

LECTURE NOTES

Subject Name: Switch Gear and Protection

Year / Branch: III year / EEE

Regulation: R23

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Unit - I.

Circuit Breakers

Introduction:

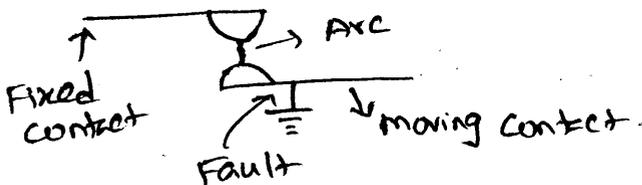
The function of circuit breaker is to isolate the faulty part of the power system, in case of abnormal conditions.

A protective relay detects abnormal conditions and sends a signal to the circuit breaker.

After receiving the trip signal from the relay, the circuit breaker isolates the faulty part of the power system.

A circuit breaker has two contacts

- a fixed contact and
- a moving contact



Under normal conditions, the two contacts are in closed position.

Once the fault is identified and the fault signal obtained from the relay, the moving

Contacts moves to interrupt the circuit, and interrupts the current flow.

As a result, the formation of arc between the contact persist.

In general, the contacts are placed in a closed chamber containing some insulating medium (liquid or gas) which extinguishes the arc.

Elementary Principles of arc interruption:

There are two methods of arc interruption

- (i) High resistance interruption
- & (ii) Current zero interruption.

(i). High resistance interruption:

In this method, the arc resistance is increased so as to reduce the current to a value insufficient to maintain the arc.

The arc resistance can be increased by cooling, lengthening, constraining and splitting the arc.

During current interruption, a high voltage appears across the contacts of circuit breaker.

If this voltage is very high and more than the withstanding capacity of the gap between contacts, the arc will strike again.

Therefore, this method is not suitable for a large-current interruption. This can be employed for low power AC and DC circuit breakers.

(ii) Current zero interruption:

In case of AC supply, the current wave passes through a zero point, 100 times per second at the supply frequency of 50 Hz.

This feature of AC is utilised for arc interruption

The current is interrupted at zero

current instant only in order to avoid a high transient voltage across the contact gap.

The current is not allowed to rise again after a zero current occurs.

There are two theories to explain the zero current interruption of the arc.

1. Recovery rate theory
2. Energy balance theory.

1. Recovery rate theory:

The arc is interrupted if ions are removed from the gap at a rate faster than the rate of ionisation.

In this method, the rate at which the gap recovers its dielectric strength is compared with the rate at which the restriking voltage (transient voltage) across the gap rises.

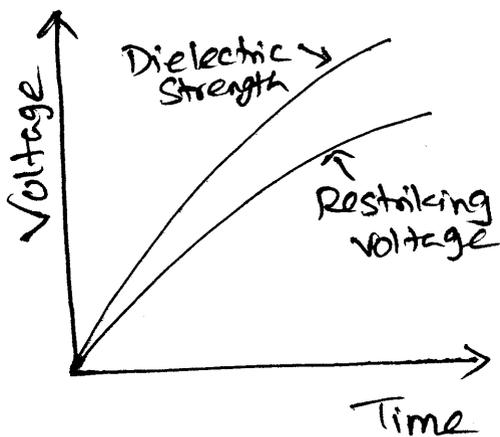
If the dielectric strength increases more

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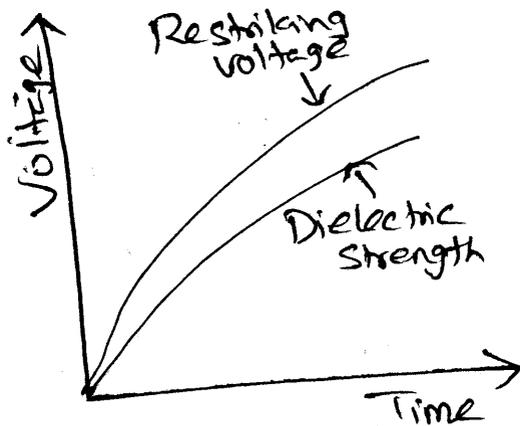
rapidly than the restriking voltage, the arc is extinguished.

If the restriking voltage rises more rapidly than the dielectric strength, the ionisation persists and breakdown of the gap occurs, resulting in an arc for another half-cycle.

Fig. explains the principle of recovery rate theory.



(a) Arc extinguishes



(b) Arc does not extinguishes.

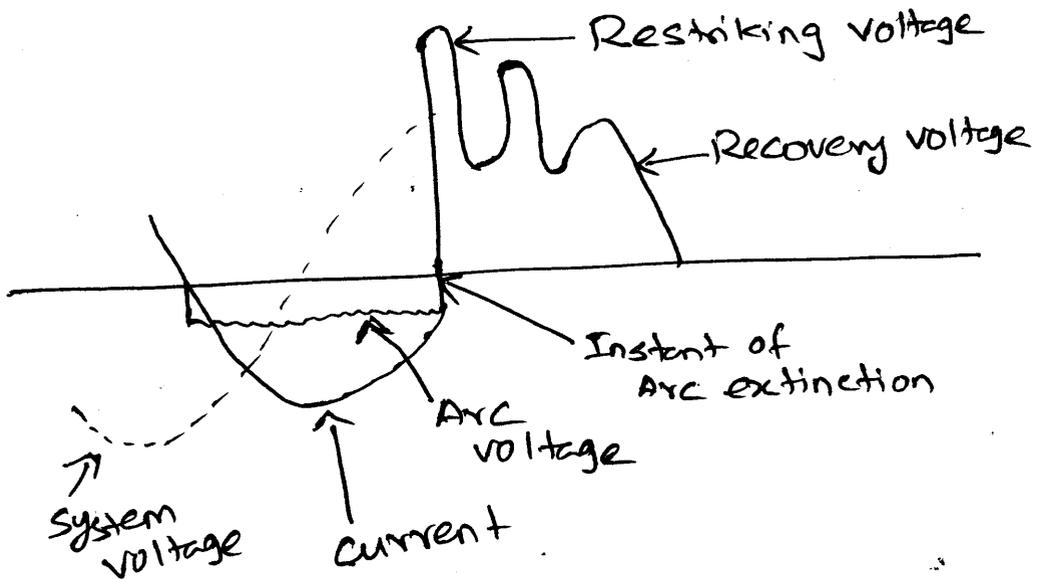
Restriking Voltage and Recovery voltage:

The voltage across the contacts of the circuit breaker is arc voltage when the

arc persists.

The arc is extinguished at the instant of current zero.

Once the arc is extinguished, the voltage across the breaker contacts does not normalise instantaneously, but it oscillates and there is a transient condition.



The transient voltage which appears across the breaker contacts at the instant of arc being extinguished is known as restriking voltage.

The power frequency rms voltage, that appears across the breaker contacts after

the arc is finally extinguished and transient oscillations die out is called recovery voltage.

Restriking Phenomenon:

Fig. shows a short circuit on a feeder beyond the location of the circuit breaker.

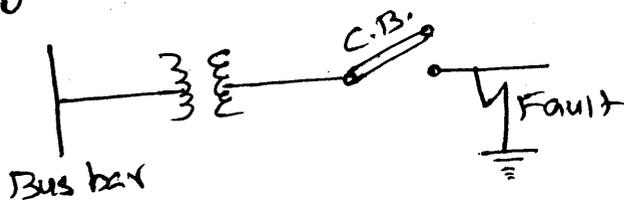
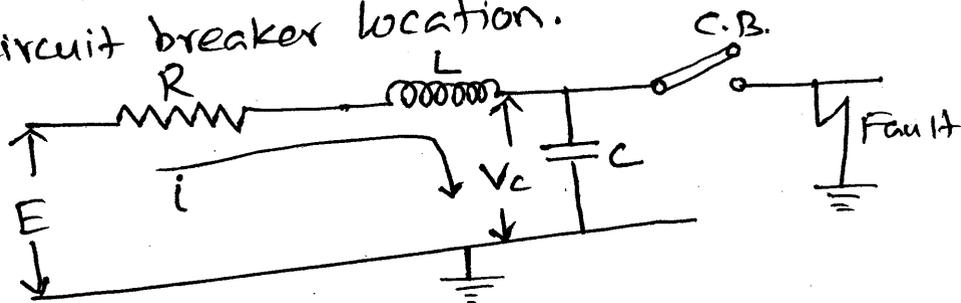


Fig. shows an equivalent circuit where L and C are the inductance and capacitance per phase of system upto the point of circuit breaker location.



When the circuit breaker is closed, the short circuit current flows through R , L and the contacts of the circuit breaker, hence the capacitance C is being short-circuited

by the fault.

When the circuit breaker contacts are opened and the arc is extinguished, the current i is diverted through the capacitance C , resulting in a transient condition.

The inductance and capacitance form a series oscillatory circuit. Therefore the voltage across the capacitance (restoring voltage) rises and oscillates (as shown in ~~the~~ Previous fig.)

The natural frequency of oscillation is given by,

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

The voltage across the capacitance which is the voltage across the contacts of circuit breaker can be calculated by,

$$E = L \cdot \frac{di}{dt} + \frac{1}{C} \int i dt \quad \text{--- (1)}$$

where,

E → System voltage at the instant of arc interruption.

As the transient oscillation is a fast

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Phenomenon, E can be treated as a constant for a short duration.

$$i = \frac{dq}{dt} = \frac{d(CV_c)}{dt} \quad \text{--- (2)}$$

where, $V_c \rightarrow$ Voltage across the capacitor.

Therefore,

$$\frac{di}{dt} = \frac{d^2(CV_c)}{dt^2} = C \cdot \frac{d^2 V_c}{dt^2} \quad \text{--- (3)}$$

and from (2),

$$\int \frac{1}{C} i dt = \frac{q}{C} = V_c \quad \text{--- (4)}$$

Substituting (3) & (4) in (1), we get

$$LC \frac{d^2 V_c}{dt^2} + V_c = E$$

Taking Laplace transform on both sides, we get

$$LCs^2 V_c(s) + V_c(s) = \frac{E}{s}$$

$$\text{(or)} \quad V_c(s) [LCs^2 + 1] = \frac{E}{s}$$

$$V_c(s) = \frac{E}{s[LCs^2 + 1]} = \frac{E}{LCs(s^2 + \frac{1}{LC})}$$

$$\text{But, } \omega_n = \frac{1}{\sqrt{LC}}; \therefore \frac{1}{LC} = \omega_n^2$$

$$\begin{aligned}\therefore V_c(s) &= \frac{\omega_n^2 E}{s(s^2 + \omega_n^2)} \\ &= \frac{\omega_n E}{s} \left(\frac{\omega_n}{s^2 + \omega_n^2} \right)\end{aligned}$$

Taking the inverse Laplace transform, we get,

$$\begin{aligned}V_c(t) &= \omega_n E \int_0^t \sin \omega_n t \\ &= \omega_n E \left[-\frac{\cos \omega_n t}{\omega_n} \right]_0^t\end{aligned}$$

As $V_c(t) = 0$ at $t = 0$; constant = 0.

$$\begin{aligned}\therefore V_c(t) &= E(1 - \cos \omega_n t) \\ &= E \left(1 - \cos \frac{1}{\sqrt{LC}} t \right) \\ &= \text{Restriking voltage}\end{aligned}$$

The maximum value of restriking voltage
= $2 E_{\text{peak}}$
= $2 \times$ peak value of the system voltage

The Rate of Rise of Restriking voltage
(RRRV)

$$= \frac{dE}{dt} (1 - \cos \omega t)$$

$$= \omega n E \cdot \sin \omega t$$

The maximum value of RRRV

$$= \omega n E$$

$$= \omega n E_{\text{peak}}$$

Problems:

1) For a 132 kV system, the reactance and capacitance up to the location of the circuit breaker is 3 ohms and $0.015 \mu\text{F}$ respectively. Calculate the following:

(a) The frequency of transient oscillation

(b) The maximum value of restriking voltage across the contacts of the circuit breaker

(c) The maximum value of RRRV.

Soln.:

(a) Frequency of transient oscillation:

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$X_L = 3\Omega$$

$$2\pi fL = 3$$

$$L = \frac{3}{2\pi f} = \frac{3}{2\pi \times 50} \left[\because f = 50 \text{ Hz} \right. \\ \left. \text{System frequency} \right]$$

$$= 0.00954 \text{ H}$$

$$C = 0.015 \mu\text{F}$$

$$\therefore f_n = \frac{1}{2\pi\sqrt{0.00954 \times 0.015 \times 10^{-6}}}$$

$$= 13.291 \text{ kHz}$$

(b) Restriking voltage:

$$V_c = E[1 - \cos \omega nt]$$

The maximum value of restriking voltage

$$= 2 E_{\text{peak}}$$

$$= 2 \times \frac{\sqrt{2} \times 132}{\sqrt{3}} = 215.56 \text{ kV}$$

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(c) The maximum value of RRRV

$$= \omega n E_{\text{peak}}$$

$$= 2\pi f_n \times \frac{132}{\sqrt{3}} \times \sqrt{2}$$

$$= 2\pi \times 13.291 \times \frac{\sqrt{2} \times 132}{\sqrt{3}}$$

$$= 9.01 \text{ kV}/\mu\text{s} \quad (\underline{\underline{9.01 \times 10^6}})$$

2) A 50Hz generator has emf to neutral 7.5 kV (rms). The reactance of generator and the connected system is 4Ω and distributed capacitance to neutral is $0.01 \mu\text{F}$, with resistance negligible. Find

i) maximum voltage across the circuit breaker contacts

ii) frequency of oscillations

iii) RRRV average upto first peak of oscillations.

Soln.:

$$X_L = 2\pi f L = 4 \Omega$$

$$L = \frac{4}{2\pi \times 50} = 0.0127 \text{ H}$$

$$E_m = \sqrt{2} \times 7.5 = 10.606 \text{ kV}$$

$$\begin{aligned}
 \text{i) maximum voltage} \\
 &= 2 E_{\text{peak}} = 2 \times 10.606 \\
 &= 21.212 \text{ kV}
 \end{aligned}$$

ii) Frequency of oscillation:

$$\begin{aligned}
 f_n &= \frac{1}{2\pi\sqrt{LC}} \\
 &= \frac{1}{2\pi\sqrt{0.0127 \times 0.01 \times 10^{-6}}} \\
 &= 14.1227 \text{ kHz}
 \end{aligned}$$

$$\text{iii) Average RRRV} = \frac{\text{Maximum Voltage}}{t_m}$$

Maximum time to reach maximum voltage

$$\begin{aligned}
 t_m &= \pi\sqrt{LC} = \frac{1}{2f_n} \\
 &= \frac{1}{2 \times 14.1227 \times 10^3} \text{ sec.}
 \end{aligned}$$

∴ Maximum RRRV

$$= \frac{21.212}{\left[\frac{1}{(2 \times 14.1227 \times 10^3)} \right]} = 0.599 \text{ kV/}\mu\text{sec}$$

3) In a 132 kV system, inductance and capacitance up to the location of the circuit breaker is 0.4 H and 0.015 μ F respectively. Determine (a) the maximum value of restriking voltage across the contacts of circuit breaker, (b) frequency of transient oscillation and (c) the maximum value of RRRV.

Soln.:

(a) Maximum value of restriking voltage

$$= 2 V_m$$

$$= 2 \frac{\sqrt{2} \times 132}{\sqrt{3}}$$

$$= 215.55 \text{ kV}$$

(b) Frequency of transient oscillation,

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{0.4 \times 0.015 \times 10^{-6}}}$$

$$= 2.0546 \text{ kHz}$$

(c) Maximum value of RRRV,

$$= \omega_n E_{peak}$$

$$= 2\pi f_n E_{peak}$$

$$= 2\pi \times 2.0546 \times 10^3 \times \frac{\sqrt{2} \times 132 \times 10^3}{\sqrt{3}}$$

$$= 1.39 \times 10^9 \text{ V/sec.}$$

$$= 1.39 \times 10^9 \times 10^{-6} \text{ V}/\mu\text{sec.}$$

$$= 1.39 \text{ kV}/\mu\text{sec.}$$

Current Chopping:

When low inductive current is being interrupted and the arc quenching force of the circuit breaker is more than necessary to interrupt a low magnitude of current, the current will be interrupted before its natural zero instant.

In such a case, an energy stored in the magnetic field appears in the form of high voltage across the stray capacitance, which will cause restriking of an arc.

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The energy stored in the magnetic field is $= \frac{1}{2} Li^2$

where, $i \rightarrow$ instantaneous ^{value of} current being interrupted.

This will appear in the form of electrostatic energy equal to $= \frac{1}{2} Cv^2$

As these two energies are equal, they can be related as,

$$\frac{1}{2} Li^2 = \frac{1}{2} Cv^2$$

$$v = i \sqrt{L/C}$$

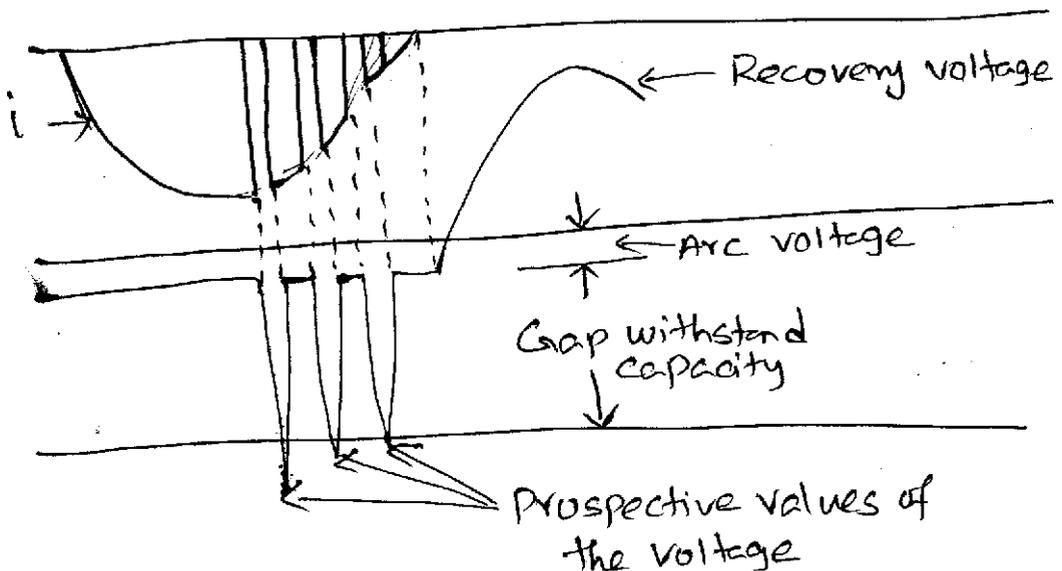


Fig. shows the current chopping phenomenon.

If the value of v is more than withstanding capacity of the gap between the contacts, the arc appears again.

Since, the quenching force is more, the current is again chopped.

This phenomenon continues till the value of v becomes less than the withstanding capacity of the gap.

The theoretical value of v is called as the prospective value of the voltage.

Resistance Switching:

To reduce the restriking voltage, RRRV and severity of transient oscillation a resistance is connected across the contacts of circuit breaker.

This is known as resistance switching.

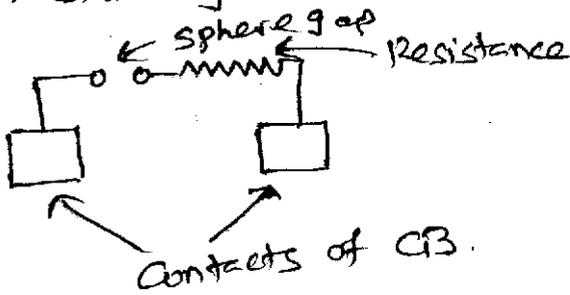
The resistance is connected in parallel to the contacts of circuit breaker and

hence with the arc.

A part of arc current flows through this resistance resulting in decrease in current through the gap. ~~but~~ between the contacts.

This process continues and current through the shunt resistance increases ~~at the~~ with a decrease in arc current.

Due to decreased arc current, RRRV and restriking voltage are reduced.



As shown in fig., the resistance may be automatically switched in with the help of a sphere gap.

The analysis of resistance switching can be made to identify the critical value of resistance that should be connected

to damp out the complete transient oscillations.

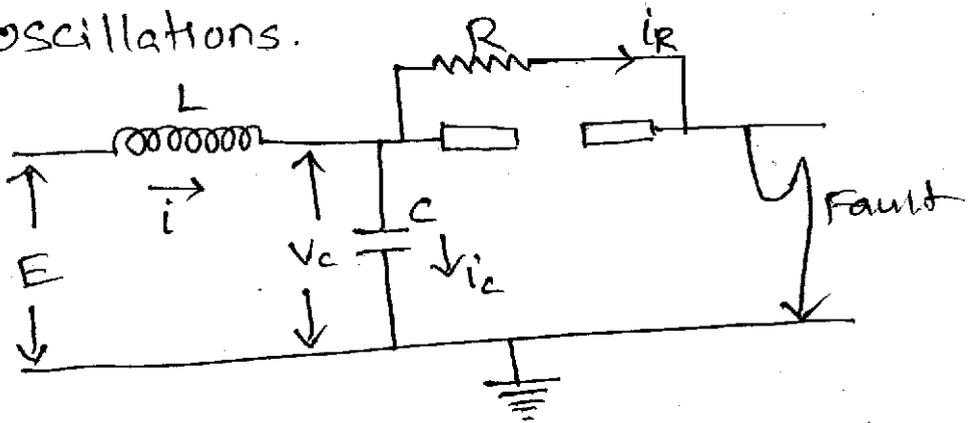


Fig. Shows an equivalent electrical circuit for the analysis:

The voltage equation is given by

$$L \cdot \frac{di}{dt} + \frac{1}{C} \int i_c dt = E \quad \text{--- (1)}$$

$$\text{and } i = i_c + i_R \quad \text{--- (2)}$$

$$\therefore L \cdot \frac{d(i_c + i_R)}{dt} + V_c = E$$

$$\Rightarrow L \frac{di_c}{dt} + L \cdot \frac{di_R}{dt} + V_c = E \quad \text{--- (3)}$$

$$\text{But, } i_c = \frac{dq}{dt} = \frac{d(CV_c)}{dt}$$

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$$\therefore \frac{dI}{dt} = \frac{d^2(CV_c)}{dt^2} = C \cdot \frac{d^2V_c}{dt^2}$$

and

$$\frac{dV_c}{dt} = \frac{d\left(\frac{V_c}{R}\right)}{dt} = \frac{1}{R} \frac{dV_c}{dt}$$

Substituting these values in (3), we get

$$L.C. \frac{d^2V_c}{dt^2} + \frac{L}{R} \frac{dV_c}{dt} + V_c = E \quad (4)$$

Taking Laplace transform on both sides,

$$LCs^2V_c(s) + \frac{L}{R} sV_c(s) + V_c(s) = \frac{E}{s}$$

$$LC \cdot V_c(s) \left[s^2 + \frac{1}{RC} s + \frac{1}{LC} \right] = \frac{E}{s}$$

$$\Rightarrow V_c(s) = \frac{E}{sLC \left[s^2 + \frac{1}{RC} s + \frac{1}{LC} \right]}$$

For no transient oscillation, all the roots of the equation should be real.

One root is zero i.e. $s=0$ which is real.

For the other two roots to be real, the roots of the quadratic equation in the denominator should be real.

For this, the following condition should be satisfied.

$$\left[\left(\frac{1}{2RC} \right)^2 - \frac{1}{LC} \right] \geq 0$$

$$\Rightarrow \frac{1}{4R^2C^2} \geq \frac{1}{LC}$$

$$\frac{1}{R^2C^2} \geq \frac{4}{LC} \Rightarrow R^2 \leq \frac{LC}{4C^2}$$

$$\Rightarrow R^2 \leq \frac{1}{4} \frac{L}{C}$$

$$\Rightarrow R \leq \frac{1}{2} \sqrt{\frac{L}{C}}$$

Therefore, if the value of resistance connected across the contacts of the circuit breaker is less than or equal to $\frac{1}{2} \sqrt{\frac{L}{C}}$, there will be no transient oscillation.

If $R > \frac{1}{2}\sqrt{L/C}$, there will be an oscillation.

$R = \frac{1}{2}\sqrt{L/C}$ is known as critical resistance.

The frequency of damped oscillation is given by,

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

Problems:

1) A circuit breaker interrupts the magnetising current of a 100 MVA transformer at 220 kV. The magnetising current of the transformer is 5% of the full load current. Determine the maximum voltage which may appear across the gap of the breaker when the magnetising current is interrupted at 53% of its peak value. The stray capacitance is 2500 μF . The inductance is 30 H.

Soln.:

The full-load current of the transformer

$$= \frac{100 \times 10^6}{\sqrt{3} \times 220 \times 10^3}$$

$$= 262.44 \text{ A}$$

Magnetising current

$$= 13.12 \text{ A}$$

$$= 262.44 \times \frac{5}{100} = 34.44 \text{ A}$$

Current chopping occurs at

$$\frac{53}{100} \times \frac{13.12}{34.44} \sqrt{2}$$

$$= 25.83 \text{ A} = 9.83 \text{ A}$$

Now, $\frac{1}{2} Li^2 = \frac{1}{2} CV^2$

$$\frac{1}{2} \times 30 \times (25.83)^2 = \frac{1}{2} \times 2500 \times 10^{-6} \times V^2$$

$$\Rightarrow V = 2829 \text{ kV}$$

$$V = 1.076 \text{ kV}$$

2) In a 220 kV system, the reactance and capacitance up to the location of circuit breaker is 8Ω and $0.025 \mu\text{F}$ respectively.

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A resistance of 600 ohms is connected across the contacts of the circuit breaker. Determine the following:

- Natural frequency of oscillation
- Damped frequency of oscillation
- Critical value of resistance which will give no transient oscillation
- The value of resistance which will give damped frequency of oscillation, one-fourth of the natural frequency of oscillation.

Soln.:

$$L = \frac{8}{2\pi \times 50} = 0.02544 \text{ H}$$

a) Natural frequency of oscillation:

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.02544 \times 0.025 \times 10^{-6}}} \\ = 6.304 \text{ KHz}$$

b) Damped frequency of oscillation:

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

$$= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times 600^2}}$$

$$= \frac{1}{2\pi} \sqrt{\frac{10^{10}}{6.36} - \frac{10^{10}}{9}} = 3.413 \text{ kHz}$$

c) Value of critical resistance:

$$R = \frac{1}{2} \sqrt{\frac{L}{C}} = \frac{1}{2} \sqrt{\frac{0.02544}{0.025 \times 10^{-6}}}$$

$$= 504.35 \Omega$$

d) The damped frequency of oscillation is

$$= \frac{1}{4} \times 6.304 = 1.576 \text{ kHz}$$

$$\therefore 1.576 \times 10^3 = \frac{1}{2\pi} \sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}}$$

$$= \frac{1}{2\pi} \sqrt{\frac{1}{0.02544 \times 0.025 \times 10^{-6}} - \frac{1}{4(0.025 \times 10^{-6})^2 \times R^2}}$$

$$\Rightarrow R = 520.8 \Omega$$

CB ratings and specifications:

A circuit breaker has to perform the following major duties under fault

Conditions.

- i) It must be capable of opening the contacts to break the faulty circuit
- ii) It must be capable of closing the contacts onto a fault
- iii) It must be capable of carrying fault current for a short-time while another circuit breaker (in series) is clearing the fault.

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

- i) breaking capacity
- ii) making capacity and
- iii) short-time capacity.

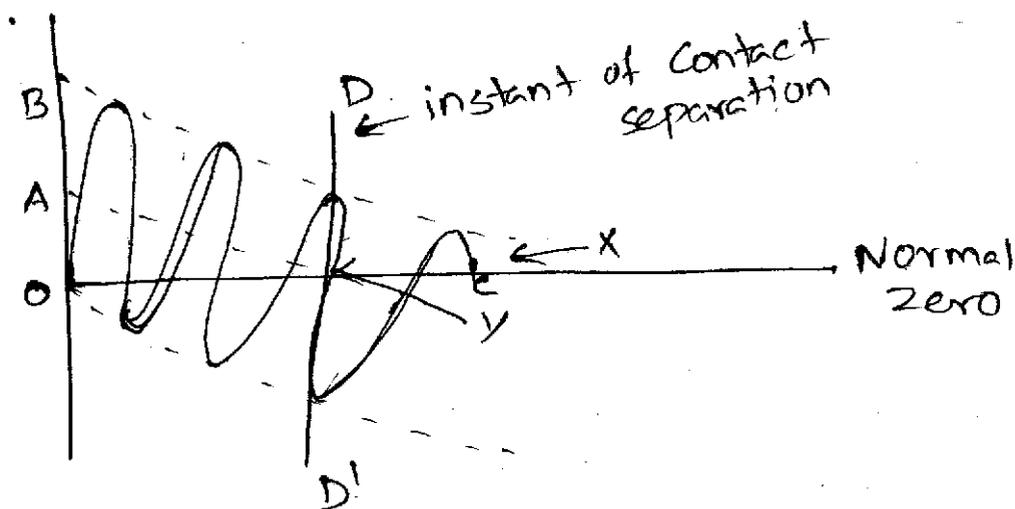
i) Breaking capacity:

It is the rms value of the fault current, that a circuit breaker is capable of breaking at a given recovery voltage under specified conditions (Power factor,

rate of rise of restriking voltage).

When a fault occurs, there is a considerable asymmetry in the fault current due to the presence of DC component.

The DC component dies away rapidly.



Referring to fig., the contacts are separated at DD' . At this instant, the fault current has

x = max. value of ac component

y = dc component

\therefore Symmetrical breaking current
= rms value of ac component

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

Asymmetrical breaking current

= rms value of total current

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

In common practice, the breaking capacity is expressed in MVA. Thus, if I is the rated breaking current in amperes and V is the rated service line voltage in volts, then for a 3-phase circuit,

$$\text{Breaking Capacity} = \sqrt{3} \times V \times I \times 10^{-6} \text{ MVA}$$

The breaking capacity will be symmetrical if the I in above expression is symmetrical. (British or Indian practice).

The breaking capacity will be asymmetrical if the I is asymmetrical (American practice).

The rated asymmetrical breaking current is taken as 1.6 times the rated symmetrical current.

ii) Making capacity:

The possibility of closing a circuit breaker contacts under fault condition is also considered.

The capacity of circuit breaker to "make" current (including DC component) and close successfully against the effect of electromagnetic forces.

Making capacity is stated in terms of a peak value of current instead of rms value.

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

Making capacity

$$= \sqrt{2} \times 1.8 \times \text{Symmetrical breaking capacity}$$

The multiplication by $\sqrt{2}$ is to obtain the peak value and by 1.8 to include the DC component of maximum asymmetry.

∴ Making Capacity

= 2.55 × Symmetrical breaking Capacity.

iii) Short-time capacity:

The circuit breaker must be capable of carrying short-circuit current for a short period while another circuit breaker (in series) is clearing the fault.

The rated short-time current is the rms value (both ac and dc components) of the current that the circuit breaker can carry safely for a specified short period.

However, if the fault persists for a duration longer than the specified time limit, the breaker will trip, disconnecting the faulty section.

iv) Rated voltage, current and Frequency:

The manufacturers of circuit breaker have specified a rated maximum

Voltage at which the operation of the circuit breaker is guaranteed.

The specified voltage is somewhat higher than the rated nominal voltage.

The rated current is the rms value of the current that a circuit breaker can carry continuously without any temperature rise in excess of its specified limit.

The rated frequency is the frequency mentioned by the manufacturer at which the circuit breaker has been designed to operate. The standard frequency is 50 Hz.

v) Rated operating duty:

The operating duty of a circuit breaker describes its operation which can be performed at a specified time intervals.

For a circuit breaker which is not meant for autoreclosing, there are two

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alternative operating duties as given below:

(i) $O-t-co-t'-co$

(ii) $O-t''-co$

where, O denotes opening operation

co denotes closing operation followed by opening without any intentional time lag.

$t, t',$ and $t'' \rightarrow$ time intervals between successive operations.

For circuit breakers with auto-reclosing the operating duty is as follows.

$O-Dt-co$

where, $Dt \rightarrow$ the dead time of the circuit breaker, which is expressed in cycle.

Types of circuit breakers:

The classification of circuit breakers has been made on the basis of insulating medium employed in the circuit breakers

to extinguish the arc. Depending on the arc quenching medium employed, the circuit breakers are of important type as follows:

- (i) Oil circuit breaker
- (ii) Air blast circuit breaker
- (iii) Sulphur Hexafluoride (SF_6) circuit breaker
- (iv) Vacuum circuit breakers.

1. Oil circuit breaker:

In such circuit breakers, some insulating oil (eg. transformer oil) is used as an arc quenching medium.

Advantages:

- i) It absorbs arc energy to decompose the oil into gases which have excellent cooling properties.
- ii) It permits smaller clearance between live conductors and earthed components.
- iii) The surrounding oil presents cooling

Surface in close proximity to the arc.

Disadvantages:

- i) Oil used is inflammable and there is a risk of fire.
- ii) It may form an explosive mixture with air.
- iii) The arcing products (eg. carbon) remain in the oil and its quality deteriorates with successive operation. This necessitates periodic checking and replacement of oil.

Types:

- i) Bulk oil circuit breaker
- ii) low oil (or) minimum oil circuit breaker.

Minimum oil circuit breaker:

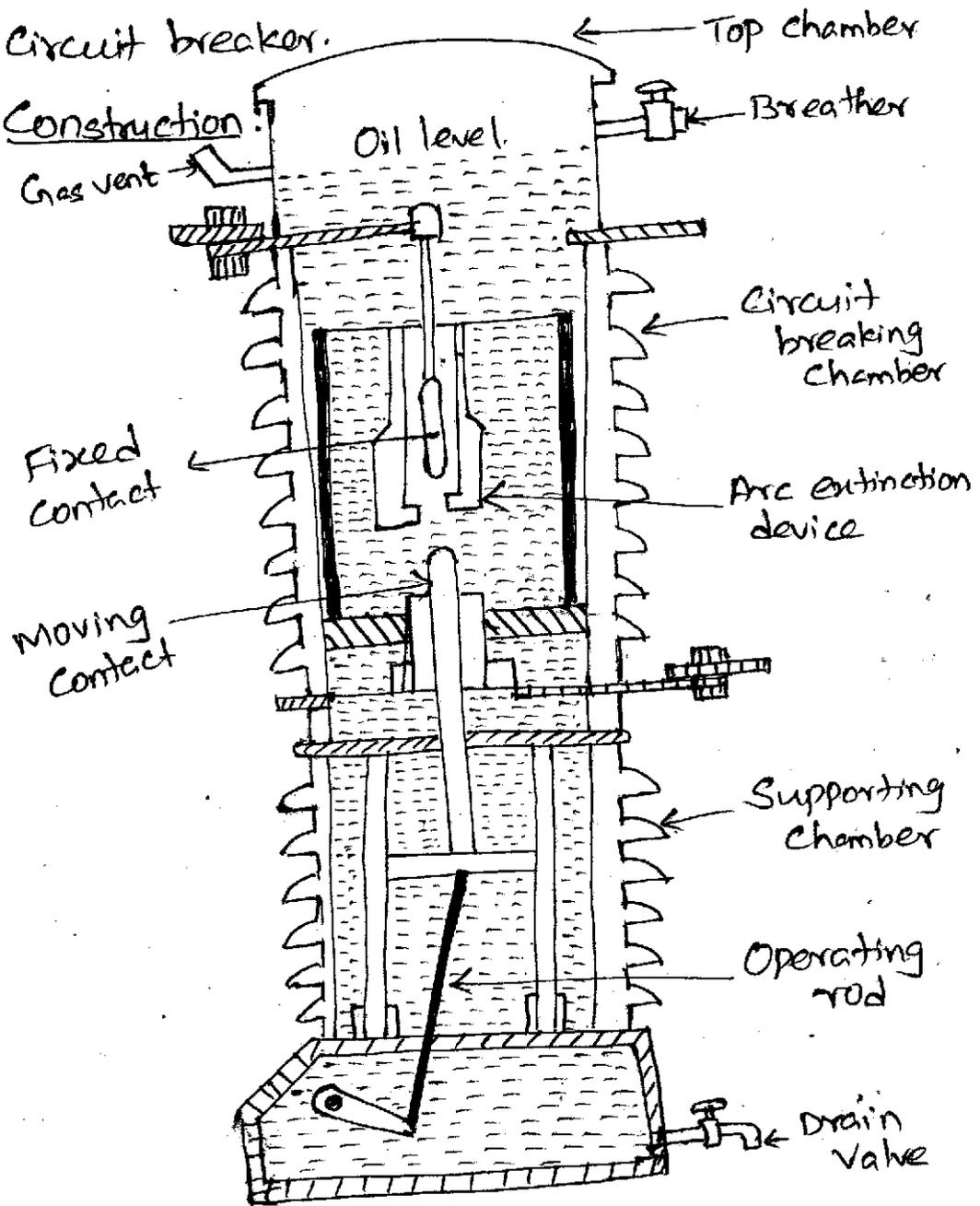
In bulk oil circuit breakers, the oil has to perform two functions. Firstly, it act as an arc quenching medium and secondly it insulates the live parts from earth.

This bulk oil not only increases the expenses, tank size and weight of the

breaker but it also increases the fire risk and maintenance problems.

This led to a development of low-oil circuit breaker.

Construction:



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Fig. shows the cross section of a single phase minimum oil circuit breaker.

There are two compartments separated from each other but both filled with oil, such that oil from one chamber is prevented from mixing with the other chamber.

The upper chamber is circuit breaking chamber while the lower one is the supporting chamber.

i) Supporting chamber:

It is a porcelain chamber mounted on a metal chamber. It is filled with oil which is physically separated from the oil in the circuit breaking chamber.

ii) Circuit-breaking chamber:

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

- a) Fixed contact
- b) moving contact
- c) turbulator

The moving contact is hollow and includes a cylinder which moves over a fixed piston.

The turbulator is an arc control device and has both axial and radial vents.

iii) Top chamber:

It is a metal chamber and is mounted on the circuit-breaking chamber which provides expansion space for the oil in the circuit breaking compartment.

Operation:

Under normal operating conditions, the moving contact remains engaged with the fixed contact.

When fault occurs, the moving contact is pulled down by the tripping springs and an arc is struck.

The arc energy vaporises the oil and produces gases under high pressure, which constrains the oil and passes through a central hole in the moving contact, at the

same time through the respective passages of the turbulator.

In the process of turbulation, the sections of the arc are successively quenched by the effect of separate streams of oil moving across each section.

Advantages:

The minimum oil circuit breaker has the following advantages over a bulk oil circuit breaker:

- i) It requires lesser quantity of oil
- ii) It requires smaller space
- iii) Reduced risk of fire
- iv) Maintenance problems are reduced.

Disadvantages:

Compared with bulk-oil circuit breaker,

- i) Due to smaller quantity of oil, the degree of carbonisation is increased.
- ii) Difficulty of removing gases from the contact space.

iii) The dielectric strength of oil deteriorates rapidly due to high degree of carbonisation.

Air-Blast circuit breakers:

These breakers employ a high pressure air-blast as an arc quenching medium.

Advantages:

1. No risk of fire
2. The arcing products are completely removed by the blast
3. The growth of dielectric strength is so rapid.
4. The arcing time is very small due to the rapid build-up of dielectric strength between contacts.

Disadvantages:

1. The air has relatively inferior arc extinguishing properties
2. These breakers are very sensitive to the variations of RRRV.

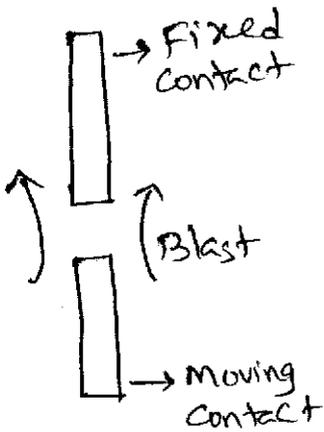
I-11

3. Considerable maintenance is required for the compressor plant which supplies the air-blast.

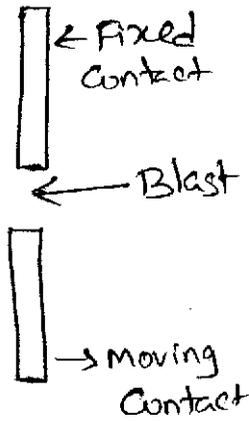
Types:

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

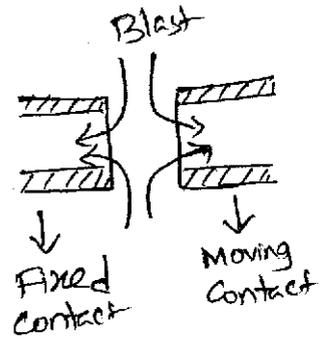
- i) Axial-blast type
- ii) Cross-blast type
- iii) Radial-blast type



(i)
Axial-blast



(ii)
Cross-blast

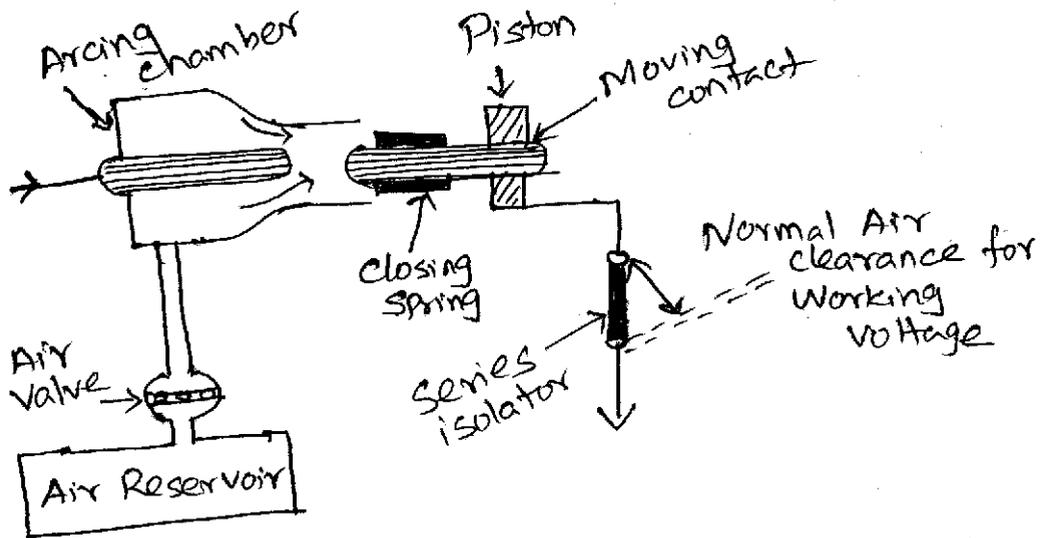


(iii)
Radial blast

i) Axial-blast type :

Fig. shows the typical axial-blast air

Circuit breaker.



The fixed and moving contacts are held in closed position by spring pressure under normal conditions.

An air reservoir is connected to the arcing chamber through an air valve, which remains closed under normal conditions, but opens automatically by the tripping impulse given due to fault current.

The opening of air-valve connects the the air reservoir to the arcing chamber.

The high pressure air entering arcing chamber pushes away the moving contact against spring pressure.

The arc struck between the contacts, an high pressure air-blast takes away the ionised gases along with it.

Therefore, an arc is extinguished and current flow is interrupted.

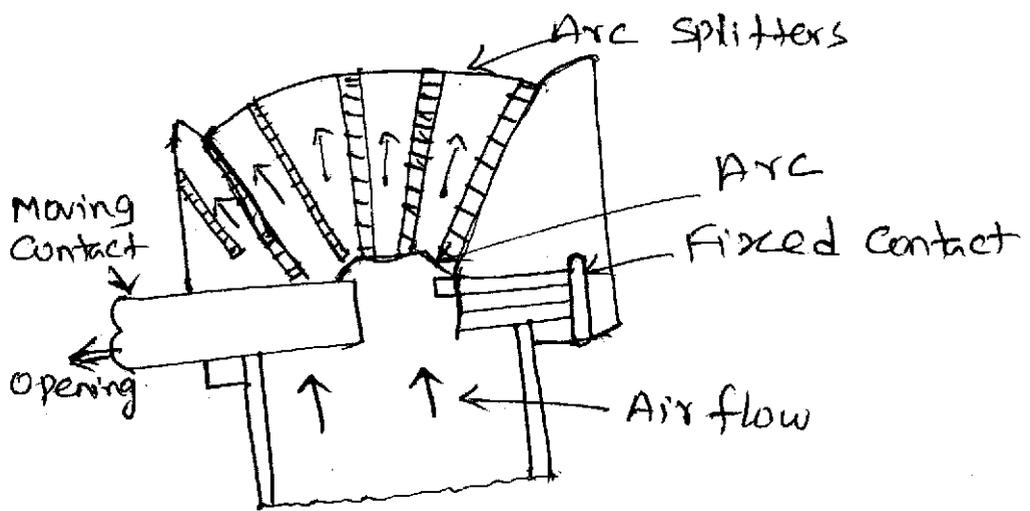
In such circuit breakers, the contact separation is generally small. Such small gap may constitute inadequate clearance for the normal service voltage.

So, an isolating switch is connected as a part of circuit breaker which opens immediately after fault interruption to provide the necessary clearance for insulation.

ii) Cross-blast type:

In this type of breakers, an air-blast is directed at right angles to the arc, which lengthens and forces the arc into a suitable chute for arc extinction.

Fig. shows a typical cross-blast air circuit breaker.



At the time of fault, when the moving contact is withdrawn, an arc is struck between the contacts.

The high pressure cross-blast pushes an arc into a chute consisting of arc splitters and baffles.

The splitters serve to increase the length of the arc and baffles give improved cooling, due to which an arc is extinguished and flow of current is interrupted.

The final gap for interruption is great enough to give normal clearance, so that a series isolating switch is not necessary.

3) Sulphur-Hexafluoride (SF_6) circuit breaker:

In such breakers, sulphur hexafluoride (SF_6) gas is used as an arc quenching medium.

The SF_6 is an electro-negative gas and has a strong tendency to absorb free electrons.

Advantages:

- i) Due to superior arc quenching property of SF_6 , such breakers have very short arcing time.
- ii) Can interrupt much larger currents.
- iii) Gives noiseless operation due to its closed gas circuit and no exhaust to atmosphere.
- iv) There is no moisture problem.
- v) There is no risk of fire because SF_6 gas is non-inflammable.
- vi) Have low maintenance cost.

Disadvantages:

- i) SF_6 breakers are costly due to high cost of SF_6 .

ii) Since, SF_6 gas has to be reconditioned after every operation of circuit breaker, an additional equipment is required for this purpose.

Construction:

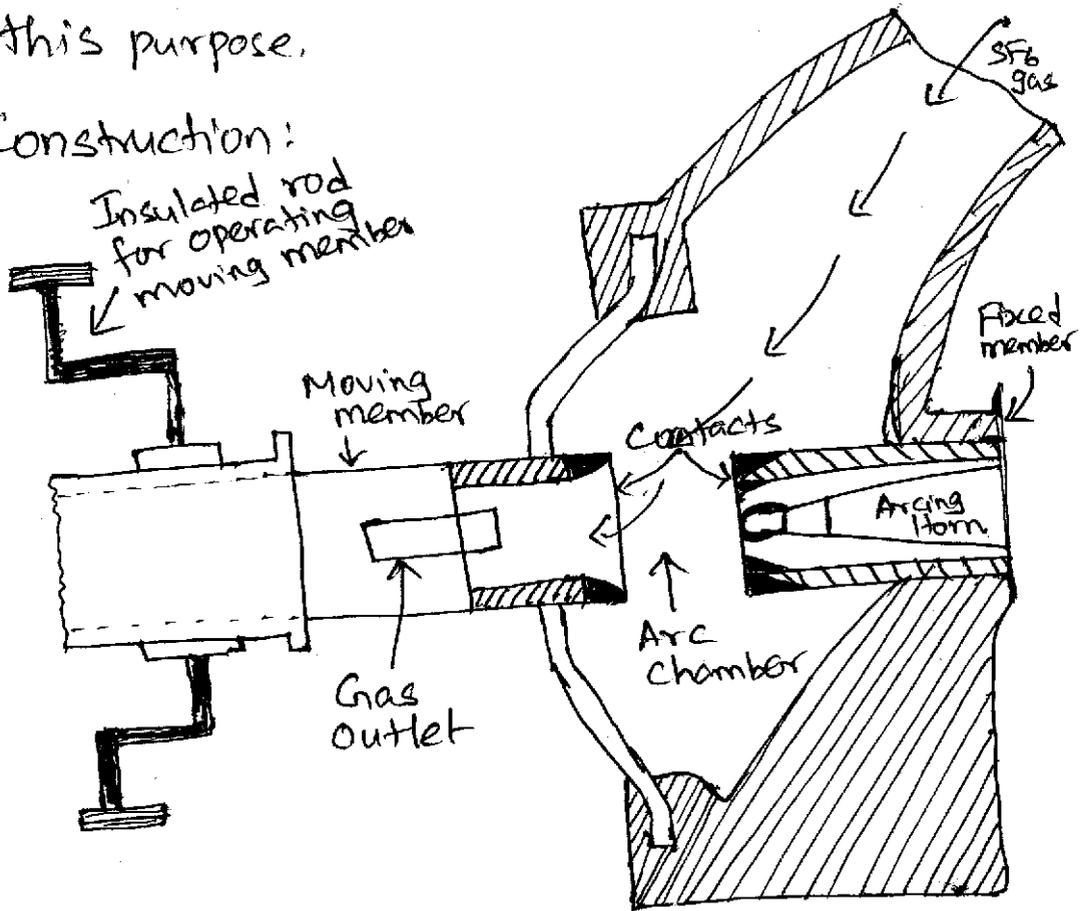


Fig. Shows a typical SF_6 circuit breaker. It consists of fixed and moving contacts enclosed in a chamber containing SF_6 gas. When the contacts of the breaker get opened, the high pressure SF_6 gas from the

reservoir flows towards the arc interruption chamber.

The fixed contact is a hollow cylindrical fitted with an arc horn.

The moving contact is also a hollow cylinder with rectangular holes in sides to permit SF₆ gas to let out.

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

Working:

When the breaker operates, the moving contact is pulled apart and an arc is struck between the contacts.

The movement of moving contact is synchronised with the opening of a valve which permits SF₆ gas at high pressure from the reservoir to the arc interruption chamber.

The high pressure SF₆ gas rapidly absorbs the free electrons in arc path.

The result is that the medium between the contacts quickly builds up dielectric

strength and causes the extinction of the arc.

After the breaker operation (i.e. after arc extinction), the valve is closed by the action of set of springs.

4) Vacuum Circuit Breaker (VCB):

In such breakers, vacuum (in the range of 10^{-7} to 10^{-5} torr) is used as the arc quenching medium.

Since vacuum offers the highest insulating strength, it has far superior arc quenching properties than any other medium.

Advantages:

- i) Compact, reliable and have longer life
- ii) No fire hazards
- iii) No generation of gas during and after operation.
- iv) Require little maintenance and quiet in operation.
- v) Can interrupt any fault current
- vi) Have low arc energy.

I-(13)

Principle:

When the contacts of the breakers are opened in vacuum (10^{-7} to 10^{-5} torr), an arc is struck between the contacts.

However, the arc is quickly extinguished because electrons and ions produced during arc are rapidly condense on the surface of the breaker contacts, resulting in quick recovery of dielectric strength.

Construction:

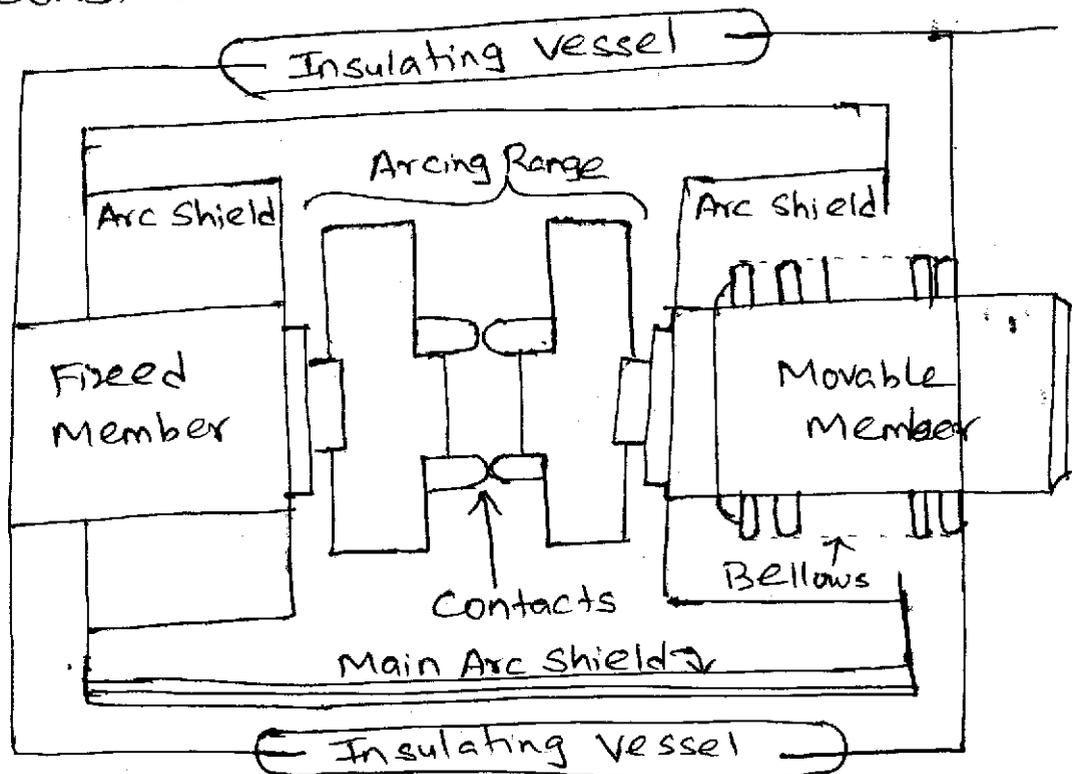


Fig. Shows the typical vacuum circuit breaker. It consists of fixed contact, moving contact and arc shield mounted inside a vacuum chamber.

The movable member is connected to the control mechanism by stainless steel bellows.

This enables the permanent sealing of the vacuum chamber so as to eliminate the possibility of leak.

A glass or ceramic vessel is used at the outer insulating body.

The arc shield prevents the deterioration of the internal dielectric strength by preventing metallic vapours falling on the inside surface of the outer insulating cover.

Working:

When the breaker operates, the moving contact separates from the fixed contact and an arc is struck between the contacts.

The arc is quickly extinguished because the metallic vapours, electrons and ions produced during arc are diffused in a

short time and seized by the surface of moving and fixed members and shields.

Since, vacuum has very fast rate of recovery of dielectric strength, the arc extinction in vacuum breaker occurs with a short contact separation.

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Important questions:

1. Explain the elementary principle of arc interruption in circuit breaker.
2. Define the term Restriking voltage and derive the equation of maximum RRRV
3. Explain in detail:
 - i. Current chopping
 - ii. Resistance switching
4. Explain in detail:
 - i. Making capacity
 - ii. Breaking capacity
 - iii. Short-time capacity rating
5. Describe the construction and operation of minimum oil circuit breaker with neat sketch.
6. Elaborately explain how a SF₆ circuit breaker works against the fault in power system.
7. Describe the operation of air-blast circuit breaker with neat sketch and denote its type of blast.
8. Explain the concept of vacuum circuit breaker with neat diagram.

UNIT - II

ELECTROMAGNETIC AND STATIC RELAYS

3.2 ELECTROMAGNETIC RELAY

The following are the important types of electromagnetic relays.

1. Attracted Armature type Relay
2. Balanced Beam Relay
3. Induction Disc Relay
4. Induction Cup Relay

The Electro magnetic Relay operator when operating torque/force is greater than the restraining torque/force.

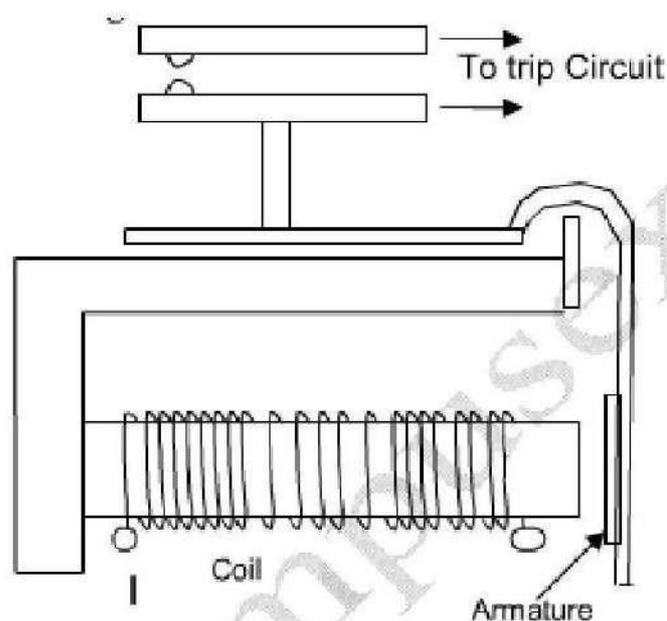
Attracted Armature Relay

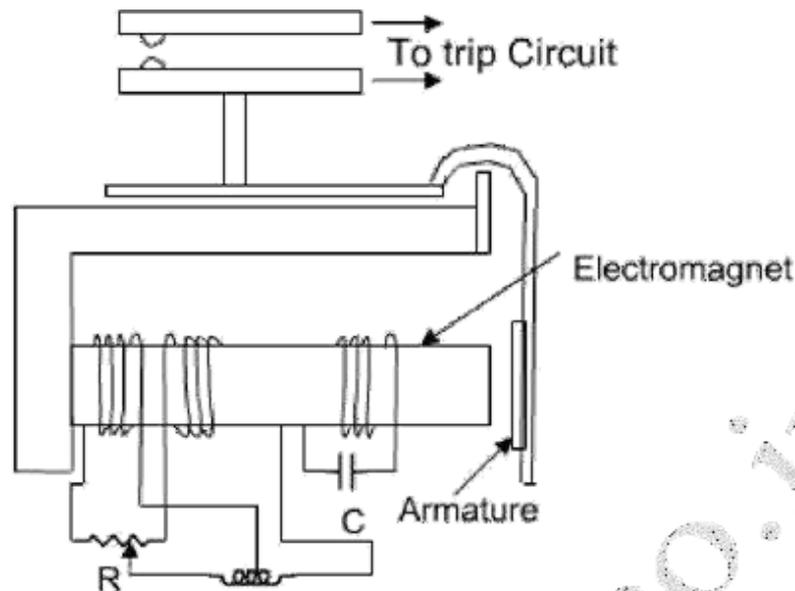
This is one of the simplest type of electromagnetic relay. Attracted armature relay has two types of constructions.

1. Hinged armature constructed
2. Plunger type construction.

Hinged armature type relay is shown in the figure 3.1(a) drawn below.

Figure:3.1





This type of relay consists of a coil and an electromagnet energized by that coil. The coil is energized by the operating quantity which may be proportional to the circuit current or voltage. This operating current produces a magnetic flux which in turn produces a electromagnetic force.

If the actuating quantity is dc then the electromagnetic force is constant. If the actuating quantity is ac, then the electromagnetic force is proportional to the square of flux or current. Since current is sinusoidal in ac $I = I_{max} \sin \omega t$

$$\text{Then } f = KI^2 = K(I_{max} \sin \omega t)^2 = \frac{1}{2}k(I_{max}^2 - I_{max}^2 \cos 2\omega t)$$

From the above equation, we can see that the net electromagnetic force consists of two components. The first component $\frac{1}{2}k(I_{max}^2)$ is constant and does not vary with time.

The second component $\frac{1}{2}k(I_{max}^2) \cos 2\omega t$ depends on time and it pulsates at double the frequency. Hence the total electromagnetic force is a double frequency pulsating force. This force may cause the armature to vibrate at double the frequency. Hence a humming noise is produced. This difficulty can be overcome by using two coils, one coil energized through a phase shifting network as shown in the figure 3.1(b) in which advantages of attracture armature type relay is

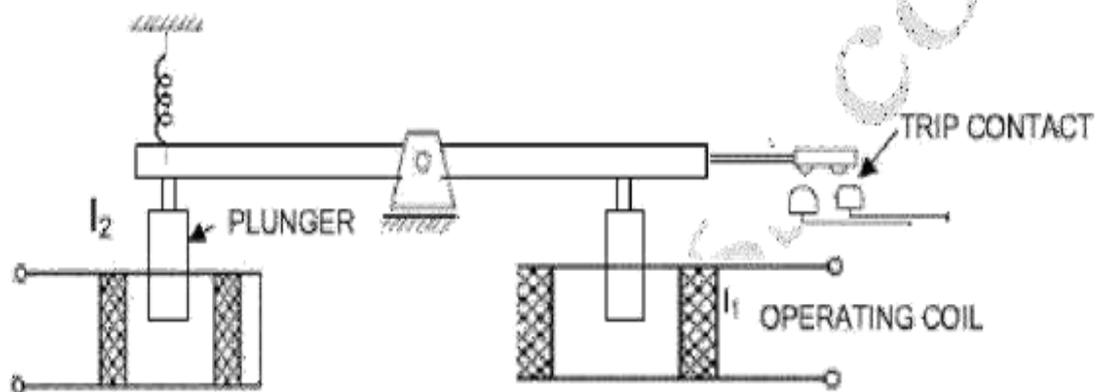
1. Its operating speed is very high
2. They can operate on both ac and dc.
3. Then dc transients can be reduced.

Balanced Beam Relay

Balanced Beam Relay consists of a horizontal relay pivoted at the centre. At the two ends of the beam, one armature is attached, and each armature is energized by two coils- operating coil and restraining coil.

When operating force is less than the restraining force, the beam remains in horizontal or slightly tilted position by means of spring such that the contacts are open. When operating force is greater than the restraining force the beam tilts down to close the contacts. The construction is shown in figure 3.2

Figure 3.2



Operating Principle

The net electromagnetic torque is given by

$$\tau = k_1 I_1^2 - k_2 I_2^2$$

Where I_1 = Current in operating coil

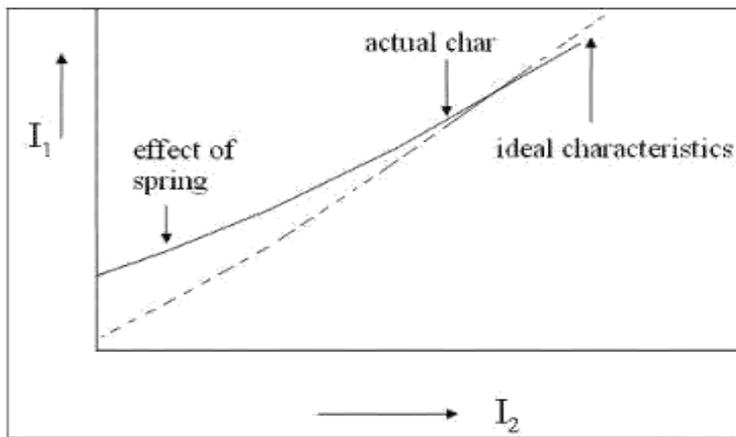
I_2 = Current in restraining coil

At the end of operation $\tau = 0$

$$k_1 I_1^2 = k_2 I_2^2$$

$$\Rightarrow \frac{I_1}{I_2} = \sqrt{\frac{K_2}{K_1}} = \text{Constant}$$

The operating characteristic is shown in the figure.



The curve is straight line, which is slightly tilted due to effect of spring. Balanced beam relay is difficult to design for large current because force is proportional to restraining current I_2 .

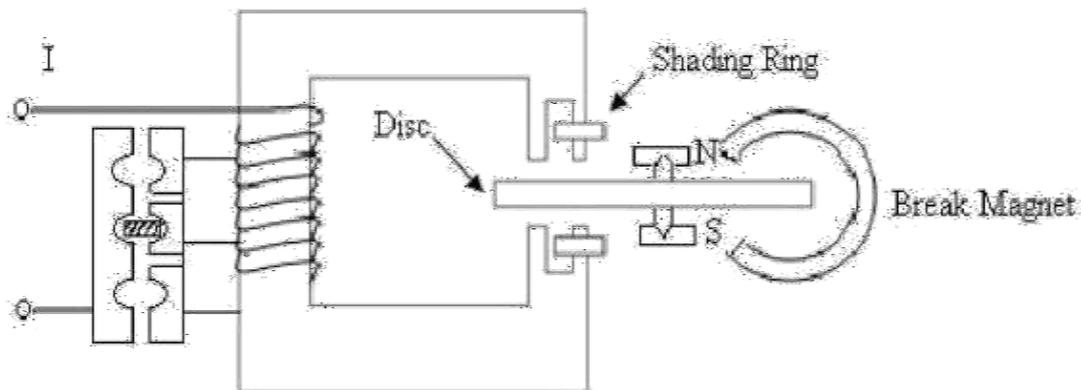
Induction Disc Relay

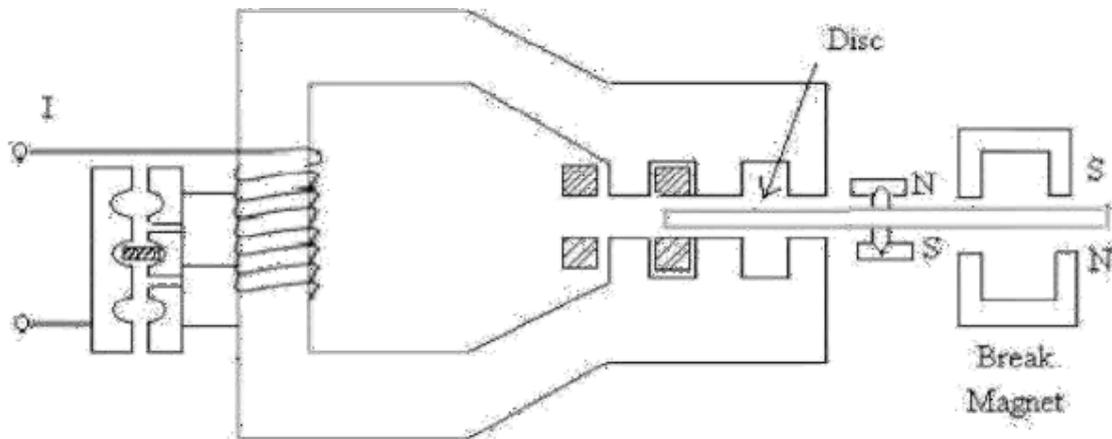
Induction Disc Relay has two types of constructions – shaded pole type induction disc relay and watt metric type induction disc relay.

Shaded – pole type disc relay

Simple construction of shaded – pole type disc relay is shown in figure 3.3(a) where as actual construction used practically is shown in figure 3.3(b).

Figure 3.3





It consists of a disc shaped electromagnet made of aluminium and a c-shaped electromagnet. One half of each pole is surrounded by a copper ring known as shaded ring. The flux produced by the pole with shading ring is displaced in phase with that of flux developed by the pole with out shading ring. These two flux induces eddy currents in electromagnet. The flux produced by one pole interacts with the eddy current produced by the flux of another pole and produces electromagnetic torque which rotates the disc.

Watt metric type Induction relay:

The construction for watt metric type induction relay is shown in the figure 3.4 drawn below.

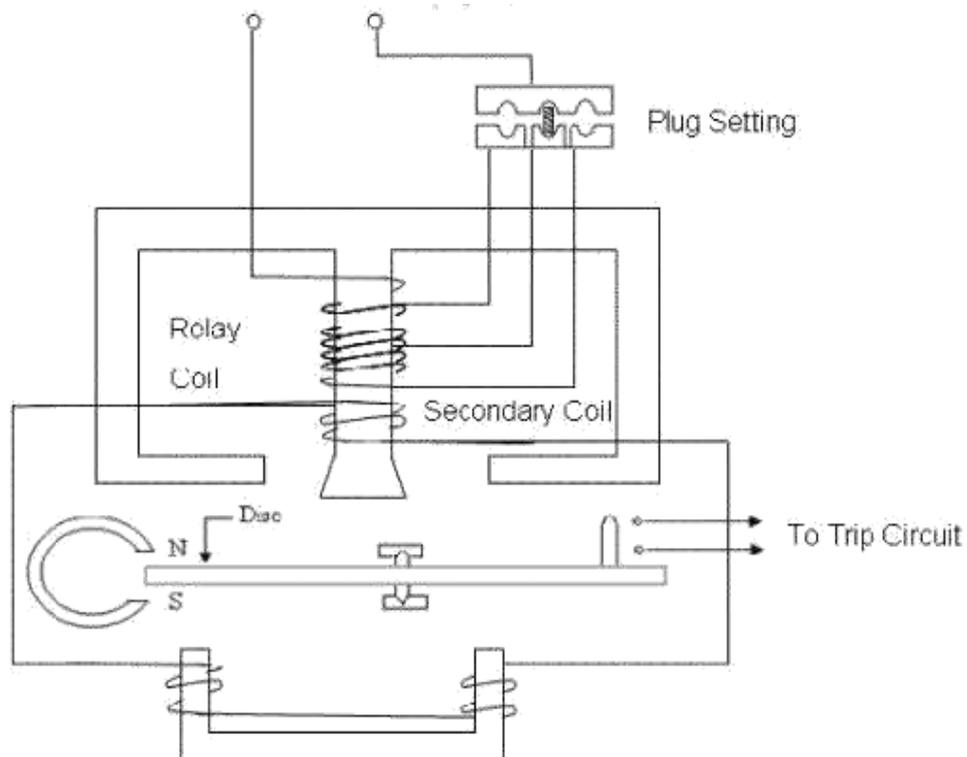


Figure 3.4

In this type of relay, there are two electromagnets wound with coils, one upper and one lower. These two coils are energized by two different supplies or a single supply with different resistance and reactance which causes phase displacement between two supplies.

The flux developed by each torque produces electromagnetic torque which tends to rotate the electromagnetic coil. The disc rotates at a speed proportional to the electromagnetic torque (or) driving torque. This driving torque is produced when operating current exceeds pick-up value; the disc remains stationary by the tension of the control spring.

Here we define two important settings for an induction disc relay.

Current Setting:

Current setting is provided by the tapping provided on coil. We can select a desired pick-up value by selecting a particular tapping.

Time Setting:

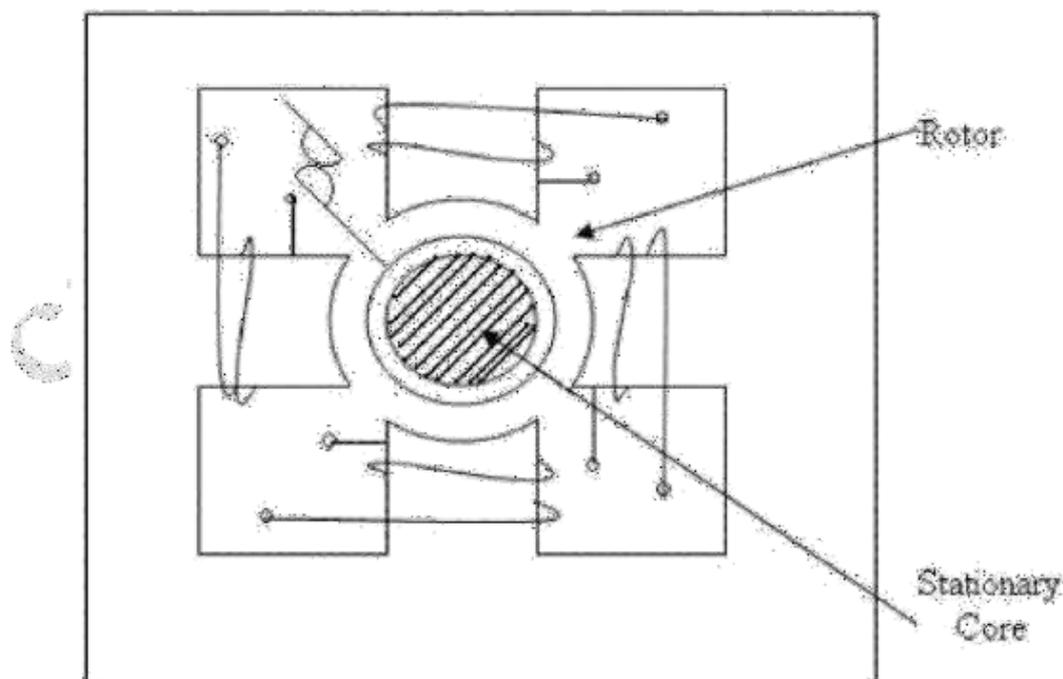
By adjusting the position of the back stop, the distance by which the disc travels before it closes the relay contact can be varied. If the back stop is advanced, the distance and hence operating time of the relay can be reduced.

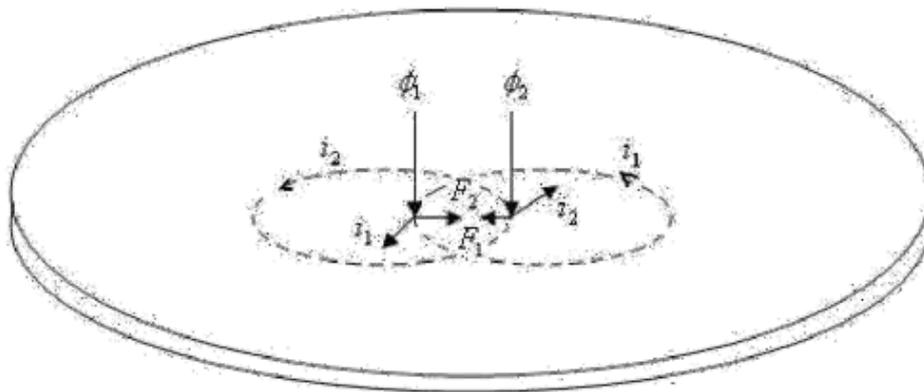
Induction Cup relay:

Induction cup relay consists of an inverted cup (Rotor) which is a hollow as Linder. It is enclosed by a 4 or 8-pole structure. To decrease the air gap with out increasing inertia, a stationary iron core is placed inside the cup. An arm is attached to spindle of cup, so that when cup is rotated, the contacts opens or closes.

Two pairs of coils are wound around the poles shown in the figure 3.5.

Figure 3.5





These currents produce flux which induces current in the cup. Due to the interaction of flux with the current, electromagnetic torque is developed which tends to rotate the cup and hence open or close the contacts.

The inertia of the cup is very much less. The magnetic leakage of the circuit is also less and hence this relay is more efficient. Its operating speed is also high. The dc transients in it are self eliminated. Magnetic saturation can be avoided in this type of relay.

Theory of Induction relay torque.

In both induction cup and disc relays, the force on the rotor is produced to interaction of one flux with the current produced by other flux.

If Φ_1 is flux produced by one coil and Φ_2 is flux produced by other coil with a phase difference of θ (i.e., Φ_2 leads Φ_1 by θ) they are expressed as

$$\phi_1 = \phi_{1m} \sin \omega t \text{ and}$$

$$\phi_2 = \phi_{2m} \sin(\omega t + \theta)$$

\therefore Voltage induced in the rotor

$$e_1 \propto \frac{d\phi_1}{dt}$$

$$\propto \phi_{1m} \cos \omega t$$

$$e_2 \propto \frac{d\phi_2}{dt}$$

$$\propto \phi_{2m} \cos(\omega t + \theta)$$

The eddy current induced in the rotor are in phase with their voltage.

$$\therefore i_1 \propto e_1 \propto \phi_{1m} \cos \omega t$$

$$i_2 \propto e_2 \propto \phi_{2m} \cos(\omega t + \theta)$$

The eddy current induced in the rotor are in phase with their voltage.

$$\therefore i_1 \propto e_1 \propto \phi_{1m} \cos \omega t$$

$$i_2 \propto e_2 \propto \phi_{2m} \cos(\omega t + \theta)$$

The torque or force produced in the rotor is proportional to the product of flux linking it and eddy current produced by other flux.

$$\therefore F_1 \propto \phi_1 i_2$$

$$\propto \phi_{1m} \sin \omega t \times \phi_{2m} \cos(\omega t + \theta)$$

$$F_1 \propto \phi_{1m} \phi_{2m} \sin \omega t \cdot \cos(\omega t + \theta)$$

$$\therefore F_2 \propto \phi_2 i_1$$

$$\propto \phi_{2m} \sin(\omega t + \theta) \times \phi_{1m} \cos \omega t$$

$$F_2 \propto \phi_{1m} \phi_{2m} \sin(\omega t + \theta) \cdot \cos \omega t$$

These forces act in opposite directions.

\(\therefore\) The net force

$$F = F_2 - F_1$$

$$\propto \phi_{1m} \phi_{2m} \sin(\omega t + \theta) \cos \omega t - \phi_{1m} \sin \omega t \times \phi_{2m} \cos(\omega t + \theta)$$

$$\propto \phi_{1m} \phi_{2m} [\sin(\omega t + \theta - \omega t)]$$

$$\propto \phi_{1m} \phi_{2m} \sin \theta$$

\(\phi_{1m}\), \(\phi_{2m}\) are taken as \(\phi_1\), \(\phi_2\) respectively. Where \(\phi_1\) and \(\phi_2\) are rms values

Then,

$$F = k \phi_{1m} \phi_{2m} \sin \theta$$

$$= k \phi_1 \phi_2 \sin \theta$$

If \(\phi_1\) and \(\phi_2\) are produced by same current I, then

$$\phi_1 \propto I$$

$$\phi_2 \propto I$$

$$\Rightarrow F = kI \times I \sin \theta$$

$$= kI^2 \sin \theta$$

If two different currents I₁ and I₂ produce flux \(\phi_1\) and \(\phi_2\), then

$$F = kI_1 I_2 \sin \theta$$

3.3 CLASSIFICATION OF RELAYS

Relays are also classified on the basis of their time-current characteristics.

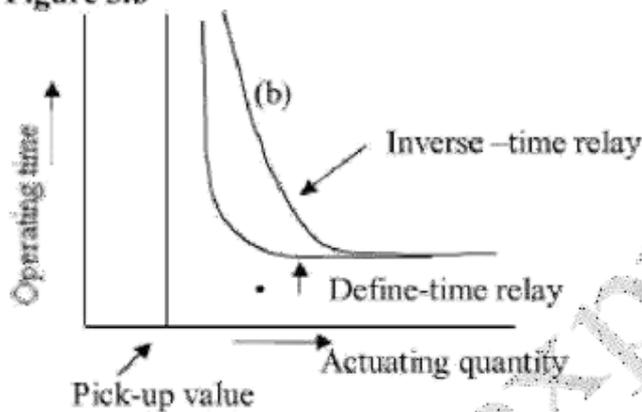
Instantaneous Relay

When the actuating quantity exceeds its pick-up value then the instantaneous relay operates in a definite time. The operating time is constant and is independent of magnitude of current. It is a very fast acting relay and there is no time delay in its operation.

Definite – time over current Relay:

A definite – time relay operates at a predetermined time when the actuating quantity exceeds its pick-up value. Assuming the actuating quantity as current, the time – current characteristic of a definite – time over current relay is shown in the figure 3.6(a)

Figure 3.6



The predetermined definite time is set up by a time – delay mechanism.

Inverse – time relay:

Inverse – time relay operates when the actuating quantity exceeds pick – up value. The operating time depends upon the actuating quantity. If the actuating quantity (eg: current) increases, then the current decreases and vice-versa. The inverse time characteristics is shown in the figure 3.6(b)

Inverse Definite Minimum Time Over current (I.D.M.T) Relay:

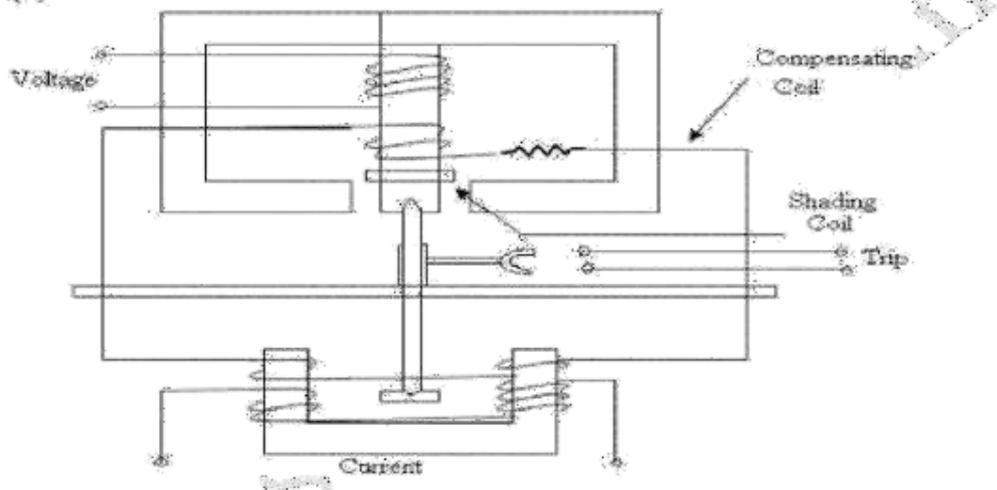
I.D.M.T Relay acts as inverse – time relay for low values of fault current and as definite – time relay for high value of fault current. If the plug setting multiplier is below 10, it shows inverse – time characteristics.

3.4. DIRECTIONAL RELAY:

A Directional Relay can be formed from an over current relay by adding a directional element to it. The directional relay operates, only when the current exceeds the pick – up value in only one direction. If the power flow is opposite to the specified direction, the directional relay does not operate. The directional relay does not measure the magnitude of the power flow, but it senses the direction of the power flow.

The figure drawn below shows electromagnetic induction disc type directional relay.

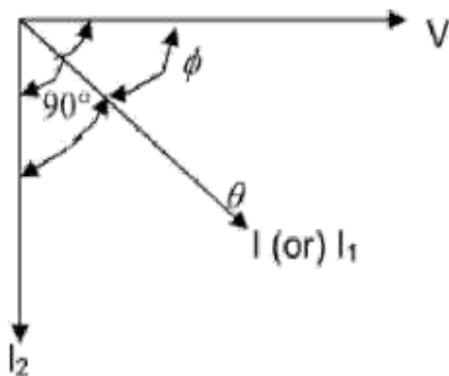
Figure 3.7(a)



It is energized two quantities current I (operating quantity) and voltage V (restraining quantity). The V and I sets up flux Φ_1 and Φ_2 respectively in the disc. Eddy current produced by Φ_1 interacts with Φ_2 and produces a torque. Similarly, eddy current produced by Φ_2 interact with Φ_1 also produces a torque. This torques tends to rotate the disc. Let the current in the voltage coil be I_2 which lags the voltage V by 90° . The load current I_1 lags the voltage V by ϕ .

Therefore the angle between I_1 and I_2 is $\theta = 90^\circ - \phi$, the phasor diagram is shown below.

Figure 3.7 (b)



∴ Torque produced is given by

$$\tau \propto I_1 I_2 \sin \theta$$

$$\propto I_1 I_2 \sin(90^\circ - \phi)$$

$$\propto I_1 I_2 \cos \phi$$

$$\tau \propto VI \cos \phi$$

∴ Maximum torque is produced when

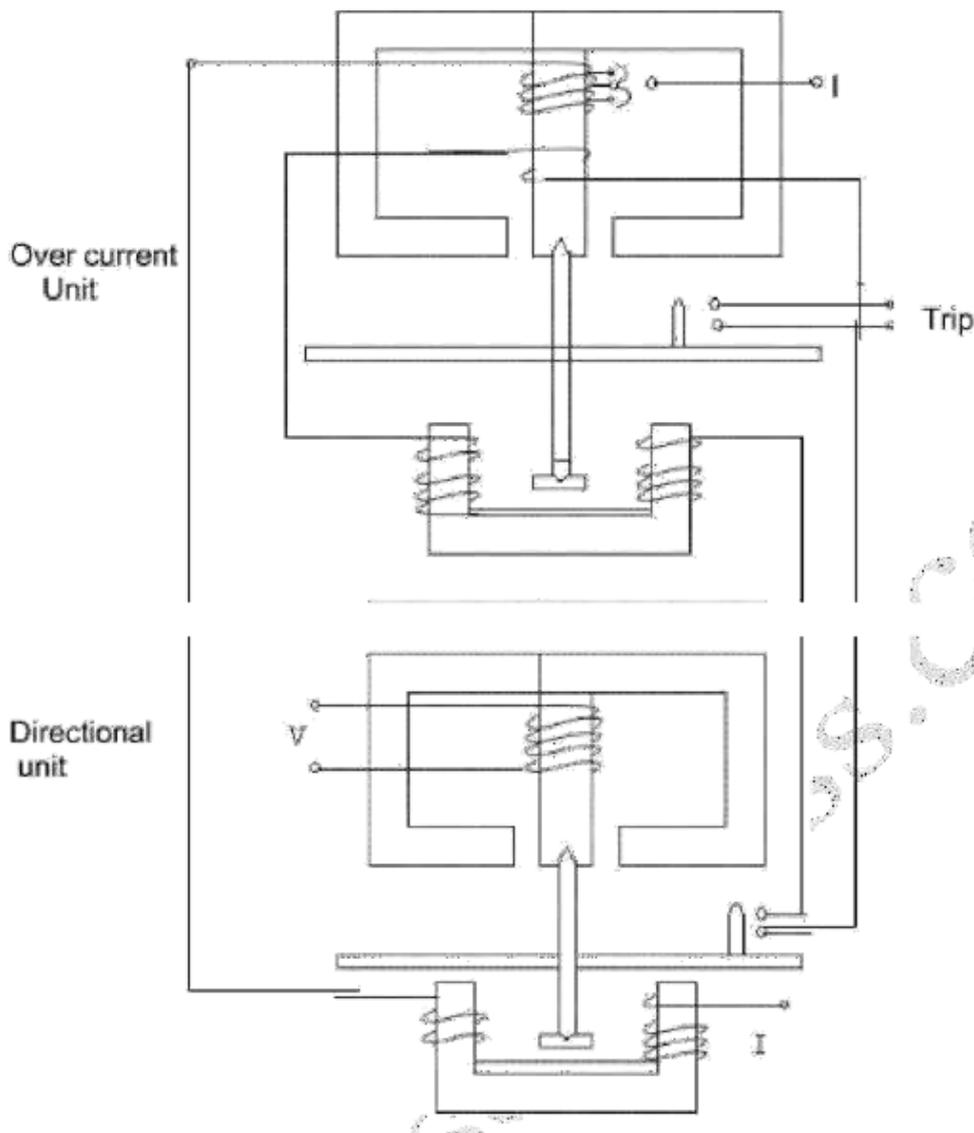
$$\cos \phi = 1 \Rightarrow \phi = 0$$

i.e., the voltage and current are in phase with each other.

Directional over Current Relay:

The figure drawn below shows directional over current relay.

Figure 3.8



In this a over current relay is used in conjunction with directional relay. The secondary winding of over current relay is kept open. When the directional relay operates, it closes the contacts of the secondary winding of the over current unit. Thus the directional feature is given to the over current relay.

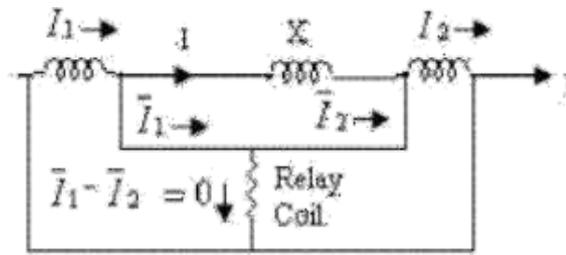
Differential Relay:

A differential relay is one which responds to the vector difference between two or more similar electrical quantities. For example, a differential relay responds to the vector difference of two currents I_1, I_2 i.e., magnitude $|\bar{I}_1 - \bar{I}_2|$ and phase angle difference $\angle(\bar{I}_1 - \bar{I}_2)$, so differential protection needs two actuating quantities.

Operating Principle:

The operating principle can be explained by considering the circulating differential protection of generators or transformers. The figure below shows the one with no internal fault.

Figure 3.9(a)



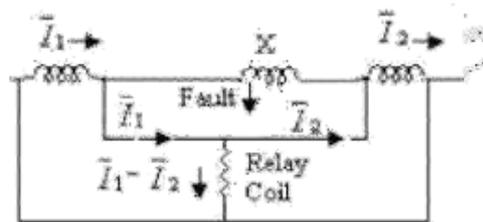
X is the winding of the machine to be protected. The current entering the winding is in phase with the current leaving the winding when there are no internal faults. The ratio of CT is such that the secondary currents of CT I_1 and I_2 are equal at normal conditions. I_1 and I_2 flow in same direction in pilot wires, connected during no internal fault. A relay coil is at the middle of the pilot wire. The relay is of over current type.

Since I_1 and I_2 are equal at normal conditions. $I_1 - I_2 = 0$

When there is some internal fault as shown in the figure $I_1 \neq I_2$

$$\therefore \bar{I}_1 - \bar{I}_2 \neq 0$$

figure 3.9(b)

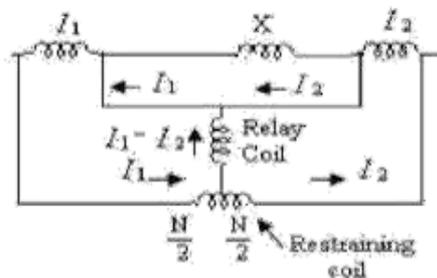


The current ($\bar{I}_1 - \bar{I}_2$) flows through the operating coil of relay. When this current is such that operating torque is greater than restraining torque then the relay operates.

Percentage differential relay:

To avoid problems due to external short circuits in differential relay an additional restraining coil is connected in pilot wire in the differential protection as shown in the figure.

Figure 3.10



The restraining coil is connected such that the operating coil is connected to middle of the restraining coil. The total ampere turns is the sum of ampere turns of two halves.

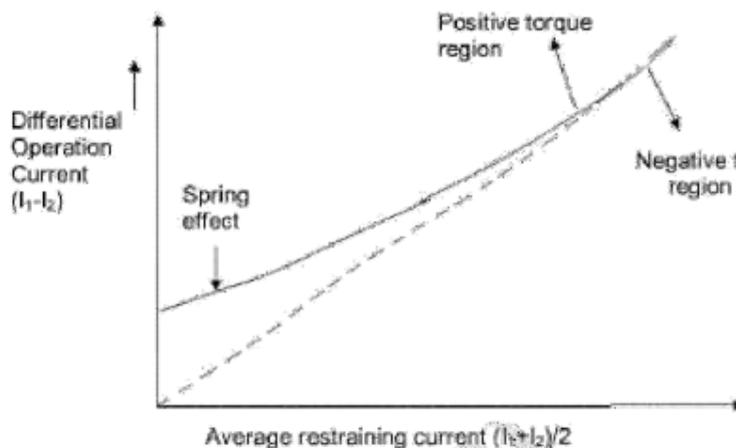
$$\text{i.e. total ampere turns} = \frac{I_1 N}{2} + \frac{I_2 N}{2}$$

$$= \left(\frac{I_1 + I_2}{2} \right) N$$

∴ Average restraining current = $\left(\frac{I_1 + I_2}{2} \right)$ in N turns

If there is an external fault then I_1 and I_2 increases, so that the average restraining current increases. When restraining torque becomes more than the operation, The characteristics of percentage differential relay is shown below.

Figure 3.11



The ratio of the differential operating current to average restraining current is a fixed percentage. Therefore the relay is also called percentage differential relay. It is also called biased differential relay.

3.5 APPLICATION OF RELAY:

Over Current Relay:

An over current relay is the relay which operates when the magnitude of current exceeds a pick up level. Over current relays are of following types.

1. Instantaneous over current relay
2. Definite – time over current relay
3. Inverse – minimum time over current relay
4. Inverse Definite minimum time over current relay

Over current relay protects the system from over loads, short circuits such as 3-phase faults, earth faults etc.,

Applications:

An over current relay has wide range of applications. They are

1. Motor Protection:

Over current relay is used for the protection of motor against over loads, short circuits in stator windings.

2. Transformer protection:

Transformer is protected against faults using over current relay in addition with differential relay.

3. Line protection:

The lines can be protected by using instantaneous, inverse time, directional over current relays.

4. Protection of utility equipment:

The industrial, commercial and domestic equipment can be protected using over current relays.

3.5.2 Directional Relay:

A Directional Relay can be formed from an over current relay by adding a directional element to it. The directional relay operates, only when the current exceeds the pick-up value in only one direction. If the current or power flow is in opposite direction, the directional relay does not operate.

The directional relay does not measure the magnitude of the power flow, but it senses the direction of the power flow.

Applications:

Directional relay is used where the selectivity can be achieved by directional relaying. Some of the applications of directional relay are

1. In feeders:

Directional relay set in feeders is used to regulate power flow in certain directions.

2. In generators:

Directional relays are used in reverse power protection of generator. The directional relay operates when the power flow is in opposite direction to that of normal power flow.

3.5.3 Differential relay:

A Differential relay is one which responds to the vector difference between two or more similar electrical quantities.

For example, the differential relay responds to the vector difference of two currents I_1 , I_2 i.e. magnitude and phase angle difference $|\bar{I}_1 - \bar{I}_2|$ and $\angle \bar{I}_1 - \bar{I}_2$ respectively. Hence differential relay needs two actuating quantities.

Applications:

1. Protection of Transformers
2. Protection of generators
3. Protection of Transmission line
4. Protection of feeders
5. Protection of large motors
6. Bus – zone protection

in

Distance Relays:

Distance protection is the protection and High Voltage (HV) and Extra High Voltage (EHV) transmission lines. It employs a number of distance relays. Each distance relay measures the impedance of the line from the fault point to the location of relay. Since the impedance is proportional to the line-length which in turn depends on the distance, the relay is called distance relay.

The distance protection provides both primary and back-up protection. Various types of distance relays are

- i. Impedance Relay
- ii. Reactance Relay
- iii. MHO Relay
- iv. Quadrilateral Relay
- v. Elliptical Relays
- vi. Angle impedance Relays

Here we discuss only first three types of relays.

3.6. IMPEDANCE RELAY:

An Impedance relay measures the impedance of the line from fault point to the point of location of relay. This impedance is proportional to the distance of the relay from the fault point. Impedance includes both resistance and reactance.

Operating Principle:

The Operating torque of an electromagnetic impedance relay is the sum of torques due to current, voltage and control-spring. Current produces operating torque (positive) and voltage produces restraining torque (negative).

$$\therefore \tau = K_1 I^2 - K_2 V^2 - K_3$$

where K_1 , K_2 and K_3 are constants.

Since K_3 is very small, it is neglected

$$\tau = K_1 I^2 - K_2 V^2$$

For the relay to operate

Operating torque > restraining torque

$$\therefore K_1 I^2 > K_2 V^2$$

$$\Rightarrow \frac{V^2}{I^2} < \frac{K_1}{K_2}$$

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

$$\Rightarrow Z < K \text{ ——— (1)}$$

For static or micro processor based impedance relays

$$K_1 I > K_2 V$$

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

$$\Rightarrow Z < K \text{ ——— (2)}$$

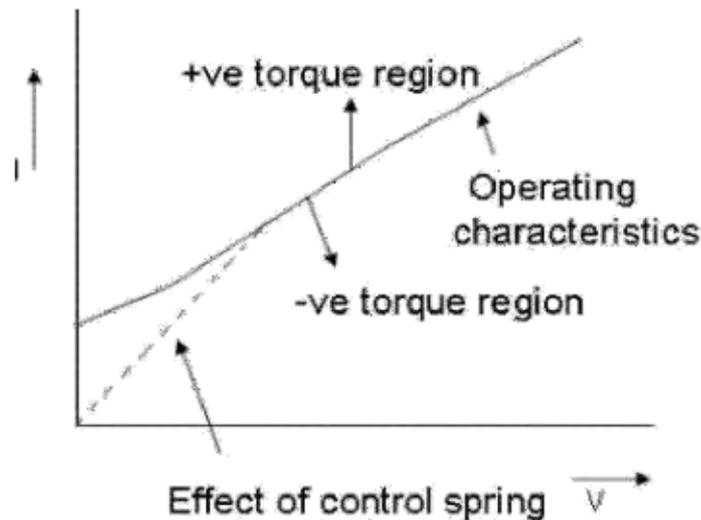
From both equation (1) and (2),

We can say that the relay operates only when the measured impedance is less than the given constant.

Characteristics:

The V – I characteristics of impedance relay is shown in the graph drawn below.

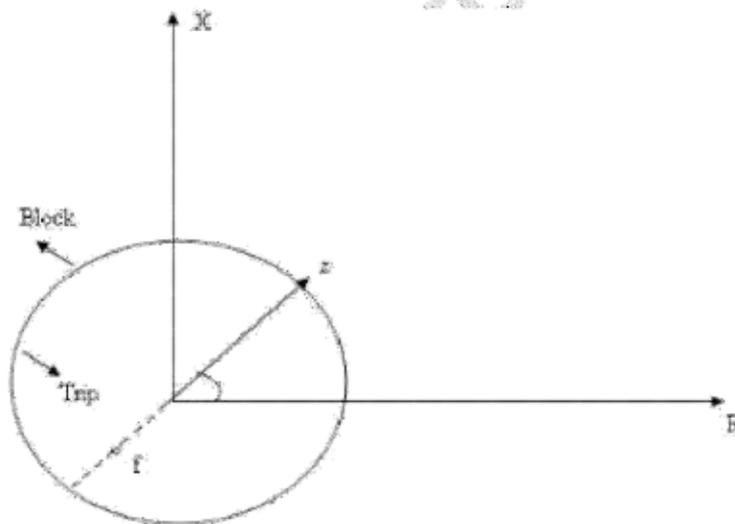
Figure 3.12



The graph is bent slightly at origin in electromagnetic relay due to the effect of control spring. For static and micro processor based relays the characteristics is a straight line.

Another way of representation of characteristics is by R-X diagram, as shown in the figure drawn below.

Figure 3.13



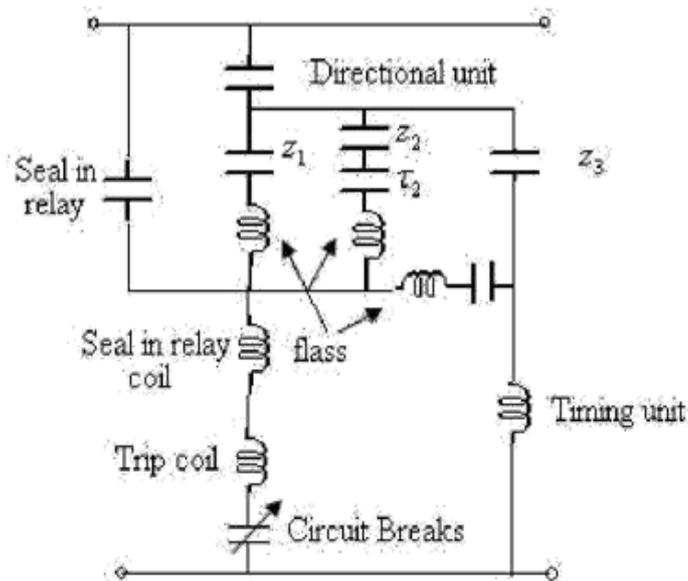
The circle shown in the above figure represents $z = k$ and outside the circle $z > k$ and inside the circle $z < k$. Φ is the phase angle between V and I . The operation of relay does not depend on Φ but depends only on the value of z . k is equal to the impedance of the line to be protected. If value of z is less than k it means fault point lies in the zone of relay and the relay operates and sends a trip signal. If value of z is greater than k , then the relay does not operate and it is in block mode i.e. fault point does not lies in into zone of operation.

Directional unit used with impedance relay:

An impedance relay without directional relay operates when the fault is in any direction i.e. either forward or backward. But when directional unit is used, the relay is

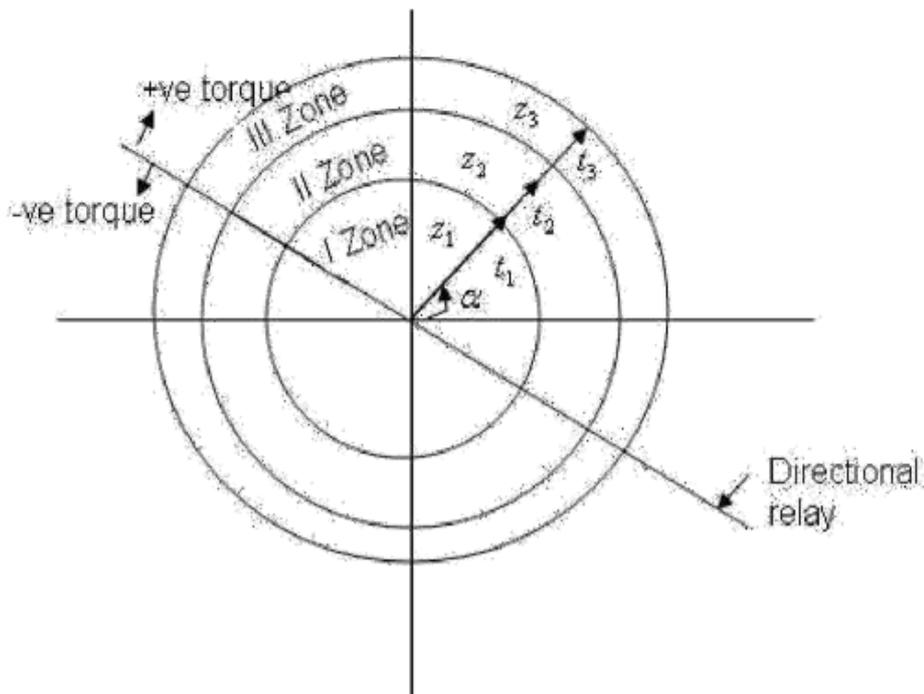
made to operate only when the fault is in specified direction. At any location, three impedance relays and a directional relay is employed. Directional relay is connected in series with the three impedance relay is shown in the figure drawn below.

Figure 3.14



t_2 and t_3 are the contacts of the timer for the second and third units. The characteristics of three-zone impedance relay with directional unit are shown in figure drawn below.

Figure 3.15



The characteristic circle is z_1 is smaller, z_2 is medium and z_3 is larger. t_1 , t_2 and t_3 are operating time for three relays.

The characteristic circle is z_1 is smaller, z_2 is medium and z_3 is larger. t_1 , t_2 and t_3 are operating time for three relays.

When a fault lies with in small circle and in the region of directional relay, the z_1 operates at a time t_1 . When the fault lies outside z_1 but inside z_2 , then T_2 closes after time t_2 when the circuit breaker trips. If the fault lies inside z_3 but outside z_1 and z_2 , the circuit breaker trips after closure of contact T_3 at time t_3 . The circuit breaker auxiliary switch is a

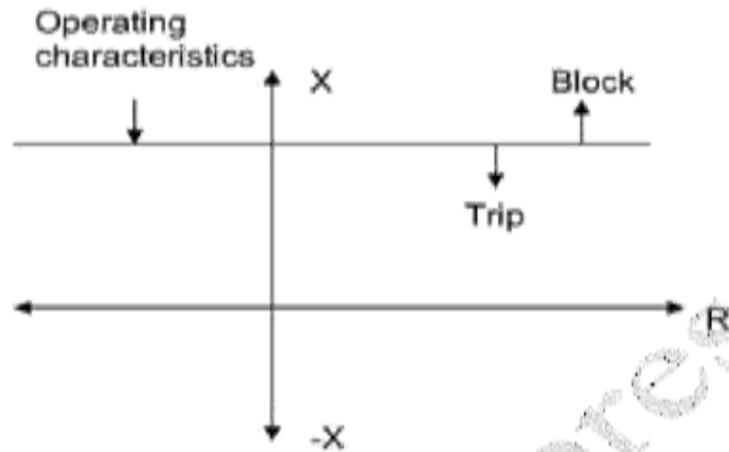
normally closed switch. When the circuit breaker trips, the auxiliary switch is opened to prevent damage of battery. A seal in relay is used to protect of contacts of main relay.

Reactance Relay:

Similar to the impedance relay, reactance relay measures the reactance of the line between the relay location and fault point. The operation of this relay is independent of resistance but depends only on reactance of line.

Hence the operating characteristics of reactance relay on R-X diagram is a straight line parallel to R-axis as shown in the figure drawn below.

Figure 3.16



Induction – cup type reactance relay:

The figure drawn below shows Induction cup type reactance relay. The current produces polarizing flux in the upper, lower and right hand side poles. The flux in right hand side pole is out of phase with that of upper and lower poles due to its secondary winding closed through a phase shifting network.

The actuating quantity for left hand side pole is voltage through a phase shifting circuit.

There fore the polarizing flux interacts with right hand side pole to develop torque $K_1 I^2$ (operating torque) and the flux interacts with left hand side pole to develop torque $K_2 V I \cos(90^\circ - \Phi)$.

There fore the total torque is given by $\tau = K_1 I^2 - K_2 V I \cos(90^\circ - \Phi) - K_3$

Where K_3 is due to control spring.

For the relay to operate

Operating torque > Restraining torque

$$\therefore K_1 I^2 > K_2 V I \cos(90^\circ - \Phi)$$

$$K_1 I > K_2 V \sin \Phi$$

$$\Rightarrow \frac{V}{I} \sin \Phi < \frac{K_1}{K_2}$$

$$\Rightarrow Z \sin \Phi < K$$

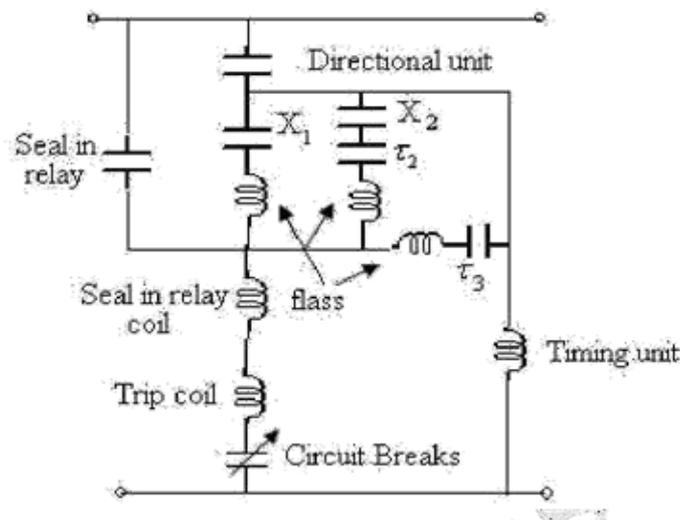
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$$\Rightarrow X < K$$

Therefore the relay operates only when the reactance is less than a given constant.

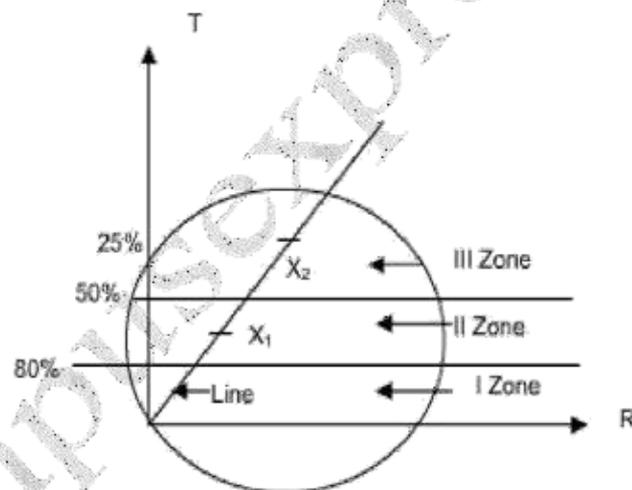
The connections for a reactance relay using directional unit is shown in the figure drawn below.

Figure 3.17



The characteristics diagram for the above reactance relay is shown below.

Figure 3.18

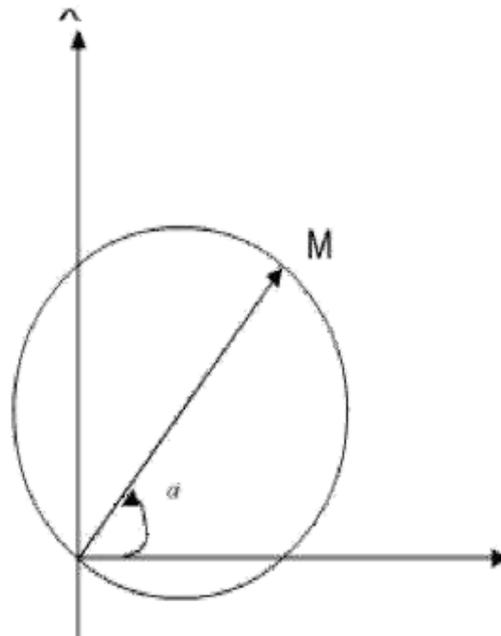


The circle represents the operating characteristics of directional unit. The unit I is used to protect 80 – 90% of the protected line. Unit II is used to protect 50% of the adjacent line. Unit III is a back – up protection for the whole adjacent line.

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MHO Relay:

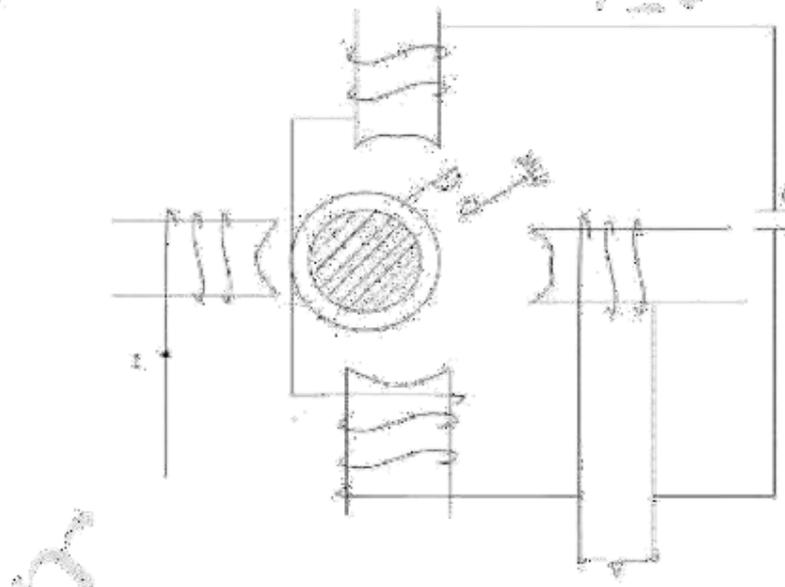
A MHO Relay or angle admittance relay measures a component of admittance $|y| \cos \theta$. It is a directional relay. The operating characteristics of MHO relay is a circle passing through origin when plotted in R-X diagram. When plotted in admittance diagram (G-B axes), its characteristics is a straight line.



Electro magnetic MHO relay:

Electro magnetic induction cup type MHO relay is shown in the figure drawn below.

Figure 3.19



The upper and lower poles are energized by voltage. The left hand side pole is energized by actuating quantity current. The flux produced interacts with the polarizing flux to develop a torque $K_1 VI \cos(\Phi - \alpha)$ which is operating torque. The right hand side pole is energized by voltage V . The flux produced in right hand side pole interacts with the polarizing flux to develop restraining torque $K_2 V^2$. Therefore the net torque is

$$\tau = K_1 VI \cos(\Phi - \alpha) - K_2 V^2 - K_3$$

Where K_3 is torque due to control spring.

For the relay to operate

Operating torque > Restraining torque

$$\therefore K_1 VI \cos(\Phi - \alpha) > K_2 V^2$$

$$(I/V) \cos(\Phi - \alpha) > (K_2/K_1)$$

$$Y \cos(\Phi - \alpha) > K$$

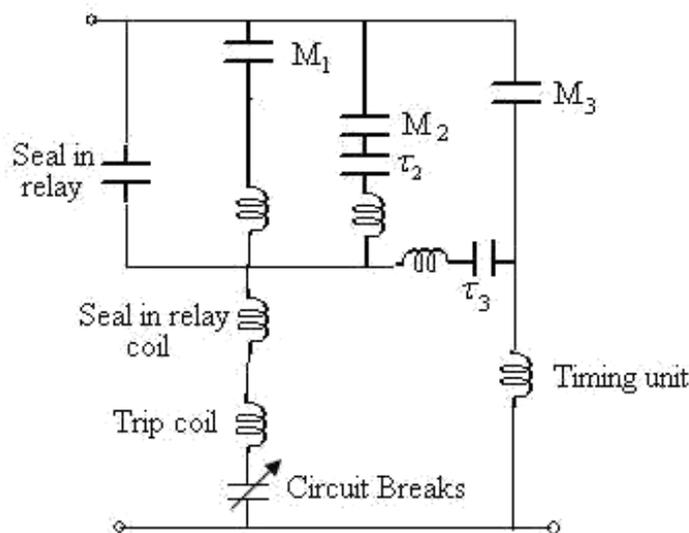
$$\frac{1}{Y \cos(\Phi - \alpha)} < K$$

$$M < K$$

\therefore The relay operates when M is less than a given constant.

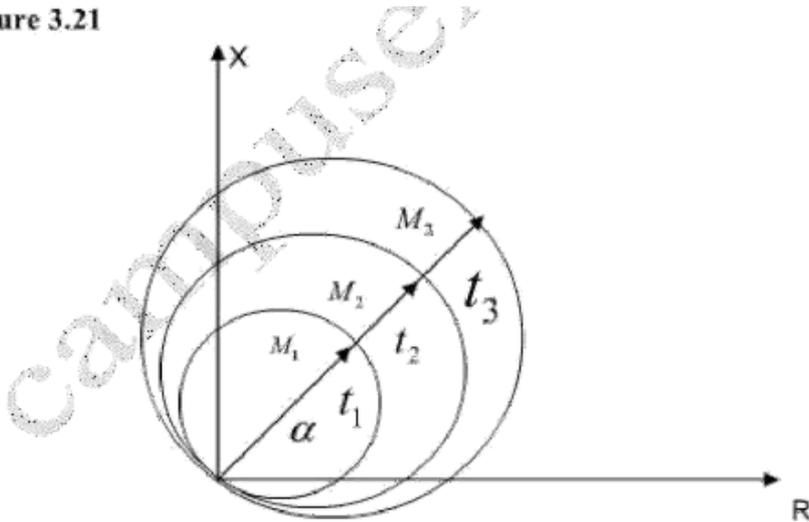
The connection of MHO relay with three units is shown in the figure drawn below.

Figure 3.20



The operating characteristics for the above connection are shown in the figure drawn below.

Figure 3.21

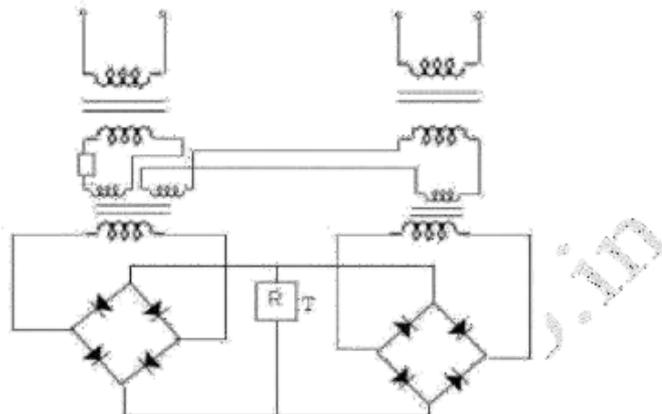


Unit I protects 80-90% of the protected section. Unit II protects 50% of the adjacent section. Unit III provides back-up protection.

Offset MHO Relay:

Offset MHO Relay can be realized using static MHO relay which is shown in figure below.

Figure 3.22



Here one actuating quantity is I (operating) and the other is $[(V/z_r) - nI]$ (restraining). Here n represents a fraction out put current of C.T is given to restrained circuit.

The relay operates only when

Operating quantity > Restraining quantity.

$$I > \left| \frac{V}{z_r} - nI \right|$$

Multiplying by z_r

$$|Iz_r| > |V - nIz_r|$$

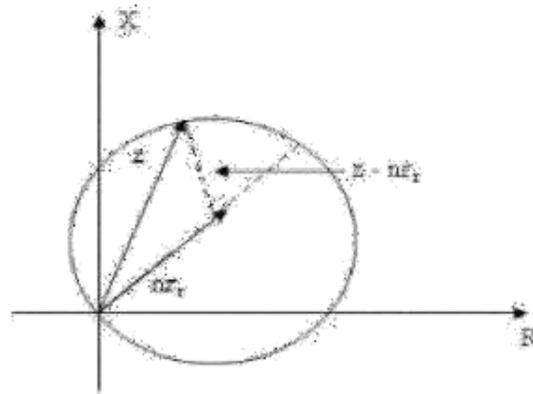
Dividing by z

$$|z_r| > \left| \frac{V}{I} - nz_r \right|$$

$$\Rightarrow |z_r| > |z - nz_r|$$

Therefore the characteristics of offset MHO relay is shown below.

Figure 3.23



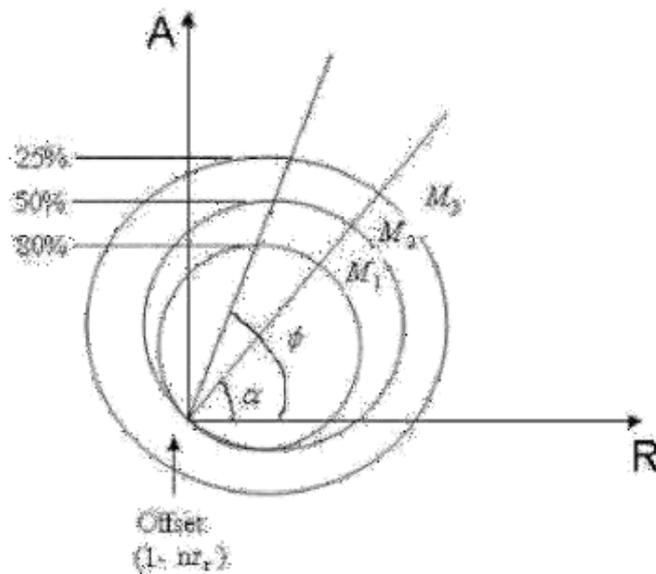
The typical offset value is 10% of protected line. When $V = 0$

$$I > |0 - nI|$$

Since n is a fraction. So the relay operates.

The offset characteristics of 3 unit relay is shown in the figure where unit III is offset MHO relay.

Figure 3.24



Notice that the characteristics of offset relay M_3 does not pass through origin. Unit III has following applications.

- i. Busbar zone back-up
- ii. Carrier starting unit
- iii. Power swing blocking

Comparison of characteristics of Distance Relay:

Impedance Relay:

Impedance relay is slightly affected by arc resistance as well as power and voltage surges. But it fails to detect a fault within 80% of protected line. Hence it is extensively used for medium lines for phase fault relay.

Reactance Relay:

Reactance relay is less affected by arc resistance and hence it is mainly used for ground fault relaying. It is also suitable for protection of short lines against phase faults. The main disadvantage of MHO relay is it is affected by power surges. So they are not suitable for longer lines since in long lines, power surges stays for a longer period.

MHO Relay:

MHO relay is less affected by power surges. MHO characteristics are best suited for protection of long lines against phase faults. But it is most affected by arc resistance.

3.7 STATIC RELAYS:

Static relay compares two electrical quantities using a static circuit and sends a tripping signal to the circuit breaker. The static circuit includes semiconductor diodes, transistors, thyristors, logic gates, diodes etc., static relays uses electromagnetic or dc polarized relays as slave relays. Slave relay do not actually measure the electrical quantity but it simply closed contact.

Static relays verses electromagnetic relays:

The advantages of static relays over electromagnetic are as follows:

1. Static relay is compact in size
2. Less maintenance is required
3. High resistance to shocks
4. Static relays consume less power. So it provides fewer burdens of potential transformers and current transformers.
5. There are no moving contacts.
6. A single static relay is used for several functions.
7. A static relay employs logic circuits. So it can do the process of reasoning.
8. It is used for remote back-up and network monitoring.

But the limitations of static relays are

1. The price of static relays is higher than the electromagnetic relays.
2. The device in the static circuit is very much affected by temperature.
3. Static devices such as thyristors are sensitive to electro-static discharges (ESD).
4. The semi conductor devices are sensitive to voltage transients. So they may get damaged.

Important questions:

- 1. Explain the constructional details of attracted armature type and balanced beam type electromagnetic attraction type relays.**
- 2. List out the basic requirements of the relay. Explain each one of them in detail**
- 3. Elaborate the operation of inverse and IDMT static relays**

Unit-3

Protection of Generators And Transformers

Introduction:

In modern electric power systems, it is desirable and necessary to protect the elements from a variety of fault conditions that may occur during their operation.

The most serious fault on an alternator which require immediate attention is the stator winding faults.

The major faults on transformers occur due to short-circuit in transformer.

The basic system used for protection against these faults is the differential protection scheme.

Protection of Generators:

Some of the important faults which may occur on a generator are:

- i) failure of prime mover
- ii) failure of field
- iii) over current

- iv) Overspeed
- v) Over voltage
- vi) Unbalanced loading
- vii) Stator winding faults.

Protection of generators against stator faults:

The stator winding faults (Phase to phase, phase to ground and inter-turn faults) are the most dangerous and are likely to cause considerable damage to the machinery.

Therefore, an automatic protection is absolutely necessary to clear such fault in the quickest time possible.

For the protection of generator against such faults, a differential protection (also known as Merz-price system) is most commonly employed.

In this scheme of protection, currents at the two ends of the protected section are compared.

Under normal operating conditions, these currents are equal but may become unequal on the occurrence of fault.

The difference of current under fault conditions is arranged to pass through the operating coil of the relay.

The relay then closes its contacts to isolate protected section from the system.

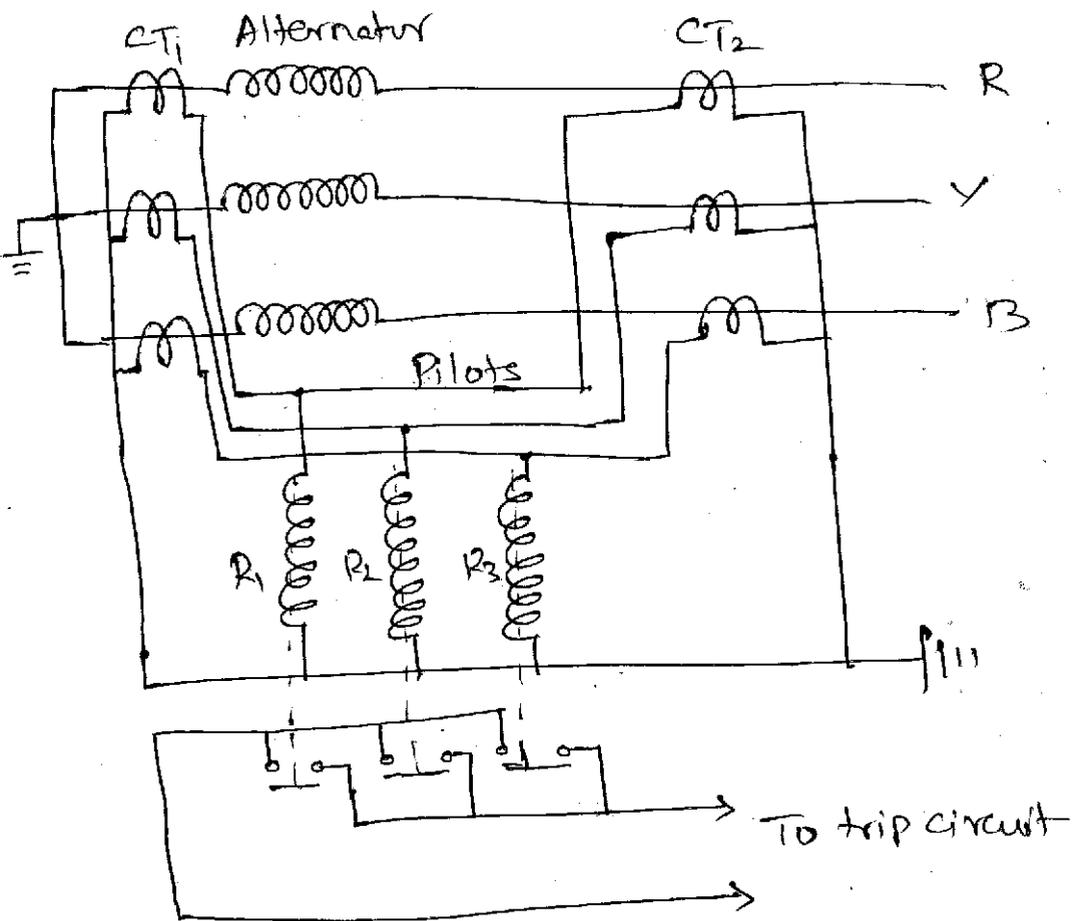
This form of protection is also known as Merz-Price circulating current scheme.

Fig. shows: the schematic arrangement of differential protection for a 3-phase generator.

Identical current transformer pairs CT_1 and CT_2 are placed on either side of each phase of stator winding.

The secondaries of CTs are connected in star by means of pilot cable.

Thus, there is an independent path for the currents circulating in each pair of CTs.



The relay coils are connected in star such that the outer ends are connected to each of the three Pilots.

In order that burden on each CT is the same, the relays are connected across equipotential points of the three pilot wires (middle of the pilot wires).

Under normal conditions, the currents

III - 2

at both ends of each winding will be equal and hence the currents in CT secondaries will also be equal.

Therefore, there is a balanced circulating current in the pilot wires and no current flows through the operating coils (R_1 , R_2 and R_3) of the relays.

When the fault occurs, the differential current flowing through the relay circuit operates the relay to trip the circuit breaker.

It should be noted that, the relay circuit is so arranged that, its energising causes

- i) opening of breaker connecting the ~~generator~~ generator to bus-bar
- and ii) opening of the field circuit of the generator.

Limitations:

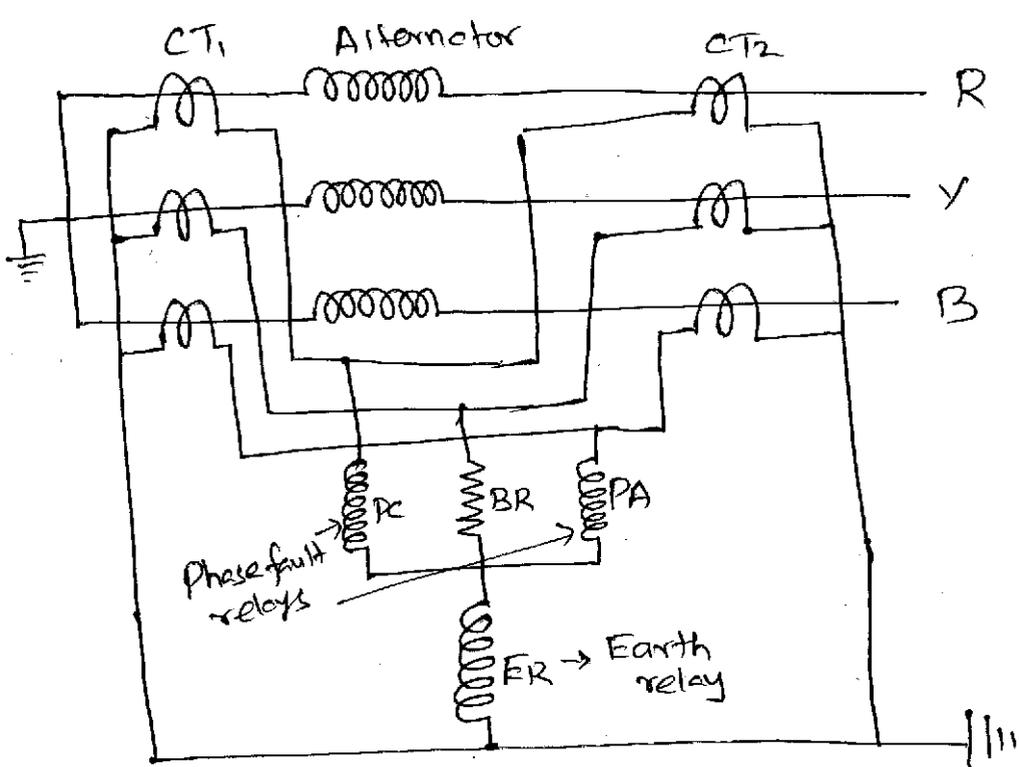
- Differential protection does not respond to external faults and overload.

- It provides complete protection against Phase-to-Phase faults.
- It provides protection against ground fault to about 80 to 85 percent of the generator windings.
- It does not provide protection to 100% of the winding because it is influenced by the magnitude of earth fault current which depends upon the method of neutral grounding.

Protection against phase-to-ground fault:

A modified form of differential protection, is used for the protection of generator against earth fault.

The modified arrangement is shown in fig. in which only the relay connections were modified, such that two relays for phase-fault protection and the third for earth-fault protection only.



The two phase elements and balancing resistance (BR) are connected in star and the earth relay (ER) is connected between this star point and the fourth wire of circulating current pilot-circuit.

Under normal operating conditions, currents at the two ends of each stator winding will be equal.

Therefore, there is a balanced circulating current in the pilot wire and no current flows through the operating coils of the relay.

If an earth fault occurs on any one phase, the out-of-balance current in CTs in that phase will flow through the earth relay (ER).

This will cause the operation of earth relay only.

For phase fault, the out-of-balance current will flow through the ~~the~~ two CTs secondaries without passing through the earth relay ER.

Therefore, only the phase-fault relays will operate.

Protection against stator inter-turn faults:

Menz-prize circulating current system does not protect against turn-to-turn fault on the same phase winding of the stator.

It is because the ^{fault} current produced can flow in a local circuit between the turns involved and does not create a difference between the currents entering and leaving the winding.

III - (3)

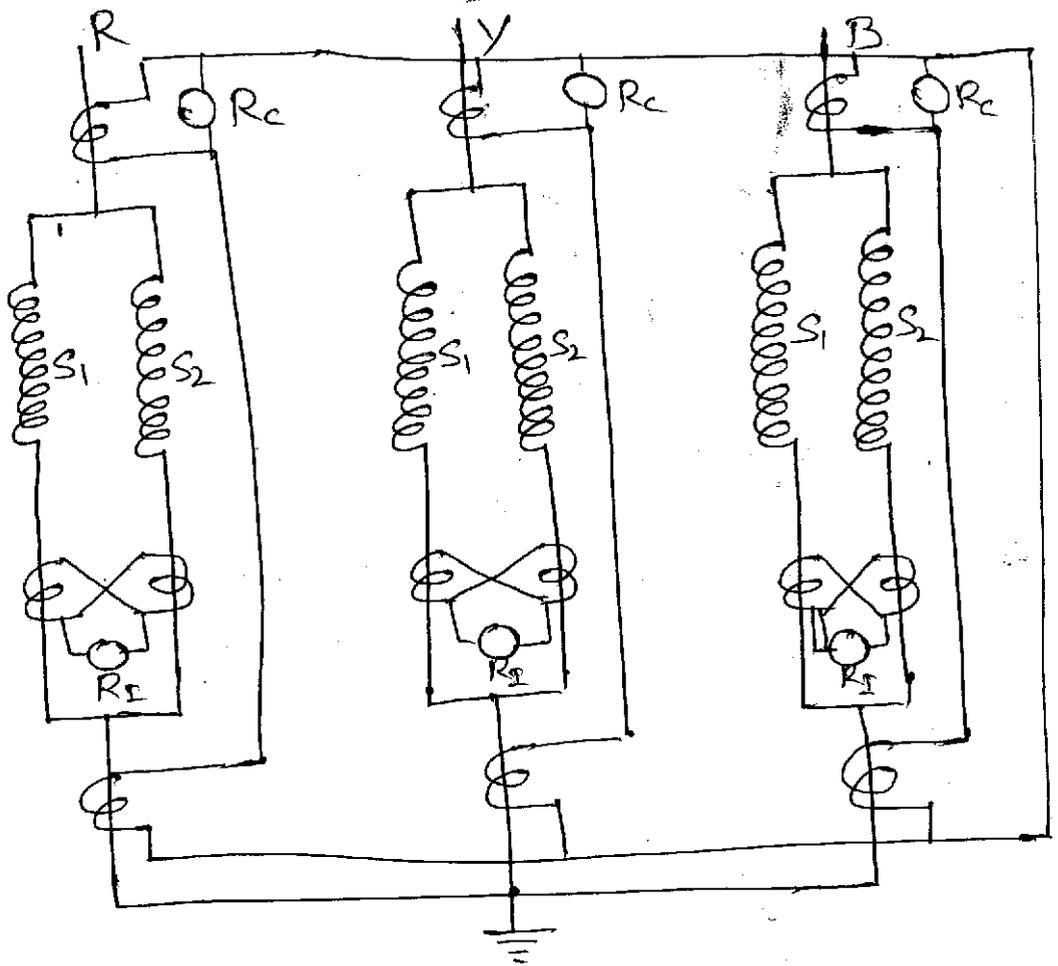
However, it is usually considered unnecessary to provide protection for inter-turn faults because they invariably develop into earth-faults.

However, inter-turn protection is provided for the generators which have double-winding armatures (i.e. each phase winding is divided into two halves), owing to the very heavy currents which they have to carry.

Fig. shows the schematic arrangement of circulating current and inter-turn protection ~~against~~ of a 3-phase double-wound generator.

The relays R_C provide protection against phase-to-ground and phase-to-phase faults whereas, relays R_I provide protection against inter-turn faults.

The two current transformers in one phase winding S_1 and S_2 are connected on the circulating current principle.



Under normal operating conditions, the currents in the stator winding S_1 and S_2 are equal and so will be the currents in the secondaries of two CTs. Therefore no current flows through the relay R_I .

If a short circuit develops between the turns, the currents in the stator windings S_1 and S_2 will no longer be equal.

Therefore, unequal currents will be induced in the secondaries of CTs and the difference of these currents flows through the relay R_I .

The relay then closes its contacts to clear the generator from the system.

Protection of generator against rotor faults:

Field failure or loss of excitation is considered to be the fault that might occur on rotor side of the generator.

The chances of loss of excitation of a generator are undoubtedly very rare. Even if it does occur, no immediate damage will be caused by permitting the generator to run without a field for a short-period.

It is sufficient to rely on the control room attendant to disconnect the faulty generator manually from the system.

Therefore, it is a universal practice

not to provide an automatic protection against this contingency.

This is the case with attendant stations, however, in unattendant stations, a loss of excitation relay may be justified.

When the excitation of generator is lost, it speeds up slightly and operates as an induction generator.

Round-rotor generators do not have damper windings and hence they are not suitable for such an operation. The rotor is overheated quickly due to heavy induced currents in the rotor iron.

The rotors of salient-pole generators are not overheated because they have damper windings which carry induced currents.

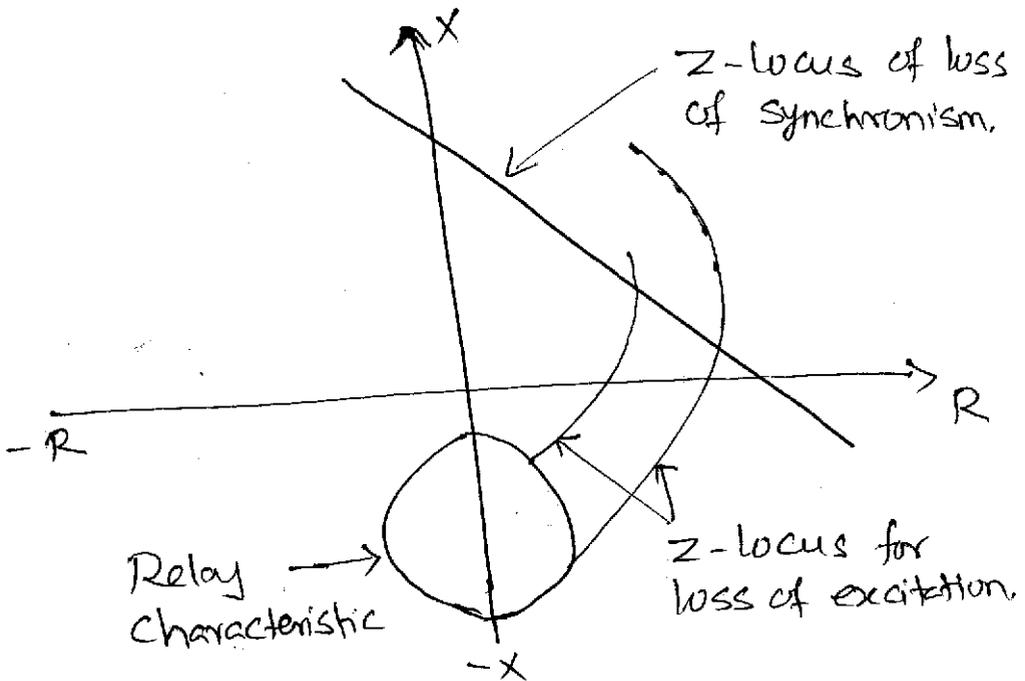
The stators of both salient and non-salient pole generators are overheated due to wattless current drawn by the machine as magnetising current from the system.

III-(4)

A large machine may upset the system stability because it draws reactive power from the system when it runs as an induction generator.

Field failure may be caused by the failure of excitation or mal-operation of a faulty field breaker.

A protective scheme employing offset mho or directional impedance relay having a characteristic as shown in fig.



When a generator loses its excitation, the locus of the equivalent generator

impedance moves from the first quadrant to the fourth quadrant irrespective of initial conditions.

This type of locus is not traced in any other conditions. The relay trips the field breaker and the generator is disconnected from the system.

Protection of generator against abnormal conditions:

a) over voltage protection: •

Over voltage may be caused by sudden loss of electrical load on generators.

When a load is lost, there is an increase in speed and hence the voltage also increases.

In steam power station, an automatic voltage regulator controls the overvoltage which is associated with over speed.

In case of hydro-plants, it is not possible to control the overspeed, therefore over voltage relays are provided with hydro and gas turbine sets.

b) Over speed protection:

The chief cause of overspeed is the sudden loss of major part of the load on a generator.

Modern generators are usually provided with mechanical centrifugal devices mounted on their driving shafts to trip the main valve of the prime-mover when a dangerous overspeed occurs.

c) Protection against failure of prime-mover:

Failure of prime-mover to an alternator, makes the machine to run as a synchronous motor and draws the current from the supply.

This motoring condition is known as "inverted running".

(i). In case of turbo-alternator, if there exist a failure of steam supply, then, the steam supply is gradually restored until an alternator picks-up a load without disturbing the system.

If the steam failure is likely to be prolonged, the machine can be isolated safely by the control room attendant since it is relatively harmless.

Therefore, automatic protection is not required.

(ii). In case of hydro-plants, inverted running can be protected by providing mechanical devices on the water-wheel.

When the water flow drops to an insufficient rate, an alternator is disconnected from the system by the control room attendant.

Therefore, in this case also electrical protection is not necessary.

(iii) In case of diesel-plants, inverted running can draw a considerable amount of power from the supply, and it is a usual practice to provide protection against motoring.

This is achieved by applying reverse power relays to the alternators.

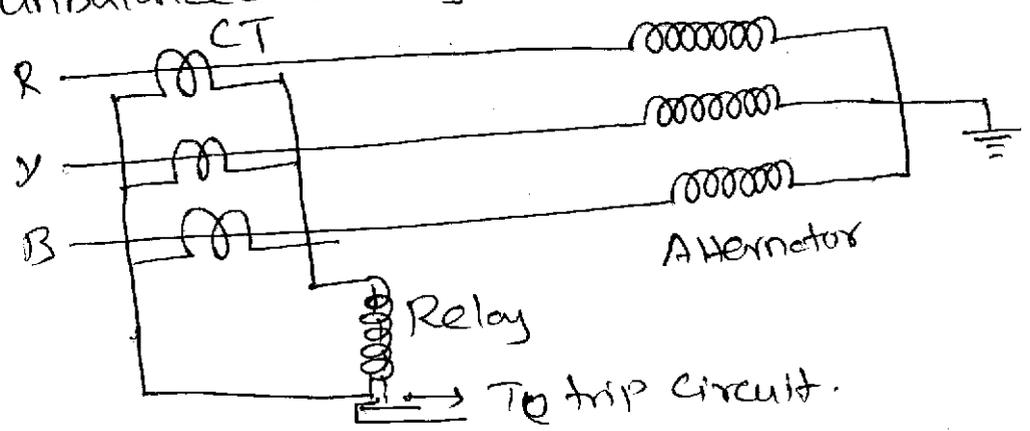
d) Overcurrent protection:

It occurs mainly due to overload on the supply system. Overcurrent protection for generators is considered unnecessary because, the modern design of alternator is with very high internal impedance, so that they withstand a short-circuit for sufficient time without overheating.

On the occurrence of an overload, the generator can be disconnected manually.

e) Protection against Unbalanced loading:

Fig. shows the schematic arrangement for the protection of generator against unbalanced loading.



It comprises of three CTs mounted on each phase, having their secondaries connected in parallel.

A relay is connected across the transformer secondaries.

Under normal operating conditions, equal current flows through an alternator winding and their algebraic sum is zero.

Therefore, the current flowing in the secondaries is also zero and no current flows through the operating coil of the relay.

However, if unbalancing occurs, the currents induced will be different and the resultant of these currents will flow through the relay.

Thus, the relay will trip the circuit breaker to disconnect the generator from the system.

Numerical Problems on percentage winding unprotected:

1) An 11 kV, 100 MVA alternator is provided with differential protection. The percentage of winding to be protected against phase to ground fault is 85%. The relay is set to operate when there is 20% out of balance current. Determine the value of resistance to be placed in the neutral to ground connection.

Soln.:

11 kV, 100 MVA

Primary earth-fault current at which the relay operates

$$= \frac{100 \times 10^6}{\sqrt{3} \times 11 \times 10^3} \times \frac{20}{100}$$

$$= 1049.76 \text{ A}$$

Suppose that the percentage of winding which remains unprotected is,

$$P = 100 - 85 = 15\%$$

Now,

$$\text{Fault current} = \frac{P}{100} \times \frac{11 \times 10^3}{\sqrt{3} \times R_n}$$

where, $R_n \rightarrow$ the resistance in the ~~net~~ neutral to ground connection.

$$\therefore 1049.76 = \frac{15}{100} \times \frac{11 \times 10^3}{\sqrt{3} R_n}$$

$$\Rightarrow R_n = \frac{15 \times 11 \times 10^3}{100 \times \sqrt{3} \times 1049.76}$$
$$= 0.91 \Omega$$

2) A star connected 3-phase, 10 MVA, 6.6 kV alternator is protected by Merz-price circulating current principle which is set to operate for fault current not less than 175 A. Calculate the value of earthing resistance to be provided in order to ensure that only 10% of the alternator winding remains unprotected.

Soln.:

3-phase, 10 MVA, 6.6 kV

Fault current = 175 A

% of winding unprotected = 10%

III - (6)

$$\text{Fault current} = \frac{10}{100} \times \frac{6.6 \times 10^3}{\sqrt{3} \times R_n}$$

where, $R_n \rightarrow$ the value of earthing resistance

$$\therefore 175 = \frac{10}{100} \times \frac{6.6 \times 10^3}{\sqrt{3} \times R_n}$$

$$\begin{aligned} \Rightarrow R_n &= \frac{10 \times 6.6 \times 10^3}{100 \times \sqrt{3} \times 175} \\ &= 2.177 \Omega \end{aligned}$$

3) A star connected 3-phase 10 MVA, 6.6 kV alternator is protected by Merz-Price circulating current principle using 1000/5 amperes current transformers. The star point of the alternator is earthed through a resistance of 7.5Ω . If the minimum operating current for the relay is 0.5 A. Calculate the percentage of each phase of the stator winding which is unprotected against earth-faults when the machine is operating at normal voltage.

Soln.:

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

Minimum fault current which will operate the relay

$$= \frac{1000}{5} \times 0.5 = 100 \text{ A}$$

We know that,

$$\text{Fault current} = \frac{x}{100} \times \frac{3810}{R_n}$$

where,

$x \rightarrow$ % of winding unprotected.

$$\therefore 100 = \frac{x}{100} \times \frac{3810}{7.5}$$

$$\Rightarrow x = \frac{100 \times 100 \times 7.5}{3810}$$

$$= 19.68\%$$

Hence, 19.68% of an alternator winding is left unprotected.

4) A 3-phase, 20 MVA, 11 kV, star-connected generator is protected by the current balancing system of protection. If the ratio of the CTs is 1200/5, the minimum operating current of the relay is 0.75 A.

and the neutral point earthing resistance is $6\ \Omega$, calculate the percentage of each phase of stator winding which is unprotected against earth faults when the machine is operating at normal voltage.

Soln.:

3-phase, 20 MVA, 11 kV

$$R_n = 6\ \Omega$$

$$C_T = 1200\ \text{S A}$$

relay operating current = $0.75\ \text{A}$.

$$\text{Voltage per phase} = \frac{11 \times 10^3}{\sqrt{3}} = 6350.85\ \text{V}$$

Minimum fault current which the relay operate,

$$= \frac{1200}{5} \times 0.75 = 180\ \text{A}$$

If x is the % of winding unprotected, then,

$$\text{Fault current} = \frac{x}{100} \times \frac{6350.85}{R_n}$$

$$180 = \frac{x}{100} \times \frac{6350.85}{6}$$

$$\Rightarrow x = \frac{180 \times 100 \times 6}{6350.85}$$

$$= 17\%$$

Hence, 17% of of an generator winding is left unprotected against earth fault when the machine is operating at normal voltage..

Protection of transformers:

Transformers are static devices, totally enclosed and oil immersed. Therefore, chances of faults occurring on them are rare.

However, the occurrence of a rare fault may be very serious unless the transformer is quickly disconnected from the system.

This necessitates to provide adequate automatic protection for transformers against possible faults.

A few of the common faults that occur in transformers are,

- i) over heating
- ii) open circuits
- & iii) winding short-circuits (earth fault, phase-to-phase fault, and inter-turn faults).

III - 7

For protection of transformers, Merz-Price circulating current system offers no particular advantage over other systems.

Under such circumstances, alternative protective systems are used such as,

- i) Buchholz relay protection
- ii) Earth fault protection.
- iii) Overcurrent protection.
- & iv) Differential protection.

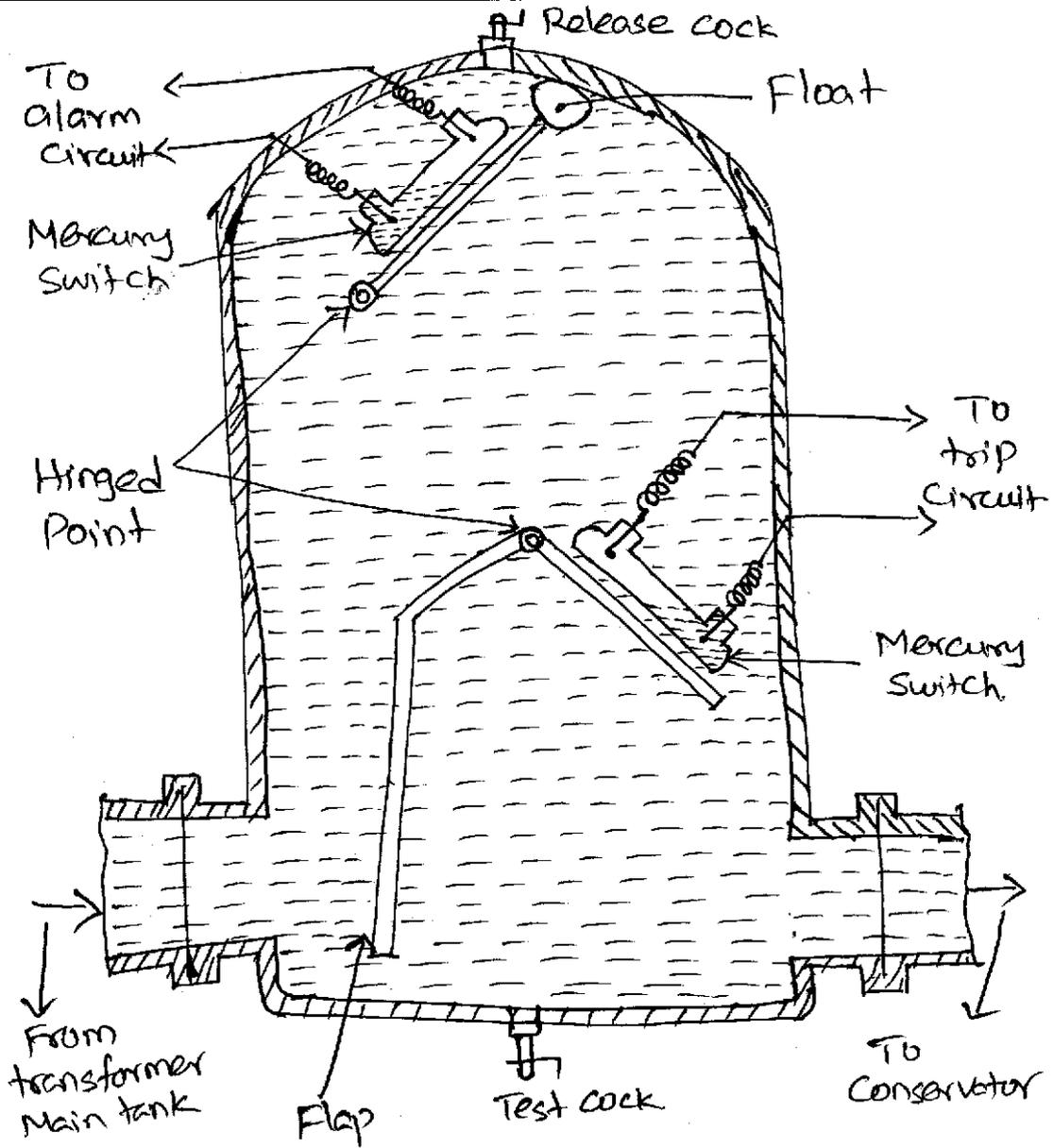
i) Buchholz relay protection:

Buchholz relay is a gas-actuated relay in an oil immersed transformers for protection against all kinds of faults.

Named after its inventor, Buchholz, it is used to give an alarm in case of incipient (slow developing fault) and to disconnect the transformer from the supply in the event of severe internal faults.

Construction:

Fig. shows the constructional details of a Buchholz relay.



It is a domed vessel placed in between the main tank and the conservator.

It consists of two elements.

1) Upper element consists of a mercury type switch attached to a float.

2) Lower element contains a mercury switch mounted on a hinged flap located in the direct path of flow of oil from transformer to conservator.

An upper element closes an alarm circuit during incipient faults, whereas the lower element is arranged to trip the circuit breaker in case of severe internal fault.

Operation:

In case of incipient fault (within the transformer) the heat produced causes the decomposition of transformer oil in the main tank.

The products of decomposition contain more than 70% of hydrogen gas, which is being light, tries to go into the conservator.

In this process, the gas gets accumulated, it exerts sufficient pressure on the float to cause it to tilt.

This closes the contact of mercury switch attached to it and completes the

alarm circuit to sound an alarm.

But, it do not call for the immediate removal of the transformer from the system, because, an air bubble in the oil circulation system may sometimes operate the float.

For this reason, float is so arranged to sound an alarm upon which, steps can be taken to verify the gas and its composition.

In case of serious faults in the transformer, an enormous amount of gas is generated in the main tank.

An oil in the main tank rushes towards Conservator via Buchholz relay which tilts the flap to close the contacts of mercury switch.

This completes the trip circuits to open the circuit breaker which disconnects the faulty transformer.

Advantages:

- i) It is the simplest form of transformer Protection.
- ii) It detects the incipient fault at a stage much earlier than is possible with other forms

Fig. shows the schematic diagram of percentage differential protection for γ - Δ transformer.

The connections are made in such a way that under normal operating conditions, the current flowing in the operating coil (O) of the relay due to CTs of primary side is in opposition to the current flowing due to the CTs of the secondary side.

Consequently, the relay does not operate under such conditions.

If a fault occurs, the polarity of the induced voltage of the CT of secondary side is reversed.

Thus, the current in the operating coil flows due to the same direction of currents in CTs of both primary and secondary side and causes the operation of relay.

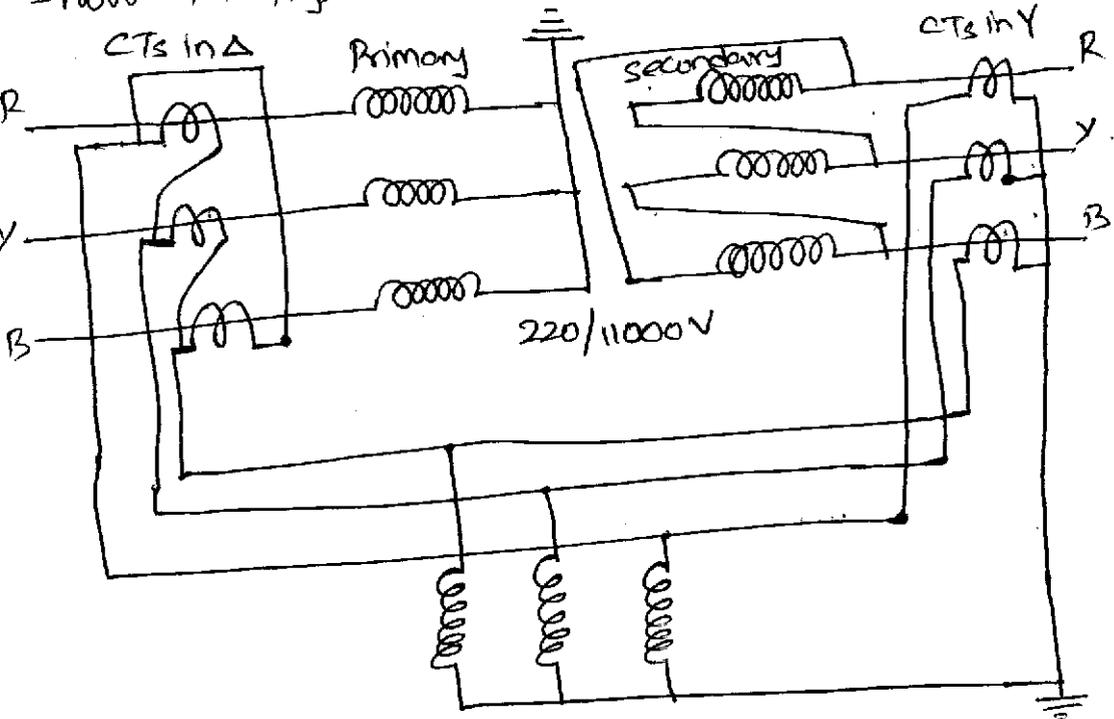
To supply the matching current in the operating coil of the relay, the CTs on star side of the transformer are connected in delta and CTs on delta side of the transformer are connected in star.

Numerical Problem on Design of CTs Ratio:

1) A 3-phase transformer of 220/11,000 line volts is connected in star/delta. The protection transformers on 220 V side have a current ratio of 600/5. What should be the CT ratio on 11,000 V side?

Soln.:

For star/delta transformer, CTs will be connected in delta on 220 V side (i.e. star side) and in star on 11,000 V side (i.e. delta side) as shown in fig



Suppose

The line current on 220V side is 600A,
 \therefore Phase current of delta connected CTs on 220V side = 5A

Line current of delta connected CTs on 220V side = $5 \times \sqrt{3} = 5\sqrt{3}$ A.

This current will flow through the pilot wires.

Obviously, this will be the current which flows through the secondary of CTs on 11,000V side.

\therefore Phase current of star connected CTs on 11,000V side = $5\sqrt{3}$ A

If I is the line current on 11,000V side, then,

Primary apparent power = Secondary apparent power

$$\therefore \sqrt{3} \times 220 \times 600 = \sqrt{3} \times 11000 \times I$$

$$\Rightarrow I = \frac{\sqrt{3} \times 220 \times 600}{\sqrt{3} \times 11000} = 12 \text{ A}$$

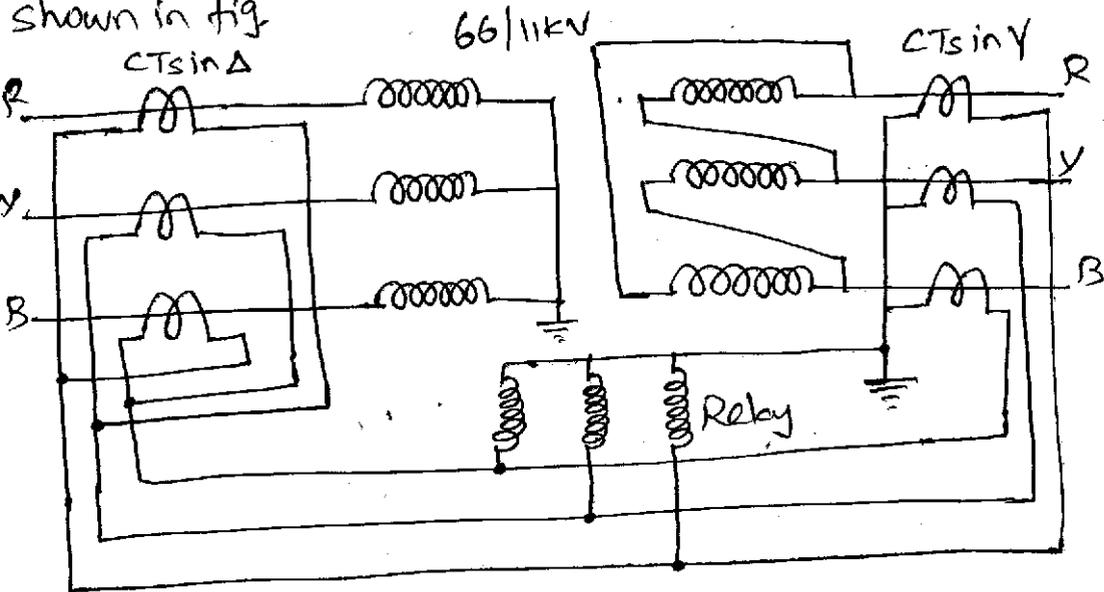
\therefore The turn-ratio of CTs on 11000V side,
= $12 : 5\sqrt{3}$
= $1.385 : 1$

III - (9)

2) A 3-phase, 66/11 kV star-delta connected transformer is protected by Merz-Price system. The CTs on LT side have a ratio of 420/5A. Find the ratio of the CTs on the HT side.

Soln:

For star-delta transformer, CTs will be connected in delta for star side (i.e. on 66 kV side) and in star for delta side (i.e. on 11 kV side) as shown in fig



Assume that line current on 11 kV side is

420 A.

∴ Line current of star connected CTs on 11 kV side = phase current of star-connected CTs on 11 kV side = 5 A

This current 5A will flow through the pilot wires.

Obviously, this will be the current which flows through the secondary of CTs on 66 kV side.

∴ Line current of delta connected CTs on 66 kV side = 5 A

Phase current of delta connected CTs on 66 kV side = $\frac{5}{\sqrt{3}}$ A

Line current on 66 kV side
= $\frac{\sqrt{3} \times 11000 \times 420}{\sqrt{3} \times 66000} = 70 \text{ A}$

∴ Turn-ratio of CTs on 66 kV side
= 70 : $5/\sqrt{3}$
= 24.25 : 1.

Beyond Syllabus | content

3) Restricted Earth fault protection:

An earth fault usually involves a partial breakdown of winding insulation to earth.

The resulting leakage current is considerably less than the short-circuit current.

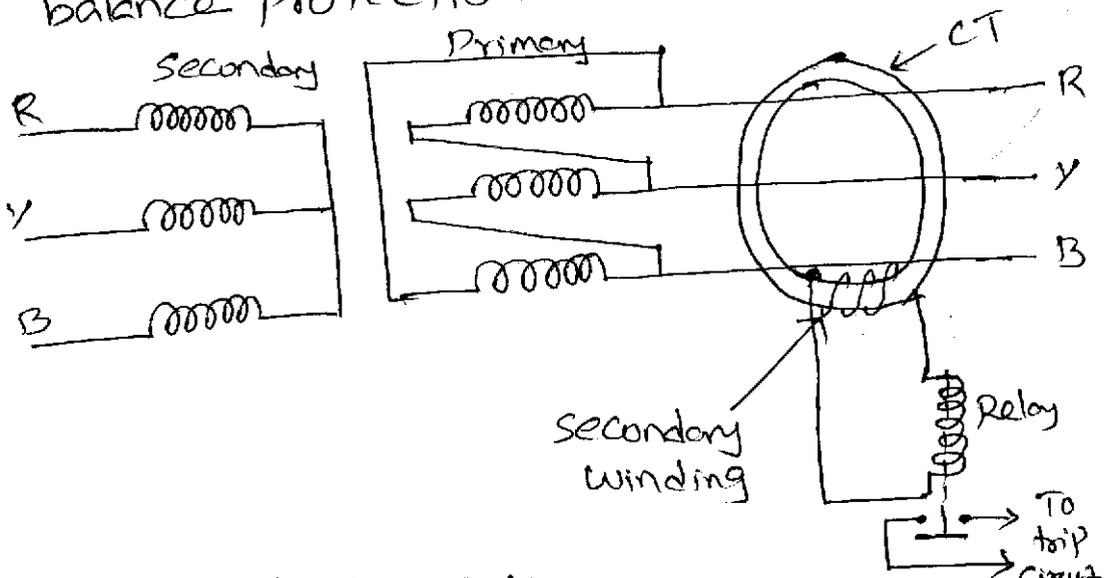
An earth fault may continue for a long time and cause considerable damage before it ultimately develops into a

short-circuit and removed from the system.

Under these circumstances, it is desirable to employ a restricted earth-fault relay in order to ensure the disconnection of faulty section in the early stage.

An earth fault relay is essentially an overcurrent relay of low setting and operates as soon as ^{an} earth fault or leak develops.

A method of protection against earth-fault in a transformer known as core-balance protection is shown in fig.



The 3 leads of the primary winding of

Power transformer are taken through a core of a current transformer.

An operating coil of a relay is connected to the secondary of CT.

Under normal conditions, the vector sum of three phase currents is zero and there is no resultant flux in the core of CT.

Consequently, no current flows through the relay and it remains inoperative.

However, on the occurrence of an earth fault, the vector sum of three phase currents is no longer zero.

The resultant current sets up flux in the core of CT, which induces emf in the secondary winding.

This energises the relay to trip the circuit breaker and disconnect the faulty transformer from the system.

— X —

Important questions:

1. Explain the protective scheme that should be followed for the protection against stator fault in a generator.
2. How an inter-turn fault in a generator can be protected from the power system? Explain
3. Name some of the faults that may occur in a transformer. And suggest few methods of protection against these faults.
4. Draw the neat diagram of Buchholz relay and explain its operation in protection against fault in a power transformer,
5. Explain percentage differential protection on transformer

Unit-4

Protection of Feeders, Transmission Lines And Busbars.

Introduction:

Feeders, busbars and transmission lines are important elements in electric power system which require an immediate attention for safeguards against the possible faults occurring on them.

The methods used for the protection of generators and transformers can also be employed with slight modifications for the busbars and lines.

Protection of Feeders:

For the protection of radial and ring main feeders, over current relays were used.

In this scheme of protection, time discrimination is incorporated. In other words, the time setting of relays is so graded that in the event of fault, the

Smallest possible part of the system is isolated.

1. Radial feeder:

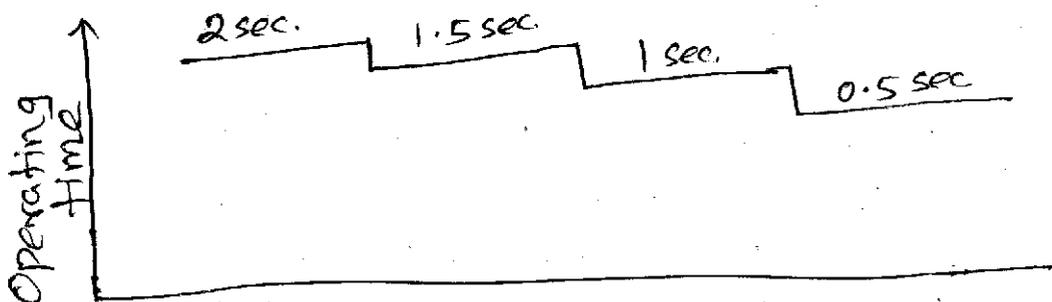
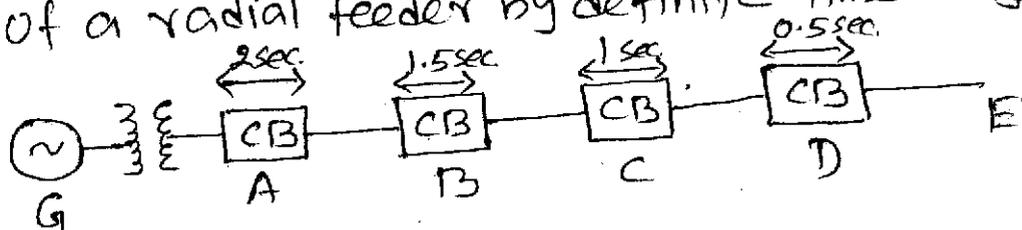
The main characteristic of a radial system is that power can flow only in one direction from generator end to the load.

A time-graded overcurrent protection of a radial feeder can be achieved by,

- i) definite time relays and
- ii) inverse time relays.

i) Using definite time relays:

Fig. Shows the overcurrent protection of a radial feeder by definite time relays.



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

Thus, relay D has an operating time of 0.5 second while for other relays time delay is successively increased by 0.5 sec.

If a fault occurs in section DE, it will be cleared in 0.5 sec. by the relay and breaker at D, because all other relays have higher operating time.

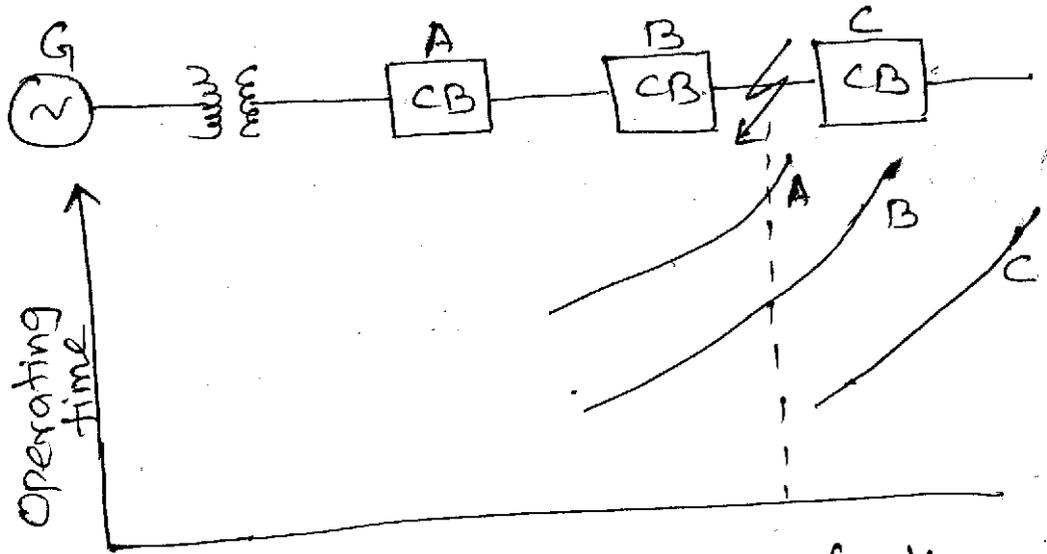
If the relay at D fails to trip, the relay at C will operate after a time delay of 0.5 second i.e. after 1 second from the occurrence of fault.

The disadvantage of this system is that, if there are a number of feeders in series the tripping time for faults near the supply end becomes high (2 seconds in this case).

This disadvantage can be overcome to a reasonable extent by using inverse-time relays.

ii) Using Inverse time relays:

Fig. shows overcurrent protection of a radial feeder using inverse time relays in which operating time is inversely proportional to the operating current.



With this arrangement, the farther the breaker from generating station, the shorter is its relay operating time.

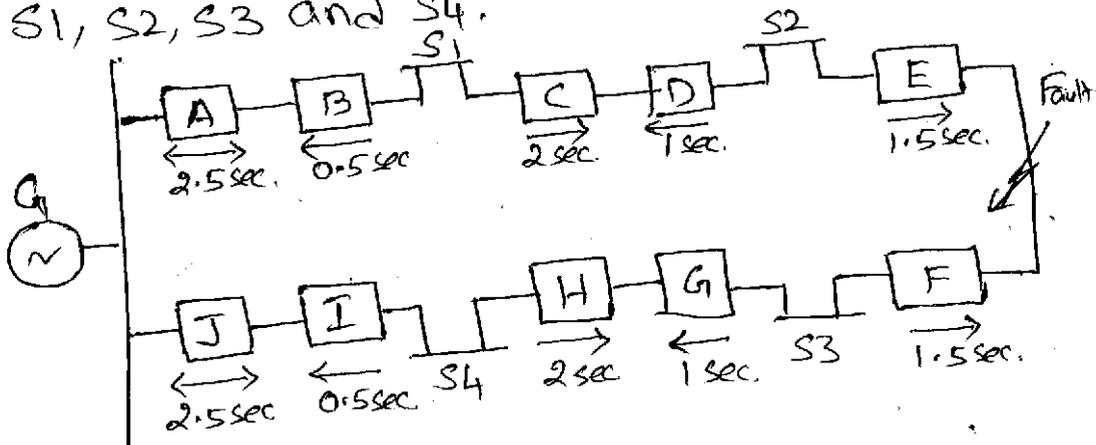
The three relays at A, B and C are assumed to have inverse-time characteristics.

A fault in section BC will give relay times which will allow breaker at B to trip out before the breaker at A.

IV - 2

2) Ring main feeder:

Fig. shows a single line diagram of a typical ring-main system consisting of one generator G supplying four substations S_1, S_2, S_3 and S_4 .



In this arrangement, power can flow in both directions under fault conditions. Therefore, it is necessary to grade in both directions round the ring and also use directional relays.

The type of relays and their settings should be as follows:

- (i). Two lines leaving generating station should be equipped with non-directional overcurrent relays. (at A and J).

(ii). At each substation, directional relays should be placed in both incoming and outgoing feeders (at B, C, D, E, F, G, H and I).

(iii) ~~There~~ There should be proper relative time-setting of the relays.

[going round the loop G, S1, S2, S3, S4, G, the outgoing relays (viz. A, C, E, G and I) are set with decreasing time limits such that,

$$A = 2.5 \text{ sec.}, C = 2 \text{ sec.}, E = 1.5 \text{ sec.}, \\ G = 1 \text{ sec. and } I = 0.5 \text{ sec.}$$

Similarly, going round the loop in opposite direction i.e. G, S4, S3, S2, S1, G, the outgoing relays are set with decreasing time limit, such that,

$$J = 2.5 \text{ sec.}, H = 2 \text{ sec.}, F = 1.5 \text{ sec.}, \\ D = 1 \text{ sec. and } B = 0.5 \text{ sec.}]$$

If the fault occurs at the point shown, only the circuit breakers at E and F should operate whereas other

Parts of the ring should be intact to maintain continuity of supply.

Protection of Transmission lines:

The probability of faults occurring on the transmission lines is much more due to their greater length and exposure to atmospheric conditions.

The protection of lines presents a problem quite different from the protection of station apparatus such as generators and transformers.

While differential protection is ideal method for transmission lines, it is much more expensive to use.

The two ends of the line may be several kilometers apart and to compare two currents, a costly pilot-wire circuit is required.

The common methods of transmission line protection are,

(i). 3 zone protection using distance relays.

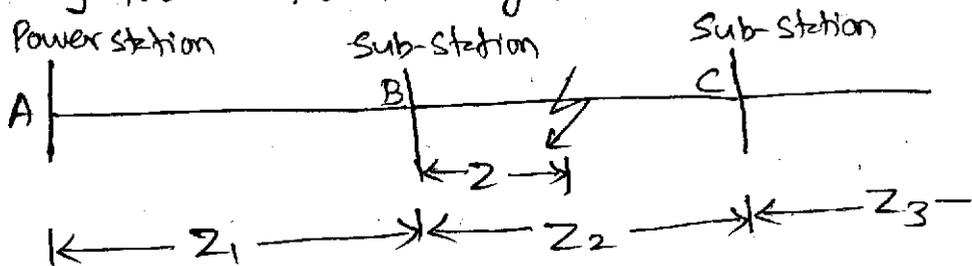
(iii). Carrier current protection,

i) Distance protection:

Distance protection is the one in which the action of relay depends upon the distance or impedance between the point where the relay is installed and the point of fault.

This system provides discrimination protection without employing pilot wires.

Fig. shows a simple system consisting of lines in series such that power can flow only from left to right.



The relays at A, B and C are set to operate for impedance less than Z_1 , Z_2 and Z_3 respectively.

Suppose a fault occurs between sub-stations B and C, the fault impedance at

IV - (3)

Power station and substation A and B will be $Z_1 + Z$ and Z respectively.

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

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

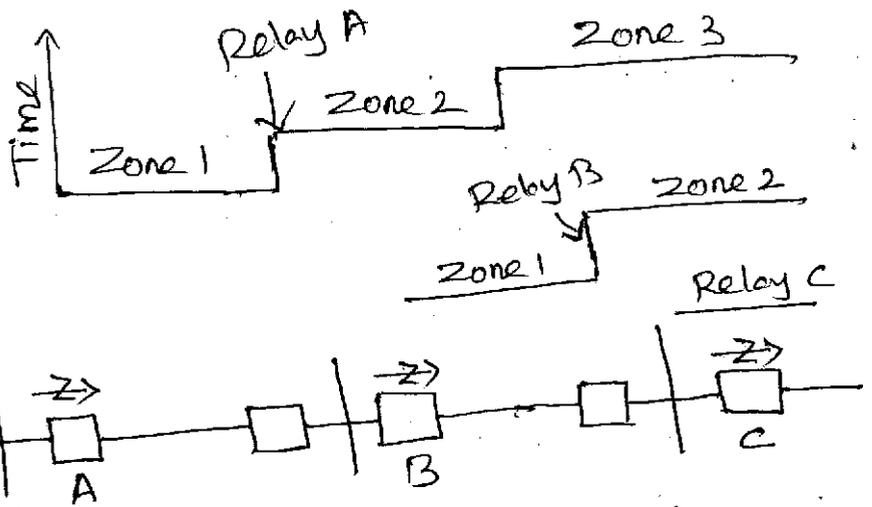
In this manner, instantaneous protection can be obtained for all conditions of operation.

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

Thus, the relay at A would not be very reliable in distinguishing between a fault at 99% of the distance AB and the one at 101% of distance AB.

This difficulty is overcome by using "three-zone" distance protection shown

in fig.



In this scheme of protection, three distance elements are used at each terminal.

The zone 1 element covers first 90% of the line and is arranged to trip instantaneously for faults in this portion.

The zone 2 element trips for faults in the remaining 10% of the line and for faults in the next line section, but a time delay is introduced to prevent the line from being tripped if the fault is in the next section.

The zone 3 element provides back-up protection in the event a fault in the next section is not cleared by its breaker.

Carrier current protection:

A carrier current protection (differential protection) is based on the principle that under normal conditions, the current entering in one end is equal to that current leaving the other end.

As soon as a fault occurs, this condition no longer holds and the difference in current is arranged to flow through a relay which operates the circuit breaker to isolate the faulty line.

The following are the two familiar schemes in use:

1. Merz-price voltage balance scheme
2. Translay scheme.

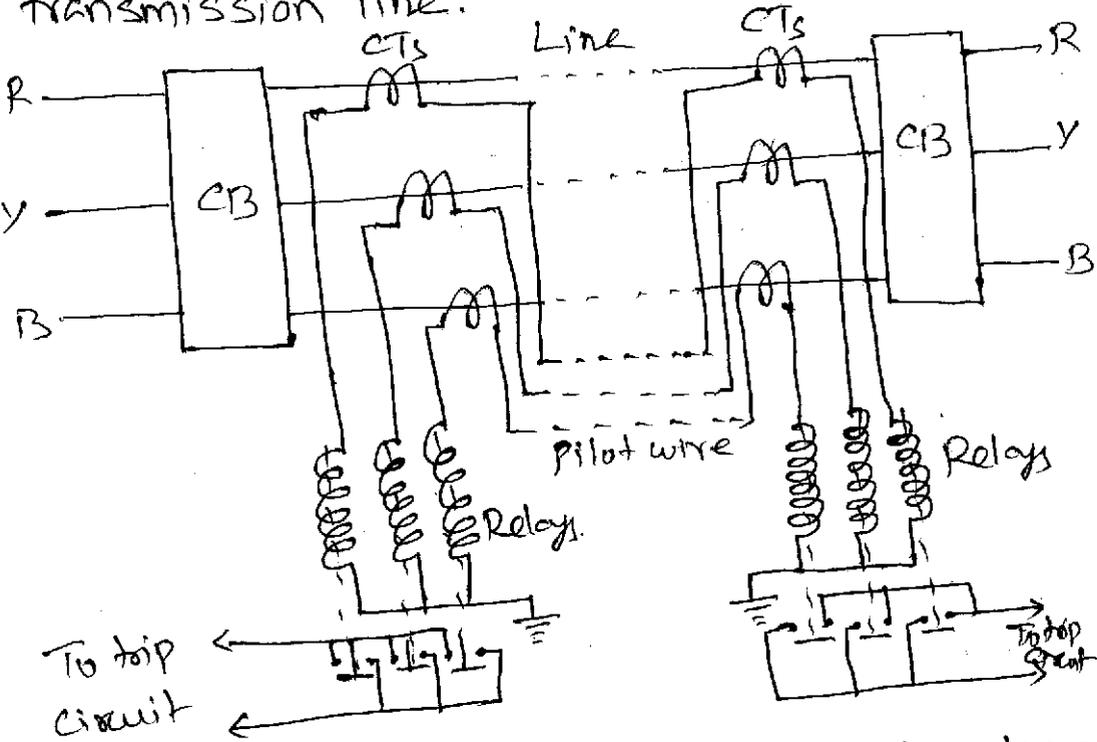
1. Merz-price voltage balance scheme:

Identical current transformers are placed in each phase at both ends of the line.

The pair of CTs in each line is connected in series with a relay in such a way that under normal conditions, their secondary voltages

are equal and in opposition, i.e. they balance each other.

Fig. Shows the connections of Merz-price voltage balance scheme for the 3-phase ~~transmission~~ transmission line.



Under healthy conditions, current entering the line at one-end is equal to that leaving at the other end.

Therefore equal and opposite voltages are induced in the secondaries of CTs at the two ends of the line.

IV - (4)

The result is that no current flows through the relays.

Suppose a fault occurs on the line, will cause a circulating current to flow through the pilot wires and relays.

The circuit breaker will trip out and the faulty line will be isolated.

Advantages:

1. This system can be used for ring main feeders.
2. It provides instantaneous protection for ground faults.
3. This system reduces the amount of damage to overhead conductors resulting from arcing faults.

Disadvantages:

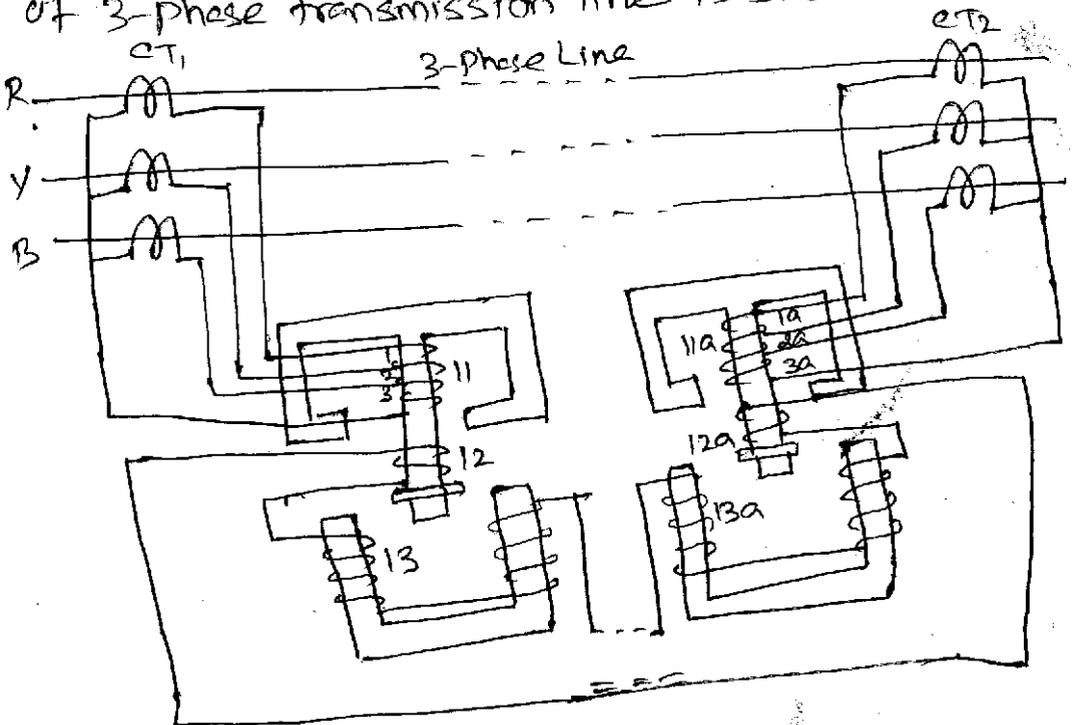
1. Accurate matching of current transformers is very essential.
2. If there is a break in the pilot-wire circuit, the system will not operate.

3. This system is very expensive owing to the greater length of pilot wires required.

2. Translay scheme:

This system is similar to voltage balance system except that, the balance is in between the voltages induced in secondary winding of the relay magnets and not between the secondary voltages of the line current transformers.

The Translay scheme for the protection of 3-phase transmission line is shown in fig.



The relays used ~~is~~^{are} usually an overcurrent induction type relays.

An upper element carries a winding (11 or 11a) which is energised from the secondaries of line CTs connected in the line to be protected.

An upper element also carries a secondary winding (12 or 12a) which is connected in series with the operating winding (13 or 13a) on the lower magnet.

12, 12a and 13, 13a are connected in series in such a way that voltages induced in them opposes each other.

When the line is sound, the current at its two ends are equal so that the secondary currents in CTs are equal.

Consequently, the currents in relay primary winding (11 and 11a) will be equal and induces equal voltages in secondary winding (12 and 12a).

Since, these ~~currents~~ windings are connected in opposition, no current flows

in them and the operating winding (13 and 13a) and pilot circuit.

Suppose, a fault occurs between the lines, it energise the primary winding (11 and 11a) and induces voltage in secondary winding (12 and 12a).

These voltages are now additive, and current will circulate through 13 and 13a and the pilot circuit.

This will cause the relay to operate and open the circuit breakers at both ends of the line.

Advantages:

1. The system is economical as only two pilot wires are required
2. Current transformers of normal design can be used.

Protection of Bus-bars:

Busbars in the generating stations and substations form important link between the incoming and outgoing circuits.

IV - (5)

If a fault occurs on a busbar, considerable damage and disruption of supply will occur unless some form of automatic protection is provided to isolate the faulty one.

The two most commonly used schemes for busbar protection are:

- i) Differential protection.
- ii) Fault bus protection.

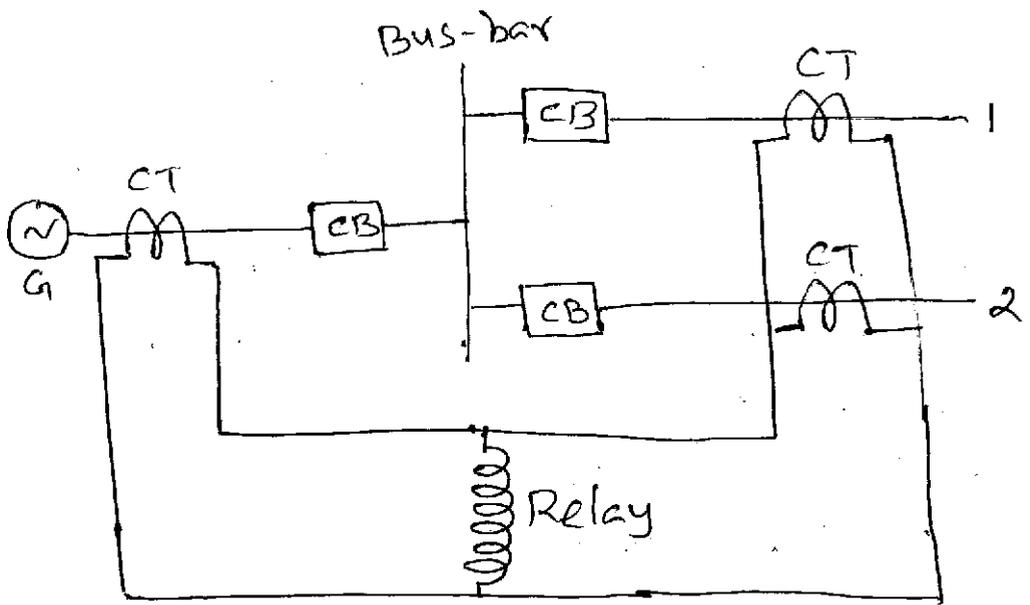
i) Differential protection:

The basic method for protection of bus bar is the differential scheme, in which currents entering and leaving the bus are totalised.

During normal conditions, the sum of these currents is equal to zero.

When a fault occurs, the fault current upsets the balance and produces a differential current to operate a relay.

Fig. shows the single line diagram of current differential scheme for a station busbar.



The busbar is fed by a generator and supplies load to two lines.

The secondaries of current transformer in the generator lead, in line 1 and in line 2 are all connected in parallel.

A protective relay is connected across this parallel connection.

Under normal load conditions, the sum of currents entering the bus is equal to those leaving it and no current flows through the relay.

If a fault occurs within the protected

zone, the currents entering the bus will no longer be equal to those leaving it.

The difference of these currents will flow through the relay and cause the opening of circuit breaker.

ii) Fault Bus protection:

(Differential pilot wire protection)

It is possible to design a station so that the faults that develop are mostly earth-faults.

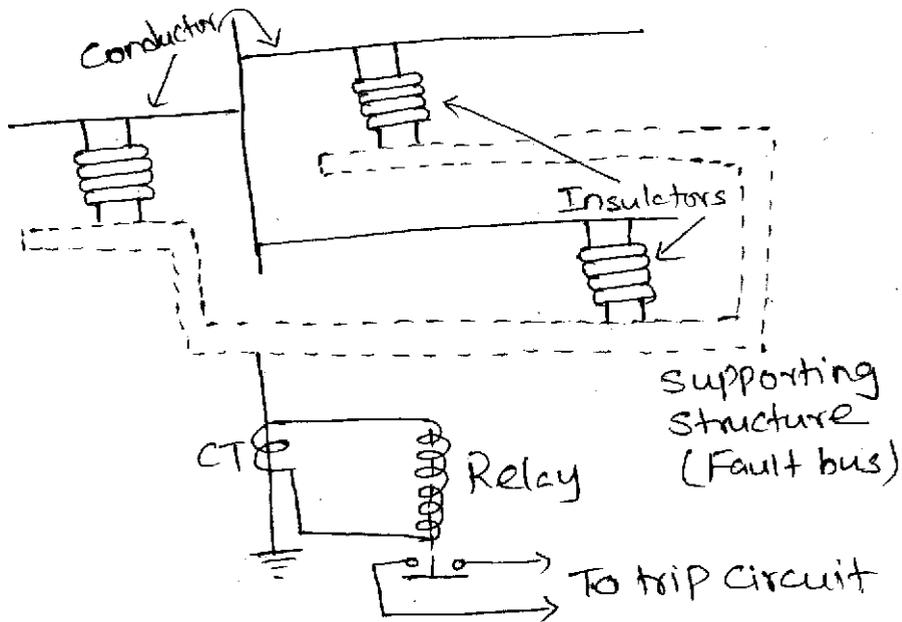
This can be achieved by providing earthed metal barrier (known as fault bus) surrounding each conductor throughout its entire length in the bus structure.

With this arrangement, every fault that might occur must involve a connection between a conductor and an earthed metal part.

By directing the flow of earth-fault current, it is possible to detect the faults and determine their location.

This type of protection is known as fault-bus protection.

Fig. shows the schematic arrangement of fault-bus protection.



The metal supporting structure or fault bus is earthed through a current transformer.

A relay is connected across the secondary of this CT.

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

A fault involving a connection between a conductor and earthed supporting structure

IV - (6)

will result in current flow to ground through the fault bus, causing the relay to operate.

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

— x —

References:

- 1) "power system protection and switchgear" - Badri ram, D. N. Vishwakarma, Tata McGraw Hill. publishing.
- 2) "Principles of power system" - V. K. Mehta, S. Chand & Company Ltd.

Important questions:

1. Elaborately explain the concept of radial and ring-main feeder protection against a fault that can occur on it.
2. Explain how a 3-zone distance protection scheme can be employed to protect a transmission line against various type of faults.
3. Write a short notes on the following with respect to bus-bar protection:
 - I. Differential protection
 - II. Fault bus protection