CHAPTER 7

Switchgear and Protection

7.1 Introduction

In a power system, faults can occur in any components like generators, transformers, buses or transmission lines and so on. The apparatus or equipments and their associated auxilaries employed for controlling, regulating or switching on or off the electrical circuits in the electrical power system is known as ***"switchgear"***. Faults in power system generally fall into two categories ***"short-circuit faults"*** and ***"open circuit faults"***. Whenever a short-circuit occurs, a heavy current flows through the equipment causing considerable damage to it and interruption of service. So, in order to protect the lines, generators, transformers and other electrical equipment from damage automatic protective device or switchgear is required. An automatic switch gear consists of the relays, circuit breakers, lightning arresters and fuse. When the fault occurs on any section of the system, protective relay of that section comes in operation and close the trip circuit of the breaker, which disconnects the faulty section. The healthy section continue to supply loads as usual and thus there is no damage to the equipment and no complete interruption of supply.

Out of the two faults namely short-circuit faults and open-circuit faults, short-circuit faults are the most severe kind, resulting in flow of abnormally high currents which can lead to extensive damage to the equipment. It can lead to fire, explosion, insulation failure, overheating of generator and sometimes even loss of synchronism. On the other hand, open-circuit faults causes abnormal system operation and danger to personnel. They can be tolerated for longer period of time than short-circuit faults. The faults are detected by relays (automatically) and the faulty section is isolated by circuit breakers. The combination of relays and circuit breakers is known as the ***"protective system"***. For the complete protection of a power system equipment there must be a coordinated operation between relay and circuit breaker. In this chapter we will first focus on switchgear and it's components and then we will go for power system protection.

7.2 Components of Switchgear

Switchgear has got mainly four components which are as follows:

1. Fuse
2. Lightning arresters
3. Circuit breakers
4. Relays

The various components along with some other equipments used have been described as follows.

Fuse

Fuse is a piece of metal which interrupts the short circuit current. It is the cheapest and simplest current-interrupting device for protection of the equipment upto 600 V against overloads and/or short circuits. The fuse is expected to allow the flow of normal working current safely without overheating and during short circuit/overloads it gets heated upto the melting point rapidly. The materials used normally are tin, silver, zinc, lead, copper, aluminium etc.

Isolators

Isolators are used to disconnect the circuit breaker from live parts of the system. It is called a ***"disconnecting switch"***. It operates under no-load condition and has no current breaking and current making capacity. Isolators are used in combination with circuit breakers which can make and break circuit under normal and short circuit conditions. A ***"load break switch"*** or ***"load interrupting switch"*** combines the function of an isolator and switch which is used for breaking the load current.

Lightning Arrester or Surge Diverter

The device/equipment used for the protection of the power system against voltage surge is called ***"surge diverter"*** or ***"lightning arrester"***. It is connected between the line and earth to divert the incoming high voltage wave to earth. A lightning arrester consists of non-linear resistor blocks connected in series with the series gap as shown in Figure 7.1. When a high voltage wave reaches the surge diverter, it sparks-over and provides a conducting path of relatively low impedance between the line and earth so that the resulting current flows to the earth. As soon as the voltage again comes to normal value, it stops the flow of current.

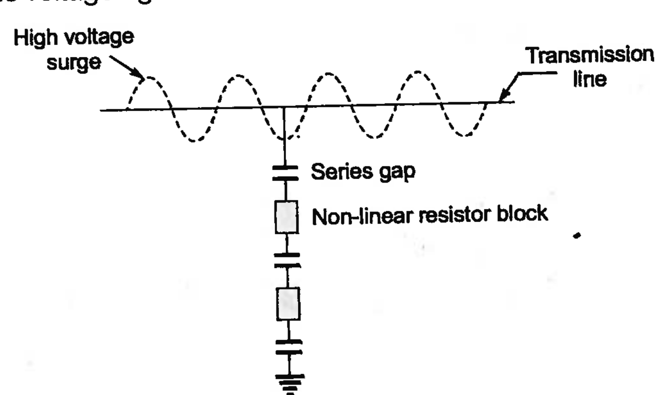


Figure-7.1 : *Protection of line against high-voltage surge using lightning arrester*

"Thyrite arresters" are the most common and is mostly used for the protection against high dangerous voltages.

Surge Absorber

The device which reduces the steepness of the wave front of a particular surge and thus minimises the danger due to over voltage is known as ***"surge modifier"*** or ***"surge absorber"***.

Circuit Breaker (CB)

Circuit breakers are mechanical (or automatic now a days) devices designed to close or open contact members, thus closing or opening an electrical circuit under normal or abnormal conditions. Automatic circuit breakers for the protection of electrical circuits are equipped with a trip coil connected to a relay or other means which are used to open the breaker automatically under abnormal conditions (i.e. over current etc.).

7.3 Operating Principle of a Circuit Breaker (CB)

A circuit breaker consists of two contacts namely ***"fixed"*** and ***"moving contacts"*** which touches each other under normal condition i.e. when circuit breaker is closed. Whenever a fault occurs, the trip coils get energized, the moving contacts get pulled by some mechanism and therefore, the circuit breaker is opened and the circuit is broken.

Initiation of Arc

When the moving contacts of a C.B. begins to part, the heavy current passes through the gap causing a small voltage drop. A small separation of contacts does not cause immediate interruption of current because as the contact separate, the resistance between them increases and a lot of heat is produced due to the ohmic loss. This heat is sufficient to ionize the air or vaporize and ionize the oil between the contacts. The ionized air or vapour acts as a conductor and thus the current remains uninterrupted across the low resistance arc produced. The potential difference between the contacts is quite small and is just sufficient to maintain the arc.

NOTE

- When the flow of charge takes place in a medium then, it is called ***"arc"***.
- Arc in a circuit breaker is initiated due to ***"field emission process"*** and is maintained due to ***"thermionic emission (thermal ionisation)"***.
- Because of the random nature of ionisation process, the voltage has high frequency components which also contribute radio frequency noise.
- The heat of the arc causes the oil in circuit breaker to decompose and liberate gases which comprises of almost 70% hydrogen, 20-25%% acetylene and 5-10% others (methane and other hydrocarbons).

7.4 Arc Interruption

The arc produced between the contacts of the C.B. provides a gradual transition from the current carrying of the voltage-isolating states of the contacts, but it is dangerous on account of the energy generated in it in the form of heat which may result in explosive forces. The interruption of this arc within shortest possible duration is an important factor in design of the breaker.

There are two methods of extinguishing the arc namely the ***"high resistance method"*** and ***"low resistance method"*** which are covered in detail as follows:

1. **High resistance method:** The resistance of an arc and the current flowing through the contacts depends upon the number of particles ionized, the cross-section of the arc and the length of the arc. If the resistance of the arc is increased then, the arc current get reduced to such a value that heat produced by it is not sufficient to maintain the arc and thus the current is interrupted or the arc is extinguished. The ***"high resistance method of arc interruption"*** is employed in DC circuit breakers and low/medium power industrial type air break circuit breakers.

   The resistance of an arc can be increased by following methods:

   (*i*) **Splitting the arc:** The arc can be splitted up by introducing some other conducting plates between the contacts of circuit breaker. If the sum of the cathode-anode voltage drops of short length becomes more than the supply voltage then, the energy fed to the arc get reduced and thus, arc is extinguished.

   (*ii*) **Increasing the length of arc:** In arc lengthening method, the length of the arc is increased by increasing the gap length between the contacts to such a length so that the voltage available becomes insufficient to maintain the arc.

(*iii*) **Reducing the cross-section of the arc:** By using a small area of contacts or by letting the arc pass through a narrow opening, the cross-section of an arc can be reduced which causes increase in the arc resistance.

(*iv*) **Decreasing the concentration of ionized particles:** The concentration of ionized particles depends upon the potential gradient and the heat produced in case of sustained arc. Hence, it can be reduced either by decreasing the voltage or by increasing the gap length between the contacts.

2. **Low resistance method:** This method is also called ***"natural current zero method"*** which is used only in ac circuit breakers because there is natural zero of current for a 50 Hz supply (or ac systems). In this method, the arc resistance is kept low until the current is zero where the arc extinguishes naturally and is prevented from restriking after it has gone out at a current zero.

7.5 Arc, Restriking and Recovery Voltages

In a C.B. as soon as the contacts separate out an arc is formed. The voltage across the contacts during arcing period is known as the ***"arc voltage"*** and is relatively low with heavy current arcs of short length. At the instant of current interruption (arc extinction) an LC transient occurs involving generator inductance and stray capacitance causing high frequency damped oscillations as shown in Figure 7.2. Here, V_B is the voltage appearing across the breaker poles during arc interruption and i_B is the arc current across the breaker poles. The various voltage and current across the C.B. poles during transient can be defined as follows:

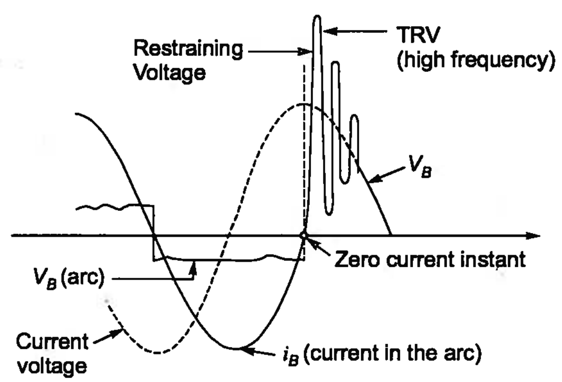


***Figure-7.2 :** Phenomenon of circuit breaker transient*

- **Recovery voltage:** The voltage appearing across the breaker poles when arc extinguishes is known as recovery voltage.
- **Prospective current:** The current which would have flown if the breaker did not open is called prospective current.
- **Transient recovery voltage (TRV):** The recovery voltage with occurs due to the transient occuring (due to the formation of LC transient) across the breaker poles is known as transient recovery voltage (TRV).
- **Transient restriking voltage:** The transient voltage appearing across the circuit breaker contacts at current zero during arc period is called the ***"restriking voltage"***.

This voltage restrikes the arc so that it persists for another half cycle. The two phenomena i.e. TRV and prospective voltage tend to restrike the arc so that the breaker would then open at a later current zero when larger pole separation has occured.

Derivation of Transient Restriking Voltage

Let a three-phase symmetrical short-circuit occurs on a generator with an intervening circuit breaker having three-circuit opening poles, one in each phase as shown in Figure 7.3.

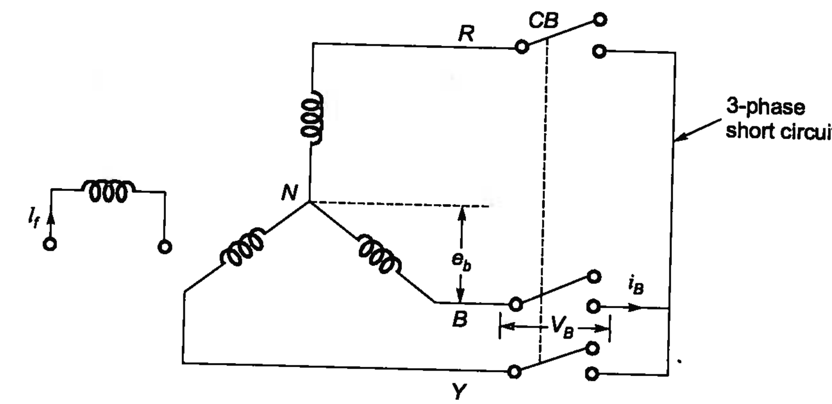


***Figure-7.3 :** Three-phase short-circuit on a generator and circuit breaking*

Now, let us consider the per phase circuit of the short-circuit generator as shown in Figure 7.4 where ωL is the generator reactance and $1/\omega C$ is the capacitive reactance of the stray generator capacitance. This is equivalent to switching the generator voltage in the series LC circuit.

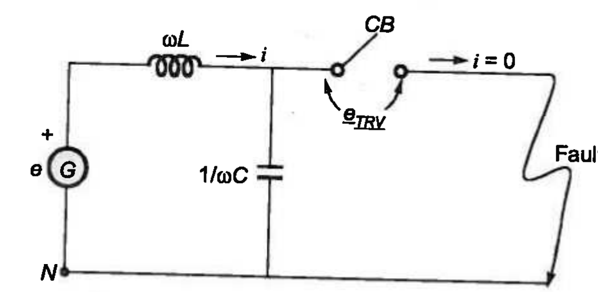


***Figure-7.4 :** The equivalent circuit during transient*

From Figure 7.4 we can write,

Generator emf, $e = E_m \cos\omega t$ ...(1)

and short circuit current, $i = \dfrac{E_m}{\omega L}\cos(\omega t - 90°) = \dfrac{E_m}{\omega L}\sin\omega t$ ...(2)

(Neglecting capacitance effect at power frequency i.e. 50 Hz)

Here, $\omega_n = \dfrac{1}{\sqrt{LC}} >> \omega$ = Natural frequency of oscillation (in kHz)

Let the C.B. opens at t = 0 to interrupt the fault current. Also, assume that the power frequency component in the circuit remains constant at it's instantaneous value at $t = 0$.

i.e., $e|_{\omega t = 0} = E_m$

Now, applying KVL in the circuit of Figure 7.4, we get

$$E_m u(t) = L\frac{di}{dt} + \frac{1}{c}\int i\,dt \quad ...(3)$$

Also, $$e_{TRV} = \frac{1}{c}\int i\,dt \quad ...(4)$$

or, $$i = C\frac{de_{TRV}}{dt} \quad ...(5)$$

Substituting the value of 'i' from equation (5) into equation (3), we get

$$LC\frac{d^2e_{TRV}}{dt^2} + e_{TRV} = E_m u(t) \quad ...(6)$$

Solving the above differential equation, we get

$$e_{TRV} = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right) \quad (t \geq 0) \quad \text{...(Important equation)} \quad ...(7)$$

The restriking voltage is found to be of the wave shape as shown in Figure 7.2 of previous article i.e. oscillating about a zero line which is the normal 50 Hz wave of recovery voltage.

The variation of the transient restriking voltage with time is shown in Figure 7.5.

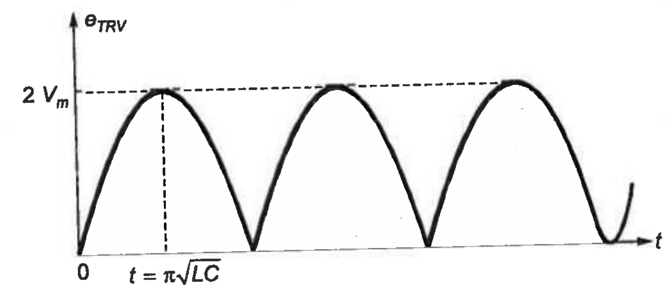


Figure-7.5 : *Restriking voltage across breaker contacts*

NOTE

- Restriking voltage depends upon E_m which is turn is a function of power factor of the system. For highly lagging system this voltage corresponds to the system peak voltage.
- The restriking voltage depends on the value of inductance and capacitance upto the point of fault location i.e. lower the value of the inductance and capacitance, the higher will be the natural frequency of oscillations and more severe will be the effect of restriking voltage and vice versa.

  For example:

  "For a short line fault", L and C will be small, $\omega_n = \frac{1}{\sqrt{LC}}$ will be more, as a result restriking voltage will be more **[using equation (7)]**.

  "For a long line fault", L and C will be high, $\omega_n = \frac{1}{\sqrt{LC}}$ will be small, as a result restriking voltage will be less **[using equation (7)]**.

  Therefore, in a view point of restriking voltage, a short line fault is more severe than a long line fault.
- The voltage at the instant of arc extinction is known as ***"active recovery voltage"***.

  Active recovery voltage is given by $e_{ar} = kE_m \sin\phi$

  (where, k = **1 for 3-ϕ grounded fault** and k = **1.5 for 3-ϕ isolated fault)**

Rate of Rise of Restriking Voltage

The rate of rise of restriking voltage is obtained by drawing a straight line through zero and tangential to the point of curve and is expressed in **kV/μs**.

Mathematically, rate of rise of restriking voltage is given by

$$RRRV = \frac{de_{TRV}}{dt} = \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}} \quad ...(8)$$

Maximum value of *RRRV*:

RRRV is maximum if, $\sin\frac{t}{\sqrt{LC}} = 1$ or $t = \frac{\pi}{2}\sqrt{LC}$

Hence, $$RRRV_{max} = \frac{E_m}{\sqrt{LC}} = 2\pi f_n E_m \quad \left(\text{where, } f_n = \frac{\omega_n}{2\pi} \text{ and } \omega_n = \frac{1}{\sqrt{LC}}\right) \quad ...(9)$$

Average *RRRV*:

$$\text{The average } RRRV = \frac{\text{Peak value of restriking voltage}}{\text{Time taken to reach the peak value}} = \frac{2E_m}{\pi\sqrt{LC}} \quad ...(10)$$

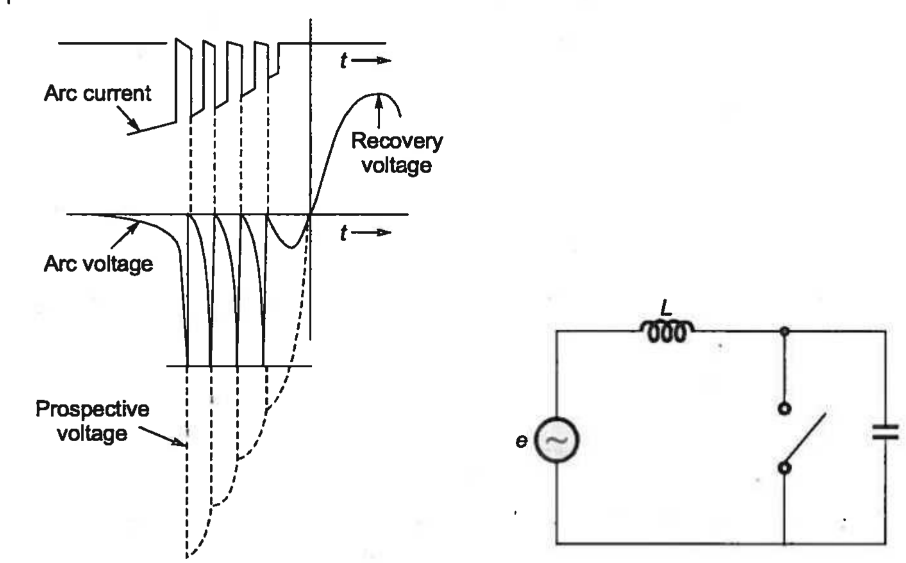
Remember

- For restriking free operation of the circuit breaker, RRRV should be less.
- For smaller value of *RRRV*, the rate at which the dielectric strength between the contacts is developed, the arc will be quenched, otherwise it will further restrike in next half cycle.

7.6 Current Chopping

When a C.B. interrupts a low inductive current i.e. current to a shunt reactor or magnetizing current of a power transformer, then current falls to zero before natural current zero. This phenomenon is called ***"current chopping"***.

It is clear from Figure 7.6 (a), that the arc current gradually reduces with low arc voltage but at a certain instant of time it suddenly becomes zero due to large de-ionizing force. Due to this sudden change in current, the energy stored in the inductance of the circuit does not reduces to zero instantaneously and hence this energy is transferred to the capacitance between the circuit breaker contacts.



(a) **(b)**

Figure-7.6 : *Current chopping phenomena*

Let 'i' be the arc current and L and C be the inductance of the circuit and capacitance between breaker contacts respectively then,

Magnetic energy lost by the inductor = Electrostatic energy gained by the capacitor

i.e. $$\frac{1}{2}Li^2 = \frac{1}{2}cv^2$$

(Here, v = developed voltage between breaker poles)

or, $$v = i\sqrt{\frac{L}{C}} \text{ (in volts)} \quad \text{...(Important result)}$$

The voltage developed across the C.B. contacts due to the transfer of energy is known as ***"prospective voltage"***. It is the maximum voltage upto which the capacitor can be charged. This voltage is extremely higher as compared to the normal system voltage. Fortunately, the C.B. restrikes before the voltage attains this value and chops the current because of de-ionisation still in action. The chopping action takes place until the current becomes zero and when the gap gets deionized completely then, no further restriking takes place [can also be observed from Figure 7.6 (b)].

NOTE: The insulation requirements for EHV lines is designed based on switching over voltages.

7.7 Resistance Switching of Circuit Breaker

During current chopping, a very high voltage ***(prospective voltage)*** appears across the circuit breaker contacts which may cause a serious damage to it. To prevent this damage, resistance switching is used by connecting a resistance across the circuit breaker contacts as shown in Figure 7.7.

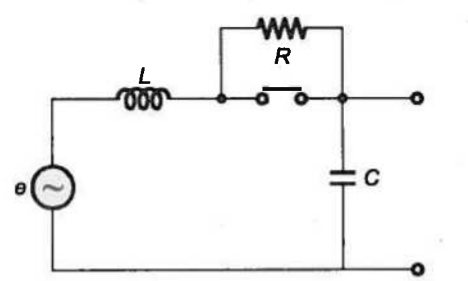


***Figure-7.7 :** Resistance switching of circuit breaker*

The resistor R connected across the breaker contacts:

(*i*) reduces the *RRRV* and thus reduces the burden on the C.B.

(*ii*) ensures the damping of the high frequency restriking voltage transients during switching out capacitive or inductive loads.

(*iii*) helps in distributing the transient recovery voltage more uniformly across all the contact gaps in a multi-break C.B.

Using Figure 7.7, the natural frequency of oscillations can be obtained as

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

For finding the critical value of R for keeping RRRV within the rating of breaker, we have,

$$f = 0 \quad \text{i.e.} \quad \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}} = 0 \quad \text{or} \quad R = 0.5\sqrt{\frac{L}{C}}$$

...(Critical value of resistance for resistance switching)

Example - 7.1 **In a 220 kV system, the line to ground capacitance is 0.02 μF and inductance is 9 H. Find out the voltage appearing across the pole of a C.B., if an instantaneous magnetizing current of 6 A is interrupted. Also find the value of resistance to be used across the contacts to eliminate the restriking voltage.**

Solution:

Given, series inductance, $L = 9\text{ H}$

Shunt capacitance, $C = 0.02 \times 10^{-6}\text{ F}$

Magnetizing current to be interrupted,

$i = 6\text{ A}$

∴ Voltage appearing across the breaker poles

= Prospective voltage = v

$$= i\sqrt{\frac{L}{C}} = 6\sqrt{\frac{9}{0.02\times10^{-6}}} = 127.28\text{ kV}$$

Also, resistance to be connected across the contacts to eliminate the restriking voltage is

$$R = 0.5\sqrt{\frac{L}{C}} = 0.5\sqrt{\frac{9}{0.02\times10^{-6}}} = 10.6\text{ k}\Omega$$

Example - 7.2 **In a power system lightening arresters are used to protect the electrical equipment against**

(a) power frequency of over-voltages.
(b) direct strokes of lightening.
(c) over-current due to lightening stroke.
(d) over voltages due to indirect lightening strokes.

Solution: (d)

Example - 7.3 **The voltage that appears across the contacts after the circuit breaker is opened is called**

(a) recovery voltage **(b) arc voltage**
(c) restriking voltage **(d) surge voltage**

Solution: (a)

The rms voltage that appears across the circuit breaker contacts after final arc interruption (or when breaker opens) is called ***"recovery voltage"***.

Example - 7.4 **In a short circuit test on a 220 kV, three-phase circuit breaker with earthed neutral the following results were obtained:**

Fault pf = 0.4; recovery voltage = 0.9 of full line value; the breaking current is symmetrical and the restriking transient had a natural frequency of 18 kHz. Determine *RRRV* for (*i*) grounded fault (*ii*) ungrounded fault.

Solution:

Peak value of phase voltage is,

$$E = \frac{220}{\sqrt{3}} \times \sqrt{2} = 179.63\text{ kV}$$

Recovery voltage, $E_m = 0.9\,E = (0.9 \times 179.63)\text{ kV} = 161.67\text{ kV}$

Time taken to reach peak value $= \dfrac{1}{2f} = \dfrac{1}{2\times 18\times 10^3} = 27.77\ \mu s$

$$\left[\text{Since } t = \pi\sqrt{LC} = \pi\times\frac{1}{\omega_n} = \pi\times\frac{1}{2\pi f_n} = \frac{1}{2f_n};\ \text{using equation (7) of previous article}\right]$$

(*i*) For grounded fault, we have

Active recovery voltage $= E_{ar} = kE_m \sin\phi$

$= 1\times 161.67\times 10^3\times \sin[\cos^{-1} 0.4]$ ($\because$ $k = 1$ for grounded fault)

$= 148.17$ kV

$\therefore$ The maximum value of restriking voltage

$= 2\times E_{ar} = 2\times 148.17 = 296.34$ kV

$$\therefore\quad RRRV = \left(\frac{\text{Maximum restriking voltage}}{\text{Time taken to reach the peak value}}\right)$$

$$= \frac{296.34}{27.77} = 10.67\ \text{kV}/\mu s$$

(*ii*) For ungrounded fault, we have

Active recovery voltage, $E_{ar} = kE_m \sin\phi$

$= 1.5\times 148.7$ ($\because$ $k = 1.5$ for ungrounded fault)

$= 222.25$ kV

$\therefore$ Maximum value of restriking voltage $= 2\,E_{ar} = 2\times 222.25 = 444.5$ kV

$$\therefore\quad RRRV = \frac{2E_{ar}}{\pi\sqrt{LC}} = \frac{444.50}{27.77}\ \text{kV}/\mu s = 16\ \text{kV}/\mu s$$

Example - 7.5 **A 50 Hz, three-phase synchronous generator has an inductance per phase of 1.75 mH and its neutral is grounded. It feeds a line through a circuit breaker. The total stray capacitance to ground of the generator and circuit breaker is 0.0025 µF. A fault occurs just beyond the circuit breaker, which opens when the symmetrical SC current is 7500 A (rms). Ignoring the first pole to clear factor, determine the following:**

(*i*) Natural frequency of oscillations
(*ii*) Peak value of transient restriking voltage
(*iii*) Time at which peak value of transient restriking voltage occurs
(*iv*) Maximum rate of rise of transient restriking voltage
(*v*) Time at which the maximum in part (*iv*) occurs

Solution:

(*i*) Natural frequency of oscillation is

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{1.75\times 10^{-3}\times 0.0025\times 10^{-6}}}$$

$$= \frac{10^6}{2\pi\times 2.092} \approx 76.1\text{kHz}$$

(*ii*) We have, $E = IX_L = I\cdot\omega L$

$= 7500\times 314\times 1.75\times 10^{-3} = 4.121$ kV

or, $E_m = \sqrt{2}E = \sqrt{2}\times 4.121 = 5.827\text{ kV}$ or 5.828 kV

$\therefore$ Peak value of transient restriking voltage $= 2\,E_m = 2\times 5.827 = 11.655$ kV

(*iii*) Time taken to reach the peak value of transient restriking voltage is

$$t_p = \pi\sqrt{LC} = \pi\sqrt{1.75\times 10^{-3}\times 0.0025\times 10^{-6}} = 6.57\ \mu s$$

(*iv*)
$$(RRRV)_{max} = \frac{E_m}{\sqrt{LC}} = \frac{5.827\times 10^3}{\sqrt{1.75\times 0.0025\times 10^{-9}}}$$

$= 2785$ V/µs or 2785.8 V/µs

$= 2.785$ kV/µs

(*v*) Time taken to reach the maximum value of $RRRV = \dfrac{\pi}{2}\sqrt{LC} = \dfrac{t_p}{2} = \dfrac{6.57}{2}\ \mu s = 3.285\ \mu s$

Example - 7.6 **Explain the terms: Restriking voltage, Rate of Rise of Restriking Voltage (RRRV). What is a low inductive current chopping problem in circuit breakers and how it is overcome to have smooth decay of restriking voltage?**

Solution:

Refer to previous articles for complete explanations.

7.8 Auto-reclosing of Circuit Breakers

In power system, most of the faults are temporary in nature (cleared quickly). Upon occurrence of a severe disturbance, say a short circuit, the power transfer between the machines is greatly reduced, causing the machine rotor to swing relatively. The circuit breakers near the fault disconnect the unhealthy part of the system so that power transfer can be partially restored, improving the chances of the system remaining stable. The shorter the time to breaker operation, the higher is the probability of the system being stable. Therefore, practically ***"autoreclose breakers"*** are used which automatically close rapidly after each of the two sequential openings.

Maximum three number of attempts are made by the C.B. to clear a fault described by it's ***"duty cycle"*** as follows:

O – 30 sec (①) – CO – 90 sec (②) – CO – 3 min (③) – CO ....(Duty cycle of a CB)

(Here, O stands for open and C stands for closing of CB)

If the fault still persists, the circuit breakers open and lock permanently till cleared manually. Since majority of faults are temporary, the first reclosure will be successful and thus chances of system stability are greatly enhanced by using ***"autoreclosing breakers"***.

7.9 Circuit Breaker Ratings

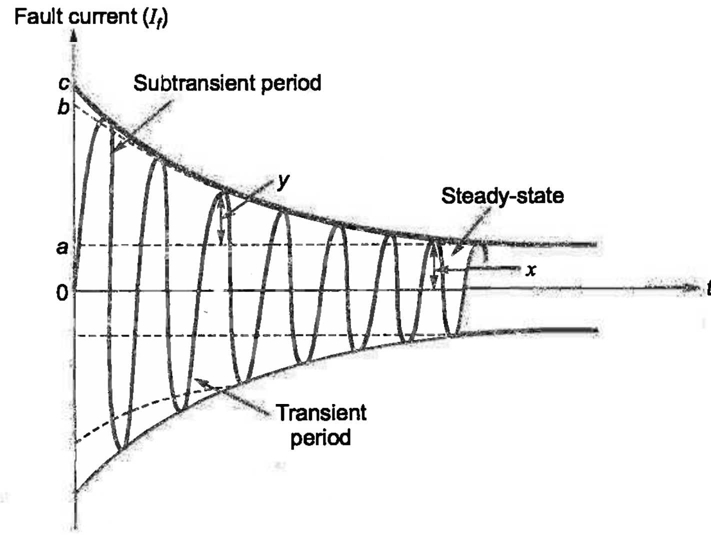
The rating of a circuit breaker depends upon the duties performed by it. Apart from normal working of circuit breakers, the circuit breaker is required to perform following 3 major duties under short circuit conditions.

(*i*) It must break the circuit and isolate the faulty section.
(*ii*) It must make circuit in the greatest asymmetrical peak in current wave.
(*iii*) It must carry the fault current safely for a short-time while another circuit breaker is clearing the fault (which is in series with it).

According to the above mentioned duties there are ***"three ratings of CBs"*** as follows:

1. **Breaking capacity**
2. **Making capacity**
3. **Short time rating**

When a fault occurs in power system, the current flowing in a synchronous machine immediately after occurrence of fault, that flowing a few cycle later and the steady state value of the fault current differ considerably due to effect of the armature current on the flux. The fault current w.r.t. time has a shape as shown in figure below.



Plot of fault current Vs time

In above figure,

Let, x = ac component of short-circuit current wave

y = dc component of short-circuit current wave

Now, symmetrical breaking current

= rms value of ac component of short circuit current wave at the instant of separation of contacts

$= \frac{x}{\sqrt{2}}$

Asymmetrical breaking current = rms value of the combined sum of ac and dc components

$= \sqrt{\left(\frac{x}{\sqrt{2}}\right)^2 + y^2}$

1. **Breaking capacity of C.B.:**

⇒ The breaking capacity of CB is generally expressed in terms of MVA and is equal to the product of rated breaking current (in kA), rated voltage (in kV) and a factor which depends upon the number of phases. (i.e. for single-phase 1 and for three-phase $\sqrt{3}$).

For a 3-ϕ C.B., ***the breaking capacity*** = $(\sqrt{3} \times I \times V)$ MVA = $\sqrt{3} \times I_{break} \times V_{rated}$

...(Important result)

Here, $\begin{cases} I_{break} = \text{Breaking current (symmetrical/unsymmetrical)} \\ V = \text{Rated voltage} \end{cases}$

⇒ Breaking capacity of CB is expressed in terms of **rms value.**

2. **Making capacity:** The making capacity of a circuit breaker is the peak value of the maximum current wave (including dc component) in the first cycle of the current after the circuit is closed by the circuit breaker. The maximum value of asymmetrical current = 2.55 × symmetrical current. Hence,

Making capacity of CB = 2.55 × (Symmetrical breaking capacity).

Making capacity of a CB is expressed in terms of ***peak value.***

3. **Short-time rating of CB:** The short-time rating of a CB is the current that can be safely applied, with the circuit breaker in its normal condition, for 3 seconds, (or for a specified duration), if the ratio of symmetrical breaking current to normal current is less than 40 or for 1 second otherwise.

Remember

- **As per Indian standard**, the breaking current = rms value of symmetrical breaking current $(= x/\sqrt{2})$.
- **As per American standard**, the breaking current = rms value of asymmetrical breaking current $\left(= \sqrt{\left(\frac{x}{\sqrt{2}}\right)^2 + y^2}\right)$.
- Practically, fault in a system is cleared within less than five cycles of fault current (i.e. within 0.10 seconds).
- **Normal current rating of CB**: It is the rms value of the current which the CB shall be able to carry continuously at its rated frequency under specified conditions.

7.10 Air-Break Circuit Breakers (ACB)

ACBs are the indoor type circuit breakers and are installed on vertical panels or indoor drawout type switchgear. In DC circuits, these are used upto 12 kV and for medium and low voltage AC circuits upto 6.6 kV, 400-2400 A and rupturing currents of 13-20 kA. In this type of C.B., the arc is lengthered in the breaker by the magnetic field and arc runners, and is finally extinguished by arc splitters as shown in Figure 7.8.

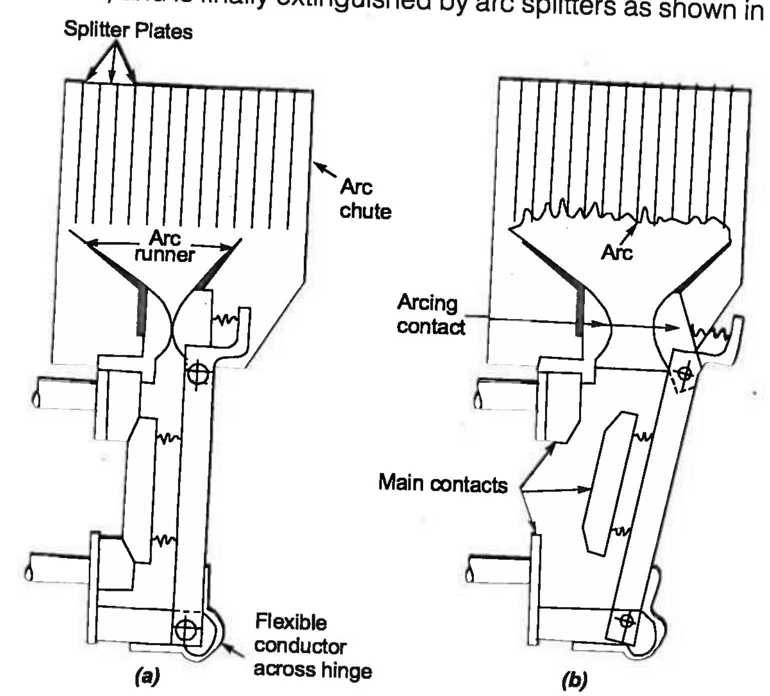


***Figure-7.8 :** Air-break circuit breaker (a) Closed (b) Open*

7.11 Oil Circuit Breakers

In oil CBs, oil is used to quench arc. The oil used is ***transformer oil.*** Earliear, oil circuit breakers were used for quenching the arc. Now a days, minimum oil circuit breaker is used in which arc is extinguished in a small arc control device filled with oil. Oil CBs are generally used upto 66 kV because for high voltages these have been replaced by *ABCB* and SF_6 CBs. The oil CBs have been developed for the following voltage ratings:

3.6 kV, 7.2 kV, 12 kV, 36 kV, 72.5 kV, 145 kV, 245 kV

A commonly used minimum oil CB having the construction as shown in Figure 7.9.

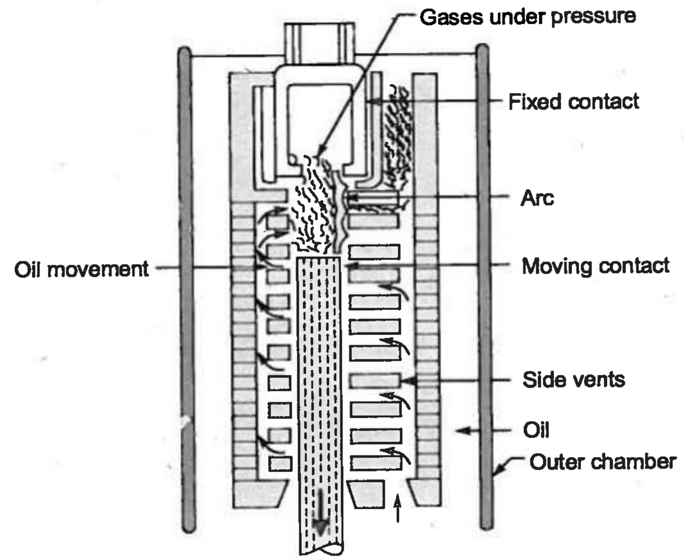


***Figure-7.9 :** Minimum oil circuit breaker*

When the contacts of the CB separates during a fault, then the heat of the arc causes the oil to decompose into gases which constitute various gases among which 70% is hydrogen. The gases so formed causes the pressure inside the arc control device to rise and as a result, the arc is pushed across the side vents, thereby somewhat elongating. As the contents of breaker move further apart lengthening the arc, it gets extinguished. The time of final arc is a function of arc current in an OCB where a smaller fault current take longer time for breaking the circuit as shown by the characteristic of Figure 7.10.

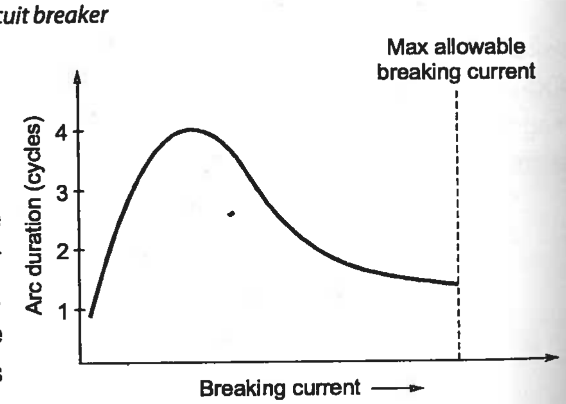


***Figure-7.10 :** Arc duration time in OCB*

Remember

- Oil CBs are generally employed in unattended substations and rural distribution schemes so that to avoid the closing of the breaker manually every time it trips.
- Transformer oil used in OCBs has mainly two application namely to provide cooling and insulation.
- In oil CBs, the strength of the deionizing force or volume of H_2 is adjusted according to the severity of the fault current. Hence, current chopping phenomenon is least in these type of breakers.
- The volume of oil required for minimum oil CBs (MOCBs) are only 10% of bulk oil circuit breakers (BOCBs) as oil in MOCBs are used for arc quenching only whereas in BOCs it is used for insulating live parts.

Disadvantage of Oil Circuit Breakers

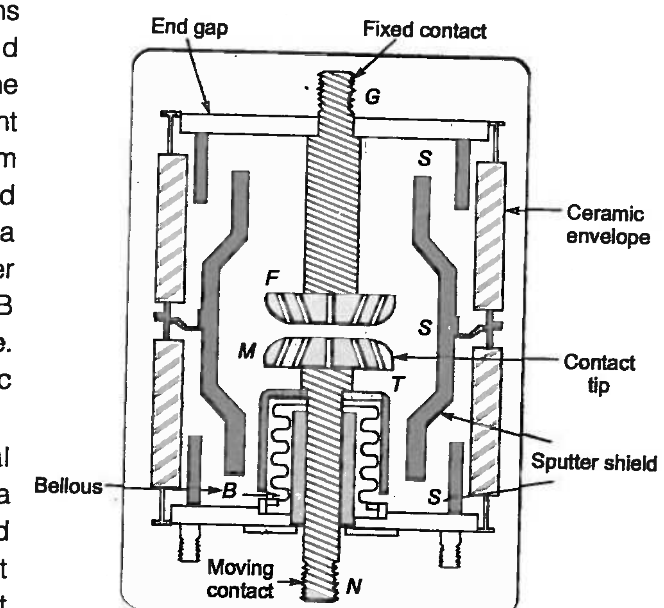
The main disadvantages are:

- There is fire hazards as oil used is inflammable.
- There is problem due to carbonization of live parts.
- Oil is hygroscopic, and must be sealed air tight in the camber.
- Due to carbonization during arcing process the dielectric strength of oil is reduced.
- Oil have to be replaced at a regular interval of time.

7.12 Vaccum Circuit Breakers (VCBs)

In these type of CBs, vaccum is used as a dielectric medium. An arc can't presist for a longer time if the vaccum is an ideal one. The separation of current carrying contacts causes the metal vapour to be released from the contacts giving rise to electrons and positive metal ions which fills the space intervening the contacts and maintaining the arc. When the current decreases, then the rate of release of metal vapour reduces. After the first current zero, the metal vapour quickly disperses and the medium regains its dielectric strength. The arc is thus extinguished in just half a cycle. The contacts of breaker separates in a very small time which is least among all circuit breaker types. The arc time constant is the least (in μs) in a VCB compared to other breakers which makes it most preferable. The rapid building up of dielectric strength after final arc extinction (20 kV/μs) is a unique feature of VCBs.

Figure 7.11 shows the basic constructional features of a VCB. Here, the contacts are enclosed in a sealed glass or ceramic bottle whose space is evacuated to a high degree of vaccum (10^{-4} torr). The moving contact is attached to metal bellows, which permits the movement without loss of vaccum. The interrupters are sealed for life and have a maintenance free life of more than 20 years.



G-Fixed electrode; N-Moving electrode; F, M-Arcing contacts; E-Ceramic or Glass bottle; B-Bellows; T-Bellows shield

***Figure-7.11 :** Vaccum circuit breaker*

Remember

- The vaccum employed in VCBs is of the order of 10^{-4} torr (1 torr = 1 mm of Hg).
- Vaccum circuit breakers give a maintenance free operation and hence are used for remote and rural electrification.
- Multi-unit VCBs are generally employed at voltages upto 72.5 kV.
- VCBs require small space than OCBs and are employed both for indoors and outdoor purposes.
- VCBs are used for interrupting high current and low voltages.
- VBCs are ideally suited for capacitor switching-restrike-free operation due to which it is capable of chopping small currents. These are also used for reactor switching, transformer and capacitor bank switching (high voltage and low current interruption are required).

7.13 Air-Blast Circuit Breakers (ABCB)

In these type of circuit breakers, blast of air at high speeds are directed at the arc which cools it effectively. The high speed air blast is produced by externally generated pressure (inside a pressure vessel), the pressure being of the order of 2-6 MN/m².

The ABCB is designed to direct a jet of air derived from the high pressure source to the contact space at the instant of contact separation. One of the type of ABCB uses axial blast which uses a hollow contact which is used for high power circuit breakers. Here, cooling and extinguishing of arc takes place at the center of the arc.

Axial blast CB may cause current chopping to take place at low current although it is more efficient. But, since the contact spacing is small, voltage surges generated would be limited by restriking. For the short break to withstand recovery voltage after final arc extinction, a series isolating switch is provided, which opens automatically after the arc is extinguished. A permanently pressurized air blast circuit breaker is shown in Figure 7.12.

Here, the movement of contacts is controlled through a system of mechanical linkages from an operating mechanism at the base of the breaker and the contacts are held closed by a latch which is released by the trip signal, so that the contacts are free to move either mechanically or pneumatically or by a combination.

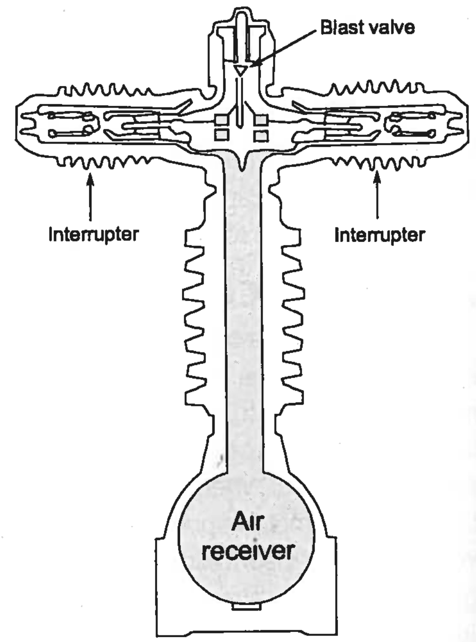


Figure-7.12 : Permanently pressurized ABCB

Remember

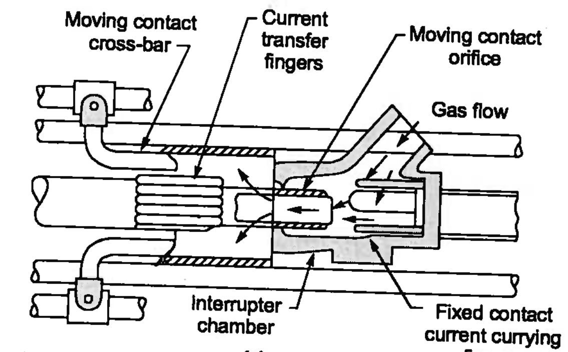
- For EHV ABCBs, interrupters are used in series (in a modern 275 kV ABCB, four interrupters are used in series).
- On every interrupter a parallel resistor is mounted to limit the rate of rise of recovery voltage.
- For each interrupter a capacitor is connected in parallel with it for voltage grading (equalizing voltages across the series interrupters).
- **Advantages of ABCBs:**
  - ⇒ No risk of explosion and fire hazard.
  - ⇒ It can be used for high speed and repeated duty of operation (because compressed air is supplied fresh at each operation).
  - ⇒ Due to less arc energy buring of contacts is less compared to OCB.
  - ⇒ It require less maintenance.
  - ⇒ It provides facility of high speed reclosure.
- **Disadvantages of ABCBs:**
  - ⇒ Compressor plant is required for compressed air.
  - ⇒ It is very sensitive to restriking voltage.
  - ⇒ More severe current chopping occurs in these type of breakers.
  - ⇒ There is possibility of leakage of air at the fittings of the pipe line.
  - ⇒ High air noise occurs which makes it unsuitable for urban areas.
- The air blast circuit breakers uses compressed air at a pressure of around 30 kg/cm^2 for arc extinction.
- **Application of ABCBs:** ABCBs are used for EHV and UHV applications (upto 400 kV).

7.14 SF_6 Circuit Breakers

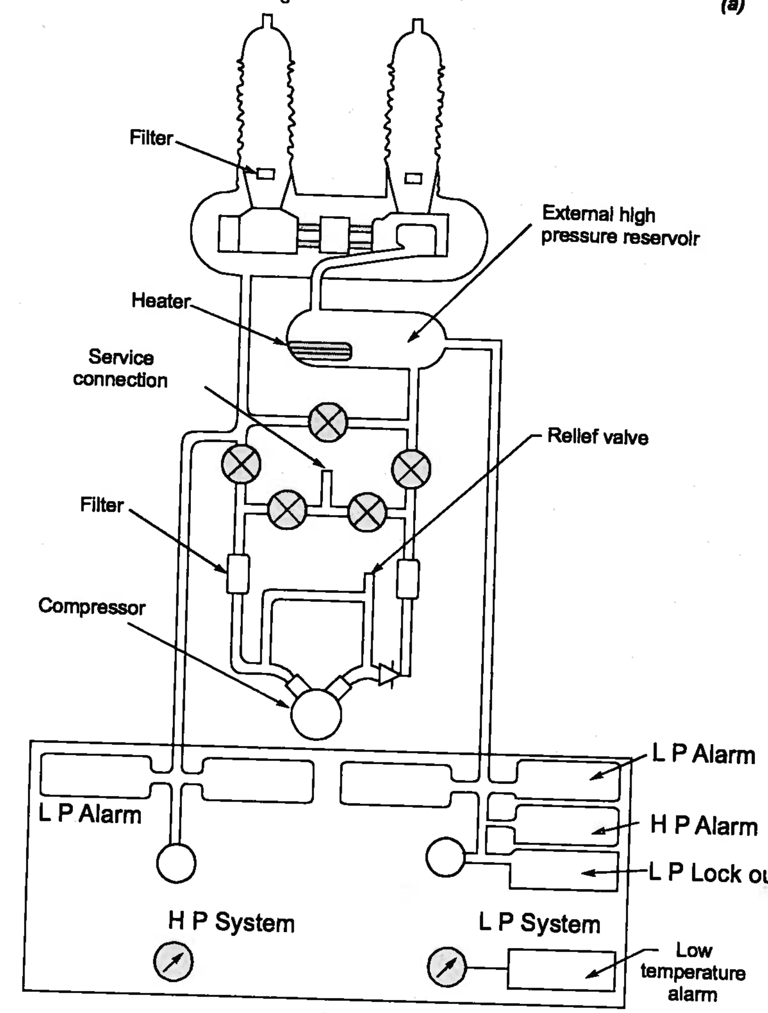
Sulphur Hexa Fluoride (SF_6) gas has the following properties which makes it superior to other mediums such as oil and air for use in circuit breakers.

- It is a heavy chemically inert non-toxic non-inflammable gas.
- It has a very high dielectric strength (two to three times better than of air).
- Due to the excellent insulating properties of SF_6 gas, reduced electrical clearances are required.
- Its heat transfer property is about 1.6 times of that of air owing to it's high density.
- Due to the small thermal time constant of SF_6, it can be stored at a relatively smaller pressure than that of air.
- Due to it's electronegatively property, its molecules rapidly absorb free electrons in the arc path forming heavy slow moving negative ions, which are ineffective as current carries. Due to this reason it has a superior arc quenching ability.
- Its arc time constant is in few μs.

In these type of CBs, the gas blast speeds need not be as high as in ABCB. Here, the gas is hermetically sealed inside the breaker body at a pressure of about 3 atm. Using a ***"puffer mechanism"***, high pressure is obtained which is required for generating the gas blast of sufficient speed. Figure 7.13 shows the basic construction of a SF_6 circuit breaker.



(a)



(b)

Figure-7.13 : SF_6 Circuit breaker

There are two basic parts of a SF_6 circuit breakers which are as follows:

1. **The interrupter:** It consists of two contacts one fixed and another moving. These contacts are surrounded by interrupting nozzles and a blast shield to control the arc displacement. When the moving contact is withdrawn, an arc is drawn between the nozzles and arcing probe, which is quenched by the gas flow from the high pressure to the low pressure system.
2. **The gas system:** It consists and deals with gas only. It uses a compressor to maintain the required pressure and a heater backed with a thermostat set at 16°C to prevent the liquidification of gas. Here, the closed gas cycle system is used as shown in Figure 7.13 (b).

Advantages of SF_6 CBs

- It gives a noiseless operation.
- Current chopping is minimum in SF_6 breakers.
- SF_6 gas has very high dielectric strength due to which electrical clearances are very much reduced.
- Its performance is independent of ambient conditions.
- Due to small arcing time it has an outstanding arc quenching properties resulting into less erosion of contact.
- Due to low gas velocity and pressure employed in SF_6 CBs, current chopping is prevented and capacitive currents are interrupted without restriking.
- No insulation tracking takes place.
- These CBs are non-inflammable and hence no fire-hazard problems.
- It's heat capacity below 6000°K is much larger than that of air and helps in continous cooling of the arc zone.

Applications of SF_6 Circuit Breakers

SF_6 circuit breakers are widely used in a voltage range of 6.6 kV to 765 kV and 20-60 kA rupturing capacity. These CBs are becoming more popular day-by-day.

Example - 7.7 The circuit breaker preferred when the current to be interrupted is low with high voltage arcs is

(a) oil circuit breaker
(b) air break circuit breaker
(c) minimum oil circuit breaker
(d) vaccum circuit breaker

Solution: (d)

When voltages are high and current to be interrupted is low, VCBs are used.

Example - 7.8 To minimize the current chopping tendency, the SF_6 gas is used at

(a) high velocity and low pressure
(b) log velocity and low pressure
(c) high velocity and high pressure
(d) low velocity and high pressure

Solution: (b)

Example - 7.9 Discuss the various advantages of a SF_6 breakers and write down it's applications.

Solution:

Refer to previous articles for explanation.

Example - 7.10 For a short line fault without switching resistor, the most suitable circuit breaker is

(a) Minimum oil circuit breaker
(b) SF_6 circuit breaker
(c) Air blast circuit breaker
(d) None of the above

Solution: (b)

In a SF_6 circuit breaker, the SF_6 gas is used at low velocity and low pressure due to which current chopping is prevented and capacitive currents are interrupted without restriking. Due to these reasons no switching resistor is required in these breakers. Hence, it is most suitable for short line fault without switching resistors.

Example - 7.11 In air blast circuit breaker for arc extinction

(a) an internal source of energy is required
(b) an external source of energy is required
(c) no any source of energy is required
(d) none of these

Solution: (b)

In an ABCB, high speed air blast is used for arc extinction which is produced by externally generated pressure (inside a vessel) i.e. an external source of energy is required for arc extinction.

Example - 7.12 Which of the following properties are associated with SF_6 circuit breakers?

1. At atmospheric pressure its dielectric strength is 2 to 3 times of air.
2. Its arc time is few μs.
3. Its molecules absorbs free electrons in the air path.
4. Its heat capacity below 6000°K is much larger than that of air.

(a) 1 and 3
(b) 2 and 3
(c) 3 and 4
(d) all of the above

Solution: (d)

Refer to the various properties of SF_6 CBs explained in previous article.

Example - 7.13 The capacitor switching is easily done with

(a) Oil C.B.
(b) ABCB
(c) Vaccum C.B.
(d) None of these

Solution: (c)

Example - 7.14 SF_6 gas has excellent heat transfer properties because of it's

(a) High molecular weight
(b) Low gaseous viscosity
(c) A combination of (a) and (b)
(d) None of these

Solution: (c)

Example - 7.15 The chances of interruption in subsequent current zeros.

(a) Increases in case of ABCB but decreases in OCB.
(b) Decreases in case of ABCB but increases in OCB.
(c) Decreases in both the cases.
(d) Increases in both the cases.

Solution: (b)

It is because current chopping is more severe in case of ABCB.

Example - 7.16 Explain the principle of operation of vaccum circuit breakers with neat figures and list advantages.

Solution:

Please refer to previous articles for complete solution.

7.15 Protective Relays

Whenever an abnormal condition occurs in an electrical power system, some action is required to isolate the abnormal condition instantaneously or after a predetermined time delay (in some cases) and leave the remainder in normal service. The protection provided by the fuse is limited to low voltage circuits. For higher voltages from 33 kV and above, the protection is provided using protective relay. When a fault occurs the relay operates to complete the trip coil circuit which results in the opening of the CB and therefore, faulty section is isolated from the rest of the system.

Some of the important features of a good protective relays/gear are as follows:

1. **Selectivity:** The property of discrimination is an absolute requirement of a protective gear i.e. the protective system must select correctly the faulty part of the system and disconnect the same without disturbing the rest part of the system.
2. **Sensitivity:** The protective system must be able to operate even for a low value of fault current i.e. it should be as sensitive as possible.
3. **Reliability:** The protective system must operate definitely under predetermined condition.
4. **Quickness:** The protective system must be capable to respond quickly in order to improve quality of service, increase safety of life and equipment and increase stability of operation.
5. **Non-interference with future extension:** The initial installation of the protective system should be such that future extension can be carried out if required without interfering the original one.

Types of Protection

There are mainly two types of protection provided for an equipment to be protected. They are:

1. **Primary protection:** It is the first line of defence and ensures quick acting and selective clearing of faults within the boundary of the circuit section or element it protects. It is provided for each section of an electrical installation.
2. **Back-up protection:** It is the second line of defence which function to isolate a faulty section of the system in case the main protection fails to function properly. Back-up protection is required because sometimes the associated CTs, PTs and circuit breakers of the protective scheme may fail to operate. It can be provided either on the same circuit breakers which would be normally opened by the main protection or by a second line of protection making use of different circuit breakers.

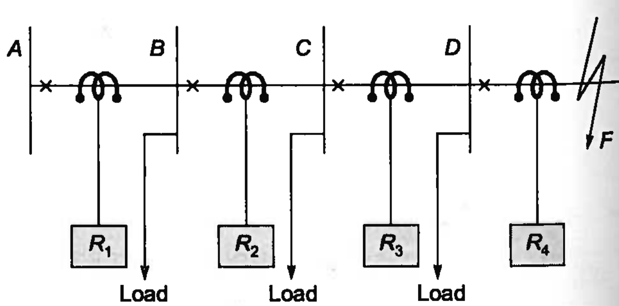


***Figure-7.14 :** Primary and Back-up protection scheme*

Figure the Figure 7.14 shown below, if a fault occurs at *F* then, the circuit breaker at *D* operates (for primary protection) and if anyhow *CB D* fails to operate then, the circuit breaker at *C* will operate (providing back-up protection) and will isolate the faulty section.

Protective Relays

The relay in power system protection ensures the safely of the circuit equipment from any damage which might be otherwise caused by the fault.

All the relays have three main fundamental elements as shown in Figure 7.15.

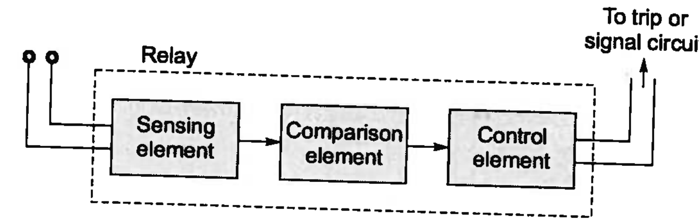


***Figure-7.15 :** Basic elements of a relay*

(*i*) **Sensing element:** It is also called measuring element which responds to the change in the actuating quality. For example current in a protected system in case of over current relay.

(*ii*) **Comparing element:** It compares the actuating quantity (i.e. current) with a pre-determined relay setting.

(*iii*) **Control element:** On pick-up of the relay, control element accomplishes a sudden change in the control quantity such as closing of the protective current circuit.

7.15.1 Definitions of Operation

Most of the relays are restrained by spring so that they are at a pre-determined position when completely de-energized. At this position if the status of the contact is closed, then it is said ***"Normally closed" (NC)*** contact and if it is open it is said to be ***"NO" (Normally open)*** contact. Some terms related to the operation of relay are as follows:

1. **Pick-up value:** The smallest value of the operating or actuating quantity for which the relay is at the verge of operation is called ***"pick-up"*** value of the relay.
2. **Reset value:** The largest value of the operating or actuating quantity for which the relay is at the verge of non-operation is called ***"reset value"*** of the relay.
3. **Operating time:** The time taken by the relay to operate the contacts is called the ***"operating time"*** of the relay.

7.15.2 Classification of Relay

The relays can be classified in different ways as follows:

1. **According to the time of operation:**

(*i*) **Instantaneous relay:** The operation of relay takes place after a very short duration of time (generally $t \leq 0.1$ sec).

(*ii*) **Definite minimum time relay (DMT):** The time of operation is fixed for these relays.

(*iii*) **Inverse time lag relay:** Time of operation is inversely proportional to the magnitude of the current or other operating quantity.

(*iv*) **Inverse definite minimum time lag relay (IDMT):** The time of operation is approximately inversely proportional to the smaller values of current or other quantity causing operation and tends to be a definite minimum time as the value increases without limit.

2. **According to construction and principle of operation:**
   (*i*) Attracted armature type:
      (a) **Attracted armature type:** In this type of relay operation depends on the movement of an armature under the influence of attractive force due to magnetic field set up by current flowing through the relay winding.
      (b) **Solenoid type relay:** Operation of relay depends on the movement of an iron plunger core along the axis of a solenoid.
   (*ii*) **Electro-magnetic induction type:** In this type of relay operation depends on the movement of a metallic disc or cylinder free to rotate by the inter-action of induced eddy currents and the alternating magnetic field.
   (*iii*) **Electro-dynamic type relay**
   (*iv*) **Moving coil type relay**
   (*v*) **Thermal type relay:** The movement depends upon the action of heat produced by the current flowing through the element of the relay.
3. **According to the applications:**
   (*i*) Over voltage or over current relay or over power relay
   (*ii*) Under voltage or under current relay or under power relay
   (*iii*) Directional or reverse current relay
   (*iv*) Directional or reverse power relay
   (*v*) Differential relay
   (*vi*) Distance relay
4. **Gas operated Buchholz relay:** It is used for the protection of oil immerged transformer from incipient fault or internal fault.
5. **Microprocessor based relay/Static relay:** Static relays are capable of performing the same functions with the use of electronic circuit control which an electro-magnetic relay performs with the use of moving parts or elements.

7.16 Induction Type Over Current Relay

The general relay equation from which the operation of over-current relay (also directional and distance relay) can be predicted is given by

$$Q = k_1|I|^2 + k_2|V|^2 + k_3|V||I|\cos(\theta - \tau) - k_4 \quad ...(1)$$

where,
$|I|$ = absolute value of current sample fed to relay
$|V|$ = absolute value of voltage sample fed to relay
θ = phase angle between V and I
τ = an adjustable parameter
k_1, k_2, k_3, k_4 = scalar constants

An over current relay operates if, the current through the relay satisfy the equation

$$Q = k_1|I|^2 - k_4 > 0 \qquad (k_2 = k_3 = 0)$$

or,
$$|I| > \sqrt{\frac{k_4}{k_1}} = |I_p| \quad \text{or} \quad |I| > |I_p| \qquad (|I_p| = \text{pick-up value of relay})$$

Hence, If $|I| > |I_p|$ .... relay will trip CB
If $|I| < |I_p|$ .... relay does't trip CB

Figure 7.16 shows a basic construction of an over current relay.

The relay has inverse time characteristic i.e. operating time decreases as the relay current increase approaching a definite minimum value.

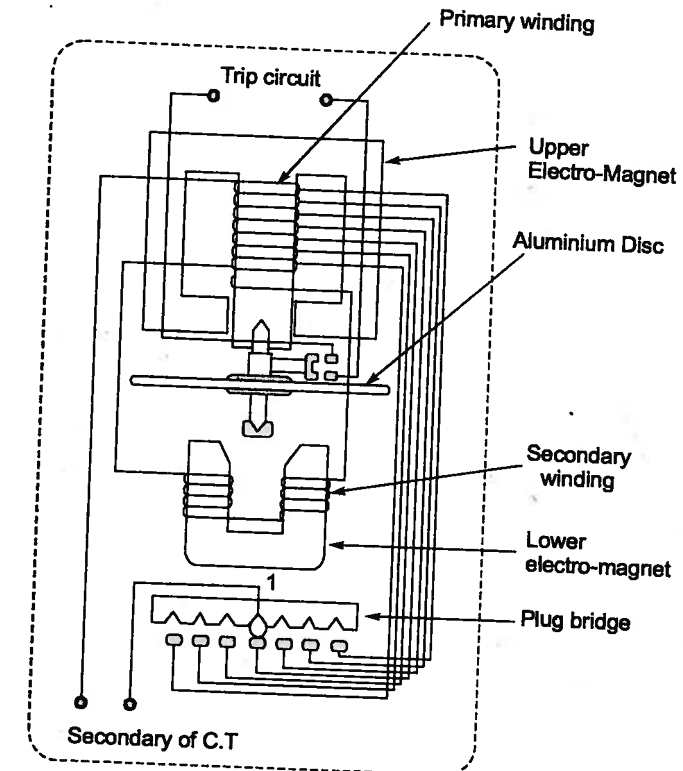


***Figure-7.16 :** An induction type over current relay*

Characteristic Curve

The current-time characteristic of an induction type over current relay is shown in Figure 7.17. This curve gives a relation between Plug Setting Multiplier (P.S.M.) along x-axis and operating time along y-axis.

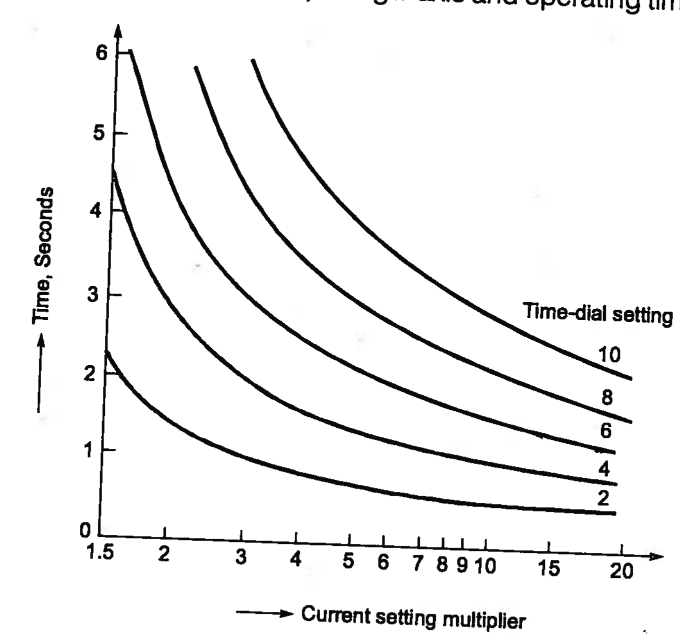


***Figure-7.17 :** Current-time characteristic of an induction relay*

The various parameters relating to the characteristic are defined as follows:

Plug Setting (PS): The value of pick-up current can be adjusted by altering the constant k_1 by means of ***"Plug Setting"*** (PS) also known as ***"tap setting"***. The plug setting current ***(pick-up current)*** is expressed as % of relays current rating (5 A or 1 A).

Plug setting multiplier (PSM):

- Plug setting multiplier is the ratio of fault current to the relay operating current.
- It is defined as the number of times the relay current is in excess of current setting.
- Corresponding to the PSM value, the operating time is determined from the current-time characteristic of the relay.

Mathematically,

Relay operating current = (Current setting × CT secondary rated current) ***(w.r.t. secondary of CT)***

or

Relay operating current = (Current setting × CT ratio × CT secondary rated current) ***(w.r.t. primary of CT)***

The minimum condition for the relay to operate is

Fault current (I_f) > rated current

Now, plug setting multiplier is given by

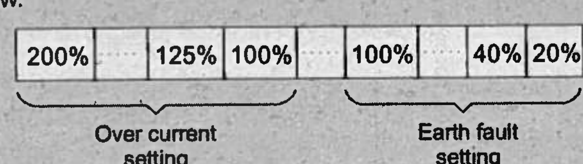
$$\text{PSM} = \left(\frac{\text{Fault current } (I_f)}{\text{Relay operating current}}\right) = \left(\frac{I_f}{\text{CS} \times (\text{CT secondary rated current}) \times \text{CT ratio}}\right) \quad \textit{(CS = current setting)}$$

Time-multiplier setting (TMS): The operating time of an IDMTL ***(inverse definite minimum time lag)*** relay is adjusted by using time multiplier setting (TMS).

Mathematically, $$\left[\text{TMS required} = \left(\frac{t_{\text{required}}}{t_{\text{TMS}=1}}\right)\right]$$

NOTE

- From the above equation of PSM, it is clear that higher the fault current, higher will be PSM and lower the operating time of the relay.
- The TMS of the primary relay is always less than the back-up relay whereas the PSM of primary relay should be greater than the PSM of back-up relay.
- The various current settings practically used for an induction type over current relay are shown below.



(Current setting for an over current relay)

7.16.1 Over Current Protection of Radial Feeder

In radial system number of feeders are connected in series as shown in Figure 7.18. When providing the over current protection for radial feeder when fault occurs then, it is desired that smallest possible part of the system should be off and the remaining part should be healthy. If the interruptions are less then, reliability will be more. This is achieved by the following three methods.

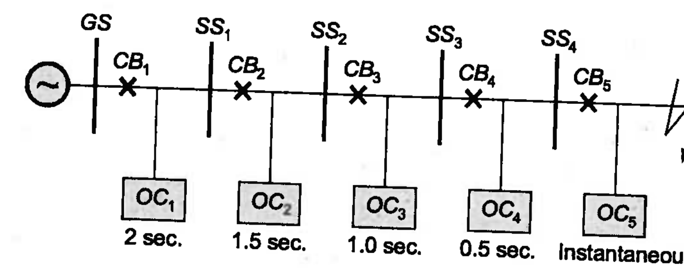


Figure-7.18 : Radial Feeder

1. **Time graded method:** According to time graded method the time of operation depends on the severity of fault. For severe fault the time of operation should automatically be less. The relay fartest from the source have minimum setting of TMS. As one approaches towards the source TMS is gradually increased. Hence, in Figure 7.18, relay OC_1 will have maximum TMS setting while relay OC_5 will have minimum TMS setting. The time-graded relays when connected in series require that their time-current characteristics should be similar in shape.
   The disadvantage of this method is that minimum fault current is cleared in minimum time and maximum fault current is cleared in maximum time.
2. **Current graded method:** In this method the relay near to the source should have current setting set to maximum value and this value decreases as one moves from source to the far end. Hence, in Figure 7.18, relay OC_1 has maximum current setting while relay OC_5 has minimum current setting. If the fault occurs at F then, relay OC_1 is having lowest PSM among the other relay therefore, for minimum fault current it is taking maximum time. Now, if the fault takes place near relay OC_1 then, the fault current becomes abnormally high due to decrease in transmission line impedance as a result of which, relay OC_1 adjust PSM to a higher value thereby time of operation decreases.
   ⇒ The disadvantage of this method is that maximum four sections can be made in this method as current setting can be only 125%, 150%, 175% and 200%.
3. **Time-current graded method:**
   In this method, for the relay farthest from the source minimum TMS and current setting is set and as one approaches towards the source these settings gradually increases.

7.16.2 Induction Type Directional Over-current Relay

An induction type directional over-current relay provides directional features to the relay. The directional relay element is made as sensitive as possible to ensure positive operation.

The directional over-current relay operates only when

(*i*) the directional over-current is in reverse direction

(*ii*) current in the reverse direction exceeds the pre-set value and

(*iii*) excessive current (greater than pre-set value) persists for duration longer than its time setting.

In a directional relay,

$$Q = k_3|V||I|\cos(\theta - \tau) - k_4$$

(using previous standard equation and setting $k_1 = k_2 = 0$)

For small value of k_4, the relay will operate if,

$$Q = k_3|V||I|\cos(\theta - \tau) > 0$$

or, if $\cos(\theta - \tau) > 0$, relay trips CB

and if $\cos(\theta - \tau) < 0$, relay prevents CB to trip

The operating characteristic of such a relay in the complex plane is shown in Figure 7.19. For the power system shown in Figure 7.20, the relay will operate for fault to the left of bus-2 (current I_{21}) and will block for fault occuring to the right of bus-2 (current I_{21}). Thus, the directional relay has the ability to discriminate between a fault on the protected zone and that outside it.

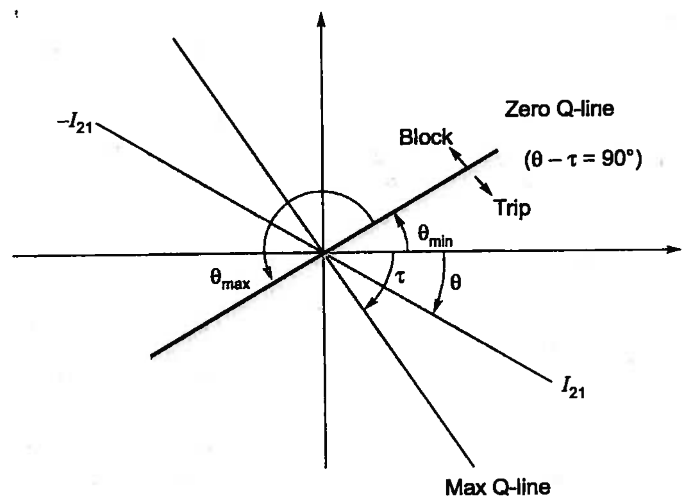


Figure-7.19 : *Operating characteristic of a directional relay*

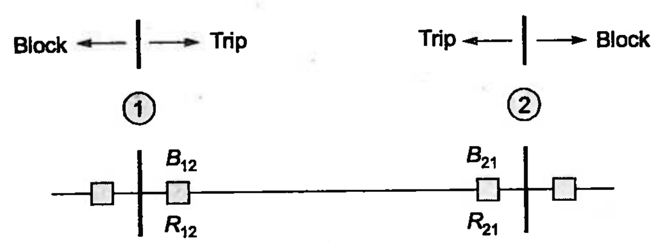


Figure-7.20 : *Applications of directional relay*

The relay characteristic for Figure 7.19 can also be expressed by the inequalities as follows:

if $\theta_{max} < \theta < \theta_{min}$, relay trip CB

and if $\theta_{min} < \theta < \theta_{max}$, relay block CB

Directional over current relays are used for the over current protection of parallel lines (feeders) and protection of ring-main feeders, since fault current can flow in either direction. These two protection have been covered in detail as follows.

7.16.3 Over-current Protection of Parallel Feeders

Special means are used for the protection of parallel feeders as shown in Figure 7.21. For the protection of parallel feeders, if a fault occurs in one feeder, then the protective device must select and isolate the defective feeder while the healthy feeder must be available to supply power to the load. For the Figure 7.21 shown below two feeders are connected in parallel to increase the transmission capacity. The feeders are fed from only one end while at the other end load is connected.

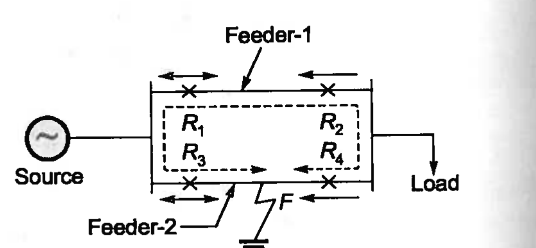


Figure-7.21 : *Over-current protection of parallel feeders*

When a fault occurs at a feeder (Say 2), the fault current will be fed with the direction shown in Figure 7.21. If can be seen that as far as the relays near the source are concerned, the direction of current is same as the normal direction of the current, whereas the direction of the current in the relay near the load end of the faulty feeder is reversed. Therefore, for proper coordination the relays near the source-end are non-directional relays whereas relays near the load-end are directional relays. The direction of the current for which the directional relays will operate is indicated by the corresponding arrows heads. As soon as the fault takes place in feeder-2, the directional relay in feeder-2 will operate first; thereby the current in feeder-1 corresponds to load current and after some time the non-directional relay in feeder-2 will operate, thereby isolating feeder-2 from the source.

7.16.4 Over-current Protection of Ring-main Feeder

The ring main is a system of interconnection between a series of power stations by an alternative route.

The basis scheme of such a system is shown in Figure 7.22. Here, the ring main feeder is divided into five sections and fed at one point which has to be protected using directional over current relays and over current relays. Let us assume a time grading of 5 ms between the relays. The fartest relays from the source takes 5 ms to operate. The buses are numbered from (1) to (5).

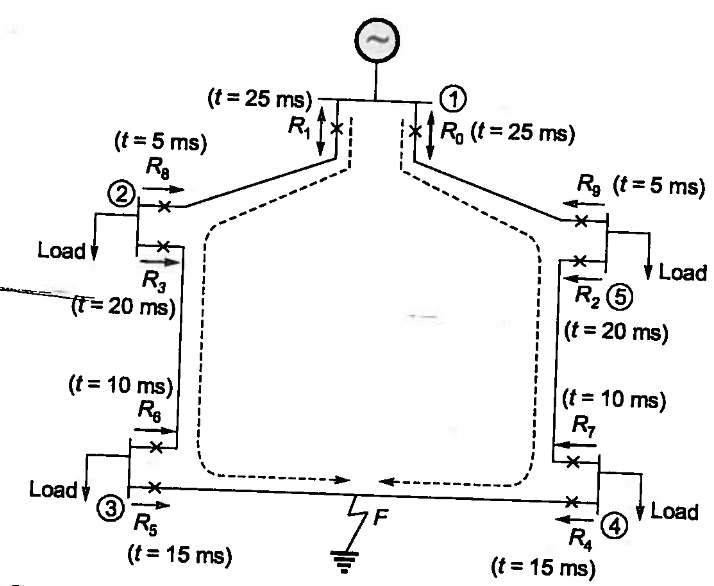
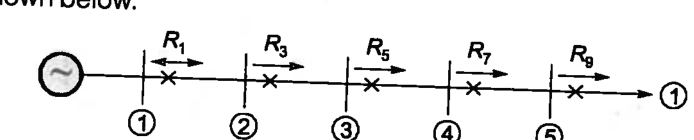


Figure-7.22 : *Over current protection of ring-main feeder with five sections fed at one end*

- Relay R_0 and R_1 near to the source are non-directional over-current relays and relays R_2, R_3, R_4, R_5, R_6, R_7, R_8 and R_9 are directional over-current relays.

  Let a fault occurs at F as shown in figure above. Now, the ring can be opened at bus (1) and is spread as shown below.



- Here, relay R_9 which is farthest from the source require minimum time (t = 5 ms) to operate. Relay R_1 which is nearest to the source takes maximum time (t = 25 ms) to operate.

Now, for the fault at point F indicated in figure, the relays R_1, R_3, R_5, R_0, R_2 and R_4 will start moving. As among R_1, R_3 and R_5, relay R_5 has minimum time set (15 ms) therefore, it will operate first. Also, among relays R_0, R_2 and R_4, relay R_6 has minimum time (t = 15 ms) therefore, relay R_4 will operate first and the relays R_0 and R_2 will reset.

After the operation of relays R_4 and R_5 the faulty section between bus ③ and ④ get isolated and power is still supplied to the other loads or healthy section.

Limitations

The limitation of this method of protection is that maximum six sections can be protected.

7.16.5 Over-current Protection of Generators

For a generator, over-current protection has to be provided for three types of possible faults. They are:

1. Protection from earth faults (LG or LLG fault)
2. Protection from phase faults (LL faults or three-phase fault)
3. Protection from unbalanced faults.

For the complete over-current protection of generator, we require two over-current relays and one earth fault relay as shown in Figure 7.23.

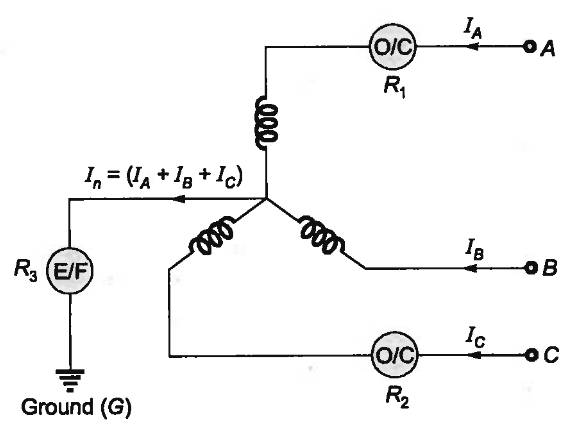


***Figure-7.23 :** Over-current protection of generator*

Here, R_1 and R_2 are over-current relays and R_3 is an earth fault relay. The operation of the relay for different faults mentioned above are listed in the table below.

Type of fault		Relay which operates
Double line to ground fault (LLG)	ABG	R_1 and R_3
	BCG	R_2 and R_3
	ACG	R_1, R_2 and R_3
Line-to-line fault (LL fault)	AB	R_1
	BC	R_2
	CA	R_1 and R_2
Line-to-ground fault (LG ground)	A	R_1 and R_3
	B	R_3
	C	R_2 and R_3
Three-phase fault	3-ϕ fault	R_1 and R_2
Severe-unbalanced condition		R_3

***Table-7.1 :** Over-current protection of generator for different type of faults*

7.17 Protection Against Inter-turn Faults on Stator Winding of Generator

Inter-turn protection is employed for multi-turn large hydro-electric generators since the coil of modern large steam-turbine generators are usually single turn and hence don't require turn-to-turn protection.

In this scheme of protection, the circuit is divided into two equal parallel groups with a CT for each group as shown in Figure 7.24. If there is a fault, currents flowing through the stator windings S_1 and S_2 are equal, the currents in the secondaries of two CTs will be equal and therefore, no current will flow through the operating coil of the relay. When a short-circuit fault between adjacent turns, say of stator winding S_1 develops, the current flowing through the stator windings will be different and a current proportional to the difference of the two current will flow through the relay operating coil which will close the trip circuit and isolate the alternator from the power system. In this way inter-turn protection for alternator is provided

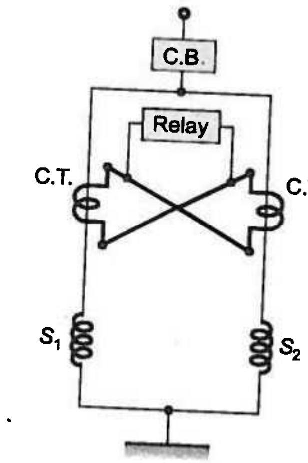


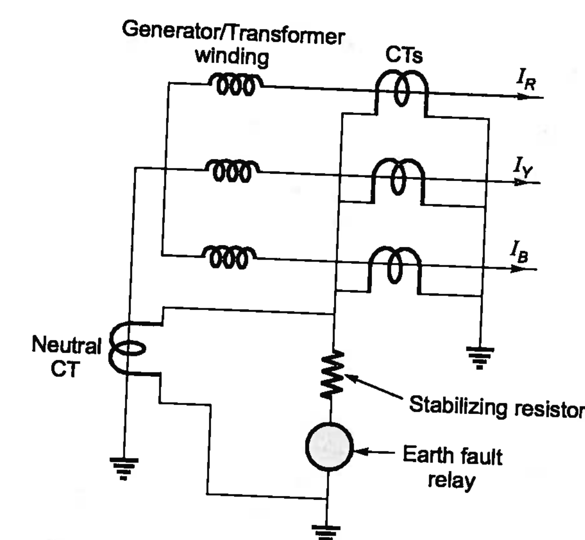
***Figure-7.24 :** Protection of alternator from inter-turn fault*

7.18 Restricted Earth Fault Protection

Earth fault relays connected in residual circuits of line. CTs protection provide protection against earth fault on the delta or unearthed star-connected windings of power transformers.

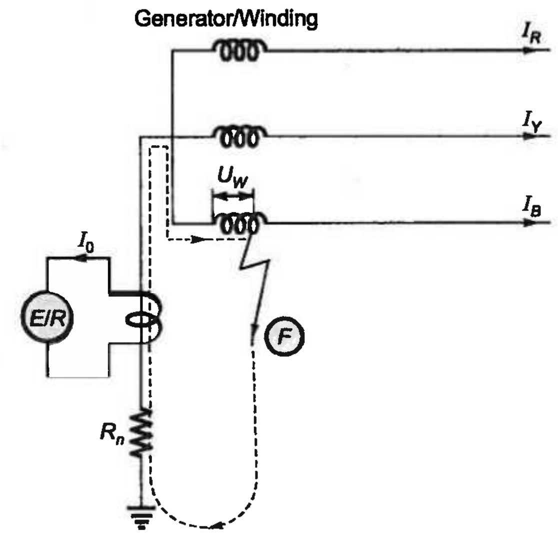
The output of CTs is proportional to the sum of zero sequence currents in the line and the neutral earth connection. For internal faults, the sum of zero sequence currents is equal to twice the total fault current.

For external faults, zero sequence currents are either absent or sum to zero in the line and neutral earth connection.



For earth fault near the neutral point of the transformer the voltage available for driving earth fault current is small. For the relay to sense such fault, it has to be the sensitive. Hence the relay is set as per practice so as to operate for earth current of the order of 15% of rated winding current. Such setting protect restricted portion of the winding so it is called **restricted earth fault protection.**

The stabilizing resistor is connected in series with the relay to avoid magnetizing inrush current and also saturation of CT core.



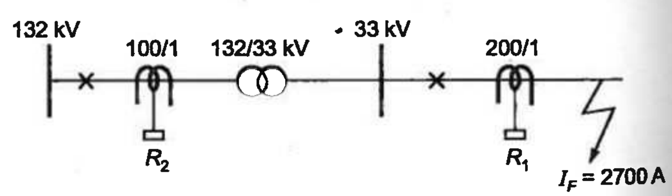
I_0 = Pick up current of relay × CT ratio
R_n = Neutral resistance
V_{ph} = Phase voltage

$$\boxed{\%U_W = \frac{I_0 R_n}{V_{ph}}}$$ ...(Percentage of unprotected winding of generator)

$$\boxed{\%P_W = 100 - \%U_W}$$ ...(Percentage of protected winding of generator)

NOTE: If CT ratio is not given then take I_0 = pick up current of relay.

Example - 7.17 **For the figure shown below, fault current level at 33 kV side is 2700 A; CT ratio at 33 kV side is 200 : 1 and 132 kV side is 100 : 1. If both the relays R_1 and R_2 are set for 100% plug setting, determine the operating time for both the relays when time grading margin of 0.6 second is given and TMS for relay R_1 is 0.15. (Given, operating time corresponding to PSM of 13.5 is 2.8 seconds and that for PSM of 6.75 is 4.2 seconds respectively).**



Solution:

Here, fault current in relay R_1 is

$$I_{R_1} = \frac{2700 \times 1}{200} = 13.5\text{ A}$$

Now, Relay operating current = CS × relay rated current

$$= \frac{100}{100} \times 1 = 1\text{ A}$$

$$\therefore \quad \text{PSM} = \frac{I_{R_1}}{\text{Relay operating current}} = \frac{13.5}{\left(\frac{100}{100} \times 1\right)} = 13.5 \quad \text{(As CS of } R_1 = 100\%\text{)}$$

Since, operating time corresponding to a PSM of 13.5 is 2.8,

∴ actual operating time of relay R_1 (t_{R_1}) = 0.15 × 2.8 = 0.42 second.

Also, on 132 kV side, the fault current is

$$I_f = 2700 \times \frac{33}{132} = 675\text{ A}$$

∴ fault current in relay R_2 is $I_{R_2} = \frac{675 \times 1}{100} = 6.75\text{ A}$

$$\therefore \quad \text{PSM for this current} = \frac{I_{R_2}}{\text{Relay operating current}} = \frac{I_{R_2}}{\text{CS} \times \text{relay rated current}}$$

$$= \frac{6.75}{\frac{100}{100} \times 1} = 6.75$$

Since operating time corresponding to a PSM of 6.75 is 4.2 and as the relay R_2 should operate 0.6 seconds after the operation of relay R_1 therefore, operating time of relay R_2 is

$$t_{R_2} = 0.42 + 0.6 = 1.02 \text{ second}$$

Also, TMS for relay $R_2 = \frac{1.02}{4.2} = 0.25$

Example - 7.18 **If the fault current is 2000 amps, the relay setting 50% and the CT ratio is 400/5, then the plug setting multiplier will be**

(a) 25 amps
(b) 15 amps
(c) 50 amps
(d) none of these

Solution: (d)

Relay operating current = CS × CT secondary rated current × CT ratio

$$= \frac{50}{100} \times 5 \times \frac{400}{5} = \frac{1}{2} \times 400 = 200$$

Fault current, $I_f = 2000$ A

$$\therefore \quad \text{PSM} = \left(\frac{I_f}{\text{Operating current of relay}}\right) = \left(\frac{2000}{200}\right) = 10$$

Example - 7.19 **If the time of operation of a relay for unity TMS is 10 seconds, the time of operation for 0.5 TMS will be**

(a) 20 secs
(b) 5 secs
(c) 10 secs
(d) None of the above

Solution: (b)

We know that, $(\text{TMS})_{required} = \frac{t_{required}}{t_{\text{TMS}=1}}$

$$\therefore \quad \frac{(\text{TMS})_2}{(\text{TMS})_1} = \frac{t_2}{t_1} \quad \text{or} \quad t_2 = \left(\frac{\text{TMS}_2}{\text{TMS}_1}\right) \times t_1 = 10 \times \frac{0.5}{1} = 5 \text{ seconds}$$

Hence, required time of operation = 5 seconds.

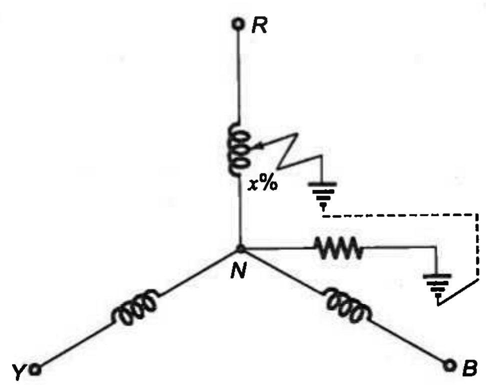
Example - 7.20 For protection of parallel feeders fed from one end the relays required are:

(a) Non-directional relays at the source end and directional relays at the load end.
(b) Non-directional relays at both ends.
(c) Directional relays at both the ends.
(d) Directional relays at the source end and non-directional at the load-end.

Solution: (d)

Example - 7.21 A 13.8 kV, 125 MVA, star-connected alternator has a synchronous reactance of 1.4 pu per phase and a negligible resistance. It is protected by a Merz-price balanced current system which operates when out of balance current exceeds 10% of the full-load current. If the neutral point is earthed through a resistance of 2 Ω, determine what proportion of winding is protected against earth fault.

Solution:



Let x% of the winding be unprotected.

Voltage per phase is, $V_{ph} = \frac{13.8 \times 10^3}{\sqrt{3}} = 7.967$ kV

Full load current is, $I = \frac{\text{MVA}}{\sqrt{3} V_L} = \frac{125 \times 10^6}{\sqrt{3} \times 13800} = 5.23$ kA

Reactance per phase is, $X = \left(\frac{V_{ph}}{I}\right) \times (\text{reactance pu}) = \frac{7.969 \times 10^3}{5230} \times 1.4 = 2.133\,\Omega$

Emf induced in unprotected winding $= 7967 \times \frac{x}{100} = 79.67x$ volts

Earth fault current caused by unprotected winding $= I \times \frac{10}{100} = 5230 \times \frac{10}{100} = 523$ A

$$\text{Earth impedance} = \frac{\text{emf induced}}{\text{Earth fault current}} = \frac{79.67x}{523}\,\Omega = 0.1523x\,\Omega$$

Reactance of unprotected winding $= \frac{x \times X_{(\text{reactance})}}{100} = \frac{x}{100} \times 2.133 = 0.02133x\,\Omega$

$\therefore$ Earth resistance is, $R = 2\,\Omega$

Since (Earth impedance) $= \sqrt{(\text{Earth resistance})^2 + (\text{Earth reactance})^2}$

$\therefore$ $0.1523x = \sqrt{(2)^2 + (0.02133x)^2}$ or $x = 13.26$

$\therefore$ Percentage of protected winding $= (100 - 13.26)\% = 86.74\%$

7.19 Differential Protection

Differential protection is provided with the help of a differential relay.

Principle of Operation of a Differential Relay

- A differential relay is a relay which operates when the phase difference of two or more similar electrical quantities exceeds a pre-determined amount or value.
- It is basically a suitably connected over-current relay.
- A differential relay operates only for a internal fault.

Let us consider the Figure 7.25 which is used for the differential protection of the phase winding of a generator.

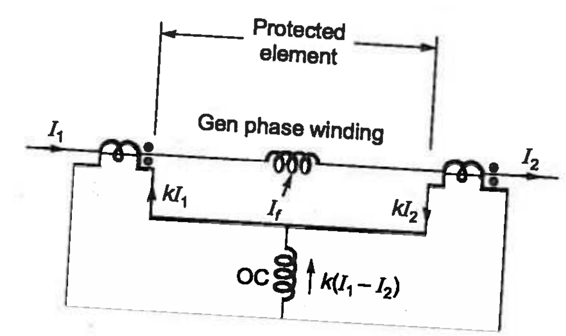


***Figure-7.25 :** A differential relay used for protection of generator phase winding*

Now, if a fault occurs outside the protected element (through fault), the current I_1 becomes equal to I_2 so that $(I_1 = I_2) = 0$ and hence, differential relay does not operates.

Also, if a fault occurs on the generator winding, then

$$I_1 - I_2 = I_f$$

and the relay operates to protect the element when

$$k|I_1 - I_2| = k|I_f| > |I_p|$$

(where, k = current transformation ratio of the two CTs)

NOTE

Practically, no two CTs are exactly identical. Their CT ratios may be same but, saturations levels are different. In addition to this, ratio error and phase fault errors produces different CT secondary currents for the same primary current. Due to these reasons in case of a through fault, I_1 and I_2 though are equal and abnormally high causes the CT ratio to change, such that $k_1 \neq k_2$ and the relay operates even though there is no fault on the generator windings (i.e. $I_1 = I_2$).

To prevent this problem, the differential relay is restrained by means of the sum of currents and the scheme employing this feature is called a ***"percentage differential relay"***.

7.19.1 Percentage Differential Protection

Pilot

Pilot is a communication channel between source and load for communicating electrical signal like current, voltage, frequency, radio signal etc.

Through Fault

The fault outside the protection zone of the unit protection relay is called through fault.

Relay should not operate for the through fault.

Difficulties of the Ordinary Differential Relay

In some case, the differential relay operate for the through faults or even if there is no fault.

Reason-1:

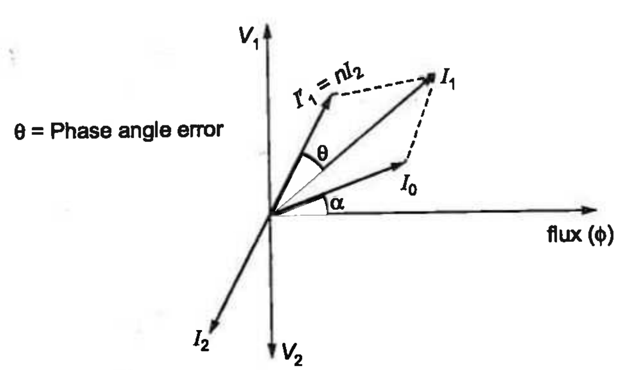
1. Saturation of CTs core.
2.. Different ratio and phase angle error for the CT_1 and CT_2.

Example:

I	i_1 CT_1 100/1 A	i_2 CT_2 100/1 A	$i_R = i_1 - i_2$	Remark
100	1	1	$1 - 1 = 0$ ←	Block
200	2	2	$2 - 2 = 0$ ←	Block
400	4	2 } Core saturate	$4 - 2 = 2$ ←	Trip
600	6	2 } Core saturate	$6 - 2 = 4$ ←	Trip

Ideal: $n = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

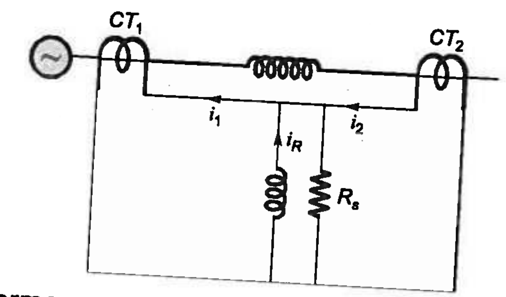
Practically, $\boxed{\frac{N_2}{N_1} = \frac{I_1}{I_2} + \frac{I_0}{I_2}}$



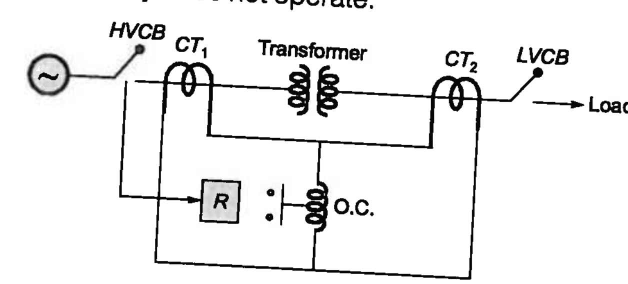
Due to no load component of current I_0, ratio and phase angle error occurs in the CTs. These error are different in CT_1 and CT_2 then there relay operate without faults or for through faults.

3. **Pilot wire wrong connection:**
If the pilot wire is wrongly connected on the one side of relay then the relay will operate. If both CTs pilot is reversed or wrongly connected then relay will not operate.

4. **Different length and resistance of the pilot wire:**
If the pilot wire having different length and resistance, potential across the relay coil is not equal to zero so that $i_R \neq 0$ and the relay will operate. For compensating this effect a stabilizing or compensating resistor is connected in series to the pilot wire which has low resistance so that voltage difference between the relay coil terminals is equal to zero. Hence, $i_R = 0$. Stabilizing resistor is considered as connected in parallel to the relay coil.



5. **Tap changing transformer:**
At the time of changing of on load tap changing transformer taps, the primary and secondary voltage of power transformer changes so that currents changes and hence C.T. currents also changes and hence after sometime results into maloperation of relay.
6. **Magnetic inrush current:**
At the time of transformer charging or connecting to the system.
At the time of initial charging of transformer the current is very high which is 5 to 10 times the full load current called magnetic in rush current due to this relay operate without fault. To compensate this effect, harmonic restraining relay is used which produces additional restraining torque for the operating coil of the relay so that relay does not operate.



Percentage Differential Relay

- The most extensively used form of differential relay is the percentage differential or biased beam relay as shown in Figure 7.26. This system consists of an additional restraining coil in which current induced in both CTs flows. The restraining coil is divided into two half halves.

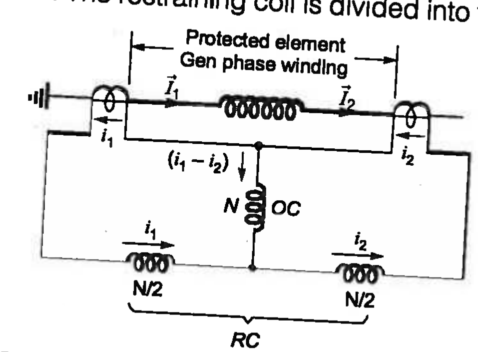


Figure-7.26 : *Percentage differential relay protecting generator phase winding*

- The differential current in the operating coil (OC) = $(i_1 - i_2)$ α operating torque and the restraining coil (RC) current $\alpha \left(\frac{i_1 + i_2}{2}\right)$ α restraining torque.

  The torque due to restraining coil prevents the closing of trip circuit contacts, while the torque due to operating coil tends to close the trip circuit contacts. Hence, this relay operates only for an internal fault.

  The operating characteristic of such a relay is shown in Figure 7.27

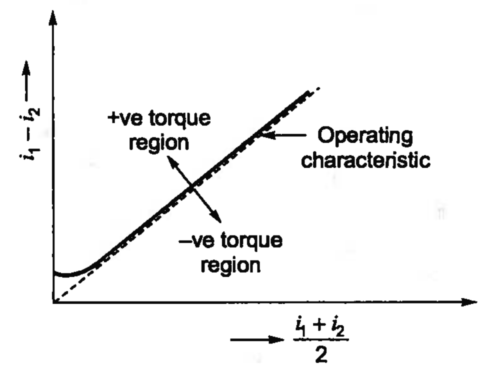


Figure-7.27 : *Operating characteristic of a percentage differential relay*

- The purpose of drawing the characteristic shown in Figure 7.27 is to determine for a given operating force the value of restraining force for which the relay is at the verge of operation. The ratio of the differential operating current to the average restraining current is a fixed percentage which is termed as percentage slope or bias of a percentage differential relay mathematically given by

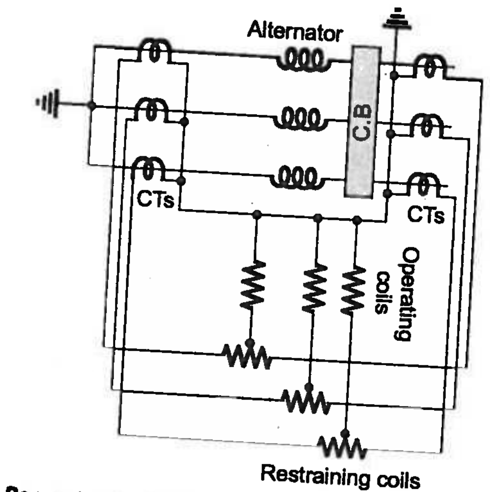
$$\% \text{ slope} = \frac{(i_1 - i_2)}{\left(\frac{i_1 + i_2}{2}\right)} \times 100$$

NOTE

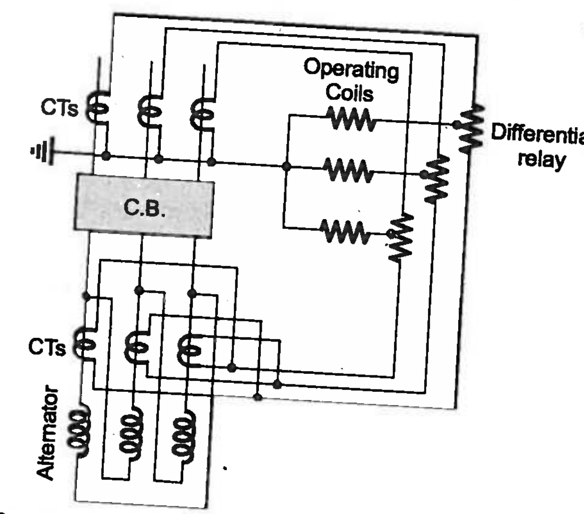
- A differential protection employing percentage differential relay is known as "***Merz price circulating current method***".
- The advantage of a percentage differential relay is that it is less likely to operate incorrectly than a differentially connected over current relay when a short circuit occurs externally to the protected zone.
- The sensitivity of percentage differential relay increases with the decrease in percentage slope.

7.19.2 Protection of Stator Winding by Percentage Differential Relays (Merz-price Protection System)

This method is the most common form of protection used for stator winding faults such as phase to phase or phase to ground short-circuit. Generally, differential protection is used for generators of rating 1 MVA or above and percentage differential protection for 10 MVA and above. Figure given below shows the arrangement of CTs and percentage differential relay for a star-connected machine and a delta-connected machine respectively.



Percentage differential relay for star connected machine



Percentage differential relay for delta connected machine

When there is no internal fault, the current at both the ends of each winding will be equal and therefore, the current in the two corresponding secondaries will also be equal, as the CTs are identical, and no current will flow through the relays. If fault in the stator winding occurs (due to phase to phase or phase to ground), the currents at the two ends of the stator windings become different so that the difference current in the two CT's secondaries flows through the relay which closes the trip circuit and isolate the alternator from the system.

7.19.3 Differential Protection of Transformers

- Differential protection for transformer is used to protect it from phase-to-phase and phase-to-earth fault. The principle of this protection is based on ***Merz-price circulating current principle*** in which the CT at each output terminals are balanced against each other. During an internal fault there is difference in the CT secondary current and due to which relay operates the circuit breaker.
- While providing differential protection for transformer, the matching CT is important because the currents entering and leaving the CT under fault and load condition differ in magnitude and phase angle due to voltage ratio and phase connection. The saturation factor of both CTs should also be identical. These things are important to avoid maloperation of relay.

  Figure 7.28 shows the connection of CTs for the differential protection of a star-delta transformer.

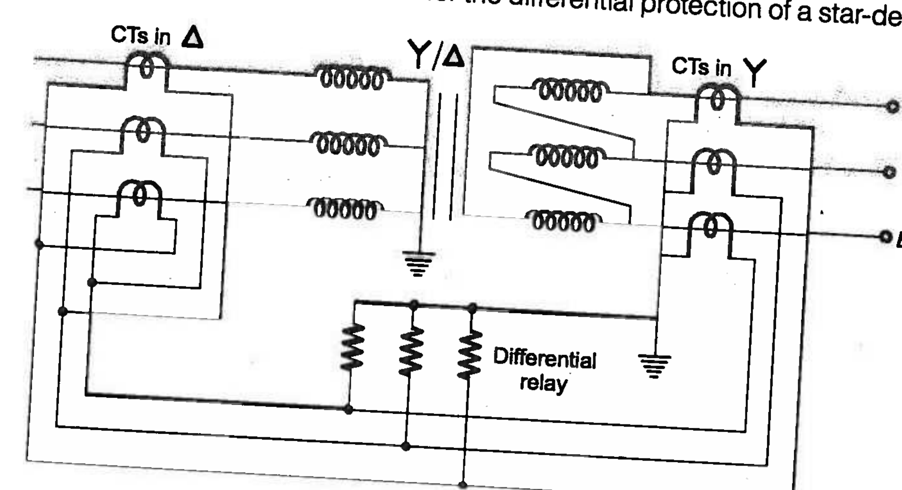


Figure -7.28 : *Differential protection of a star-delta three 3-ϕ transformer and connection of CTs*

For different power transformer connections, the CTs must be connected in the order as listed in Table 7.2 below.

S.No.	Power Transformers		Protection Transformers	
	Connection of primary	Connection of secondary	Connection on primary side in	Connection on secondary side in
1.	Star with neutral earthed	Delta	Delta	Star
2.	Delta	Star with neutral earthed	Star	Delta
3.	Star	Star with neutral earthed	Delta	Delta
4.	Delta	Delta	Star	Star

Table-7.2

7.20 Protection of Transformer Using Buchholz Relay

For the protection of transformer against internal faults, Buchholz relay is used. It is installed between the transformer and conservator and is used to give warning in case of less severe internal faults in oil immerged transformer and to disconnect the transformer from supply mains in case of severe internal faults. It is practically used in all oil immersed transformers having rating more than 750 kVA.

The construction of a Buchholz relay is shown in Figure 7.29. It consists of two elements mounted in a small chamber located in the pipe connection between the conservator and the transformer tank. When a fault occurs (internal fault), transformer oil evaporates and thus the oil level falls due to which the mercury type switch attached to the float is tilted so closes the alarm circuit and rings the bell.

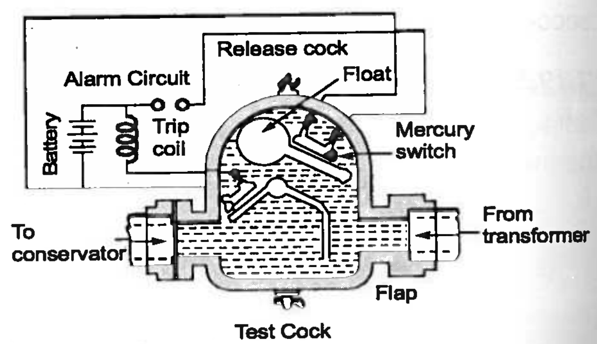


***Figure-7.29 :** Buchholz relay*

7.21 Protection of Alternators

The major faults occuring in an alternator and the protection used have been described as follows:

1. **Failure of prime mover:** If the steam input to a turbo-generator fails then, the alternator continue running as a synchronous motor and draws only a small fraction of full load power from the supply system. It remain in synchronism and operate as an alternator when steam supply is restored, therefore, no protection is required against failure of prime mover. Similarly, no protection is required for a hydro-generator since here mechanical protection is provided to disconnect the generator from the system.
2. **Loss of excitation:** When a generator losses excitation, it draws reactive power from the system upto an extent of 2 to 3 times the generator's rated load and starts acting as an induction generator. Due to the loss of excitation, heavy currents are induced in the rotor teeth and wedges. This large reactive load suddenly thrown on the system together with the loss of generator's reactive power output may cause wide spread voltage reduction which in turn may cause extensive instablity. To protect the generator against loss of excitation directional distance relay operated from alternating current and voltage at the generator's terminals is used.
3. **Over-current:** It is not necessary to provide protection against over-current generally as modern alternators are capable of withstanding their complete short-circuit current for sufficient time without serious overheating or damage.
4. **Over-speed:** To protect the transformer against over-speeding, some form of over-speed device usually an ***over frequency relay*** is used.
5. **Over-voltage:** The protection against over-voltage has two units:
   (*i*) An instantaneous relay set for pick-up at about 130-160% of rated voltage.
   (*ii*) An IDMT relay set for pick-up at about 108% of rated voltage.
6. **Unbalanced loading:** Unbalanced operation of stator causes rotor overheating because of second harmonic field current induced by negative sequence rotating field. Protection against unbalanced loading is provided by means of over current relays used in conjuction with sequence filters sensitive to negative sequence voltages/currents.
7. **Failure of insulation:** Failure of insulation can cause:
   (*i*) Fault between phases
   (*ii*) Fault between phase and ground
   (*iii*) Fault on turns on the same phase winding
   Usually differential protection is provided for protection against failure of insulation which has already been discussed in the previous article.

7.22 Power Line Carrier Communication (PLCC)

The reliable and fast communication is necessary for safe, efficient and economic power supply. As the power lines can serve a very reliable physical path for communication therefore, power line communication is found to be the most economical and reliable system of communication. In PLCC, the power lines are utilized as communication media.

PLCC serves the following purposes:

(*i*) Remote control
(*ii*) Telephony
(*iii*) Telemetering
(*iv*) Tele-protection
(*v*) Teleprinting

Remember

- All types of information to be sent to the other end of power line are modulated on carrier wave of high frequency of the order of 50-500 kHz. At receiving end this signal is filtered out with the help of L-C filters.
- **Line trap/wave trap:** Line trap is basically an inductor which offers high impedance for carrier signal and low impedance for power signal. It blocks the carrier signal and bypass the power signal.
- **Coupling capacitor:** offers high impedance for power signals and low impedance for carrier signal. They bypasses carrier signal but blocks the power signal.

Example - 7.22 **A Buchholz relay is used for**

(a) transformer
(b) alternator
(c) induction motor
(d) HVDC line

Solution: (a)

Example - 7.23 While energizing a transformer, to prevent the maloperation of a differentially connected relay, the relay restrained coil is biased with

(a) third harmonic current (b) second harmonic current
(c) seventh harmonic current (d) fifth harmonic current

Solution: (b)

Example - 7.24 The frequency of the carrier in the case of carrier current-pilot scheme is in the range of

(a) 1 kHz to 10 kHz (b) 15 kHz to 25 kHz
(c) 25 kHz to 50 kHz (d) 50 kHz to 500 kHz

Solution: (d)

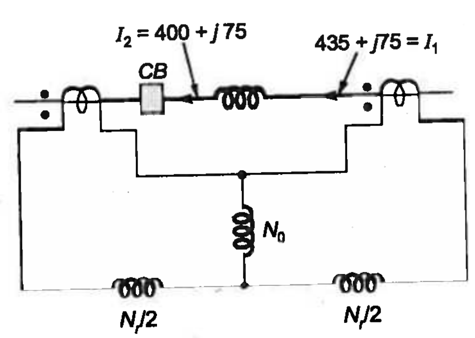
Example - 7.25 For a 3-phase line, complete protection is provided by

(a) three-phase and two-earth fault relays
(b) two-phase and three-earth fault relays
(c) two-phase and one-earth fault relays
(d) two-phase and two-earth fault relays are required

Solution: (c)

Example - 7.26 The given figure shows the connections of a percentage differential relay to protect one phase of a generator. A high resistance fault occurs near the neutral end with the current distribution as shown in figure. The relay has a slope of 10% i.e. $N_r/N_0 = 0.1$ and a pick up of 0.15 A. The CT ratio is 500/5.

(*i*) Would the relay operate under conditions indicated in the figure?
(*ii*) Would the relay operate if this fault were to occur under no-load condition?



Solution:

Given that, C.T ratio $= \frac{500}{5}$

$$k = \text{slope} = \frac{N_r}{N_0} = 0.1 \text{ or } 10\%$$

$$\text{Pickup current} = i_0 = 0.15 \text{ A}$$

Relay operating coil current, $i_R = i_1 - i_2$

$$\text{Relay restraining coil-current} = \frac{i_1 + i_2}{2}$$

Condition:

If, $i_R > k\left(\frac{i_1 + i_2}{2}\right) + i_0 \rightarrow$ Relay will operate

$i_R < k\left(\frac{i_1 + i_2}{2}\right) + i_0 \rightarrow$ Relay will not operate

Both the C.T ratio $= \frac{500}{5}$

$$i_1 = \frac{I_1}{(\text{C.T ratio})_1} = \frac{435}{500/5} \text{A}$$

$$i_2 = \frac{I_2}{(\text{C.T ratio})_2} = \frac{400}{500/5} \text{A}$$

$$i_1 - i_2 = 4.35 - 4 = 0.35 \text{ A}$$

$$\frac{i_1 + i_2}{2} = \frac{8.35}{2} = 4.175 \text{ A}$$

$$k\left(\frac{i_1 + i_2}{2}\right) = 0.1 \times 4.175 = 0.4175 \text{ A}$$

$$k\left(\frac{i_1 + i_2}{2}\right) + i_0 = 0.4175 + 0.15 = 0.5675 \text{ A}$$

$$i_R < k\left(\frac{i_1 + i_2}{2}\right) + i_0 \quad \text{i.e. relay will not operate}$$

Example - 7.27 A 40 MVA, 3-phase, 345/34.5 kV transformer is star/delta connected. Select standard CT ratios on the two sides of the transformer for percentage differential protection of the transformer. Would an autotransformer be required? If so, what would be it's current rating?

Solution:

The CT connections for a star-delta transformer will be as shown in Figure 7.28 of the previous article i.e. CTs will be delta-star connected.

Now, line current on the star-side (345 kV) $= \frac{40 \times 10^3}{\sqrt{3} \times 345} = 66.9$ A or 66.94 A

line current on the delta-side (34.5 kV) $= \frac{40 \times 10^3}{\sqrt{3} \times 34.5} = 669$ A or 669.4 A

Choosing a CT ratio of 800/5 on the 34.5 kV side, the current flowing to the differential relay from the star-connected CTs will be

$$\frac{5}{800} \times 669 = 4.18 \text{ A}$$

To balance this current from the delta-connected CTs on the 345 kV side, the current in the secondary windings of the CTs should be

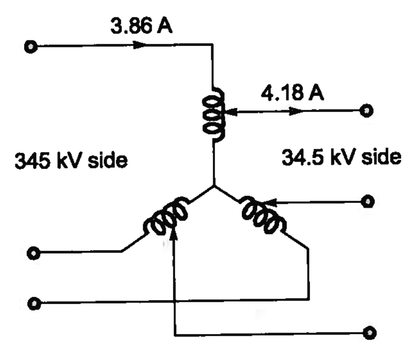
$$= \frac{4.18}{\sqrt{3}} = 2.41\text{ A}$$

$\therefore$ The CT ratio on the 345 kV side $= \frac{66.9}{2.41} = 27.8 \approx \frac{150}{5}$

Also, with this CT ratio the current fed to the differential relay from the delta-connected CTs of the 345 kV side is

$$66.9 \times \frac{5}{150} \times \sqrt{3} = 3.86\text{ A}$$

This current mismatch (3.86 A against 4.18 A) must be removed by using an autotransformer CT ratio of $\frac{4.18}{3.86} = 1.1$ as shown in figure below.



Example - 7.28 **Explain the various types of protection required to protect a synchronous generator in a power system.**

Solution:

Refer to previous article of protection of generators for detailed solution.

Example - 7.29 **For which of the following reasons a differential relay biased to avoid molaperation when used for transformer protection?**

(a) Saturation of CTs
(b) Mismatch to CT ratios
(c) Difference in connection of both sides
(d) Current setting multiplier

Solution: (b)

Actually no two CTs are identical practically. They may have different saturation level and/or different CT ratio which may cause the differential relay to maloperate. Due to this reason differential relays are biased to avoid the undesired maloperation.

7.23 Translay Protection System

- This system can be employed for protection of 1-ϕ or 3-ϕ feeders, transformer feeders and parallel feeders against both earth and phase faults.
- This system is based on the principle of current entering at one end of the feeder being equal at any instant to that leaving at the other end.
- This system has got following advantages over Merz-price system.

(*i*) The capacitive currents do not affect the operation of the relays.
(*ii*) The pilot resistance does not affect the operation as major part of energy required to operate the relay is obtained from current transformer.
(*iii*) Only two pilot wires are required.
(*iv*) CTs of normal designs i.e. with air gap can be employed.

Negative Phase Sequence or Phase Unbalanced Relay

This relay is provided for protection of generators and motors against unbalanced loading that may arise due to phase to phase faults.

7.24 Distance Protection

Distance relay which is used for distance protection is basically an induction type relay similar to the non-directional over-current relay shown in Figure 7.16 of previous article. In induction type distance relay one additional magnet system, operated by voltage is provided such that under normal operating conditions torque exerted by the voltage operated magnet system is greater than that exerted by current operated magnet system and the trip circuit remains open.

Principle of Operation

The basic principle of operation of distance relay involves measurements and comparison of the fault current seen by the relay with the voltage at the relaying point. By comparing these quantities it is possible to measure the impedance of the line upto the point of occurrence of fault.

Here, operating force/torque α (current)^2 α $I^2 = k_1 I^2$

restraining force/torque α (voltage)^2 α $V^2 = k_2 V^2$

The relay operates if, operating force becomes greater than restraining force.

i.e. $k_2 V^2 < k_1 I^2$ or $\boxed{\frac{V}{I} < \sqrt{\frac{k_1}{k_2}}}$

Remember

- A distance relay is also called ***"ratio relay"*** because relay operates if the ratio of voltage to current is less than some set or designed value.
- Since the ratio of voltage and current gives impedance, therefore it is also called ***"impedance relay"***.
- Since impedance and distance are proportional quantities therefore, it is also called ***"distance relay"***.

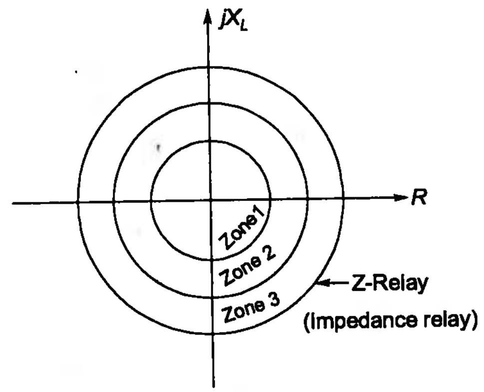
7.24.1 Three-zone of Protection of Transmission Line

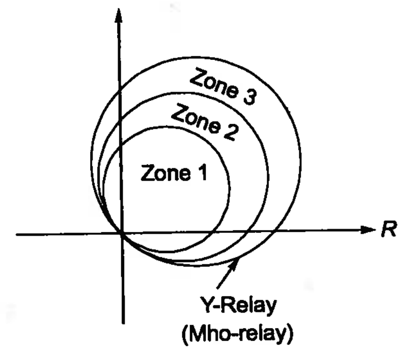
REACH: Distance of the line protected by the distance relay is called REACH.

Under Reach: If the distance relay fails to operate for the faults within its zone (or) reach is called under reach.

Over Reach: If the distance relay operates for the faults outside its reach is called over reach.

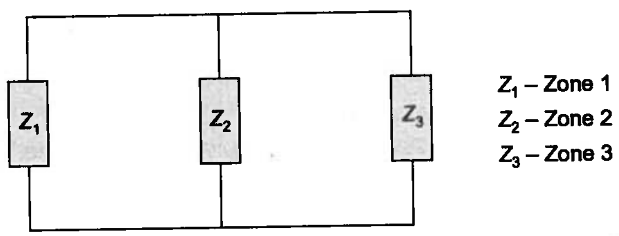
For complete protection of transformer line, three-zone protection used as a back up protection. It is provided in every transmission line (medium and long line) above for 132 kV, 220 kV, 400 kV and 720 kV.





⇒ Z_1 Z_2 and Z_3 are connected in parallel to each other.

- Operating time of Z_1 is (20 - 40) msec.
- Operating time of Z_2 is (0.2 - 0.5) sec.
- Operating time of Z_3 is (0.4 - 1) sec.



In distance protection scheme, there are various operating zones. In most of the distance protection schemes, there is one starting zone which initiates the operation of distance scheme and it is formed as the fourth zone. Besides this, there are three measuring zones explained as below.

Zone-I: This zone covers only 80% of the principle line section because due to the errors in CT ratio, PT ratio and measuring errors it is not possible to cover 100% of the protected line in first zone. The fault in zone-I is cleared by relay with high speed without any adjustment of time delay i.e. it provides high speed protection for the line under consideration. Here, $Z_1 = 0.8\ Z_{L1}$.

Zone-II: In this zone, the remaining 20% of the line left in zone-I is protected. Addition to this, some portion of the line section at the adjacent bus-*B* (shown in Figure 7.30) is also protected. Theoretically, the maximum setting of zone-II can be extended to the 80% of the next line but due to some limitations as explained in case-I above only 64% is covered.

Hence, for zone-II, we have

$$(Z_2)_{min} = 1.2\ Z_{L1}$$

$$(Z_2)_{max} = 0.8\ (Z_{L1} + 0.8\ Z_{L2})$$

Zone-III: Zone-III has the main advantage that it provides remote back-up protection for the adjacent line section and therefore, longest adjacent line section should be protected in zone-III. Hence, for zone-III, we have

$$(Z_3)_{min} = 1.2\ (Z_{L1} + Z_{L2})$$

Thus, it covers remaining section left in zone-II and further reach into the system.

Starting Zone or Zone-IV: The setting of the starting zone should be 125% of the setting of zone-III so that starting zone relays may safely operate for faults within zone-III reach.

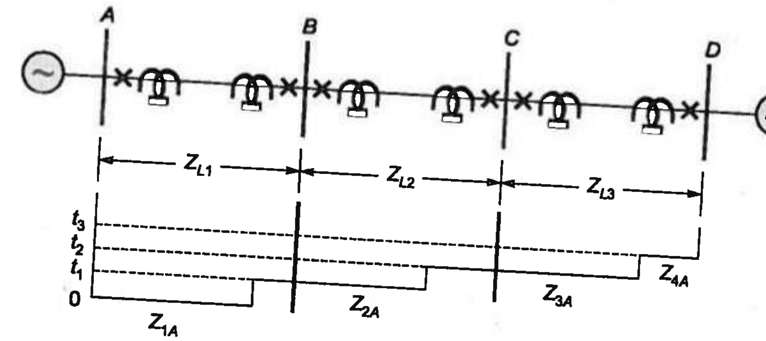


Figure-7.30 : *Three-zone of protection of transmission line*

NOTE

From Figure 7.30 we can see that distance protection provided for line *AB* serves as a back-up protection for lines *BC* and *CD*, because in case of occurrence of faults in line *BC* or *CD* it will clear those in their respective zone time from tripling the *CB* at end *A*.

7.24.2 Carrier Aided Distance Protection Scheme

From three-zone of protection of transmission line, we see that the distance protection scheme can't be set to cover 100% of the line section in zone-I and 20% of the line remains to be protected in zone-II time which is not desirable. This problem is overcome by having carrier aided distance protection scheme as shown in Figure 7.3.

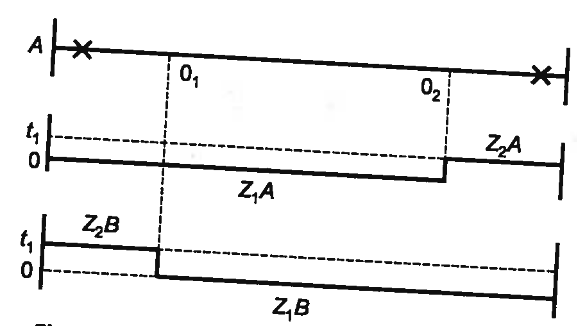


Figure-7.31 : *Carrier aided distance protection scheme*

In this scheme, if the fault occurs between the 20% end portions of the line one circuit breaker is tripped in zone-I time which immediately sends a trip signal command to the other end circuit breaker through carrier communication and thus makes the simultaneously opening of both the circuit breakers.

7.24.3 Types of Distance Relay

Distance relays are of three types:

1. Impedance relay
2. Reactance relay
3. Mho relay

1. Impedance Relay

In an impedance relay, the torque produced by the current element is balanced against the torque developed by voltage element. The current element produces a positive torque, whereas the voltage element produces negative torque.

The torque equation is, $T = k_1|I|^2 - k_2|V|^2 - k_4$

Neglected the effect of control spring (k_4), we have

$$T = k_1|I|^2 - k_2|V|^2$$

When a relay is at the verge of operation, net torque is zero

$$\therefore \quad k_1|I|^2 - k_2|V|^2 = 0 \text{ or } \frac{|V|}{|I|} = |Z| = \sqrt{\frac{k_1}{k_2}} = |Z_{set}|$$

If $|Z| < |Z_{set}|$, relay trips the CB ...**(Important relations)**

If $|Z| > |Z_{set}|$, relay blocks the CB from tripling

The operating characteristic of this relay is shown in Figure 7.32 (shown on ***impedance*** or ***R-X diagram***).

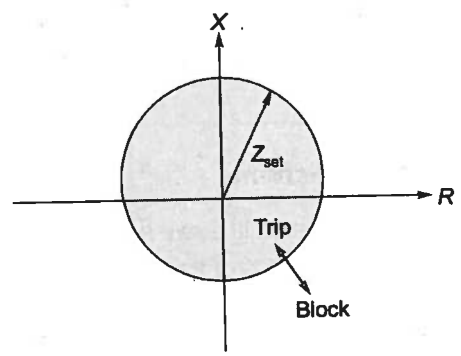


***Figure-7.32 :** Operating characteristic of an impedance relay*

NOTE

- For an impedance relay, voltage is a restrained quantity while current its operating quantity, therefore, it is also called ***"voltage restrained over-current relay"***.
- The operating characteristic of a simple impedance relay is a circle with it's center at the origin.
- If the value of $|Z|$ is less than the radius of the circle it will result into a positive torque and if it is more than the radius then, it will result into a negative torque.
- For transmission line protection, a distance relay consists of three high speed impedance relay units, a timing unit and a directional unit.
- For fault on medium length line generally impedance relay is used.

2. Reactance Relay

A reactance relay is an over-current relay with directional restraint. The directional element is arranged to yield maximum torque contribution when its current lags its voltage by 90° (i.e. $\tau = 90°$). Here, an over-current element develops a positive torque and a current voltage directional element either opposes or aids the over-current element, depending on the phase angle between the current and voltage.

The torque equation is,

$$T = k_1|I|^2 - k_3|V||I|\sin\theta - k_4$$

Neglecting k_4, the relay operates if

$$k_1|I|^2 - k_3|V||I|\sin\theta > 0$$

or, $\frac{|V|}{|I|}\sin\theta < \frac{k_1}{k_3}$ or $|Z|\sin\theta < \frac{k_1}{k_3}$ or $X < \frac{k_1}{k_3}$

The characteristic of the reactance relay on R-X diagram is shown in Figure 7.33.

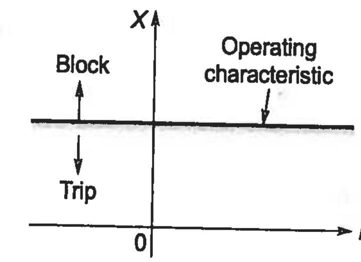


***Figure-7.33 :** Operating characteristic of a reactance relay*

NOTE

- A reactance relay is also called an ***"over-current relay with directional restraint"***.
- It does not sense resistance under fault condition i.e. it is insensitive to the resistance of arcing type fault.
- For earth faults, reactance relay is normally used.
- For phase faults on short line reactance relay is used.
- The characteristic of a reactance relay is a straight line parallel to the real axis.

3. Mho Relay

A modified impedance relay called ***mho relay*** results if a directional relay is restrained by voltage. The torque equation is given by

$$T = k_3|V||I|\cos(\theta - \tau) - k_2|V^2| - k_4$$

Neglecting k_4, the relay operates if

$$k_3|V||I|\cos(\theta - \tau) - k_2|V^2| > 0$$

or, $$\frac{|V|}{|I|} = |Z| < \frac{k_3}{k_2}\cos(\theta - \tau)$$

The right hand side of the above equation is a circle with center located on the line determined by the parameter τ (torque angle) and passing through the origin as shown in Figure 7.34.

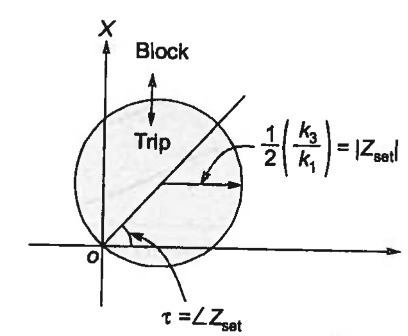


***Figure-7.34 :** Characteristic of a mho relay on R-X plane*

Here, If $|Z - Z_{set}| < |Z_{set}|$, relay trips the CB

If $|Z - Z_{set}| > |Z_{set}|$, relay block the CB from trippling

NOTE

- A mho relay is inherently directional.
- Where the power swings are high, mho relay is generally used.
- Mho relays are used for the protection of long *EHV* transmission lines.
- The operating characteristic of a mho relay is a circle passing through the origin.
- **Offset-mho relay:** The center of the mho relay can be shifted to any point in the R-X plane by characterizing the relay as

if $|Z - Z_s| < |Z_{set}|$, relay trip CB

and if $|Z - Z_s| > |Z_{set}|$, relay blocks CB

Such type of relay is called ***"offset mho relay"***. It's characteristic on R-X plane is shown in Figure 7.35.

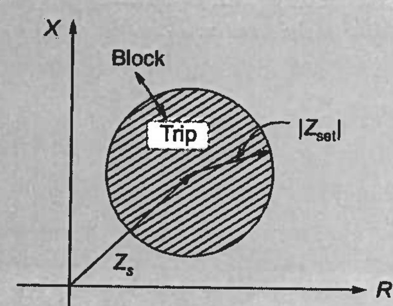


Figure-7.35 : *Operating characteristic of offset mho relay*

7.25 Insulation Coordination

"Insulation coordination" is the economic relationship between the impulse strength of an equipment insulation and protective voltage level provided by protective device. The protective devices like lightening arresters, are used to prevent flash over or break down of an equipment insulation from over-voltages of sufficient magnitude. The basic concept of insulation coordination is shown in Figure 7.36. For proper insulation coordination, the breakdown (volt-time) characteristics of all the equipment must be above the lightening arrester.

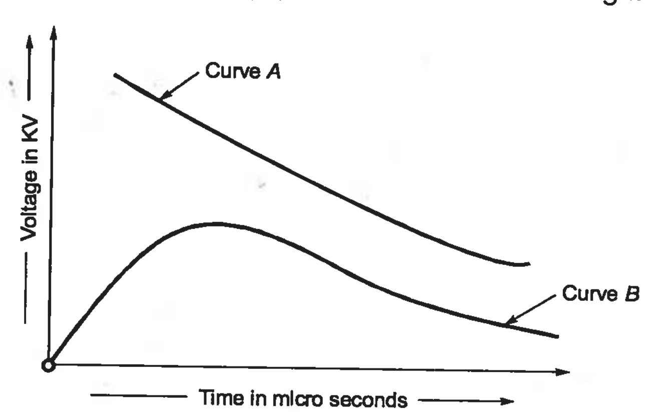


Figure-7.36 : *Breakdown or volt-time characteristic*

In Figure 7.36, curve *A* gives the impulse strength of an electrical equipment to be protected whereas curve *B* gives the protective level afforded by the lightning arrester installed for the protection of the equipment against any lightning surge.

Properties of a good surge diverter/lightning arresters

The important properties are as follows:

- The break-down voltage of a good surge diverter must be more than system normal working voltage.
- The breakdown of a surge diverter must occur due to any abnormal transient voltage above the break-down value and must occur as quickly as possible so that it may provide a conducting path to the earth.
- In case of a breakdown it must be capable of carrying the resulting discharge current without getting damaged and without the voltage across it exceeding the breakdown voltage.
- Arcing should not be continued due to ***"power frequency current"***.

Ground Wire

Ground wire is used to protect the transmission line from direct strokes of lightning which are placed over the towers or poles and earthed at regular intervals, preferably at every pole or tower. It also provides a certain amount of electrostatic screening as it causes the capacitance of ground to increase and so the voltages induced in the conductors, owing to the discharge of a neighbouring cloud, to decrease.

Example - 7.30 **Match List-I (Relay used) and List-II (Equipment) and select the correct answer using the codes below in the list.**

List-I	List-II
A. Mho relay	1. Transformer
B. Negative sequence relay	2. Motor
C. Thermal relay	3. Generator
	4. Transmission line

Codes:

	A	B	C
(a)	1	2	4
(b)	2	4	3
(c)	4	3	2
(d)	3	1	2

Solution : (c)

Example - 7.31 **A distance relay measures**

(a) difference in voltage
(b) difference in impedance
(c) difference in current
(d) difference in phase

Solution : (b)

Example - 7.32 **Match List-I (Types of distance relay) and List-II (Alternate name) and select the correct answer using the codes below in the list.**

List-I	List-II
A. Mho relay	1. Voltage restrained over-current relay
B. Impedance relay	2. Directional restrained over-current relay
C. Reactance relay	3. Voltage restrained directional relay

Codes:

	A	B	C
(a)	1	2	3
(b)	2	1	3
(c)	3	2	1
(d)	3	1	2

Solution: (d)

The basic torque equation is,

$$T = k_1|I|^2 + k_2|V|^2 + k_3|V||I|\cos(\theta - \tau) - k_4$$

Neglecting k_4,

$$T = k_1|I|^2 + k_2|V|^2 + k_3|V||I|\cos(\theta - \tau)$$

⇒ **For an impedance relay**, k_1 is positive, k_2 is negative and $k_3 = 0$

and relay operates if $[k_1|I|^2 - k_2|V|^2] > 0$ or $\frac{|V|}{|I|} = |Z| < \sqrt{\frac{k_1}{k_2}}$

i.e. $\boxed{|Z| < |Z_{set}|}$ (Hence, ***"voltage restrained over-current relay"***)

⇒ **For a reactance relay**, k_1 is positive $k_2 = 0$ and k_3 is negative with $\theta = 90°$.

So, relay operates if $T = k_1|I|^2 - k_3|V||I|\cos(90 - \tau) > 0$

or, $\frac{|V|}{|I|}\sin\theta < \frac{k_1}{k_3}$ or $|Z|\sin\theta < \frac{k_1}{k_3}$ or $X < \frac{k_1}{k_3}$

Hence, reactance relay is ***"direction restrained-over current relay"***.

⇒ **For a mho relay**, k_3 = positive, k_2 = negative and $k_1 = 0$ and relay operates

if $$T = k_3|V||I|\cos(\theta - \tau) - k_2|V|^2 > 0$$

or, $$\frac{|V|}{|I|} = |Z| < \frac{k_3}{k_2}\cos(\theta - \tau)$$

Hence, mho relay is ***"voltage restrained-directional relay"***.

Example-7.33 **Explain carrier current protection of transmission lines with a neat diagram.**

Solution:

Please refer to previous article for explanation as already discussed.

Example-7.34 **A relay most likely to operate undesirably on power swings is the**

(a) over-current relay
(b) IDMT relay
(c) mho relay
(d) reactance relay

Solution: (d)

During power swing out of the three available distance relay, the reactance relay has the maximum probability of maloperation i.e. can operate undesirably.

7.26 Static Relays

The conventional type of electro-magnetic relays can be replaced by static relays which consists of an electronic circuit to develop all those characteristic which are achieved by moving parts in electro-magnetic relays (i.e. operating time etc.) The static relays are capable of performing the same function with the use of electronic circuit control which an electro-magnetic relay performs with the use of moving parts or elements.

Some of the ***advantages of static relays over electro-magnetic relays*** are as follows:

(*i*) Apart from the moving part for final tripping contact, all the moving parts and the contacts are eliminated.

(*ii*) As static relay require a very little volt-ampere for their operation therefore, VA ratings required for CTs and PTs are reduced.

(*iii*) It increases the speed of operation and provides more accuracy.

7.27 Concept of Neutral Grounding/Earthing

- The term ***"grounding"*** means connecting the non-current carrying parts of an electrical equipment or the neutral point of the supply system to the general mass of the earth in such a manner that all the time an immediate discharge of electrical energy takes place without danger.
- The main ***advantages of providing earthing*** are as follows:
  (*i*) It provides safety of personnel from the electric shock.
  (*ii*) It provides safety of equipment and personnel against lightning.
  (*iii*) It controls the earth fault currents for protective relays.

Methods of Neutral Grounding

Following are the methods employed to earth the neutral of the power system.

1. **Solid grounding:**

⇒ In solid grounding/earthing the neutral is directly connected to an electrode having a good contact with the earth as shown below.

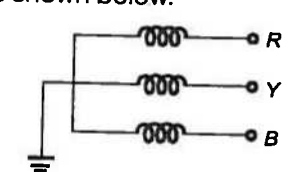


Figure-3.37: *Solid grounding*

⇒ The ***disadvantages of solid grounding*** are as follows:

(*i*) Heavy earth fault current results in greater interference to neighbouring communication circuits.

(*ii*) Heavy fault currents are quite difficult to be handled in the circuit breakers.

2. **Resistance grounding/earthing**

⇒ This type of earthing helps to limit the earth fault current where a resistor is inserted between the neutral and earth to limit the current to a safer value as shown below.

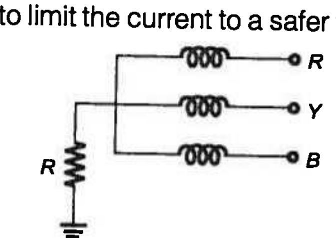


Figure-7.38: *Resistance grounding*

⇒ Resistance earthing is usually used for system operating at voltages upto 33 kV with capacity above 5 MVA as the circuit characteristics of such a system usually give rise to excessive current under earth fault conditions.

3. **Reactance earthing**

⇒ This is similar to resistance earthing system except that the resistance in the neutral is replaced by a reactance or an impedance having the ratio of reactance to resistance more than 3.

⇒ The main ***advantages of reactance earthing*** are that it ensures satisfactory relaying, partial grading of the system insulation, reduced interference to neighbouring communication circuit as compared with that in solidly grounded system.

⇒ The main ***disadvantage of reactance grounding*** is that high transient over-voltages occur in the system due to which it is least preferred.

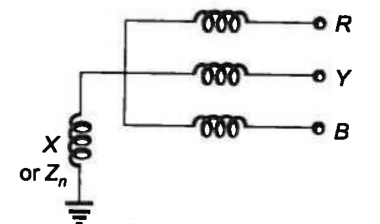
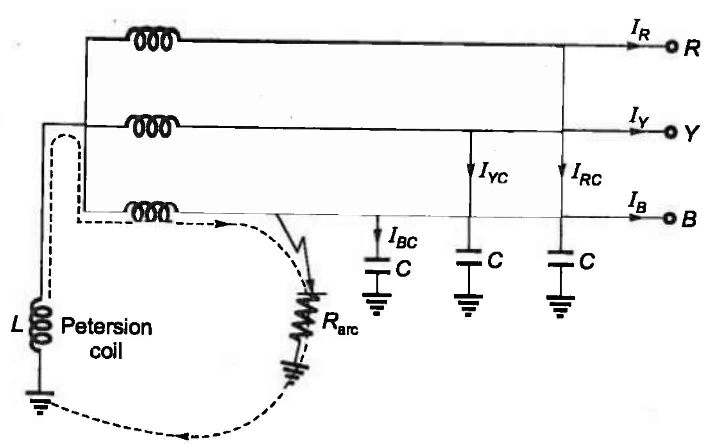


Figure-7.39 : Reactance grounding

Arc Suppression Coil Grounding/Resonant Coil/Peterson Coil Grounding



It operates on the principle that if an inductance of appropriate value is connected in parallel with the capacitance, the fault current can be reduced considerably or even it can be neutralized. Thus magnitude of inductance (L) of the coil depends upon the capacitive current flowing into the ground capacitances. When fault does not occur i.e. balanced condition or healthy condition,

$$I_R + I_Y + I_B = 0 \quad \text{i.e.} \quad I_N = 0$$

When fault occurs,

$$I_R + I_Y + I_B \neq 0 \quad \text{i.e.} \quad I_N \neq 0$$

During occurrence of ground fault in phase '*B*', a lagging reactive current flows from the faulted phase to the ground and returns to the system through the inductive coil.

Simultaneously, capacitive currents also flow from healthy phases to ground. The lagging fault current I_F and leading capacitive current I_C are almost in phase opposition. By a proper selection of the value of inductance '*L*' of the arc suppression coil, the two currents can be made almost equal so that there is no current through the ground fault and so there will be no arc.

The combination of neutral reactance '*L*' and capacitance '*C*' acts as a parallel resonant circuit.

If V_P is line to neutral voltage,

$$I_{CR} = I_{CY} = \sqrt{3}\, V_P\, \omega C$$

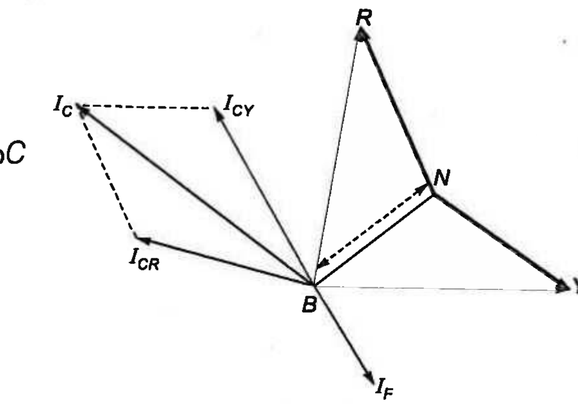
Capacitive current, $\quad I_C = I_{CR} + I_{CY}$

$$= \sqrt{3} \cdot \sqrt{3}\, V_P\, \omega C = 3\, V_P \omega C$$

For balance condition, $\quad I_L = I_C$

$$\frac{V_P}{\omega L} = 3\, V_P\, \omega C$$

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



Phasor diagram

Important Expressions

1. Restriking voltage in a circuit breaker is given by $e_{TRV} = E_m\left(1 - \cos\frac{t}{\sqrt{LC}}\right)$ $(t \geq 0)$

2. Rate of rise of restriking voltage is given by $RRRV = \frac{E_m}{\sqrt{LC}} \sin\frac{t}{\sqrt{LC}}$

3. Maximum value of *RRRV* is given by $(RRRV)_{max} = \frac{E_m}{\sqrt{LC}}$ which occurs at $t = \frac{\pi}{2}\sqrt{LC}$

4. Average $RRRV = \left(\frac{\text{Peak value of restriking voltage}}{\text{Time taken to reach the peak value}}\right) = \frac{2E_m}{\pi\sqrt{LC}}$

5. Voltage developed across the breaker poles due to transfer of energy called "prospective voltage" is given by $\left[v = i\sqrt{\frac{L}{C}}\right]$

6. Critical value of resistance for resistance switching of the circuit breaker is given by $\left[R = 0.5\sqrt{\frac{L}{C}}\right]$

7. The duty cycle of a circuit breaker is given by
   O – 30 sec – CO – 90 sec – CO – 3 min – CO
   (Here, O stands for open and C stands for closing of C.B.)

8. For a 3-ϕ C.B., the breaking capacity = $\sqrt{3} \times I_{break} \times V_{rated}$

9. Making capacity of a C.B. = 2.55 × (symmetrical breaking capacity)

10. The general torque equation is given by $T = k_1|I|^2 + k_2|I|^2 + k_3|V||I|\cos(\theta - \tau) - k_4$

11. Relay operating current = (current setting × CT secondary rated current) (w.r.t. secondary of CT)
    Relay operating current = (current setting × CT ratio × CT secondary rated current) (w.r.t. primary of CT)

12. Plug setting multiplier is given by

$$PSM = \left(\frac{\text{Fault current}}{\text{Relay operating current}}\right) = \left(\frac{I_f}{\text{CS} \times \text{CT secondary rated current} \times \text{CT ratio}}\right)$$

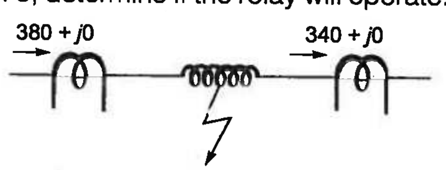
Here, CS = Current setting of relay

13. Time-multiplier setting (TMS) is given by $\text{TMS required} = \left(\frac{t_{\text{required}}}{t_{\text{TMS}} = 1}\right)$

14. For a percentage differential relay, % slope or % bias $= \frac{(i_1 - i_2)}{\left(\frac{i_1 + i_2}{2}\right)} \times 100$

Student's Assignments 1

Q.1 Figure below shows the % differential relay used for the protection of an alternator winding. The relay has a minimum pickup current of 0.25 A and has a % slope of 10%. A high resistance ground fault occurs near the grounded neutral and of the generator winding with the current distribution as shown. Assume a CT ratio of 400 : 5; determine if the relay will operate.



Q.2 A three-phase transformer rated for 66 kV/11 kV is connected in Y/Δ and the protecting CTs on the LV side have a ratio of 400/5. Determine the ratio of the CTs on the HV side.

Q.3 A 2 MVA, 33/11 kV Δ/Y transformer is supplied from the 33 kV side and is earthed through a resistance R on the star side. It is protected by differential protection scheme, and the fault current for a single-phase to earth fault at the terminals of the star winding is to be limited to a full load value. Prepare a table showing percentage of winding protected to a base of fault setting which would be required to protect 70% of the star winding against earth faults under these circumstands. Comment on the suitability of the calculated setting for protecting 70% of the winding.

Student's Assignments 1 Explanations

1. Relay will not operate.

2. $\frac{200}{\sqrt{3}} : 5$

3. The plug setting for 70% protection = 5.2% which is too low; restricted earth fault protection is needed.

% Setting	0	10	20	30	40
% Winding (Y not protected)	0	41.6	58.9	72	83.2

Student's Assignments 2

Q.1 Buchholz relay is used for the protection of
(a) transmission line
(b) synchronous machine
(c) transformer
(d) lightning arrester

Q.2 Sparking occurs when a load is switched off because the circuit has high
(a) inductance (b) resistance
(c) capacitance (d) magnetism

Q.3 An isolator is installed
(a) to isolate one protection of the circuit from another
(b) usually on both sides of a circuit breaker
(c) as a substitute for a circuit breaker
(d) both (a) and (b)

Q.4 A fuse is
(a) always connected in series with the circuit.
(b) always connected in parallel with the circuit.
(c) normally connected in series with the circuit.
(d) normally connected in parallel with the circuit.

Q.5 A pilot exciter is provided on synchronous generator to
(a) provide starting torque to the generator.
(b) to supplement the power generated by the main generator.
(c) excite the main exciter.
(d) none of the above

Q.6 Isolators used in transmission lines are capable of breaking
(a) fault current (b) no current
(c) charging current (d) load current

Q.7 A fuse is
(a) normally inserted in phase wire
(b) normally inserted in neutral wire
(c) never inserted in neutral wire
(d) never inserted in phase wire

Q.8 A circuit breaker is essentially
(a) an arc extinguisher
(b) a current interrupting device
(c) a power factor correcting device
(d) a device for neutralaising the effects of transients

Q.9 Current rating is not necessary in case of
(a) isolator
(b) circuit breaker
(c) load breaker switches
(d) circuit breakers and load break switches

Q.10 Protective relays are the devices that detect abnormal condition in electrical circuits by measuring
(a) voltage
(b) current
(c) constantly the electrical quantities which differ during normal and abnormal conditions
(d) none of these

Q.11 On occurance of fault on the connected circuit, a circuit breaker operates
(a) manually
(b) automatically
(c) manually through a control switch
(d) depending upon the circuit breaker design

Q.12 In the protection scheme, relay functions as a
(a) switching device (b) sensing device
(c) breaking device (d) none of these

Q.13 In case of electro-mechanical relay, relay coil is normally designed for
(a) 50 and 100 A (b) 10 and 25 A
(c) 5 and 10 A (d) 1 and 5 A

Q.14 A lighting arrester provides
(a) low impedance path
(b) high impedance path
(c) low resistance path
(d) high resistance path between line and earth during operation

Q.15 Earthing of electrical equipment is necessary for the protection against
(a) over-loading
(b) voltage fluctuation
(c) danger of electric shock
(d) high conductor temperature

Q.16 Location of lightning arrester is near a
(a) generator (b) transformer
(c) bus-bar (d) circuit breaker

Q.17 Isolated neutral system has the disadvantage of
(a) voltage oscillation
(b) difficult earth fault relaying
(c) persistent arcing ground
(d) all of the above

Q.18 When fault occurs in a high voltage transmission line, first the
(a) circuit breaker operates then the relay
(b) relay operates then the circuit breaker
(c) relay operates, then successively the isolator and the circuit breaker
(d) isolator operates, then successively the relay and the circuit breaker

Q.19 The initiation of electric arc at the instant of contact separation is caused by
(a) thermionic emission of electron
(b) field emission of electron
(c) (a) and (b) both
(d) none of these

Q.20 Sparking between contacts can be reduced by inserting
(a) a resistor in parallel with the contacts
(b) a capacitor in series with the contacts
(c) a resistor in the line
(d) a reactor in the line

Q.21 For a high speed circuit breaker the total clearing time is around
(a) few minutes (b) few seconds
(c) 1 to 2 cycles (d) 5 to 20 cycles

Q.22 In air blast circuit breaker resistance switching is used to
(a) reduce the magnitude of fault current
(b) control the CB operating time
(c) damp out of the fast transient
(d) change the fault current power factor

Q.23 SF_6 circuit breaker have the advantages of
(a) very much reduced electrical clearance, reduced moisture problem and minimum current chopping problem.
(b) noiseless operation, less arcing time resulting in less contact erosion.
(c) no reduction in dielectric strength of SF_6
(d) all of the above

Q.24 To limit current chopping in vaccum circuit breakers, the contact material employed should have the property of
(a) low conductivity and high vapour pressure
(b) low conductivity and low vapour pressure
(c) high conductivity and high vapour pressure
(d) high conductivity and low vapour pressure

Q.25 Which of the following circuit breakers has high reliability and negligible maintenance?
(a) Air-blast (b) SF_6
(c) Oil (d) Vaccum

Q.26 The making to breaking current ratio for an EHV circuit breaker is
(a) more than 1 (b) less than1
(c) equal to 1 (d) a negative number

Q.27 Purpose of backup protection is
(a) to increase the speed
(b) to increase a reach
(c) to leave no blind spot
(d) to guard against failure of primary

Q.28 To domains of power system where directional over current relay is indispensable are
(a) in case of parallel feeder protection
(b) in case of ring main feeder protection
(c) both (a) and (b)
(d) none of these

Q.29 If the fault occurs near the relay, the V/I ratio will be
(a) lower than that of if the fault occurs away from the relay.
(b) constant for all distances.
(c) higher than that of if the fault occurs away from the relay.
(d) none of these

Q.30 The operating characteristics of a plain impedance relay in a complex z-plane is a
(a) circle passing through origin
(b) circuit with the center at the origin
(c) straight line passing through origin
(d) straight line offset from the origin

Q.31 A differential relay responds to
(a) algebraic difference of two or more similar electrical quantities.
(b) phasor difference of two ore more similar electrical quantities.
(c) algebraic difference between two currents.
(d) algebraic difference between two voltages.

Q.32 The operating characteristics of a reactance relay in the complex impedance plane is s
(a) circle with its origin at the center of the R-X plane
(b) circle passing through the origin
(c) straight line passing through the origin
(d) straight line parallel to the X-axis

Q.33 Time graded protection of a radial feeder can be achieved by using
(a) definite time relays
(b) inverse time relays
(c) both definite and inverse time relays
(d) none of these

Q.34 In carrier current protection the purpose of the wavetrap is for
(a) trapping power frequency waves
(b) trapping high frequency waves entering into generators/transformer unit
(c) both (a) and (b)
(d) none of these

Direction of Questions (35 to 37):
Each of the following question consists of two statements, one labelled the **'Assertion (A)'** and the other labelled the **'Reason (R)'**. Examine the two statements carefully and decide if the Assertion (A) and Reason (R) are individually true and if so whether the Reason (R) is correct explanation of the Assertion (A). Select your answers to these questions using the codes given below:
Codes:
(a) Both A and R are true and R is the correct explanation of A.
(b) Both A and R are true but R is not a correct explanation of A.
(c) A is true but R is false.
(d) A is false but R is true.

Q.35 **Assertion (A):** For ground fault protection, the reactance relay is preferred.
Reason (R): Ground fault involves variable fault resistance and the operation of reactance relay is not affected by fault resistance.

Q.36 **Assertion (A):** Zero-sequence currents flow from a line into a transformer tank.
Reason (R): Transformer windings are connected in grounded star/delta.

Q.37 **Assertion (A):** Thyrite arrestor is most common and is mostly used for the protection against high dangerous voltages.
Reason (R): The thyrite arrestor discharges several thousand amperes without the slightest tendency to flash-over on the edges and there is absolutely no time lag in its performance.

Q.38 Match **List-I (Equipments)** with **List-II (Symbols)** and select the correct answer using the code given below the lists:

List-I
A. Earthing
B. Fuse
C. Isolator
D. Busbar

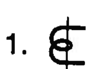
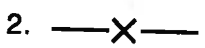
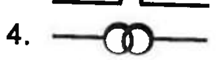
List-II
1. 
2. 
3. 
4. 

Codes:

	A	B	C	D
(a)	3	2	4	1
(b)	1	2	3	4
(c)	2	3	4	1
(d)	3	4	1	2

Q.39 Match **List-I (Equipments)** with **List-II (Symbols)** and select the correct answer using the code given below the lists:

List-I
A. Lightning arrester
B. Current transformer
C. Circuit breaker
D. Potential transformer

List-II
1. 
2. 
3. 
4. 

Codes:

	A	B	C	D
(a)	1	2	3	4
(b)	2	3	4	1
(c)	3	1	2	4
(d)	4	1	2	3

Answer Key:

1. (c)	**2.** (a)	**3.** (d)	**4.** (a)	**5.** (c)
6. (b)	**7.** (c)	**8.** (b)	**9.** (a)	**10.** (c)
11. (b)	**12.** (b)	**13.** (d)	**14.** (a)	**15.** (c)
16. (b)	**17.** (d)	**18.** (b)	**19.** (c)	**20.** (a)
21. (c)	**22.** (c)	**23.** (d)	**24.** (a)	**25.** (b)
26. (a)	**27.** (d)	**28.** (c)	**29.** (a)	**30.** (b)
31. (b)	**32.** (d)	**33.** (c)	**34.** (b)	**35.** (a)
36. (a)	**37.** (a)	**38.** (a)	**39.** (c)	

Student's Assignments 2 Explanations

1. (c)
Buchholz relay is used for protecting the transformer from all types of internal faults.

2. (a)
An inductor opposes a sudden change in current and due to it's presence in the circuit when the load is switched-off due to the stored magnetic field energy in it, sparking occurs.

3. (d)
An isolator is an off load device which is used for the maintenance of a circuit breaker (installed on both sides of the circuit breaker). Also, it is used to isolate one portion of the circuit from another.

4. (a)
Fuse is a piece of metal which interrupts a short-circuit current and is connected in series with the circuit.

6. (b)
Isolator is an off load device therefore, it is not used for breaking any current.

8. (b)
A circuit breaker is used for interrupting a fault current. Hence, it is a current interrupting device.

10. (c)
During a fault in a circuit (abnormal condition) fault current and voltage (over voltage) is very high which is detected by protective relays for giving instruction to the circuit breaker for tripping the circuit. During normal condition voltage and current are normal which are measured by the protective relay and hence the circuit remain in healthy condition.

11. (b)
During abnormal condition (occurance of fault), circuit breaker operates automatically and isolates the faulted circuit.

12. (b)
Relay used to sense abnormal condition (over voltage, over current etc.) and hence it is a sensing device.

14. (a)
A lighting arrester provides a low impedance path so that the lightning over voltages easily get discharged into the earth and the equipment remain undamaged due to lightning.

15. (c)
Earthing of electrical equipment is provided so that the fault current get discharged into the earth and the personnel handling the equipment does not get electric shock.

18. (b)
When a fault occurs in a high voltage transmission line, first the relay operates (senses the fault) and sends the trip signal to the circuit breaker to isolate teh faulted line.

19. (c)
In a circuit breaker, arc is initiated due to "field emission" and is maintained due to "thermionic emission of electrons".

21. (c)
Fault in a power system must be cleared within 5 cycles of fault current. High speed CBs clears the fault within 1 to 2 cycles of fault current.

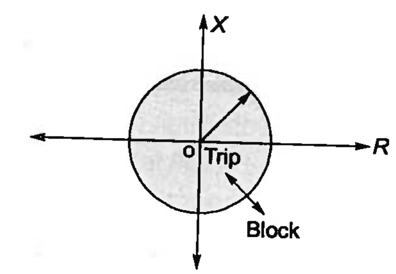
26. (a)
Making capacity = 2.55 × Breaking capacity

or, $\left(\dfrac{\text{Making current}}{\text{Breaking current}}\right) = 2.5 > 1$

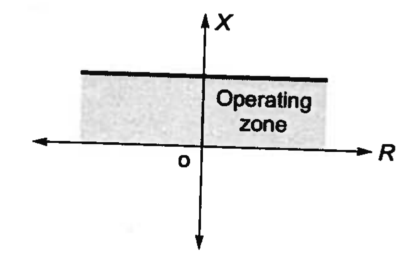
28. (c)
In case of parallel feeder as well as in case of a ring main feeder protection there should be availability of power to the remaining line/portion of the line which are not affected due to the occurance of fault. Hence, a directional relay is must in these two cases.

29. (a)
When a fault occurs near the relay itself, the impedance (V/I ratio) of the line seen by the relay (Z_{seen}) will be very less than that if the fault occurs away from the relay.

30. (b)
An impedance relay has a characteristic as shown below.



32. (d)
The operating characteristic of a reactance relay is shown below.



34. (b)
Line trap/wave trap is basically an inductor which is used to block carrier signal (high frequency signal) and bypass power signal (50 Hz signal).

♦■♦■♦■♦