

Code: 23EE4601A

**III B.Tech - II Semester - Regular Examinations – APRIL 2026****SWITCHGEAR AND PROTECTION  
(ELECTRICAL & ELECTRONICS ENGINEERING)**

Duration: 3 hours

Max. Marks: 70

Note: 1. This question paper contains two Parts A and B.

2. Part-A contains 10 short answer questions. Each Question carries 2 Marks.

3. Part-B contains 5 essay questions with an internal choice from each unit. Each Question carries 10 marks.

4. All parts of Question paper must be answered in one place.

BL – Blooms Level

CO – Course Outcome

**PART – A**

		BL	CO
1.a)	What is a MCB? Write its function.	L2	CO1
1.b)	Define the term RRRV.	L3	CO2
1.c)	Mention the difference between a fuse and a relay.	L3	CO2
1.d)	Why are differential relays more sensitive than over current relays?	L3	CO2
1.e)	Mention the most used protection scheme for alternators.	L3	CO4
1.f)	Name any two different transformer faults.	L2	CO1
1.g)	How earth fault protection is achieved in case of feeder?	L2	CO1
1.h)	Define Plug-setting multiplier.	L3	CO4
1.i)	Mention the function of lightning Arrester.	L3	CO4
1.j)	Define neutral grounding.	L3	CO4

## PART – B

			BL	CO	Max. Marks
<b>UNIT-I</b>					
2	a)	Describe the phenomenon of (i) Current chopping (ii) Resistance switching.	L3	CO2	5 M
	b)	A circuit breaker is rated at 1500 A, 2000 MVA, 33 kV, 3 sec, 3-phase oil circuit breaker. Determine (i) the rated normal current (ii) breaking current (iii) making current (iv) short time rating current.	L4	CO3	5 M
<b>OR</b>					
3	a)	Discuss the principle of operation of an air-blast circuit breaker. What are the advantages and disadvantages of using air as the arc quenching medium?	L2	CO1	5 M
	b)	Compare the performance of SF6 gas with air when used for circuit breaking.	L4	CO3	5 M
<b>UNIT-II</b>					
4	a)	Describe the construction and principle of operation of an induction type over current relay.	L3	CO2	5 M
	b)	Compare IDMT and DMT overcurrent relays in terms of operating characteristics and applications.	L4	CO3	5 M
<b>OR</b>					
5	a)	Describe the operating principle, constructional features and area of applications of directional relay.	L2	CO1	5 M

	b)	Draw and explain the characteristics of a mho relay on an R-X diagram	L3	CO3	5 M
<b>UNIT-III</b>					
6	a)	Describe protection scheme of an alternator against inter-turn fault.	L3	CO4	5 M
	b)	A star-connected, 3-phase, 10-MVA, 6.6 kV alternator has a per phase reactance of 10%. It is protected by Merz-Price circulating-current principle which is set to operate for fault currents not less than 175 A. Calculate the value of earthing resistance to be provided in order to ensure that only 10% of the alternator winding remains unprotected.	L4	CO5	5 M
<b>OR</b>					
7	a)	Describe the construction and working of a Buchholz relay.	L3	CO4	5 M
	b)	A 3-phase transformer of 220/11,000 line volts is connected in star/delta. The protective transformers on 220 V side have a current ratio of 600/5. What should be the CT ratio on 11,000 V side?	L4	CO5	5 M
<b>UNIT-IV</b>					
8	a)	Explain the principle of operation of impedance-type distance relays and discuss their application in transmission line protection.	L2	CO1	5 M

	b)	A relay is connected to 200/5 ratio current transformer with current setting of 120%. Calculate the Plug Setting Multiplier when circuit carries a fault current of 2000A.	L4	CO5	5 M
<b>OR</b>					
9	a)	Explain the principle of operation of differential protection scheme used for bus bar protection.	L3	CO4	5 M
	b)	Explain the construction and basic components of a static relay and describe its operation.	L2	CO1	5 M
<b>UNIT-V</b>					
10	a)	What is lightning? Describe the mechanism of lightning discharge.	L2	CO1	5 M
	b)	Explain the operation of Zinc-Oxide Lighting Arresters.	L3	CO4	5 M
<b>OR</b>					
11	a)	Discuss the advantages of (i) Grounding the neutral of the system (ii) keeping the neutral isolated.	L3	CO4	5 M
	b)	Explain the phenomenon of “arcing grounds” on overhead transmission lines.	L3	CO4	5 M

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 Department of Electrical and Electronics Engineering  
 III B.Tech -II Sem Regular examinations (Apr 2026)  
 Key for Switch Gear & Protection (23EE4601A)

Q1 a)	MCB definition function	1M 1M
Q1 b)	Definition of RRRV	2 M
Q1 c)	Fuse function Relay function	1M 1M
Q1 d)	Explanation based on time of operation CT and pilot wire connection	2M
Q1 e)	Stator, rotor, miscellaneous any 2 types from the three	2M
Q1 f)	Internal faults External faults	1M 1M
Q1 g)	Explanation or diagram of earth fault connection	2M
Q1 h)	Formula for PSM	2M
Q1 i)	Explanation of connection and function during surge	2M
Q1 j)	Definition of grounding	2M
Q 2 a)	Current chopping diagram, Resistance switching Explanation chopping & resistance switching	1M 1M 3M <hr/> 5M
2 b)	Calculation of Nominal current Breaking current Making current Short time rating	1M 2M 1M 1M <hr/> 5M
Q 3a)	Diagram of air blast circuit breaker Explanation Advantages disadvantages	1M 2M 2M <hr/> 5M
3b)	Properties of SF <sub>6</sub> in comparison with air any four points	5M <hr/> 5M
Q4a)	Diagram of induction disc Explanation	2M 3M <hr/> 5M
b)	Characteristics of DMT and IDMT Explanation	2M 3M <hr/> 5M
Q 5 a)	Diagram of directional relay Explanation	2M 3M <hr/> 5M
b)	R-X diagram of mho relay characteristics Explanation	2M 3M

		5M
Q 6 a)	Circuit diagram inter turn fault Explanation	2M 3M <hr/> 5M
b)	Calculation of x Calculation of r	2M 3M <hr/> 5M
Q7a)	Diagram Explanation	2 M 3M <hr/> 5M
b)	Calculation of primary current on 11000 V side Calculation of CT ration on 11000 V side	3 M 2M <hr/> 5M
Q8 a)	R-X diagram of impedance relay Explanation of zone protection	2 M 3M <hr/> 5M
b)	Calculation of relay cuurent Calculation of PSM	2 M 3M <hr/> 5M
Q 9 a)	Diagram Explanation	2M 3M <hr/> 5M
Q b)	Classification of components Explanation of any one comparator	2M 3 M <hr/> 5M
Q10a)	Diagram of lightning phenomena Explanation	2M 3M <hr/> 5M
b)	Diagram of Zn O arrester & characteristics Explanation	3M 2M <hr/> 5M
10 a)	Advantages of neutral any three points Advantages of keeping neutral isolated	3M 2M <hr/> 5M
10 b)	Diagram Phasor diagram Explanation	2M 1M 2M <hr/> 5M

1a) An MCB (Miniature Circuit Breaker) is an automatic electrical safety switch designed to protect from damage caused by overload or short circuits. Uses electromechanical principles to detect excess current and break the circuit immediately.

1b) The rate of Rising of Restriking Voltage (RRRV)– It is defined as the slope of the steepness tangent of the restriking voltage curve. It is expressed in kV/μs. RRRV is directly proportional to the natural frequency. The expression for the restriking voltage is expressed as

$$RRRV = \frac{V_{max}}{\sqrt{LC}} \sin \frac{t}{\sqrt{LC}}$$

1c) Fuse :A fuse acts as a safety device that breaks a circuit by melting during overcurrent. Once the circuit break we have rewire the fuse.

Relay : A relay is an automatic device by means of which an electrical circuit is indirectly controlled (opened or closed) and is governed by a change in the same or another electrical circuit.

1d) Differential protection systems require pilot-wire circuits for interconnecting secondaries of CTs incorporating overcurrent relays. These protective systems can inherently discriminate without the use of time-grading and are fast in fault clearance. Differential protection systems are unit protection systems which are instantaneous and their time setting are independent of other protective systems. Overcurrent protection systems are non-unit systems of protection which discriminate by virtue of time-grading.

1e) Protective schemes of generators are . (i) Stator protection

(a) Percentage differential protection (b) Protection against stator inter-turn faults (c) Stator-overheating protection

(ii) Rotor protection

(a) Field ground-fault protection (b) Loss of excitation protection (c) Protection against rotor overheating because of unbalanced three-phase stator currents

(iii) Miscellaneous (a) Overvoltage protection (b) Overspeed protection (c) Protection against motoring

1f) Types of Faults Encountered in Transformers The faults encountered in transformer can be placed in two main groups.

(a) External faults

In case of external faults, the transformer must be disconnected if other protective devices meant to operate for such faults, fail to operate within a predetermined time.

(b) Internal faults

(i) Short circuits in the transformer winding and connections These are electrical faults of serious nature and are likely to cause immediate damage. Such faults are detectable at the winding terminals by unbalances in voltage or current.

(ii) Incipient faults Initially, such faults are of minor nature but slowly might develop into major faults. Such faults are not detectable at the winding terminals by unbalance in voltage or current and hence, the protective devices meant to operate

under short circuit conditions are not capable of detecting this type of faults. Such faults include poor electrical connections, core faults, failure of the coolant, regulator faults and bad load sharing between transformers.

1g) Residual Connection of CTs (Residual Method)

This is the most common method for radial feeders. Three CTs are placed on each phase (R, Y, B), and their secondary circuits are connected in parallel. Under normal balanced load, the sum of three phase currents are zero. The relay receives no current. During an earth fault, the currents become unbalanced. The residual current flows through the earth fault relay, tripping the breaker.

1h) Plug-setting multiplier (P.S.M.). It is the ratio of fault current in relay coil to the pick-up current i.e.

$$P.S.M = \frac{\text{Fault current relay}}{\text{Pickup current}} \\ = \frac{\text{Fault current relay}}{\text{Rated secondary current of C.T} \times \text{Current setting}}$$

1i) Lighting arresters are devices that help prevent damage to apparatus due to high voltages. The arrester provides a low-impedance path to ground for the current from a lightning strike or transient voltage and then restores to a normal operating condition.

1j) Neutral grounding or neutral earthing means electrically connecting the neutrals of the system (i.e., the neutral points of star-connected 3-phase windings of power transformers, generators, motors, grounding transformers etc.) to low resistance ground (ground electrode/ground mat) either directly or through some circuit element (resistance or reactance). The neutral grounding is an important aspect of the power system design since the performance of the system in terms of the faults, stability, protection, etc., is greatly affected by the state of the neutral.

2a) Current chopping:

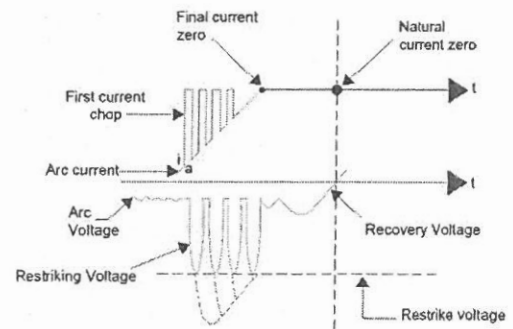
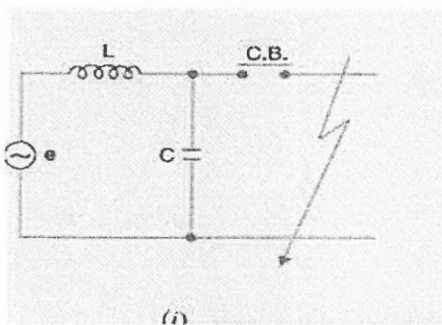
It is the phenomenon of current interruption before the natural current zero is reached. Current chopping mainly occurs in air-blast circuit breakers because they retain the same extinguishing power irrespective of the magnitude of the current to be interrupted. When breaking low currents (e.g., transformer magnetizing current) with such breakers, the powerful deionizing effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached. This phenomenon is known as current chopping and results in the production of high voltage transient across the contacts of the circuit breaker as discussed below:

Consider again Fig. 1 (ii) repeated as Fig. 3 (i). Suppose the arc current is  $i$  when it is chopped down to zero value as shown by point a in Fig. 3 (ii). As the chop occurs at current  $i$ , therefore, the energy stored in inductance is  $L i^2 / 2$ . This energy will be transferred to the capacitance  $C$ , charging the latter to a prospective voltage  $e$  given by:

The stored energy in the inductance of reactor is transferred to capacitor

$$\frac{1}{2} Li^2 = \frac{1}{2} Cv^2 = v = i \sqrt{\frac{L}{c}}$$

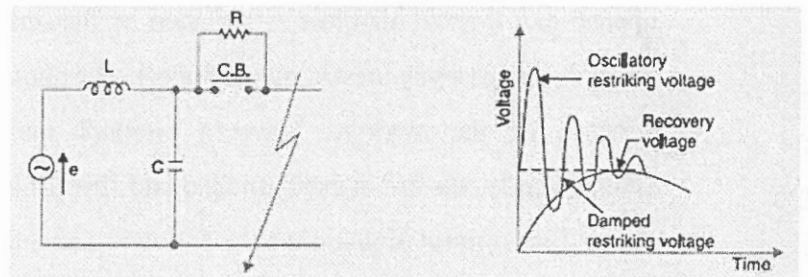
The prospective voltage  $v$  is very high as compared to the dielectric strength gained by the gap so that the breaker restrikes. As the deionizing force is still in action, therefore, chop occurs again but the arc current this time is smaller than the previous case. This induces a lower prospective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



### 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. This is known as resistance switching.

Referring to Fig. , 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 deionization of the arc path. Consequently, the arc resistance is increased. The increased arc resistance leads to a further increase in current through shunt resistance. This process continues until the arc current becomes so small that it fails to maintain the arc. Now, the arc is extinguished and circuit current is interrupted.



The shunt resistor also helps in limiting the oscillatory growth of re-striking voltage. It can be proved mathematically that natural frequency of oscillations (or) the frequency of damped oscillation of the circuit shown in Fig. is given by:

The effect of shunt resistance  $R$  is to prevent the oscillatory growth of re-striking voltage and

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

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. 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:

- (i) To reduce the rate of rise of re-striking voltage and the peak value of re-striking voltage.
- (ii) To reduce the voltage surges due to current chopping and capacitive current breaking.
- (iii) To ensure even sharing of re-striking voltage transient across the various breaks in multi break circuit breakers.

2b) Given data 1500 A ,33 kV ,2000 MVA, 3 sec

Rated Normal current 1500A

Symmetrical breaking current

$$I = \frac{MVA}{\sqrt{3} V_L} = \frac{2000 \times 10^6}{\sqrt{3} \times 33 \times 10^3} = 34.99 \text{ kA}$$

Rated making capacity of CB. = 2.55 Symmetrical breaking current

$$= 2.55 \times 34.99 \times 10^3 = 89.22 \text{ kA}$$

Short time rating – 34.99kA- 3 sec

3a) Air-Blast Circuit Breakers:

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

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

1. The risk of fire is eliminated.
2. The arcing products are completely removed by the blast whereas the oil deteriorates with successive operations; the expense of regular oil replacement is avoided.
3. The growth of dielectric strength is so rapid that final contact gap needed for arc extinction is very small. This reduces the size of the device.
4. The arcing time is very small due to the rapid build-up of dielectric strength between contacts. Therefore, the arc energy is only a fraction of that in oil circuit breakers, thus resulting in less burning of contacts.
5. Due to lesser arc energy, air-blast circuit breakers are very suitable for conditions where frequent operation is required.

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

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

1. The air has relatively inferior arc extinguishing properties.
2. The air-blast circuit breakers are very sensitive to the variations in the rate of rise of re striking voltage.
3. Considerable maintenance is required for the compressor plant which supplies the air-blast.
4. The air blast circuit breakers are finding wide applications in high voltage installations.
5. Majority of the circuit breakers for voltages beyond 110 kV are of this type.

Types of Air-Blast Circuit Breakers:

Depending upon the direction of air-blast in relation to the arc, air-blast circuit breakers are classified into:

**Axial-blast type** in which the air-blast is directed along the arc path as shown in Fig. (i).

**Cross-blast type** in which the air-blast is directed at right angles to the arc path as shown in Fig. (ii).

**Radial-blast type** in which the air-blast is directed radially as shown in Fig. (iii).

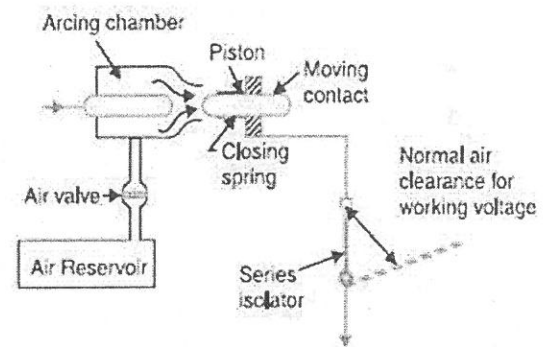
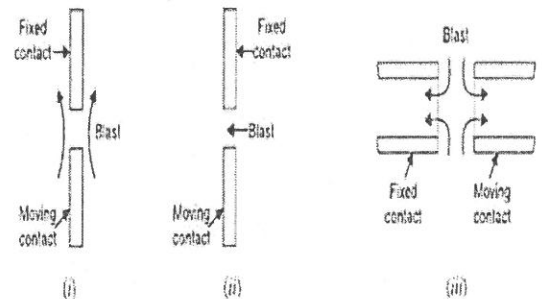
**Axial-blast air circuit breaker:**

Fig shows the essential components of a typical axial blast air circuit breaker. The fixed and moving contacts are held in the closed position by spring pressure under normal conditions. The air reservoir is connected to the arcing chamber through an air valve. This valve remains closed under normal conditions but opens automatically by the tripping impulse when a fault occurs on the system. When a fault occurs, the tripping impulse causes opening of the air valve which connects the circuit breaker reservoir to the arcing chamber. The high-pressure air entering the arcing chamber pushes away the moving contact against spring pressure. The moving contact is separated and an arc is struck. At the same time, high pressure air blast flows along the arc and takes away the ionized gases along with it. Consequently, the arc is extinguished and current flow is interrupted.

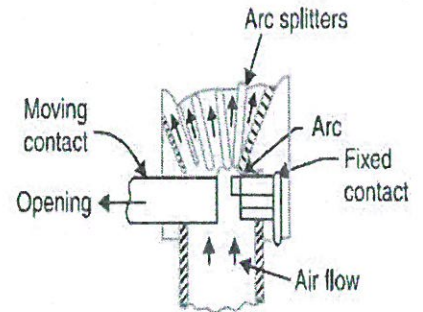
It may be noted that in such circuit breakers, the contact separation required for interruption is generally small (1.75 cm or so). Such a small gap may constitute inadequate clearance for the normal service voltage. Therefore, an isolating switch is incorporated as a part of this type of circuit breaker. This switch opens immediately after fault interruption to provide the necessary clearance for insulation.

**Cross-blast air breaker:**

In this type of circuit breaker, an air-blast is directed at right angles to the arc. The cross-blast lengthens and forces the arc into a suitable chute for arc extinction. Fig. shows the essential



parts of a typical cross-blast Air circuit breaker. When the moving contact is withdrawn, an arc is struck between the fixed and moving contacts. The high-pressure cross-blast forces the arc into a chute consisting of arc splitters and baffles. The splitters serve to increase the length of the arc and baffles give improved cooling. The result is that arc is extinguished and flow of Current is interrupted. Since blast pressure is same for all currents, the inefficiency at low currents is eliminated. The final gap for interruption is great enough to give normal insulation clearance so that a series isolating switch is not necessary.



### 3b) Sulphur Hexafluoride (SF<sub>6</sub>) Circuit Breakers:

Properties of Sulphur hexafluoride Circuit Breaker Sulphur hexafluoride possesses very good insulating and arc quenching properties. These properties are

- It is colorless, odourless, non-toxic, and non-inflammable gas.
- SF<sub>6</sub> gas is extremely stable and inert, and its density is five times that of air.
- It has high thermal conductivity better than that of air and assists in better cooling current carrying parts.
- SF<sub>6</sub> gas is strongly electronegative, which means the free electrons are easily removed from discharge by the formation of negative ions.
- It has a unique property of fast recombination after the source energizing spark is removed. It is 100 times more effective as compared to arc quenching medium.
- Its dielectric strength is 2.5 times than that of air and 30% less than that of the dielectric oil. At high pressure the dielectric strength of the gas increases.

Moisture is very harmful to SF<sub>6</sub> circuit breaker. Due to a combination of humidity and SF<sub>6</sub> gas, hydrogen fluoride is formed (when the arc is interrupted) which can attack the parts of the circuit breaker.

### 4a) Induction Relays :

Induction Type Overcurrent Relay (non-directional)

This type of relay works on the induction principle and initiates corrective measures when current in the circuit exceeds the predetermined value. The actuating source is a current in the circuit supplied to the relay from a current transformer. These relays are used on a.c. circuits only and can operate for fault current flow in either direction. Constructional details. Fig. shows the important constructional details of a typical non directional induction type overcurrent relay. It consists of a metallic (aluminium) disc which is free to rotate in between the poles of two electromagnets. The upper electromagnet has a primary and a secondary winding. The primary is

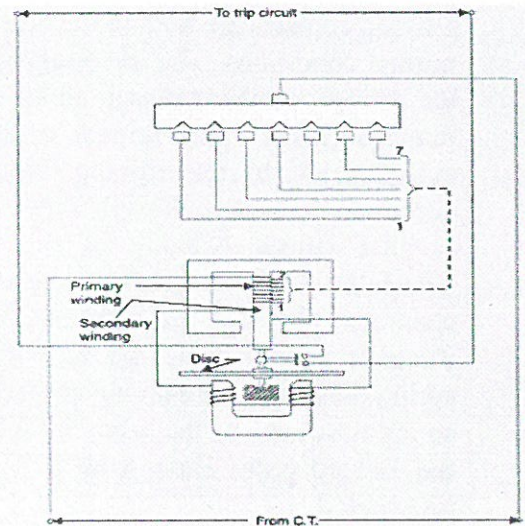


FIG . Induction disc type over current relay

connected to the secondary of a C.T. in the line to be protected and is tapped at intervals. The tapings are connected to a plug-setting bridge by which the number of active turns on the relay operating coil can be varied, thereby giving the desired current setting. The secondary winding is energised by induction from primary and is connected in series with the winding on the lower magnet. The controlling torque is provided by a spiral spring. The spindle of the disc carries a moving contact which bridges two fixed contacts (connected to trip circuit) when the disc rotates through a pre-set angle. This angle

can be adjusted to any value between  $0^\circ$  and  $360^\circ$ . By adjusting this angle, the travel of the moving contact can be adjusted and hence the relay can be given any desired time setting.

**Operation.** The driving torque on the aluminium disc is set up due to the induction principle as discussed. Electromagnetic induction relays operate on the principle of induction motor and are widely used for protective relaying purposes involving a.c. quantities. They are not used with d.c. quantities owing to the principle of operation. 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. 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. To understand the production of torque in an induction relay, refer to the elementary arrangement shown in Fig

The two a.c. fluxes  $\phi_2$  and  $\phi_1$  differing in phase by an angle  $\alpha$  induce e.m.f.s' in the disc and cause the circulation of eddy currents  $i_2$  and  $i_1$  respectively. These currents lag behind their respective fluxes by  $90^\circ$ . Where the two a.c. fluxes and induced currents are shown separately for clarity,

$$\text{let } \phi_1 = \phi_{1\max} \sin \omega t$$

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

where  $\phi_1$  and  $\phi_2$  are the instantaneous values of fluxes and  $\phi_2$  leads  $\phi_1$  by an angle  $\alpha$ . Assuming that the paths in which the rotor currents flow have negligible self-inductance, the rotor currents will be in phase with their voltages.

$$\therefore i_1 \propto d\phi_1 / dt \propto d(\phi_{1\max} \sin \omega t) / dt$$

$$\propto \phi_{1\max} \cos \omega t \, dt$$

$$\therefore i_2 \propto d\phi_2 / dt \propto d(\phi_{2\max} \sin \omega t + \alpha) / dt$$

$$\propto \phi_{2\max} \cos (\omega t + \alpha)$$

Now,  $F_1 \propto \phi_1 i_2$  and  $F_2 \propto \phi_2 i_1$

$$\therefore \text{Net force } F \text{ at the instant considered is } F \propto F_2 - F_1 \propto \phi_2 i_1 - \phi_1 i_2 \propto$$

$$\phi_{2\max} \cos (\omega t + \alpha) \phi_{1\max} \cos \omega t - \phi_{1\max} \sin \omega t \phi_{2\max} \cos (\omega t + \alpha)$$

$$\propto \phi_{1\max} \phi_{2\max} [\sin (\omega t + \alpha) \cos \omega t - \sin \omega t \cos (\omega t + \alpha)]$$

$$\propto \phi_{1\max} \phi_{2\max} \sin \alpha \propto \phi_1 \phi_2 \sin \alpha$$

This torque is opposed by the restraining torque provided by the spring. Under normal operating conditions, restraining torque is greater than the driving torque produced by the relay coil current. Therefore, the aluminium disc remains stationary. However, if the current in the protected circuit exceeds the pre-set value, the driving torque becomes greater than the restraining torque. Consequently, the disc rotates and the moving contact bridges the fixed contacts when the disc has rotated through a pre-set angle. The trip circuit operates the circuit breaker which isolates the faulty section.

**4b) Definite-time Overcurrent Relay** A definite-time overcurrent relay operates after a predetermined time when the current exceeds its pick-up value. Curve (a) of Fig. 5.1 shows the time-current characteristic for this type of relay. The operating time is constant, irrespective of the magnitude of the current above the pick-up value. The desired definite operating time can be set with the help

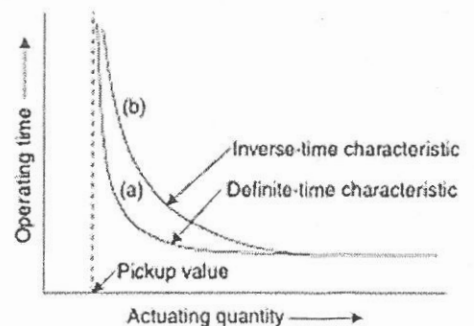


Fig. 5.1 Definite-time and inverse-time characteristics of overcurrent relays

of an intentional time-delay mechanism provided in the relaying unit.

Inverse-time Over-current Relay Operating time (b) (a) Inverse-time characteristic Definite-time characteristic An inverse-time overcurrent relay operates when the current exceeds its pick-up value. The operating time depends on the magnitude of the operating current. The operating time decreases as the current increases. Curve (b) of Fig. 5.1 shows the inverse time-current characteristic of this types of relays

Inverse Definite Minimum Time Overcurrent (I.D.M.T) Relay This type of a relay gives an inverse-time current characteristic at lower values of the fault current and definite-time characteristic at higher values of the fault current. Generally, an inverse-time characteristic is obtained if the value of the plug setting multiplier is below 10. For values of plug setting multiplier between 10 and 20, the characteristic tends to become a straight line, i.e. towards the definite time characteristic. Figure 5.2 shows the characteristic of an I.D.M.T. relay along with their characteristics. I.D.M.T. relays are widely used for the protection of distribution lines. Such relays have a provision for current and time settings which will be discussed later on.

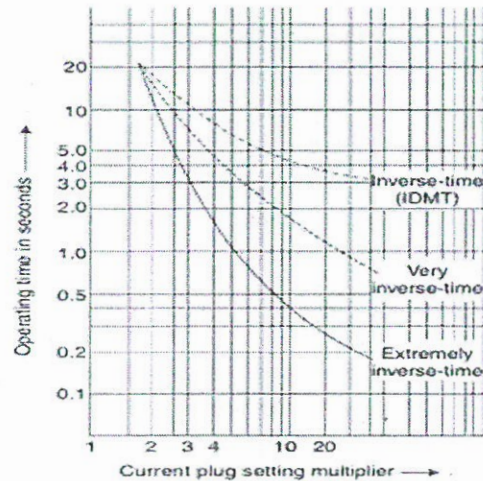


Fig. 5.2 I.D.M.T., very inverse-time and extremely inverse-time characteristics

#### Method of Defining Shape of Time-current Characteristics

The general expression for time-current characteristics is given by

$$t = \frac{K}{I^{n-1}}$$

The approximate expression is

$$t = \frac{K}{I^n}$$

For definite-time characteristic, the value of n is equal to 0.

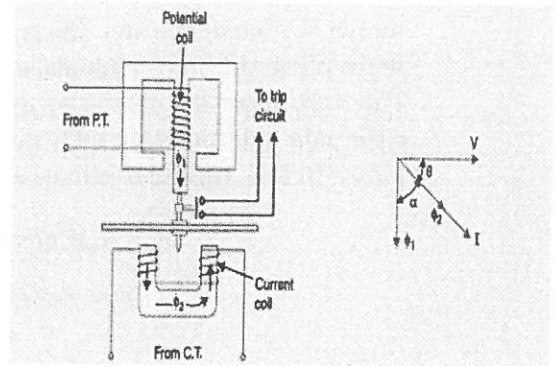
According to the British Standard, the following are the important characteristics of overcurrent relays.

- (i) I.D.M.T.:  $t = \frac{0.14}{I^{0.02-1}}$
- (ii) Very inverse:  $t = \frac{13.5}{I-1}$
- (iii) Extremely inverse:  $t = \frac{80}{I^2-1}$

The inverse time-current characteristics obtained from the above expressions are not straight line characteristics. A microprocessor-based relay can easily give straight line characteristics of the form  $t = K/I^n$  with any value of n. These characteristics are straight line characteristics on log t/log I graph. The advantage of such simplified time-current curves is the saving in time in calculating relay time settings.

### 5a) Induction Type Directional Power Relay :

This type of relay operates when power in the circuit flows in a specific direction. Unlike a \*non directional overcurrent relay, a directional power relay is so designed that it obtains its operating torque by the interaction of magnetic fields derived from both voltage and current source of the circuit it protects. Thus this type of relay is essentially a wattmeter and the direction of the torque set up in the relay depends upon the direction of the current relative to the voltage with which it is associated. Constructional details. Fig. shows the essential parts of a typical induction type directional power relay. It consists of an aluminium disc which is free to rotate in between the poles of two electromagnets. The upper electromagnet carries a winding (called potential coil) on the central limb which is connected through a potential transformer (P.T.) to the circuit voltage source. The lower electromagnet has a separate winding (called current coil) connected to the secondary of C.T. in the line to be protected. The current coil is provided with a number of tapping's connected to the plug setting bridge (not shown for clarity). This permits to have any desired current setting. The restraining torque is provided by a spiral spring.



Operation. The flux  $\phi_1$  due to current in the potential coil will be nearly  $90^\circ$  lagging behind the applied voltage  $V$ . The flux  $\phi_2$  due to current coil will be nearly in phase with the operating current  $I$ . The interaction of fluxes  $\phi_1$  and  $\phi_2$  with the eddy currents induced in the disc produces a driving torque given by :

$$T \propto \phi_1 \phi_2 \sin \alpha$$

$$\text{Since } \phi_1 \propto V, \phi_2 \propto I \text{ and } \alpha = 90 - \theta$$

$$\therefore T \propto V I \sin (90 - \theta) \propto V I \cos \theta \propto \text{power in the circuit}$$

It is clear that the direction of driving torque on the disc depends upon the direction of power flow in the circuit to which the relay is associated. When the power in the circuit flows in the normal direction, the driving torque and the restraining torque (due to spring) help each other to turn away the moving contact from the fixed contacts. Consequently, the relay remains inoperative. However, the reversal of current in the circuit reverses the direction of driving torque on the disc. When the reversed driving torque is large enough, the disc rotates in the reverse direction and the moving contact closes the trip circuit. This causes the operation of the circuit breaker which disconnects the faulty section.

### 5b) MHO (ADMITTANCE OR ANGLE ADMITTANCE) RELAY

A MHO relay measures a component of admittance  $|Y|$ . But its characteristic, when plotted on the impedance diagram (R-X diagram) is a circle, passing through the origin. It is inherently a directional relays as it detects the fault only in the forward direction. This is obvious from its circular characteristic passing through the origin, as shown in Fig. 6.20. It is also called an admittance or angle admittance relay. It is called a MHO relay because its characteristic is a straight line when plotted on an admittance diagram (G-B axes)

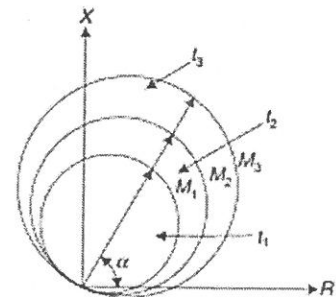
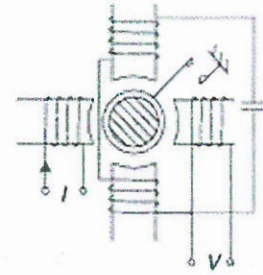


Fig. 6.20 Characteristics of MHO relay

Electromechanical MHO Relay An induction cup structure, as shown in Fig. is used to realise a MHO characteristic. The torque equation is given by

torque  $K_1 VI \cos(90 - \alpha)$ . The angle  $\alpha$  can be adjusted by varying resistance in the phase shifting circuit placed on the left pole (not shown in the figure). The right-hand side pole is energised by voltage. The flux produced by the right side pole interacts with the polarising flux to produce a restraining torque  $K_2 V^2$ . The relay will operate when



$$T = K_1 VI \cos(90 - \alpha) - K_2 I^2 - K_3$$

$$T = K_1 VI \sin \alpha - K_1 I^2 - K_3$$

$$K_1 VI \cos(\phi - \alpha) > K_2 V^2 \quad \text{or} \quad \frac{1}{V} \cos(\phi - \alpha) > \frac{K_2}{K_1}$$

$$\text{or} \quad Y \cos(\phi - \alpha) > \frac{K_2}{K_1} \quad \text{or} \quad \frac{1}{Y \cos(\phi - \alpha)} < K$$

$$\text{or} \quad \frac{Z}{\cos(\phi - \alpha)} < K \quad \text{or} \quad M < K$$

### 6a) Protection against Stator Interturn Faults

Longitudinal percentage differential protection does not detect stator interturn faults. A transverse percentage differential protection, as shown in Fig. 9.4 is employed for the protection of the generator against stator interturn faults. This type of protection is used for generators having parallel windings separately brought out to the terminals. The coils of modern large steam turbine driven generators usually have only one turn per phase per slot and hence they do not need interturn fault protection. Hydro generators having parallel windings in each phase employ such protection which thus provides back-up protection and detects interturn faults. This scheme is also known as split phase protection.

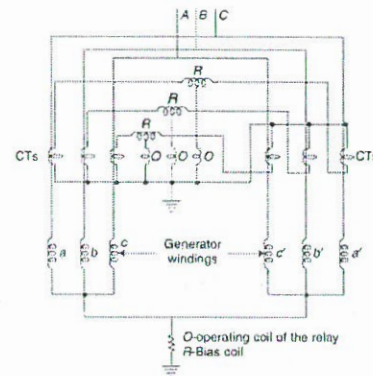


Fig. 9.4 Transverse percentage differential protection for multi-winding generators

A faster and more sensitive split-phase protection as shown in Fig. 9.5 can be employed. In this scheme, a single CT having double primary is used. No bias is necessary because a common CT is employed so that errors due to CT differences do not occur.

### Interturn protection based on zero-sequence component

If generators do not have access to parallel windings, a method based on zero-sequence voltage measurement can be employed for the protection against stator interturn faults. This type of scheme will also be applicable to single winding generators having multi-turn per phase per slot to protect against interturn faults. Figure 9.6 shows the schematic diagram of interturn protection by zero-sequence voltage measurement across the machine.

The zero-sequence voltage does not exist during normal conditions. If one or more turns of a phase are short circuited, the generated emf contains zero-sequence component. A voltage transformer as shown in the figure is employed to extract zero-sequence component. The secondary winding of the voltage transformer is in open-delta connection to provide the zero-sequence component of the voltage to the protective relay. A filter is provided to extract a third harmonic component from the VT output and apply it as the relay bias.

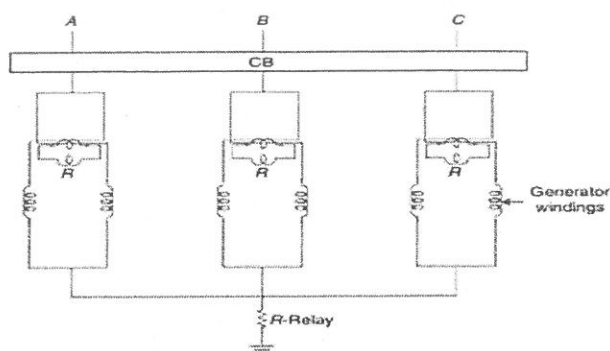


Fig. 9.5 Split-phase protection of generator using double primary CTs

The zero-sequence voltage is also produced in case of an external earth fault. But most of this voltage appears across the earthing resistor. A very small amount, 1 or 2 per cent, appears across the generator. Therefore, the zero-sequence voltage and Switchgear is measured across the generator windings at the line terminals rather than the zero sequence voltage to the earth as shown in the figure to activate the relay on the occurrence of internal faults.

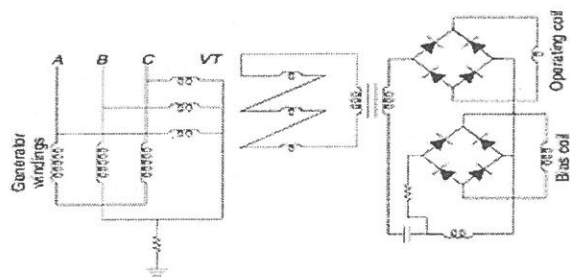


Fig. 9.6 Interturn protection of generator using zero-sequence voltage

6b)

$$\text{Voltage per phase, } V_{ph} = \frac{6.6 \times 10^3}{\sqrt{3}} = 3810 \text{ V}$$

$$\text{Full-load current, } I = \frac{10 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3} = 875 \text{ A}$$

Let the reactance per phase be  $x$  ohms.

$$\therefore 10 = \frac{\sqrt{3} \times x \times 875}{6600} \times 100$$

$$\text{or } x = 0.436 \Omega$$

$$\text{Reactance of 10\% winding} = 0.436 \times 0.1 = 0.0436 \Omega$$

$$\text{E.M.F. induced in 10\% winding} = V_{ph} \times 0.1 = 3810 \times 0.1 = 381$$

Impedance offered to fault by 10% winding is

$$Z_f = \sqrt{(0.0436)^2 + r^2}$$

Earth-fault current due to 10% winding

$$= \frac{381}{Z_f} = \frac{381}{\sqrt{(0.0436)^2 + r^2}}$$

When this fault current becomes 175 A, the relay will trip.

$$\therefore 175 = \frac{381}{\sqrt{(0.0436)^2 + r^2}}$$

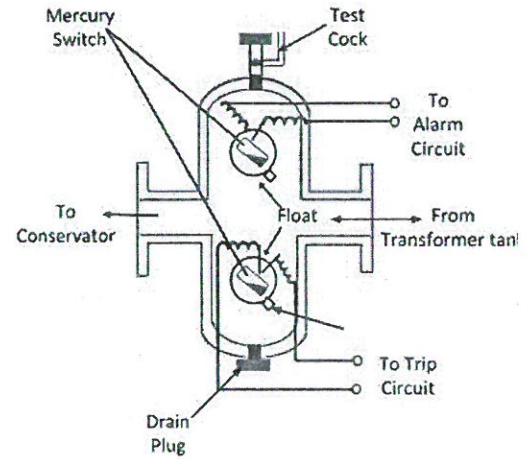
$$\text{or } (0.0436)^2 + r^2 = \left(\frac{381}{175}\right)^2$$

$$R = 2.171 \text{ ohms}$$

### 7a) Buchholz Relay

It is a gas actuated relay. It is used to detect incipient faults which are initially minor faults but may cause major faults in due course of time. The Buchholz relay is used to supplement biased differential protection of the transformer because the Buchholz relay cannot necessarily detect short circuits within the transformer or at the terminals.

There is a chamber to accommodate Buchholz relay, in between the transformer tank and the conservator as shown in Fig. A simple diagram to explain the operating principle of Buchholz relay. When gas accumulates, the oil level falls down and thus the float also comes down. It causes an alarm to sound and alert the operator. For reliable operation, a mercury switch is attached with the float. Some manufacturers use open-topped bucket in place of a bob. When the oil level falls because of gas accumulation, the bucket is filled up with oil. Thus, the force available to operate the contacts is greater than with hollow floats. The accumulated gas can be drawn off through the petcock via a pipe for analysis to know the type of fault. If there is a severe fault, large volumes of gases are produced which cause the lower float to operate. It finally trips the circuit breakers of the transformer.

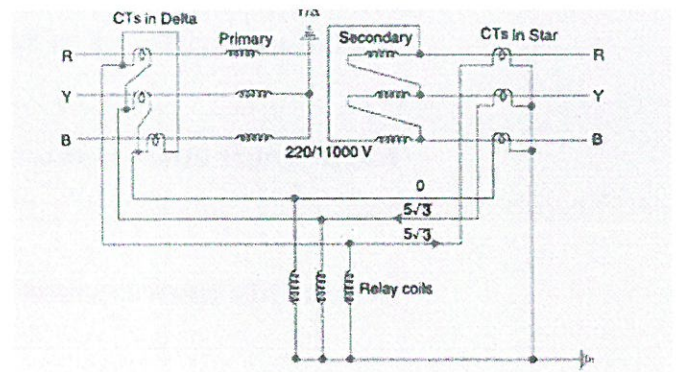


When a fault develops slowly, it produces heat, thereby decomposing solid or liquid insulating material in the transformer. The decomposition of the insulating material produces inflammable gases. The Buchholz relay gives an alarm when a specified amount of gas is formed. The gas analysis of gas collected in the relay chamber indicates the type of the incipient fault.

- (a)  $C_2H_2$  and  $H_2$  shows arcing in oil between conductors.
- (b)  $C_2H_2$ ,  $CH_4$  and  $H_2$  shows sparking with some deterioration of phenolic insulation.
- (c)  $CH_4$ ,  $C_2H_4$  and  $H_2$  indicates hot spot in core joints.
- (d)  $C_2H_4$ ,  $C_2H_6$ ,  $H_2$  and  $CO_2$  shows a hot spot in the winding.

### 7b)

Suppose that line current on 220 V side is 600 A.  
 $\therefore$  Phase current of delta connected CTs on 220V side = 5 A  
 Line current of delta connected CTs on 220 V side =  $5 \times \sqrt{3} = 5\sqrt{3}$  A  
 $\therefore$  Phase current of star connected CTs on 11,000 V side =  $5\sqrt{3}$  A  
 If  $I$  is the line current on 11,000 V side, then,  
 Primary apparent power = Secondary apparent power  
 or  $\sqrt{3} \times 220 \times 600 = \sqrt{3} \times 11,000 \times I$   
 or  $I = \frac{\sqrt{3} \times 220 \times 600}{\sqrt{3} \times 11000} = 12$  A  
 $\therefore$  Turn-ratio of CTs on 11000 V side =  $12 : 5\sqrt{3} = 1.385 : 1$



### 8 a) Impedance relays

An impedance relay measures the impedance of the line at the relay location. When a fault occurs on the protected line section, the measured impedance is the impedance of the line section between the relay location and the point of fault. It is proportional to the length of the line and hence, to the distance along the line. In general, the term impedance can be applied to a resistance alone, a reactance alone or a combination of the two. But in distance relaying terminology the term impedance includes both resistance as well as reactance. An Impedance relay is a voltage restrained over current relay.

**Operating Principle of an Impedance Relay** To realise the characteristics of an impedance relay, current is compared with voltage at the relay location. The current produces a positive torque (operating torque) and the voltage produces a negative torque (restraining torque).

The equation for the operating torque of an electromagnetic relay can be written as

$$T = K_1 I^2 - K_2 V^2 - K_3$$

where  $K_1$ ,  $K_2$  and  $K_3$  are constants,  $K_3$  being the torque due to the control-spring effect.

Neglecting the effect of the spring used, which is very small, the torque equation can be written as  $T = K_1 I^2 - K_2 V^2$

For the operation of the relay, the following condition should be satisfied.

$$K_1 I^2 > K_2 V^2 \text{ or } K_2 V^2 < K_1 I^2 = \frac{V^2}{I^2} < \frac{K_1}{K_2}$$

$$\frac{V}{I} < \frac{K_1}{K_2} = Z < \frac{K_1}{K_2}$$

where  $K$  is a constant or  $Z < K$

The above expression explains that the relay is on the verge of operation when the ratio of  $V$  to  $I$ , i.e. the measured value of line impedance is equal to a given constant. The relay operates if the measured impedance  $Z$  is less than the given constant.

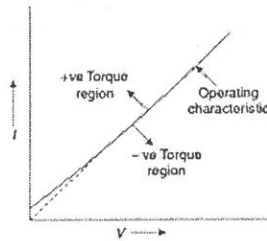


Fig. 6.1 Operating characteristic of an impedance relay

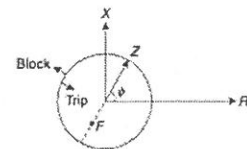
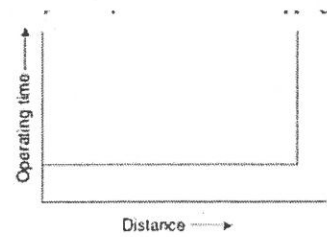


Fig. 6.2 Operating characteristic of an impedance relay on the R-X diagram

Figure 6.1 shows the operating characteristic of an impedance relay in terms of voltage and current. In case of an electromagnetic relay, the characteristic is slightly bent near the origin due to the effect of the control spring. In case of microprocessor based or static relay, the characteristic will be a straight line. A more useful way is to draw a distance relay characteristic on the R-X diagram. Figure 6.2 shows an impedance relay characteristic on the R-X diagram, where  $Z = K$  represents a circle and  $Z < K$  indicates the area within the circle. Thus, it is seen that the zone within the circle is the operating zone of the relay. Its radius is  $Z = K$ , which is the setting of the relay.  $K$  is equal to the impedance of the line which is to be protected.  $\phi$  is the phase angle between  $V$  and  $I$ . As the operating characteristic is a circle, the relay operation is independent of the phase angle  $\phi$ . The operation depends on the magnitude of  $Z$ . If a fault point is on the protected section of the line, it will lie within the circle. For this condition, the relay will operate and send a tripping signal to the circuit breaker. The region outside the circle is the blocking zone. If a fault point lies in this zone, i.e. it is beyond the protected section of the line, the relay will not respond. In such a situation, the fault point may lie in the protection zone of some other relay.



The operating time of the relay is constant, irrespective of the fault location within the protected section, as shown in Fig. 6.3.

## Directional Units Used with Impedance Relays

It is evident from the impedance relay characteristic on the R-X diagram that an impedance relay is a non-directional relay. As its characteristic is a circle, the relay will trip for a fault point lying within the circle, irrespective of the fact that the fault point lies either in the forward direction or in the reverse direction. For example, the relay will trip for a fault point F which is behind the relay location, i.e. in the reverse direction as shown in Fig. 6.2. It is always desired that a relay should operate for faults lying only in the forward direction. It

should never operate for fault points lying in the reverse direction. To restrict the tripping zone in the forward direction only, a directional unit is included in the protective scheme. At any location, three impedance relays and a directional unit are employed. Their

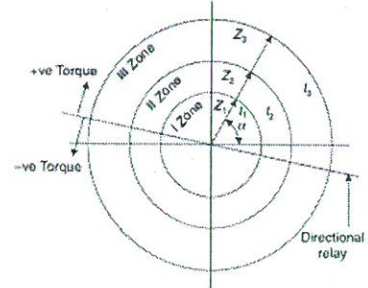
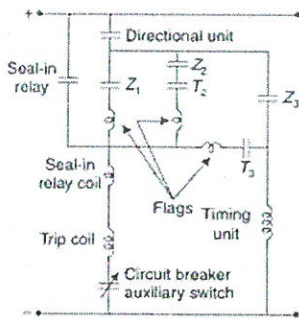


Fig 6.4 Characteristics of three-zone impedance relays with directional unit

characteristics are shown in Fig. below. The directional unit is connected in series with the impedance relays as shown in Fig. 6.5. Figure 6.5 shows connections if only one measuring unit is employed. In such a scheme zone II and zone III are set by adjusting ohmic reach of the relay after appropriate delay.



The directional unit has a straight-line characteristic as shown in the figure. It allows impedance relays to see only in the forward direction. The torque equation of the directional unit is given by  $T = KV \cos(\varphi - \alpha)$ , neglecting spring-effect. Here,  $\varphi$  is the angle between  $V$  and  $I$ , and  $\alpha$  is the angle of maximum torque. For the operation of the relay,  $T$  should be positive and hence,

$$T = KV \cos(\varphi - \alpha) > 0$$

$$\text{Or } \cos(\varphi - \alpha) > 0 \quad \text{or } (\varphi - \alpha) < \pm 90^\circ$$

Fig 6.5 Connections of impedance relay

The circuit connections for circuit breaker trip coil, the contacts of directional and impedance relays, flags, timer, etc. are shown in Fig. 6.5.  $Z_1$ ,  $Z_2$  and  $Z_3$  represent impedance relays.  $T_2$  and  $T_3$  are contacts of the timer for the second and the third unit, respectively. Figure 6.4 shows the characteristics of directional and impedance relays, where  $t_1$ ,  $t_2$  and  $t_3$  are the operating times of the impedance relays. The characteristic circle for  $Z_1$  is the smallest, the circle for  $Z_3$  is the largest and the circle for  $Z_2$  is intermediate. If any fault point lies within the circle  $Z_1$  and it is in the forward direction, the directional relay and all the three impedance relays operate. Due to the operation of the first unit and the directional unit, the circuit breaker trips in a very short time period of  $t_1$ . A timer is energised whenever the directional unit and  $Z_3$  operate. After a definite time-delay, the timer closes the contact  $T_2$  first and then after some more delay, the contact  $T_3$  also closes. The delay times for  $T_2$  and  $T_3$  are independently adjustable. Therefore, if a fault point lies in the characteristic circle  $Z_2$  but outside the circle  $Z_1$ , the circuit breaker trips after the closure of the contact  $T_2$ , in time  $t_2$ . If a fault point lies within the characteristic circle  $Z_3$  but outside the circles  $Z_1$  and  $Z_2$ , the circuit breaker trips after the closure of the contact  $T_3$ , in time  $t_3$ . Whenever a relay operates, its flag indicates its operation. A seal-in relay is used to bypass the contacts of the main relays to save their costly and delicate contacts. Once the contacts of the main relay are closed and the current passes through the trip coil, the coil of the seal-in relay is energised and its contacts are closed. The circuit breaker auxiliary switch is a normally closed switch. When the circuit breaker trips, the auxiliary switch is opened to prevent unnecessary drainage

of the battery. If only one measuring unit is employed, the circuit connection can be modified, as shown in Fig. 6.5(b).

8b)

$$P.S.M = \frac{\text{Fault current relay}}{\text{Pickup current}}$$

$$= \frac{\text{Fault current relay}}{\text{Rated secondary current of C.T} \times \text{Current setting}}$$

relay is connected to a 200/5 current transformer and set at 120%. With a primary fault current of 2000 A, the plug-setting multiplier can be calculated as under :

Pick-up value = Rated secondary current of CT × Current setting

$$= 5 \times 1.2 = 6A$$

$$\therefore PSM = \frac{2000}{6 \times \frac{200}{5}} = 8.333$$

### 9a) BUSZONE PROTECTION

#### Differential Current Protection

Figure 10.13 shows a scheme of differential current protection of a bus zone. The operating principle is based on Kirchhoff's law. The algebraic sum of all the currents entering and leaving the busbar zone must be zero, unless there is a fault therein. The relay is connected to trip all the circuit breakers. In case of a bus fault the algebraic sum of currents will not be zero and relay will operate.

The main drawback of this type of differential scheme is that there may be a false operation in case of an external fault. This is due to the saturation of one of the CT of the faulted feeder. When the CT saturates, the output is reduced and the sum of all the CT secondary currents will not be zero. To overcome this difficulty, high impedance relay or biased differential scheme can be employed.

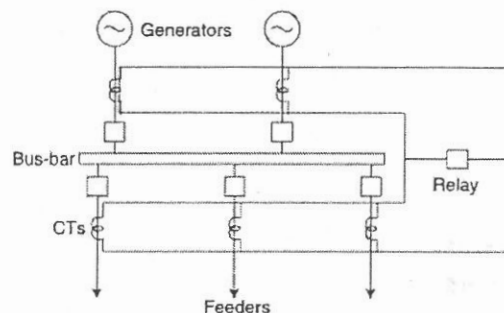


Fig. 10.13 Differential current protection of bus-zone

### 9b) components of static relays

#### Static Relays :

In a static relay, the comparison or measurement of electrical quantities is performed by a static circuit which gives an output signal for the tripping of a circuit breaker. Most of the present day static relays include a dc polarised relay as a slave relay. The slave relay is an output device and does not perform the function of comparison or measurement. It simply closes contacts. It is used because of its low cost.

#### Comparators

The static relay circuitry is designed to recognise the changes and to distinguish between healthy and faulty conditions. Either magnitudes of voltage/current (or corresponding derived quantities) are

compared or phase angle between voltage and current (or corresponding derived quantities) are measured by the static relay circuitry and a trip signal is sent to the circuit breaker when a fault occurs. The part of the circuitry which compares the two actuating quantities either in amplitude or phase is known as the comparator. There are two types of comparators—amplitude comparator and phase comparator.

### Amplitude Comparator

An amplitude comparator compares the magnitudes of two input quantities, irrespective of the angle between them. One of the input quantities is an operating quantity and the other a restraining quantity. When the amplitude of the operating quantity exceeds the amplitude of the restraining quantity, the relay sends a tripping signal.

### Phase Comparator

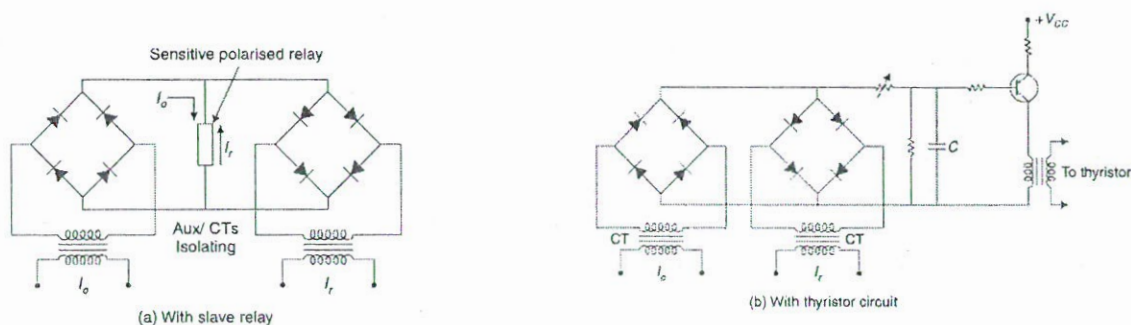
A phase comparator compares two input quantities in phase angle, irrespective of their magnitudes and operates if the phase angle between them is  $< 90^\circ$ .

### Types of Amplitude Comparators

The amplitude comparison can be done in a number of different ways. The following are some important methods which will be described to illustrate the principle.

- (i) Circulating current type rectifier bridge comparators
- (ii) Phase splitting type comparators
- (iii) Sampling comparators.

**Rectifier Bridge Type Amplitude Comparator** The rectifier bridge type comparators are widely used for the realisation of overcurrent and distance relay characteristics. The operating and restraining quantities are rectified and then applied to a slave relay or thyristor circuit. Figure (a) shows a rectifier bridge type amplitude comparator. There are two full wave rectifiers, one for the operating quantity and the other for the restraining quantity. The outputs of these bridges are applied to a dc polarised relay. When the operating quantity exceeds the restraining quantity, the relay operates.



Rectifier bridge type amplitude comparator

Rectifier bridge type amplitude comparator

Figure (b) shows a rectifier bridge type amplitude comparator with the thyristor circuit as an output device. To get more accurate results the bridge rectifier can be replaced by a precision rectifier employing an operational amplifier. The circuit for the precision rectifier has been discussed while describing microprocessor-based relays.

**Phase Splitting Type Amplitude Comparators** Figure shows a phase splitting of inputs before rectification. The input is split into six components  $60^\circ$  apart, so that output after rectification is smoothed within 5%. As both input signals to the relay are smoothed out before they are compared, a continuous output signal is obtained. The

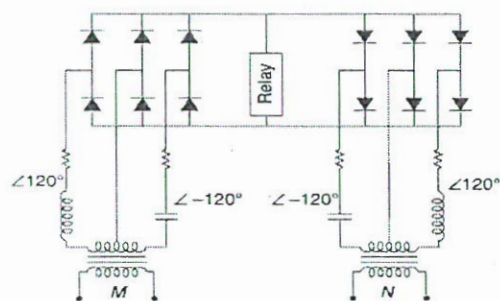


Fig. 2.24 Phase splitting type amplitude comparator

operating time depends on the time constant of the slowest arm of the phase-splitting circuit and the speed of the output device.

### Types of Phase Comparators

Phase comparison can be made in a number of different ways. Some important techniques are described below.

- (i) Vector product phase comparators
- (ii) Coincidence type phase comparators.

### Phase-splitting Type Phase Comparator

In this technique, both inputs are split into two components shifted  $\pm 45^\circ$  from the original wave, as shown in Fig. 2.26(a). All the four components, which are now available, are fed into an AND gate as shown in Fig. 2.26(b). The tripping occurs when all the four signals become simultaneously positive at any time during the cycle. An AND gate is used as a coincidence detector. The coincidence of all the four signals occurs only when  $\theta$  is less than  $90^\circ$ . The full range of operation is  $-90^\circ < \theta < 90^\circ$ . It is a technique of direct comparison.

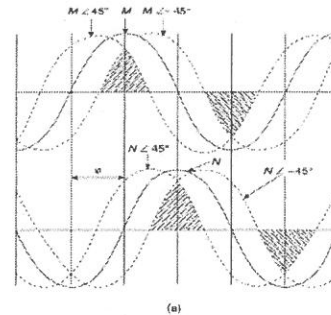
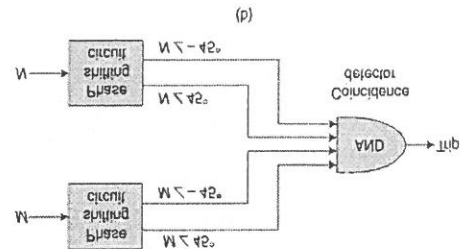


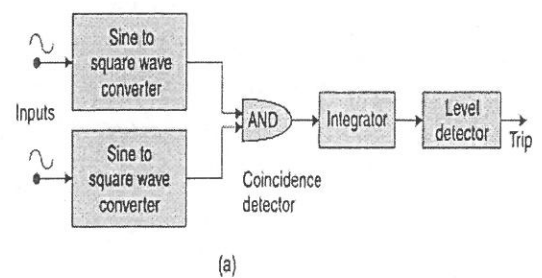
FIG. 2.26 Phase-comparator with phase-split inputs



### Integrating Type Phase Comparator

In this technique, the coincidence time is measured for each cycle by integrating the output of an AND gate (coincidence detector) to which input signals are applied. Figure 2.25(a) shows two sinusoidal input signals. The hatched area shows the time of overlap (time of coincidence) of the two inputs. During this period, both inputs are positive. This period is represented by  $\psi$ . The phase difference between the two inputs is  $\theta$ . The angle  $\psi = 180 - \theta$ . If  $\theta$  is less than  $90^\circ$ ,  $\psi$  is greater than  $90^\circ$ . If these two inputs are applied to an AND gate, the output of the gate is a series of square pulses. We get a square wave output during the period of coincidence and no output for the rest of the period of a cycle, as shown in Fig. 2.25 (b).

Figure 2.27(a) shows the block diagram of a phase comparator. The sinusoidal inputs are first converted into square waves and then are applied to an AND gate. The output of the AND gate is a chain of pulses as shown in Fig. 2.27(b). This is for  $\theta < 90^\circ$ , i.e.  $\psi > 90^\circ$ . The relay will provide a trip output. The output of the AND gate is applied to an integrator. The output of the integrator is shown in Fig. 2.27(c). This output is applied to a level detector which finally gives a TRIP signal. The integrating circuit may be employed as shown in Fig. 2.28. The level detector may be a thyristor circuit. Relay Construction and Operating Principles Figure 2.27(d) and (e) show the outputs of the AND gate and the integrator, respectively. This situation is for  $\psi = 90^\circ$  and is the limiting condition. The relay may be set to operate at  $\psi = 90^\circ$ .



## 10A)Lightning phenomena

**Lightning** An electric discharge between cloud and earth, between clouds or between the charge centres of the same cloud is known as lightning. Lightning is a huge spark and takes place when clouds are charged to such a high potential (+ve or -ve) with respect to earth or a neighbouring cloud that the dielectric strength of neighbouring medium (air) is destroyed. There are several theories which exist to explain how the clouds acquire charge.

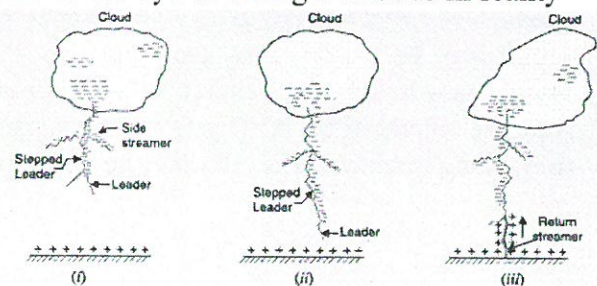
**Mechanism of Lightning Discharge** Let us now discuss the manner in which a lightning discharge occurs. When a charged cloud passes over the earth, it induces equal and opposite charge on the earth below. Fig. shows a negatively charged cloud inducing a positive charge on the earth below it. As the charge acquired by the cloud increases, the potential between cloud and earth increases and, therefore, gradient in the air increases. When the potential gradient is sufficient ( $5 \text{ kV/cm}$  to  $10 \text{ kV/cm}$ ) to break down the surrounding air, the lightning stroke starts. The stroke mechanism is as under :

(i) As soon as the air near the cloud breaks down, a streamer called leader streamer or pilot streamer starts from the cloud towards the earth and carries charge with it as shown in Fig. 24.4 (i). The leader streamer will continue its journey towards earth as long as the cloud, from which it originates feeds enough charge to it to maintain gradient at the tip of leader streamer above the strength of air. If this gradient is not maintained, the leader streamer stops and the charge is dissipated without the formation of a complete stroke.

In many cases, the leader streamer continues its journey towards earth until it makes contact with earth or some object on the earth. As the leader streamer moves towards earth, it is accompanied by points of luminescence which travel in jumps giving rise to stepped leaders. The velocity of stepped leader exceeds one-sixth of that of light and distance travelled in one step is about 50 m. It may be noted that stepped leaders have sufficient luminosity and give rise to first visual phenomenon of discharge.

(iii) The path of leader streamer is a path of ionisation and, therefore, of complete breakdown of insulation. As the leader streamer reaches near the earth, a return streamer shoots up from the earth to the cloud, following the same path as the main channel of the downward leader. The action can be compared with the closing of a switch between the positive and negative terminals; the downward leader having negative charge and return streamer the positive charge. This phenomenon causes a sudden spark which we call lightning. With the resulting neutralisation of much of the negative charge on the cloud, any further discharge from the cloud may have to originate from some other portion of it. The following points may be noted about lightning discharge :

- A lightning discharge which usually appears to the eye as a single flash is in reality made up of a number of separate strokes that travel down the same path.
- It has been found that 87% of all lightning strokes result from negatively charged clouds and only 13% originate from positively charged clouds.
- Lightning discharge may have currents in the range of 10 kA to 90 kA.



Lighting Phenomena

10 b )

Metal-oxide surge arrester (MOA)

The metal oxide surge arrester abbreviated as MOA is a recently developed ideal surge arrester. It is a revolutionary advanced surge protective device for power systems. It is constructed by a series connection of zinc oxide (ZnO) elements having a highly non-linear resistance. The excellent non-linear characteristic of zinc oxide element has enabled to make surge arresters without series connected spark gaps, i.e. fully solid-state arresters suitable for system protection up to the highest voltages. As mentioned earlier, the conventional non-linear surge diverters almost exclusively use Silicon Carbide (SiC) non-linear resistors. As this material is not ideal, it is not non-linear enough and thus imposes certain design restrictions. Also, its characteristics call for a large number of spark gaps. A new class of non-linear material was recently developed in Japan by Japan's Matsushita Electric Company. The new ceramic material is basically formed from zinc oxide together with addition of other oxides, such as bismuth and cobalt oxides. As the main constituent of this new ceramic material is zinc oxide, the non-linear resistor made of this material is popularly known as zinc oxide element and surge arresters made of zinc oxide elements are called metal oxide surge arresters. Such material can be used to make resistors with a much higher degree of non-linearity over a large current range. With such resistors, one can design arresters having voltage-current characteristics very close to ideal. Because of the high degree of non-linearity, this material allows considerable simplification in arrester (diverter) design. The metal oxide surge arrester (MOA) which consists of a series connected stack of discs of zinc oxide elements, operates in a very simple fashion. It is dimensioned so that the peak value of the phase to ground voltage in normal operation never exceeds the sum of the rated voltages of the series-connected discs. The resistive losses in the arrester in normal operation are therefore very small. When an overvoltage occurs, the current will rise with the wavefront according to the characteristics without delay. No breakdown occurs but a rather continuous transition to the conducting state is observed. At the end of the voltage transient, the current is reduced closely following the I-V curve (i.e. in contrast to the conventional arrester, there is no follow-up current). The metal oxide surge arrester has the following marked advantages over conventional arresters.

- (i) Series spark-gap is not required.
- (ii) It has very simple construction and is a fully solid-state protective device.
- (iii) Significant reduction in size.
- (iv) Quick response for steep discharge current.
- (v) Very small time delay in responding to over voltages.
- (vi) Superior protective performance.

Outstanding durability for multiple operating duty cycle.

No abrupt transient such as that occurs at the time of sparkover in a conventional arrester.

Negligible power follow-up current after a surge operation.

MOA is especially suitable for gas insulated sub-stations (GIS), since it can be installed directly in SF

6 . Figure 16.20 illustrates the difference in the operations of MOA and conventional arresters, responding to an on-coming surge  $v(t)$ . The voltage wave shape of MOA is smooth and can be expressed as follows

The voltage wave shape of the conventional arrester has a peak value at the time of sparkover of the series gap. The voltage after sparkover or the discharge voltage can be expressed by Eq. (16.18). As seen from Fig. 16.20, the protection performance of the conventional arrester is controlled by both the sparkover voltage and the

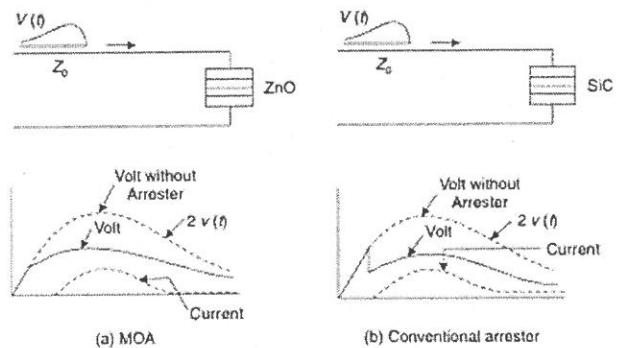


Fig. 16.20 Operation of MOA and conventional arrester responding to an on-coming surge

$$V = 2v(t) - Z_0 i$$

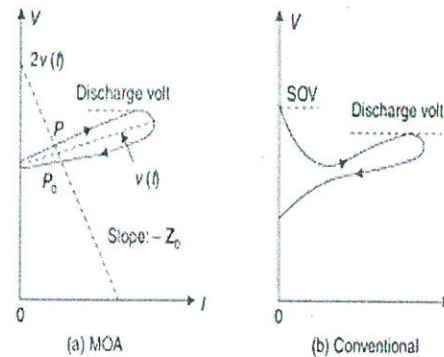
(16.18)

discharge voltage. However, the protection performance of MOA is simply related to the discharge voltage, given by Eq. (16.18). The protection level of MOA is decided by the maximum discharge voltage encountered under normal operating conditions. Though it is difficult to get a clear cut expression like the V-t curve in a conventional arrester, the individual voltage waveform should be considered in precise discussion of insulation coordination. For rough estimation of the voltage waveform, it is convenient to assume a fixed functional relation between the voltage and current of MOA, as follows.

$$V = v(i) \quad (16.19)$$

The voltage waveform or the time dependence of V can be calculated by connecting Eqs. (16.18) and (16.19). A graphical method of solving the equation is shown in Fig. 16.21 (a). The V and I values corresponding to  $v(t)$  are represented by P 0 which is the intersection point of two curves corresponding to Eqs. (16.18) and (16.19). In this simple treatment, the point P 0 moves on the  $v(i)$  curve shown by a dotted line in Fig. 16.21(a). However, the actual V-I point moves along the thick line which cannot be conformed to a single line. A typical V-I characteristic of conventional SiC arrester is conceptually shown in Fig. 16.21(b) for comparison. In this case, the change from sparkover voltage (SOV) to a lower discharge voltage is abrupt.

The main drawback of MOA is that the absence of spark-gaps results in a continuous flow of current through the device so that there is theoretically speaking the danger of thermal runaway. However, as very stable resistors have been developed, these apprehensions are almost eliminated. Furthermore, the absence of spark-gaps makes the voltage grading system unnecessary. The MOA is inherently self-regulating in that the current flow of 0.5 to 1 mA at normal supply voltage leads to reliable operation even in polluted conditions.



Transient V-I characteristics of MOA and conventional arrester

### 11a)

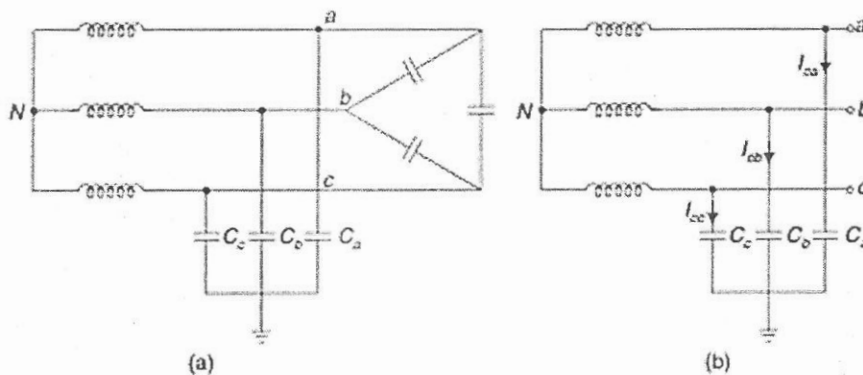
- (i) Persistent arcing grounds are eliminated and hence the system is not subjected to over voltages due to arcing grounds.
- (ii) The neutral point remains stable and is not shifted.
- (iii) The voltages of healthy phases (lines) with respect to ground remain at normal value. They do not increase to root 3 times normal value as in the case of an ungrounded (isolated neutral) system.
- (iv) The ground-fault relaying is relatively simple because sufficient amount of ground-fault current is available to operate ground fault relays.
- (iv) The life of insulation is increased due to prevention of voltage surges caused by arcing grounds. Hence, maintenance, repairs and breakdowns are reduced and service continuity is improved.
- (v) By employing resistance or reactance in ground connection, the ground-fault current can be controlled.
- (vi) The over voltages due to lightning are discharged to ground.
- (vii) Improved service reliability is provided because of limitation of arcing grounds and prevention of unnecessary tripping of circuit-breakers.

(viii) Greater safety is provided to personnel and equipment.

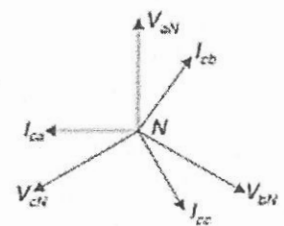
In spite of many disadvantages as discussed above, the following are the few advantages of ungrounded (isolated) neutral system.

- (i) In case of a single line-to-ground fault, the fault current is very small. Hence, it is possible to maintain the supply with a fault on one line.
- (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 their disadvantages. With the growth of power systems in terms of power transmitted, voltage level and distance of transmission, many difficulties were being encountered in ungrounded systems. Therefore, ungrounded systems are no more used. The modern power systems operate with neutral grounding at every volt age level.

11b) A simple ungrounded neutral system is shown in Fig. (a). The line conductors have capacitances between one another and to ground, the former being delta connected while the latter are star-connected. The delta-connected capacitances have little effect on the grounding characteristics of the system and, therefore, can be disregarded. The circuit then reduces to the one shown in Fig. (b).



In the system having perfectly transposed line, each conductor will have the same capacitance to ground, i.e.,  $c_a = c_b = c_c = c$ . Therefore, under normal conditions (i.e., steady state and balanced conditions), the line to neutral charging currents  $I_{ca}$ ,  $I_{cb}$ ,  $I_{cc}$  will form a balanced set of currents as shown in Fig. (c). The phasors  $V_{aN}$ ,  $V_{bN}$  and  $V_{cN}$  which represent the phase to neutral voltage of each phase have the same magnitude and are displaced from one another by  $120^\circ$ .



The charging currents  $I_{ca}$ ,  $I_{cb}$  and  $I_{cc}$  lead their respective phase voltages by  $90^\circ$  and are equal. Let,  $V_{aN} = V_{bN} = V_{cN} = V_p$  (Phase Voltage) In magnitude each of the charging current is  $I_{ca} = I_{cb} = I_{cc} = I_c = \frac{V_R}{X_c} = \frac{V_p}{\frac{1}{\omega c}} = V_p \omega c$

Where,  $V_p$  = Phase voltage (i.e., line to neutral voltage)

$X_c = \frac{1}{\omega c}$  = capacitive reactance of the line to ground.

The resultant of balanced phasor currents is zero and so no current flows to ground. In case of a line-to-ground fault in line 'a' at point F, the circuit becomes as shown in Fig. 2(a). Under this fault condition, the faulty line a takes up the ground voltage while the voltages of the remaining two healthy lines b and c rise from phase values to line value. When a line-to-ground fault occurs on any line, the capacitance to ground of that line gets shorted and does not come into picture for analysis. That is why the capacitance to ground of line a is not shown in Fig. 4.72(a). The capacitive currents become unbalanced and the components of the capacitive fault current  $I_f$  flow through the healthy lines b and c, and their capacitances and returns to the system via ground, the fault and the faulty line a. Thus the capacitive fault current (i.e., the current in line a) has two components: one,  $I_{ba}$ , through line b, capacitance  $C_b$  and the fault to line a; second,  $I_{ca}$ , through line c, capacitance  $C_c$  and the fault to line a. The voltages driving the currents  $I_{ba}$  and  $I_{ca}$  are  $V_{ba}$  and  $V_{ca}$  respectively. These currents lead their respective voltages by  $90^\circ$  and their phasor sum is equal to the fault current  $I_f$  as shown in the phasor diagram of Fig. 4.72(b)

$$I_{ba} = \frac{V_{ba}}{X_c} = \frac{\sqrt{3}V_p}{X_c} = \frac{\sqrt{3}V_p}{\frac{1}{\omega C}} = \sqrt{3}V_p\omega C = \sqrt{3}I_c$$

Similarly

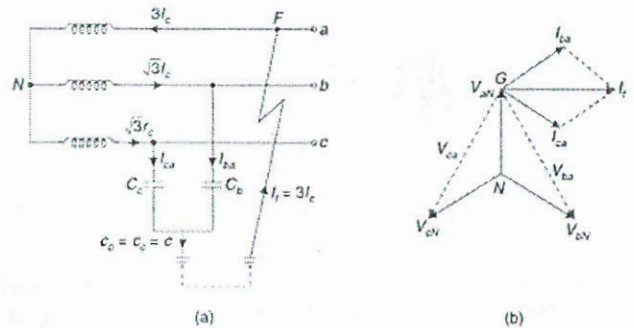
$$I_{ca} = \frac{V_{ca}}{X_c} = \frac{\sqrt{3}V_p}{X_c} = \frac{\sqrt{3}V_p}{\frac{1}{\omega C}} = \sqrt{3}V_p\omega C = \sqrt{3}I_c$$

Where  $I_c = V_p\omega C$ , is the per phase capacitive (charging) current under normal conditions.

The capacitive fault current  $I_f$  in line a is the phasor sum of  $I_{ba}$  and  $I_{ca}$ . From the phasor diagram of ,

$$I_f = \sqrt{3}I_{ba} = \sqrt{3}I_{ca} = \sqrt{3} \times \sqrt{3}I_c = 3I_c$$

= 3 × Per phase capacitive current under normal conditions.



(a) A ground fault on one of the lines of the ungrounded system. (b) Phasor diagram for fault on line a

Thus the capacitive fault current  $I_f$  which is three times the normal per phase capacitive current  $I_c$ , flows into the ground and in the faulty line. After occurrence of the ground fault, when the gap between the fault point F and the ground breaks down and the fault path becomes ionized, the capacitance discharges through the fault and capacitive current flows. If the capacitive current exceeds about 4 amperes, it is sufficient to maintain an arc in the ionized path of the fault, even though the medium causing the fault has cleared itself. The repeated charging and discharging of the line to ground capacitance results in the flow of capacitive current and repeated arcs between line and ground. The persistence of the arc due to the flow of capacitive current gives rise to a phenomenon known as "arcing grounds". The cyclic charging and discharging of the system capacitance through the fault under arcing ground conditions results in severe voltage oscillations reaching 5 to 6 times normal voltage. The build-up of high voltages may result in insulation breakdown. Thus, a temporary fault may grow into a permanent fault due to arcing grounds.