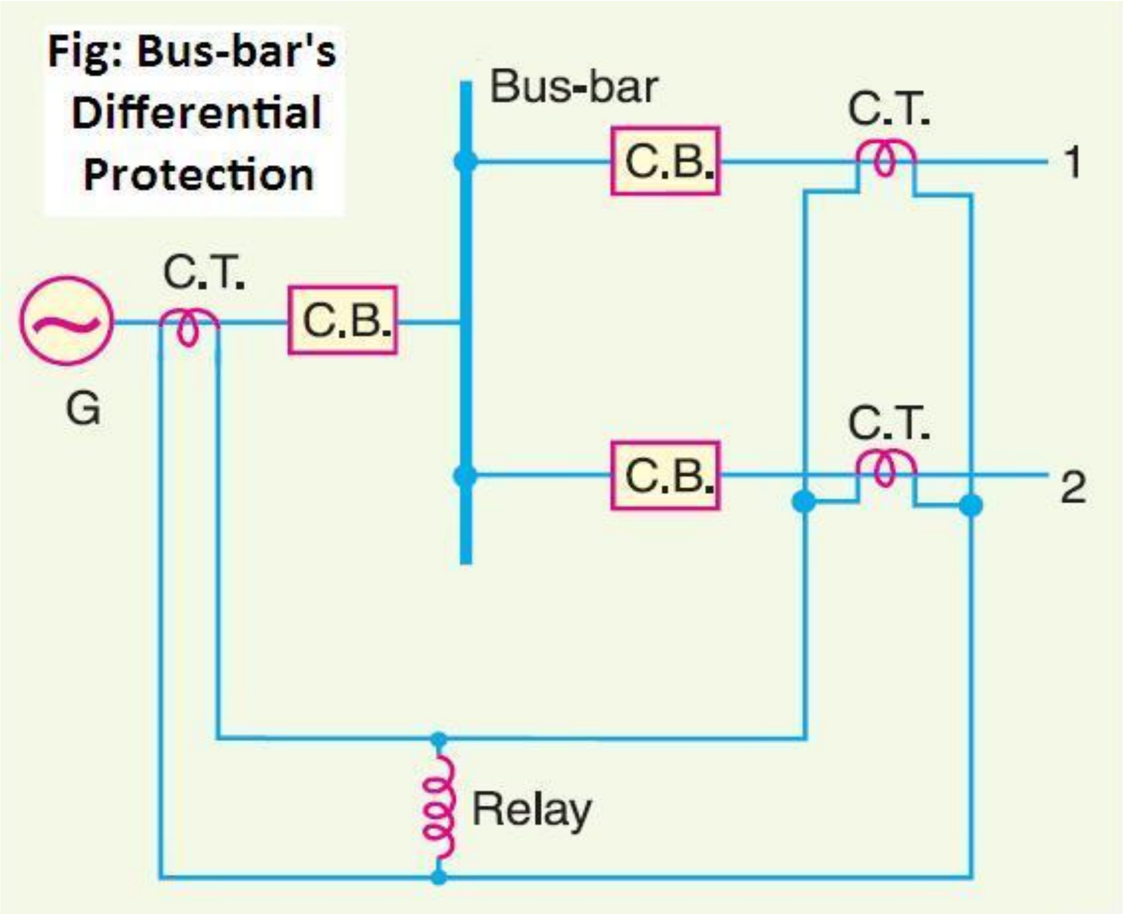
- *Differential protection*
- *Fault bus protection*

1.DIFFERENTIAL PROTECTION

PRINCIPLE

The basic Principle for bus bar protection is the differential scheme in which currents entering and leaving the bus are totalised. During normal load condition, the sum of these currents is equal to zero. When a fault occurs, the fault current upsets the balance and produces a differential current to operate a relay

CONSTRUCTION



- Fig. shows the single line diagram of current differential scheme for a station bus bar.
- The bus bar is fed by a generator and supplies load to two lines.
- The secondaries of current transformers in the generator lead, in line 1 and in line 2 are all connected in parallel.
- The protective relay is connected across this parallel connection.
- All CTs must be of the same ratio in the scheme regardless of the capacities of the various circuits.

OPERATION

- Under normal load conditions or external fault conditions, the sum of the currents entering the bus bar is equal to those leaving it and no current flows through the relay.
- If a fault occurs within the protected zone, the currents entering the bus will no longer be equal to those leaving it.
- The difference of these currents will flow through the relay and cause the opening of the generator, circuit breaker and each of the line circuit breakers.

2.FAULT BUS PROTECTION

Fault bus

Earthed metal barrier surrounding each conductor throughout its entire length in the bus structure is known as fault bus.

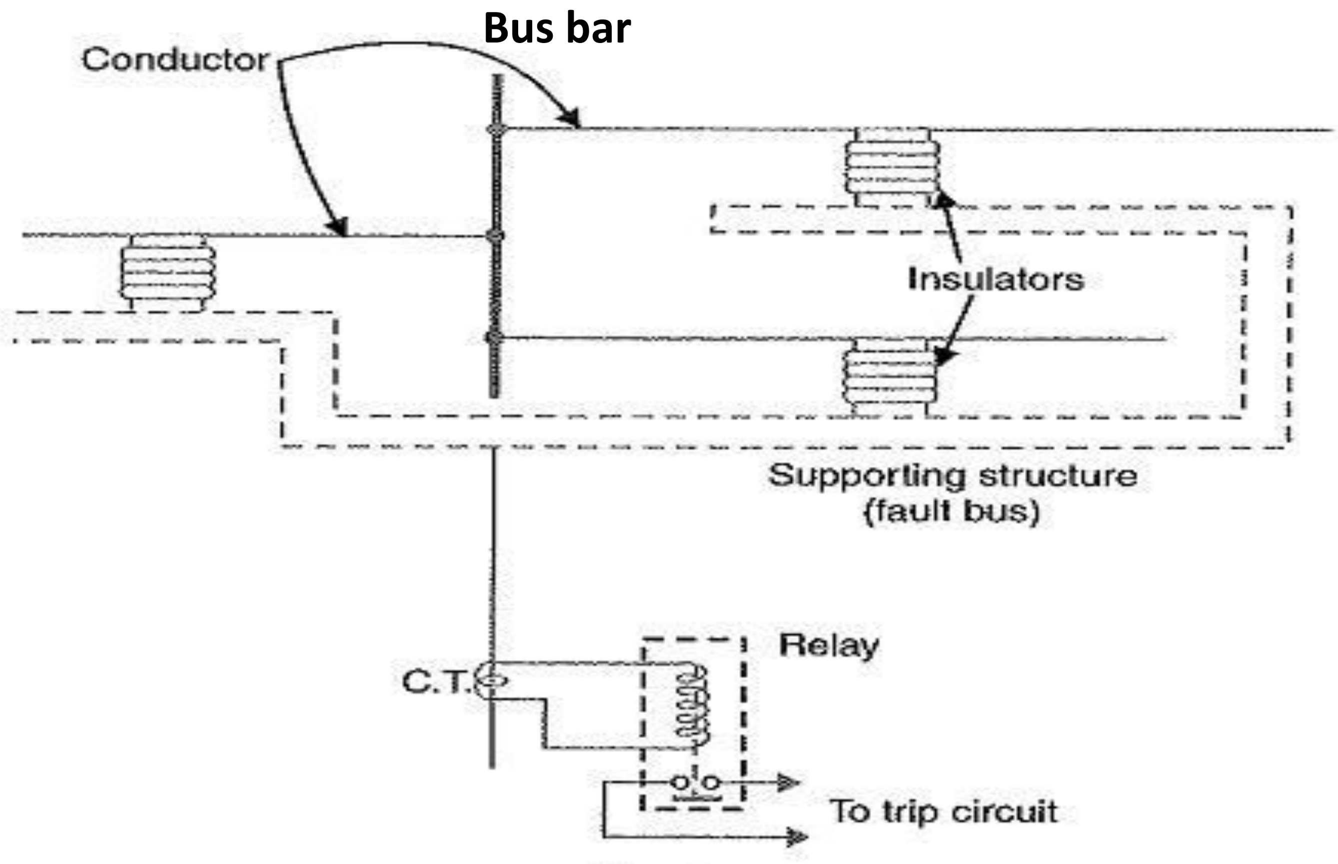


Fig. 23.2

Fig. Fault bus protection

Fig shows the schematic arrangement of fault bus protection. The metal supporting structure or fault bus is earthed through a current transformer. A relay is connected across the secondary of this CT.

OPERATION

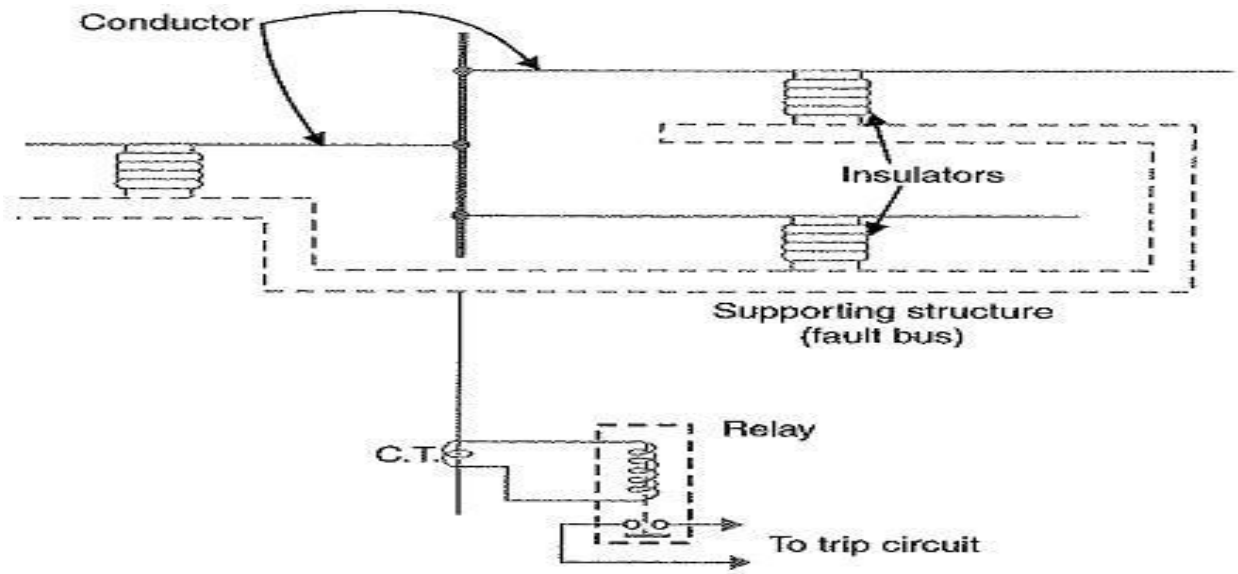


Fig. 23.2

- Under normal operating conditions, there is no current flow from fault bus to ground and the relay remains inoperative.

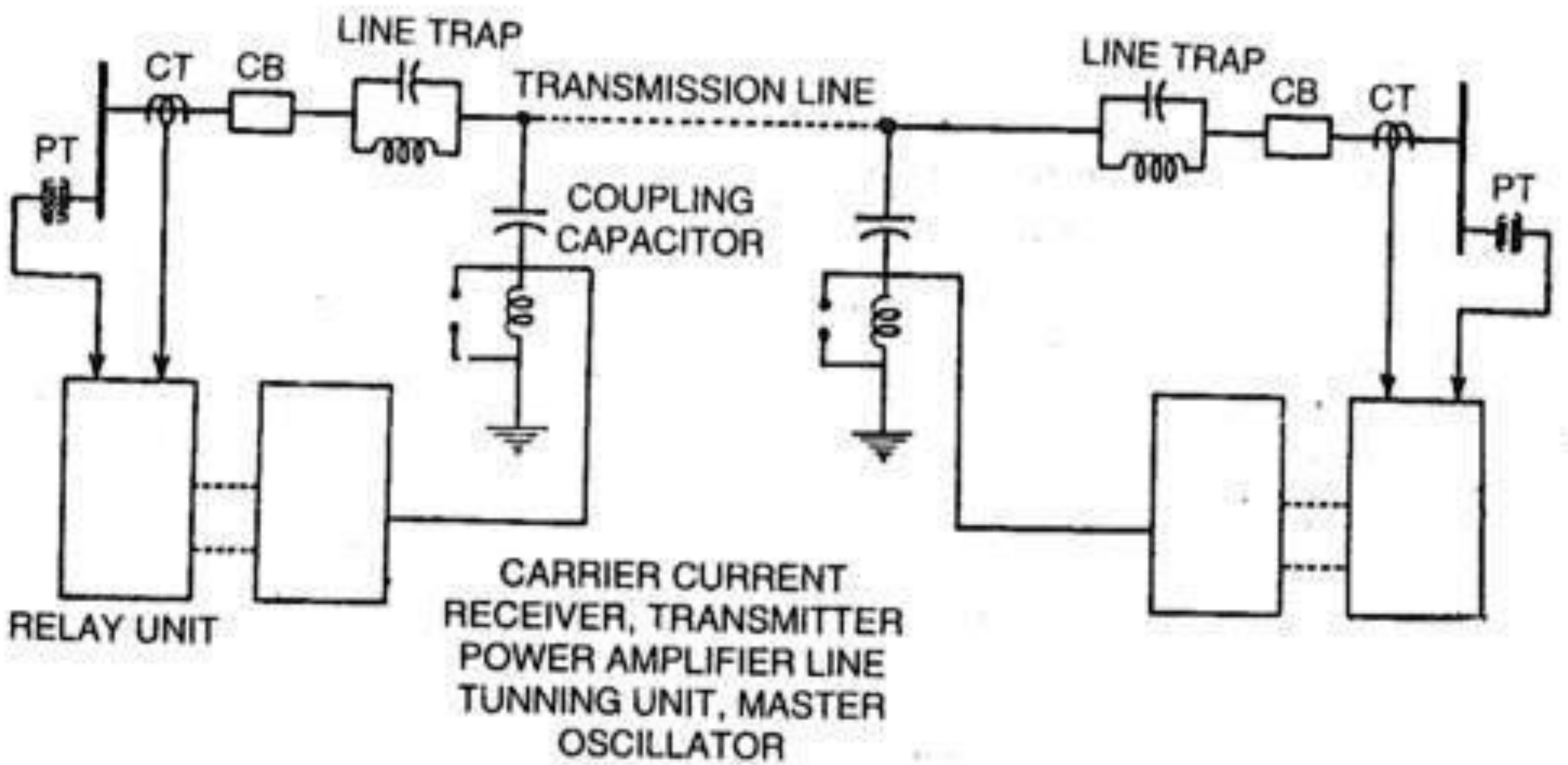
- A fault involving a connection between a conductor and earthed supporting structure will result in current flow to ground through the fault bus, causing the relay to operate.

- The operation of relay will trip all breakers connecting equipment to the bus.

carrier current protection

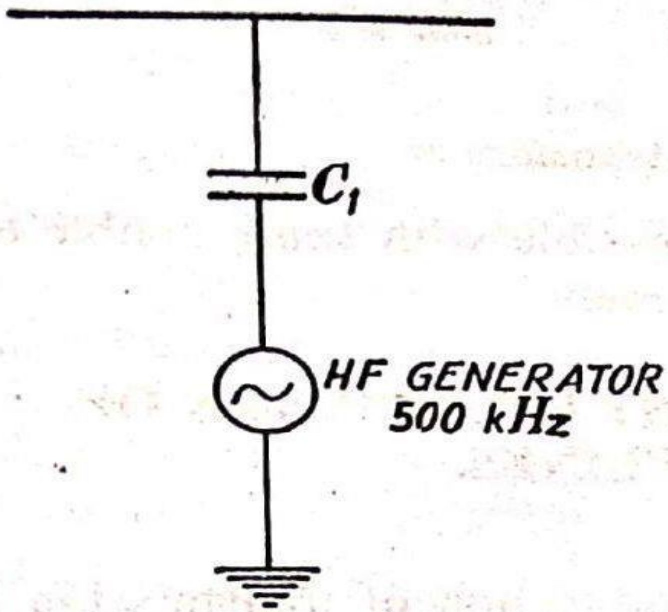
Carrier-current protection is the most widely used scheme for the protection of Extra High Voltage (EHV) and Ultra High Voltage (UHV) over head power lines.

This type of protection is used for protection of transmission lines Carrier currents of the frequency range 30 to 200 kc/s in USA and 80 to 500 kc/s (kHz) in UK are transmitted and received through the transmission lines for the purpose of protection.



1. **Coupling capacitor.** The carrier equipment is connected to the transmission line through 'Coupling Capacitor' which is of such a capacitance that it offers low reactance $\left(\frac{1}{\omega C}\right)$ to carrier frequency but high reactance power frequency. For example, 2000 pF capacitor offers 1.5 megohms to 50 Hz and 150 ohms to 500 KHz.

Thus coupling capacitors allows carrier frequency signals to enter the carrier equipment but does not allow 50 Hz power frequency currents to enter the carrier equipment. To reduce impedance further a low inductance is connected in series with coupling capacitors to form a resonance at carrier frequency.



$$Z = \frac{1}{\omega C_1}$$

= 1.5 mega ohms for 50 Hz.

= 150 ohms for 500 kHz.

Fig. 30.26. Function of coupling capacitor.

2. Line Trap Unit. Line trap unit is inserted between busbar and connection of coupling capacitor to the line. It is a parallel tuned circuit comprising *L* and *C*. It has a low impedance (less than 0.1 ohm) to 50 Hz and high impedance to carrier frequencies. This unit prevents the high frequency signals from entering the neighbouring line, and the carrier currents flow only in the protected line.

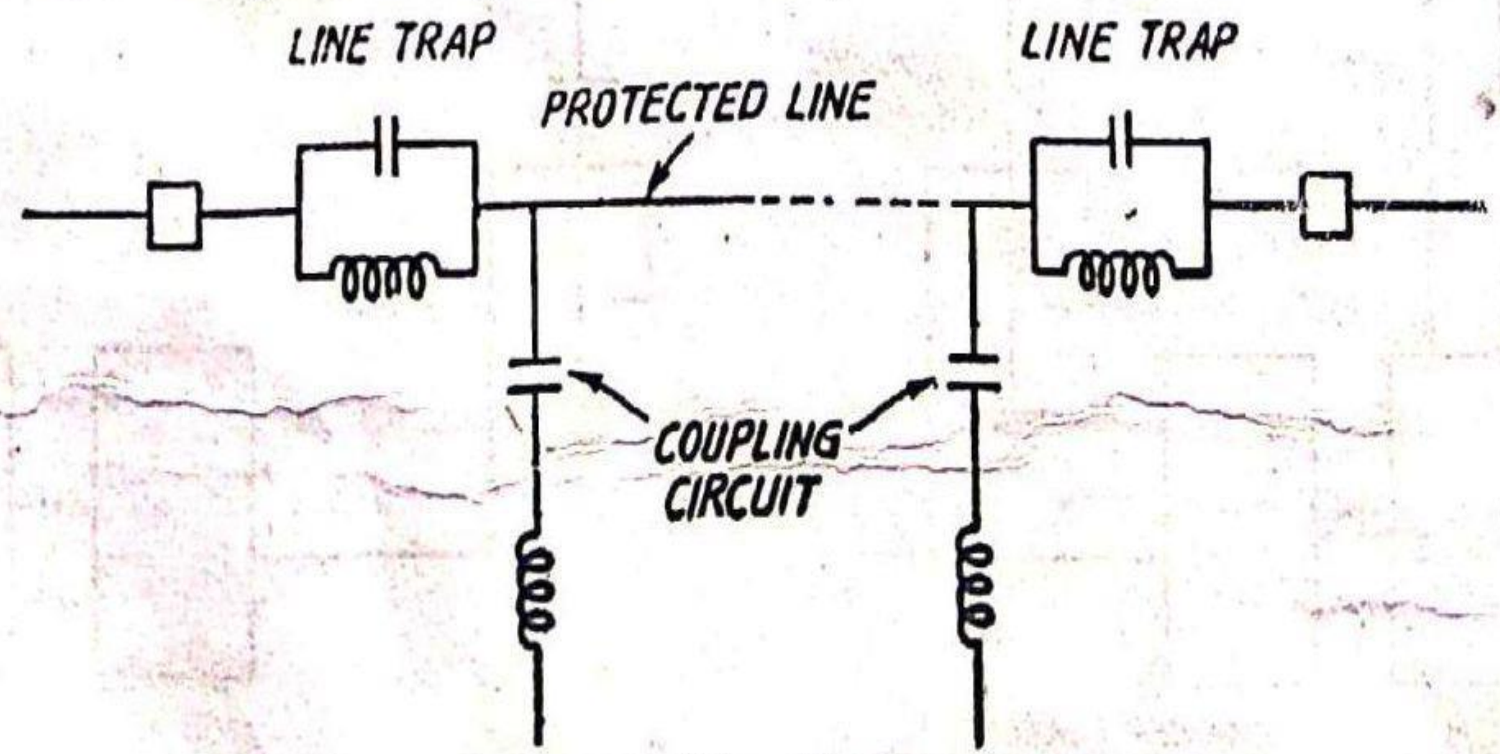


Fig. 30.27. Line Trap Units.

3. **Protection and Earthing of Coupling Equipment.** Overvoltages on power lines are caused by lightning, sw:tching, faults, etc. produce

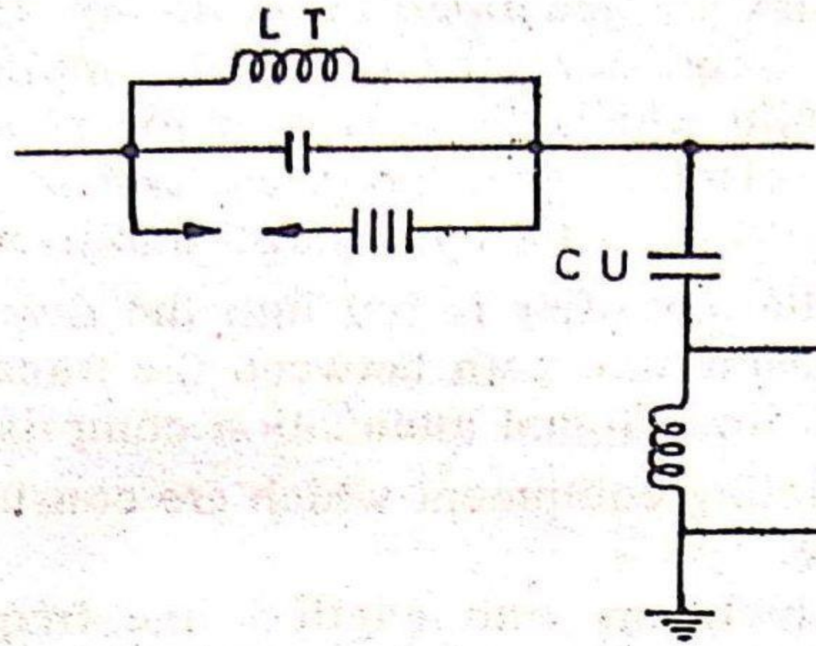


Fig. 30.28. Protective gap for line trap and coupling capacitor.

stress on coupling equipment and line trap unit. Non-linear resistors in series with a protective gap is connected across the line trap unit and inductor of the coupling unit. The gap is adjusted to spark at a set value of overvoltage.

Base of coupling unit is earthed by earth rod in the vicinity to obtain low earth-resistance. Carrier panel usually installed in relay room is connected to station earthing system.

4. **Electronic Equipment.** There are generally identical units at each end :

(*i*) Transmitter unit. (*ii*) Receiver unit (*iii*) Relay unit.

(*i*) **Transmitter unit.** Fig. 30.29 gives the general arrangement of power line carrier protection scheme.

Frequencies between 50 to 500 kHz are employed in different frequency bands. Each band has certain band width (say 150—300kHz, 90—115kHz).

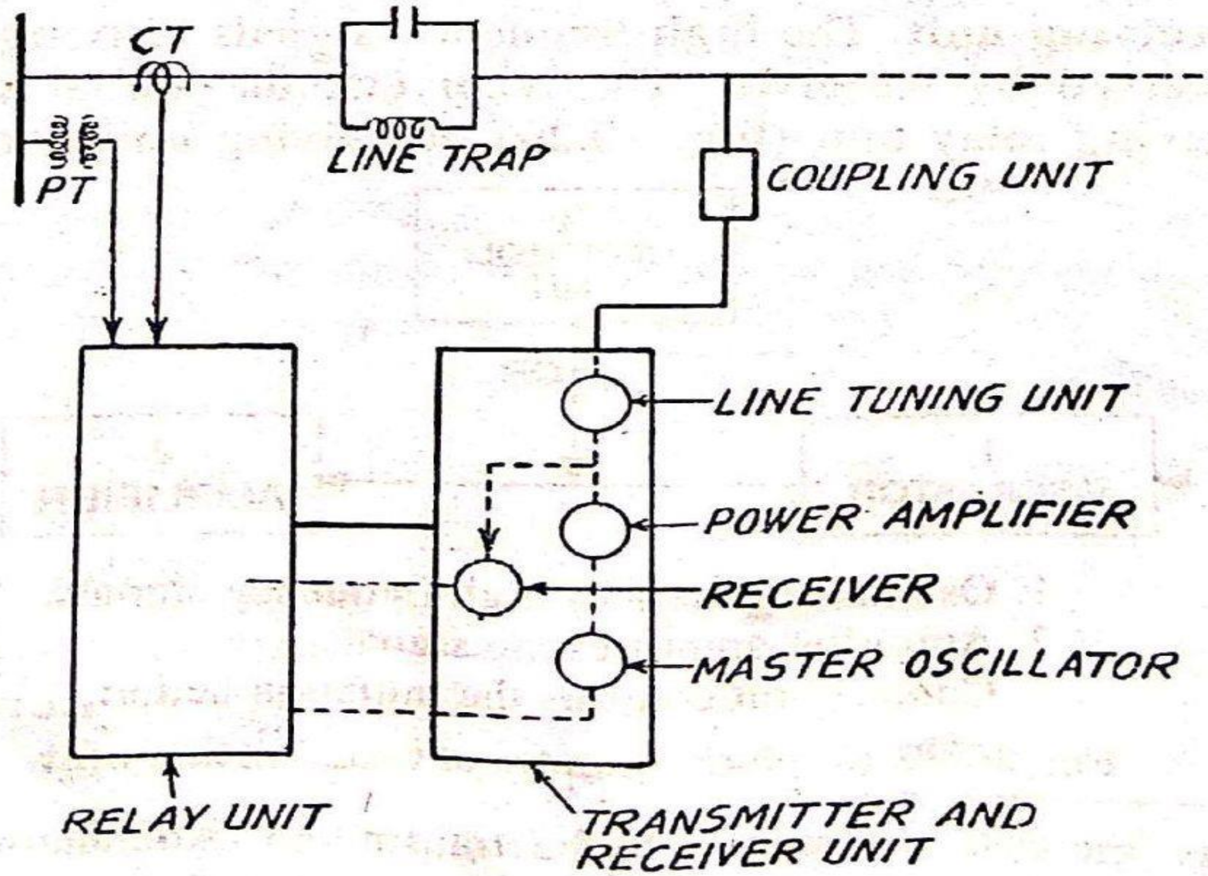


Fig. 30.29. (*a*) Schematic Diagram of Carrier Current Units.

PROTECTION AGAINST OVER VOLTAGES

Voltage Surge: **A sudden rise in voltage for a very short duration on the power system is known as a voltage surge or transient voltage.**

- **Transients or surges are of temporary nature and exist for a very short duration but they cause over voltages on the power system.**

- **They originate from switching and from other causes but by far the most important transients are those caused by lightning striking a transmission line.**

- **When lightning strikes a line, the surge rushes along the line, just as a flood of water rushes along a narrow valley when the retaining wall of a reservoir at its head suddenly gives way.**

- **In most of the cases, such surges may cause the line to flash over and may also damage the nearby transformers, generators or other equipment connected to the line if the equipment is not suitably protected.**

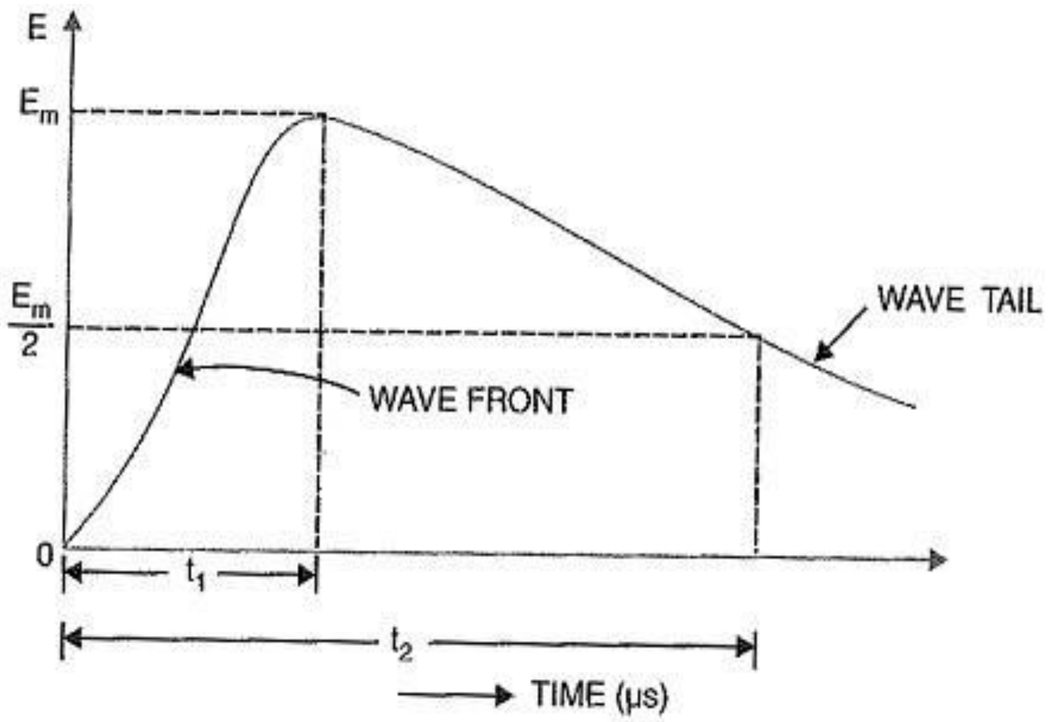


Fig. 24.1

CAUSES OF OVER VOLTAGES

The over voltages on a power system may be broadly divided into two main categories viz.

1. **Internal causes**
   - **Switching surges**
   - **Insulation failure**
   - **Arcing ground**
   - **Resonance**
2. **External causes i.e. lightning**

Internal Causes of Over voltages

1. Switching Surges: The over voltages produced on the power system due to switching operations are known as switching surges.

(i) Case of an open line: When the unloaded line is connected to the voltage source, a voltage wave is set up which travels along the line. On reaching the receiving end, it is reflected back to the supply end without change of sign. This causes voltage doubling i.e. voltage on the line becomes twice the normal value. If Er.m.s. is the supply voltage, then instantaneous voltage which the line will have to withstand will be 2 √2 E .

(ii) Case of a loaded line:

Over voltages will also be produced during the switching operations of a loaded line. Suppose a loaded line is suddenly interrupted. This will set up a voltage of 2 Zn i across the break (i.e. switch) where i is the instantaneous value of current at the time of opening of line

Zn is the natural impedance of the line.

For example, suppose the line having Zn = 1000 Ω carries a current of 100 A (r.m.s.) and the break occurs at the moment when current is maximum. The voltage across the breaker (i.e. switch) = 2 √2 × 100 × 1000/1000 = 282·8 kV. If V m is the peak value of voltage in kV, the maximum voltage to which the line may be subjected is = (V m + 282·8) kV.

(iii) Current chopping: Current chopping results in the production of high voltage transients across the contacts of the air blast circuit breaker. Unlike oil circuit breakers, which are independent for the effectiveness on the magnitude of the current being interrupted, air-blast circuit breakers retain the same extinguishing power irrespective of the magnitude of this current. When breaking low currents with air-blast breaker, the powerful deionising effect of air-blast causes the current to fall abruptly to

zero well before the natural current zero is reached. This phenomenon is called current chopping and produces high transient voltage across the breaker contacts. Over voltages due to current chopping are prevented by resistance switching

2. Insulation failure: The most common case of insulation failure in a power system is the grounding of conductor (i.e. insulation failure between line and earth) which may cause over voltages in the system.

Suppose a line at potential E is earthed at point X. The earthing of the line causes two equal voltages of −E to travel along XQ and XP containing currents −E/Zn and +E/Zn respectively. Both these currents pass through X to earth so that current to earth is 2 E/Zn.

3. Arcing ground:

The phenomenon of intermittent arc taking place in line-to-ground fault of a 3φ system with consequent production of transients is known as arcing ground.

The transients produced due to arcing ground are cumulative and may cause serious damage to the equipment in the power system by causing breakdown of insulation. Arcing ground can be prevented by earthing the neutral.

4. Resonance: Resonance in an electrical system occurs when inductive reactance of the circuit becomes equal to capacitive reactance. Under resonance, the impedance of the circuit is equal to resistance of the circuit and the p.f. is unity. Resonance causes high voltages in the electrical system. In the usual transmission lines, the capacitance is very small so that resonance rarely occurs at the fundamental supply frequency.

However, if generator e.m.f. wave is distorted, the trouble of resonance may occur due to 5th or higher harmonics and in case of underground cables too.

Lightning

Definition: ***An electric discharge between cloud and earth, between clouds or between the charge centres of the same cloud is known as lightning.***

Mechanism of Lightning Discharge

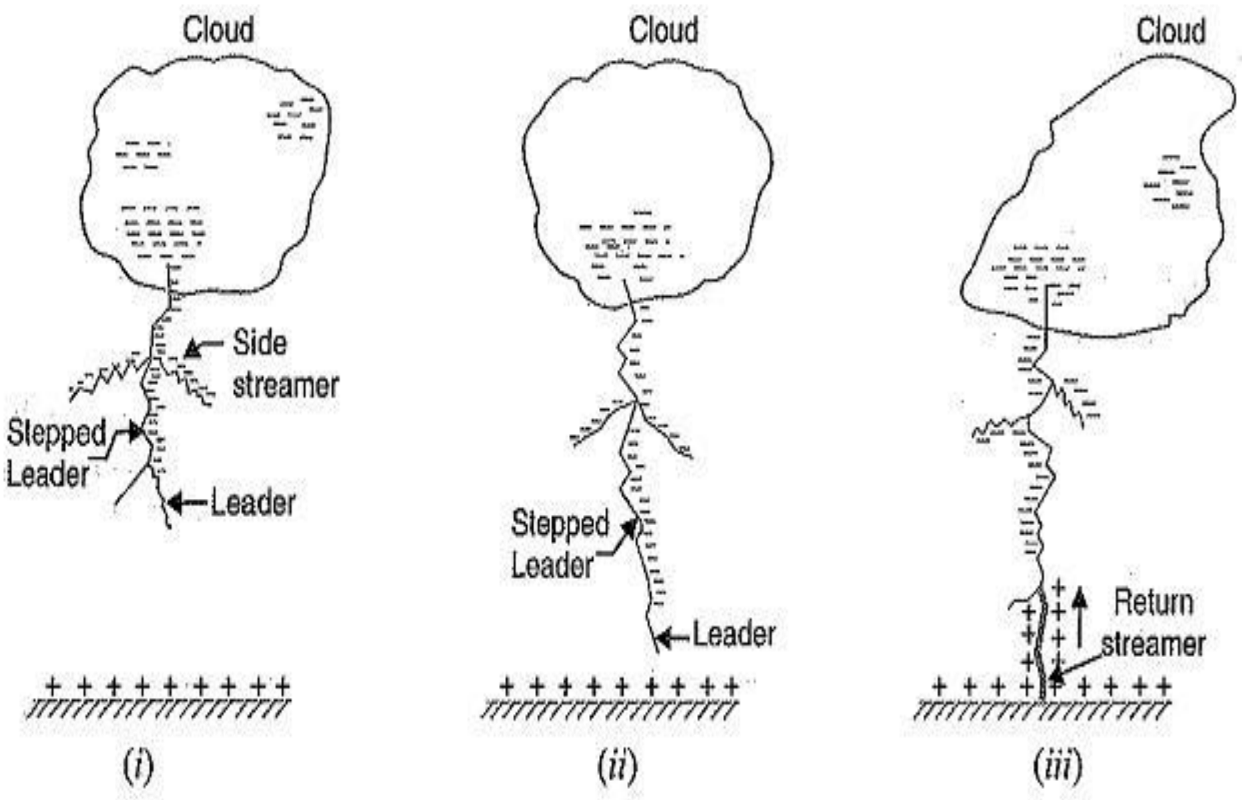


Fig. 24.4

Types of Lightning Strokes

1. Direct stroke

2. Indirect stroke

1. Direct stroke:

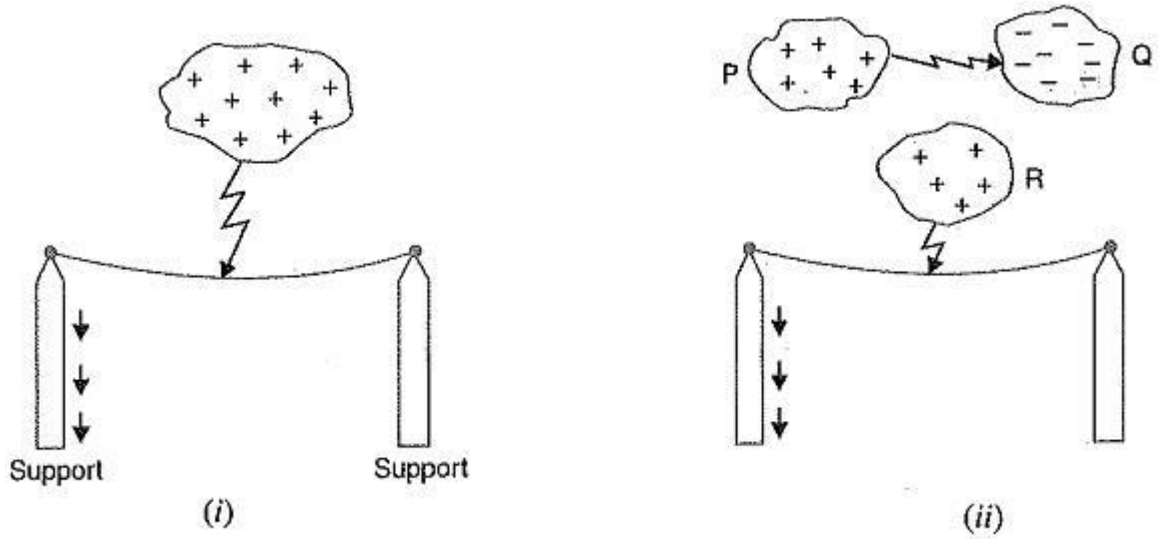
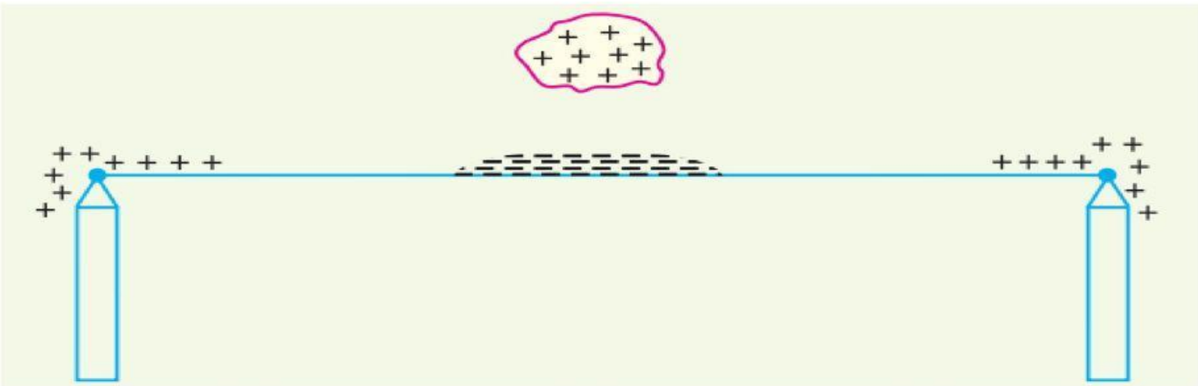


Fig. 24.5

Indirect stroke



Majority of the surges in a transmission line are caused by indirect lightning strokes

Protection Against Lightning

Protection Schemes of Lightning

- **Earthing screen**

  Earthing screen provides protection to power stations and sub-stations against direct strokes

- **Overhead ground wires**

  overhead ground wires protect the transmission lines against direct lightning strokes.

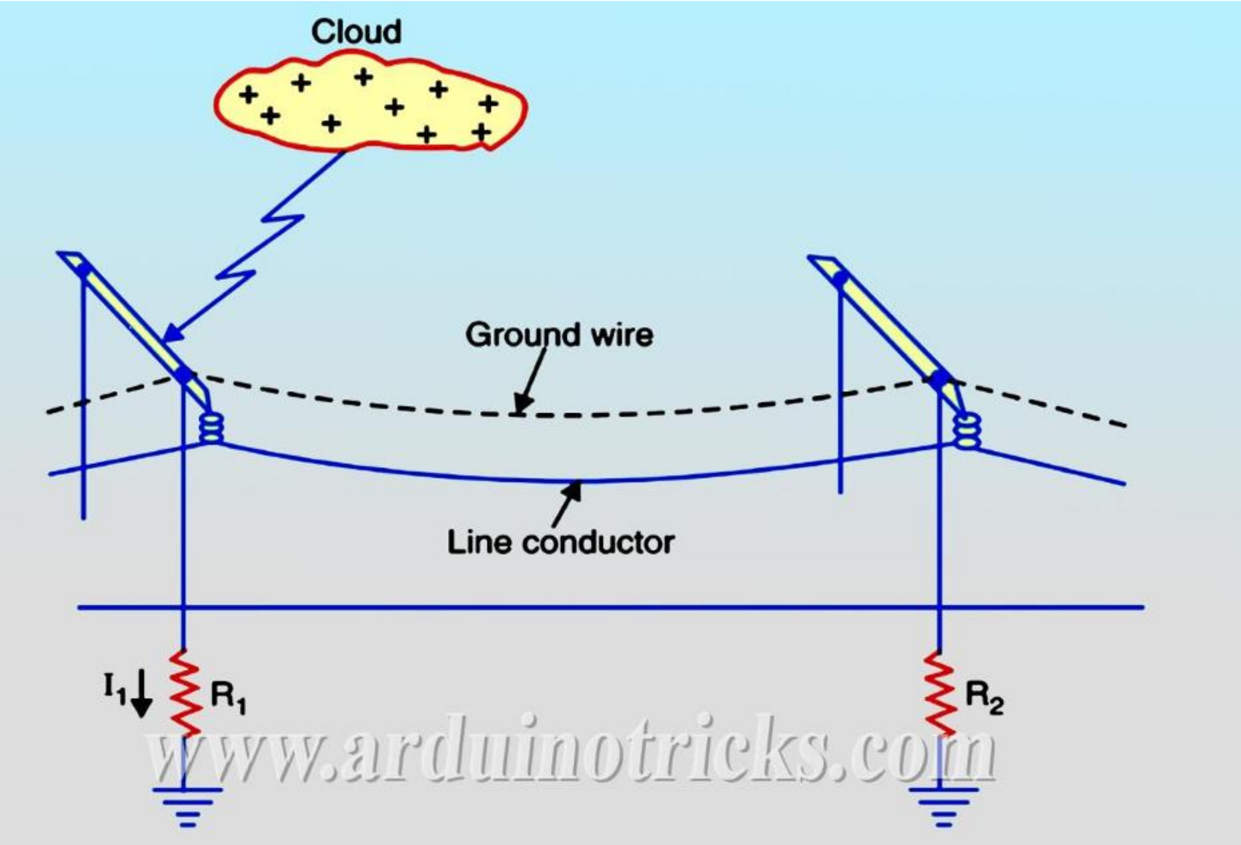
- **Lightning arresters or surge diverters**

  lightning arresters or surge diverters protect the station apparatus against both direct strokes and the strokes that come into the apparatus as travelling waves.

The Earthing Screen

- **The power stations and sub-stations generally house expensive equipment.**
- **These stations can be protected against direct lightning strokes by providing earthing screen.**
- **It consists of a network of copper conductors (generally called shield or screen) mounted all over the electrical equipment in the sub-station or power station.**
- **The shield is properly connected to earth on atleast two points through a low impedance.**
- **On the occurrence of direct stroke on the station, screen provides a low resistance path by which lightning surges are conducted to ground. In this way, station equipment is protected against damage.**

Overhead Ground Wires



Advantages

- ✓ It provides considerable protection against direct lightning strokes on transmission lines.

- ✓ A grounding wire provides damping effect on any disturbance travelling along the line as it acts as a short-circuited secondary.

- ✓ It provides a certain amount of electrostatic shielding against external fields. Thus it reduces the voltages induced in the line conductors due to the discharge of a neighbouring cloud.

Disadvantages

- **It requires additional cost.**
- **There is a possibility of its breaking and falling across the line conductors, thereby causing a short-circuit fault.**

Lightning Arrester

- **The earthing screen and ground wires can well protect the electrical system against direct lightning strokes but they fail to provide protection against travelling waves which may reach the terminal apparatus.**
- **The lightning arresters or surge diverters provide protection against such surges.**

Definition:

A lightning arrester or a surge diverter is a protective device which conducts the high voltage surges on the power system to the ground.

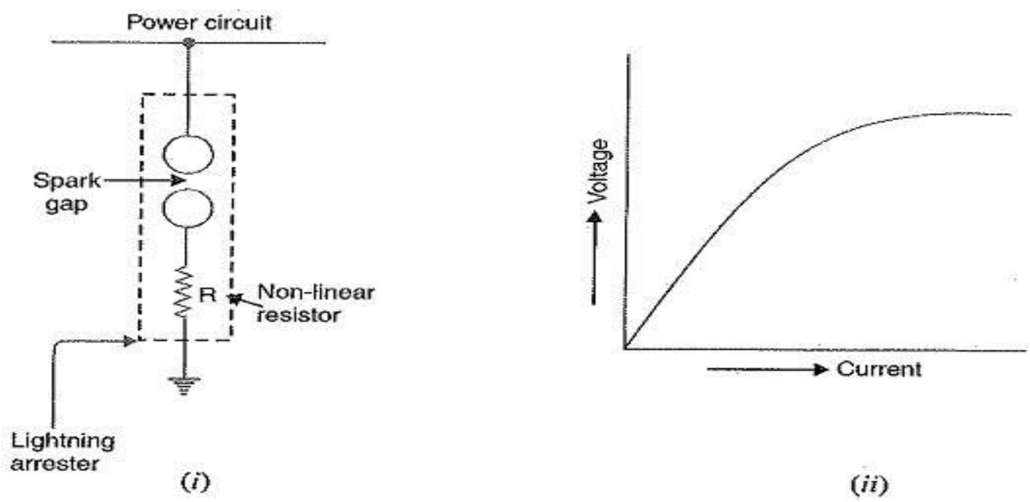


Fig. 24.8

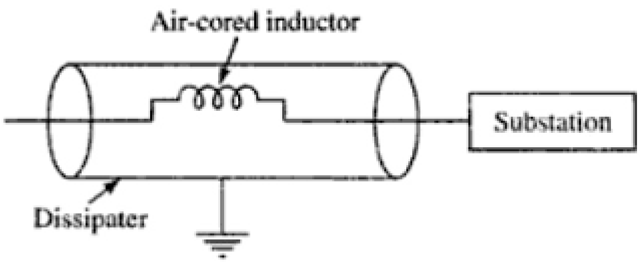
Operation:

- **Under normal operation, the lightning arrester is off the line i.e. it conducts no current to earth or the gap is non-conducting.**

- **On the occurrence of overvoltage, the air insulation across the gap breaks down and an arc is formed, providing a low resistance path for the surge to the ground.**

Surge absorbers:

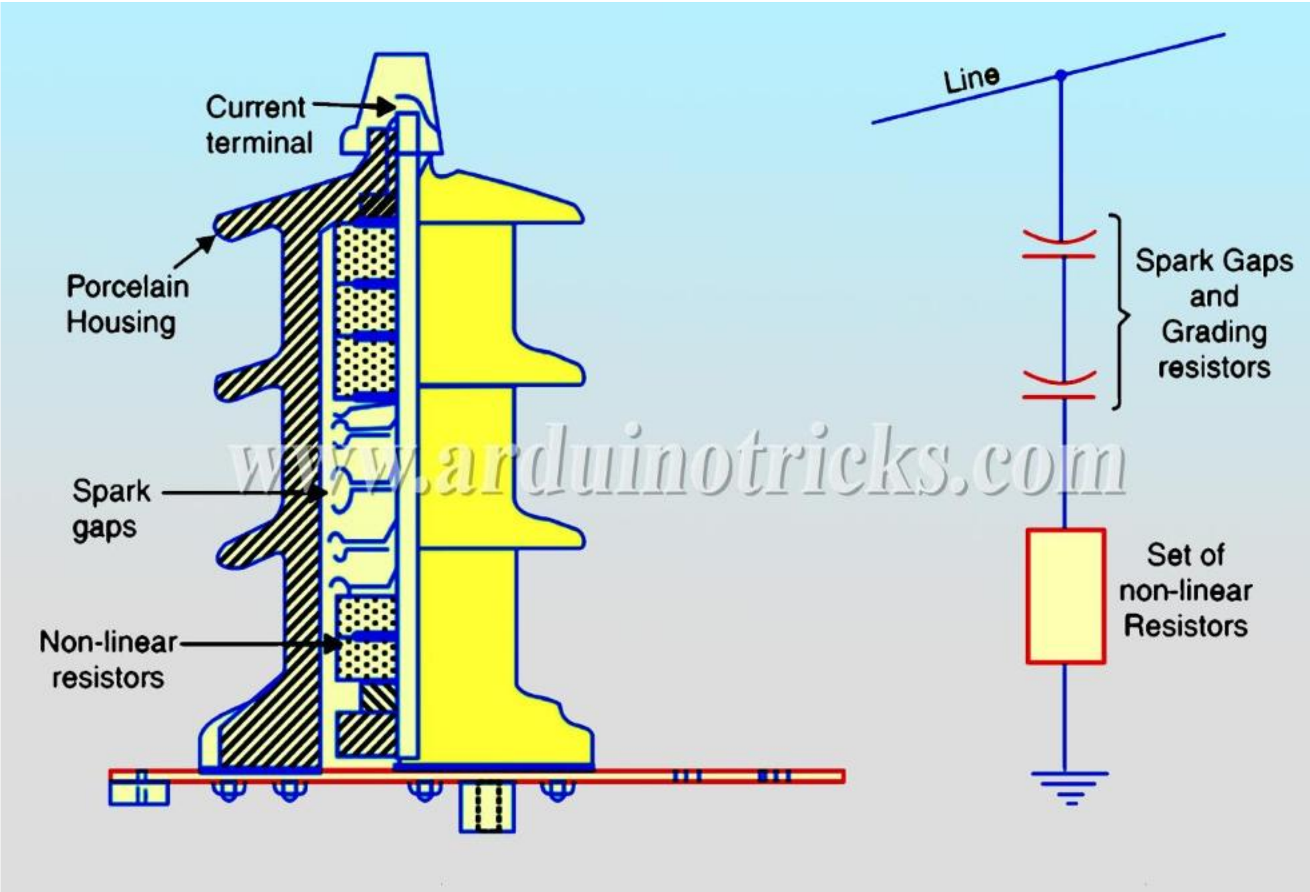
Surge absorbers are protective devices used to absorb the complete surge i,e. due to lightening surge or any transient surge in the system unlike the lightening arrestor in which a non-linear resistor is provided which provides a low resistance path to the dangerously high voltages on the system to the earth.



Types of Lightning Arresters

1. Rod gap arrester
2. Horn gap arrester
3. Multigap arrester
4. Expulsion type lightning arrester
5.Valve type lightning arrester
6.Zinc or metal oxide arrester

VALVE TYPE ARRESTER



OPERATION:

- **Under normal conditions, the normal system voltage is insufficient to cause the breakdown of air gap assembly.**

- **On the occurrence of an overvoltage, the breakdown of the series spark gap takes place and the surge current is conducted to earth via the non-linear resistors. Since the magnitude of surge current is very large, the non-linear elements will offer a very low resistance to the passage of surge. The result is that the surge will rapidly go to earth instead of being sent back over the line. When the surge is over, the non-linear resistors assume high resistance to stop the flow of current.**

Advantages

- **They provide very effective protection (especially for transformers and cables) against surges.**
- **They operate very rapidly taking less than a second.**
- **The impulse ratio is practically unity.**

Limitations

- **They may fail to check the surges of very steep wave front from reaching the terminal apparatus. This calls for additional steps to check steep-fronted waves.**
- **Their performance is adversely affected by the entry of moisture into the enclosure. This necessitates effective sealing of the enclosure at all times.**

Metal Oxide Surge Arrester

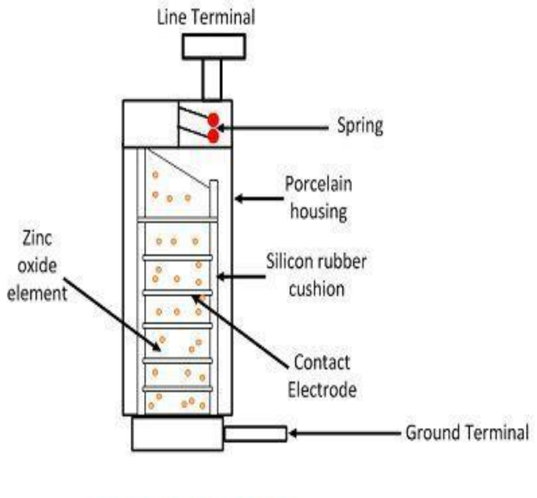
Definition: **The arrester which uses zinc oxide semiconductor as a resistor material, such type of arrester is known as a metal oxide surge arrester or ZnO Diverter.**

- **This arrester provides protection against all types of AC and DC over voltages. It is mainly used for overvoltage protection at all voltage levels in a power system.**

Construction:

The zinc oxide is a semiconducting material of N-type. It is pulverised and finely grained. More than ten doping materials are added in the form of fine powders of insulating oxides such as Bismuth (Bi_2O_3), Antimony Trioxide (Sb_2O_3), Cobalt Oxide(CoO), Manganese Oxide (MnO_2), Chromium oxide (Cr_2O_3). The powder is treated with some processes, and the mixture is spray dried to obtain a dry powder.

The dry powder is compressed into disc-shaped blocks. The blocks are sintered to obtain a dense poly- crystalline ceramic.The metal oxide resistor disc is coated with a conducting compound to protect the disc from undesirable environmental effect.



Zinc Oxide Surge Arrester

Working of Metal Oxide Surge Arrester:

- ✓ **At normal voltage, the potential barrier does not allow the current to flow through it.**
- ✓ **At over voltage the barrier collapse and sharp transition of current from insulating to conducting state take place. The current start flowing and the surge is diverted to ground.**

- ✓ **After the travelling of the surge, the voltage across the diverters falls, and the current is reduced to the negligible value of the resistor units, and there is no power follow current.**

Advantages of Metal Oxide Surge Arrester

- ✓ **It eliminates the risk of spark over and also the risk of shock to the system when the gaps break down.**
- ✓ **It eliminates the need of voltage grading system.**
- ✓ **At the normal operating condition, the leakage current in the ZnO is very low as compared to other diverters.**
- ✓ **There is no power follow current in ZnO diverter.**
- ✓ **It has high energy absorbing capability.**
- ✓ **ZnO diverters possess high stability during and after prolonged discharge.**
- ✓ **In ZnO diverter, it is possible to control the dynamic overvoltages in addition to switching surges.**

CHAPTER

26

Neutral Grounding

Introduction

In power system, **grounding* or *earthing* means connecting frame of electrical equipment (non-current carrying part) or some electrical part of the system (*e.g.* neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth *i.e.* soil. This connection to earth may be through a conductor or some other circuit element (e.g. a resistor, a circuit breaker etc.) depending upon the situation. Regardless of the method of connection to earth, grounding or earthing offers two principal advantages. First, it provides protection to the power system. For example, if the neutral point of a star-connected system is grounded through a circuit breaker and phase to earth fault occurs on any one line, a large fault current will flow through the circuit breaker. The

* In electrical and electronic circuits, all the points which are electrically the same (called common points) are connected to the metal chassis. This method of grounding is called *chassis ground* or *circuit ground.* Circuit ground may or may not be connected to earth (*i.e.* soil). For example, in most cars, the negative terminal of the battery and one side of all electrical circuits are connected to the the metal chassis.

circuit breaker will open to isolate the faulty line. This protects the power system from the harmful effects of the fault. Secondly, earthing of electrical equipment (*e.g.* domestic appliances, hand-held tools, industrial motors etc.) ensures the safety of the persons handling the equipment. For example, if insulation fails, there will be a direct contact of the live conductor with the metallic part (*i.e.* frame) of the equipment. Any person in contact with the metallic part of this equipment will be subjected to a dangerous electrical shock which can be fatal. In this chapter, we shall discuss the importance of grounding or earthing in the line of power system with special emphasis on neutral grounding.

26.1 Grounding or Earthing

The process of connecting the metallic frame (i.e. non-current carrying part) of electrical equipment or some electrical part of the system (e.g. neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth (i.e. soil) is called **grounding** *or* **earthing.**

It is strange but true that grounding of electrical systems is less understood aspect of power system. Nevertheless, it is a very important subject. If grounding is done systematically in the line of the power system, we can effectively prevent accidents and damage to the equipment of the power system and at the same time continuity of supply can be maintained. Grounding or earthing may be classified as : ***(i)*** Equipment grounding ***(ii)*** System grounding.

Equipment grounding deals with earthing the non-current-carrying metal parts of the electrical equipment. On the other hand, system grounding means earthing some part of the electrical system *e.g.* earthing of neutral point of star-connected system in generating stations and sub-stations.

26.2 Equipment Grounding

The process of connecting non-current-carrying metal parts (i.e. metallic enclosure) of the electrical equipment to earth (i.e. soil) in such a way that in case of insulation failure, the enclosure effectively remains at earth potential is called **equipment grounding.**

We are frequently in touch with electrical equipment of all kinds, ranging from domestic appliances and hand-held tools to industrial motors. We shall illustrate the need of effective equipment grounding by considering a single-phase circuit composed of a 230 V source connected to a motor M as shown in Fig. 26.1. Note that neutral is solidly grounded at the service entrance. In the interest of easy understanding, we shall divide the discussion into three heads *viz*. ***(i)*** Ungrounded enclosure ***(ii)*** enclosure connected to neutral wire ***(iii)*** ground wire connected to enclosure.

***(i)* Ungrounded enclosure.** Fig. 26.1 shows the case of ungrounded metal enclosure. If a person touches the metal enclosure, nothing will happen if the equipment is functioning correctly. But if the winding insulation becomes faulty, the resistance R_e between the motor and enclosure drops to a low value (a few hundred ohms or less). A person having a body resistance R_b would complete the current path as shown in Fig. 26.1.

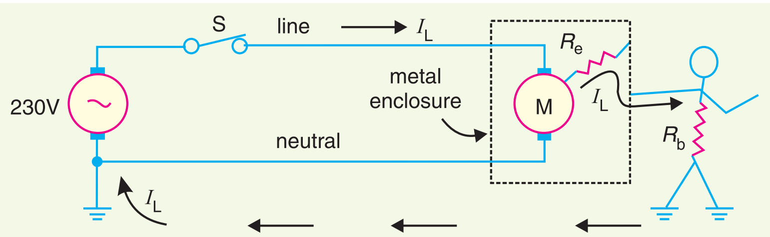


Fig. 26.1

If R_e is small (as is usually the case when insulation failure of winding occurs), the leakage current I_L through the person's body could be dangerously high. As a result, the person would get severe *electric shock which may be fatal. Therefore, this system is unsafe.

***(ii)* Enclosure connected to neutral wire.** It may appear that the above problem can be solved by connecting the enclosure to the grounded neutral wire as shown in Fig. 26.2. Now the leakage current I_L flows from the motor, through the enclosure and straight back to the neutral wire (See Fig. 26.2). Therefore, the enclosure remains at earth potential. Consequently, the operator would not experience any electric shock.

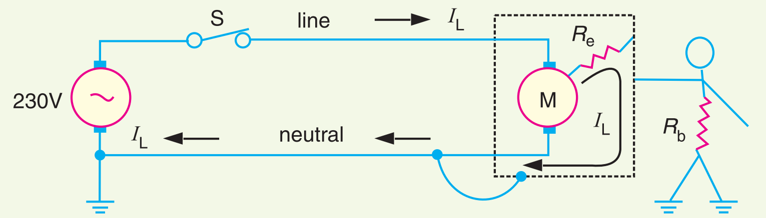


Fig. 26.2

The trouble with this method is that the neutral wire may become open either accidentally or due to a faulty installation. For example, if the switch is inadvertently in series with the neutral rather than the live wire (See Fig. 26.3), the motor can still be turned on and off. However, if someone touched the enclosure while the motor is *off*, he would receive a severe electric shock (See Fig. 26.3). It is because when the motor is off, the potential of the enclosure rises to that of the live conductor.

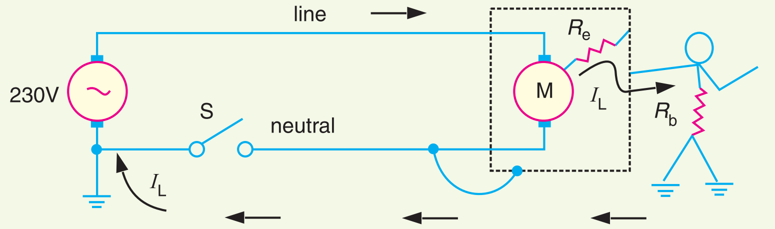


Fig. 26.3

***(iii)* Ground wire connected to enclosure.** To get rid of this problem, we install a third wire, called *ground wire,* between the enclosure and the system ground as shown in Fig. 26.4. The ground wire may be bare or insulated. If it is insulated, it is coloured green.

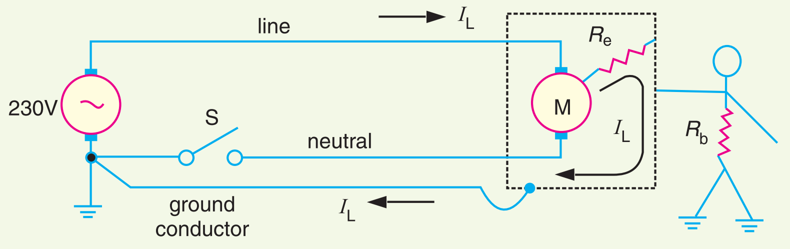


Fig. 26.4

* **Electric shock.** It is generally believed that currents below 5 mA are not dangerous. Between 10 mA and 20 mA, the current is dangerous because the victim loses muscular control. The resistance of the human body, taken between two hands or between one hand and a leg ranges from 500 Ω to 50 kΩ. If the resistance of human body is assumed to be 20 kΩ, then momentary contact with a 230 V line can be potentially fatal.

$$I_L = \frac{230\text{ V}}{20\text{ k}\Omega} = 11{\cdot}5\text{ mA}$$

Electrical outlets have three contacts — one for live wire, one for neutral wire and one for ground wire.

26.3 System Grounding

The process of connecting some electrical part of the power system (e.g. neutral point of a star-connected system, one conductor of the secondary of a transformer etc.) to earth (i.e. soil) is called **system grounding.**

The system grounding has assumed considerable importance in the fast expanding power system. By adopting proper schemes of system grounding, we can achieve many advantages including protection, reliability and safety to the power system network. But before discussing the various aspects of *neutral grounding*, it is desirable to give two examples to appreciate the need of system grounding.

(*i*) Fig. 26.5 (*i*) shows the primary winding of a distribution transformer connected between the line and neutral of a 11 kV line. If the secondary conductors are *ungrounded*, it would appear that a person could touch either secondary conductor without harm because there is no ground return. However, this is not true. Referring to Fig. 26.5, there is capacitance C_1 between primary and secondary and capacitance C_2 between secondary and ground. This capacitance coupling can produce a high voltage between the secondary lines and the ground. Depending upon the relative magnitudes of C_1 and C_2, it may be as high as 20% to 40% of the primary voltage. If a person touches either one of the secondary wires, the resulting capacitive current I_C flowing through the body could be dangerous even in case of small transformers [See Fig. 26.5(*ii*)]. For example, if I_C is only 20 mA, the person may get a fatal electric shock.

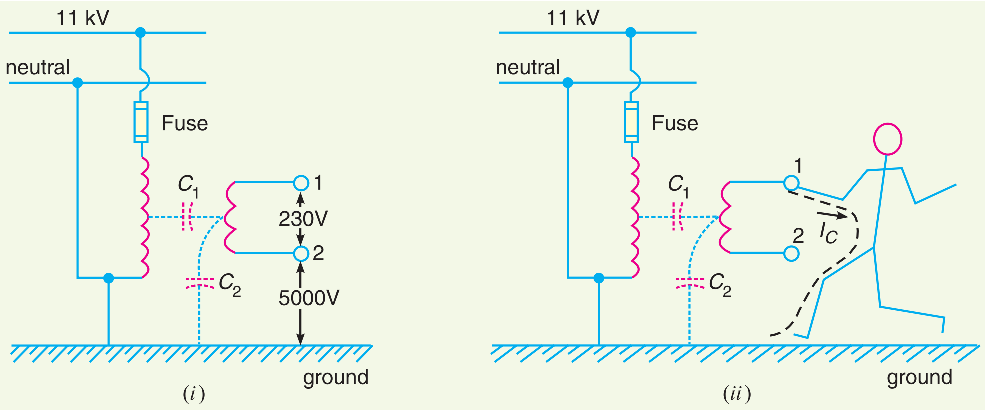


Fig. 26.5

If one of the secondary conductors is grounded, the capacitive coupling almost reduces to zero and so is the capacitive current I_C. As a result, the person will experience no electric shock. This explains the importance of system grounding.

(*ii*) Let us now turn to a more serious situation. Fig. 26.6 (*i*) shows the primary winding of a distribution transformer connected between the line and neutral of a 11 kV line. The secondary conductors are ungrounded. Suppose that the high voltage line (11 kV in this case) touches the 230 V conductor as shown in Fig. 26.6 (*i*). This could be caused by an internal fault in the transformer or by a branch or tree falling across the 11 kV and 230 V lines. Under these circumstances, a very high voltage is imposed between the secondary conductors and ground. This would immediately puncture the 230 V insulation, causing a massive flashover. This flashover could occur anywhere on the secondary network, possibly inside a home or factory. Therefore, ungrounded secondary in this case is a potential fire hazard and may produce grave accidents under abnormal conditions.

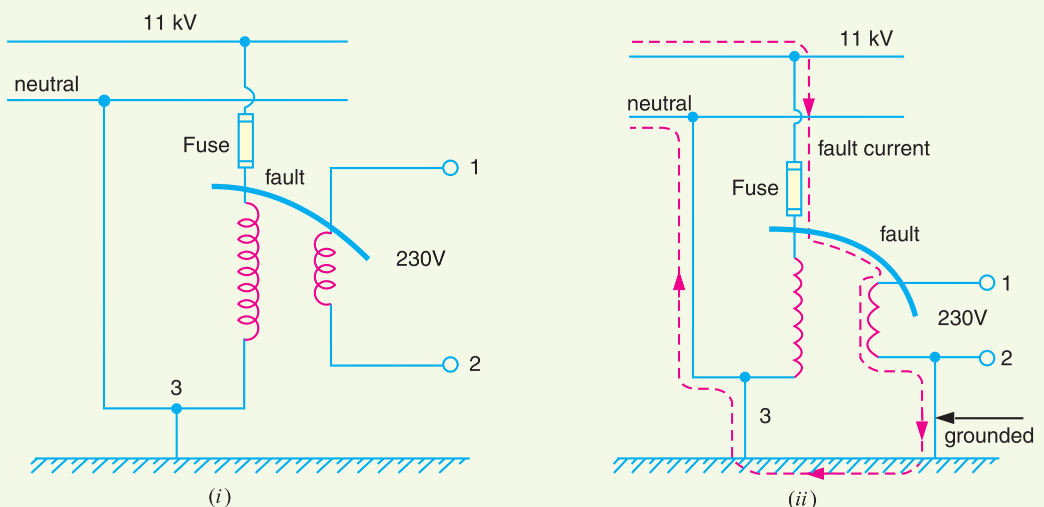


Fig. 26.6

If one of the secondary lines is grounded as shown in Fig. 26.6(*ii*), the accidental contact between a 11 kV conductor and a 230 V conductor produces a dead short. The short-circuit current (*i.e.* fault current) follows the dotted path shown in Fig. 26.6 (*ii*). This large current will blow the fuse on the 11 kV side, thus disconnecting the transformer and secondary distribution system from the 11 kV line. This explains the importance of system grounding in the line of the power system.

26.4 Ungrounded Neutral System

In an ungrounded neutral system, the neutral is not connected to the ground *i.e.* the neutral is isolated from the ground. Therefore, this system is also called *isolated neutral system* or *free neutral system*. Fig. 26.7 shows ungrounded neutral system. The line conductors have capacitances between one another and to ground. The former are delta-connected while the latter are star-connected. The delta-connected capacitances have little effect on the grounding characteristics of the system (*i.e.* these capacitances do not effect the earth circuit) and, therefore, can be neglected. The circuit then reduces to the one shown in Fig. 26.8(*i*).

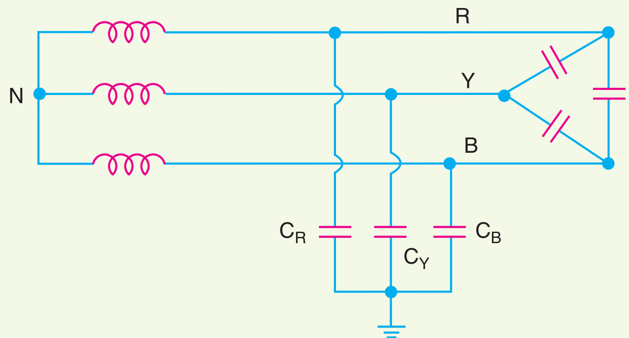


Fig. 26.7

Circuit behaviour under normal conditions. Let us discuss the behaviour of ungrounded neutral system under normal conditions (*i.e.* under steady state and balanced conditions). The line is assumed to be perfectly transposed so that each conductor has the same capacitance to ground.

Therefore, $C_R = C_Y = C_B = C$ (say). Since the phase voltages V_{RN}, V_{YN} and V_{BN} have the same magnitude (of course, displaced 120° from one another), the capacitive currents I_R, I_Y and I_B will have the same value *i.e.*

$$I_R = I_Y = I_B = \frac{V_{ph}}{X_C} \quad \text{.... in magnitude}$$

where V_{ph} = Phase voltage (*i.e.* line-to-neutral voltage)

X_C = Capacitive reactance of the line to ground.

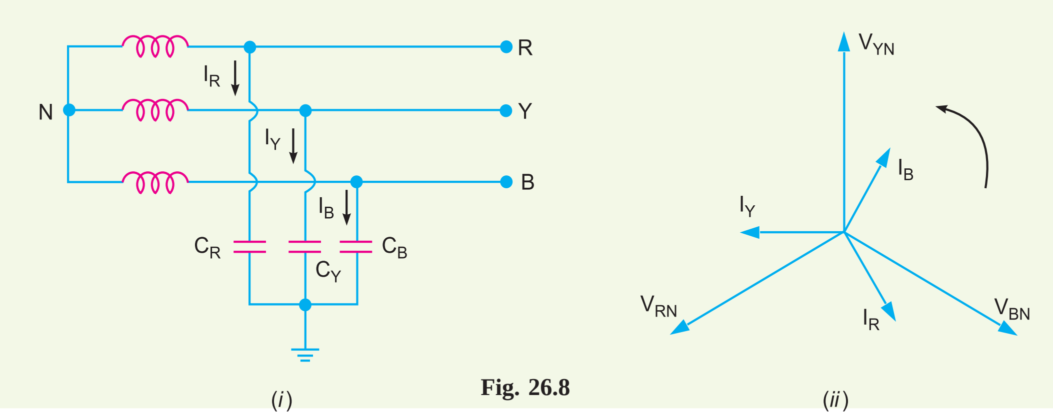


Fig. 26.8

The capacitive currents I_R, I_Y and I_B lead their respective phase voltages V_{RN}, V_{YN} and V_{BN} by 90° as shown in the phasor diagram in Fig. 26.8(*ii*). The three capacitive currents are equal in magnitude and are displaced 120° from each other. Therefore, their phasor sum is zero. As a result, no current flows to ground and the *potential of neutral is the same as the ground potential.* Therefore, ungrounded neutral system poses no problems under normal conditions. However, as we shall see, currents and voltages are greatly influenced during fault conditions.

Circuit behaviour under single line to ground-fault. Let us discuss the behaviour of ungrounded neutral system when single line to ground fault occurs. Suppose line to ground fault occurs in line *B* at some point *F*. The *circuit then becomes as shown in Fig. 26.9(*i*). The capacitive currents I_R and I_Y flow through the lines *R* and *Y* respectively. The voltages driving I_R and I_Y are V_{BR} and V_{BY} respectively. Note that V_{BR} and V_{BY} are the line voltages [See Fig. 26.9 (*ii*)]. The paths of I_R and I_Y are essentially capacitive. Therefore, I_R leads V_{BR} by 90° and I_Y leads V_{BY} by 90° as shown in Fig. 26.9 (*ii*). The capacitive fault current I_C in line *B* is the phasor sum of I_R and I_Y.

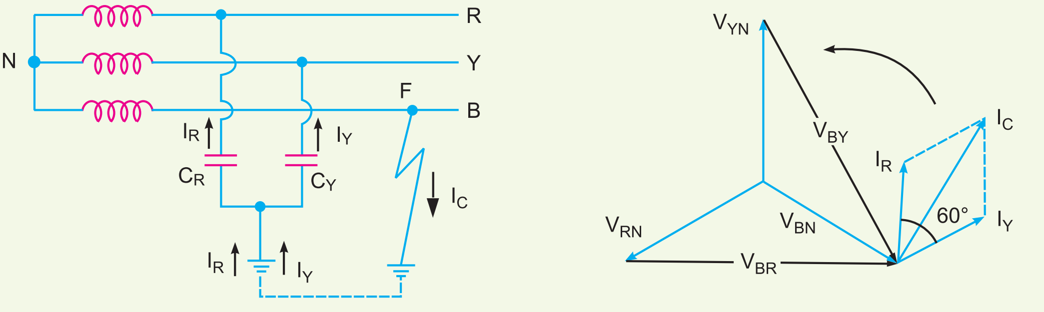
Fault current in line *B*, $\quad I_C = I_R + I_Y$ .... Phasor sum

Now, $$I_R = \frac{V_{BR}}{X_C} = \frac{\sqrt{3}\,V_{ph}}{X_C}$$

and $$I_Y = \frac{V_{BY}}{X_C} = \frac{\sqrt{3}\,V_{ph}}{X_C}$$

$$\therefore \quad I_R = I_Y = \frac{\sqrt{3}\,V_{ph}}{X_C}$$

* Due to line-to-ground fault in line *B*, the potential of phase *B* becomes equal to the ground potential. This short circuits the capacitance of this line (*i.e.* capacitance C_B). Hence no capacitive current flows through C_B.



(*i*) (*ii*)

Fig. 26.9

$$= \sqrt{3} \times \text{Per phase capacitive current under normal conditions}$$

Capacitive fault current in line *B* is

$$I_C = \text{Phasor sum of } I_R \text{ and } I_Y$$

$$= {}^{\dagger}\sqrt{3}\, I_R = \sqrt{3} \times \frac{\sqrt{3}\, V_{ph}}{X_C} = \frac{3V_{ph}}{X_C}$$

$$\therefore \quad I_C = \frac{3V_{ph}}{X_C} = 3 \times \frac{V_{ph}}{X_C}$$

$$= 3 \times \text{Per phase capacitive current under normal conditions}$$

Therefore, when single line to ground fault occurs on an ungrounded neutral system, the following effects are produced in the system:

(*i*) The potential of the faulty phase becomes equal to ground potential. However, the voltages of the two remaining healthy phases rise from their normal phase voltages to full line value. This may result in insulation breakdown.

(*ii*) The capacitive current in the two healthy phases increase to $\sqrt{3}$ times the normal value.

(*iii*) The capacitive fault current (I_C) becomes 3 times the normal per phase capacitive current.

(*iv*) This system cannot provide adequate protection against earth faults. It is because the capacitive fault current is small in magnitude and cannot operate protective devices.

(*v*) The capacitive fault current I_C flows into earth. Experience shows that I_C in excess of 4A is sufficient to maintain an arc in the ionized path of the fault. If this current is once maintained, it may exist even after the earth fault is cleared. This phenomenon of *persistent arc is called *arcing ground*. Due to arcing ground, the system capacity is charged and discharged in a cyclic order. This sets up high-frequency oscillations on the whole system and the phase voltage of healthy conductors may rise to 5 to 6 times its normal value. The overvoltages in healthy conductors may damage the insulation in the line.

† Referring to Fig. 26.9(*ii*), the magnitudes of I_R and I_Y are equal and the angle between them is 60°. Therefore, the resultant capacitive fault current I_C is given by:

$$I_C = 2I_R \cos 60°/2 = 2I_R \cos 30° = 2\, I_R \times \sqrt{3}/2 = \sqrt{3}\, I_R .$$

* When the arc is formed, the voltage across it becomes zero and the arc is extinguished. As a result, the potential of the faulty conductor is restored and the formation of second arc takes place. This phenomenon of intermittent arcing is called arcing ground.

Due to above disadvantages, ungrounded neutral system is not used these days. The modern high-voltage 3-phase systems employ grounded neutral owing to a number of advantages.

26.5 Neutral Grounding

The process of connecting neutral point of 3-phase system to earth (i.e. soil) either directly or through some circuit element (e.g. resistance, reactance etc.) is called **neutral grounding.**

Neutral grounding provides protection to personal and equipment. It is because during earth fault, the current path is completed through the earthed neutral and the protective devices (*e.g.* a fuse etc.) operate to isolate the faulty conductor from the rest of the system. This point is illustrated in Fig. 26.10.

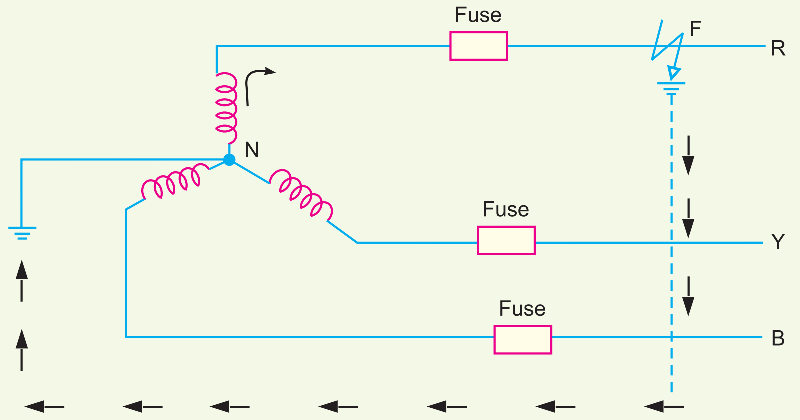


Fig. 26.10

Fig. 26.10 shows a 3-phase, star-connected system with neutral earthed (*i.e.* neutral point is connected to soil). Suppose a single line to ground fault occurs in line *R* at point *F*. This will cause the current to flow through ground path as shown in Fig. 26.10. Note that current flows from *R*-phase to earth, then to neutral point *N* and back to *R*-phase. Since the impedance of the current path is low, a large current flows through this path. This large current will blow the fuse in *R*-phase and isolate the faulty line *R*. This will protect the system from the harmful effects (*e.g.* damage to equipment, electric shock to personnel etc.) of the fault. One important feature of grounded neutral is that the potential difference between the live conductor and ground will not exceed the phase voltage of the system *i.e.* it will remain nearly constant.

26.6 Advantages of Neutral Grounding

The following are the advantages of neutral grounding :

- (*i*) Voltages of the healthy phases do not exceed line to ground voltages *i.e.* they remain nearly constant.
- (*ii*) The high voltages due to arcing grounds are eliminated.
- (*iii*) The protective relays can be used to provide protection against earth faults. In case earth fault occurs on any line, the protective relay will operate to isolate the faulty line.
- (*iv*) The overvoltages due to lightning are discharged to earth.
- (*v*) It provides greater safety to personnel and equipment.
- (*vi*) It provides improved service reliability.
- (*vii*) Operating and maintenance expenditures are reduced.

Note : It is interesting to mention here that ungrounded neutral has the following advantages :

(i) In case of earth fault on one line, the two healthy phases will continue to supply load for a short period.

(ii) Interference with communication lines is reduced because of the absence of zero sequence currents.

The advantages of ungrounded neutral system are of negligible importance as compared to the advantages of the grounded neutral system. Therefore, modern 3-phase systems operate with grounded neutral points.

26.7 Methods of Neutral Grounding

The methods commonly used for grounding the neutral point of a 3-phase system are :

(i) Solid or effective grounding *(ii)* Resistance grounding

(iii) Reactance grounding *(iv)* Peterson-coil grounding

The choice of the method of grounding depends upon many factors including the size of the system, system voltage and the scheme of protection to be used.

26.8 Solid Grounding

*When the neutral point of a 3-phase system (e.g. 3-phase generator, 3-phase transformer etc.) is directly *connected to earth (i.e. soil) through a wire of negligible resistance and reactance, it is called* **solid grounding** *or* **effective grounding**.

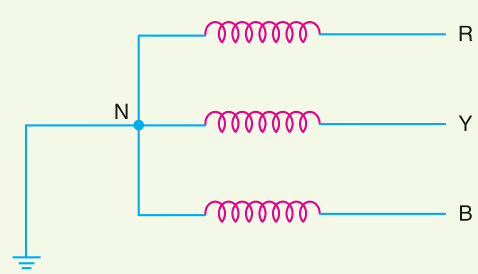


Fig. 26.11

Fig. 26.11 shows the solid grounding of the neutral point. Since the neutral point is directly connected to earth through a wire, the neutral point is held at earth potential under all conditions. Therefore, under fault conditions, the voltage of any conductor to earth will not exceed the normal phase voltage of the system.

Advantages. The solid grounding of neutral point has the following advantages :

(i) The neutral is effectively held at earth potential.

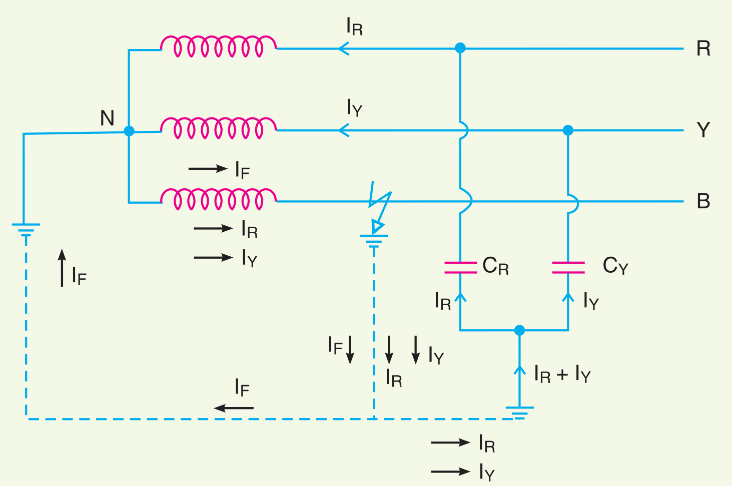


Fig. 26.12

* This is a metallic connection made from the neutral of the system to one or more earth electrodes consisting of plates, rods or pipes buried in the ground.

(*ii*) When earth fault occurs on any phase, the resultant capacitive current I_C is in phase opposition to the fault current I_F. The two currents completely cancel each other. Therefore, no arcing ground or over-voltage conditions can occur. Consider a line to ground fault in line *B* as shown in Fig. 26.12. The capacitive currents flowing in the healthy phases *R* and *Y* are I_R and I_Y respectively. The resultant capacitive current I_C is the phasor sum of I_R and I_Y. In addition to these capacitive currents, the power source also supplies the fault current I_F. This fault current will go from fault point to earth, then to neutral point *N* and back to the fault point through the faulty phase. The path of I_C is capacitive and that of I_F is *inductive. The two currents are in phase opposition and completely cancel each other. Therefore, no arcing ground phenomenon or over-voltage conditions can occur.

(*iii*) When there is an earth fault on any phase of the system, the phase to earth voltage of the faulty phase becomes zero. However, the phase to earth voltages of the remaining two healthy phases remain at normal phase voltage because the potential of the neutral is fixed at earth potential. This permits to insulate the equipment for phase voltage. Therefore, there is a saving in the cost of equipment.

(*iv*) It becomes easier to protect the system from earth faults which frequently occur on the system. When there is an earth fault on any phase of the system, a large fault current flows between the fault point and the grounded neutral. This permits the easy operation of earth-fault relay.

Disadvantages. The following are the disadvantages of solid grounding :

(*i*) Since most of the faults on an overhead system are phase to earth faults, the system has to bear a large number of severe shocks. This causes the system to become unstable.

(*ii*) The solid grounding results in heavy earth fault currents. Since the fault has to be cleared by the circuit breakers, the heavy earth fault currents may cause the burning of circuit breaker contacts.

(*iii*) The increased earth fault current results in greater interference in the neighbouring communication lines.

Applications. Solid grounding is usually employed where the circuit impedance is sufficiently high so as to keep the earth fault current within safe limits. This system of grounding is used for voltages upto 33 kV with total power capacity not exceeding 5000 kVA.

26.9 Resistance Grounding

In order to limit the magnitude of earth fault current, it is a common practice to connect the neutral point of a 3-phase system to earth through a resistor. This is called *resistance grounding*.

When the neutral point of a 3-phase system (e.g. 3-phase generator, 3-phase transformer etc.) is connected to earth (i.e. soil) through a resistor, it is called **resistance grounding.**

Fig. 26.13 shows the grounding of neutral point through a **resistor *R*. The value of *R* should neither be very low nor very high. If the value of earthing resistance *R* is very low, the earth fault current will be large and the system becomes similar to the solid grounding system. On the other hand, if the earthing resistance *R* is very high, the system conditions become similar to ungrounded

* By symmetrical components, the fault current I_F is given by :

$$I_F = \frac{3V_{ph}}{Z_1 + Z_2 + Z_0}$$

Since $Z_1 + Z_2 + Z_0$ is predominantly inductive, I_F lags behind the phase to neutral voltage of the faulted phase by nearly 90°.

** It may be a metallic resistor or liquid resistor. Metallic resistors do not change with time and practically require no maintenance. However, a metallic resistor is slightly inductive and this poses a problem with overhead lines exposed to lightning, Liquid resistors are free from this disadvantage.

neutral system. The value of R is so chosen such that the earth fault current is limited to safe value but still sufficient to permit the operation of earth fault protection system. In practice, that value of R is selected that limits the earth fault current to 2 times the normal full load current of the earthed generator or transformer.

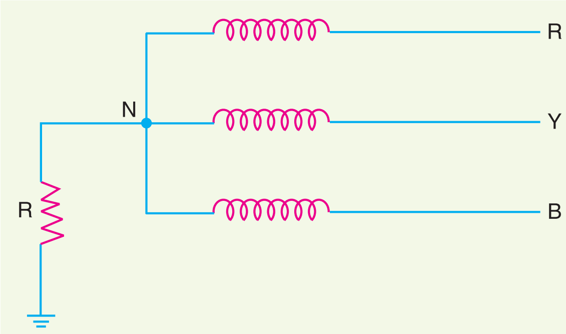


Fig. 26.13

Advantages. The following are the advantages of resistance earthing:

(i) By adjusting the value of R, the arcing grounds can be minimised. Suppose earth fault occurs in phase B as shown in Fig. 26.14. The capacitive currents I_R and I_Y flow in the healthy phases R and Y respectively. The fault current I_F lags behind the phase voltage of the faulted phase by a certain angle depending upon the earthing resistance R and the reactance of the system upto the point of fault. The fault current I_F can be resolved into two components *viz*.

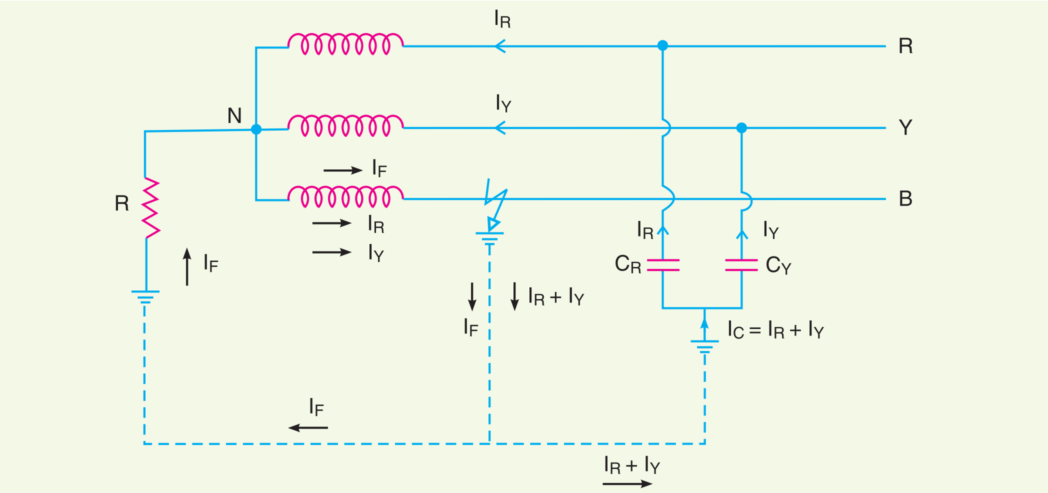


Fig. 26.14

(a) I_{F1} in phase with the faulty phase voltage.

(b) I_{F2} lagging behind the faulty phase voltage by 90°.

The lagging component I_{F2} is in phase opposition to the total capacitive current I_C. If the value of earthing resistance R is so adjusted that $I_{F2} = I_C$, the arcing ground is completely eliminated and the operation of the system becomes that of solidly grounded system. However, if R is so adjusted that $I_{F2} < I_C$, the operation of the system becomes that of ungrounded neutral system.

(ii) The earth fault current is small due to the presence of earthing resistance. Therefore, interference with communication circuits is reduced.

(iii) It improves the stability of the system.

Disadvantages. The following are the disadvantages of resistance grounding :

(i) Since the system neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.

(ii) This system is costlier than the solidly grounded system.

(*iii*) A large amount of energy is produced in the earthing resistance during earth faults. Sometimes it becomes difficult to dissipate this energy to atmosphere.

Applications. It is used on a system operating at voltages between 2.2 kV and 33 kV with power source capacity more than 5000 kVA.

26.10 Reactance Grounding

In this system, a reactance is inserted between the neutral and ground as shown in Fig. 26.15. The purpose of reactance is to limit the earth fault current. By changing the earthing reactance, the earth fault current can to changed to obtain the conditions similar to that of solid grounding. This method is not used these days because of the following disadvantages :

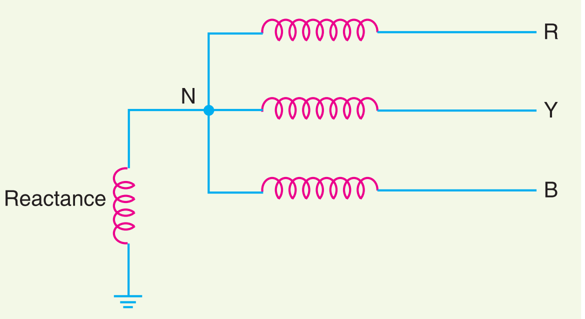


Fig. 26.15

(*i*) In this system, the fault current required to operate the protective device is higher than that of resistance grounding for the same fault conditions.

(*ii*) High transient voltages appear under fault conditions.

26.11 *Arc Suppression Coil Grounding (or Resonant Grounding)

We have seen that capacitive currents are responsible for producing arcing grounds. These capacitive currents flow because capacitance exists between each line and earth. If inductance L of appropriate value is connected in parallel with the capacitance of the system, the fault current I_F flowing through L will be in phase opposition to the capacitive current I_C of the system. If L is so adjusted that $I_L = I_C$, then resultant current in the fault will be zero. This condition is known as *resonant grounding.*

When the value of L of arc suppression coil is such that the fault current I_F exactly balances the capacitive current I_C, it is called **resonant grounding.**

Circuit details. An arc suppression coil (also called Peterson coil) is an iron-cored coil connected between the neutral and earth as shown in Fig. 26.16(*i*). The reactor is provided with tappings to change the inductance of the coil. By adjusting the tappings on the coil, the coil can be tuned with the capacitance of the system i.e. resonant grounding can be achieved.

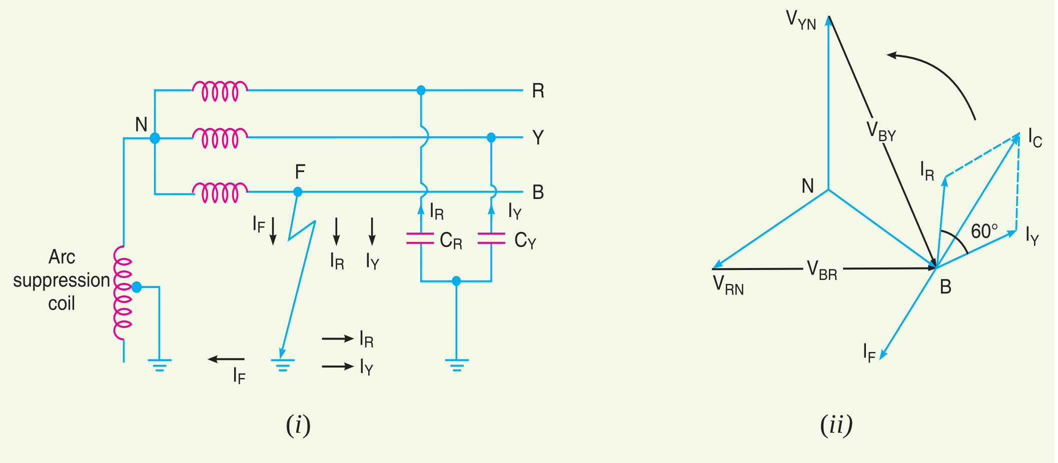


Fig. 26.16

* Also called **Peterson coil grounding.**

Operation. Fig. 26.16(*i*) shows the 3-phase system employing Peterson coil grounding. Suppose line to ground fault occurs in the line *B* at point *F*. The fault current I_F and capacitive currents I_R and I_Y will flow as shown in Fig. 26.16(*i*). Note that I_F flows through the Peterson coil (or Arc suppression coil) to neutral and back through the fault. The total capacitive current I_C is the phasor sum of I_R and I_Y as shown in phasor diagram in Fig. 26.16(*ii*). The voltage of the faulty phase is applied across the arc suppression coil. Therefore, fault current I_F lags the faulty phase voltage by 90°. The current I_F is in phase opposition to capacitive current I_C [See Fig. 26.16(*ii*)]. By adjusting the tappings on the Peterson coil, the resultant current in the fault can be reduced. If inductance of the coil is so adjusted that $I_L = I_C$, then resultant current in the fault will be zero.

Value of L for resonant grounding. For resonant grounding, the system behaves as an ungrounded neutral system. Therefore, full line voltage appears across capacitors C_R and C_Y.

$$\therefore \quad I_R = I_Y = \frac{\sqrt{3}V_{ph}}{X_C}$$

$$\therefore \quad I_C = \sqrt{3}\, I_R = \sqrt{3} \times \frac{\sqrt{3}V_{ph}}{X_C} = \frac{3V_{ph}}{X_C}$$

Here, X_C is the line to ground capacitive reactance.

Fault current, $$I_F = \frac{V_{ph}}{X_L}$$

Here, X_L is the inductive reactance of the arc suppression coil.

For resonant grounding, $I_L = I_C$.

or $$\frac{V_{ph}}{X_L} = \frac{3V_{ph}}{X_C}$$

or $$X_L = \frac{X_C}{3}$$

or $$\omega L = \frac{1}{3\omega C}$$

$$\therefore \quad L = \frac{1}{3\omega^2 C} \qquad ...(i)$$

Exp. (*i*) gives the value of inductance *L* of the arc suppression coil for resonant grounding.

Advantages. The Peterson coil grounding has the following advantages:

(*i*) The Peterson coil is completely effective in preventing any damage by an arcing ground.

(*ii*) The Peterson coil has the advantages of ungrounded neutral system.

Disadvantages. The Peterson coil grounding has the following disadvantages :

(*i*) Due to varying operational conditions, the capacitance of the network changes from time to time. Therefore, inductance *L* of Peterson coil requires readjustment.

(*ii*) The lines should be transposed.

26.12 Voltage Transformer Earthing

In this method of neutral earthing, the primary of a single-phase voltage transformer is connected between the neutral and the earth as shown in Fig. 26.17. A low resistor in series with a relay is connected across the secondary of the voltage transformer. The voltage transformer provides a high reactance in the neutral earthing circuit and operates virtually as an ungrounded neutral system. An earth fault on any phase produces a voltage across the relay. This causes the operation of the protective device.

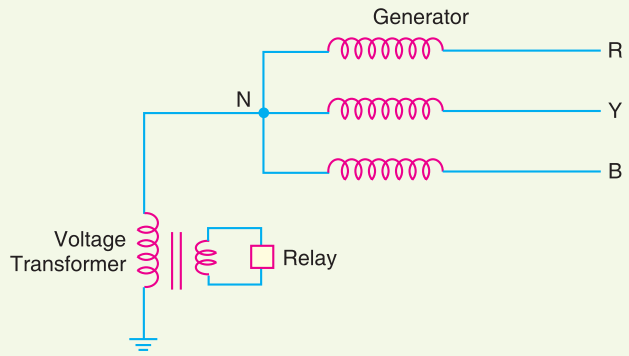


Fig. 26.17

Advantages. The following are the advantages of voltage transformer earthing :

(*i*) The transient overvoltages on the system due to switching and arcing grounds are reduced. It is because voltage transformer provides high reactance to the earth path.

(*ii*) This type of earthing has all the advantages of ungrounded neutral system.

(*iii*) Arcing grounds are eliminated.

Disadvantages. The following are the disadvantages of voltage transformer earthing :

(*i*) When earth fault occurs on any phase, the line voltage appears across line to earth capacitances. The system insulation will be overstressed.

(*ii*) The earthed neutral acts as a reflection point for the travelling waves through the machine winding. This may result in high voltage build up.

Applications. The use of this system of neutral earthing is normally confined to generator equipments which are directly connected to step-up power transformers.

Example 26.1. *Calculate the reactance of Peterson coil suitable for a 33 kV, 3-phase transmission line having a capacitance to earth of each conductor as 4.5 μF. Assume supply frequency to be 50 Hz.*

Solution. Supply frequency, $f = 50$ Hz

Line to earth capacitance, $C = 4{\cdot}5\ \mu\text{F} = 4{\cdot}5 \times 10^{-6}$ F

For Peterson coil grounding, reactance X_L of the Peterson coil should be equal to $X_C/3$ where X_C is line to earth capacitive reactance.

$$\therefore \quad \text{Reactance of Peterson coil, } X_L = \frac{X_C}{3} = \frac{1}{3\,\omega C} = \frac{1}{3 \times 2\pi f \times C}$$

$$= \frac{1}{3 \times 2\pi \times 50 \times 4{\cdot}5 \times 10^{-6}} = \mathbf{235{\cdot}8\Omega}$$

Example 26.2. *A 230 kV, 3-phase, 50 Hz, 200 km transmission line has a capacitance to earth of 0·02 μF/km per phase. Calculate the inductance and kVA rating of the Peterson coil used for earthing the above system.*

Solution. Supply frequency, $f = 50$ Hz

Capacitance of each line to earth, $C = 200 \times 0{\cdot}02 = 4 \times 10^{-6}$ F

Required inductance of Peterson coil is

$$L = \frac{1}{3\omega^2 C}$$

$$= \frac{1}{3\times(2\pi\times 50)^2\times 4\times 10^{-6}} = \mathbf{0{\cdot}85\ H}$$

Current through Peterson coil is

$$I_F = \frac{V_{ph}}{X_L} = \frac{230\times 10^3/\sqrt{3}}{2\pi\times 50\times 0{\cdot}85} = 500\ A$$

Voltage across Peterson coil is

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{230\times 1000}{\sqrt{3}}\ V$$

$\therefore$ Rating of Peterson coil $= V_{ph} \times I_F = \dfrac{230\times 1000}{\sqrt{3}} \times 500 \times \dfrac{1}{1000}$ **kVA = 66397 kVA**

Example 26.3. *A 50 Hz overhead line has line to earth capacitance of 1.2 μF. It is desired to use *earth fault neutralizer. Determine the reactance to neutralize the capacitance of (i) 100% of the length of the line (ii) 90% of the length of the line and (iii) 80% of the length of the line.*

Solution.

(*i*) Inductive reactance of the coil to neutralize capacitance of 100% of the length of the line is

$$X_L = \frac{1}{3\omega C} = \frac{1}{3\times 2\pi\times 50\times 1{\cdot}2\times 10^{-6}} = \mathbf{884{\cdot}19\Omega}$$

(*ii*) Inductive reactance of the coil to neutralize capacitance of 90% of the length of the line is

$$X_L = \frac{1}{3\omega\times 0{\cdot}9C} = \frac{1}{3\times 2\pi\times 50\times 0{\cdot}9\times 1{\cdot}2\times 10^{-6}} = \mathbf{982{\cdot}43\Omega}$$

(*iii*) Inductive reactance of the coil to neutralize capacitance of 80% of the length of the line is

$$X_L = \frac{1}{3\omega\times 0{\cdot}8C} = \frac{1}{3\times 2\pi\times 50\times 0{\cdot}8\times 1{\cdot}2\times 10^{-6}} = \mathbf{1105{\cdot}24\Omega}$$

Example 26.4. *A 132 kV, 3-phase, 50 Hz transmission line 200 km long consists of three conductors of effective diameter 20 mm arranged in a vertical plane with 4 m spacing and regularly transposed. Find the inductance and kVA rating of the arc suppression coil in the system.*

Solution. Radius of conductor, $r = 20/2 = 10$ mm $= 0{\cdot}01$ m

Conductor spacing, $d = 4m$

$\therefore$ Capacitance between phase and neutral or earth

$$= \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}}\ F/m = \frac{2\pi\times 8{\cdot}885\times 10^{-12}}{\log_e \frac{4}{0{\cdot}01}} = 9{\cdot}285 \times 10^{-12}\ \text{F/m}$$

$$= 9{\cdot}285 \times 10^{-12} \times 10^3\ \text{F/km} = 9{\cdot}285 \times 10^{-9}\ \text{F/km}$$

$\therefore$ Capacitance C between phase and earth for 200 km line is

* Note that Peterson coil is also known as earth fault neutralizer.

Basic Insulation Level (BIL)

Basic Insulation Level (BIL) it is the ability of electrical equipment, such as transformers, circuit breakers, and insulators, to withstand high-voltage surges, such as those caused by lightning strikes or switching events.

The BIL rating is expressed in kilovolts (kV) and is a critical parameter in ensuring that equipment can operate safely and reliably under transient voltage conditions.

Key Points about BIL

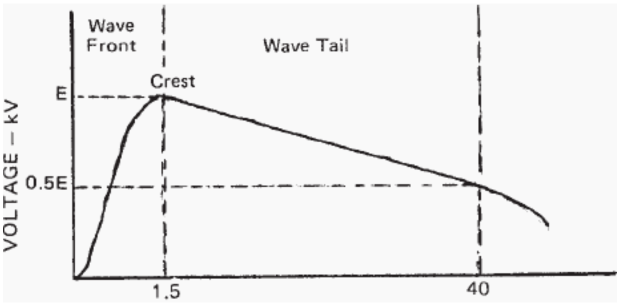
1. Definition: BIL is the maximum voltage of electrical equipment can tolerate without being damaged.

2. Purpose: It ensures protection against voltage surges caused by lightning strikes or switching events.

3. Application: Commonly used in high-voltage systems (like power grids) to determine insulation design.

4. Testing: Equipment is tested under controlled conditions using impulse tests, where a simulated high-voltage pulse is applied to verify its insulation strength.

5. Standardization: BIL ratings are standardized based on international guidelines, such as those from the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC).



Insulation Coordination

Electrical insulation is a non-conductive material or substance that resists the flow of electric current.

- It is used to isolate electrical conductors from each other and from any other conductive materials or grounded surfaces.
- The insulation helps to prevent electric shocks, short circuits, and other electrical hazards.

Insulation Coordination is the selection and design of insulation levels for equipment in a power system to ensure reliable performance and protection against overvoltages.

The **primary objective** of insulation coordination is to achieve optimal balance between the insulation levels of different components while minimizing the risk of damage from voltage surges, such as lightning or switching events.

Key Concepts of Insulation Coordination:

1. Purpose:

- To ensure that all components of an electrical system are properly insulated relative to the voltages they are expected to experience.

- To prevent equipment damage or failure by ensuring that insulation levels are sufficient to handle expected voltage stresses.

2. Overvoltage Categories:

Temporary Overvoltage (TOV): Caused by system operating conditions (e.g., load changes, faults).

Switching Overvoltage: Transients generated during switching operations in high-voltage circuits.

Lightning Overvoltage: Caused by lightning strikes or induced by nearby strikes.

3. Coordination of Insulation Levels:

- Equipment is rated based on its Basic Insulation Level (BIL), which defines the maximum impulse voltage it can withstand.

- Different equipment types (e.g., transformers, cables, surge arresters) are designed with insulation levels that can safely coexist within the system.

- Surge arresters are often used to limit overvoltage and protect more expensive components by diverting high-energy surges.

4. Approach:

Protection Margin: Insulation levels are chosen to ensure a safe margin above the expected maximum overvoltage.

Energy Coordination: Ensuring that energy from surges is managed and dissipated safely by devices like surge arresters, without damaging the system's insulation.

5. Standards and Design:

- International standards (such as IEC 60071 and IEEE C62) provide guidelines for determining proper insulation levels and coordinating them across different system components.

- Simulations and modeling are often performed to predict overvoltage conditions and ensure that insulation levels will withstand them.

Steps in Insulation Coordination:

1. Determine maximum expected overvoltages from events like lightning or switching surges.

2. Select the insulation level (BIL or Basic Switching Impulse Level, BSIL) for each component based on these overvoltages.

3. Use protective devices like surge arresters to limit overvoltages and protect critical equipment.

4. Perform testing and validation of insulation systems to ensure they meet the required performance under actual conditions.