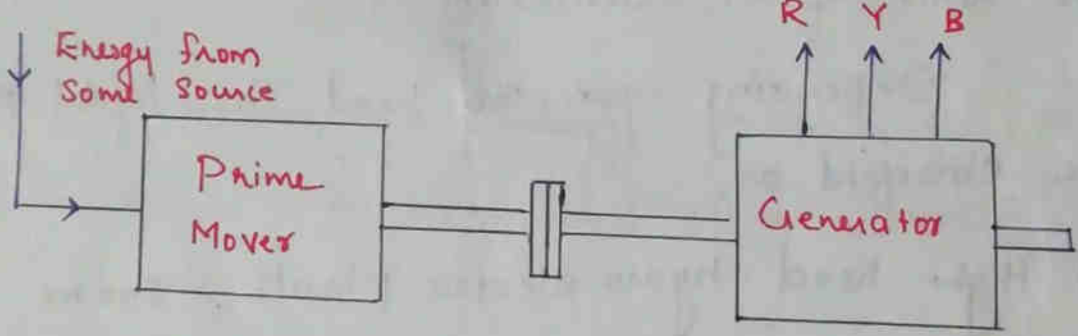
MODULE I

MODULE - I

GENERATION OF ELECTRIC POWER

The conversion of energy available in different forms in nature into electrical energy is known as generation of electrical energy.

The arrangement of energy generation is shown below.



Types Of Generation

Conventional energy Sources	Non Conventional energy Sources
Hydro-electric Thermal Nuclear	Solar wind

I Conventional Energy Sources:

① Hydro-electric Power Plants

Hydro electric (hydel) power plants converts the energy stored in water into electrical energy by the use of water turbines coupled with generators. The water from a height (water head) is allowed to fall on the blades of a turbine through long pipes or tunnels called penstocks. This causes the turbine blades to rotate which in turn rotates the rotor of an alternator.

Depending upon the head, the hydel plants are classified as,

1) High head hydro electric plants : 200 m & above
2) Medium head hydro electric plants : 50 m to 200 m
3) Low head hydro electric plants : upto 50 m

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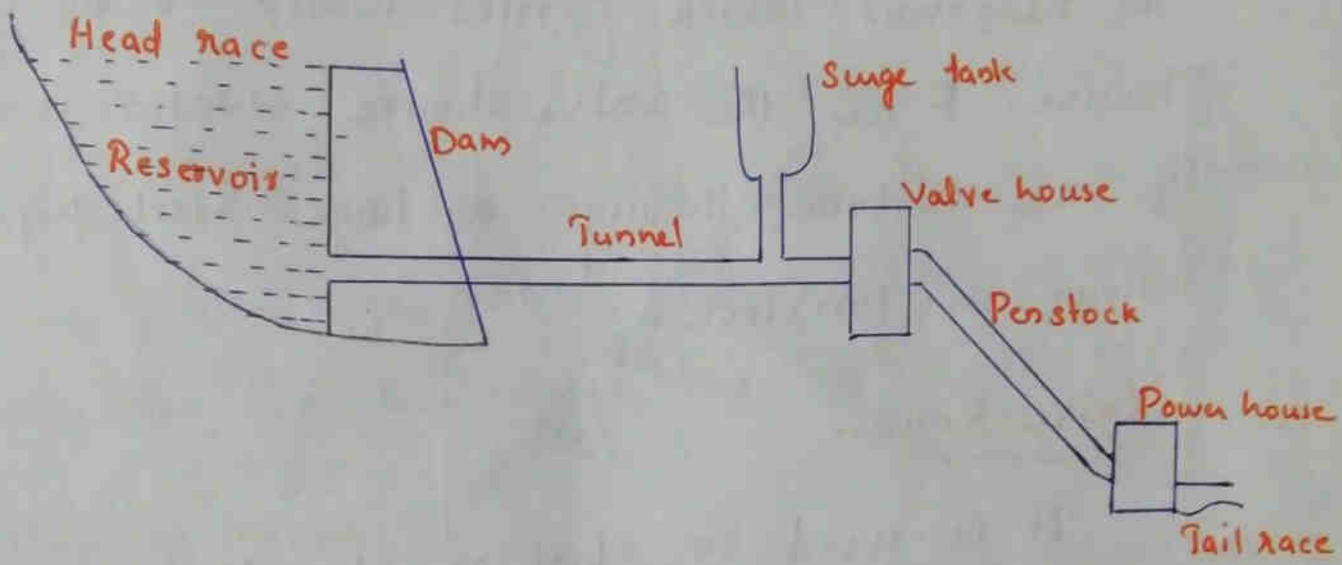
Lay out of hydro electric Power Station



The main parts are dam, tunnel, surge tank, Valve house, Pen stock and Power house

Dam.

The dam is constructed across a river or lake and forms a reservoir. It provides a steady water head for the turbine to operate. The water level of the reservoir is called head race.

Tunnel and Penstock.

It carries water from the reservoir to the turbine of Power house. A pressure tunnel is taken from the reservoir, which carries water to the valve house. From the valve house, water is brought to the turbine through a huge Steel pipe known as penstock.

Valve house.

It is used to start or stop the water flow into the power house for normal operation and maintenance.

Surge tank

It is a small additional storage facility, implemented just before the valve house. It is required when there is considerable distance between the power house & the reservoir. When the distance is more, non-uniform intake to the power house results in water hammering. The surge tank allows sudden rise of water into it, when the water flow is stopped or reduced. When the water requirement of the turbine suddenly increases due to an increase in load, water from the surge tank will be taken to meet the quick demand. Thus the surge tank functions as a pressure regulator in the water-line.

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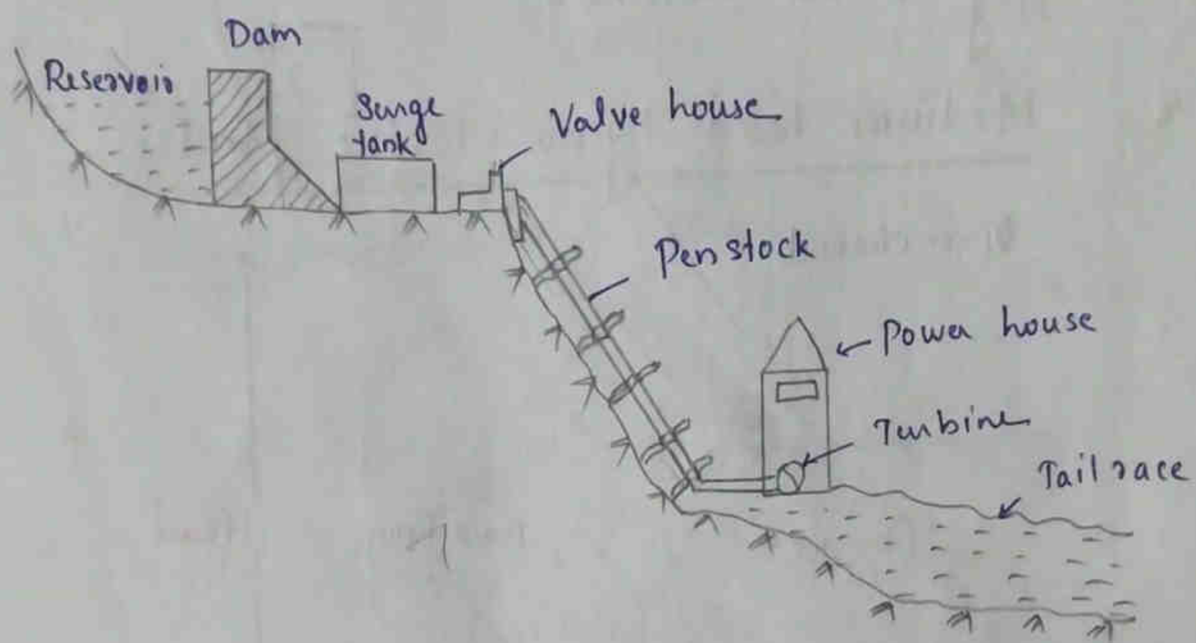
Power house

It is located near the foot of the dam. Water is brought to the power house with the help of penstocks. A power house employs turbine & generator. The turbine convert the hydraulic energy from the flowing water to mechanical energy. The generator, which is mechanically coupled to the turbine converts the mechanical energy to electrical energy. The used water from the turbine is released through the tail race. The location of Power house is determined by maximum Possible water head (ie difference in height from head race to tail race)

Tail race

Water is discharged into the tail race after passing through the turbine which carries into the river. A tail race is an open channel or a tunnel depending upon the power house location. The discharge from all the turbines is collected in tail race. The tail race may discharge into the original river or into some other river.

I High head hydroelectric plants.

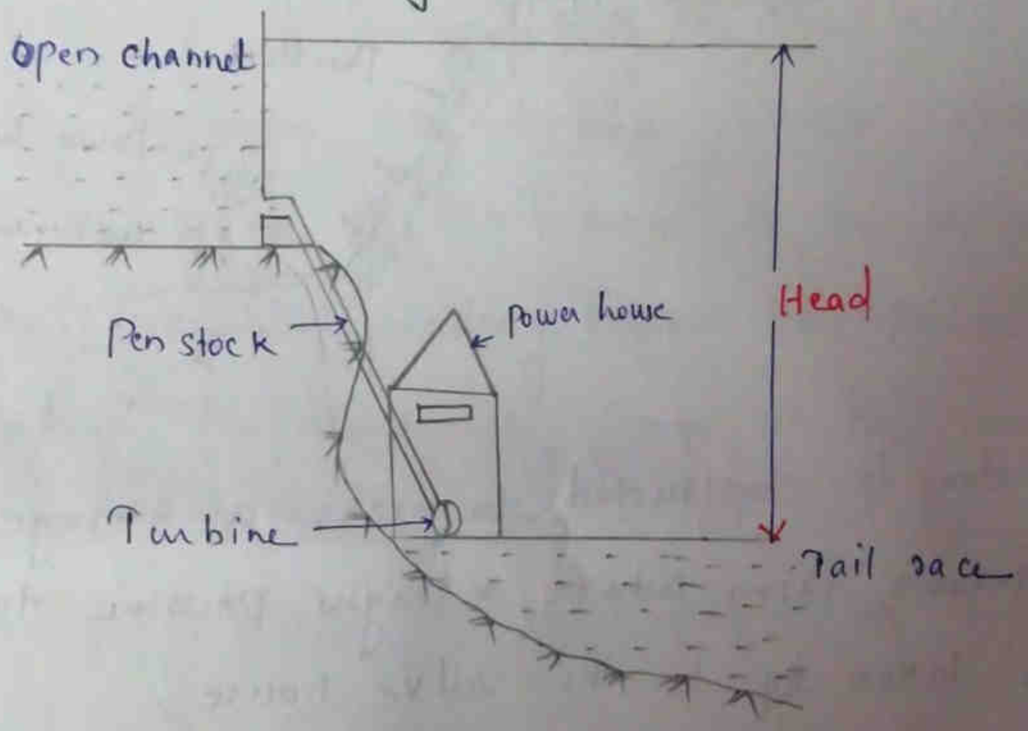


A dam is constructed to make a storage reservoir, from where a high pressure tunnel is taken off to the valve house.

The penstocks are large pipes, which carry huge quantity of water from valve houses to the power house. A surge tank is situated beside the valve house. In case, reduction of load on the turbines, the inlet valve to the turbine are suddenly closed, water hammer due to very high pressure is created which damage the penstocks.

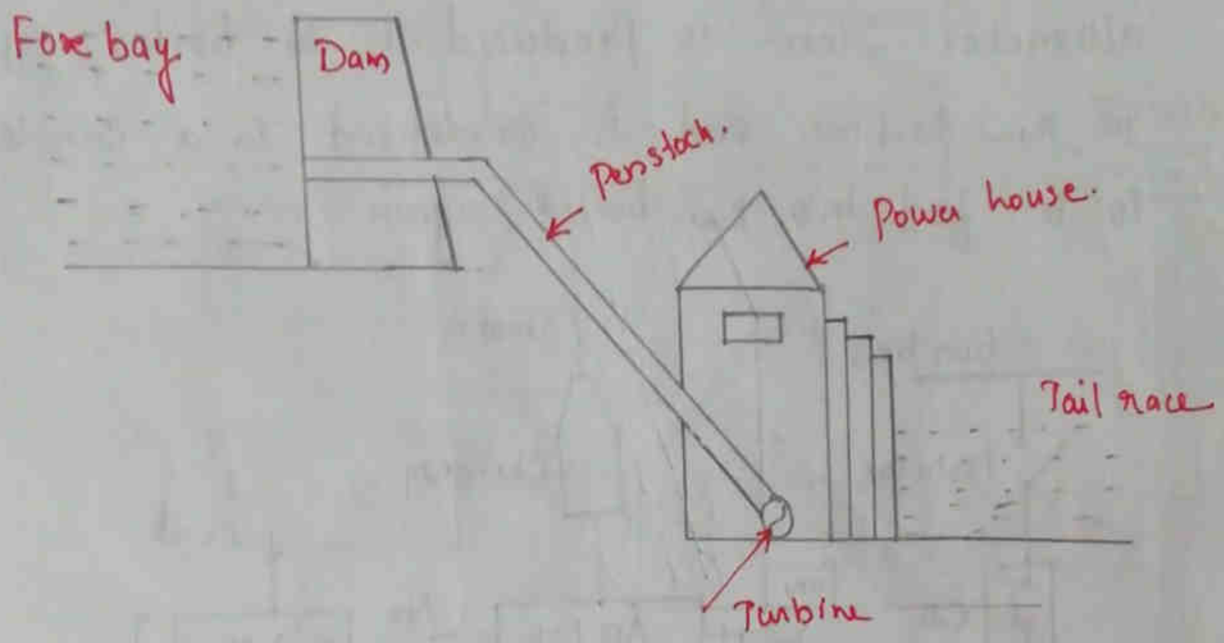
Surge tank absorb water hammer by increasing the water level. In case of heavy load, it will lower its water level & will increase the water supply to the turbine.

II Medium head hydro electric Plants.



In these types of plants, there is no need of surge tank. Water is generally carried in open channels from the main reservoir & then to the power house through the penstock.

III Low head hydro electric Plants

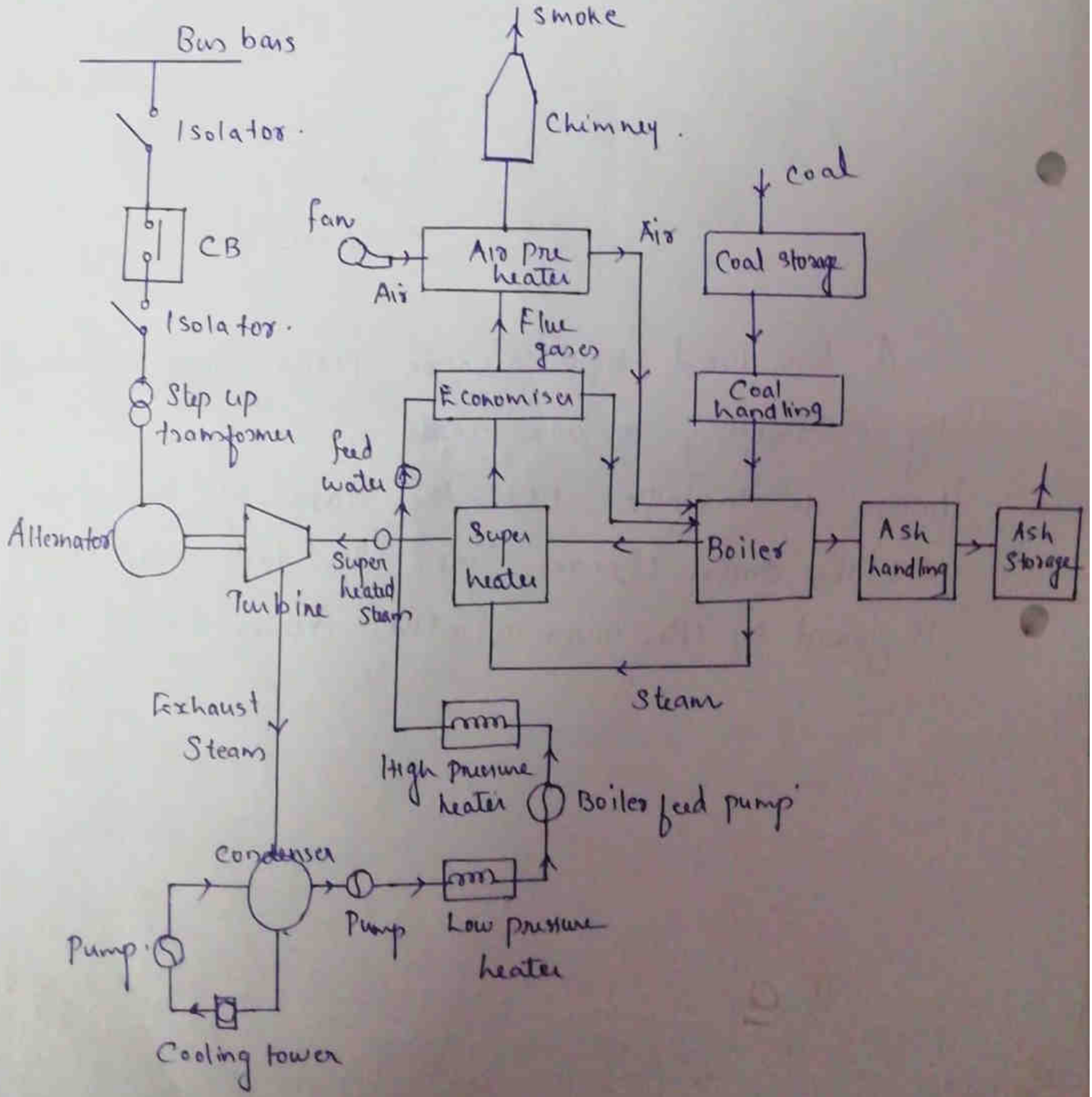


A low head hydro electric plant stores water by constructing a dam across a river & the power house is installed near the base of the dam on the down stream side. The tail race of turbine is joined to the river on the down stream side.

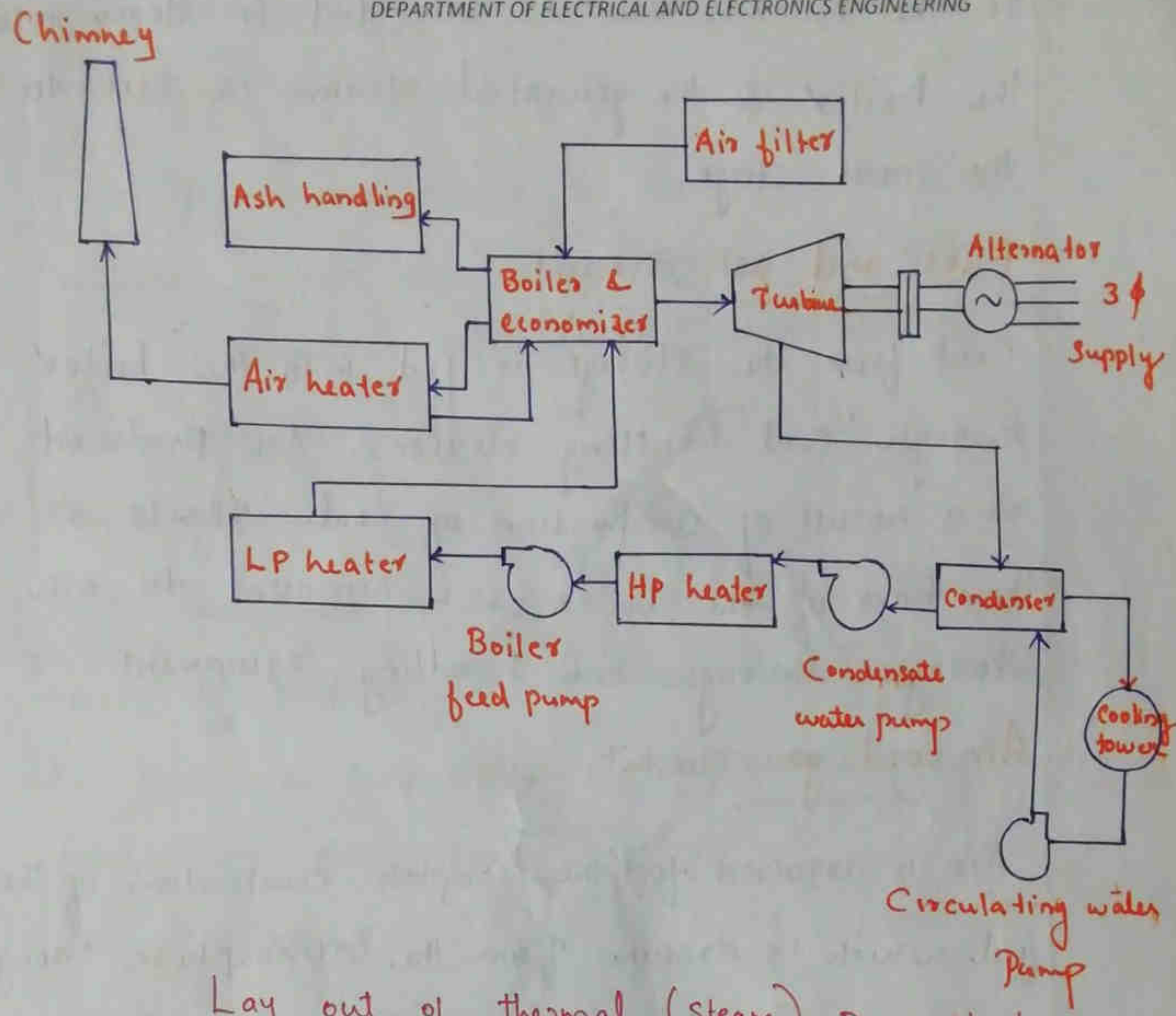
(2)

Thermal Power Plant

These plants use steam turbines to run the alternator. Steam is produced in a boiler, expanded in the turbine and is condensed in a condenser to be fed into the boiler again.



Block Diagram of thermal Power plant



Lay out of thermal (steam) power plant

The major parts of thermal power plant are,

Boiler:

Boiler is used for producing steam at high pressure. Fuel is burned in the boiler. Fuel & air are used in the correct proportion for combustion. The boiler feed pump supplies water to the boiler. Water is converted to steam inside the boiler & the generated steam is sent to the next stage.

Fuel and ash circuit

Coal from the storage is fed into the boiler through coal handling devices. Ash produced as a result of combustion of coal collects at the back of the boiler & is removed to ash storage through ash handling equipment.

Air and gas circuit

Air is required for the complete combustion of the fuel, which is drawn from the atmosphere through an air filter and a drought fan. This air is preheated in the air preheater by the heat of flue gases which is then made to pass to the chimney.

Super heater

The power transferred to the steam turbine increases when the steam pressure is more. High pressure is obtained by superheating the steam available from the boiler.

Economizer

They are used to extract heat from the flue gases for heating feed water. The feed water to the boiler is heated to a temperature near boiling point in the economizer.

Air Preheater

It is used to extract heat from flue gases to combustion air. The air from the atmosphere is preheated before sending it to the boiler.

Drought system

The main purpose of this is to supply air to the furnace & to take the flue gases from the boiler through the chimney.

Condenser

The steam produced in the boiler is sent to the turbine through the Superheater. The steam coming out of the turbine is condensed to water using the condenser & cooling tower arrangement.

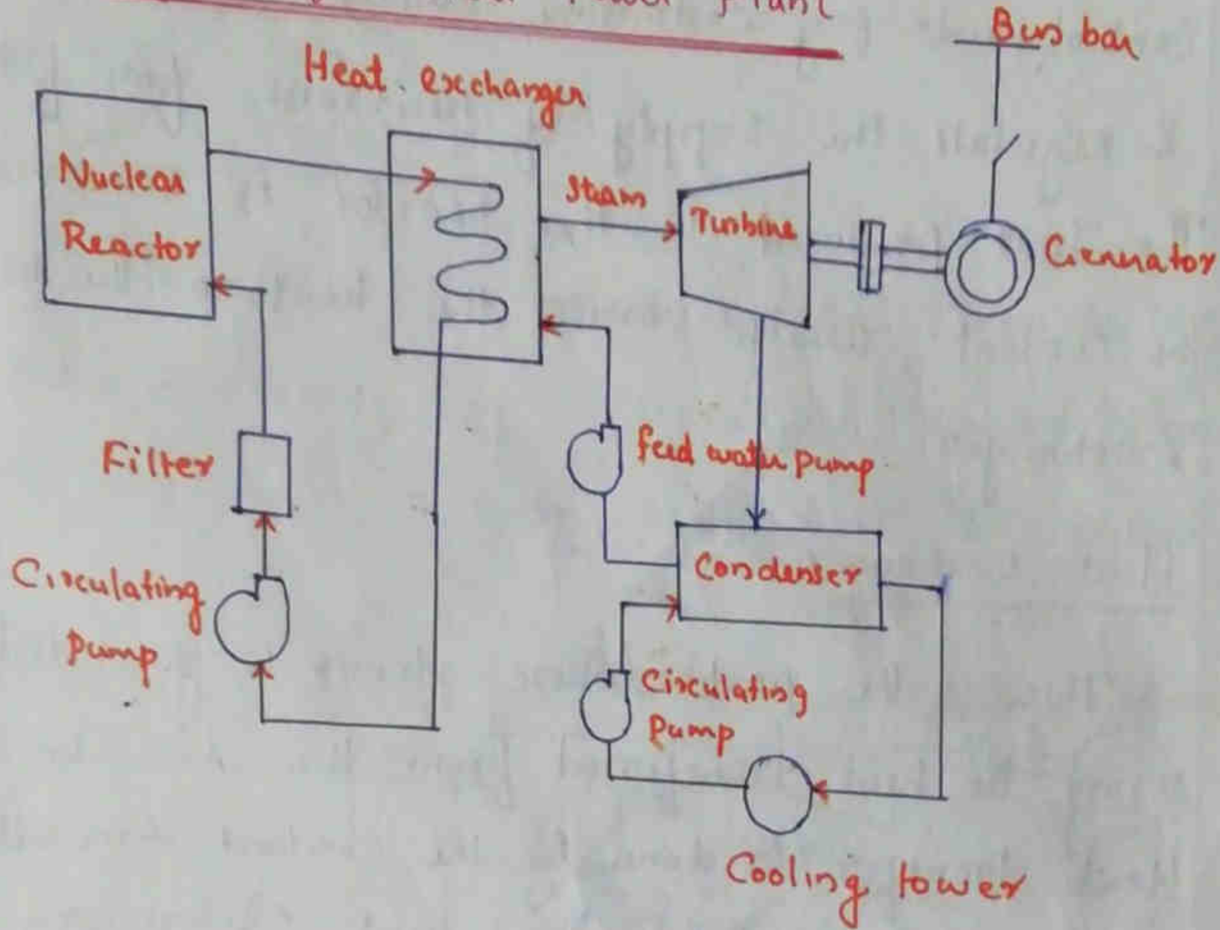
Turbine and alternator

Steam turbines are used to rotate the alternator which converts mechanical energy to electrical energy.

③ Nuclear Power Plant

Nuclear power plant convert nuclear energy into electrical energy. They work based on the chemical process of fission. In nuclear power plants, heavy elements such as Uranium (U^{235}) or Thorium (Th^{232}) are subjected to nuclear fission in a special apparatus known as a reactor. The heat energy thus released is utilized to produce steam at high pressure & temperature. The steam runs the turbine which converts steam energy into mechanical energy. The turbine drives the alternator which converts mechanical energy into electrical energy

Layout of Nuclear Power Plant



The main parts are nuclear reactor, heat exchanger, turbine & alternator.

1. Nuclear Reactor.

It is an apparatus in which nuclear fuel is subjected to nuclear fission, which controls the chain reaction. It is a cylindrical stout pressure vessel and houses fuel rods of Uranium, moderator (graphite) and control rods. The moderators are used to slow down the neutrons produced during the nuclear reaction. The Control rods (eg Cadmium, Boron) absorbs neutron & regulate the supply of neutrons for fission. The heat produced in the reactor is removed by the coolant, which carries the heat to the heat exchanger.

2. Heat exchanger

This is the part where steam is generated using the heat transferred from the reactor. Heat transfer is done by the coolant circulated through the reactor & the heat exchanger.

3. Steam turbine

The steam produced in the heat exchanger is fed to the steam turbine through a valve. After the useful work in the turbine, the steam is exhausted to condenser. The condenser condenses the steam which is fed to the heat exchanger through feed water pump.

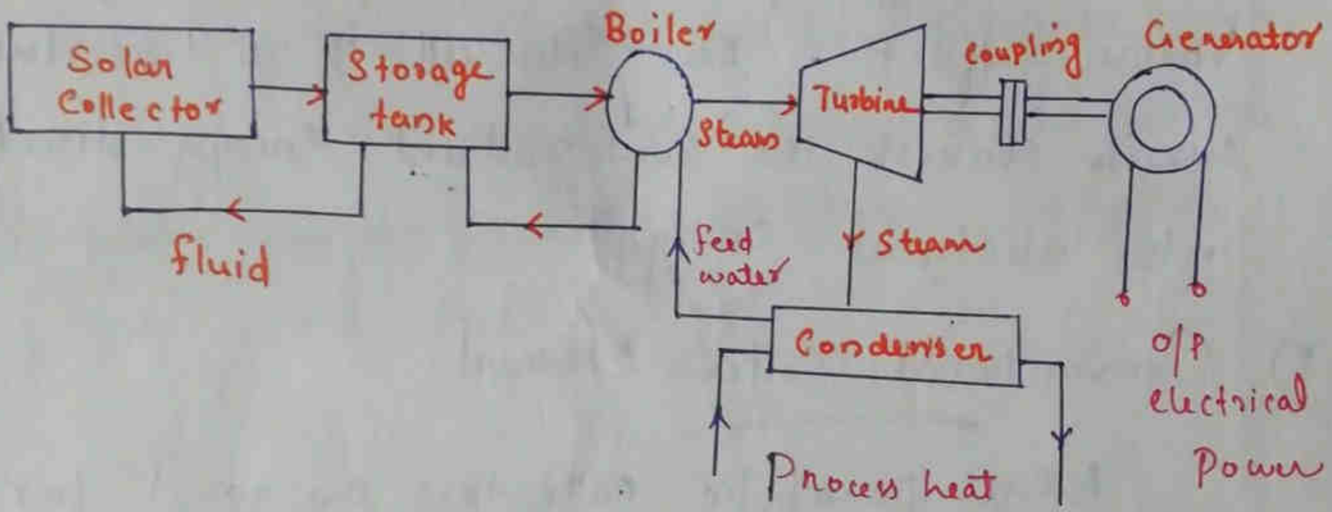
4. Alternator

The steam turbine drives the alternator which converts the mechanical energy into electrical energy.

II Non- Conventional Energy Sources:

(1) Solar Power Plant

The Solar cells operate on the principle of Photo electricity. ie, electrons are liberated from the surface of a body when light is incident on it.



Solar collectors are used for collecting solar energy, which is used to heat a fluid (water). This heat energy is finally transferred to feed water which is converted into steam. This steam is used to run the steam turbine coupled to an generator, which generates electric power. Steam is condensed in the condenser & feed water returns to the boiler for re use

These are 2 methods for converting Solar energy into electrical energy.

1) Direct Conversion Method.

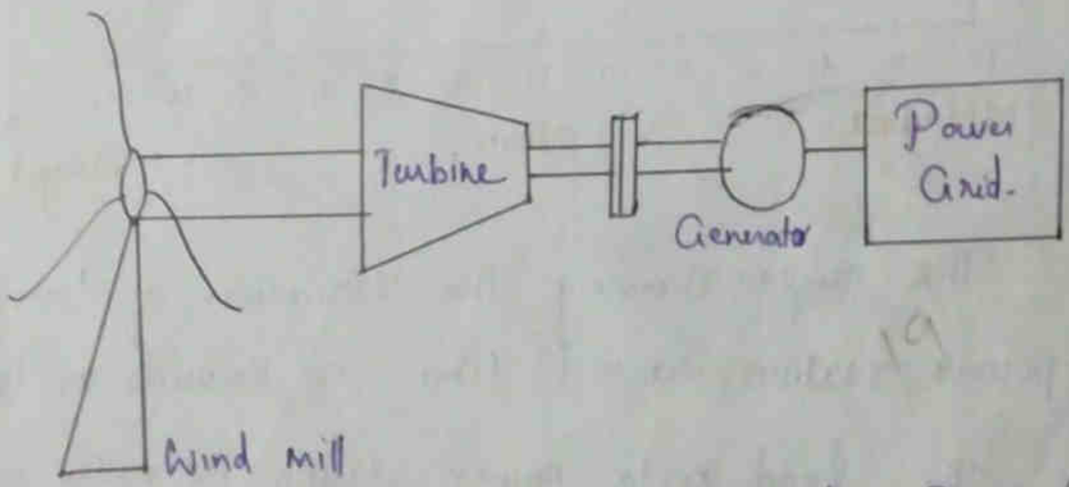
In this method, Solar energy is directly converted into electrical energy by the use of solar cells. The Solar cells operate on the principle of Photo Voltaic effect. Thus Solar cell is a transducer which converts the sun's radiant energy directly into electrical energy.

2) Conventional Boiler Method

Large parabolic collectors are used for Collecting Solar energy, which is used to heat a fluid. This heat energy is finally transferred to feed water which is converted into steam. This Steam is utilized to run a prime mover Coupled to the generator, which generates the electrical power.

② Wind Power

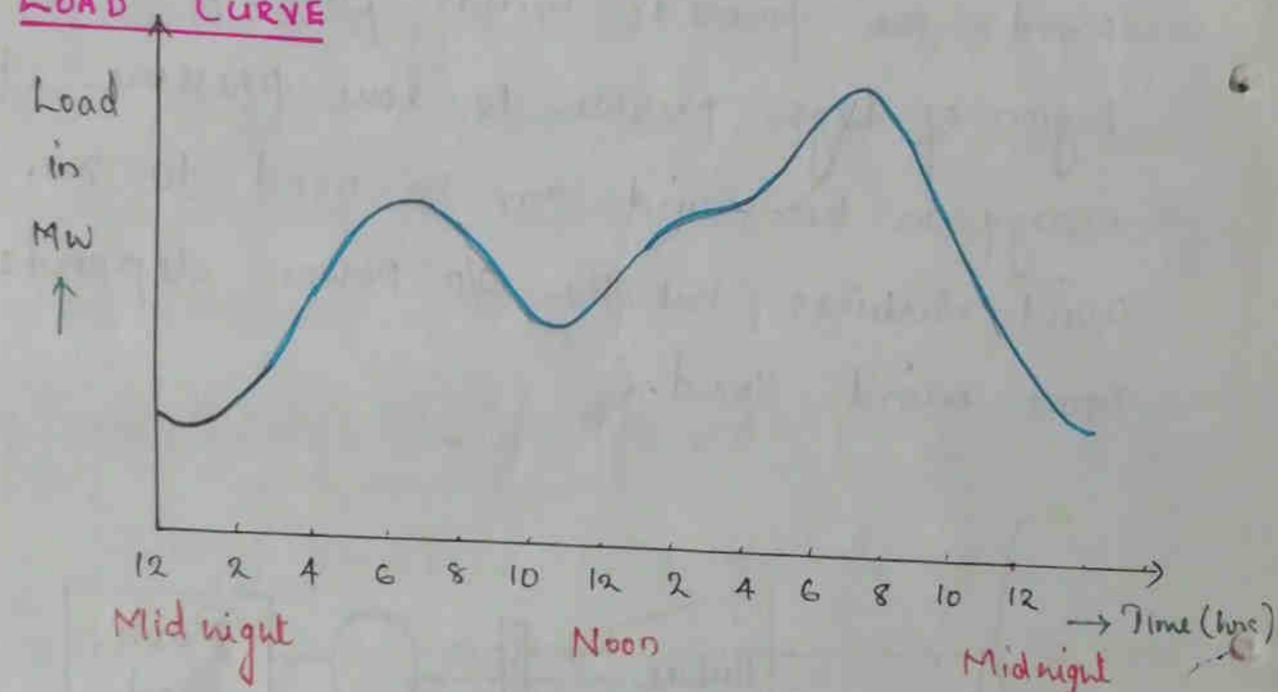
The origin of wind energy is from the sun. When the sun rays falls on earth, its surface get heated unevenly & as a consequence, winds are formed. Winds flow from a region of high pressure to low pressure. Kinetic energy in the wind can be used to run the wind turbines, but the o/p power depends upon wind speed.



The wind turbine generates power cheaply, safely & without pollution. There are 2 types of wind mills, Vertical axis turbine & horizontal axis turbine. The wind energy is used to run the wind turbine which drives the generator. Since wind flow is not dependable as it is not continuous, the generated o/p is connected to the batteries. The batteries are for supplying electrical energy in the absence of wind.

ECONOMICS OF GENERATION

LOAD CURVE



The curve showing the variation of load on a power station w.r.t time is known as load curve.

The load on a power station is never constant, but it varies from time to time. These load variations during the whole day (ie, 24 hrs) are recorded and are plotted against time.

The curve thus obtained is known as Daily load curve as it shows the variation of load w.r.t time during the day.

The monthly load curve can be obtained from the daily load curve of that month. The yearly load curve is obtained from the monthly load curve of that particular year. The yearly load curve is generally used to determine the annual load factor.

Significance

* The daily load curve shows the variation of load on the power station during different hours of the day.
* The area under the daily load curve gives the number of units generated in the day.

Units generated / day = Area under the daily load curve

- The highest point on the daily load curve represents the maximum demand on the station on that day.

Commonly used Terms

* Connected Load

Each device at consumers terminal has its rated capacity. Connected load is the sum of continuous ratings of all the equipments connected to the supply system.

* Maximum Demand

It is the greatest demand of load on the power station during a given period. The highest point on the load curve gives the maximum demand on the power station.

* Average Load or Average Demand

The average of loads occuring on the power station in a given period (day or month or year) is known as average load.

Daily average load = $\dfrac{\text{No. of units (kwh) generated in a day}}{24 \text{ hrs}}$

Monthly average load = $\dfrac{\text{No. of units (kwh) generated in a month}}{30 \times 24}$

Yearly average load = $\dfrac{\text{No. of units (kwh) generated in a year}}{8760}$

LOAD FACTOR

The ratio of average load to the maximum demand during a given period is known as load factor.

$$\boxed{\text{Load factor} = \dfrac{\text{Average Load}}{\text{Maximum demand}}}$$

$$\text{L.F} = \dfrac{\text{Energy generated in a given period of time}}{\text{Maximum demand} \times \text{Hours of operation in the given period.}}$$

* The value of load factor is less than 1.

Significance

Load factor help in determining the overall cost per unit generated. Higher the load factor, lesser will be the cost per unit generated.

$$\text{Daily load factor} = \frac{\text{No. of units generated in a day}}{\text{Max. demand} \times 24}$$

$$\text{Monthly load factor} = \frac{\text{No. of units generated in a month}}{\text{Max demand} \times 30 \times 24}$$

$$\text{Yearly load factor} = \frac{\text{No. of units generated in a year}}{\text{Max demand} \times 8760}$$

DIVERSITY FACTOR

The ratio of the sum of individual maximum demands to the maximum demand on a power station is known as diversity factor.

$$\boxed{\text{Diversity factor} = \frac{\text{Sum of individual maximum demand}}{\text{Maximum demand on power station}}}$$

The value of diversity factor is greater than 1

Significance.

The greater the diversity factor, the lesser is the cost of generation of power.

PROBLEMS

1. The maximum demand on a power station is 100 MW. If the annual load factor is 40 %, Calculate the total energy generated in a year.

$$\text{Annual load factor} = \frac{\text{No. of units generated in a year}}{\text{Max. demand} \times 8760}$$

$$\therefore \text{No of units generated / year} = (.40 \times 100 \times 8760) \text{ Mwh}$$

$$= 350.4 \times 10^3 \text{ Mwh}$$

$$= 350.4 \times 10^6 \text{ kwh}$$

2. A generating station has a connected load of 43 MW & a maximum demand of 20 MW, the units generated being 61.5×10^6 kwh per annum.

Calculate
1) Demand factor
2) Load factor

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}}$$

$$= \frac{20}{43}$$

$$= 0.465$$

$$\text{Load factor} = \frac{\text{No. of units generated / year}}{\text{Max. demand} \times 8760}$$

$$= \frac{61.5 \times 10^6 \text{ (kWh)}}{\underset{\uparrow \text{MW}}{20} \times 8760}$$

$$= \frac{61.5 \times 10^6}{20 \times 10^3 \times 8760}$$

$$= \underline{\underline{0.351}}$$

3) A 100 MW power station delivers 100 MW for 2 hrs, 50 MW for 6 hrs, and is shut down for rest for each day. It is also shut down for maintenance for 45 days each year. Calculate its annual load factor.

Energy supplied for each working day

$$= (100 \times 2) + (50 \times 6)$$

$$= 500 \text{ MWh}$$

working time

Station operates for $= 365 - 45 = 320$ days in a year

$\therefore$ Energy supplied per year $= 320 \times 500$

$$= 1,60,000 \text{ MWh}$$

$$\text{Annual load factor} = \frac{\text{Energy supplied / year}}{\text{Max. demand} \times \text{working time}}$$

$$= \frac{1,60,000}{100 \times (320 \times 8)}$$

$$= \underline{\underline{0.625}}$$

4) A diesel station supplies the following loads to various consumers :

Industrial consumer = 1500 kW

Commercial establishment = 750 kW

Domestic power = 100 kW

Domestic light = 450 kW

If the max. demand on the station is 2500 kW & the no. of kwh generated / year is 45×10^5.

Determine 1) The diversity factor

2) Annual load factor.

1) $$\text{Diversity factor} = \frac{\text{Sum of individual max demand}}{\text{Max. demand on power station}}$$

$$= \frac{1500 + 750 + 100 + 450}{2500}$$

$$= \underline{\underline{1.12}}$$

2) Annual load factor $= \frac{\text{No. of units generated / year}}{\text{Max. demand} \times 8760}$

$= \frac{45 \times 10^5}{2500 \times 8760}$

$= \underline{\underline{0.205}}$

5) A power station has to meet the following demand

6

Group A : 200 kW between 8 am & 6 pm

Group B : 100 kW between 6 am & 10 am

Group C : 50 kW between 6 am & 10 am

Group D : 100 kW between 10 am & 6 pm and then between 6 pm & 6 am.

Plot the daily load curve and determine

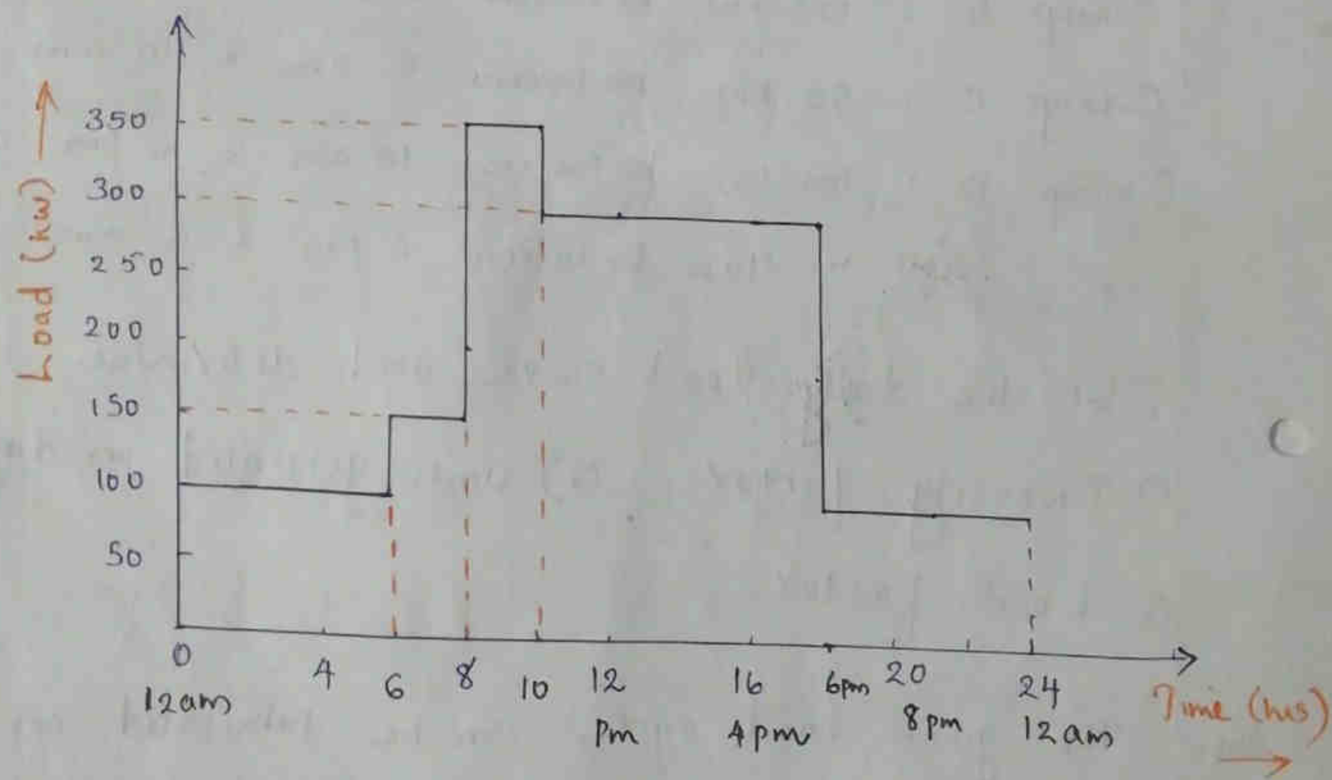
6

i) Diversity factor (2) units generated per day

3) Load factor

Ans: The given load cycle can be tabulated as given below.

Time (hrs)	12 am - 6 am	6 am - 8 am	8 am - 10 am	10 am - 6 pm	6 pm - 12 am
Group A	–	–	200 kw	200 kw	–
Group B	–	100 kw	100 kw	–	–
Group C	–	50 kw	50 kw	–	–
Group D	100 kw			100 kw	100 kw
Total load on Power Station	100 kw	150 kw	350 kw	300 kw	100 kw



1) Diversity factor $= \dfrac{\text{Sum of individual max demand}}{\text{Max. demand on power station}}$

$= \dfrac{200 + 100 + 50 + 100}{350}$

$= \underline{\underline{1.286}}$

2) Units generated per day = Area under load curve

$$= (100 \times 6) + (150 \times 2) + (350 \times 2) + (300 \times 8) + (100 \times 6)$$

$$= \underline{\underline{4600 \text{ kWh}}}$$

3) Load factor $= \dfrac{\text{No. of units generated / day}}{\text{Max. demand} \times 24}$

$$= \frac{4600}{350 \times 24}$$

$$= \underline{\underline{0.547}}$$

PLANT CAPACITY FACTOR

It is the ratio of actual energy produced to the maximum possible energy that could have been produced during a given period.

ie,

$$\boxed{\text{Capacity Factor} = \frac{\text{Actual energy produced}}{\text{Maximum energy that could have been produced}}}$$

No. of units generated = Avg load x Time
(Actual energy produced)

$$= \frac{\text{Average demand} \times \text{Time}}{\text{Maximum demand} \times \text{Time}}$$

$$\boxed{\text{Capacity factor} = \frac{\text{Average demand}}{\text{Plant Capacity}}}$$

* For 1 year period,

Avg demand

$$\boxed{\text{Annual Capacity Factor} = \frac{\text{Annual kwh output}}{\text{Plant Capacity} \times 8760}}$$

Significance

* The capacity factor is an indication of the reserve capacity of the plant. So when a

Power station is designed, it has some reserve capacity for meeting the increased load demand in future. Therefore the installed capacity of the plant is always greater than the maximum demand on the plant.

$$\boxed{\text{Reserve Capacity} = \text{Plant capacity} - \text{Max. demand}}$$

PLANT USE (UTILISATION) FACTOR

It is the ratio of kwh generated to the product of plant capacity and the number of hours for which the plant was in operation.

$$\text{Plant use factor} = \frac{\text{Station output in kwh}}{\text{Plant Capacity} \times \text{Hours of use}}$$

or

$$\text{Plant use factor} = \frac{\text{Maximum demand}}{\text{Plant capacity}}$$

Problems :-

UQ

1) A power station has a maximum demand of 15000 kw. The annual load factor is 50 % and capacity factor is 40 %. Determine the reserve capacity of the plant.

Reserve capacity = Plant capacity − Max. demand

$$\text{Capacity factor} = \frac{\text{Avg demand}}{\text{Plant capacity}}$$

$$\text{load factor} = \frac{\text{Avg. load}}{\text{Max. demand}}$$

$$\therefore \text{Avg. load} = 0.50 \times 15000$$

$$= 7500\,\text{kw}$$

$$\therefore \text{Plant capacity} = \frac{\text{Average demand}}{\text{Capacity factor}}$$

$$= \frac{7500}{.4} = 18750\,\text{kw}$$

$$\therefore \text{Reserve Capacity} = 18750 - 15000$$

$$= \underline{\underline{3750\,\text{kw}}}$$

Power Factor

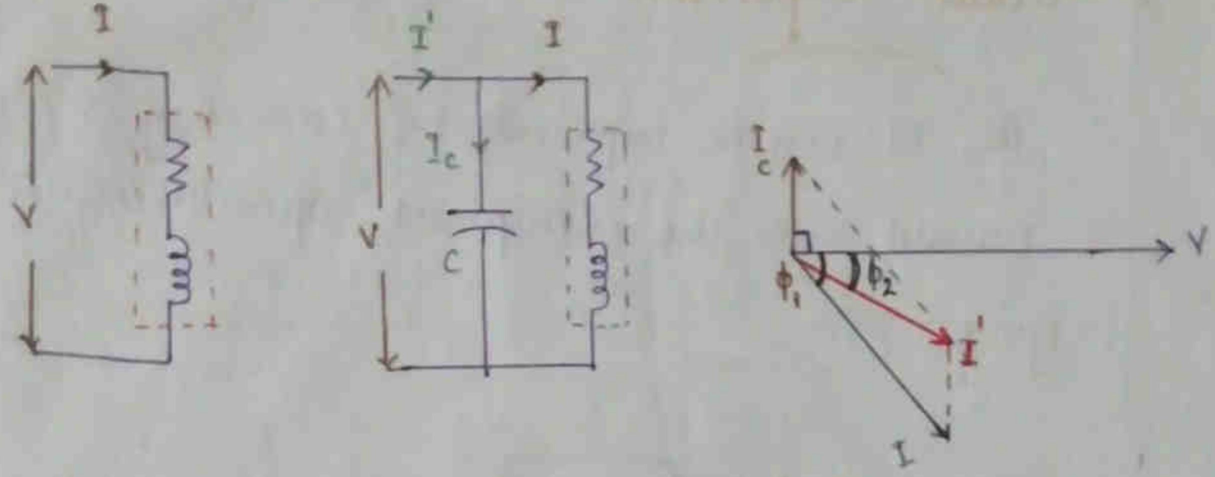
The cosine of angle between voltage & current in an ac circuit is known as power factor

Power Factor Improvement Techniques

The Pf can be improved by,

1) Static capacitors
2) Synchronous Condenser
3) Phase Advancers.

The low Pf is mainly due to the fact that the most of the power loads are inductive and therefore take lagging currents. In order to improve the Pf, some device taking leading power should be connected in parallel with the load. One of such device is a capacitor. The capacitor draws a leading current & neutralises the lagging reactive component of load current. This will increase the Pf of load.



Consider a single phase load taking lagging current I at a pf $\cos\phi_1$..

The capacitor C is connected in parallel with the load. The capacitor draws current I_c which leads the supply voltage by 90°. The resulting current I' is the phasor sum of I & I_c which lags the voltage by an angle ϕ_2.

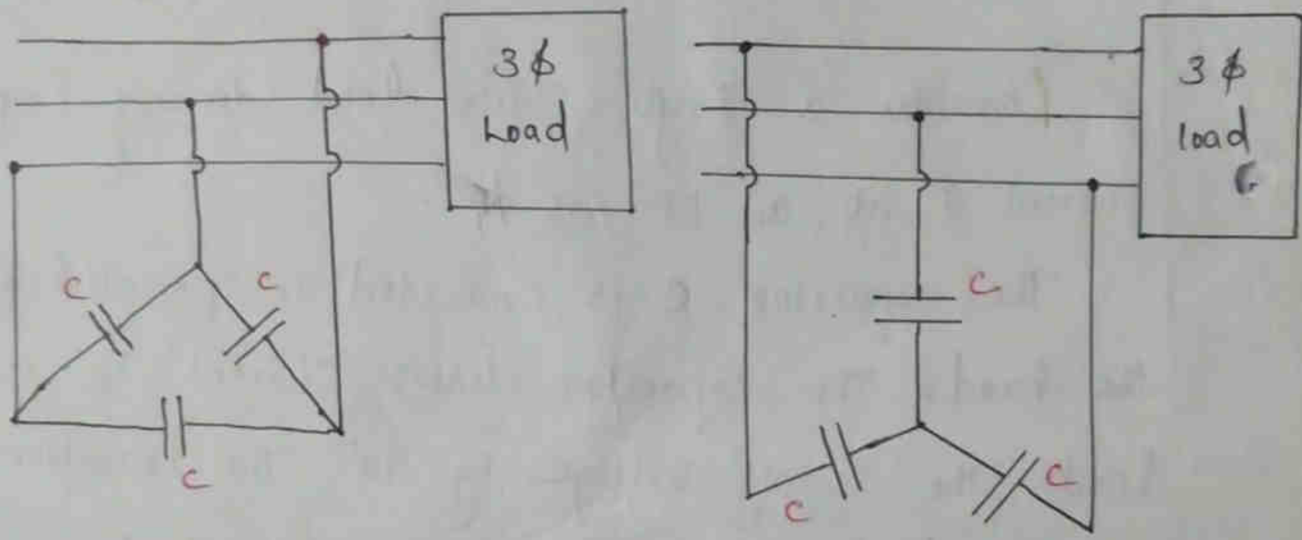
$\phi_2 < \phi_1$

$\therefore \cos\phi_2 > \cos\phi_1$

Hence, the pf of the load is improved.

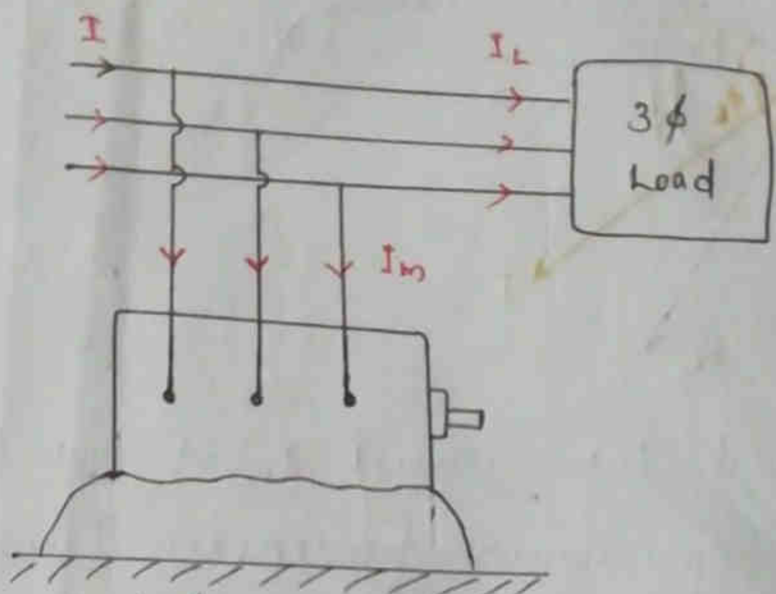
1) Static Capacitors.

The Pf can be improved by connecting capacitors in parallel with the equipment operating at lagging Pf.



The capacitor generally known as static capacitor draws a leading current & neutralises the lagging reactive component of load current. This increases the Pf of the load. For 3 ϕ loads, the capacitors can be connected in delta or star.

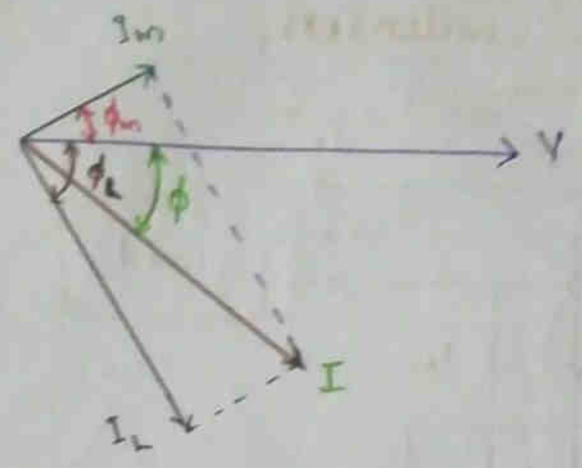
2) Synchronous Condensers



3 ϕ synchronous motor

A synchronous motor takes a leading current when over excited & therefore behaves as a capacitor. An overexcited synchronous motor running on no load is known as synchronous condenser.

When such a machine is connected in parallel with the supply, it takes a leading current which neutralises the lagging reactive component of the load. Thus the pf can be improved.



The 3ϕ load takes current I_L at low lagging pf $\cos\phi_L$. The synchronous condenser takes a current I_m which leads the voltage V by an angle ϕ_m. The resultant current, I is the phasor sum of I_m & I_L and lags behind the voltage by an angle ϕ. Here $\phi < \phi_L$ $\therefore \cos\phi > \cos\phi_L$. Thus the pf is increased from $\cos\phi_L$ to $\cos\phi$.

3) Phase Advancers

Phase advancers are used to improve the pf of induction motors. The low pf of induction motor is due to the fact that its stator winding draws exciting current which lags behind the supply voltage by 90°

2) Power factor of a 3 ϕ load of 25 kw at 415 V, 50 Hz is to be improved from 0.6 to 0.9. Calculate the value of capacitance required in each branch, if the capacitor bank is in delta configuration.

$\cos\phi_1 = 0.6$; $\cos\phi_2 = 0.9$

$\therefore \phi_1 = \cos^{-1}(0.6) = \cancel{60}\ 53.63$

$\phi_2 = \cos^{-1}(0.9) = 25$

Leading KVAR $= kw(\tan\phi_1 - \tan\phi_2)$

$= 25(\tan 53 - \tan 25)$

$= \underline{\underline{21.23\ \text{KVAR}}}$

KVAR required for one branch $= \dfrac{21.23}{3}$

$= 7.075$ KVAR.

Phase current of capacitor, $I_{Ph} = \dfrac{V_{Ph}}{X_C}$

$= V_{Ph} / \dfrac{1}{CW}$

$= V_{ph} \times C \times W = V_{Ph} \times C \times 2\pi f$

$= 2\pi \times 50 \times C \times 415$

$= \cancel{41500}\ 130310\,C$

KVAR / Phase $= \dfrac{V_{Ph} \times I_{Ph}}{1000} = \dfrac{415 \times 130310\,C}{1000} = 54078\,C$

ie, $54078\,C = 7.075$

$\therefore C = \underline{\underline{130.83\ \mu F}}$

MODULE - II

POWER TRANSMISSION LINE PARAMETERS

RESISTANCE

The resistance of transmission line conductors is the most important cause of power loss in a transmission line.

The effective AC resistance is given by,

$$R = \frac{\text{Average Power loss in Conductor}}{I^2}$$

where, I is the rms current in the conductor

Ohmic or DC resistance is given by,

$$R = \frac{\rho l}{a}$$

where,

ρ = resistivity of the conductor

l = length

A = cross sectional area

For small changes in temperature, the resistance increases linearly with temperature and the resistance at a temperature t is given by,

$$R_t = R_0 (1 + \alpha_0 t)$$

Where, R_t = Resistance at $t^\circ C$

R_0 - Resistance at $0^\circ C$

α_0 = temperature coefficient of resistance at $0^\circ c$

* Resistor ...

○ Transmission line inductance

* When current flows through a conductor, a flux is created, when current varies, varying flux produces or induce an emf.
* Induced emf, $e = L\frac{di}{dt}$

$$L = \frac{\lambda}{I}$$

λ = Flux linkage

* Flux linkage can be of two types
  1) Internal
  2) External.
* Inductance due to internal flux linkage

$$L_{int} = \frac{10^{-7}}{2}$$

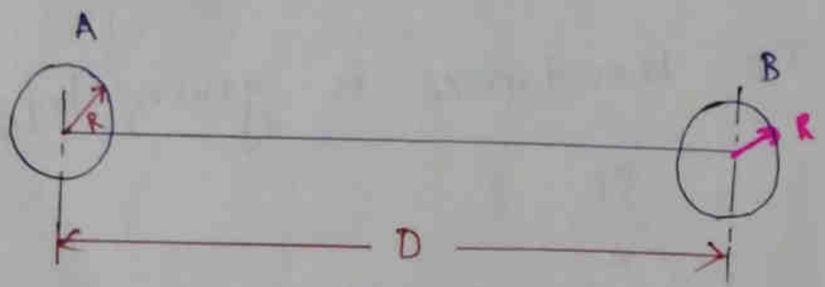
* Inductance due to external flux linkage } = $L_{ext} = 2\times10^{-7}$ ln ...

D: Distance of conductor to the external point
r: Radius of conductor.

at 0 c

INDUCTANCE OF A 1-ϕ, 2 WIRE CONDUCTOR

Consider a single phase over head line consist of 2 parallel conductors A & B spaced 'D' m apart.



For conductor A, there are two fluxes. One is due to internal flux & the other is due to external flux.

$$L_{int} = \frac{10^{-7}}{2}$$

$$L_{ext} = 2\times10^{-7} \ln \frac{D}{R}$$

Inductance of the circuit due to current in conductor A only is,

$$L_A = L_{int} + L_{ext}$$

$$= \frac{10^{-7}}{2} + 2\times10^{-7} \ln \frac{D}{R}$$

$$= 2\times10^{-7}\left(\frac{1}{4} + \ln \frac{D}{R}\right)$$

$$= 2\times10^{-7}\left(\ln e^{1/4} + \ln \frac{D}{R}\right) \quad (\because \ln e^x = x)$$

$$= 2\times10^{-7}\left(\ln \left\{e^{1/4} \cdot \frac{D}{R}\right\}\right) \quad (\because \ln ab = \ln a + \ln b)$$

$$= 2\times10^{-7}\left(\ln \frac{D}{e^{-1/4} R}\right)$$

$$= 2\times10^{-7}\left(\ln \frac{D}{R'}\right) \text{ H/m}$$

where $R' = e^{-1/4} \cdot R$

or, $R' = 0.7788\ R$, which is called as

line
var
f

Geometric Mean Radius (GMR)

Similarly, inductance due to current in conductor-B only is,

$$L_B = 2\times10^{-7} \ln \frac{D}{R'} \text{ H/m}$$

$\therefore$ Total inductance, $L_{tot} = L_A + L_B$

$$= 2\times10^{-7} \ln \frac{D}{R'} + 2\times10^{-7} \ln \frac{D}{R'}$$

$$\boxed{L_{tot} = 4\times10^{-7} \ln \frac{D}{R'} \text{ H/m}}$$

$$L_B = 2\times10^{-7}\left(\ln\left(\frac{D}{R'}\right)\right)$$

$\therefore$ Total inductance, $L_{Total} = L_A + L_B$

$$\boxed{L_{total} = 4\times10^{-7}\left(\ln\left(\frac{D}{R'}\right)\right) H/m}$$

1. A single phase line has 2 parallel conductors 2 meter apart, the diameter of each conductor is 1.2 cm, calculate the loop inductance/km of the line

Ans:- $D = 2m$

$$R = \frac{1.2\times10^{-2}}{2}$$

$$L_{total} = 4\times10^{-7}\left(\ln\frac{2}{\frac{1.2\times0.7788\times10^{-2}}{2}}\right) H/m$$

$$= 4\times10^{-7}\left(\ln\left(\frac{D}{R'}\right)\right)$$

$$= 2.423\times10^{-6} H/m$$

$$= 2.423\times10^{-6}\times10^{+3} H/km$$

$$= 24.23\times10^{-4} H/km.$$

- Inductance of composite conductors

* Flux linkage in a composite conductors

Consider a group of conductors, 1, 2, ... n
Let 'p' be an external point with respect to conductors.
... 1st conductor to P

Logarithmic Properties

$\ln a + \ln b = \ln ab$

$\ln a - \ln b = \ln\left(\frac{a}{b}\right)$

$\ln a^m = m \log a$

$\frac{1}{2} \ln a =$

$\frac{1}{2} \ln \frac{1}{a}$

$\frac{1}{m} \cancel{\log} \ln a = \ln(a)^{1/m}$

$= \ln \sqrt[m]{a}$

$\frac{1}{m} \ln \frac{1}{a} = \ln\left(\frac{1}{a}\right)^{1/m}$

$= \ln \frac{1}{\sqrt[m]{a}}$

$-\ln a = + \ln \frac{1}{a}$

$\frac{1}{2} \ln a = \ln(a)^{1/2} = \ln \sqrt{a}$

$\frac{1}{2} \ln \frac{1}{a} = \ln\left(\frac{1}{a}\right)^{1/2} = \ln \frac{1}{\sqrt{a}}$

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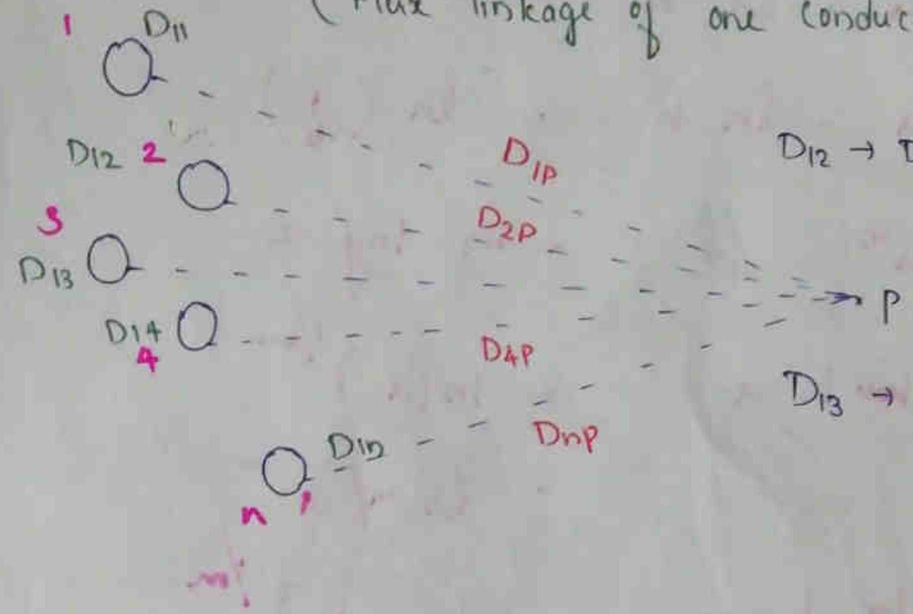
Just Read

NB: **Flux linkage In a Composite Conductor**

(Flux linkage of one conductor in an array)



$D_{12} \to$ Distance b/w Cond^n 1 & 2

$D_{13} \to$ Distance b/w Cond^n 1 & 3

Consider a group of n composite conductors, which are connected in parallel.

The current carried by the individual Composite conductors are $I_1, I_2, I_3, \ldots I_n$

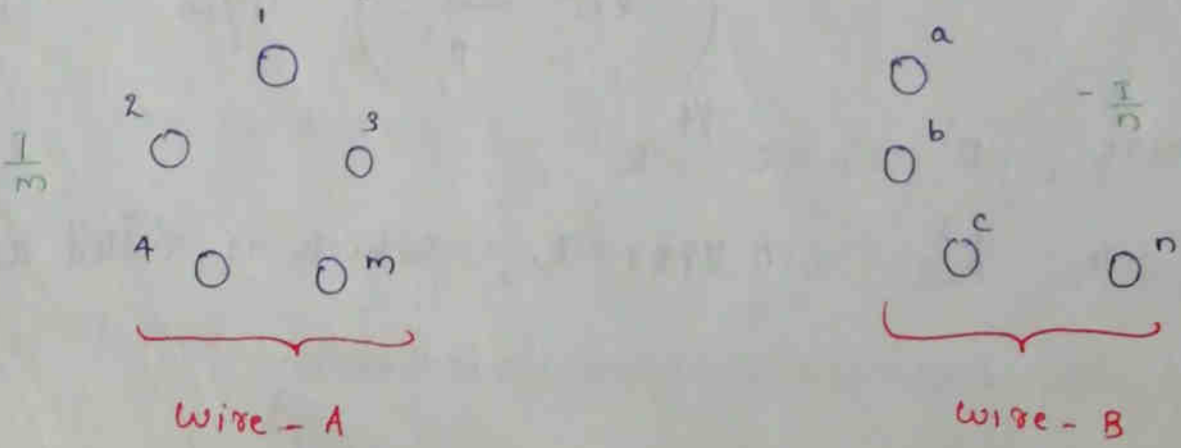
The flux linkage in conductor - 1 due to current in all the conductors will be,

$$\boxed{\lambda_1 = 2\times10^{-7}\left[I_1 \ln\frac{1}{D_{11}} + I_2 \ln\frac{1}{D_{12}} + I_3 \ln\frac{1}{D_{13}} + \ldots\ldots I_n \ln\frac{1}{D_{1n}}\right]}$$

where $D_{11} = R_1'$ ($R_1 \to$ radius of cond^n 1) tot R'

INDUCTANCE OF SINGLE PHASE TWO WIRE COMPOSITE CONDUCTOR LINE

Consider two wires A & B consist of respectively m and n composite conductors as shown in fig. The current in each conductor of wire A will be I/m and of wire B will be $-I/n$.



The flux linkage of any conductor (say 1) due to current in all the conductors will be,

$$\lambda_1 = 2\times10^{-7}\left[\frac{I}{m}\ln\frac{1}{D_{11}} + \frac{I}{m}\ln\frac{1}{D_{12}} + \cdots \frac{I}{m}\ln\frac{1}{D_{1m}}\right]$$

$$+\ 2\times10^{-7}\left(-\frac{I}{n}\ln\frac{1}{D_{1a}} - \frac{I}{n}\ln\frac{1}{D_{1b}} - \cdots - \frac{I}{n}\ln\frac{1}{D_{1n}}\right)$$

$$= 2\times10^{-7}\times I\ \ln\frac{\sqrt[n]{D_{1a}D_{1b}\cdots D_{1n}}}{\sqrt[m]{D_{11}D_{12}\cdots D_{1m}}}$$

$$= 2\times10^{-7}\times I\left[\ln\frac{1}{\sqrt[m]{D_{11}}} + \ln\frac{1}{\sqrt[m]{D_{12}}} + \cdots \ln\frac{1}{\sqrt[m]{D_{1m}}}\right]$$

$$-2\times10^{-7}\times I\left[\ln\frac{1}{\sqrt[n]{D_{1a}}} + \ln\frac{1}{\sqrt[n]{D_{1b}}} + \cdots \ln\frac{1}{\sqrt[n]{D_{1n}}}\right]$$

$$= 2\times10^{-7}\times I\left[\ln\frac{1}{\sqrt[m]{D_{11}D_{12}\cdots D_{1m}}}\right] - 2\times10^{-7}\times I\left[\ln\frac{1}{\sqrt[n]{D_{1a}D_{1b}\cdots D_{1n}}}\right]$$

$$= 2\times10^{-7}\times I\left[\ln\frac{\sqrt[n]{D_{1a}D_{1b}\cdots D_{1n}}}{\sqrt[m]{D_{11}D_{12}\cdots D_{1m}}}\right]$$

The inductance of conductor - 1 in wire A is,

$$L_1 = \frac{\lambda_1}{I/m} = 2m\times10^{-7}\ \ln\frac{\sqrt[n]{D_{1a}D_{1b}\cdots D_{1n}}}{\sqrt[m]{D_{11}D_{12}\cdots D_{1m}}}$$

Similarly, Inductance of conductor - 2 in wire A

$$L_2 = \frac{\lambda_2}{I/m} = 2m \times 10^{-7} \times \ln \frac{\sqrt[n]{D_{2a} D_{2b} \cdots D_{2n}}}{\sqrt[m]{D_{21} D_{22} \cdots D_{2m}}}$$

The average inductance of m conductors in wire - A,

$$L_{avg} = \frac{L_1 + L_2 + \cdots L_m}{m}$$

Since wire A consist of m conductors electrically in parallel, the inductance of wire A will be,

$$L_A = \frac{L_{avg}}{m} = \frac{L_1 + L_2 + L_3 + \cdots L_m}{m^2}$$

$$= 2 \times 10^{-7} \ln \frac{\sqrt[mn]{(D_{1a} D_{1b} \cdots D_{1n})(D_{2a} D_{2b} \cdots D_{2n}) \cdots (D_{ma} D_{mb} \cdots D_{mn})}}{\sqrt[m^2]{(D_{11} D_{12} \cdots D_{1m})(D_{21} D_{22} \cdots D_{2m}) \cdots (D_{m1} D_{m2} \cdots D_{mm})}}$$

Where $D_{11}, D_{22} \cdots D_{mm}$ represent the 0.7788 times the radius of conductors 1, 2, ... m respectively.

The numerator is known as Geometric Mean Distance (GMD) or mutual GMD & is denoted as D_m.

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The Denominator is known as Geometric Mean Radius (GMR) or self GMD and is denoted as D_s.

$$\therefore L_A = 2 \times 10^{-7} \ln \frac{D_m}{D_{SA}} \text{ H/m} \rightarrow \text{Inductance of wire A}$$

$$L_B = 2 \times 10^{-7} \ln \frac{D_m}{D_{SB}} \text{ H/m.} \rightarrow \text{Inductance of wire B.}$$

The total inductance of Composite conductors of both wires,

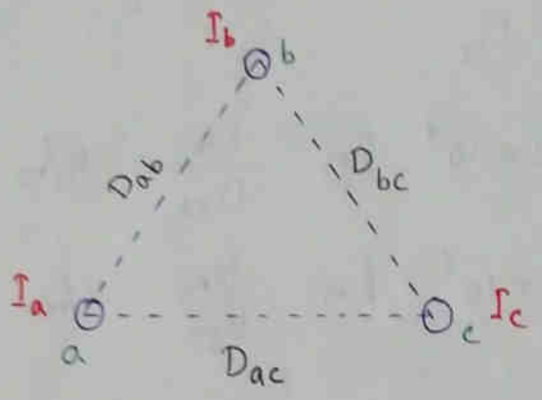
$$L = L_A + L_B$$

$$= 2 \times 10^{-7} \ln \left(\frac{D_m D_m}{D_{SA} D_{SB}} \right)$$

If the wires A & B are identical, then $D_{SA} = D_{SB}$

INDUCTANCE OF THREE PHASE TRANSMISSION LINE

(Unsymmetrical Spacing & Untransposed)



A 3 ϕ system shown in fig is having 3 conductors a, b and c with current I_a, I_b & I_c respectively. Let us assume that the radius of each conductor is R.

The flux linkage of conductor - a due to currents I_a, I_b & I_c can be written as,

$$\lambda_a = 2\times10^{-7}\left[I_a \ln\frac{1}{R'} + I_b \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{ac}}\right]$$

Similarly,

$$\lambda_b = 2\times10^{-7}\left[I_a \ln\frac{1}{D_{ab}} + I_b \ln\frac{1}{R'} + I_c \ln\frac{1}{D_{bc}}\right]$$

$$\lambda_c = 2\times10^{-7}\left[I_a \ln\frac{1}{D_{ac}} + I_b \ln\frac{1}{D_{bc}} + I_c \ln\frac{1}{R'}\right]$$

If currents in phases are symmetrical, the phase current I_b & I_c can be represented in terms of phase current I_a as,

$$I_a = I_a \angle 0 = I_a (1 + j0)$$

$$I_b = I_a \angle -120 = I_a (-0.5 - j\,0.866)$$

$$I_c = I_a \angle +120 = I_a (-0.5 + j\,0.866)$$

let $\alpha = -0.5 - j\,0.866$

then $\alpha^2 = -0.5 + j\,0.866$

ie,

$$I_b = \alpha I_a$$

$$I_c = \alpha^2 I_a$$

$0.866 = \frac{\sqrt{3}}{2}$

On substituting these values,

$$\lambda_a = 2 \times 10^{-7} \left[I_a \ln \frac{1}{R'} + \alpha I_a \ln \frac{1}{D_{ab}} + \alpha^2 I_a \ln \frac{1}{D_{ac}} \right]$$

$$= 2 \times 10^{-7} \times I_a \left[\ln \frac{1}{R'} + (-0.5 - j\,0.866) \ln \frac{1}{D_{ab}} + (-0.5 + j\,0.866) \ln \frac{1}{D_{ac}} \right]$$

$$= 2\times10^{-7}\times I_a\left[\ln\frac{1}{R'} - \frac{1}{2}\ln\frac{1}{D_{ab}} - \frac{1}{2}\ln\frac{1}{D_{ac}} - j\frac{\sqrt{3}}{2}\ln\frac{1}{D_{ab}} + j\frac{\sqrt{3}}{2}\ln\frac{1}{D_{ac}}\right]$$

$$= 2\times10^{-7}\times I_a\left[\ln\frac{1}{R'} - \ln\left(\frac{1}{D_{ab}}\right)^{1/2} - \ln\left(\frac{1}{D_{ac}}\right)^{1/2} + j\frac{\sqrt{3}}{2}\ln\frac{1}{D_{ac}} - j\frac{\sqrt{3}}{2}\ln\frac{1}{D_{ab}}\right]$$

$$= 2\times10^{-7}\times I_a\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ab}}} - \ln\frac{1}{\sqrt{D_{ac}}} + j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ab}}{D_{ac}}\right)\right]$$

$$= 2\times10^{-7}\times I_a\left[\ln\frac{1}{R'} - \left(\ln\frac{1}{\sqrt{D_{ab}}} + \ln\frac{1}{\sqrt{D_{ac}}}\right) - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ac}}{D_{ab}}\right)\right]$$

$$= 2\times10^{-7}\times I_a\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ab}D_{ac}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ac}}{D_{ab}}\right)\right]$$

$\therefore$ Inductance of conductor a is,

$$L_a = \frac{\lambda_a}{I_a} = 2\times10^{-7}\left(\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ab}D_{ac}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ac}}{D_{ab}}\right)\right)$$

a b c   b c a   c a b

Similarly,

$$L_b = 2\times10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{bc}\,D_{ba}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ba}}{D_{bc}}\right)\right]$$

$$L_c = 2\times10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ca}\,D_{cb}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{cb}}{D_{ca}}\right)\right]$$

Conductors At Equal Spacing

When the conductors are at equal spacing, they are called symmetrically spaced. If the spacing is D (ie, $D_{ab} = D_{ac} = D_{bc} = D$), then

$$L_a = 2\times10^{-7}\left(\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D\times D}} - j\frac{\sqrt{3}}{2}\ln\frac{D}{D}\right)$$

$$= 2\times10^{-7}\left(\ln\frac{1}{R'} - \ln\frac{1}{D} - j\frac{\sqrt{3}}{2}\underbrace{\ln 1}_{0}\right)$$

$$= 2\times10^{-7}\left(\ln\frac{1}{R'} - \ln\frac{1}{D}\right)$$

$$\boxed{L_a = 2\times10^{-7}\left(\ln\frac{D}{R'}\right)}$$

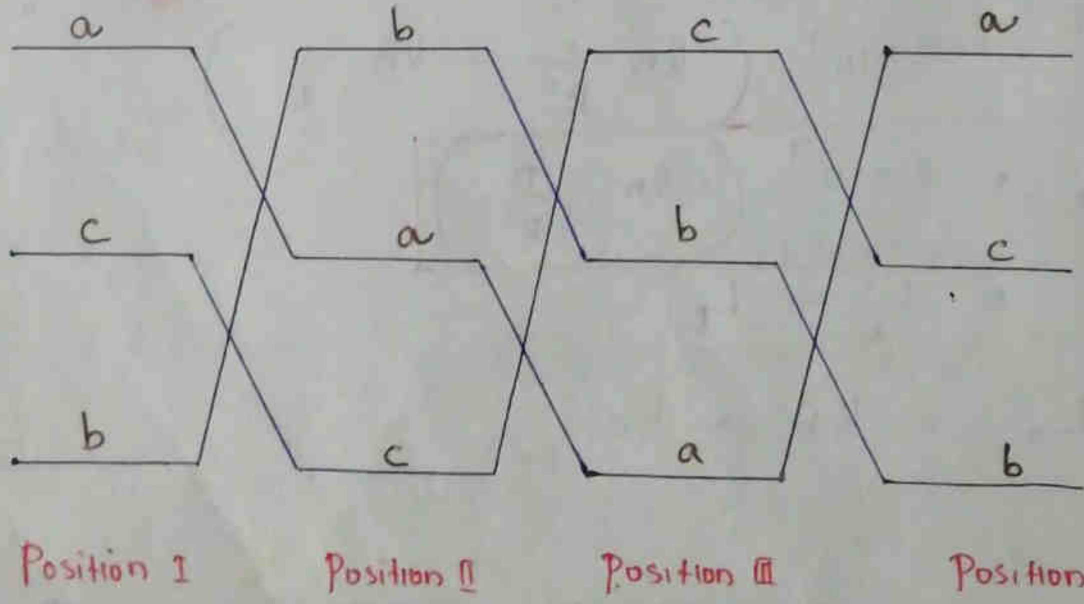
$$= L_b \approx L_c$$

$$L_a = L_b = L_c$$

TRANSPOSITION OF LINES (Unsymmetrical)

Transposition of overhead line conductors refers to exchanging the position of power conductors at regular intervals along the line so that each Conductor occupy the original position of every other conductor over an equal distance. If transmission lines are not transposed, the voltage drop in the transmission line will not be same due to unequal inductances. Another problem is the radio interference.

The purpose of transposition is to balance the Capacitance of the line and also to reduce the electromagnetically induced emf.



If a line is transposed, each line will take all the 3 positions for the one third length of the line. The average value of inductance will be.

$$L = \frac{L_a + L_b + L_c}{3}$$

$$L_a = 2\times10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ab}D_{ac}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ac}}{D_{ab}}\right)\right]$$

$$L_b = 2\times10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{bc}D_{ba}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ba}}{D_{bc}}\right)\right]$$

$$L_c = 2\times10^{-7}\left[\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ca}D_{cb}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{cb}}{D_{ca}}\right)\right]$$

$$\therefore L = \frac{1}{3}\left(L_a + L_b + L_c\right)$$

$$L = \frac{1}{3}\times 2\times10^{-7}\left[3\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ab}D_{ac}D_{bc}D_{ba}D_{ca}D_{cb}}} - j\frac{\sqrt{3}}{2}\ln\left(\frac{D_{ac}}{D_{ab}}\times\frac{D_{ba}}{D_{bc}}\times\frac{D_{cb}}{D_{ca}}\right)\right]$$

$$= \frac{1}{3}\times 2\times10^{-7}\left[3\ln\frac{1}{R'} - \ln\frac{1}{\sqrt{D_{ab}D_{ac}D_{bc}D_{ba}D_{ca}D_{cb}}} - j\frac{\sqrt{3}}{2}\ln\frac{1}{\cancel{1}}0\right]$$

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$$= \frac{1}{3} \times 2 \times 10^{-7} \left[3 \ln \frac{1}{R'} - \ln \frac{1}{\sqrt{D_{ab}^2 D_{bc}^2 D_{ca}^2}} \right]$$

$$= \frac{1}{3} \times 2 \times 10^{-7} \left[3 \ln \frac{1}{R'} - \ln \frac{1}{D_{ab} D_{bc} D_{ca}} \right]$$

$$= 2 \times 10^{-7} \left[\ln \frac{1}{R'} - \frac{1}{3} \ln \frac{1}{D_{ab} D_{bc} D_{ca}} \right]$$

$$= 2 \times 10^{-7} \left[\ln \frac{1}{R'} - \ln \frac{1}{\sqrt[3]{D_{ab} D_{bc} D_{ca}}} \right]$$

$$\boxed{L = 2 \times 10^{-7} \left[\ln \frac{\sqrt[3]{D_{ab} D_{bc} D_{ca}}}{R'} \right]}$$

INDUCTANCE OF A THREE PHASE DOUBLE CIRCUIT ...

1] Symmetrical Spacing

In symmetrical spacing,

$D_{ab} = D_{bc} = D_{ac} = D$

$\therefore L = 2\times10^{-7} \ln \frac{\sqrt[3]{D^3}}{R'}$

$$\boxed{\therefore L = 2\times10^{-7} \ln \frac{D}{R'}}$$

Inductance
1) Untransposed
a) Symmetrical
b) Unsymmetrical
2) Transposed
a) Symmetrical
b) Not symmetrical

* Inductance of 1-ϕ, 2 wire line

$$L = 4\times10^{-7}\left(\ln\left(\frac{D}{R'}\right)\right) \text{ H/m}$$

* Inductance of 3-ϕ transmission line

→ Symmetrical spacing (both transposed & untransposed)

$$L = 2\times10^{-7}\left[\ln\left(\frac{D}{R'}\right)\right] \text{ H/m}$$

→ Unsymmetrical spacing

Transposed

$$L = 2\times10^{-7} \ln\left[\frac{\sqrt[3]{D_{ab} D_{bc} D_{ac}}}{R'}\right] \text{ H/m}$$

* Find the inductance/km of a 3-phase transmission line using 1.24 cm diameter

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conductors when these are placed at the corners of an equilateral triangle of each side 2m.

Ans:- 3-phase

Equilateral triangle ⇒ Symmetrical spacing

$$\therefore L = 2\times10^{-7} \ln\left(\frac{D}{R'}\right)$$

$$= 2\times10^{-7} \ln \frac{2}{\frac{1.24\times10^{-2}}{2}\times0.7788}$$

$$= \underline{\underline{1.205\times10^{-6}}} \ H/m$$

$$L = \underline{\underline{1.205\times10^{-3}}} \ H/km$$

* The 3 conductors of a 3phase line are arranged at the corners of a triangle of sides 2m, 2.5m, 4.5m. Calculate the inductance/km of the line when the conductors are regularly transposed. Diameter of each conductor is 1.24 c.m.

Ans:- 3-phase

Unsymmetrical - Transposed.

$$L = 2\times10^{-7} \ln\left[\frac{\sqrt[3]{D_{ab}D_{bc}D_{ac}}}{R'}\right]$$

$$= 2\times10^{-7} \ln\left[\frac{\sqrt[3]{2.5\times4.5\times2}}{\frac{1.24\times10^{-2}}{2}\times0.7788}\right]$$

$$= 1.27\times10^{-6} \ H/m$$

$$= \underline{\underline{1.27\times10^{-3} \ H/km}}$$

* Calculate the inductance of each conductor in 3-ϕ, 3 wire system when the conductors

are arranged in a horizontal plane with spacing such that $D_{31} = 4m$, $D_{12} = D_{23} = 2m$. The conductors are transposed and have a diameter 2.5 cm.

1.11×10^{-3} H/km

Ans:- 3-phase,

Transposed unsymmetrical.

$$L = 2\times10^{-7} \ln\left[\frac{\sqrt[3]{D_{12} D_{23} D_{13}}}{R'}\right]$$

$$= 2\times10^{-7} \ln\left[\frac{\sqrt[3]{4\times2\times2}}{\frac{2.5}{2}\times10^{-2}\times 0.7788}\right]$$

$$= 1.11\times10^{-6}\ \text{H/m}$$

$$= 1.11\times10^{-3}\ \text{H/km}$$

The analysis of transmission line is done to know its performance to transfer power from the sending end to the receiving end.

The end where load is connected is called as receiving end, while the end that supplies power is known as sending end.

Performance of a transmission line includes efficiency and regulation.

For analysis purpose, lines are represented by its single phase equivalent using resistance, inductance and line to neutral capacitance with the assumption that supply & load are balanced in transmission line.

For the transmission lines, efficiency is defined as the ratio of power delivered at the receiving end to the power sent at the sending end.

ie, Efficiency = $\dfrac{\text{Power delivered at the receiving end}}{\text{Power sent from the sending end}}$

or

$$\text{Efficiency} = \frac{\text{Power delivered at the receiving end}}{\text{Power delivered at the receiving end + losses}}$$

$$\left(\because \eta = \frac{o/p}{i/p} = \frac{o/p}{o/p + \text{Losses}}\right) \quad \eta = \frac{V_R I_R \cos\phi_R}{V_R I_R \cos\phi_R + \text{Losses}}$$

Regulation of transmission line is defined as the ratio of change in voltage at the receiving end from no load to full load, keeping the sending end voltage & frequency constant to the full load voltage.

$$\%\ \text{Regulation} = \frac{\text{No load Voltage} - \text{Full load Voltage}}{\text{Full load Voltage}} \times 100$$

$$= \frac{V_r' - V_r}{V_r} \times 100$$

where,

V_r' → Receiving end voltage magnitude at no load

V_r → Receiving end voltage magnitude at full load.

NB: $V_r' = V_s$

$$\therefore \%\ \text{Regulation} = \frac{V_s - V_r}{V_r} \times 100$$

CLASSIFICATION OF TRANSMISSION LINES

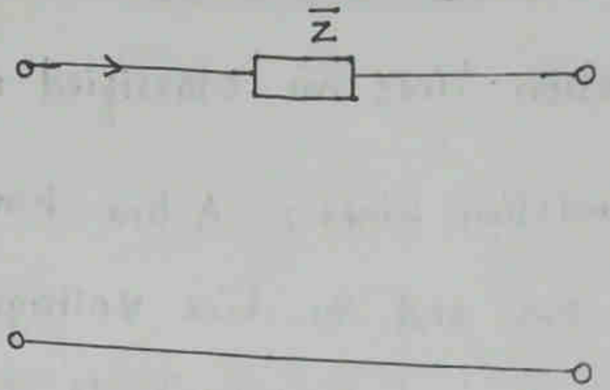
Transmission lines are classified into 3 categories.

1. Short Transmission Lines : A line having length less than 80 km and the line voltage is comparatively low (< 20 kV) is called short Transmission Line. For the analysis, Capacitance effect is neglected and only resistance & Inductance are considered.

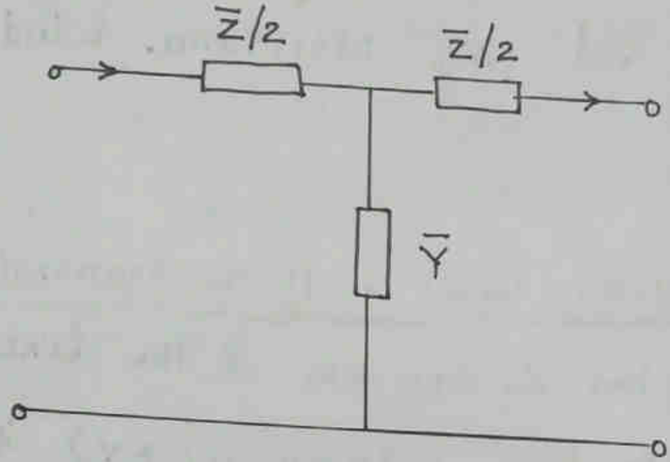
2. Medium Transmission Lines : If the transmission line is between 80 km & 200 km & the line Voltage is moderately high (20 kV - 100 kV), it is called a medium transmission line. Here capacitance effect is considered and it can be represented as nominal - T and nominal - π.

3. Long Transmission Lines : When the length of line is more than 200 km & the line voltage is very high (>100 kV), it is considered as long transmission lines. It can also be represented as T or π and they are known as equivalent - T and equivalent - π representations. Here also capacitance effect is considered. Rigorous method is used for the solution of these lines.

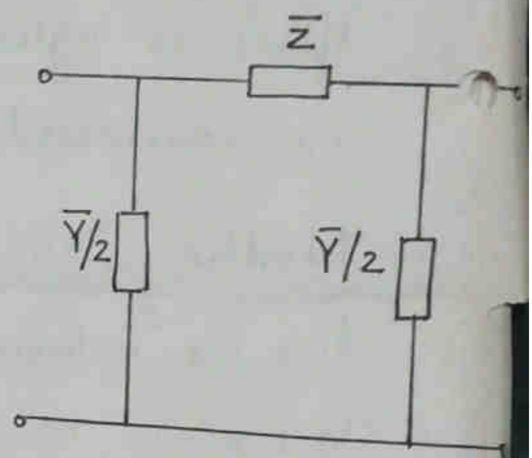
Short Transmission Line Representation



Medium Transmission Line Representation

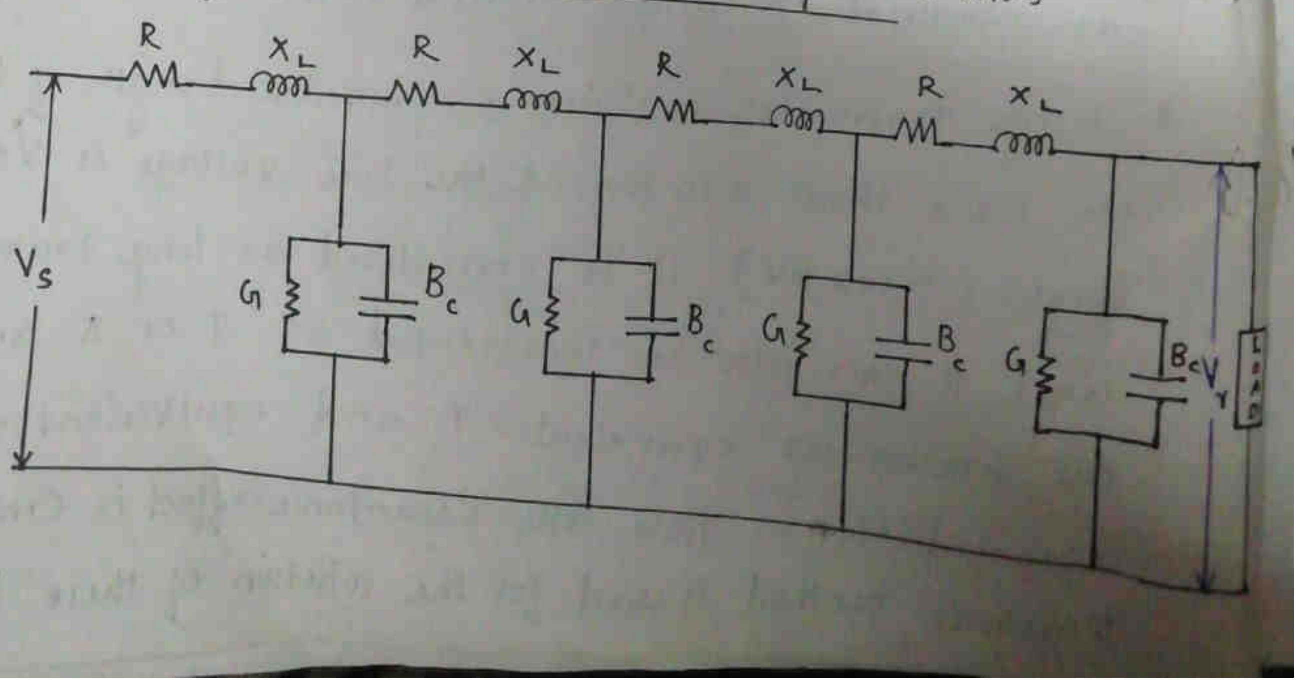


nominal - T

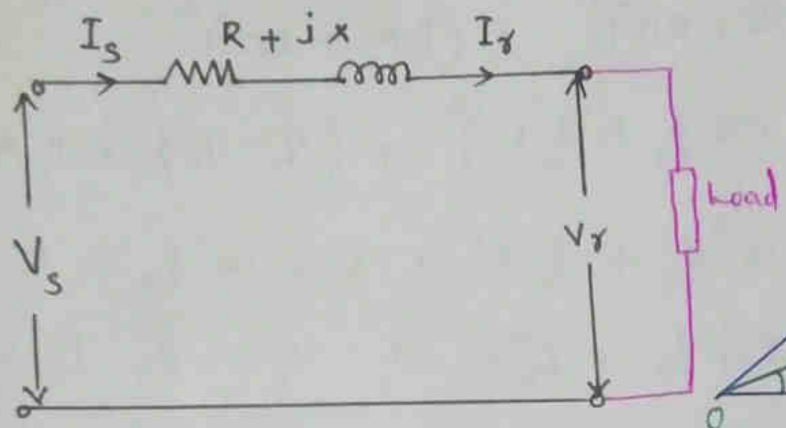


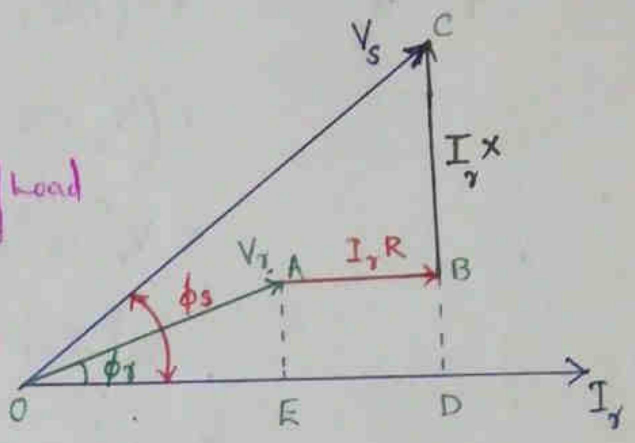
nominal - π

Long Transmission Line Representation



Short Transmission Lines





Let

- $R \rightarrow$ Per phase Resistance
- $x \rightarrow$ Per phase ~~Inductance~~ inductive reactance
- $V_s \rightarrow$ Sending end Voltage
- $V_r \rightarrow$ Receiving end Voltage
- $\cos\phi_r \rightarrow$ Receiving end power factor (lagging)
- $\cos\phi_s \rightarrow$ Sending end Power factor

For Phasor diagram, receiving end current (I_r) is taken as reference. Receiving end Voltage (V_r) leads I_r by ϕ_r. AB represents the drop $I_r R$ in phase with I_r. BC represents the inductive drop $I_r x$, which leads I_r by 90°. OC represents the sending end voltage V_s, which leads I_r by ϕ_s.

From the phasor diagram,

$$(OC)^2 = (OD)^2 + (DC)^2$$

or, $$V_s^2 = (OE + ED)^2 + (DB + BC)^2$$

$$= \left(V_r \cos\phi_r + I_r R\right)^2 + \left(V_r \sin\phi_r + I_r X\right)^2$$

$$= V_r^2 \cos^2\phi_r + I_r^2 R^2 + 2 V_r \cos\phi_r I_r R +$$
$$V_r^2 \sin^2\phi_r + I_r^2 X^2 + 2 V_r \sin\phi_r I_r X$$

$$= V_r^2 + 2 V_r I_r R \cos\phi_r + 2 V_r I_r X \sin\phi_r + I_r^2 (R^2 + X^2)$$

$$V_s^2 = V_r^2 \left[1 + \frac{2 I_r R \cos\phi_r}{V_r} + \frac{2 I_r X \sin\phi_r}{V_r} + \frac{I_r^2 (R^2+X^2)}{V_r^2}\right]$$

$$\therefore V_s = V_r \left[1 + \frac{2 I_r R \cos\phi_r}{V_r} + \frac{2 I_r X \sin\phi_r}{V_r} + \frac{I_r^2 (R^2+X^2)}{V_r^2}\right]^{1/2}$$

Using Taylor Series expansion & neglecting the higher order terms,

$$(1+x)^n = 1 + nx + \frac{n(n-1)}{2!} x^2 + \cdots\cdots$$

$$V_s \simeq V_r \left(1 + \frac{I_r R \cos\phi_r}{V_r} + \frac{I_r X \sin\phi_r}{V_r}\right)$$

$$V_s \simeq V_r + I_r R \cos\phi_r + I_r X \sin\phi_r$$

Percentage Regulation $= \dfrac{V_s - V_r}{V_r} \times 100$

$$= \frac{I_r R \cos\phi_r + I_r X \sin\phi_r}{V_r} \times 100$$

Percentage Efficiency $= \dfrac{V_r I_r \cos\phi_r}{V_r I_r \cos\phi_r + I_r^2 R} \times 100$

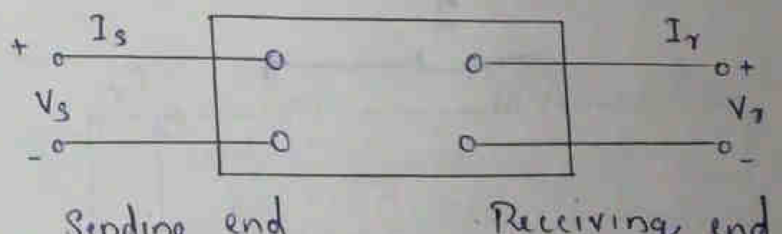
P → Power delivered at the receiving end.

GENERALIZED CIRCUIT CONSTANTS

It is important to represent the transmission line in terms of the sending end and receiving end voltages and current. A transmission line can be represented as 4 terminal (2 port) network.

$$\bar{V_s} = A\bar{V_r} + B\bar{I_r}$$

$$\bar{I_s} = C\bar{V_r} + D\bar{I_r}$$



2 port Network Representation

In matrix form, it is

$$\begin{bmatrix} \bar{V_s} \\ \bar{I_s} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} \bar{V_r} \\ \bar{I_r} \end{bmatrix}$$

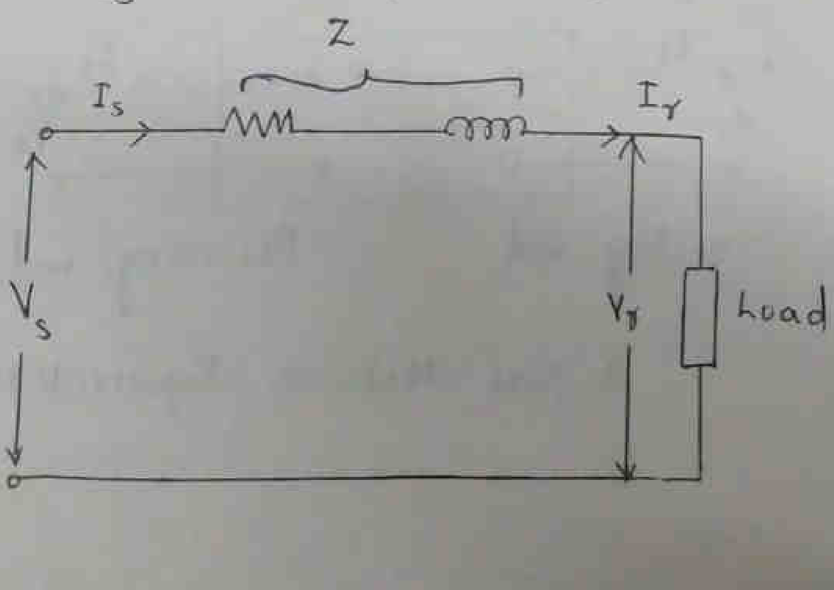
where A, B, C and D are generalized circuit constants and it has the following properties.

- These are complex constants
- They hold, $AD - BC = 1$
- If symmetrical network, $A = D$
- A and D are dimensionless
- B is impedance, C is admittance.

ABCD Constants for Short Transmission Lines

We have, $\bar{V_s} = A \bar{V_r} + B \bar{I_r}$

$\bar{I_s} = C \bar{V_r} + D \bar{I_r}$



From the figure,

$$\bar{I}_s = \bar{I}_r$$

$$\bar{V}_s = \bar{V}_r + \bar{I}_r Z$$

Comparing it with the general equation

$$A = 1 \quad ; \quad B = Z$$

$$C = 0 \quad ; \quad D = 1$$

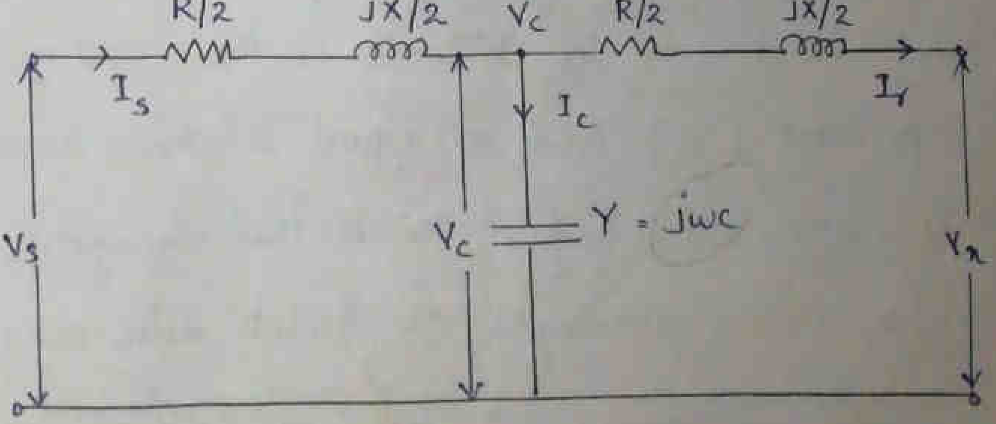
Hence $AD - BC = 1 \times 1 - (Z \times 0)$

$$= \underline{\underline{1}}$$

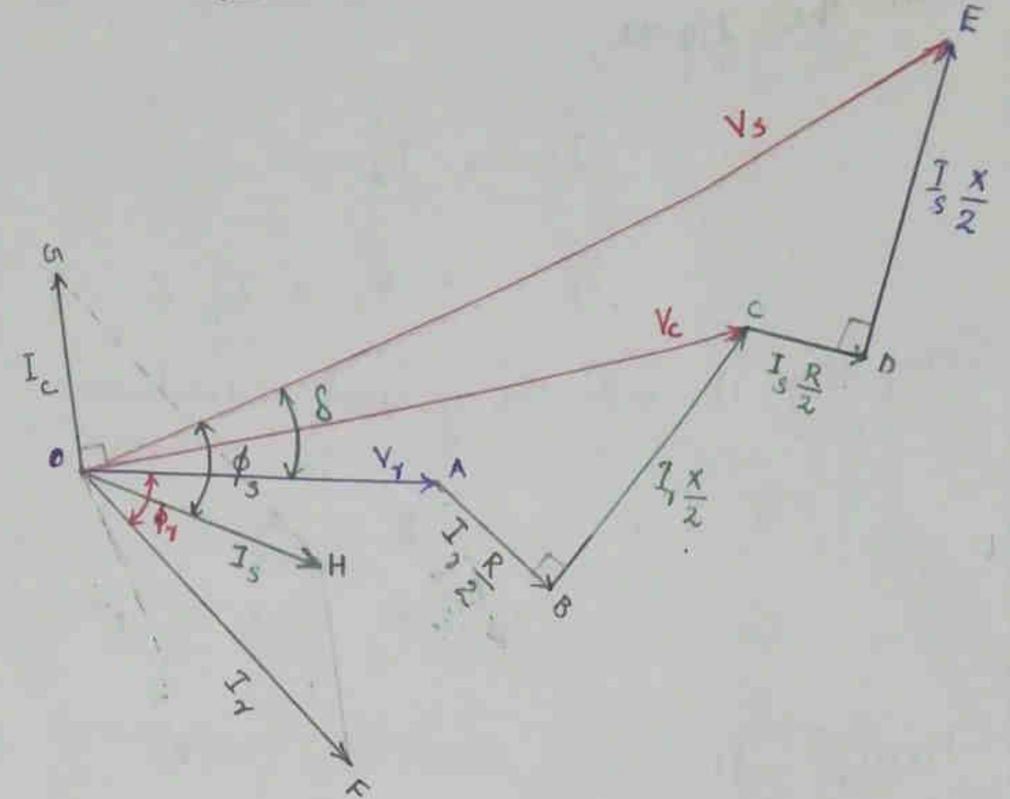
Medium Transmission Lines

I Nominal - T Method

In this method, the capacitance of each conductor is assumed to be concentrated at the midpoint of the line with half the series impedance on either side of it. Here 'Y' represents the shunt admittance.



PHASOR DIAGRAM



The horizontal line OA is the per phase receiving end voltage (V_r) and it is taken as reference phasor. OF is the load current (I_r) passing through the right half of the series impedance and lags behind V_r by an angle ϕ_r. AB is the resistive voltage drop ($I_r \frac{R}{2}$) in the right half of the series impedance and is in phase with I_r. BC is the reactive voltage drop ($I_r \frac{X}{2}$) in the right half of the series impedance and leads I_r by 90°. OC is the voltage across the capacitor (V_c) and is equal to the phasor sum of V_r, $I_r \frac{R}{2}$ and $I_r \frac{X}{2}$. OG is the charging current (I_c) which passes through the shunt admittance and this current leads the capacitor Voltage V_c by 90°. OH is the sending end current (I_s) passing through the left half of the series impedance and is equal to the phasor sum of receiving end current (I_r) and the charging current (I_c). CD is the resistive voltage drop ($I_s \frac{R}{2}$) in the left half of the series impedance which is in phase with I_s. DE is the reactive Voltage drop ($I_s \frac{X}{2}$) in the left half of the series impedance and this Voltage drop leads the sending end current (I_s) by 90°. OE is the sending end Voltage (V_s) and is equal to the phasor sum of V_c, $I_s \frac{R}{2}$ and $I_s \frac{X}{2}$.

ϕ_s is the angle between V_s and I_s ; ϕ_r is the angle between V_r and I_r and the angle between V_s and V_r is known as load angle (δ)

From the fig, we have

$$V_c = V_r + I_r \frac{Z}{2}$$

The current through the shunt admittance is,

$$I_c = V_c Y$$

$$= \left(V_r + I_r \frac{Z}{2}\right) Y$$

$$= Y V_r + \frac{YZ}{2} I_r$$

The sending end current is,

$$I_s = I_r + I_c$$

$$= I_r + YV_r + \frac{YZ}{2} I_r$$

$$I_s = YV_r + \left(1 + \frac{YZ}{2}\right) I_r \quad \text{—— (1)}$$

The sending end voltage is,

$$V_s = V_c + I_s \frac{Z}{2}$$

$$= V_r + I_r \frac{Z}{2} + \left[YV_r + \left(1 + \frac{YZ}{2}\right) I_r\right] \frac{Z}{2}$$

$$= V_r + I_r \frac{Z}{2} + YV_r \frac{Z}{2} + I_r \frac{Z}{2} + I_r \frac{YZ^2}{4}$$

$$= V_r \left(1 + \frac{YZ}{2}\right) + I_r \left(\frac{Z}{2} + \frac{Z}{2} + \frac{YZ^2}{4}\right)$$

$$= V_r \left(1 + \frac{YZ}{2}\right) + I_r \cdot Z \left(\frac{1}{2} + \frac{1}{2} + \frac{YZ}{4}\right)$$

$$= V_r \left(1 + \frac{YZ}{2}\right) + I_r \cdot Z \left(1 + \frac{YZ}{4}\right)$$

$$V_s = \left(1 + \frac{YZ}{2}\right) V_r + Z \left(1 + \frac{YZ}{4}\right) I_r \quad \text{—— (2)}$$

Comparing eqns (1) & (2) with generalized circuit constants,

ie, $V_s = A V_r + B I_r$

$$I_s = C V_r + D I_r$$

We have,

$$A = 1 + \frac{YZ}{2} \quad ; \quad B = Z\left(1 + \frac{YZ}{4}\right)$$

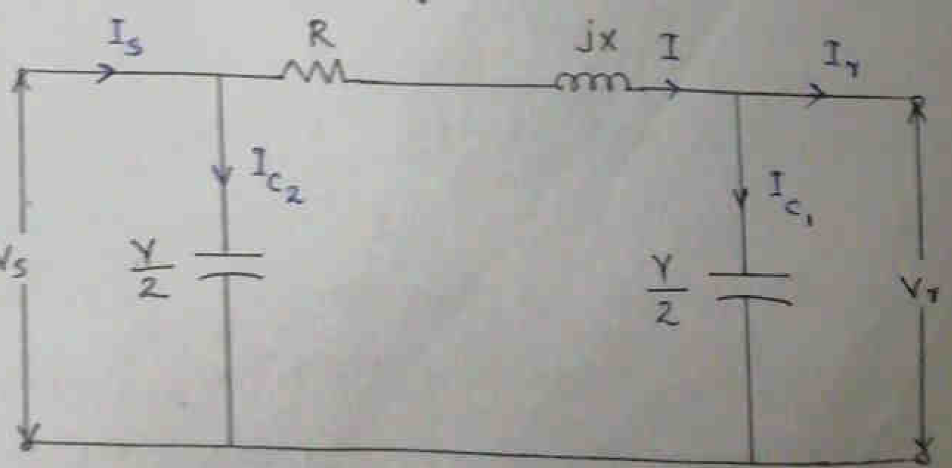
$$C = Y \quad ; \quad D = 1 + \frac{YZ}{2}$$

The transfer matrix for the network is,

$$\begin{bmatrix} 1 + \frac{YZ}{2} & Z\left(1 + \frac{YZ}{4}\right) \\ Y & 1 + \frac{YZ}{2} \end{bmatrix}$$

II **Nominal - π Method**

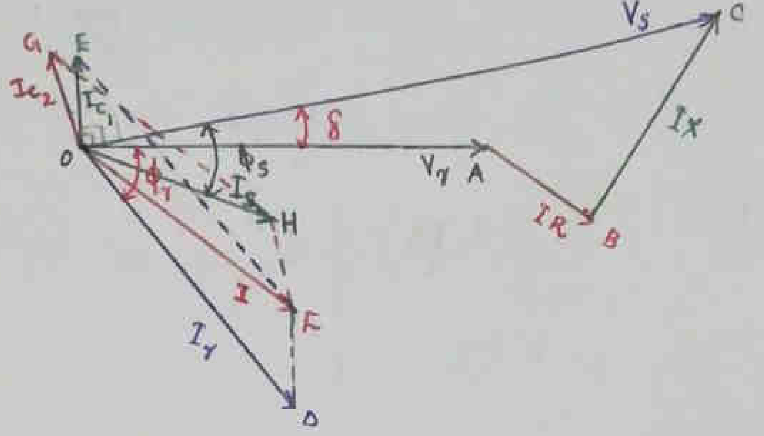
In this method, the capacitance of each conductor is assumed to be divided into two halves. One being shunted between conductor and neutral at the receiving end and the other half at the sending end. The total impedance is placed in between them as shown in fig.



Phasor Diagram

$OG \perp^r OC$

$OK \perp^r OA$



The horizontal line OA is the per phase receiving end voltage (V_r), taken as the reference phasor. OD is the load current (I_r) and this current lags behind V_r by an angle ϕ_r. OE is the charging current (I_{c_1}) leads V_r by 90°, which passes through the right half of the shunt admittance and is equal to $V_r \frac{Y}{2}$. OF is the current passing through the series impedance (I) & is equal to the phasor sum of I_r and I_{c_1}. AB is the resistive voltage drop (IR) in phase with I. BC is the reactive voltage drop (IX), which leads current I by 90°. OC is the voltage at the sending end or the voltage across the shunt admittance connected at the sending end (V_s) and is equal to the phasor sum of V_r, IR and IX. OG is the charging current (I_{c_2}) which passes through the Shunt admittance at the sending end and this current leads the voltage (V_s) by 90°. OH is the Sending end current (I_s) and is equal to the phasor Sum of the current (I) and charging current (I_{c_2})

ϕ_s is the angle between V_s & I_s ; ϕ_r is the angle between V_r & I_r ; the angle between V_s & V_r is known as load angle (torque angle) δ.

$$V_{c_1} = V_r$$

$$I_{c_1} = V_{c_1} \frac{Y}{2} = V_r \frac{Y}{2}$$

$$I = I_r + I_{c_1}$$

$$= I_r + V_r \frac{Y}{2}$$

$$V_{c_2} = V_{c_1} + I Z$$

$$= V_r + \left(I_r + V_r \frac{Y}{2} \right) Z$$

$$= V_r \left(1 + \frac{YZ}{2} \right) + I_r Z$$

$$V_{c_2} = V_s$$

$$\therefore V_s = \left(1 + \frac{YZ}{2} \right) V_r + Z I_r \quad \text{——— (1)}$$

The charging current, $I_{c_2} = V_s \frac{Y}{2}$

The sending end current, $I_s = I + I_{c_2}$

ie, $I_s = I_r + V_r \frac{Y}{2} + V_s \frac{Y}{2}$.

$$= I_r + V_r \frac{Y}{2} + \left[\left(1+\frac{YZ}{2}\right)V_r + Z I_r\right]\frac{Y}{2}$$

$$= I_r + V_r \frac{Y}{2} + V_r \frac{Y}{2} + \frac{Y^2 Z}{4} V_r + \frac{YZ I_r}{2}$$

$$= V_r\left[\frac{Y}{2} + \frac{Y}{2} + \frac{Y^2 Z}{4}\right] + I_r\left[1 + \frac{YZ}{2}\right]$$

$$= V_r\left[Y + \frac{Y^2 Z}{4}\right] + I_r\left[1 + \frac{YZ}{2}\right]$$

$$I_s = Y\left(1+\frac{YZ}{4}\right)V_r + \left(1+\frac{YZ}{2}\right)I_r$$

Comparing eqns (1) & (2) with the general eqns

$A = \left(1+\frac{YZ}{2}\right)$; $B = Z$

$C = Y\left(1+\frac{YZ}{4}\right)$; $D = \left(1+\frac{YZ}{2}\right)$

The transfer matrix for the network is,

$$\begin{bmatrix} 1+\frac{YZ}{2} & Z \\ Y\left(1+\frac{YZ}{4}\right) & \left(1+\frac{YZ}{2}\right) \end{bmatrix}$$

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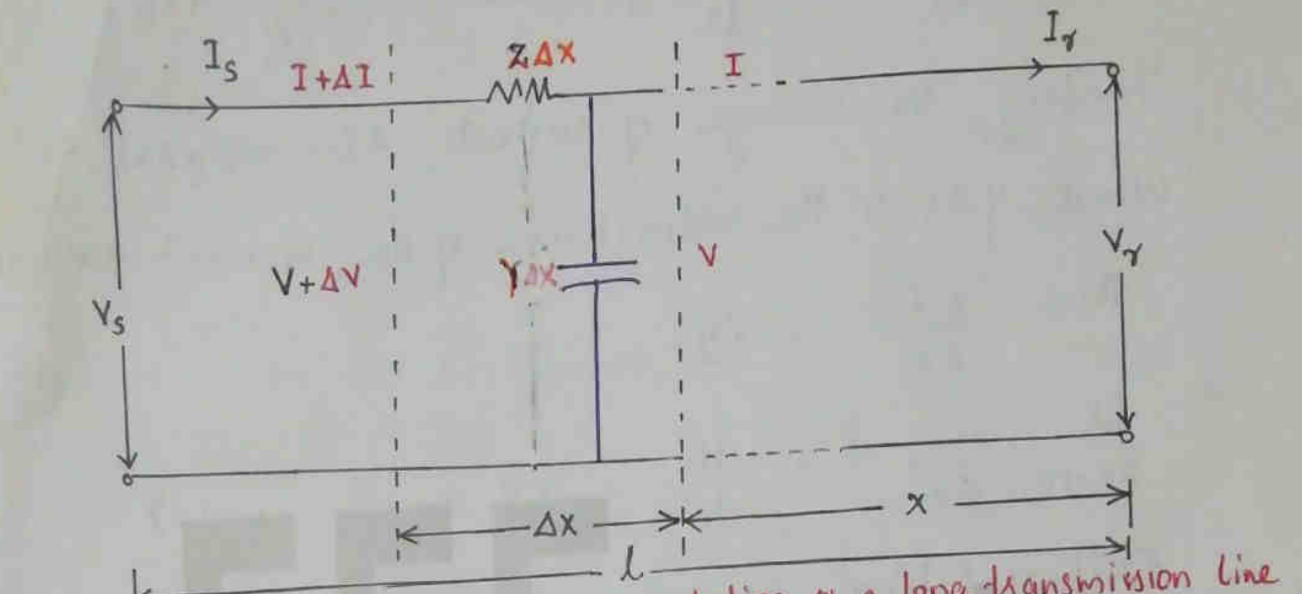
Long Transmission Lines - Rigorous Solution



Equivalent Single Phase representation of a long transmission line

Let z = Series impedance per unit length

y = Shunt admittance per unit length

l = length of the line

Total imp. of elemt = $z\Delta x$

" adm " = $y\Delta x$

Then $Z = zl$ = Total Series impedance of the line

$Y = yl$ = Total Shunt admittance of the line

Consider a very small element of length Δx at a distance of x from the receiving end of the line.

The Voltage and current at a distance x from the receiving end are V, I and at a distance $x+\Delta x$ are $V+\Delta V$ and $I+\Delta I$ respectively.

$\therefore$ The ~~Change of Voltage~~ Voltage drop across the element Δx is, $\Delta V = Iz\Delta x$

where $z\Delta x$ is the impedance of the element considered.

Then $\frac{\Delta V}{\Delta x} = Iz$

$$\lim_{\Delta x \to 0} \frac{\Delta V}{\Delta x} = \frac{dV}{dx} = Iz \quad \text{------- (1)}$$

Similarly, the change of current, $\Delta I = Vy\Delta x$

where $y\Delta x$ is the admittance of the element considered

Then $\frac{\Delta I}{\Delta x} = Vy$

$$\lim_{\Delta x \to 0} \frac{\Delta I}{\Delta x} = \frac{dI}{dx} = Vy \quad \text{------- (2)}$$

Differentating eqn (1) w.r.t x,

$$\frac{d^2V}{dx^2} = z \cdot \frac{dI}{dx} \quad \text{------- (3)}$$

Substituting the value of $\frac{dI}{dx}$ from eqn (2) in eqn (3)

$$\frac{d^2V}{dx^2} = zVy \quad \text{------- (4)}$$

Eqn (4) is a second order differential eqn. The solution of the equation is,

$$V = Me^{x\sqrt{yz}} + Ne^{-x\sqrt{yz}} \quad \text{---- (5)}$$

Differentiating eqn (5) w.r.t x,

$$\frac{dV}{dx} = Me^{x\sqrt{yz}} \sqrt{yz} + Ne^{-x\sqrt{yz}} \cdot \sqrt{yz} \times -1$$

$$\frac{dV}{dx} = M\sqrt{yz}\, e^{x\sqrt{yz}} - N\sqrt{yz}\, e^{-x\sqrt{yz}} \quad \text{—— (6)}$$

Equating eqns (1) & (6);

ie, $$IZ = M\sqrt{YZ}\, e^{x\sqrt{YZ}} - N\sqrt{YZ}\, e^{-x\sqrt{YZ}}$$

$$\therefore I = M\sqrt{Y/Z}\, e^{x\sqrt{YZ}} - N\sqrt{Y/Z}\, e^{-x\sqrt{YZ}} \quad \text{-----} (7)$$

Eqn (5) can be written as,

$$V = Me^{\gamma x} + Ne^{-\gamma x} \quad \text{-----} (8)$$

Eqn (7) can be written as,

$$I = \frac{M}{Z_c} e^{\gamma x} - \frac{N}{Z_c} e^{-\gamma x} \quad \text{----} (9)$$

where $Z_c = \sqrt{\frac{Z}{Y}}$ is known as characteristic impedance (surge impedance)

$\gamma = \sqrt{YZ}$ is known as propagation constant

Also, $\boxed{\gamma = \alpha + j\beta}$ where $\alpha \rightarrow$ attenuation const, $\beta \rightarrow$ phase const.

The constants M & N can be evaluated by using the conditions at the receiving end of the line.

The conditions are,

at $x = 0$, $V = V_r$ and $I = I_r$

$$\therefore V_r = M + N \quad (\because e^0 = 1) \ (\because \text{eqn } 8)$$

$$I_r = \frac{1}{Z_c}(M - N) \quad (\because \text{eqn } 9)$$

By solving the above two eqns, we will get

$$V_r = M + N \quad \text{----} (10)$$

$$I_r Z_c = M - N \quad \text{----} (11)$$

$$(10) + (11) \Rightarrow V_r + I_r Z_c = 2M$$

$$\therefore M = \frac{V_r + I_r Z_c}{2}$$

$$(10) - (11) \Rightarrow V_r - I_r Z_c = 2N$$

$$\therefore N = \frac{V_r - I_r Z_c}{2}$$

Substituting the values of M & N in eqns (8) & (9)

$$V = \left(\frac{V_r + I_r Z_c}{2}\right) \cdot e^{\gamma x} + \left(\frac{V_r - I_r Z_c}{2}\right) e^{-\gamma x}$$

$$= V_r \left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right) + I_r Z_c \left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right)$$

$$\therefore V = V_r \cosh \gamma x + I_r Z_c \sinh \gamma x \quad \text{------} \quad (12)$$

$$I = \frac{1}{Z_c}\left(\left(\frac{V_r + I_r Z_c}{2}\right) \cdot e^{\gamma x}\right) - \frac{1}{Z_c}\left(\left(\frac{V_r - I_r Z_c}{2}\right) \cdot e^{-\gamma x}\right)$$

$$= \frac{1}{Z_c} V_r \left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right) + I_r \left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right)$$

$$I = \frac{V_r}{Z_c} \sinh \gamma x + I_r \cosh \gamma x \quad \text{----} \quad (13)$$

Where V & I are the voltages & currents at any distance x from the receiving end.

At $x = l$, $V = V_s$ and $I = I_s$

Putting the above values in eqns (12) & (13)

$$V_s = V_r \cosh \gamma l + I_r Z_c \sinh \gamma l$$

$$I_s = \frac{V_r}{Z_c} \sinh \gamma l + I_r \cosh \gamma l$$

Comparing the above eqns with general transmission circuit constants,

$$A = \cosh \gamma l \quad ; \quad B = Z_c \sinh \gamma l$$

$$C = \frac{1}{Z_c} \sinh \gamma l \quad ; \quad D = \cosh \gamma l$$

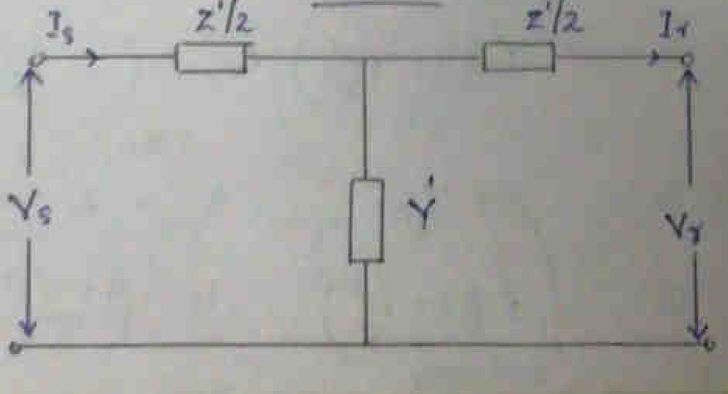
The transfer matrix for the network is,

$$\begin{bmatrix} \cosh \gamma l & Z_c \sinh \gamma l \\ \frac{1}{Z_c} \sinh \gamma l & \cosh \gamma l \end{bmatrix}$$

Lumped Circuit Equivalent Representation of Long Transmission Lines

In nominal - π or T representations, lumped parameters are taken instead of distributed parameters. After ~~tat~~ deriving the ABCD Constants of the line in terms of distributed parameters, they are represented as lumped circuit equivalent - T or equivalent - π

Equivalent - T representation



The values of Y' and Z' can be determined in terms of distributed parameters. (ABCD Parameters ap

From the fig,

$$V_s = V_r + I_r \frac{Z'}{2} + \left[Y' V_r + \left(1 + \frac{Y'Z'}{2}\right) I_r \right] \frac{Z'}{2}$$

$$V_s = \left(1 + \frac{Y'Z'}{2}\right) V_r + Z' \left(1 + \frac{Y'Z'}{4}\right) I_r$$

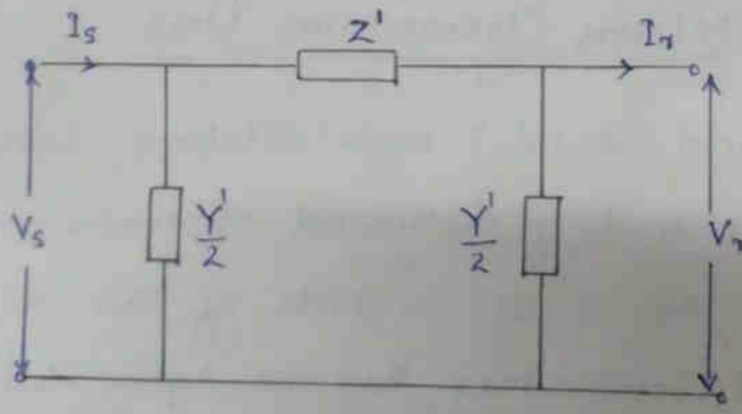
$$I_s = Y' V_r + \left(1 + \frac{Y'Z'}{2}\right) I_r$$

Comparing with generalized circuit constant equations,

$$A = 1 + \frac{Y'Z'}{2} \quad ; \quad B = Z'\left(1 + \frac{Y'Z'}{4}\right)$$

$$C = Y' \quad ; \quad D = 1 + \frac{Y'Z'}{2}$$

Equivalent - π Representation



From the fig,

$$V_s = \left(1 + \frac{Y'Z'}{2}\right) V_r + Z' I_r$$

$$I_s = Y'\left(1 + \frac{Y'Z'}{4}\right) V_r + \left(1 + \frac{Y'Z'}{2}\right) I_r$$

On comparing,

$$A = 1 + \frac{Y'Z'}{2} \quad ; \quad B = Z'$$

$$C = Y'\left(1 + \frac{Y'Z'}{4}\right) \quad ; \quad D = \left(1 + \frac{Y'Z'}{2}\right)$$

Comparing the above eqns with the transfer matrix of long transmission line,

$$Z' = Z_c \sinh \gamma l$$

$$1 + \frac{Y'Z'}{2} = \cosh \gamma l$$

ie, $$\frac{2 + Y'Z'}{2} = \cosh \gamma l$$

$$2 + Y'Z' = 2 \cosh \gamma l$$

$$\therefore Y' = \frac{2 \cosh \gamma l - 2}{Z'} = \frac{2 (\cosh \gamma l - 1)}{Z_c \sinh \gamma l}$$

or $$\frac{Y'}{2} = \frac{1}{Z_c} \left(\frac{\cosh \gamma l - 1}{\sinh \gamma l} \right)$$

$$= \frac{1}{Z_c} \left(\tanh \frac{\gamma l}{2} \right)$$

$$= \sqrt{\frac{y}{z}} \tanh \frac{\gamma l}{2} \qquad \left(\because Z_c = \sqrt{z/y} \right)$$

$$= \sqrt{\frac{y \times y}{z \times y}} \times \frac{l}{l} \tanh \frac{\gamma l}{2}$$

$$= \frac{y}{\gamma} \times \frac{l}{l} \tanh \frac{\gamma l}{2}$$

$$= \frac{Y}{\gamma l} \tanh \frac{\gamma l}{2} \qquad \left(\because Y = yl \right) \quad \gamma = \sqrt{zy}$$

$$\frac{Y'}{2} = \frac{Y}{2} \left(\frac{\tanh (\gamma l/2)}{\gamma l/2} \right)$$

If the line is not long, then the term $\frac{\tanh \gamma l/2}{\gamma l/2}$ will be equal to unity.

Similarly $z' = Z_c \sinh \gamma l$

$$= \sqrt{\frac{z}{y}} \sinh \gamma l$$

$$= \sqrt{\frac{z \times z}{y \times z}} \times \frac{l}{l} \sinh \gamma l$$

$$= \frac{z \times l}{\gamma \times l} \sinh \gamma l$$

$$z' = Z \frac{\sinh(\gamma l)}{\gamma l}$$

($\because z \times l = Z$, total series impedance of the line)

FERRANTI EFFECT

When medium or long transmission lines are operated at no load or light load the receiving end voltages become more than sending end voltage. The phenomenon of rise in voltage at the receiving end of a transmission line during no load or light load condition is called the Ferranti effect. This occurs due to high charging current.

Under no load, $I_r = 0$. Therefore the eqn,

$$V_s = V_r \cosh(\gamma l) + I_r Z_c \sinh(\gamma l) \text{ becomes,}$$

$$V_s = V_r \cosh(\gamma l)$$

$$\text{or } V_r = \frac{V_s}{\cosh(\gamma l)}$$

Since the value of $\cosh(\gamma l)$ is always less than or equal to unity, V_r is always greater or equal to V_s

TUNED POWER LINES

In a long transmission line if the sending end voltage and current are numerically equal to the receiving end voltage and current, then the line is called a tuned line. So there is no voltage drop on load.

ie, $|V_s| = |V_r|$ and

$|I_s| = |I_r|$

The length of line for tuning is,

$$l = \frac{n}{2f\sqrt{LC}}$$

$$= \frac{n}{2 \times 50} \times 3 \times 10^8 \quad (\because f = 50\ Hz)$$

where $\frac{1}{\sqrt{LC}} \approx v$, the velocity of light (3×10^8)

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PROBLEMS (Module - II)

1. A Single phase overhead transmission line delivers 1100 kW at 33 kV at 0.8 Pf lagging. The total resistance and inductive reactance of the line are 10Ω & 15Ω respectively. Determine
   1) Sending end Voltage
   2) Sending end Pf
   3) Transmission Efficiency.

Ans: $\cos\phi = 0.8$

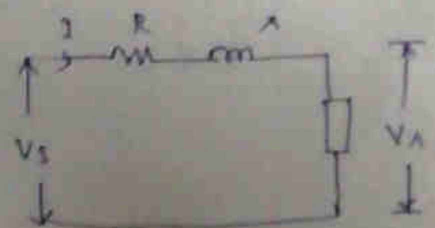
$Z = R + jX_L = 10 + j15$

Receiving end Voltage, $V_r = 33\text{ kV} = 33000\text{ V}$

For 1ϕ line, $P = VI\cos\phi$

$$\therefore I = \frac{1100\times10^3}{33000\times0.8} = \underline{41.67\text{ A}}$$

$\because \cos\phi = 0.8$, then $\sin\phi = 0.6$



$\bar{I} = I(\cos\phi - j\sin\phi)$

$= 41.67(0.8 - j0.6)$

$= 33.33 - j25$

$= 41.66\angle{-36.87}$

1) Sending end Voltage, $V_s = V_r + IZ$

$$= 33000 + [33.33 - j25] * [10 + j15]$$

$$V_s = 33000 + 333.3 - j250 + j500 + 375$$

$$= 33708.3 + j250 = \underline{33709.22} \angle 0.424$$

$$\therefore |V_s| = \sqrt{(33708.3)^2 + 250^2} = \underline{\underline{33,709 \text{ V}}}$$

2) Sending end Pf = $\cos \phi_s$

ϕ_s is the angle b/w V_s & I_s

ie, $\phi_s = (-36.87 - 0.424)$

$$= -37.29$$

$$\therefore \text{Pf} = \cos(-37.29) = \underline{\underline{0.7955}}$$

3) Transmission Efficiency = $\dfrac{\text{O/P Power}}{\text{I/P Power}}$

$$= \frac{\text{O/P Power}}{\text{O/P Power} + \text{Losses}}.$$

$$\text{losses} = I^2 R$$

$$= (41.67)^2 \times 10 = \underline{\underline{17363.8 \text{ W}}}$$

$$\therefore \eta = \frac{1100 \times 10^3}{(1100 \times 10^3 + 17363.8)}$$

$$= \underline{\underline{98.44\ \%}}$$

An Overhea

An Overhead 3 ϕ transmission line delivers 5000 kW at 22 kV at 0.8 Pf lagging. The resistance & reactance of each conductor is 4Ω & 6Ω respectively.

Determine 1) Sending end voltage

2) Percentage regulation

3) Transmission efficiency.

Ans:

$\cos\phi = 0.8$

$Z = R + jX_L = 4 + j6$

Receiving end Voltage / Phase, $V_r = \frac{22000}{\sqrt{3}} = 12700\ V$

(∵ assume that star connected)

For 3 ϕ line, $P = 3 V_{Ph} I_{Ph} \cos\phi$

or

$P = \sqrt{3} V_L I_L \cos\phi$

$V_L = 22\ kV$

$$\therefore I = \frac{5000 \times 10^3}{3 \times 12700 \times 0.8}$$

$$= \underline{\underline{164.04\ A}}$$

$\cos\phi = 0.8 \quad \therefore \sin\phi = 0.6$

$$\bar{I} = I(\cos\phi - j\sin\phi)$$

$$= 164.04(0.8 - j0.6)$$

$$= 131.2 - j98.4$$

$$= \underline{164 \angle{-36.86}}$$

1) Sending end Voltage, $V_s = V_r + IZ$

i.e., $V_s = 12700 + [131.2 - j\,98.4][4 + j6]$

$= 13815.2 + j\,393.6$

$\therefore |V_s| = \sqrt{(13815.2)^2 + 393.6^2} = \underline{\underline{13820.8\ V}}$

2) % Regulation $= \dfrac{V_s - V_r}{V_r} \times 100$

Line Value of $V_s = 13820.8 \times \sqrt{3} = 23938\ V$

$\therefore$ % Regulation $= \dfrac{23938 - 22000}{22000} \times 100$

$= \underline{\underline{8.80\ \%}}$

OR

% Reg^n $= \dfrac{13820.8 - 12700}{12700} \times 100$

$= \underline{\underline{8.82\ \%}}$

3) Line losses $= \underline{3I^2R}$

$= 3 \times (164.04)^2 \times 4$

$= \underline{\underline{322909}}\ W$

$\therefore \eta = \dfrac{5000 \times 10^3}{(5000 \times 10^3) + 322909}$

$= \underline{\underline{93.93}}\ \%$

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A 3 ϕ 50 Hz overhead transmission line 100 km long has the following constants.

Resistance / km / Phase = $0.1\ \Omega$

Inductive reactance / km / phase = $0.2\ \Omega$

Capacitive Susceptance / km / phase = 0.04×10^{-4} Siemens

Determine i) The sending end current

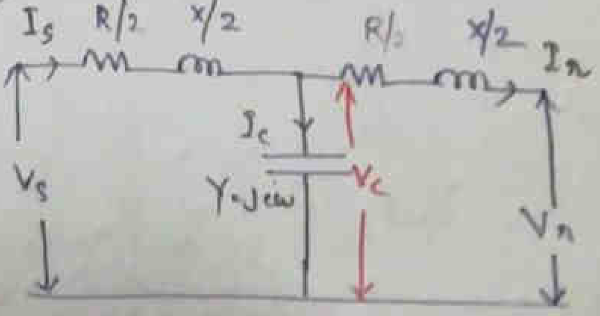
2) Sending end Voltage

3) Sending end Pf

4) Transmission efficiency

when supplying a balanced load of 10000 kW at 66 kV, 0.8 Pf lagging. Use nominal T method.

Ans:



Total resistance / Phase = $0.1 \times 100 = 10\ \Omega$

Total reactance / Phase = $0.2 \times 100 = 20\ \Omega$

Capacitive Susceptance, $Y = 0.04 \times 10^{-4} \times 100 = 4 \times 10^{-4}$ S

Receiving end Voltage / Phase, $V_r = \dfrac{66000}{\sqrt{3}} = 38105$ V

$P = 3 V_{ph} I_{ph} \cos\phi$

$\therefore I_r = \dfrac{10000 \times 10^3}{3 \times 38105 \times 0.8} = \underline{\underline{109 \text{ A}}}$

$\cos\phi = 0.8 \; ; \; \therefore \sin\phi = 0.6$

$Z = 10 + j20$

$\bar{I}_r = I_r(\cos\phi - j\sin\phi)$

$= 109(0.8 - j0.6) = 87.2 - j65.4$

1) Sending end current, $I_s = I_c + I_r$

$= \cancel{V_c Y + I_r}$

$= \cancel{\left[V_r + I_r \frac{Z}{2}\right] Y + I_r}$

$= \cancel{Y V_r + I_r \left[1 + \frac{YZ}{2}\right]}$

$\bar{I}_r = \bar{I}$

~~i) $I_s = (4 \times 10^{-4})$~~

$\bar{I}_c = jY\bar{V}_c$

But $\bar{V}_c = V_r + I_r \frac{Z}{2}$

$= (38105) + (87.2 - j65.4)\left(\frac{10 + j20}{2}\right)$

$= 39195 + j545$

$\therefore \bar{I}_c = j \times 4 \times 10^{-4} \times (39195 + j545)$

$= \underline{\underline{-0.218 + j15.6}}$

$\therefore I_s = I_r + I_c$

$= (87.2 - j65.4) + (-0.218 + j15.6)$

$= 100\angle -29.47 \; A = 87 - j49.8$

2) Sending end Voltage, $V_s = V_c + I_s \frac{Z}{2}$

ie, $V_s = (39195 + j545) + (87 - j49.8)\left(\frac{10 + j20}{2}\right)$

$= 40128 + j1170$

$= 40145 \angle 1.67 \; V$

3) Sending end Pf $= \cos\phi_s$

$= \cos[1.67 - (-29.47)]$

$= \cos(31.14)$

$= 0.855$ lag

4) Transmission $\eta = \dfrac{\text{Receiving end Power}}{\text{Sending end Power}}$

Sending end Power $= 3 V_s I_s \cos\phi_s$

$= 3 \times 40145 \times 100 \times 0.855$

$= 10297.105$ kW

Receiving end Power $= 10,000$ kW

$\therefore$ Transm^n η $= \dfrac{10000}{10273.105} \times 100$

$= \underline{\underline{97.34\ \%}}$

4) A 3ϕ transmission line 200 km long has the following constants.

Resistance / Phase / km $= 0.16\ \Omega$

Reactance / Phase / km $= 0.25\ \Omega$

Shunt admittance / Phase / km $= 1.5 \times 10^{-6}$ S.

Calculate by rigorous method the sending end voltage and current when the line is delivering a load of 20 MW at 0.8 pf lagging. The receiving end voltage is kept constant at 110 kV.

Ans: Total resistance / phase, R $= 0.16 \times 200 = 32\ \Omega$

Total reactance / Phase, $X_L = 0.25 \times 200 = 50\ \Omega$

Total Shunt admittance / Phase, $Y = j1.5 \times 10^{-6} \times 200$

$= 0.0003 \angle 90$

Impedance, $Z = R + jX_L = 32 + j50 = 59.4 \angle 58$

$V_s = V_r \cosh \gamma l + I_r Z_c \sinh \gamma l$

$= V_r \cosh \sqrt{YZ} \times l + I_r \sqrt{\frac{Z}{Y}}$

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5) A 100 km long, 3 ϕ, 50 Hz transmission line has the following line constants;

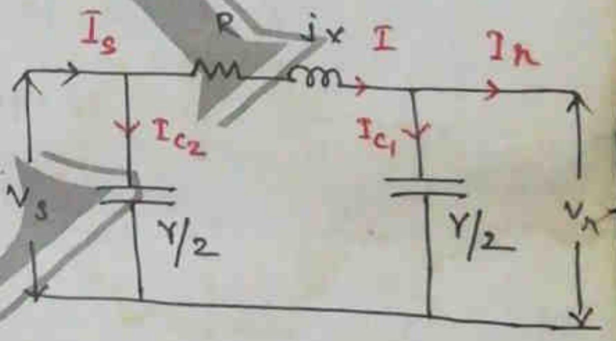
Resistance / Phase / km = 0.1 Ω

Reactance / Phase / km = 0.5 Ω

Susceptance / Phase / km = 10×10^{-6} S

If the line supplies load of 20 MW at 0.9 pf lagging at 66 kV at the receiving end, calculate by nominal π method,

1) Sending end power factor
2) Regulation
3) Transmission efficiency.



Ans: Total resistance / phase = $0.1 \times 100 = 10\ \Omega$

Total reactance / phase = $0.5 \times 100 = 50\ \Omega$

Total Susceptance / phase = $10 \times 10^{-6} \times 100 = 10 \times 10^{-4}$ S

Receiving end Voltage / Phase, $V_r = \dfrac{66 \times 10^3}{\sqrt{3}} = 38105$ V

$\therefore$ Load current, $I_r = \dfrac{P}{3 V_{ph} \cos\phi}$

$\cos\phi = 0.9$

$= \dfrac{20 \times 10^6}{3 \times 38105 \times 0.9}$

$\therefore \sin\phi = 0.435$

$Z = R + jX_L = 10 + j50$

$= 195$ A

1) $V_s = V_{c_2} = V_r + IZ$ Q5

But $I = I_r + I_{c_1}$

$$I_r = I_r(\cos\phi - j\sin\phi)$$
$$= 195(0.9 - j0.435)$$

$$I_{c_1} = j\frac{Y}{2}V_r$$
$$= j\left(\frac{10\times10^{-4}}{2}\right)\times 38105$$
$$= \underline{\underline{j19}}$$

$$\therefore I = 195(0.9 - j0.435) + j19$$
$$= 175.5 - j84.825 + j19$$
$$= 175.5 - j65.82$$
$$= \underline{\underline{176 - j66}}$$

$$\therefore V_s = 38105 + (176 - j66)(10 + j50)$$
$$= 43165 + j8140$$
$$= \underline{\underline{43925\angle 10.65}} \qquad \therefore |V_s| = \underline{\underline{43925.8}}\ V$$

$$I_s = I_{c_2} + I$$

$$I_{c_2} = j\frac{Y}{2}V_s$$
$$= j\left(\frac{10\times10^{-4}}{2}\right)(43165 + j8140)$$
$$= \underline{\underline{-4 + j21.6}}$$

$$I_s = (-4 + j\,21.6) + (176 - j\,66)$$
$$= 172 - j\,44.4$$
$$= 177.6 \angle -14.5$$

$\therefore \phi_s = 10.65 - (-14.5) = 25.15$

$\therefore$ Sending end Pf $= \cos\phi_s = \cos(25.15)$
$= 0.905$

2) Voltage Regulation $= \dfrac{V_s - V_r}{V_r} \times 100$

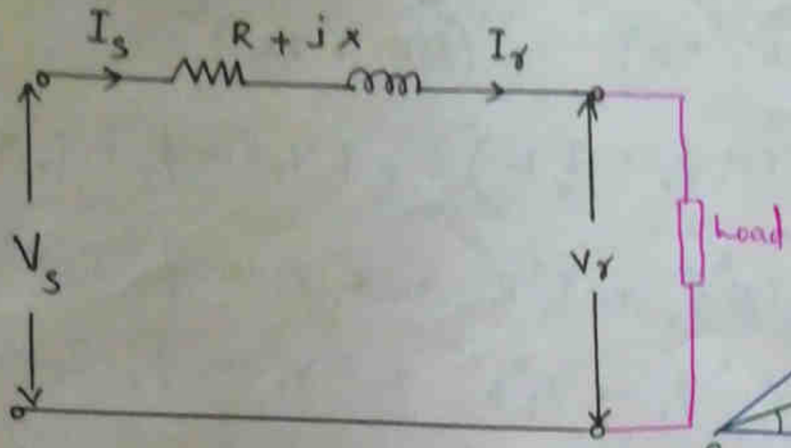
$$= \frac{43925.8 - 38105}{38105} \times 100$$
$$= 15.27\ \%$$

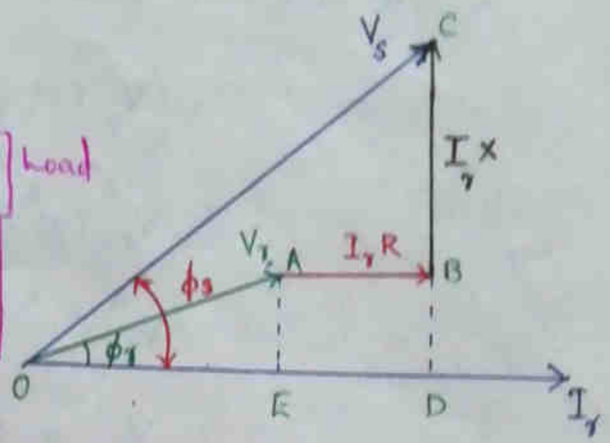
3) Transmission $\eta = \dfrac{\text{Receiving end Power}}{\text{Sending end Power}}$

Sending end Power $= 3\,V_s\,I_s\cos\phi_s$
$= 3 \times 43925.8 \times 177.6 \times 0.905$
$= 21.18$ MW

$\therefore$ Transm^n $\eta = \dfrac{20 \times 10^6}{21.18 \times 10^6}$
$= 94.4\ \%$

Short Transmission Lines





Let

$R \rightarrow$ Per phase Resistance

$x \rightarrow$ Per phase ~~Inductance~~ inductive reactance

$V_s \rightarrow$ Sending end Voltage

$V_r \rightarrow$ Receiving end Voltage

$\cos\phi_r \rightarrow$ Receiving end power factor (lagging)

$\cos\phi_s \rightarrow$ Sending end Power factor

For Phasor diagram, receiving end current (I_r) is taken as reference. Receiving end voltage (V_r) leads I_r by ϕ_r. AB represents the drop $I_r R$ in phase with I_r. BC represents the inductive drop $I_r x$, which leads I_r by 90°. OC represents the Sending end voltage V_s, which leads I_r by ϕ_s.

From the phasor diagram,

$$(OC)^2 = (OD)^2 + (DC)^2$$

$$\text{or, } V_s^2 = (OE + ED)^2 + (DB + BC)^2$$

$$= (V_r \cos\phi_r + I_r R)^2 + (V_r \sin\phi_r + I_r X)^2$$

$$= V_r^2 \cos^2\phi_r + I_r^2 R^2 + 2 V_r \cos\phi_r I_r R + V_r^2 \sin^2\phi_r + I_r^2 X^2 + 2 V_r \sin\phi_r I_r X$$

$$= V_r^2 + 2 V_r I_r R \cos\phi_r + 2 V_r I_r X \sin\phi_r + I_r^2 (R^2 + X^2)$$

$$V_s^2 = V_r^2 \left[1 + \frac{2 I_r R \cos\phi_r}{V_r} + \frac{2 I_r X \sin\phi_r}{V_r} + \frac{I_r^2 (R^2 + X^2)}{V_r^2} \right]$$

$$\therefore V_s = V_r \left[1 + \frac{2 I_r R \cos\phi_r}{V_r} + \frac{2 I_r X \sin\phi_r}{V_r} + \frac{I_r^2 (R^2 + X^2)}{V_r^2} \right]$$

Using Taylor Series expansion & neglecting the higher order terms,

$$(1+x)^n = 1 + nx + \frac{n(n-1)}{2!} x^2 + \cdots\cdots$$

$$V_s \simeq V_r \left(1 + \frac{I_r R \cos\phi_r}{V_r} + \frac{I_r X \sin\phi_r}{V_r} \right)$$

$$V_s \simeq V_r + I_r R \cos\phi_r + I_r X \sin\phi_r$$

Percentage Regulation $= \dfrac{V_s - V_r}{V_r} \times 100$

$$= \frac{I_r R \cos\phi_r + I_r X \sin\phi_r}{V_r} \times 100$$

Percentage Efficiency $= \dfrac{V_r I_r \cos\phi_r}{V_r I_r \cos\phi_r + I_r^2 R} \times 100$

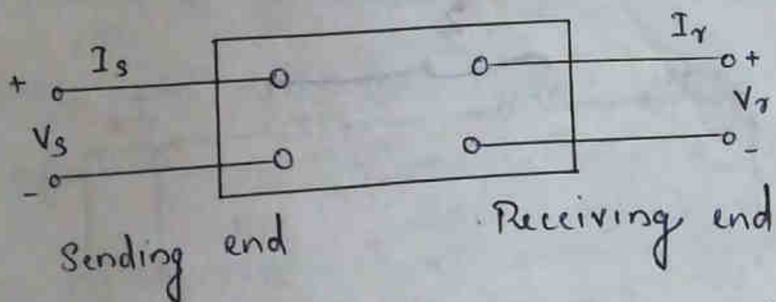
P → Power delivered at the receiving end.

GENERALIZED CIRCUIT CONSTANTS

It is important to represent the transmission line in terms of the sending end and receiving end voltages and current. A transmission line can be represented as 4 terminal (2 port) network.

$$\bar{V_s} = A\bar{V_r} + B\bar{I_r}$$

$$\bar{I_s} = C\bar{V_r} + D\bar{I_r}$$



2 port Network Representation

In matrix form, it is

$$\begin{bmatrix} \bar{V_s} \\ \bar{I_s} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} \bar{V_r} \\ \bar{I_r} \end{bmatrix}$$

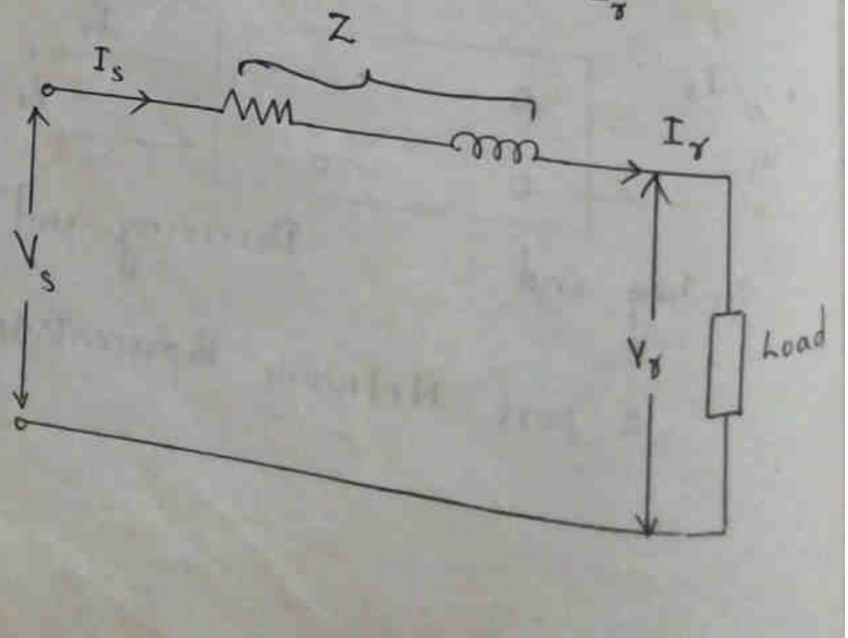
where A, B, C and D are generalized circuit con[stants] and it has the following Properties.

- These are complex constants
- They hold, $AD - BC = 1$
- If symmetrical network, $A = D$
- A and D are dimensionless
- B is impedance, C is admittance.

ABCD Constants for Short Transmission

We have, $\bar{V_s} = A\bar{V_r} + B\bar{I_r}$

$\bar{I_s} = C\bar{V_r} + D\bar{I_r}$



rom the figure,

$$\bar{I}_s = \bar{I}_r$$

$$\bar{V}_s = \bar{V}_r + \bar{I}_r Z$$

Comparing it with the general equation

$A = 1$; $B = Z$

$C = 0$; $D = 1$

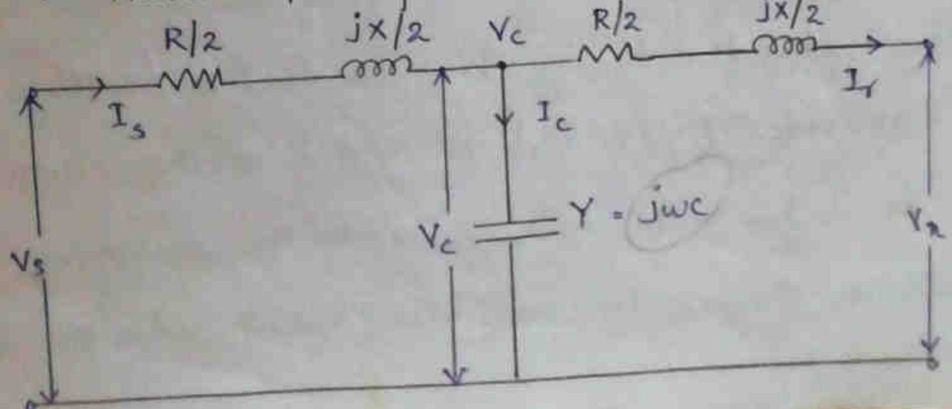
Hence $AD - BC = 1 \times 1 - (Z \times 0)$

$= \underline{\underline{1}}$

Medium Transmission Lines

Nominal - T Method

In this method, the capacitance of each conductor is assumed to be concentrated at the midpoint of the line with half the series impedance on either side of it. Here 'Y' represents the shunt admittance.



MODULE - III

INTRODUCTION OF OVERHEAD TRANSMISSION AND UNDERGROUND TRANSMISSION

CONDUCTORS

The conductors carry electric power from the sending end station to the receiving end station.

The conductor materials should have the following characteristics.

- High electrical conductivity
- High tensile strength in order to withstand mechanical stresses.
- Low cost so that it can be used for long distances
- Easy availability
- Should not be brittle

The most commonly used conductor materials for overhead lines are Copper, Aluminium, steel-cored aluminium, galvanised steel & Cadmium Copper. All conductors used for O.H lines are Stranded.

1. Copper

It has high electrical conductivity & greater tensile strength. The current density of copper is high i.e, it has 2 advantages.

→ Smaller X-sectional area of conductor is required

→ The area offered by the conductor to wind loads is reduced

Also copper is homogeneous & durable.

Due to high cost & non-availability, it is rarely used.

2. Aluminium

Al is cheap & light as compared to copper, but it has smaller conductivity & tensile strength.

→ The conductivity of Al is 60% that of copper.

i.e, For any particular transmission efficiency, the X-sectional area of conductor must be larger in Al than in copper.

→ The specific gravity of Al is lower than that of copper ie, An Al conductor has almost one-half the weight of equivalent copper conductor.

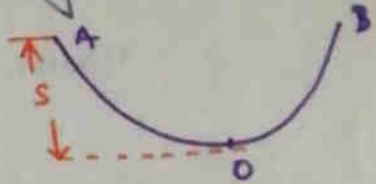
→ Al conductor is light

Hence it is liable to greater swings & hence large cross-arms (which provide support to insulators) are required.

→ Low tensile strength & high coefficient of linear expansion

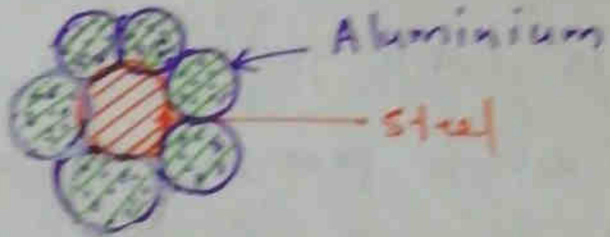
Hence the sag is greater in Al. conductors.

3. Steel Cored Aluminium (ACSR)



Al conductor produce greater sag due to its low tensile strength. & hence it can not be used for long distance transmission. In order to increase the tensile strength, the Al conductor is reinforced with a core of galvanised steel wires. The composite conductor thus obtained is known as Steel cored Aluminium or ACSR (Aluminium conductor Steel Reinforced)

It consist of central core of galvanised steel wires surrounded by a number of Al. strands. Diameter of both steel & Al wires is the same.



In the fig shows one steel wire surrounded by 6 wires of Al.

Adv of ACSR Conductor

- Due to smaller sag, towers of smaller heights can be used.
- It will produce smaller sag & hence longer spans can be used.

VOLUME OF CONDUCTOR REQUIRED FOR VARIOUS SYSTEMS OF TRANSMISSION

(Normal → 3 ϕ 3wire ac transm)

The various systems of Power transmission are,

a) DC systems.

i) DC two-wire system.

ii) DC two-wire s/m with mid point earthed

iii) DC three-wire s/m

b) Single Phase AC s/m

i) 1 ϕ 2 wire s/m

ii) 1 ϕ 2-wire s/m with mid point earthed

iii) 1 ϕ 3-wire s/m

c) Two phase AC s/m

i) 2 ϕ 4-wire s/m

ii) 2 ϕ 3-wire s/m

d) Three Phase AC s/m

i) 3 ϕ 3 wire s/m

ii) 3 ϕ 4 wire s/m.

3. Comparison of Conductor Material in Overhead and System

- The maximum vge b/w any conductor & earth (V_m) is same

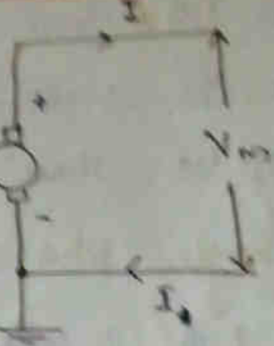
I 2-wire DC S/m with One Conductor Earthed

Max. vge b/w conductors = V_m

Power to be transmitted = P

$\therefore$ Load current, $I = P/V_m$

Resistance, $R = \frac{\rho l}{a}$



One is outgoing or +ve wire & the other is return or -ve wire. The load is connected b/w the 2 wire

Line losses, $W = 2I^2R$

$$W = 2 \times \left(\frac{P}{V_m}\right)^2 \frac{\rho l}{a}$$

$\therefore$ area of X-section, $a = \frac{2P^2 \rho l}{W V_m^2}$

$\therefore$ Volume of conductor material required $= 2al$

$$= 2 \times \frac{2P^2 \rho l}{W V_m^2} \times l$$

$$= \frac{4P^2 \rho l^2}{W V_m^2}$$

It can be used as reference

So take $\frac{4P^2 \rho l^2}{W V_m^2} = K$

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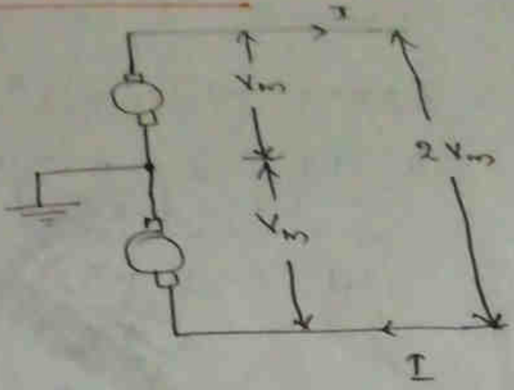
1 2-wire DC s/m with mid point Earthed



Max. vge b/w the conductors $= 2V_m$

Current, $I = \dfrac{P}{2V_m}$

Losses, $W = 2I^2R$

$$= 2\left(\frac{P}{2V_m}\right)^2 \times \frac{\rho l}{a}$$

$$W = 2\frac{P^2}{4V_m^2}\frac{\rho l}{a} = \frac{P^2 \rho l}{2V_m^2 a} \quad \therefore \cancel{a = \frac{P^2 \rho l}{}}$$

~~Volume of conductor required = 2 al~~

$$W = \frac{P^2 \rho l}{2V_m^2 a} \qquad \therefore a = \frac{P^2 \rho l}{W \times 2V_m^2}$$

Volume of conductor required $= 2al$

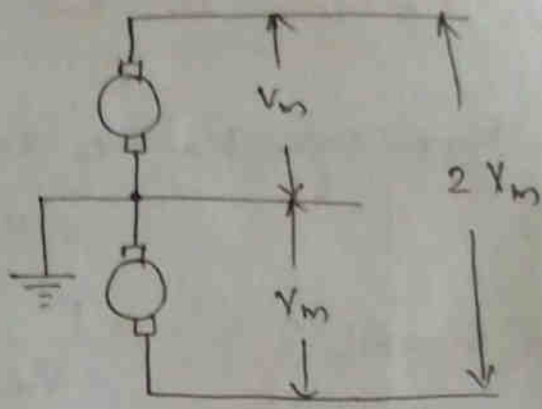
$$= 2 \times \frac{P^2 \rho l}{2WV_m^2} \times l$$

$$= \frac{P^2 \rho l^2}{WV_m^2}$$

$$= \frac{K}{4}$$

ie, Volume of conductor material required is 1/4 th of that required in 2-wire dc s/m.

III 3-wire dc s/m



Current, $I = \frac{P}{2V_m}$

Losses, $W = 2I^2R$

or, $W = 2\left(\frac{P}{2V_m}\right)^2 R$

$$W = \cancel{2}\frac{P^2}{2\,\cancel{4}V_m^2}\frac{\rho l}{a}$$

$$\therefore\ a = \frac{P^2\rho l}{2WV_m^2}$$

Volume of conductor required $= 2.5\,al$

$$= 2.5\left(\frac{P^2\rho l}{2WV_m^2}\right)l$$

$$= \frac{2.5}{2}\left(\frac{P^2\rho l^2}{WV_m^2}\right)$$

$$= \frac{5}{16}K$$

and so on

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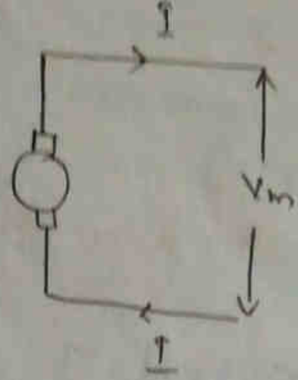
X Comparison of Conductor Material In Underground System

- The max. vge b/w the conductors (V_m) is same.

I Two-wire DC s/m



Load current, $I = P/V_m$

Line losses, $W = 2I^2R$

$$W = 2\frac{P^2}{V_m^2}\frac{\rho l}{a}$$

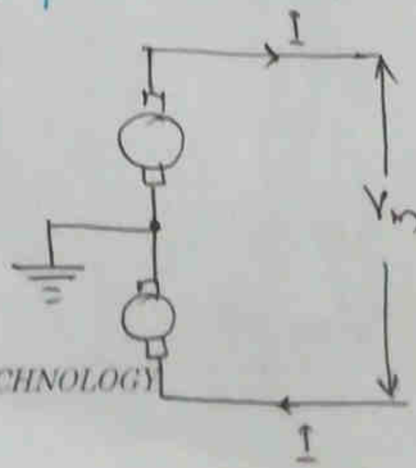
$$\therefore a = \frac{2P^2\rho l}{WV_m^2}$$

Volume of conductor material required $= 2al$

$$= 2 \times \frac{2P^2\rho l}{WV_m^2} \times l$$

$$= \frac{4P^2\rho l^2}{WV_m^2} = k$$

II 2 wire DC s/m with mid point earthed



Current, $I = P/V_m$

Losses, $W = 2I^2R$

$$= 2\frac{P^2}{V_m^2}\frac{\rho l}{a}$$

$$\therefore a = \frac{2P^2\rho l}{W V_m^2}$$

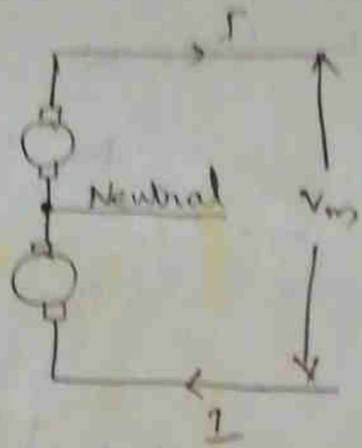
Volume of conductor required $= 2al$

$$= 2 \times \frac{2P^2\rho l}{W V_m^2} \times l$$

$$= \frac{4P^2\rho l^2}{W V_m^2}$$

$$= K$$

III 3-wire DC System



Current, $I = \frac{P}{V_m}$

Losses, $W = 2I^2R$

$$= 2\left(\frac{P}{V_m}\right)^2 \frac{\rho l}{a}$$

$$W = \frac{2P^2\rho l}{V_m^2 a}$$

$$\therefore a = \frac{2P^2\rho l}{W V_m^2}$$

Volume of conductor required $= 2.5\, al$

$$= 2.5\left(\frac{2P^2\rho l^2}{W V_m^2}\right)$$

$$= \frac{5P^2\rho l^2}{W V_m^2}$$

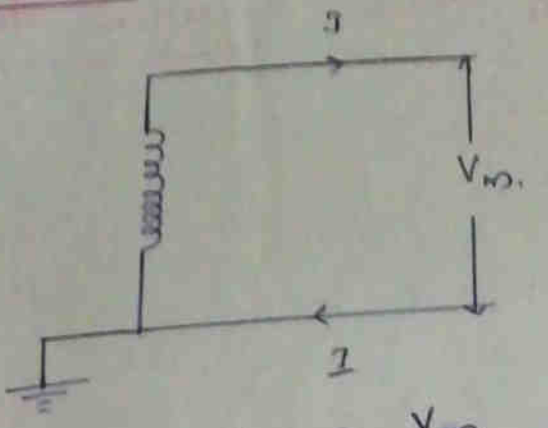
$$= 1.25\left(\frac{4P^2\rho l^2}{W V_m^2}\right)$$

$$= 1.25\, K$$

COMPARISON

Systems	Volume of conductor material required	
	Overhead system (Assuming same maximum vge b/w conductor & earth)	Underground system (Assuming same maximum vge b/w any 2 conductors)
a) DC systems		
i) 2-wire	1	1
ii) 2 wire with mid-point earthed	0.25	1
iii) 3 wire	0.3125	1.25
b) AC 1 ϕ systems		
i) 2-wire	$2/\cos^2\phi$	$2/\cos^2\phi$
ii) 2 wire with mid point earthed	$0.5/\cos^2\phi$	$2/\cos^2\phi$
iii) 3 wire	$0.625/\cos^2\phi$	$2.5/\cos^2\phi$
c) AC 2 ϕ systems		
i) 2 phase 4 wire	$0.5/\cos^2\phi$	$2/\cos^2\phi$
ii) 2 phase 3 wire	$1.457/\cos^2\phi$	$2.914/\cos^2\phi$
d) AC 3 ϕ systems		
i) 3 ϕ 3 wire	$0.5/\cos^2\phi$	$1.5/\cos^2\phi$
ii) 3 ϕ 4 wire	$0.583/\cos^2\phi$	$1.75/\cos^2\phi$

1 Single Phase 2-wire AC System with one Conductor Earthed



$$P = V I \cos\phi$$

Max. voltage b/w the conductors $= V_m$

$\therefore$ Rms " $= \dfrac{V_m}{\sqrt{2}}$

$\therefore$ Load current, $I = \dfrac{P}{V_m/\sqrt{2}\,\cos\phi} = \dfrac{\sqrt{2}\,P}{V_m \cos\phi}$

$\therefore$ Line losses, $W = 2 I^2 R$

$$W = 2\left(\frac{\sqrt{2}\,P}{V_m \cos\phi}\right)^2 \cancel{R} \times \frac{\rho l}{a}$$

$\therefore$ area of cross section, $a = \dfrac{4 P^2 \rho l}{W V_m^2 \cos^2\phi}$

$\therefore$ Volume of conductor material required $= 2 a l$

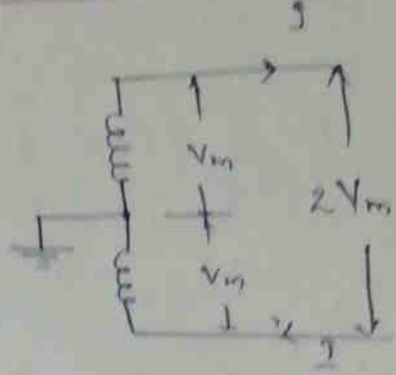
$$= 2\left(\frac{4 P^2 \rho l}{W V_m^2 \cos^2\phi}\right) \times l$$

$$= \frac{2}{\cos^2\phi} \times \frac{4 P^2 \rho l^2}{W V_m^2}$$

$$= \frac{2}{\cos^2\phi} \times K \quad \left(\because K = \frac{4 P^2 \rho l^2}{W V_m^2}\right)$$

ie, In this case Volume is $\frac{2}{\cos^2\phi}$ times that of 2 wire dc s/m.

VI Single Phase 2 wire s/m with mid point earthed



Max. vge b/w the conductors $= 2V_m$

$\therefore$ RMS " " $= \frac{2V_m}{\sqrt{2}} = V_m\sqrt{2}$

Load current, $I = \frac{P}{V_m\sqrt{2}\cos\phi}$

Line losses, $W = 2I^2R$

$$W = 2 \times \left(\frac{P}{V_m\sqrt{2}\cos\phi}\right)^2 \frac{\rho l}{a}$$

$$\therefore a = \frac{P^2\rho l}{W V_m^2 \cos^2\phi}$$

Volume of conductor material required $= 2al$

$$= 2 \times \frac{P^2\rho l}{W V_m^2 \cos^2\phi} \cdot l$$

$$= \frac{2}{\cos^2\phi} \times \frac{4}{4}\, \frac{P^2\rho l^2}{W V_m^2}$$

$$= \frac{[illegible]\,k}{2\cos^2\phi \times [illegible]}$$

$$= \frac{k}{2\cos^2\phi}$$

ie, $\frac{1}{2\cos^2\phi}$ times that of 2 wire dc system

with one conductor earthed.

KELVIN'S LAW

The design of a transmission line depends up..

i) Economic choice of conductor size

ii) Economic choice of transmission voltage

Economic Choice of Conductor Size

The cost of conductor material is a very considerable part of the total cost of a transmission line. ∴ the determination of proper size of conductor for the line is very important.

"The most economical area of conductor is that for which the total annual cost of transmission line is minimum". This is known as Kelvin's Law

The total annual cost of transmission line can be divided into 2-parts.

i) Annual change on capital outlay

ii) Annual cost of energy wasted in the conductor.

(i) Annual Charge on Capital Outlay

This is on account of interest & depreciation on the capital cost of complete installation of transmission line. In case of over head s/m, it will be the annual interest and depreciation on the capital cost of conductors, supports & insulators and the cost of their erection.

For an over head line, insulator cost is constant, conductor cost $\propto$ to area of cross section;

cost of supports & their erection } partly constant
partly $\propto$ to area of c.s of conductor

$$\therefore \text{ Annual charge} = P_1 + P_2 a$$

where P_1 and P_2 are constants

a is the area of c.s of conductor.

(ii) Annual cost of energy wasted

This is on account of energy lost in conductor due to I^2R losses.

Assuming a constant current in the con[ductor]
throughout the year,

then energy loss $\propto$ Resistance

$\propto \frac{\rho l}{a}$

$\propto \frac{1}{a}$

i, Annual cost of energy wasted $= \frac{P_3}{a}$

where P_3 is constant.

$\therefore$ Total Annual cost, $C = P_1 + P_2 a + \frac{P_3}{a}$

The total annual cost 'C' is minimum

when $\frac{d}{da}(C) = 0$

i, $\frac{d}{da}\left(P_1 + P_2 a + \frac{P_3}{a}\right) = 0$

$\Rightarrow P_2 + P_3 \times \frac{-1}{a^2} = 0$

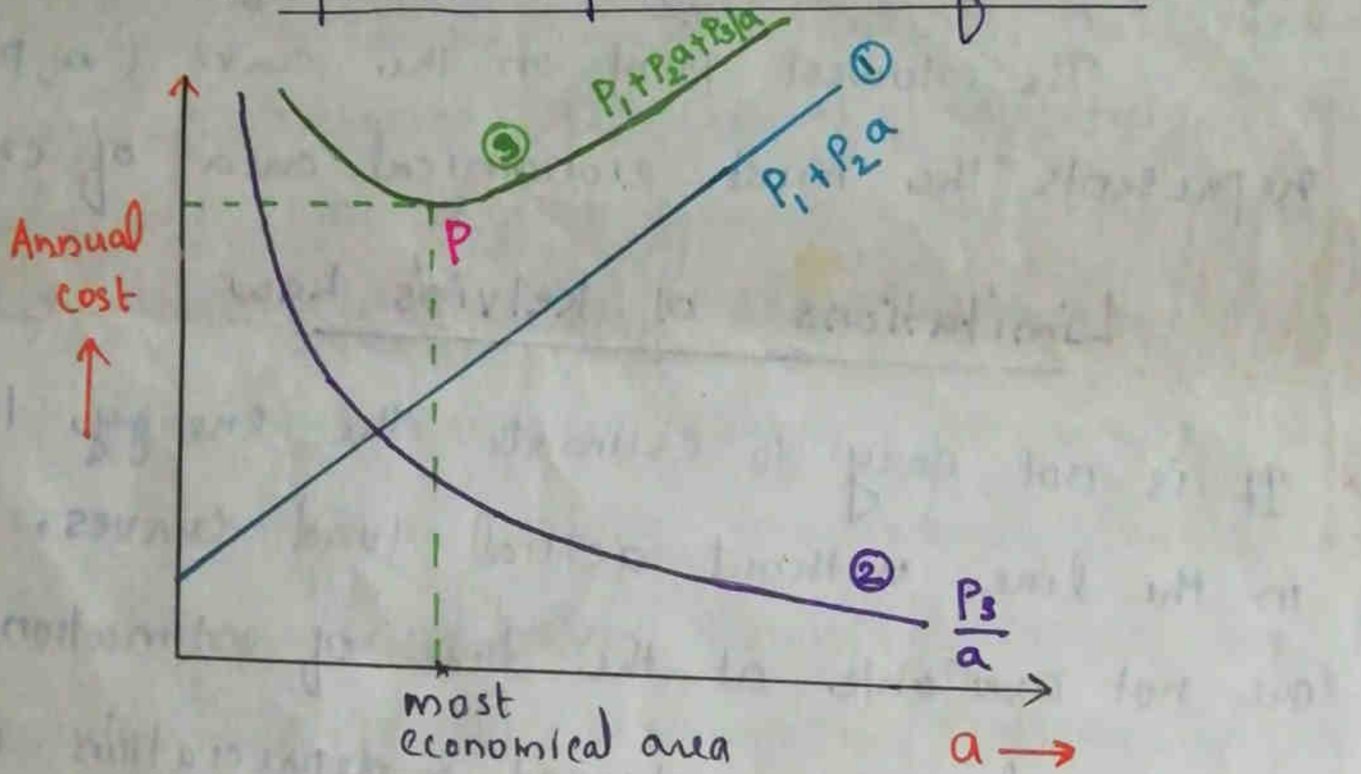
$\Rightarrow P_2 = \frac{P_3}{a^2}$

$$\Rightarrow \boxed{P_2 a = \frac{P_3}{a}}$$

i, Variable part of annual charge = Annual cost of energy wasted.

Kelvin's law can also be stated that " the most economical area of conductor is that for which the variable part of annual charge is equal to the cost of energy losses per year".

Graphical Representation of Kelvin's Law



In the graph,

$P_1 + P_2 a$ is a straight line, which shows the relation b/w the annual change (ie, $P_1 + P_2 a$) and the area of c.s 'a' of the conductor.

* $\frac{P_3}{a}$ is a rectangular hyperbola, gives the relation b/w annual cost of energy wasted & the c.s area 'a'.

* By adding the ordinates of curves (1) & (2), the curve (3) is obtained. This curve shows the relation b/w total annual cost $(P_1 + P_2 a + P_3/a)$ of transmission line & the area of c.s 'a'.

The lowest point on the curve (ie, Point P) represents the most economical area of cross section

Limitations of kelvin's Law

* It is not easy to estimate the energy loss in the line without actual load curves, which are not available at the time of estimation.
* The annual cost of interest & depreciation on capital outlay in the form $P_1 + P_2 a$ is not acutally true.
* This law does not take into account several Physical factors like safe current density, mechanical strength, corona loss etc
* Interest & depreciation on capital outlay cannot be determined accurately.

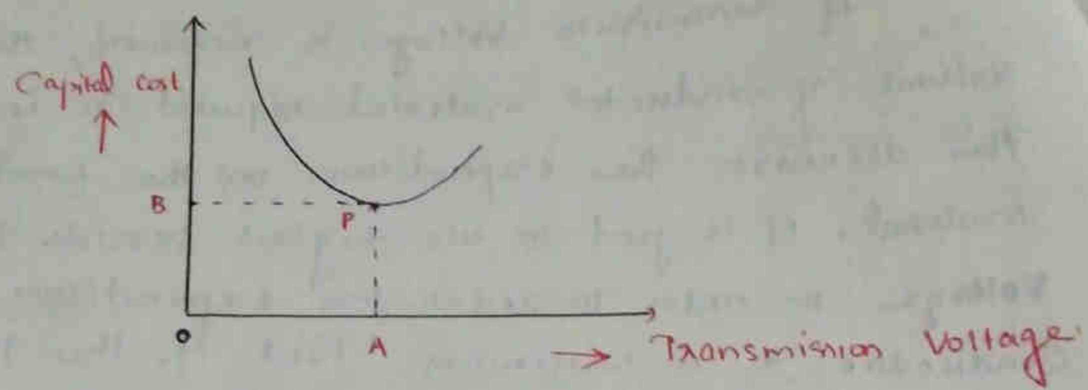
Economic Choice of Transmission Voltage

If transmission voltage is increased, the volume of conductor material required is reduced. This decreases the expenditure on the conductor material. It is good to use highest possible transmission voltage in order to reduce the expenditure on conductors to a minimum. But if the transmission voltage is increased, the cost of insulating the conductors, cost of transformers, switch gear & other terminal apparatus also increases.

The transmission voltage for which the cost of conductors, cost of insulators, transformers, switch gear and other terminal apparatus is minimum is called economical transmission voltage.

The cost of transformers, switch gear, lightning arrestor, Insulation & supports increases with increase in transmission voltage, but the cost of conductor decreases with increase in transmission voltage.

The sum of all the above costs gives the total cost of transmission for the voltage



A curve is drawn for total cost of transmission against voltage. The lowest point (P) on the curve gives the economical transmission voltage. OA is the optimum transmission vge.

The empirical formulae for finding the economical transmission voltage is given by,

$$\boxed{V = 5.5\sqrt{0.62\,l + \frac{3P}{150}}}$$

where V = line voltage in kV

P = Maximum kW / Phase

l = distance of transmission in km.

MECHANICAL CHARACTERISTICS OF TRANSMISSION LINES

TOWERS (LINE SUPPORTS)

The function of tower is to suppoort the conductors. The line supports are of various types including wood, steel, reinforced concrete poles and steel towers

The main requirements of towers are

- High mechanical strength
- Light in weight
- Cheaper in cost
- Long life
- Low maintenance cost.

The different types of poles which can be used as line supports are

i) Wooden Poles

It is used for low Voltage purposes Initially these are cheap & provide an insulating propert

The poles must be straight, strong etc.

ii) RCC Poles (Reinforced Cement Concrete Po

Poles made of reinforced cement concrete are stronger but costlier than wood poles. They have very long life and need little maintenance. They are bulky & heavy.

iii) Steel Tubular Poles

The wooden poles are substituted by steel tubular poles. They are stronger than wood. To increase the life of poles, they must be galvanized or painted regularly.

iv) Steel Towers

Lines of 66 kV & above are supported on steel towers. They are fabricated from painted or galvanized angle sections which can be transported separately. They have a very long life & reliability. They can withstand severe weather conditions.

They are classified into a) tangent towers
b) Deviation towers.

MECHANICAL DESIGN OF TRANSMISSION LINES

Factors Affecting Mechanical Design

The factors affecting the mechanical design of an overhead transmission lines are,

1. Selection of Line Route :

The selection of the route depends upon the distance, geographical conditions, transportation facility etc.

2. Types of Towers / Poles :

The selection of the type of towers / Poles depends upon the line span, conductor weight, line operating voltage cost etc. Distance b/w adjacent supporting towers → span

3. Ground and Conductor Clearance :

The clearance of conductors is decided by the working voltage, length of span etc.

4 Tower Spacing and Span length :

The tower spacing and span length depends the weight of the conductor, wind direction, ice loading, Soil conditions etc.

3. Mechanical loading

Mechanical loading depends upon the weight of the conductor material.

- SAG AND TENSION

When a flexible wire of uniform cross sectional area is suspended between two supports at the same level, it experiences a tensile stress which is due to the weight of conductor acting vertically downwards. Due to this, the conductor forms a catenary curve between the towers.

The difference in level between the points of supports and the lowest point on the conductor is known as sag.

The factors affecting the sag are;

a) Weight of the Conductor

The Sag is directly proportional to the weight of the conductor. ie, Sag increases with an increase in the weight of the conductor.

b) Length of the Span

Sag is directly proportional to the span length. Higher the value of span length, higher is the sag.

c) Working Tensile Strength:

Sag is inversely proportional to the working tensile strength of the conductor at constant temperature.

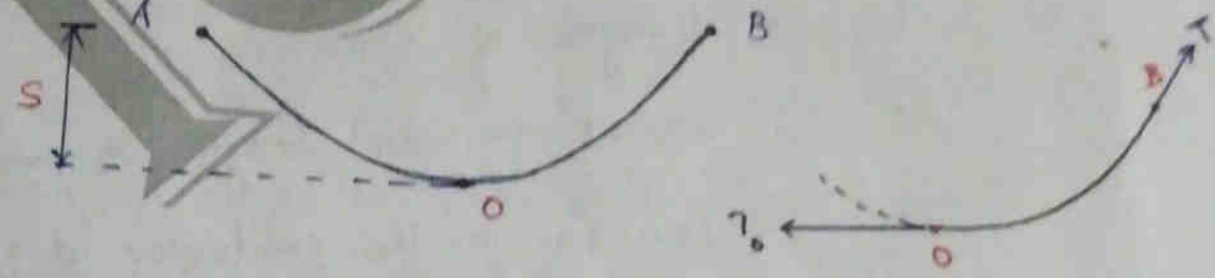
d) Temperature

The sag will increases with an increase in temperature.

SAG IN OVERHEAD LINES

The difference in level between points of supports and the lowest point on the conductor is known as sag.

Fig shows a conductor suspended between two equilevel supports A & B. The lowest point on the conductor is O and the sag is S.

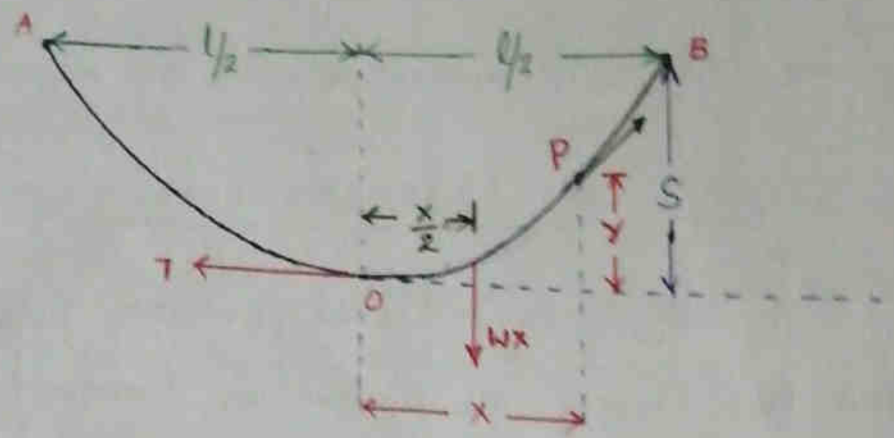


- When the conductor is suspended between two supports at the same level, it takes the shape of catenary
- The tension at any point on the conductor acts tangentially. Thus tension T_o at the lowest point o

acts horizontally as shown in fig.

- The horizontal component of tension is constant throughout the length of the wire.

I CALCULATION OF SAG AT EQUAL SUPPORTS



When the conductor is supported by two supports A & B as shown in fig. It forms a catenary curve due to the weight of the conductor and is horizontal at O.

Let l = Length of span

w = weight per unit length of conductor

T = Tension in the conductor at pt. O acting horizontally

S = Maximum Sag

Consider a point P on the conductor. Taking the lowest point O as the origin, let the coordinates of the point P be x & y. Assuming that the curvature is so small that curved length is equal to its horizontal projection (ie, OP = x)

The 2 forces acting on the portion OP of the conductor are

a) The weight wx of conductor acting at a distance x/2 from O.

b) The tension T acting at O.

Equating the moments of above 2 forces about the point 'O',

ie, $T \times y = wx \times \frac{x}{2}$

$$y = \frac{wx^2}{2T}$$

The maximum sag is represented by the value of Y at either of the supports A & B

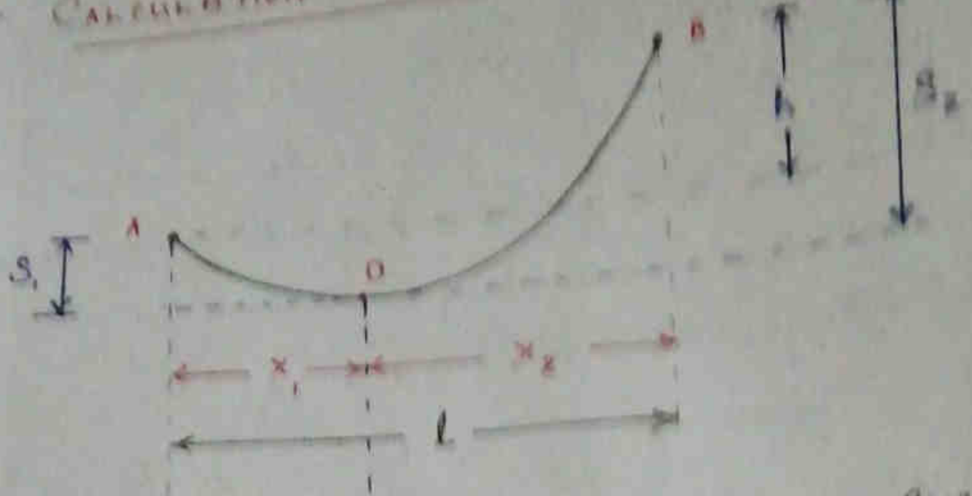
At support A, $x = l/2$ & $Y = S$

$$\therefore \text{Sag, } S = \frac{w(l/2)^2}{2T} = \frac{wl^2}{8T}$$

ie,

$$\boxed{\text{Sag } S = \frac{wl^2}{8T}}$$

II. Calculation of Sag at Unequal Level Supports



In hilly areas, the conductors are suspended between the supports at unequal levels.

Fig shows a conductor suspended between 2 supports A & B which are at different levels. The lowest point on the conductor is O.

Let

l = Span length

h = Difference in level between 2 supports

x_1 = Distance of the lowest point from the lower support.

x_2 = Distance of the lowest point from the upper support.

The sag w.r.t lower support, $S_1 = \frac{Wx_1^2}{2T}$

The Sag w.r.t upper Support, $S_2 = \frac{Wx_2^2}{2T}$

The difference in level, $h = S_2 - S_1$

$$= \frac{w}{2T}\left[x_2^2 - x_1^2\right]$$

$$= \frac{w}{2T}\left[(x_2+x_1)(x_2-x_1)\right]$$

$\because x_1 + x_2 = l$

$$= \frac{w}{2T}\left[l \times (x_2-x_1)\right]$$

$$h = \frac{wl}{2T}(x_2-x_1)$$

$$\therefore x_2 - x_1 = \frac{2Th}{wl} \quad \text{—— (1)}$$

$$x_2 + x_1 = l \quad \text{—— (2)}$$

Adding eqns (1) & (2),

ie, $2x_2 = \frac{2Th}{wl} + l$

$$\therefore x_2 = \frac{Th}{wl} + \frac{l}{2}$$

$$x_1 = l - x_2$$

$$= l - \left[\frac{Th}{wl} + \frac{l}{2}\right]$$

$$x_1 = \frac{l}{2} - \frac{Th}{wl}$$

ie, $$\boxed{\begin{aligned} x_1 &= \frac{l}{2} - \frac{Th}{wl} \\ x_2 &= \frac{l}{2} + \frac{Th}{wl} \end{aligned}}$$

From the values of x_1 & x_2, S_1 & S_2 can be found.

EFFECT OF ICE AND WIND LOADING

The sag and tension of lines are different in ~~normal~~ differ. weather conditions. Since lines are designed for all the conditions, it is important to calculate the sag & tension during the ice and wind loading conditions.

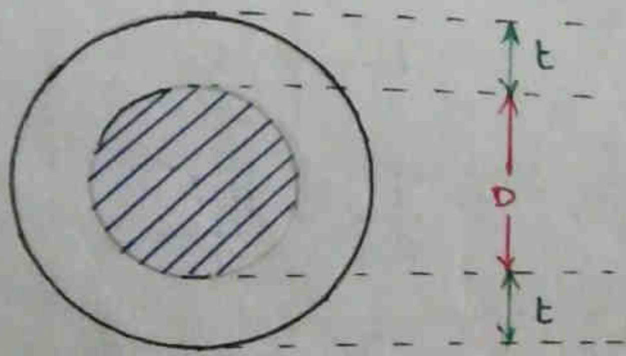
Effect of Ice

In snowy areas, ice is deposited on conductors & sometimes thickness of ice is more than the conductor diameter and its accumulation on the conductor affects the design of the line,

a) by increasing the weight per metre

b) by increasing the projected surface area

Due to ice, the sag and tension of the conductor increases.



Let the diameter of a conductor is D and the thickness of ice is t.

Then the cross-sectional area of ice (A_i) will be the C.S area of ice along with the conductor minus C.S area of the conductor.

ie, $A_i = \frac{\pi}{4}\left[(D+2t)^2 - D^2\right]$

$= \frac{\pi}{4}\left[D^2 + 4Dt + 4t^2 - D^2\right]$

$= \frac{\pi}{4}\left[4t(D+t)\right]$

$= \pi\left[(D+t)\,t\right]$

If the density of ice is ρ_i (normally 915 kg/m³), then the weight of ice acting downward will be,

the weight of ice per unit length

w_i = Weight of ice per unit length

= Density of ice × Volume of ice per unit length

$= \rho_i \times A_i \times 1$ (area, length)

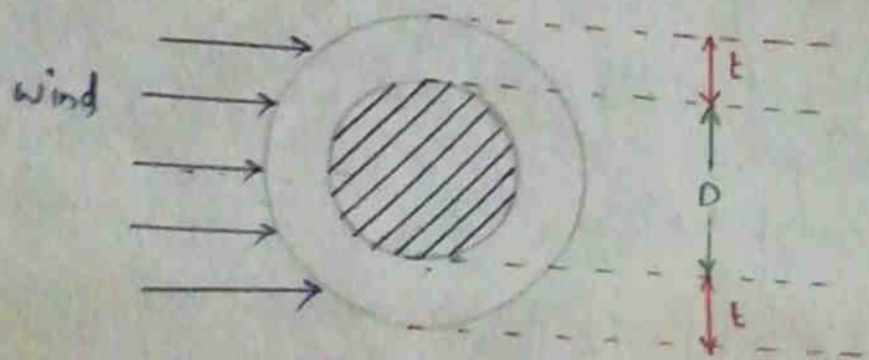
$= \rho_i \times \pi\left[(D+t)\,t\right] \times 1$

$= \rho_i \times \pi\left((D+t)\,t\right)$ kg where diameter and thickness are in metres. If the weight per unit length of the conductor is w and weight per unit length of ice is w_i, then the total weight per unit length,

$$w_T = w + w_i$$

Effect of Wind

The effect of wind is ~~taken~~ acting horizontally across the Projected area of the conductor covered with ice.



If D is the diameter of bare conductor in metre, t is thickness of ice in metre, Projected surface area for l metre length will be $(D+2t)\,l$. If the wind Pressure is P kg/m^2, the wind loading will be,

$$W_w = (D+2t)\,l\,P \ kg/m$$

The wind pressure depends on 1) the shape of conductors and also on 2) the velocity of wind, which can be calculated by using, $P = 0.006\,V^2 \ kg/m^2$, where V is the velocity of wind in km/hr

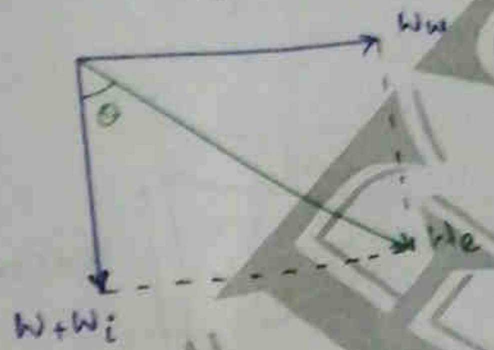
The effective load acting on the conductor will be

$$W_e = \sqrt{W_w^2 + (w + w_i)^2}$$

$W_w \rightarrow$ wt. due to wind loading
$w_i \rightarrow$ wt due to ice deposition
$w \rightarrow$ wt due to conductor

where w and w_i are per unit weight of conductor and ice respectively.

The loading is acting at an angle, $\theta = \tan^{-1}\left(\frac{W_w}{w + w_i}\right)$



The sag in vertical plane $= \frac{W_e l^2}{8T} \cos\theta$

$\boxed{\text{Vertical Sag} = S \cos\theta}$ $= \cancel{\frac{W_e l^2}{8T}} \cancel{\cos\theta}$

The sag in horizontal plane $= \frac{W_e l^2}{8T} \sin\theta$

$\boxed{\text{Horizontal Sag} = S \sin\theta}$ $= \cancel{\frac{W_e l^2}{8T}} \cancel{\sin\theta}$

The resultant sag or total sag $= \frac{W_e l^2}{8T}$

$= \cancel{\frac{W_e l^2}{8T}}$

$l \rightarrow$ Span length

• STRINGING CHART

For the erection of a transmission line, the designer has to design the line so that it is able to withstand the worst conditions. Hence the designer must know the sag and tension in the overhead line to be allowed with temperature (The curve of Sag and tension variations is called the Stringing chart)

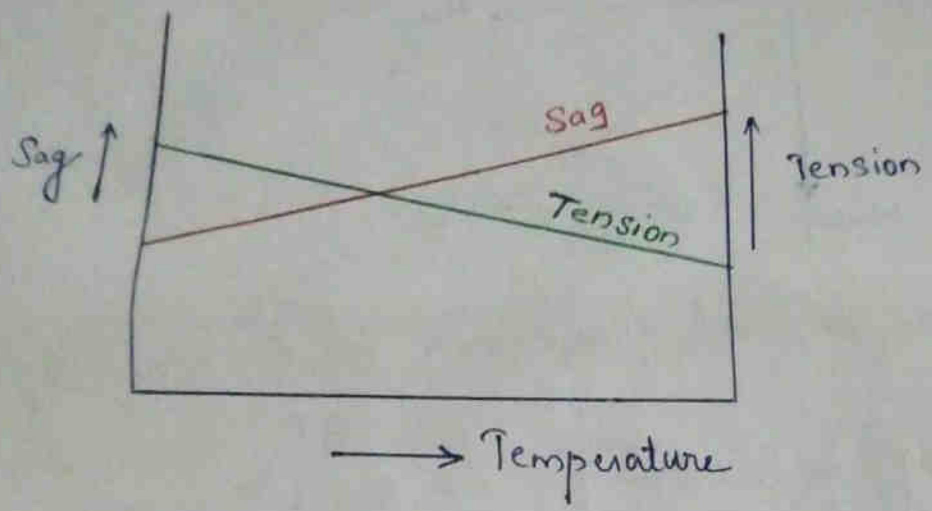
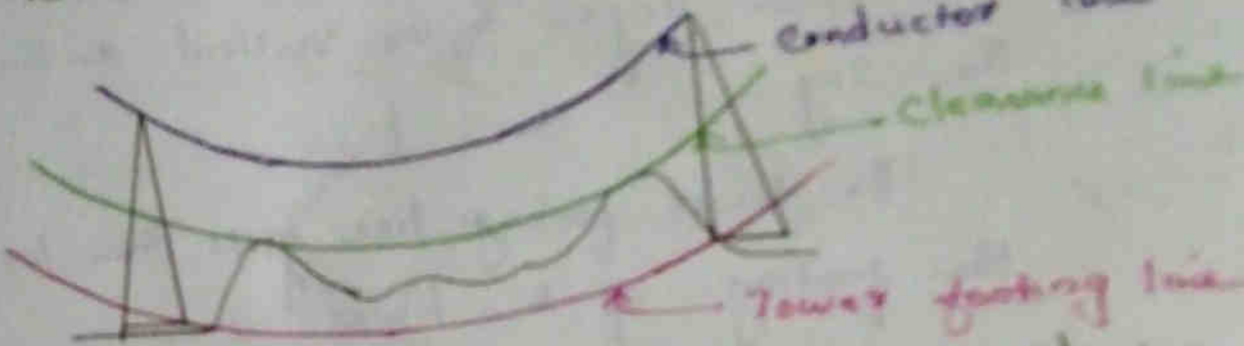


Fig. Shows the effect of temperature on the sag and tension of a given transmission line under loading conditions. At high temperature, the sag in still air is more and tension is less. In case of low temperature, sag is less and tension is more.

Sag Template

It is a convenient way of locating the towers in the field. This template is prepared on celluloid and the curves are drawn to the same horizontal & vertical scales.



The upper curve represents the conductor. The middle curve is below the upper curve by a uniform vertical distance equal to the desired minimum vertical clearance to ground. The lower curve is below the upper one by a uniform vertical distance equal to the height of a standard tower measured to the point of support of the conductor.

In order to locate the position of towers, first step is to know a suitable value for the Support height.

The next step is to plot a sag template on a piece of transparent paper which consist of a set of curves. The horizontal distance represents the span length & the Vertical distance represent the sag.

The tower footing line gives the location of the footing of the tower.

The clearance line represents the minimum Clearance of power conductor from the ground.

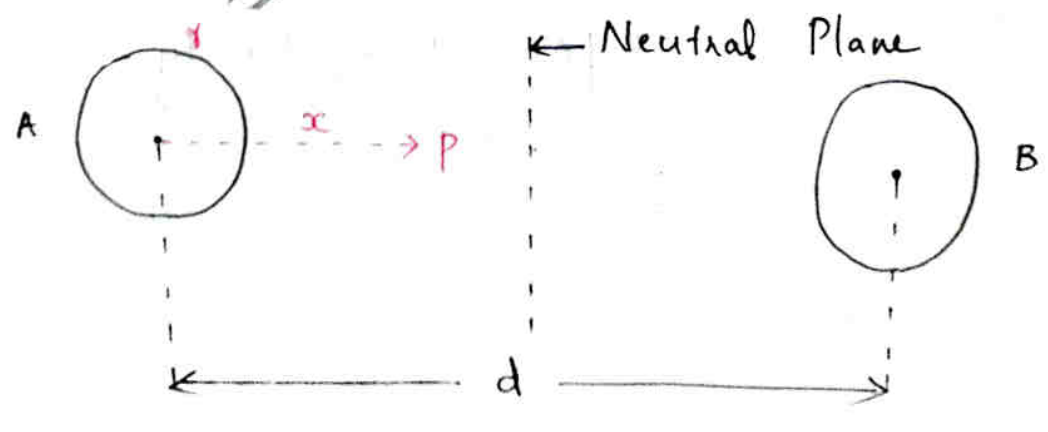
CORONA

If the potential difference is increased between two conductors spaced some distance apart in air, at some potential a faint luminous glow of violet colour will appear adjacent to the conductor surface with a hissing noise. There is also formation of ozone gas. If the potential is further increased, the intensity of glow & noise will increase. This phenomenon is known as corona, which is due to the ionization of air near power conductor.

The phenomenon of violet glow, hissing noise & production of ozone gas in an overhead transmission line is known as Corona.

CRITICAL VOLTAGE

It is the voltage required to ionise the air.



Consider 2 conductors of transmission line as shown in fig. The radius of each conductor is r, charge density is q, d is the distance b/w the 2 conductors.

Then the voltage required to ionise the air is

$$V' = r g_0 \delta \ln \frac{d}{r}$$

Where

g_0 = Potential gradient (break down strength of air)

= 30 kV/cm (max) or 21.1 kV/cm (rms)

δ = Air density correction factor

$$= \frac{3.92\, b}{273 + t}$$

Where $b \rightarrow$ Barometer Pressure

$t \rightarrow$ temperature

CRITICAL DISRUPTIVE VOLTAGE

It is the voltage at which complete disruption of dielectric occurs or it is the minimum phase-neutral voltage at which corona occurs but it is not visible.

Critical disruptive voltage $\boxed{V_c = r g_0 m \delta \ln \frac{d}{r}}$

where m is the surface irregularity factor

$$0.8 < m < 1$$

VISUAL CRITICAL DISRUPTIVE VOLTAGE

This is the voltage at which corona is visible. When the voltage increases above critical disruptive voltage at some point, the corona is visible. The voltage at that point is known as visual critical disruptive voltage (V_v).

The gradient for critical visual corona is denoted by g_v.

$$g_v = g_0 \delta \left(1 + \frac{0.3}{\sqrt{r\delta}}\right) \text{ kV/cm}$$

The visual critical disruptive voltage is given by,

$$V_v = r g_v m_v \ln\left(\frac{d}{r}\right)$$

$$\boxed{V_v = 21.1\, m_v\, r\, \delta \left(1 + \frac{0.3}{\sqrt{r\delta}}\right) \ln \frac{d}{r} \text{ kV}}$$

where d & r are in cm.

The value of surface factor m_v is different from m. (roughness factor)

m_v is 0.72 for local corona &
0.82 for general corona.

Problem

1. A 3 ϕ transmission line is having 3 conductors equilaterally spaced 6 m apart. The diameter of each conductor is 2 cm. The air temperature is 27 °C & pressure is 72 cm of Hg. If the surface factor is 0.82 & irregularity factor is 0.9, find the critical disruptive voltage & visual critical disruptive voltage.

U.Q

Ans: $d = 6 \text{ m} = 600 \text{ cm}$

Radius, $r = \frac{2}{2} = 1 \text{ cm}$

Temp, $t = 27°C$

Pressure, $b = 72$ cm of Hg

Surface factor, $m_r = 0.82$

Irregularity factor, $m = 0.9$

i) Critical disruptive voltage, $V_c = r\, g_0\, m\, \delta \ln\left(\frac{d}{r}\right)$

Air density factor, $\delta = \frac{3.92\, b}{273 + t}$

$$= \frac{3.92 \times 72}{273 + 27} = 0.9408$$

∴ Phase to neutral critical disruptive voltage

$$V_c = 1 \times 21.1 \times 0.9 \times 0.9408 \times \ln\left(\frac{600}{1}\right)$$

$$= 114.29 \text{ kV}$$

∴ Line to line critical disruptive voltage

$= 114.29 \times \sqrt{3}$

$= 197.95 \text{ kV}$

2) Visual critical disruptive voltage, V_v =

$$V_v = 21.1\, m_v\, r\, \delta \left(1 + \frac{0.3}{\sqrt{r\delta}}\right) \ln \frac{d}{r}$$

$$= 21.1 \times 0.82 \times 1 \times 0.9408 \left(1 + \frac{0.3}{\sqrt{1 \times .9408}}\right) \ln \frac{600}{1}$$

$= 136.33 \text{ kV}$

∴ Line to line visual critical disruptive voltage

$= 136.33 \times \sqrt{3}$

$= 236.14 \text{ kV.}$

CORONA LOSS

The ionized charge near the conductor surface take some energy from the supply & thus there is a loss of some energy due to corona, and this loss is resistive in nature). For calculating corona loss there is no particular formula.

Peek's empirical formula for corona loss under the fair weather condition is,

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} \, (V_p - V_c)^2 \text{ kw/phase/km}$$

where

$f \rightarrow$ Supply frequency in Hz

$V_p \rightarrow$ Phase to neutral operating voltage in kV

Peek's empirical formula for bad weather condition is,

$$P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} \, (V_p - 0.8 V_c)^2 \text{ kw/phase/km}$$

This equation give correct result if

1. Corona loss is predominant
2. Frequency lies between 25 & 120 Hz
3. Ratio $V_p / V_c > 1.8$
4. The radius of conductor is > 0.25 cm

If the ratio V_p/V_c is less than 1.8, then the Peterson's formula is given by,

$$P_c = \frac{1.11066 \times 10^{-4} f V^2}{[\ln (d/r)]^2} \times F \text{ kw/phase/km.}$$

Where F is the factor which varies with the ratio V_p/V_c

1. A 3 phase 220 kV, 50 Hz, transmission line consists of 1.5 cm radius conductor spaced 2 m apart in equilateral triangular formation. If the temperature is 40°C & atmospheric pressure is 76 cm. Calculate the corona loss/km of the line. Take m_0 = 0.85

Ans.

$r = 1.5$ cm

$d = 2$ m $= 200$ cm

$t = 40°C$

$b = 76$ cm of Hg

Irregularity factor, $m = 0.85$

Corona loss, $P_c = 241 \times 10^{-5} \times \frac{f+25}{\delta} \sqrt{\frac{r}{d}} \, (V_p - V_c)^2$ kW/phase/km

Air density factor, $\delta = \frac{3.92\, b}{273+t}$

$= \frac{3.92 \times 76}{273+40} = \underline{\underline{0.952}}$

Take $g_0 = 21.1$ kV/cm

Critical disruptive Voltage, $V_c = r g_0 m \delta \ln \frac{d}{r}$

$= 1.5 \times 21.1 \times 0.85 \times 0.952 \times \ln \frac{200}{1.5}$

$= 125.9$ kV

Supply Voltage Per phase, $V_p = 220/\sqrt{3} = 127$,

(Given, the line Voltage, $V_L = 220$ kV)

$\therefore$ Corona loss $= 241 \times 10^{-5} \times \frac{50+25}{0.952}\sqrt{\frac{1.5}{200}} \times (127 - 125.9)^2$

$= 0.0198$ kw/km/phase

$\therefore$ Total Corona loss per km for 3 phases

$= 3 \times 0.0198$ kw

$= \underline{\underline{0.0596 \text{ kw}}}$

2) A 3 ϕ, 50 Hz, 220 kV transmission line consists of conductors of 2 cm diameter & spaced equilaterally at a distance of 4 m. The line conductors have smooth surface with value of $m = 0.96$. The barometric pressure is 73 cm of Hg & temp. of 20°C. Determine the fair & stormy weather corona loss per km per phase.

Ans: $r = 2/2 = 1$ cm

$d = 4$ m $= 400$ cm

$m = 0.96$

$b = 73$ cm of Hg

$t = 20°C$

Fair Weather Condition

Corona loss, $P_c = 241 \times 10^{-5} \times \dfrac{f+25}{\delta} \sqrt{\dfrac{r}{d}} \left(V_p - V_c\right)^2$ kw/phase/km

$$\delta = \frac{3.92 \times b}{273 + t}$$

$$= \frac{3.92 \times 73}{273 + 20} = \underline{0.9767}$$

Line Voltage, $V_L = 220$ kV

∴ Supply Voltage / Phase, $V_p = \dfrac{220}{\sqrt{3}} = 127$ kV

$$V_c = r\, g_0\, m\, \delta \ln\left(\frac{d}{r}\right)$$

$$= 1 \times 21.1 \times 0.96 \times 0.9767 \times \ln\left(\frac{400}{1}\right)$$

$$= \underline{118.53 \text{ kV}}$$

$$\therefore P_c = 241 \times 10^{-5} \times \frac{50+25}{0.9767} \sqrt{\frac{1}{400}} \left(127 - 118.53\right)^2$$

$$= \underline{0.6629} \text{ kw / Phase / km}$$

2) <u>Stormy Weather Condition</u>

Corona loss, $P_c = 241 \times 10^{-5} \times \dfrac{f+25}{\delta} \sqrt{\dfrac{r}{d}} \left(V_p - 0.8\, V_c\right)^2$

kw/phase/km

ie, $P_c = 241 \times 10^{-5} \times \dfrac{50+25}{0.9767} \times \sqrt{\dfrac{1}{400}} \left(127 - 0.8 \times 118.53\right)^2$

$= 9.57$ kw/phase/km

FACTORS AFFECTING CORONA

The different factors affect corona are.

1. Number of ions
2. Size and charge per ion
3. Line Voltage
4. d/r ratio
5. State of the conductor surface
6. Size and shape of the surface.

These factors can be classified into 3 groups

a. Atmospheric factors
b. Electric factors
c. Condition of line.

a. Atmospheric factors

1) Temperature

With the increase in temperature, the value of δ will be reduced & corona loss will be increased.

2) Pressure.

With the decrease in pressure, δ will be reduced & thus corona loss will be increased.

3) Dust & Dirt

Due to the presence of dust & dirt, corona loss is more.

4) Rain, Snow, fog, hail etc

Bad weather Conditions like rain, snow, fog etc will increase the corona loss.

5. Electrical factors

1) Frequency.

Corona loss is proportional to $(f+25)$. If the frequency is more, Corona loss is also more

2) Supply Voltage

If the supply Voltage is high, Corona loss will be high.

c. Effect of line Conditions

1. Conductor Spacing

Corona loss will be decreased with the increase in conductor Spacing.

2. Conductor height

If the conductors are placed at more height, corona loss will be less.

Surface Condition of the Conductor

If the Surface is polished & uniform, there will be less Corona loss. If the surface is rough, Corona loss will be high

4) Diameter of conductor

Increase in conductor diameter will ~~reduce~~ increase the Corona loss.

5) Number of Conductors / Phase

If the no. of conductors increases, Corona loss reduces.

6) Heating of Conductor

Due to heating of Conductors there is no fog or snow to the conductor. So corona loss will be reduced.

7) Profile of the Conductor

The corona loss in the cylindrical Conductor is always less than Conductor with any other shape.

Advantages of corona

x With the formation of corona, the air surrounding the conductor become conducting & hence virtual diameter of conductor increases. The increased diameter reduces the electrostatic stress between the conductors.

Disadvantages of Corona

1. Transmission efficiency is affected by corona loss
2. Corona causes radio interference with communication lines.
3. Ozone gas is produced by corona & it chemically react with the conductor & causes corrosion.

* RADIO INTERFERENCE

The radio interference (radio influence) is a noise that occurs in the communication line. If the power line is running along the same route as the communication line there will be an interference in the communication line due to electromagnetic & electrostatic effect. The electromagnetic effect produces current & causes distortion of communication line. Electrostatic effect induces voltage in the communication line.

The radio interference (RI) for both ac & dc EHV lines depends on the field strength & is given by,

$$RI = C E_{max}^{2n} \ dB$$

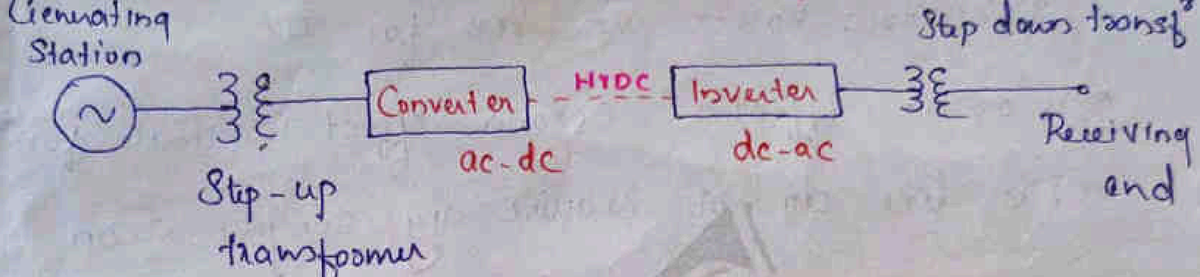
where C - Constant

E_{max} - Field Strength

n lies between 5 & 7 in fair weather and between 1.5 & 3.5 in bad weather

S5 EEE Neethu miss
Power generation
*14

HVDC TRANSMISSION



Comparison b/w ac & dc transmission

1 Economics of Transmission

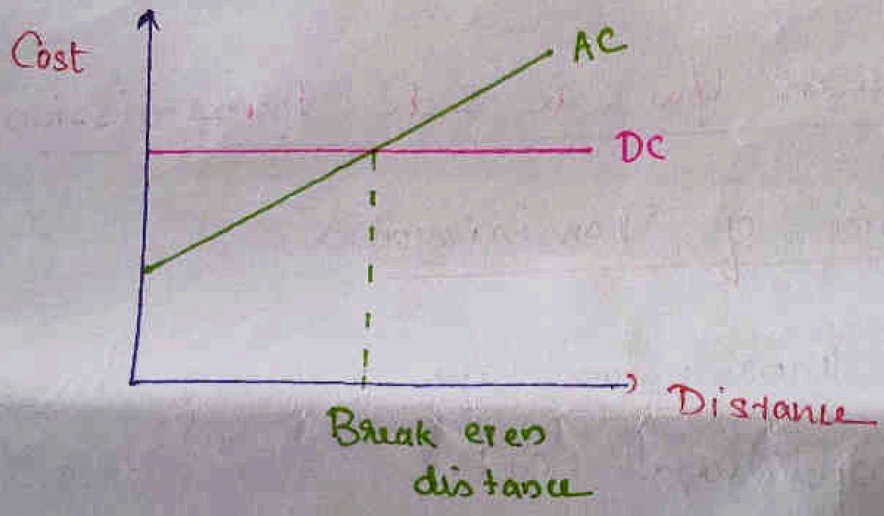
* Cost of transmission line includes investment cost & operational cost.

Investment cost includes cost of transmission tower, conductors, insulators & terminal equipment

Operational cost include the cost of towers.

With the same insulation level DC line carry same power with 2 conductors, but AC requires 3 conductors of same size. i.e, for a given power level, DC lines are simpler & cheaper & reduce conductor and insulator cost.

* The power losses are reduced in DC
* Skin effect is absent in DC
* Dielectric losses are less for DC
* Corona effect - corona effect is small for dc
* DC line do not require any compensation



From the graph, it is seen that AC will be more economical than DC for distance less than break even distance (500-800 km) for over head line & costlier for long distances.

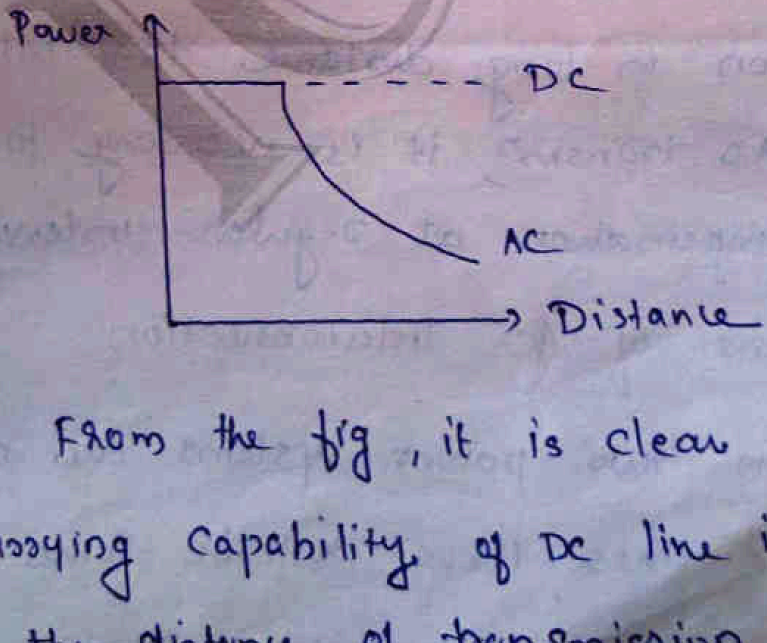
II Technical Performance

The DC transmission has some advantages

- Full control over power transmitted
- The ~~abil~~ ability to enhance transient & dynamic stability in associated AC network
- Fast control to limit the fault current in DC lines.

Also, the DC transmission overcome some of the ~~RbT~~ problems of AC transmission

a) Stability Limit



From the fig, it is clear that the pow carrying capability of DC line is unaffected by the distance of transmission, but in AC it depends on distance.

b) Voltage Control

The voltage control in AC line is difficu by the line charging and inductive voltage drops. The voltage varies with line loading. In order to maintain the constant voltage at the 2 ends reactive power control is required, which increases with increasing line length.

But in DC transmission, only Converter station require reactive power but the line do not require reactive power

c) Line Compensation

DC line require shunt & series Compensation in long distance transmission But in AC transmⁿ, it is necessary to provide Shunt compensation at regular intervals.

d) Problems of AC Interconnection

When two power systems are connected through AC lines, there will be some problem like presence of large power oscillations which leads to repeat, increasing fault level, transmission of disturbances from one s/m to other.

The controllability of Power flow in Dc lines eliminate all the above problem.

e) Ground Impedance

The existence of ground current affect efficient power transfer, telephone interference etc. The ground impedance is negligible for Dc current & Dc link can operate using one conductor with ground as return.

III Reliability

The DC transmission s/m is more reliable compared to that of ac transmⁿ s/m.

FLEXIBLE AC TRANSMISSION SYSTEMS

FACTS.

- Alternating current transmission systems incorporating power electronic based & other static controllers to enhance controllability and to increase power transfer capability.

NEED OF FACTS. ~~AND ITS BENEFITS~~

- Economic reasons
- To reduce the cost of electricity
- To improve the reliability of power supply
- Less transmission capability means that more generation resources are required.
- FACTS technology enhance the grid reliability
- To increase the power transfer capability of transmission systems.

  - ie, Power flow in a given line can be increased upto the thermal limit

- To keep the power flow through designated

  ie, Power flow can be restricted to select the transmission path by controlling the current in a line.
- To implement new control techniques

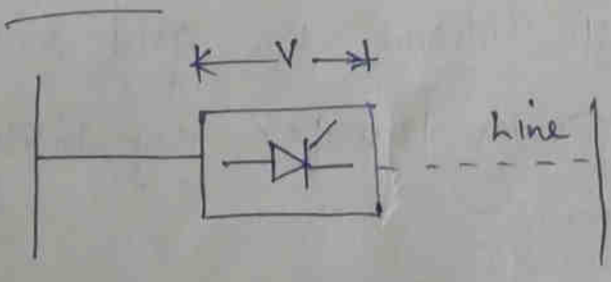
BENEFITS

* Optimum power flow.
* Increase the s/m security
* Provide greater flexibility
* Reduce reactive power flow.
* Reduce power s/m oscillations.

FACTS DEVICES

FACTS controllers can be divided into 4 types.

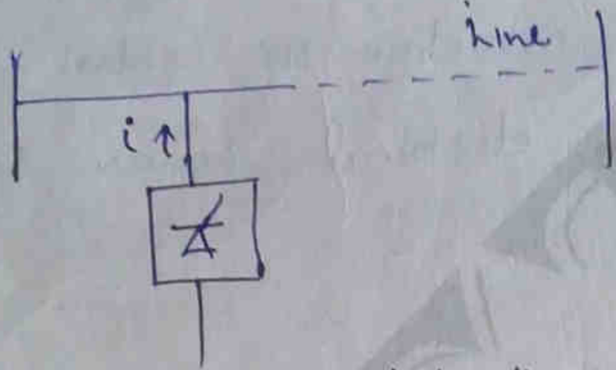
1. Series Controllers



- It should be of variable impedance such as capacitor, reactor etc or power electronic based variable source.

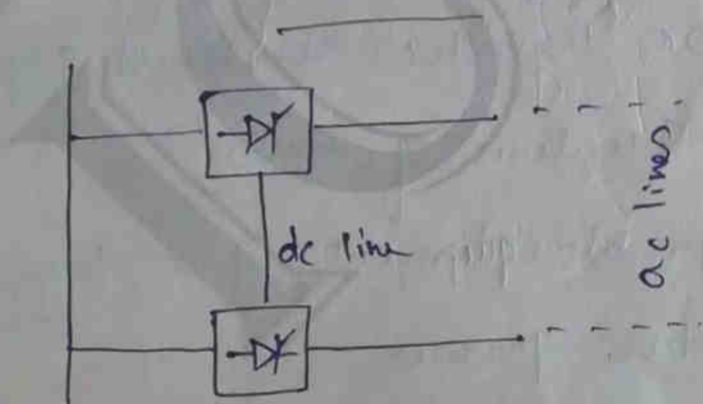
- All series controllers inject voltage in series with the line.

2) Shunt Controllers.

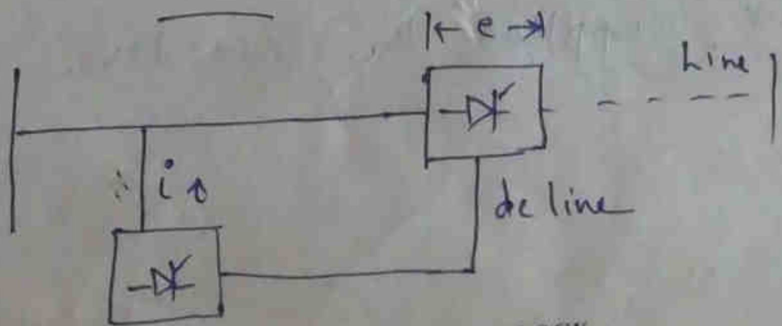


* It inject current into the s/m at the point of connection

3) Combined Series - Series Controllers

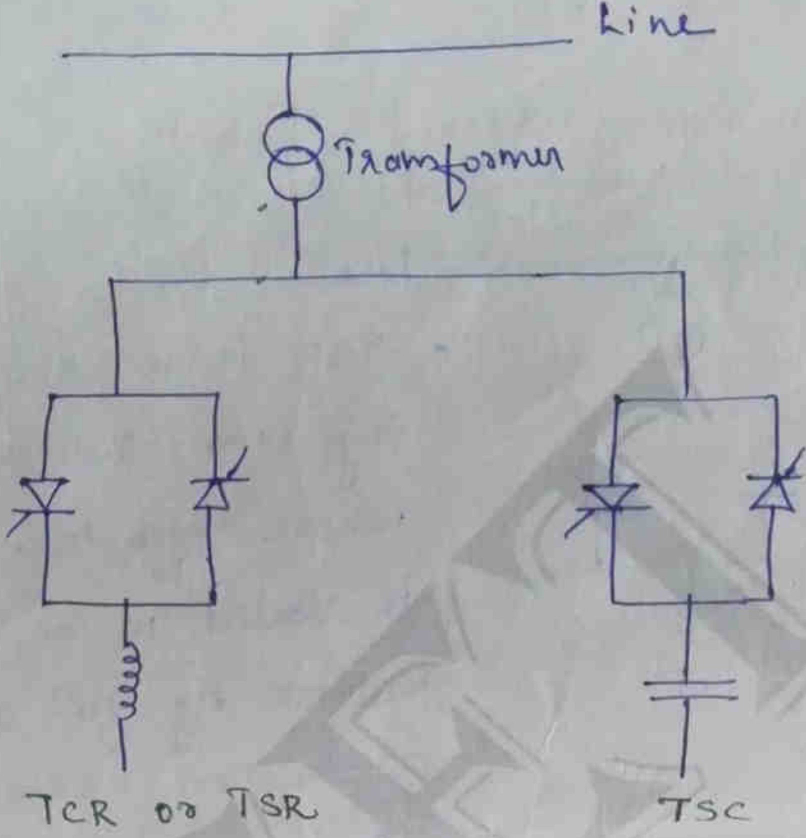


4) Combined Series - Shunt controllers

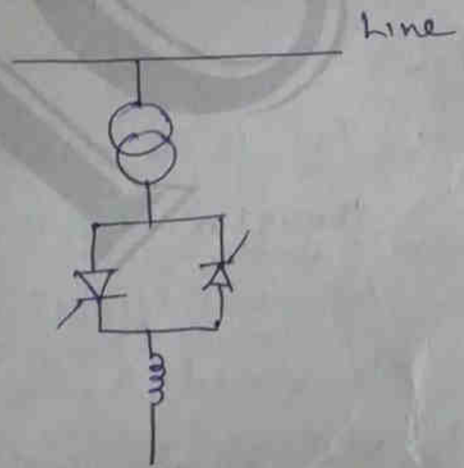


STATIC VAR COMPENSATOR (SVC)

- It is defined as the Shunt connected, Variable impedance type FACTS device whose o/p is adjusted to control capacitive or inductive current so as to maintain or control the specific parameters of the electrical power s/m, especially voltage
- SVC can generate or absorb reactive power
- Generally SVC consist of Thyristor controlled Reactor (TCR) or Thyristor switched reactor (TSR) and or Thyristor switched capacitor (TSC) or combination of two.
- It include separate equipment for lagging & leading ~~va~~reactive power
- i, reactor absorb the reactive power & Capacitor supplies the reactive power.



Thyristor Controlled Reactor (TCR)

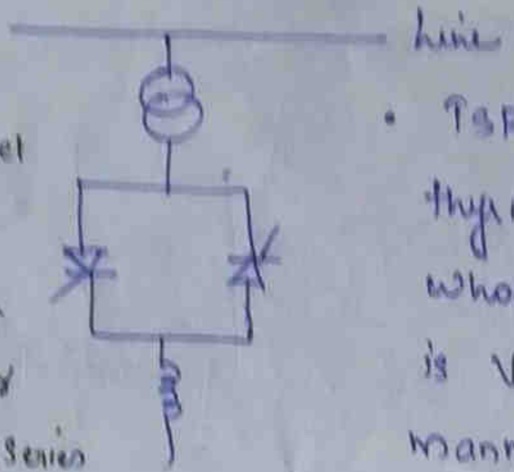


- It is a subset of SVC
- It consist of a linear reactor connected in Series with a thyristor Valve

- TCR is a shunt connected thyristor controlled inductor, whose effective reactance is Varied

in a continuous manner by partial condu[ction]
control of the thyristor valve.

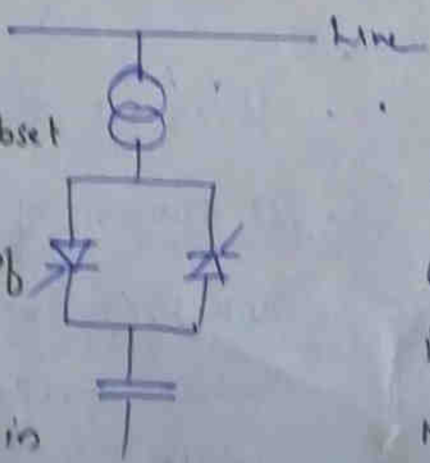
Thyristor Switched Reactor (TSR)



- It is a subset of SVC
- It consist of a linear reactor connected in series with a thyristor valve.

- TSR is a shunt connected thyristor switched inductor whose effective reactance is varied in a step wise manner by full or zero conduction operation of the thyristor valve.

Thyristor Switched Capacitor (TSC)

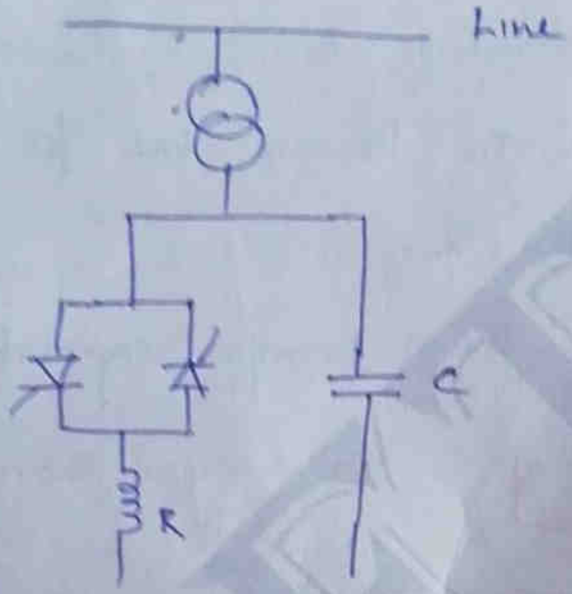


- It is a subset of SVC
- It consist of a linear capacitor connected in series with a thyristor valve.

- TSC is a shunt connected thyristor switched capacitor whose effective reactance is varied in a step wise manner by full or zero conduction operation of the thyristor valve.

Scanned with CamScanner

Configuration of FC + TCR



SERIES COMPENSATION

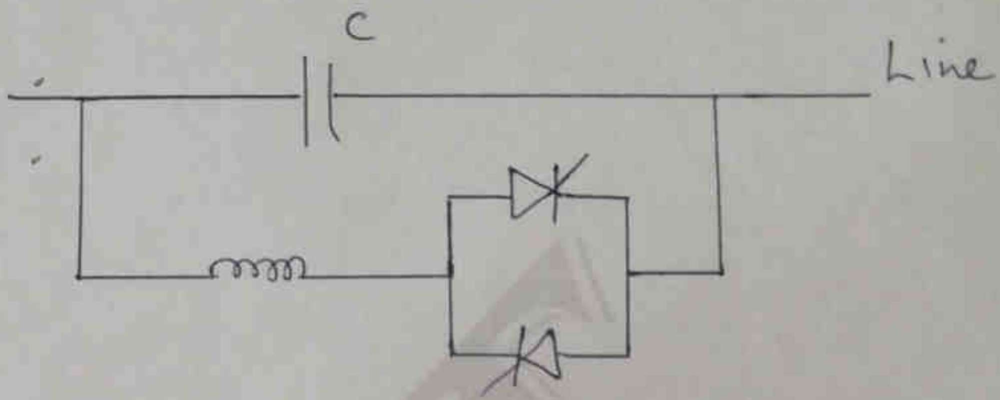
- To control the Power flow in transmsn line
- To improve the Stability
- By series compensation, the overall effective Series transmission impedance from SE to RE can be reduced
- The capacitive reactance cancels a portion of Series line reactance & therefore the transmission line impedance is reduced.

- Series Compensation is the method of improving the system voltage by connecting a capacitor in series with the transmⁿ line.
- In series compensation, reactive power is inserted in series with the transmⁿ line for improving the impedance of the s/m.
- It improves the power transfer capability of the line.

Advantages of Series Compensation

- To increase the power transfer capability
- To improve the s/m stability
- Load division among parallel line ckts
- Less installation time
- Control of voltage

Thyristor Controlled Series Capacitor (TCSC)



- It consist of a variable reactor such as a thyristor controlled reactor (TCR) is connected in parallel with a series capacitor.
- When the TCR firing angle is 180°, the reactor becomes non conducting.
- If the firing angle reduces from 180°, the capacitive impedance increases.
- When the TCR firing angle is 90°, the reactor become fully conducting & help in limiting the fault current.

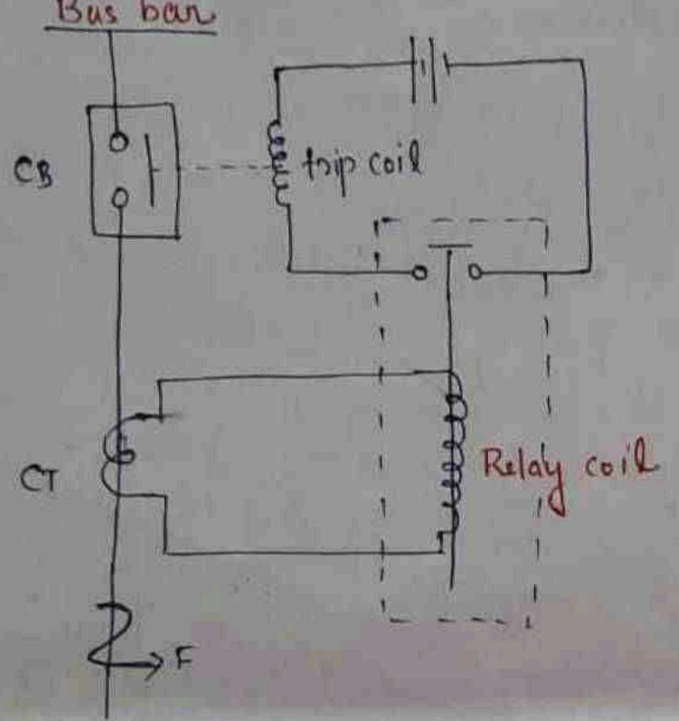
unprotected (blind) areas. If an area remains unprotected, it means that any fault occuring in that area will not be cleared at all & such an area is called blind spot.

Protective Relays.

A protective relay is a device that detect the fault & initiates the operation of CB to isolate the defective element from the rest of the system.

Operating Principle

The relays detect the abnormal conditions in the electrical ckt by constantly measuring the electrical quantities which are different under normal & fault conditions. The electrical quantities which may change under fault conditions are Voltage, current, frequency & phase angle. Thus change in one or more of these quantities, the fault can be detected. When the fault is detected, the relay operates to close the trip ckt of CB. This result in the opening of CB & disconnection of the faulty ckt.



Relay Circuit

The relay ckt connections can be divided into 2 parts.

i) First part is the 1° wdg of current transf^r (CT) which is connected in series with the line to be protected.

ii) Second part consist of 2° wdg of CT & relay operating coil.

iii) Third part is the tripping ckt which may be either ac or dc. It consist of Source of supply, the trip coil of CB & relay stationary contacts.

When a short ckt occurs at point F on the transmn line, the current flowing in the line increases to an enormous value. This results in a heavy current flow through the relay coil, causing the relay to operate by closing its contacts. This in turn closes the trip ckt of the breaker, making the CB open & isolating the faulty section from the rest of the system.

* Types of Protection.

(i) Main or Primary Protection.

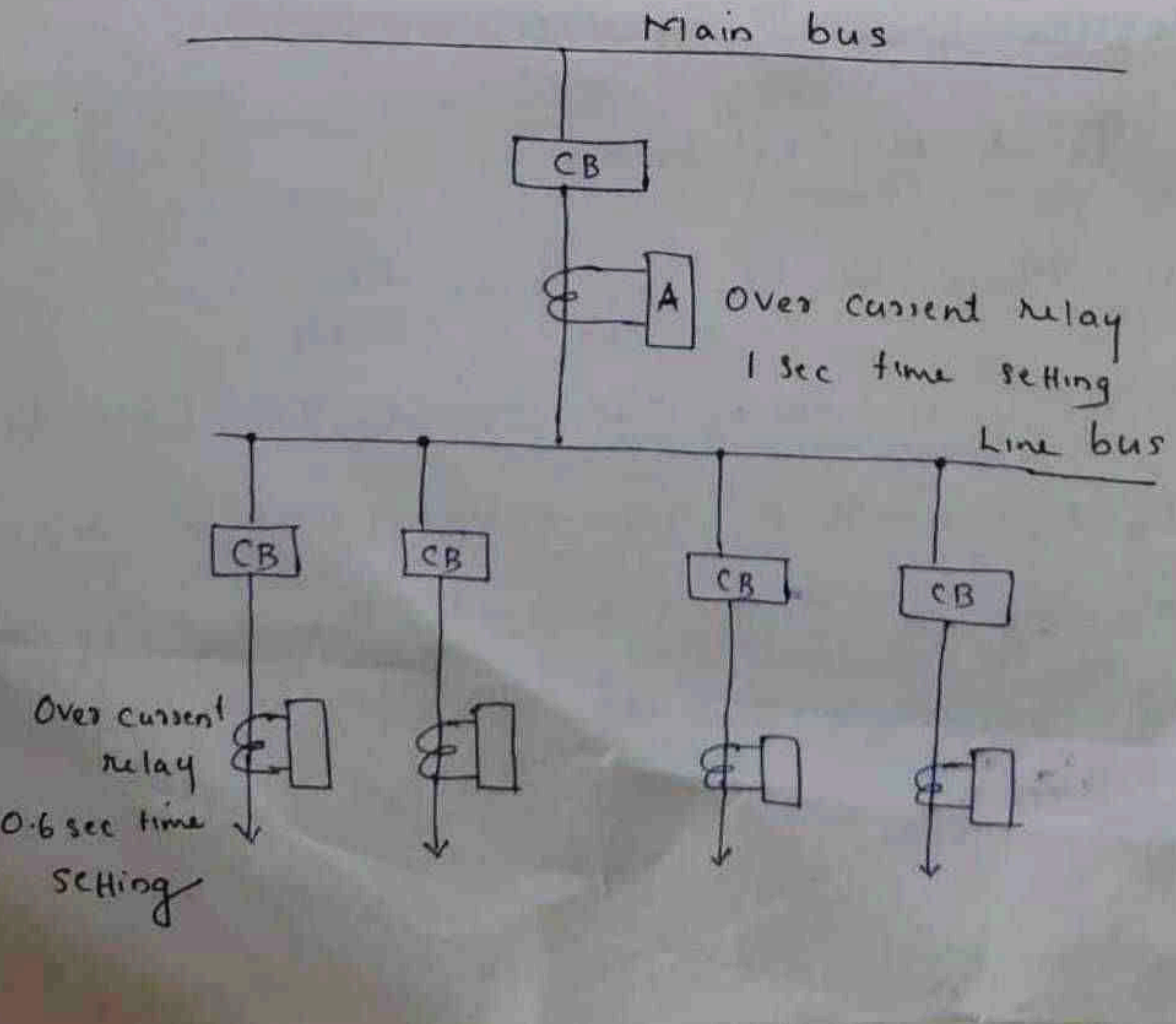
This type of protection is the first line of defence. It ensures quick acting & selective clearing of fault within the boundary of the ckt section it produces. It is provided for each section of an electrical installation.

(ii) Back up or Secondary Protection

→ It is the second line of defence which functio for to isolate a faulty section of the S/m when the main protectⁿ fails to function properly, because of trouble within the relay or CB.

→ Back up protectⁿ is only provided where the main protectⁿ of adjacent ckt is unable to back up the main protectⁿ of the given ckt

→ It operates after a time delay to give the 1° relay sufficient time to operate



In the fig, relay A provides back up protectn for each of the four lines. If a line fault is not cleared by its relay & CB, the relay A on the group breaker will operate after a definite time delay & clear the entire group of lines. When back up relaying functions, a larger part is disconnected than when primary relaying functions correctly.

* Basic Requirements.

- Selectivity.

It is the ability of the protective s/m to select correctly that part of s/m in trouble & disconnect the faulty part without disturbing the rest of the s/m.

- Speed

The relay s/m should disconnect the faulty section as fast as possible.

- Sensitivity

It is the ability of relay s/m to operate wi
low value of actuating quantity. (i.e., fault current)

- Reliability

It is the ability of relay s/m to operate under
Predetermined conditions.

- Simplicity

The relay s/m Should be Simple So that it can
be easily maintained.

- Economy.

As a rule, the Protective gear Should not cost
more than 5 % of total cost.

Important Terms

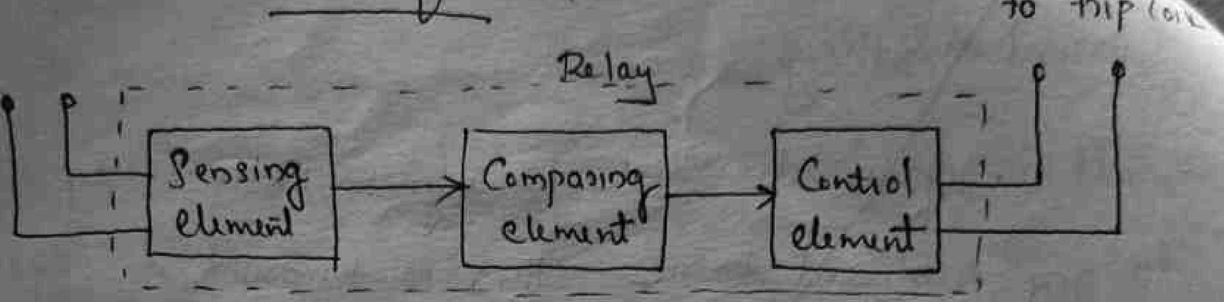
Pick up

A relay is said to pick-up when it moves
from the 'off' position to 'on' position.

Operating / Pick-up current

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

Elements of Relay



Sensing element

It responds to the change in actuating quantity eg: current in the case of over current relay.

Comparing Element

Compare actuating quantity with pre selected relay setting.

Control Element

Accomplishes a sudden change in the control quantity such as closing of operative current circuit.

Classification of Relays

The protective relays are mainly classified into 2 types.

i) Electromagnetic Relays, Thermal Relay
ii) Static Relays. μP Based relay

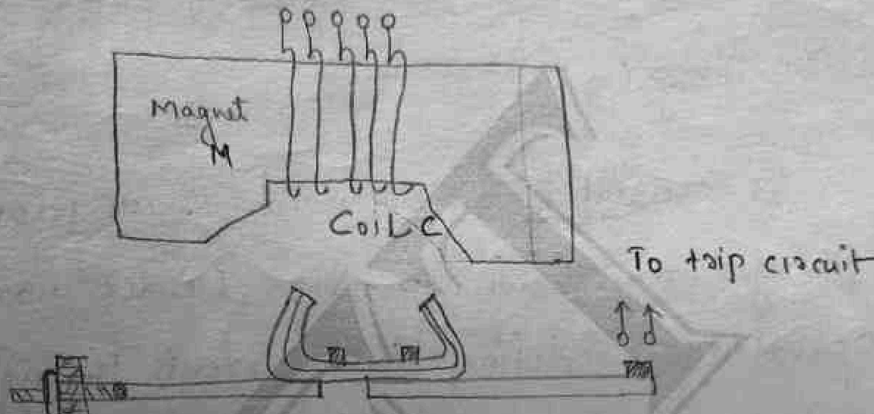
Electro magnetic Relays

- Electromagnetic Attraction Relay
  - Attracted Armature type Relay
    - Operation depends on the movement of an armature under the influence of attractive force due to mag. field set up by the current flowing through the relay wdg
  - Solenoid type Relay
    - operation depends on the movement of an iron plunger core along the axis of Solenoid
  - Balanced Beam type Relay
- Electromagnetic Induction type Relay
  - Shaded Pole Structure
  - Watthour meter Structure
  - Induction Cup Structure

$\underbrace{\text{Shaded Pole Structure} \quad \text{Watthour meter Structure}}_{\text{Induct}^n\ \text{Disc Relay}}$

Electromagnetic Attraction Relay

i) Attracted Armature Type Relay

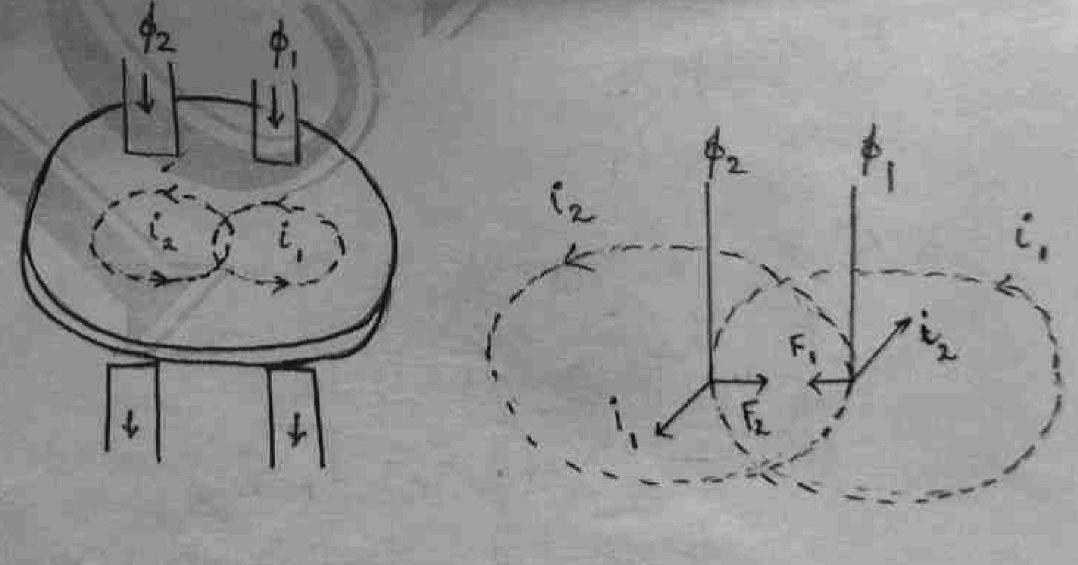


It consist of a laminated electromagnet M carrying a coil C & a pivoted laminated armature. The armature is balanced by a counter weight & carries a pair of spring contact fingers at its free end. Under normal operating condition, the current through the relay coil C is such that counter wt holds the armature in the position shown. When short ckt occurs, the current through the relay coil increases sufficiently & the relay armature is attracted upwards. This complete the trip ckt which result in opening of CB. & the disconnection of the faulty circuit.

Electro Magnetic Induction Relay

Electromagnetic induction relay operate on the principle of induction motor. They are used with ac quantities only.

It consist of a pivoted Aluminium disc placed in two alternating mag. field of same frequency, but displaced in time & space. The torque is produced in the disc by the interaction of one of the mag. fields with the current induced in the disc by the other.



The two ac fluxes ϕ_2 & ϕ_1 differing in phase by an angle α induce emf in the disc & cause the circulation of eddy current i_2 & i_1 respectively.

These current lags behind the flux by $90°$

If ϕ_1 & ϕ_2 are the instantaneous values of fluxes and ϕ_2 leads ϕ_1 by an angle α.

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

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

$$i_1 \propto \frac{d\phi_1}{d\omega t} \propto \frac{d}{d\omega t}\left[\phi_{1max} \sin \omega t\right]$$

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

db

$$i_2 \propto \frac{d\phi_2}{d\omega t} \propto \frac{d}{d\omega t}\left[\phi_{2\,max} \sin(\omega t + \alpha)\right]$$

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

$$F_1 \propto \phi_1 i_2$$

$$F_2 \propto \phi_2 i_1$$

F_1 & F_2 are opposite to each other.

Net force, $F \propto (F_2 - F_1)$

$$\propto (\phi_2 i_1 - \phi_1 i_2)$$

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

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

$$\propto \phi_{1_{max}} \phi_{2_{max}} \sin \alpha$$

$$\propto \phi_1 \phi_2 \sin \alpha \quad \text{——— (1)}$$

ϕ_1, ϕ_2 are rms value of fluxes.

From (1),

a) The greater the value of α, greater is the net force applied to the disc.

b) The net force is same at every instant

c) The directⁿ of net force & hence the directⁿ of disc depends upon which flux is leading

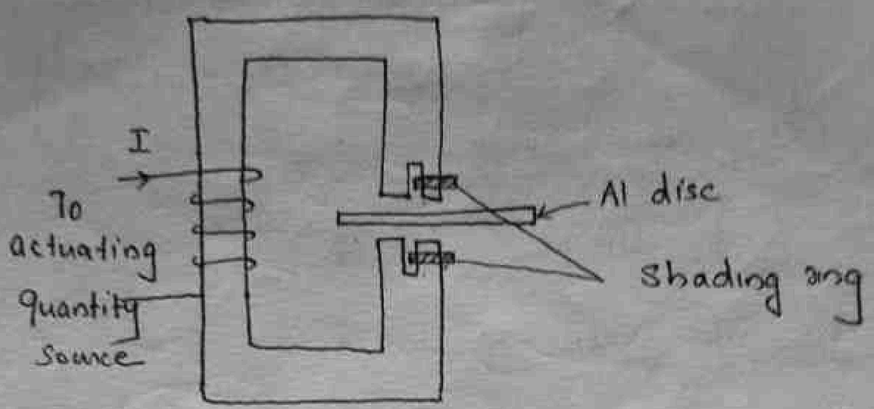
Appln.

Induction type relays are employed for protectⁿ against overload, short ckt & earth fault on transmⁿ or distribⁿ lines & in Industrial plants.

3 types of Induction Relays are

a) Shaded Pole Structure } Induction Disc Relay
b) Watt hour meter "
c) Inductⁿ Cup "

Shaded Pole structure



- It consist of a pivoted Al disc free to rotate in the air gap of an electromagnet.
- One half of each pole of magnet is surrounded by a copper band known as shading ring
- The alternating flux ϕ_s in the shaded portion of the pole lags behind the flux ϕ_u in the unshaded portion by an angle α
- These 2 ac fluxes differing in phase will produce the necessary torque to rotate the disc.

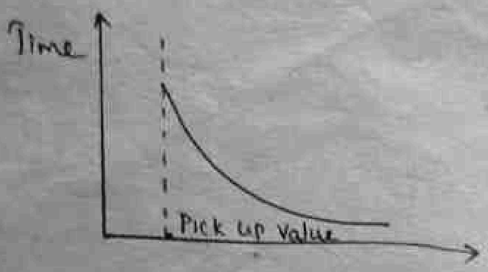
$$\text{ie,} \quad T \propto \phi_s \phi_u \sin\alpha$$

Assume that ϕ_s & ϕ_u proportional to the current I in the relay coil.

$$\text{ie,} \quad T \propto I^2 \sin\alpha$$

ie, Driving torque is $\propto$ to square of current in relay coil.

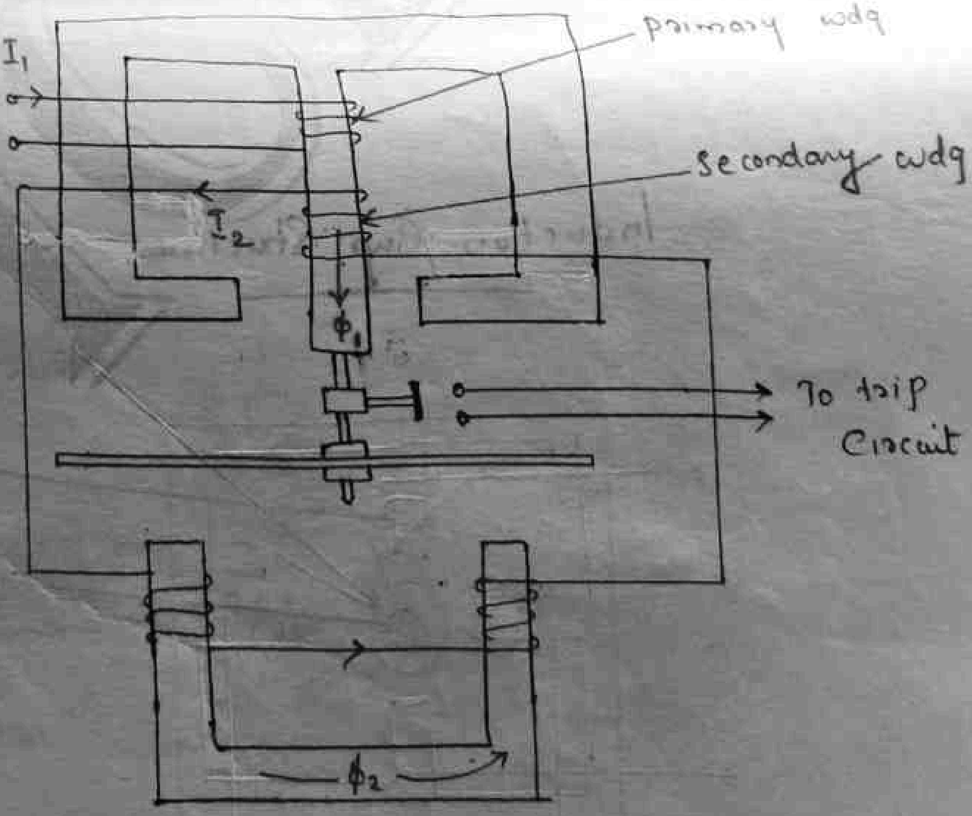
Characteristics



Here the operating time is inversely ∝ to the magnitude of actuating qty. At values of current less than pick up, the relay never operates. At high current values, the oper^n time of relay ↓ steadily with ↑ of current.

The time current characteristics of induction relays are inverse characteristics. ie, the time reduces as the current increases

Watt hour Meter Structure



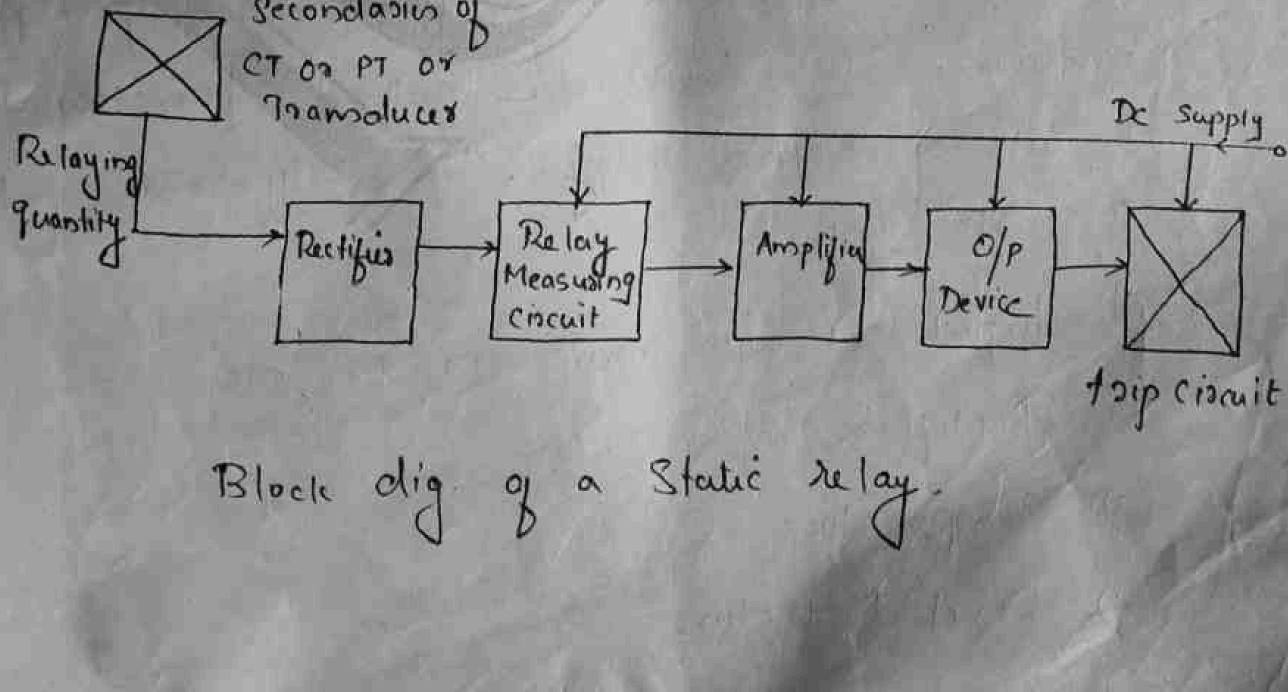
- It consist of a pivoted Al disc arranged to rotate freely b/w the poles of 2 electromagnet
- The upper electromagnet carries 2 wdg; 1° & 2°
- The 1° wdg carries the relay current I_1, while the 2° wdg is connected to the wdg of the lower magnet.
- The 1° current induces emf in the 2° & so circulates a current I_2 in it.
- The flux ϕ_2 induced in the lower magnet by the current I_2 in the 2° wdg of upper magnet will lag behind ϕ_1 by an angle α.
- The 2 fluxes ϕ_1 & ϕ_2 differing in phase by an angle α will produce a driving torque on the disc proportional to $\phi_1 \phi_2 \sin \alpha$

Mod-3

STATIC RELAYS

A Static relay refers to a relay in which there is no armature or other moving element & response is developed by electronic, magnetic or other components without mechanical motion. The solid state components used are transistors, diodes, resistors, capacitors etc. The function of comparison & measurement are done by static circuits.

STATIC RELAY COMPONENTS



Block dig of a Static relay.

The essential components of a static relay is shown below. The relaying quantity ie, o/p of CT or PT or transducer is rectified by a rectifier. The rectified o/p is supplied to a measuring unit comprising of comparators, level detectors, filters, logic circuits. The o/p is actuated when the relaying quantity attains the threshold value. Thus o/p of the measuring unit is amplified by amplifier & fed to the o/p unit device, which is an electromagnetic one. The o/p unit energizes the trip coil only when the relay operates.

A static relay assembly is built up of various blocks. Each serving certain specific functions. Such blocks are called functional circuits of static relay. The different functional circuits are,

1) Input ckt with main CT, PT etc
2) Rectifiers
3) Comparators
4) Level Detectors

5) Amplifiers

6) Timer Circuits

7) Setting Devices

8) Differentiating Ckts

9) Integrating Ckts

10) O/P Circuits

Advantages of Static Relay

1) Lower power Consumption

2) quick response, long life, high reliability, high degree of accuracy, shock proof

3) They are very compact

4) They can be designed for repeated operations because of the absence of moving parts in the measuring ckts

5) The risk of unwanted tripping is less with Static relays

6) There is no effect of gravity on operation of Static relays & ∴ they can be installed in Vessels, air crafts etc.

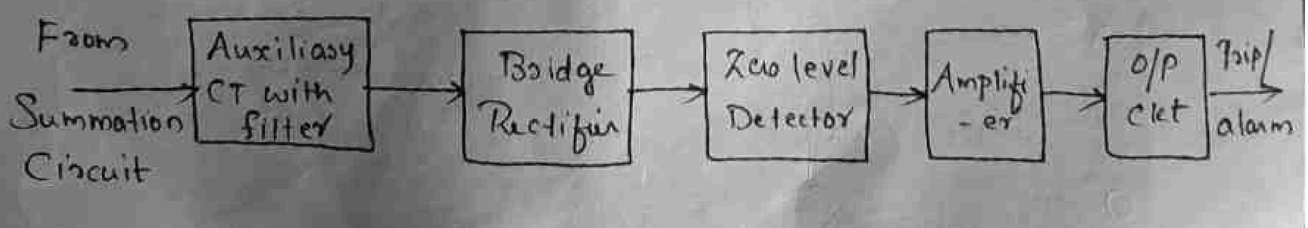
Limitations

1) Auxiliary dc supply is required.
2) Semiconductor components are sensitive to electrostatic discharges.
3) They are sensitive to voltage transients
4) They are costlier.
5) Highly trained persons are required for their servicing & maintenance.

STATIC OVERCURRENT RELAY / STATIC EARTHFAULT RELAY

{operates when the current ↑ above a specified value}

The block diagram of an instantaneous overcurrent relay is shown. The same construction may be used for under voltage, over voltage or earth fault relays too.



The 2°s of line CTs are connected to a Summation ckt (not shown). The o/p of this Summation ckt is fed to an auxiliary CT, whose o/p is rectified, smoothened & supplied to a measuring unit (level detector). The measuring unit determines whether the qty has attained the threshold value (set value) or not. When the i/p to measuring unit is less than the threshold value, the o/p of the level detector is zero.

For an Over Current relay,

For $I_{input} < I_{Threshold}$; $I_{output} = 0$

For $I_{input} \geq I_{Threshold}$; I_{output} = Present

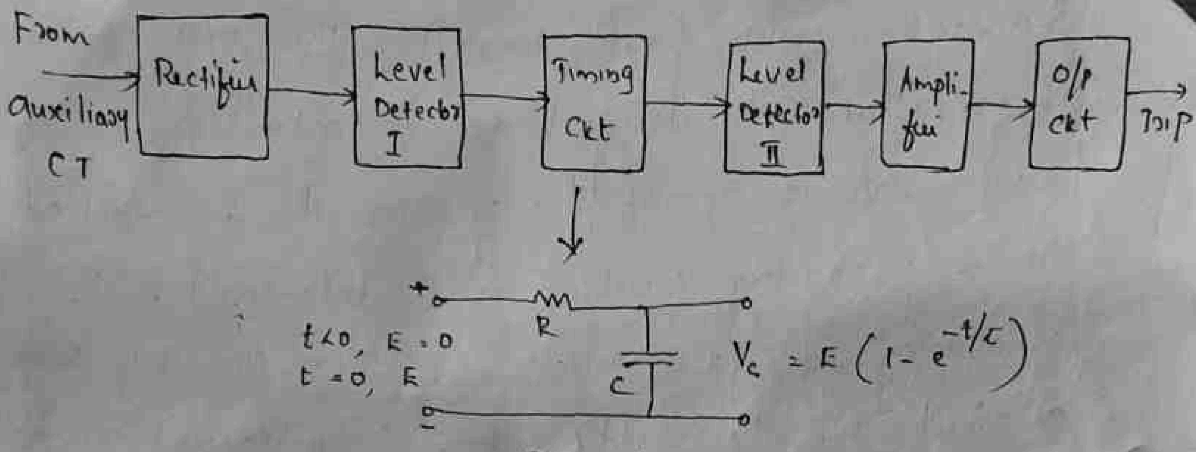
In an actual relay, $I_{threshold}$ can be adjusted.

The o/p of measuring unit is amplified & is given to o/p ckt to cause trip or alarm.

If time delay is desired, a timing ckt is introduced before the level detector.

Smoothing ckt & filters are introduced in the o/p of the bridge rectifier.

Block dig. of static Over Current Time Relay



R-C timing ckt

Directional Static Over Current Relay

(when phase angle b/w V & I exceeds a predetermined value)

Directional relay senses direct^n of power flow by means of phase angle b/w V & I. When the phase angle b/w V & I exceeds the predetermined value, the directional relay operate with a condition that the current is above the pick up value. Thus the directional relay is a double actuating qty relay, one i/p as I, current from CT & other V, vge from PT.

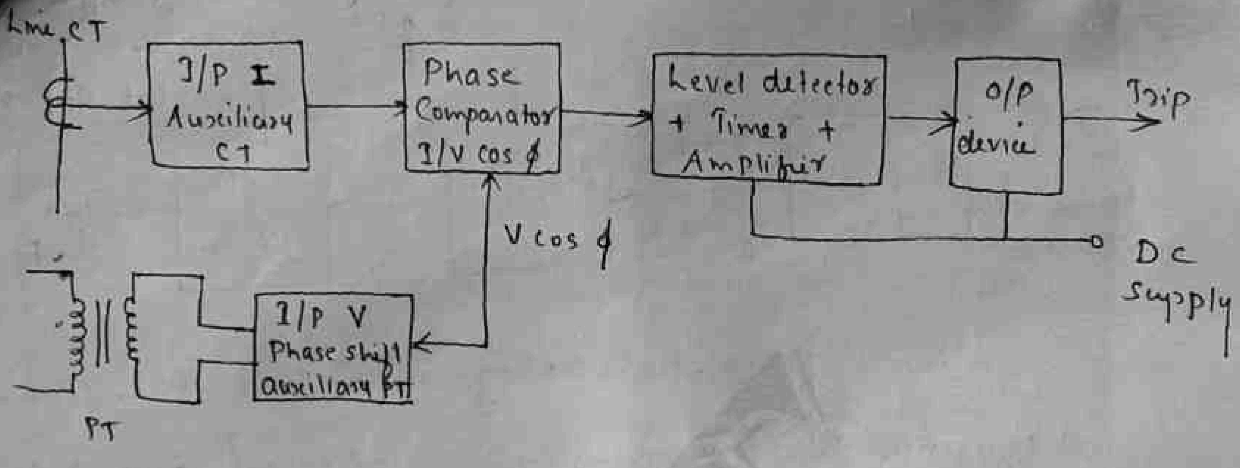


Fig represents a static directional relay with 2 i/p (V & I). The i/p are supplied to the Phase comparators. A phase shifter is included in the Vge i/p ckt. The o/p of the phase comparator is fed to the level detector. The o/p of the level detector is amplifed & in case a timer is necessary, the o/p is applied to the o/p device through timer.

Relay will operate, when $\underline{I_s \angle I \cos(\phi - \theta)}$

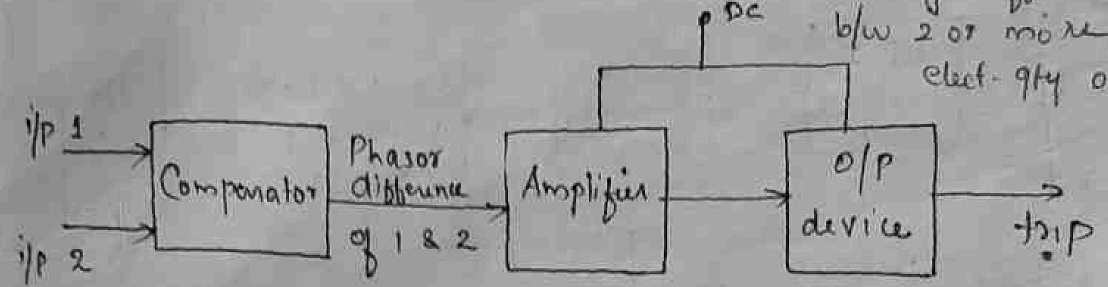
where $I_s \rightarrow$ magnitude of set current

$\phi \rightarrow$ Phase angle b/w V & I

$\theta \rightarrow$ Relay characteristic angle

For maximum sensitivity of relay, $\phi = \theta$

Static Differential Relay (when Phase or mag. difference b/w 2 or more elect. qty occurs)



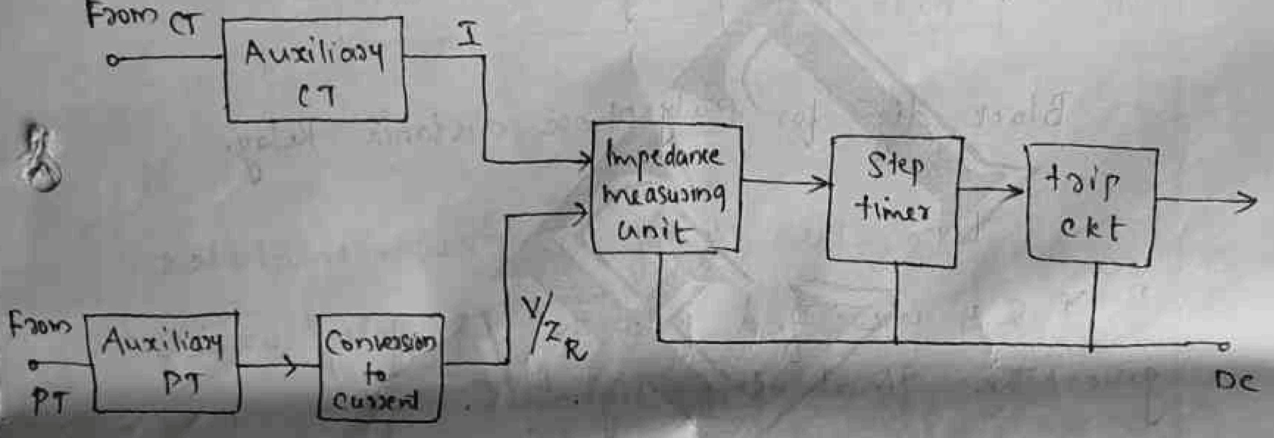
The differential relay measures the phasor difference b/w 2 similar electrical quantities. Inputs 1 & 2 are supplied to the comparator. Comparator o/p (i.e., phase diff of i/p 1 & 2) is amplified & used to operate the relay. The static differential relays are most commonly used for the protectⁿ of generators & transformers for any type of internal fault.

Static Distance Relay (operⁿ depends on the ratio of V to I ≈ Z)

When V/I ratio falls below ~~the~~ set value

In a static distance relay, it is necessary that the 2 inputs are similar. The comparators used in these relays are of either voltage comparator or current comparator. In a voltage comparator, line current is converted into eqvt voltage by passing it through an impedance $Z_R \angle \theta$. The vge drop IZ_R is then compared with the line vge V.

Similarly in case of current comparator, a current is derived from CT & the vge from PT is converted to eqvt current V/Z_R by connecting Z_R in series with PT 2°. This current is compared with I



Static Polyphase Relay

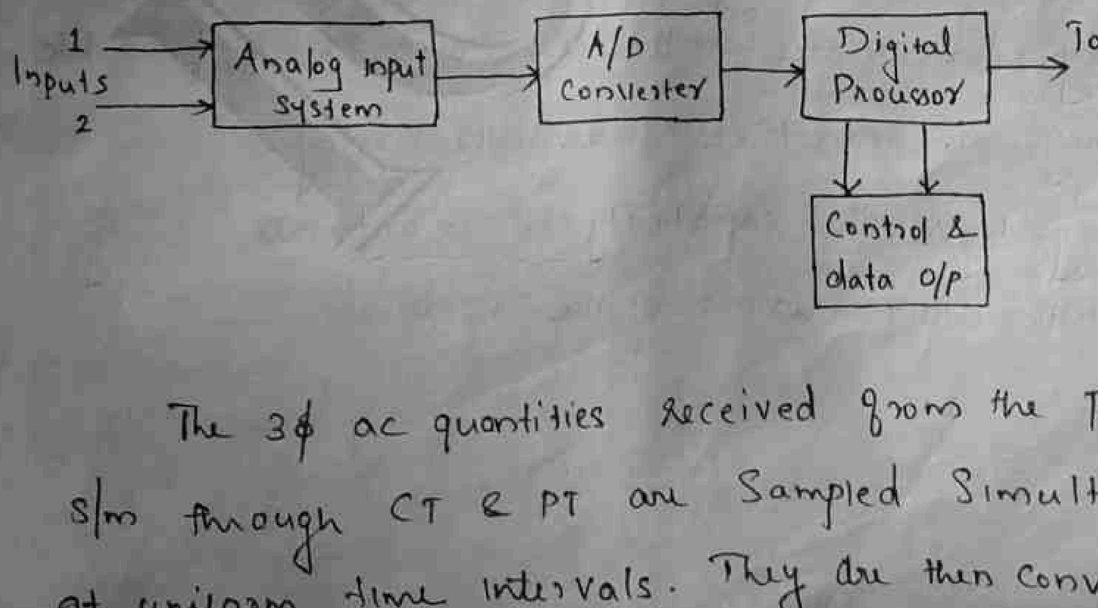
A poly phase (3 ϕ) relay consist of 3 modules, one each for the R, Y & B phases. Phase modules R, Y & B are basically single phase comparators. Input signals are fed to the comparators through suitable measuring ckt. ∴ the polyphase relay responds to all types of faults.

Microprocessor Based Digital Relay.

Microprocessor based relays have attractive Compactness & flexibility. They reduce the number of types of relay units.

An interface employing op-amps, analog multiplexer, Analog - to digital (A/D) converter, Voltage Comparators & passive elements have been developed to provide the characteristics of various types of relays.

The block dig of this type relay is given below.



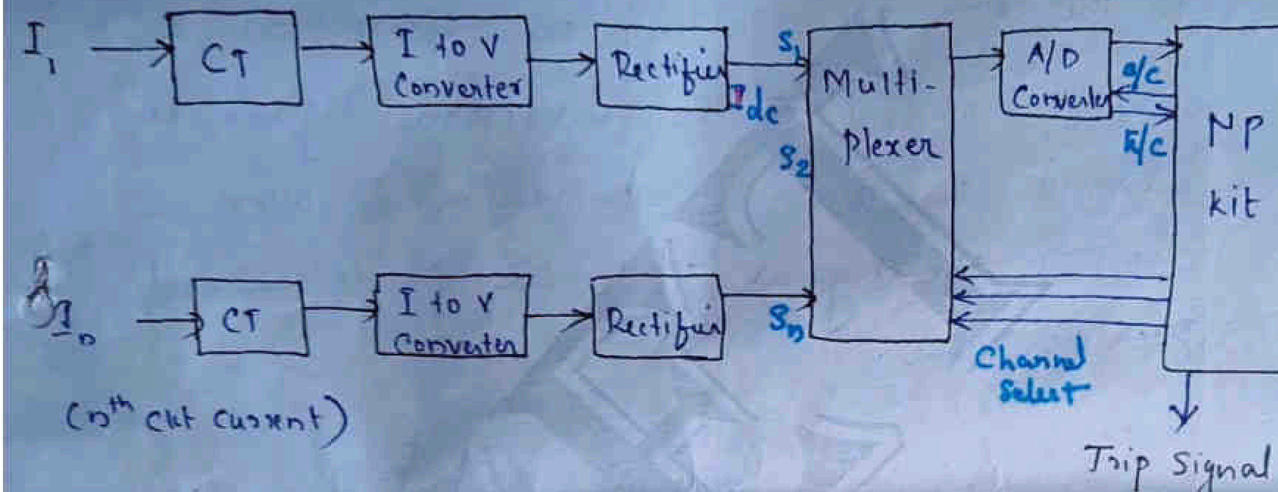
The 3ϕ ac quantities received from the power s/m through CT & PT are Sampled Simultaneously at uniform time intervals. They are then converted into digital form through an A/D converter and transferred to digital processor. Digital signals are in the form of coded square pulses which represent discrete data. These signals are in binary form. The μp or digital processor being set with the recommended values compares the dynamic i/p & decides accordingly to generate trip signal to the o/p device.

Adv.

* They have a very small burden on CTs & PTs
* They can process & display the signals very efficiently, accurately & in a fastest manner
* They are programmable & ∴ can be applied in the protectn of electrical Power s/ms.
* They are more reliable, compact & flexible
* They are sensitive than other relay
* They have the capability to coordinate easily with other devices of the network.

Microprocessor Based OverCurrent Relay / Earth Fault Relay

They operate when the ckt current exceeds the Predetermined Value.

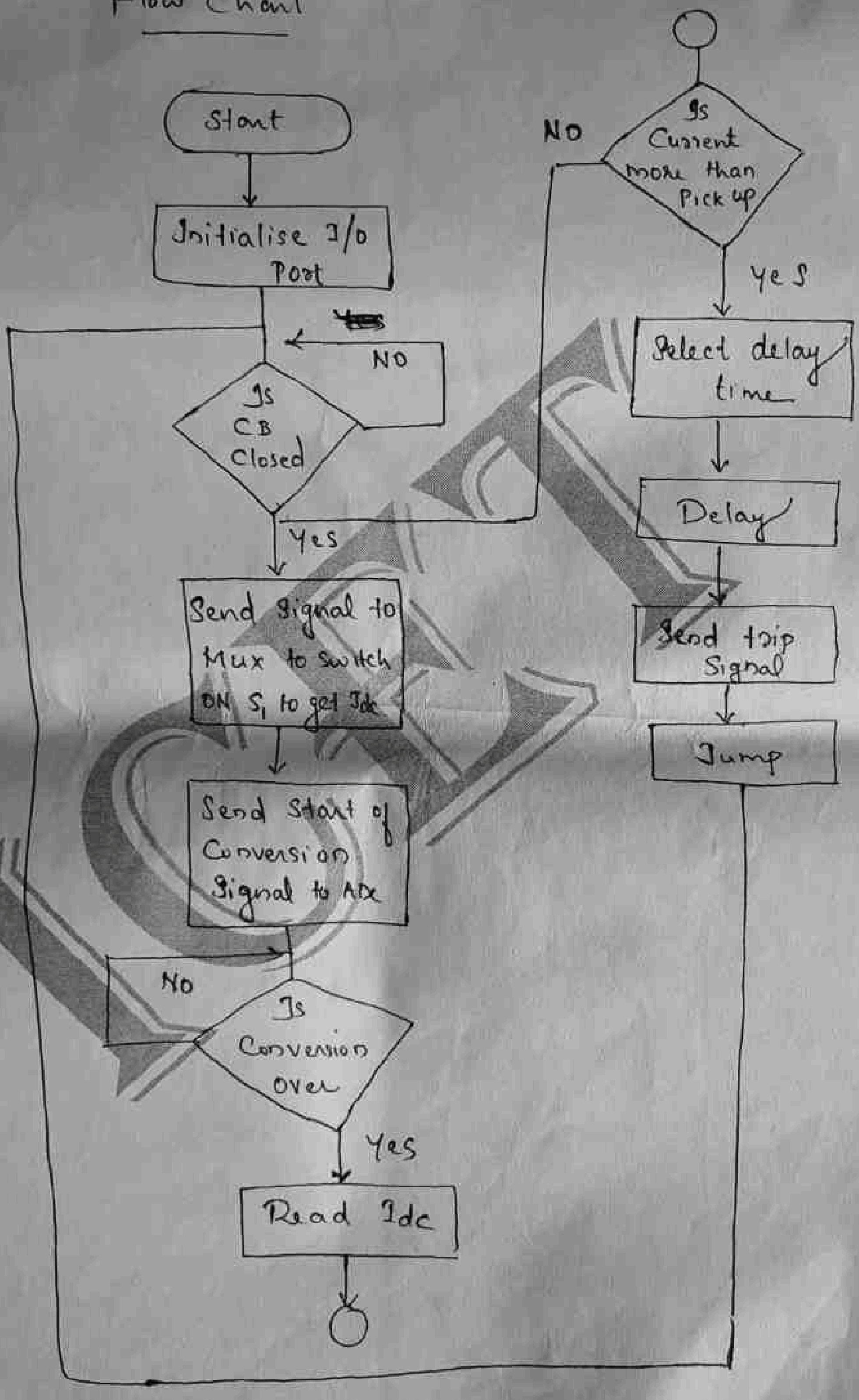


The Microprocessor uses a multiplexer for sensing the fault currents. The μp accepts the signals in the voltage form, for that the CT fault current derived is first converted into proportionate voltage signals & then fed to the rectifier, multiplexer, A/D converter & the micro processor.

The o/p of the rectified vge signals is fed into the multiplexer. The μp then send command for switching ON the desired channel of the multiplexer in order to obtain the rectified vge in the particular ckt.

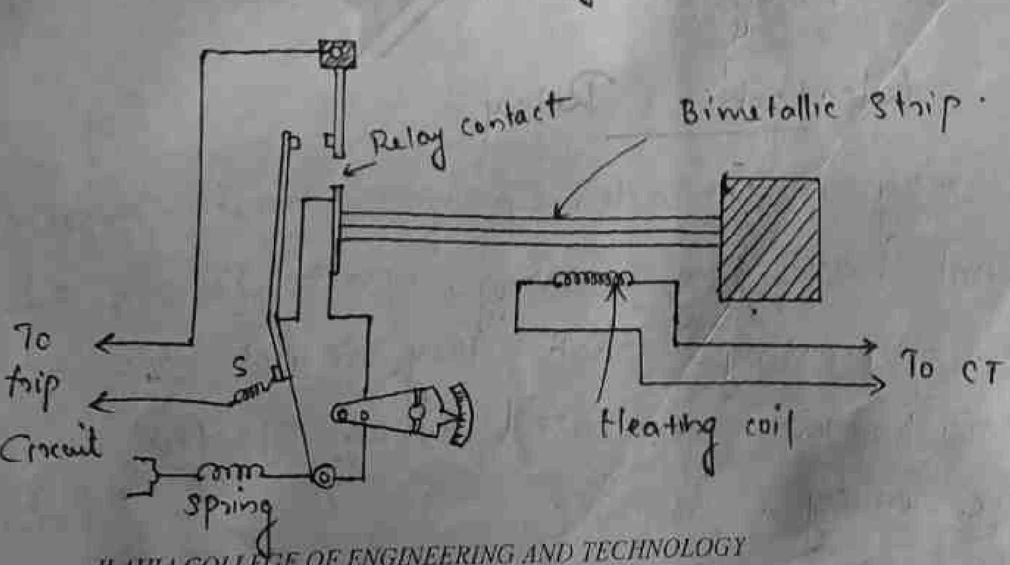
After this, since the μp needs digital signals, the o/p of the multiplexer is fed into the ADC. (A/D converter). Again μp send signals to the ADC for starting the conversion & reads the end of the conversion signal to examine whether the conversion is over & compare the signal with the predetermined pick up value.

Flow Chart


Start
Initialise I/O Port
NO
Is CB Closed
Yes
Send Signal to Mux to switch ON S1 to get Idc
Send Start of Conversion Signal to ADC
No
Is Conversion over
Yes
Read Idc
NO
Is Current more than Pick up
Yes
Select delay time
Delay
Send trip Signal
Jump

THEMAL RELAYS

Thermal relay operate on the principle of thermal effect of electric current. When an abnormally high current flows through the ckt, the current raises the temperature due to i^2R heating. The main working element is a bimetallic strip through which the fault current is made to pass. A bimetalic strip has 2 different metals of different thermal expansion coefficients. As the combined strip is heated up by the passage of current, it gets deflected through a system of levers, which closes the relay contacts. The bimetallic strip is heated by heating coil or strips supplied through a CT.

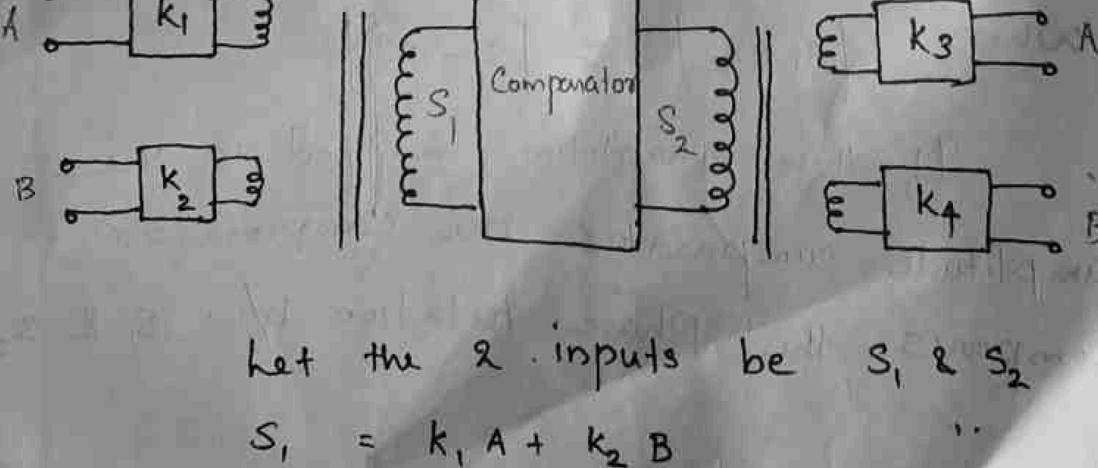


Under normal operating condition, the strip remains straight, but under the action of fault current, the strip is heated & bent. Thus the relay contacts are closed which energises the trip circuit.

Thermal relays are used for the protection of transformers, motors etc.

Duality & Comparison of Amplitude & Phase Comparator.

The relay senses the fault in a s/m through comparison. The relay do this by comparing 2 quantities either in amplitude or in phase. The amplitude & phase are a function of the s/m conditions. The device which makes these comparison are known as comparator. The comparator decides the operating characteristics of a relay.



Let the 2 inputs be S_1 & S_2

$$S_1 = k_1 A + k_2 B$$

$$S_2 = k_3 A + k_4 B$$

~~One input~~ It should be set a threshold value to the comparator.

Duality b/w Amplitude & Phase Comparator

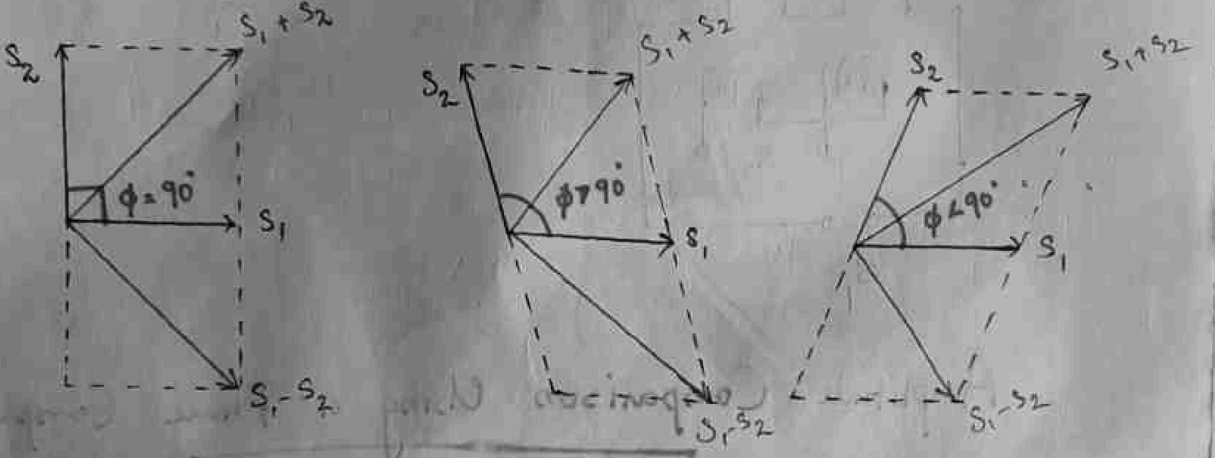
An amplitude comparator becomes a phase comparator & vice versa if the i/p quantities to the comparator are changed to the sum & difference of the original 2 i/p quantities.

For eg. Consider an amplitude comparator with i/p S_1 & S_2 such that it operates when $|S_1| > |S_2|$

Now if the i/ps are changed to $|S_1 + S_2|$ & $|S_1 - S_2|$, so that it operates when $|S_1 + S_2| > |S_1 - S_2|$.

If these quantities are fed to the amplitude comparator the comparator compares the phase relation b/w S_1 & S_2.

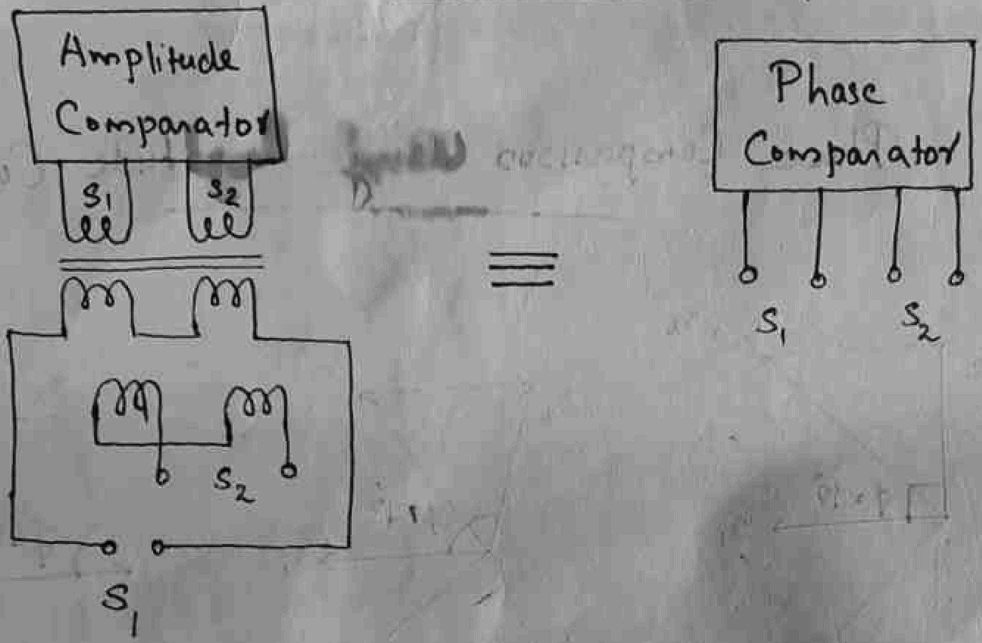
Phase Comparison Using Amplitude Comparator



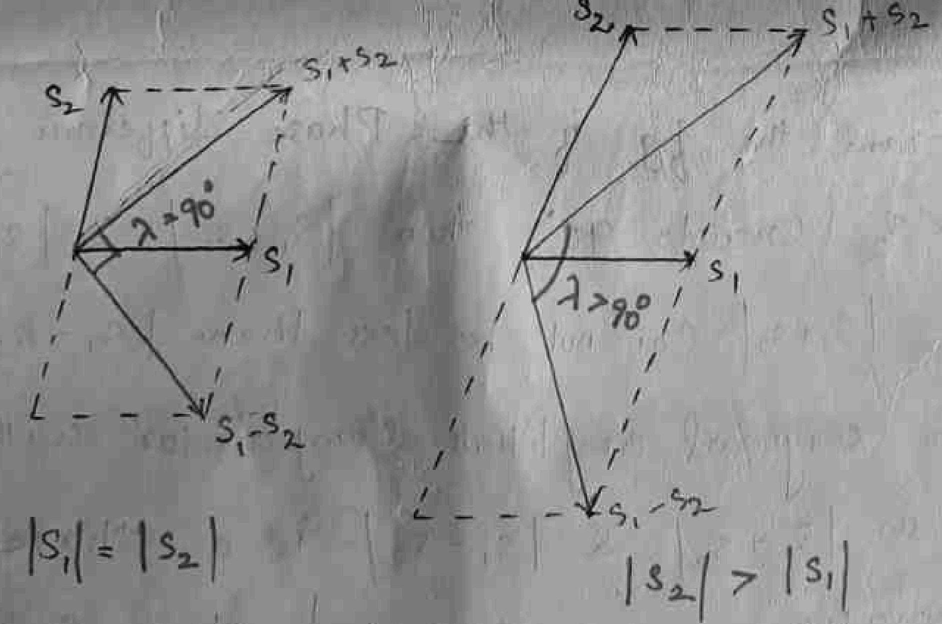
$|S_1+S_2| = |S_1-S_2|$ $\quad$ $|S_1+S_2| < |S_1-S_2|$ $\quad$ $|S_1+S_2| > |S_1-S_2|$

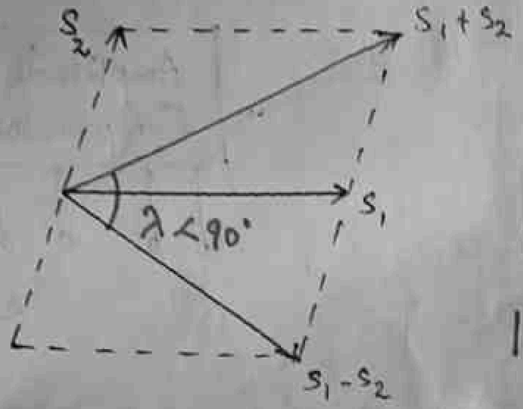
From the fig, if the Phase difference b/w S_1 & S_2 exceeds 90°, then $|S_1+S_2| < |S_1-S_2|$
But $|S_1+S_2|$ can not be less than $|S_1-S_2|$.
$\therefore$ The original amplitude comparator with i/p now as $|S_1+S_2|$ & $|S_1-S_2|$ is a phase comparator. ie, a converted phase comparator.

Equivalence of Phase Comparator



Amplitude Comparison Using a Phase Comparator





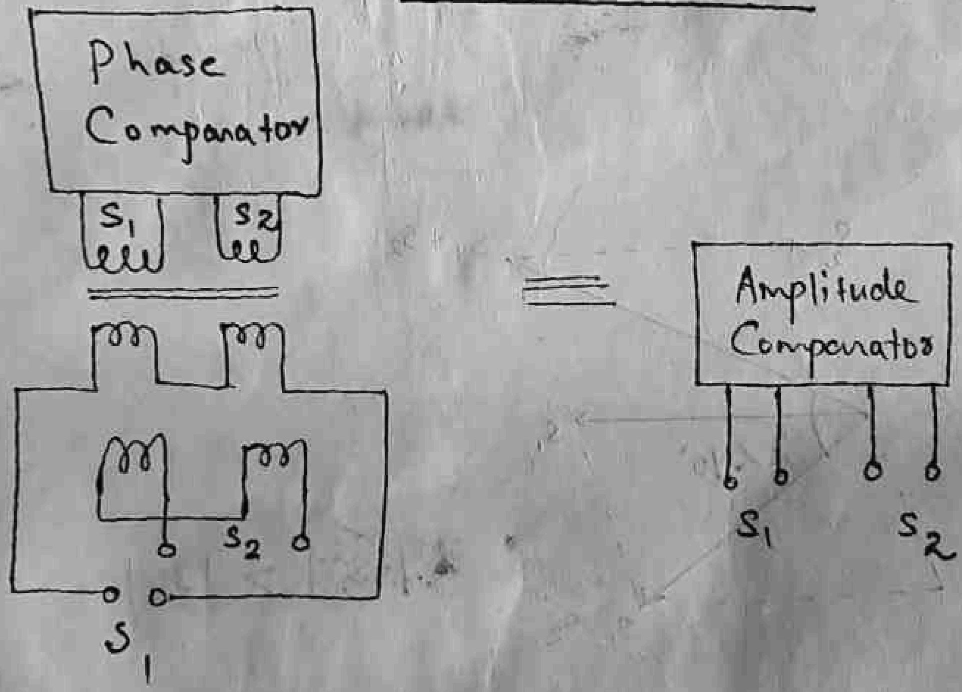
$|S_1| > |S_2|$.

If the original i/ps S_1 & S_2 to the phase Comparator, then ~~it~~ will operate

The original i/ps to the phase Comparator are S_1 & S_2. Now, if the i/ps are changed to $|S_1+S_2|$ & $|S_1-S_2|$, then the comparator Compares amplitude relation b/w S_1 & S_2.

Unless $|S_1| > |S_2|$, the phase relation b/w $|S_1+S_2|$ & $|S_1-S_2|$ will not be less than 90° & hence the phase comparator with i/ps $|S_1+S_2|$ & $|S_1-S_2|$ will be an amplitude Comparator. ie, a Converted amplitude comparator.

Equivalence of Amplitude Comparator



Numerical Relay

MODULE VI

PROTECTION OF ALTERNATOR, TRANSFORMERS, TRANSMISSION LINES, OVERVOLTAGES

Protection of Alternators

Some of the important faults which may occur on an alternator are :

(*i*) failure of prime-mover **(*ii*)** failure of field **(*iii*)** overcurrent **(*iv*)** overspeed **(*v*)** overvoltage **(*vi*)** unbalanced loading **(*vii*)** stator winding faults

(*i*) Failure of prime-mover. When input to the prime-mover fails, the alternator runs as a synchronous motor and draws some current from the supply system. This motoring conditions is known as "inverted running".

(*ii*) Failure of field. The chances of field failure of alternators are undoubtedly very rare. Even if it does occur, no immediate damage will be caused by permitting the alternator to run without a field for a short-period. It is sufficient to rely on the control room attendant to disconnect the faulty alternator manually from the system bus-bars. Therefore, it is a universal practice not to provide †automatic protection against this contingency.

(*iii*) Overcurrent. It occurs mainly due to partial breakdown of winding insulation or due to overload on the supply system. Overcurrent protection for alternators is considered unnecessary because of the following reasons :

(*a*) The modern tendency is to design alternators with very high values of internal impedance so that they will stand a complete short-circuit at their terminals for sufficient time without serious overheating. On the occurrence of an overload, the alternators can be disconnected manually.

(*b*) The disadvantage of using overload protection for alternators is that such a protection might disconnect the alternators from the power plant bus on account of some momentary troubles outside the plant and, therefore, interfere with the continuity of electric service.

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

(*v*) Over-voltage. Overvoltage in an alternator occurs when speed of the prime-mover increases due to sudden loss of the alternator load.

(*vi*) Unbalanced loading. Unbalanced loading means that there are different phase currents in the alternator. Unbalanced loading arises from faults to earth or faults between phases on the circuit external to the alternator. The unbalanced currents, if allowed to persist, may either severely burn the mechanical fixings of the rotor core or damage the field winding.

***(vii)* Stator winding faults.** These faults occur mainly due to the insulation failure of the stator windings. The main types of stator winding faults, in order of importance are

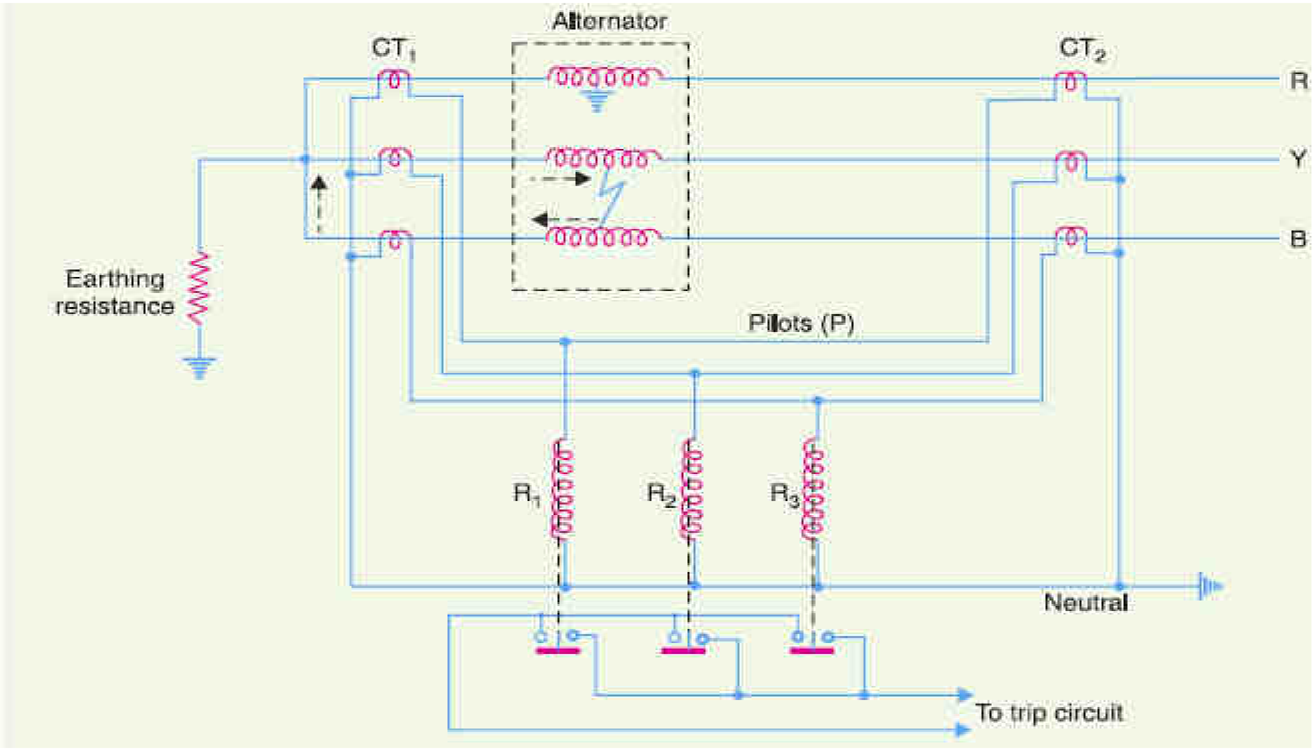
(a)fault between phase and ground

(*b*) fault between phases

(*c*) inter-turn fault involving turns of the same phase winding

Differential Protection of Alternators

- 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 a fault in the protected section. The difference of the currents 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*.
- **Schematic arrangement.** The protection system requires two identical transformers which are mounted on both sides of the protection zone. The secondary terminals of the current transformers are connected in stars, and their end terminals are connected through the pilot wire. The relay coils are connected in delta. The neutral of the current transformer and the relay are connected to the common terminal.



- **Operation.** Under normal operating conditions, the current at both ends of each winding will be equal and hence the currents in the secondaries of two CTs connected in any phase will also be equal. Therefore, there is balanced circulating current in the pilot wires and no current flows through the operating coils ($R1$, $R2$ and $R3$) of the relays. When an earth-fault or phase-to-phase fault occurs, this condition no longer holds good and the differential current flowing through the relay circuit operates the relay to trip the circuit breaker.

Problem Associated with Differential Protection System

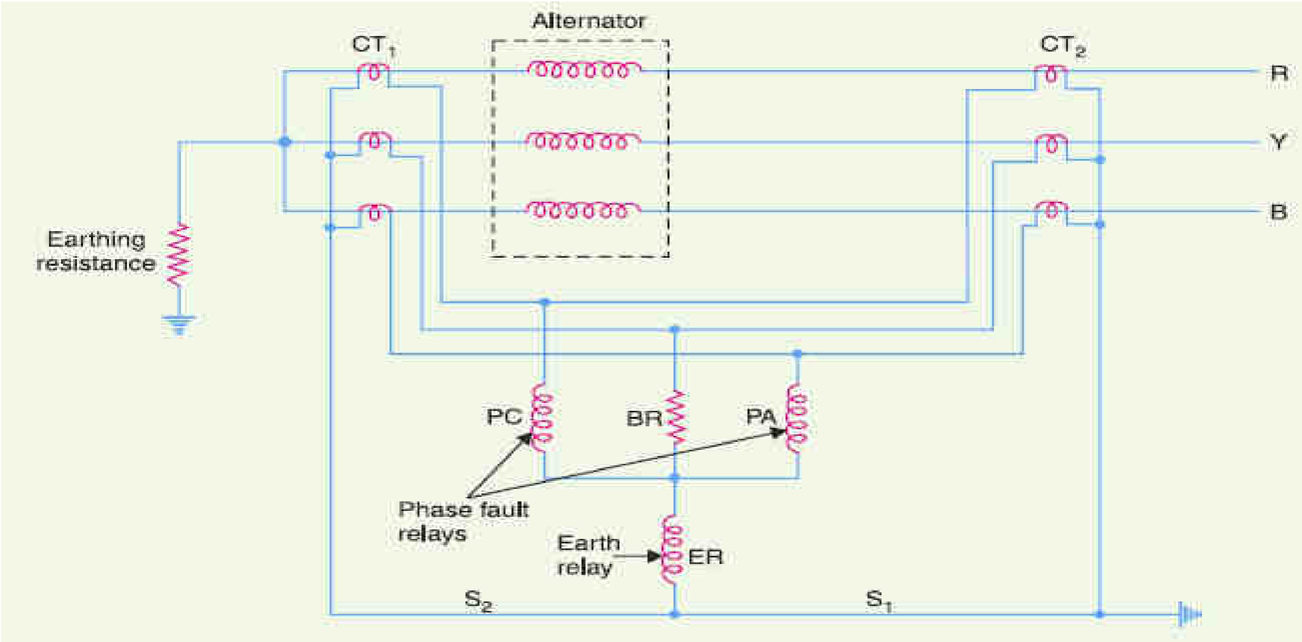
- A neutral resistance wire is used in the differential protection system for avoiding the adverse effect of earth fault currents. When an earth fault occurs near the neutral, it will cause a small, short circuit current to flow through the neutral point because of small emf. This current is further reduced by the resistance of the neutral grounding. Thus, the small current will flow through the relay. This small current will not operate the relay coil, and hence the generator gets damage.

(i) Consider the earth fault occurs on the R phase of the network. Because of the fault, the current in the secondary of the transformer becomes unequal. The differential currents flow through the relay coil. Thus, the relay becomes operative and gives the command to the circuit breaker for operation.

(ii) If the fault occurs between any two phases, say Y and B then short-circuit current flows through these phases. The fault unbalanced the current flows through CTs. The differential current flows through the relay operating coil and thus relay trips their contacts.

Modified Differential Protection for Alternators

- To overcome the above problem, the modified scheme has been developed. In this scheme two elements are arranged, one for the protection of the phase fault and other for the earth fault protection.
- The phase elements are connected in stars along with the resistor. The earth fault relay is kept between the star and neutral. The two phase elements (PC and PA) and balancing resistance (BR) are connected in star and the earth relay (ER) is connected between this star point and the neutral.
- The star-connected circuit is symmetrical, and any balanced overflow current from the current circulating point will not flow through the earth fault relay. So in this system, the sensitive earth fault relay will operate at a high degree of stability.



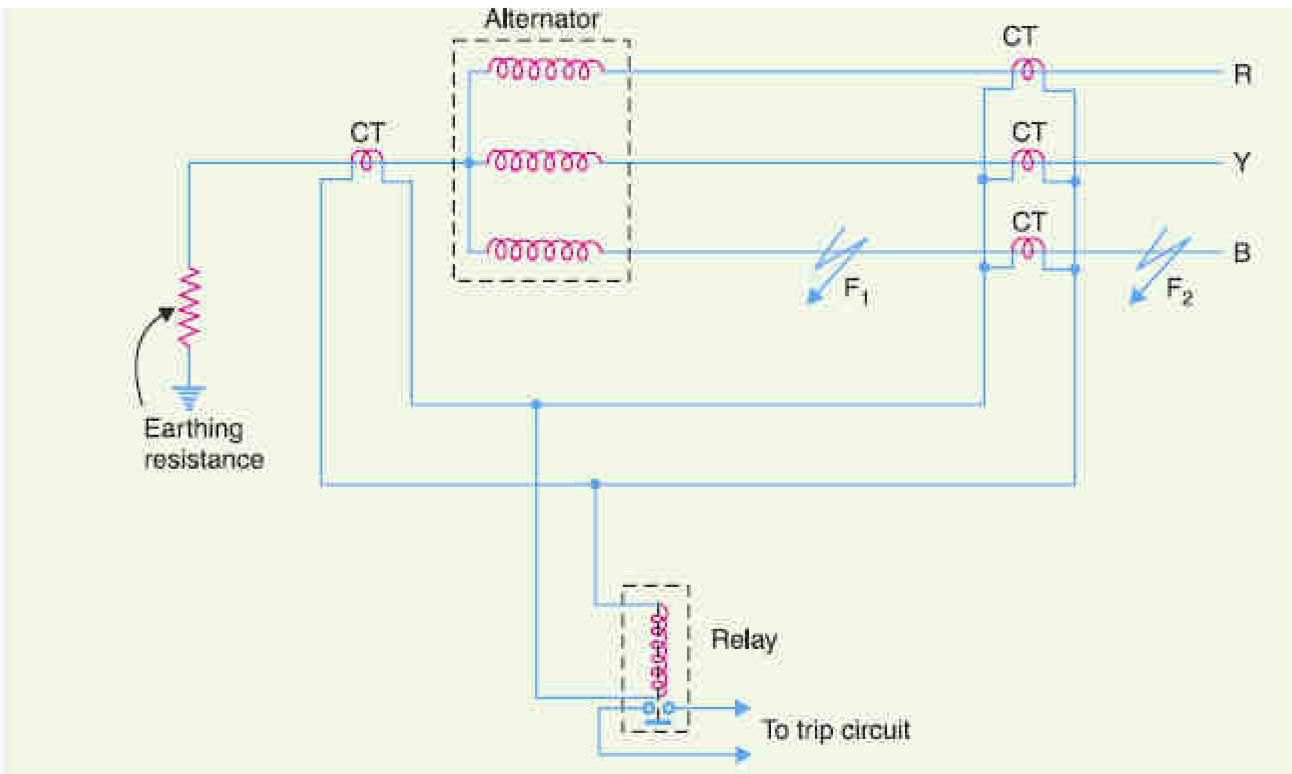
Balanced Earth-fault Protection

In a small generator, the neutral end of the three phase windings is connected internally to a single terminal. So the neutral end is not available, and protection against earth fault is provided by using the balanced earth protection scheme. In this scheme, the current transformers are mounted on each phase. Their secondary is connected in parallel with that of CT mounted on a conductor joining the star point of the generator to earth. A relay is connected across the secondaries of the CTs.

Operation. When the generator is in a normal operating condition the sum of the currents flow in the secondary of the current transformers is zero and the current flow into secondary to neutral is also zero. Thus the relay remains de-energized. When the fault occurs in the protected zone (left of the line) the fault current flow through the primary of current transformers and the corresponding secondary current flow through the relay which trips the circuit breaker.

- When the fault develops external of the protective zone F2 (right of the current transformer) the sum of the currents at the terminal of the generator is exactly equal to the current in the neutral connection. Hence, no current flows through the relay operating coil.
- When an earth fault occurs at F1 these currents are no longer equal and the differential current flows through operating coil of relay. The relay then closes its contacts to disconnect alternator from system.

Balanced Earth-fault Protection



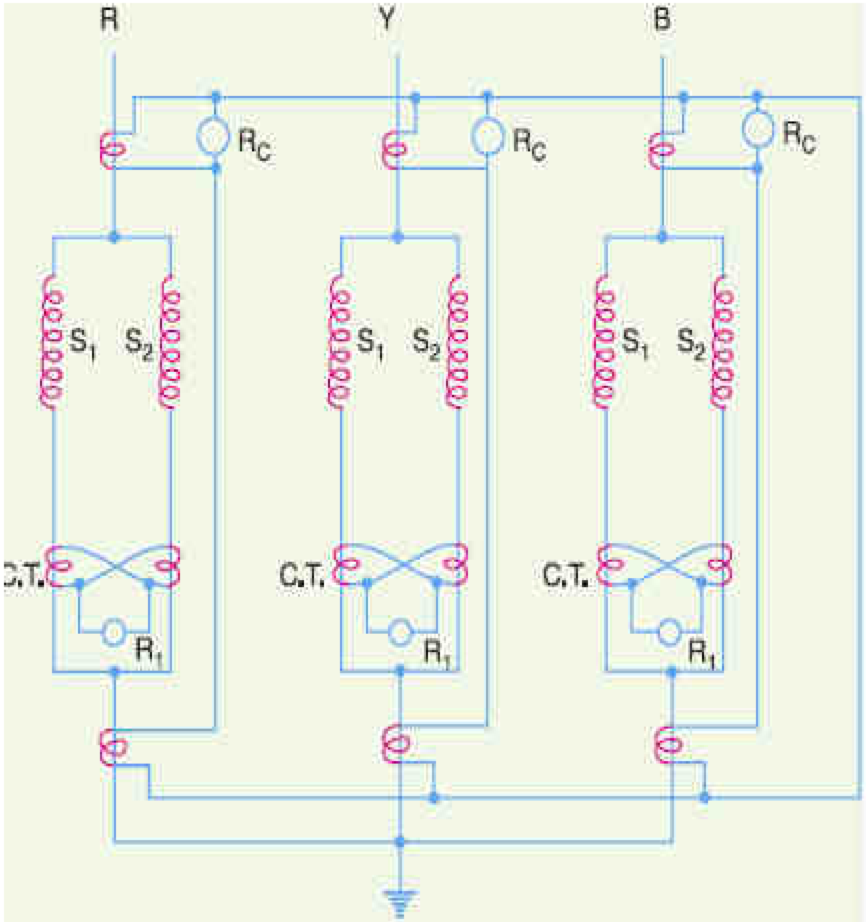
Stator Inter-turn Protection

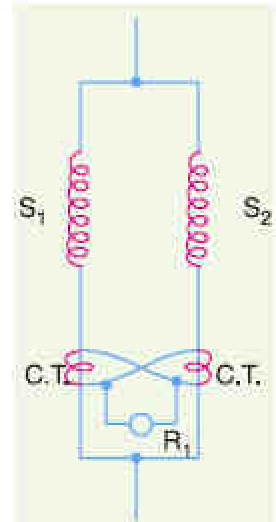
- Merz-price circulating-current system protects against phase-to-ground and phase-to-phase faults. It does not protect against turn-to-turn fault on the same phase winding of the stator. It is because the current that this type of fault produces flows in a local circuit between the turns involved and does not create a difference between the currents entering and leaving the winding at its two ends where current transformers are applied.

- Inter-turn protection is provided for multi-turn generators such as hydro-electric generators. These generators 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.

- Figure 1 shows the schematic arrangement of circulating-current and inter-turn protection of a 3-phase double wound generator. The relays *RC* provide protection against phase-to-ground and phase-to-phase faults whereas relays *R*1 provide protection against inter-turn faults.

- Figure 2 shows the duplicate stator windings *S*1 and *S*2 of one phase only with a provision against inter-turn faults. Two current transformers are connected on the circulating-current principle. Under normal conditions, the currents in the stator windings *S*1 and *S*2 are equal and so will be the currents in the secondaries of the two CTs and no current flows through the relay *R*1. If a short-circuit develops between adjacent turns, say on *S*1, 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 two currents flows through the relay *R*1. The relay then closes its contacts to clear the generator from the system.


R
Y
B
R_C
R_C
R_C
S_1
S_2
S_1
S_2
S_1
S_2
C.T.
C.T.
C.T.
R_1
R_1
R_1


S_1
S_2
C.T.
C.T.
R_1

Protection of Transformers

Common transformer faults.

- As compared with generators, in which many abnormal conditions may arise, power transformers may suffer only from :

  (i) open circuits (ii) overheating (iii) winding short-circuits e.g. earth-faults, phase-to-phase faults and inter-turn faults.
- An open circuit in one phase of a 3-phase transformer may cause undesirable heating. On the occurrence of such a fault, the transformer can be disconnected manually from the system.
- Overheating of the transformer is usually caused by sustained overloads or short-circuits and very occasionally by the failure of the cooling system.
- Winding short-circuits (also called internal faults) on the transformer arise from deterioration of winding insulation due to overheating or mechanical injury. When an internal fault occurs, the transformer must be disconnected quickly from the system because a prolonged arc in the transformer may cause oil fire. Therefore, relay protection is absolutely necessary for internal faults.
- The principal relays and systems used for transformer protection are :

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

  (ii) Earth-fault relays providing protection against earth-faults only.

  (iii) Overcurrent relays providing protection mainly against phase-to-phase faults and overloading.

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

Buchholz Relay

- Buchholz is used to give an alarm in case of incipient (i.e. slow-developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults. It is usually installed in the pipe connecting the conservator to the main tank. It is a universal practice to use Buchholz relays on all such oil immersed transformers having ratings in excess of 750 kVA.
- **Construction**. It takes the form of a domed vessel placed in the connecting pipe between the main tank and the conservator. The device has two elements. The lower element contains a mercury switch mounted in the direct path of the flow of oil from the transformer to the conservator. The upper element also contains a mercury switch which closes an alarm circuit during incipient faults whereas the lower element is arranged to trip the circuit breaker in case of severe internal faults.
- **Operation.**

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

.

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

Advantages

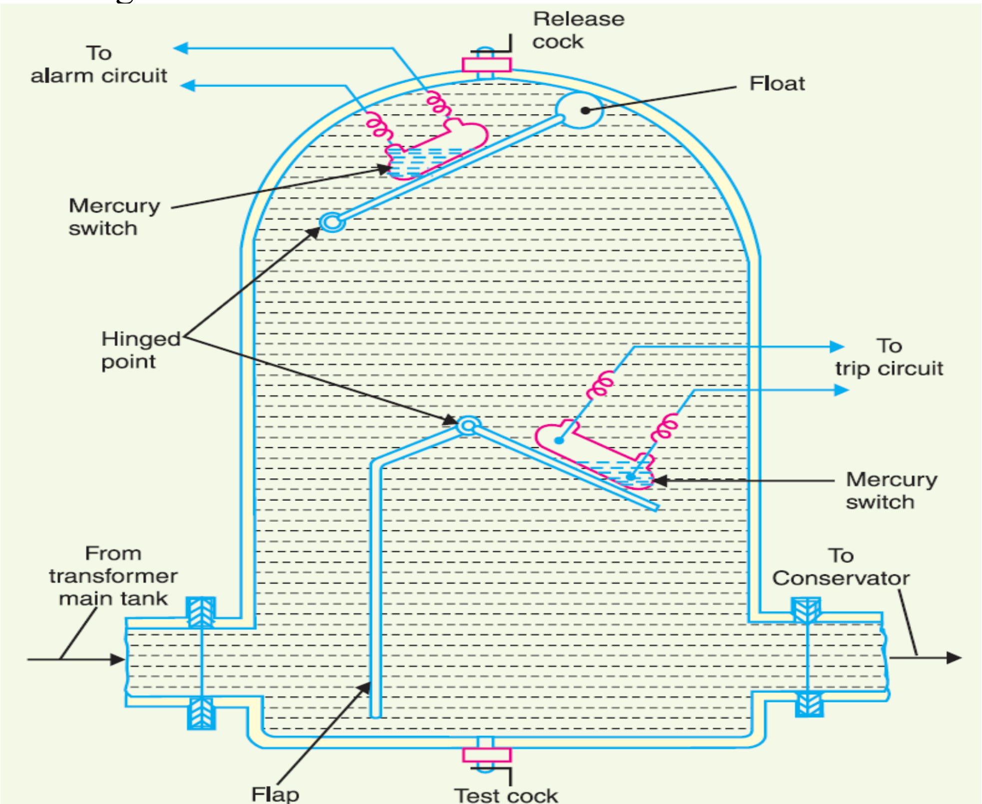
(i) It is the simplest form of transformer protection.

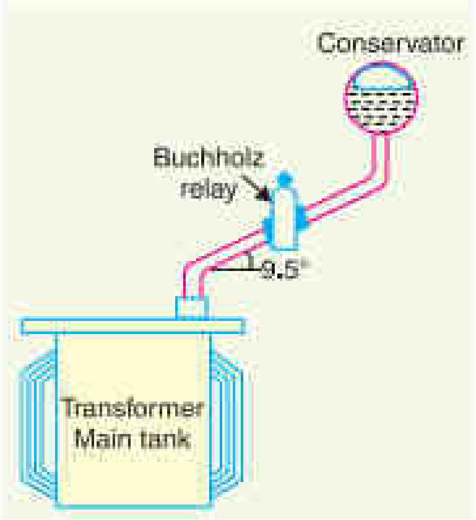
(ii) It detects the incipient faults at a stage much earlier than is possible with other forms of protection.

Disadvantages

(i) It can only be used with oil immersed transformers equipped with conservator tanks.

(ii) The device can detect only faults below oil level in the transformer. Therefore, separate protection is needed for connecting cables





Applying Circulating- current System to Transformers(Differential protection)

- Merz-Price circulating -current principle is commonly used for the protection of power transformers against earth and phase faults. Same as that for generators but with certain complications

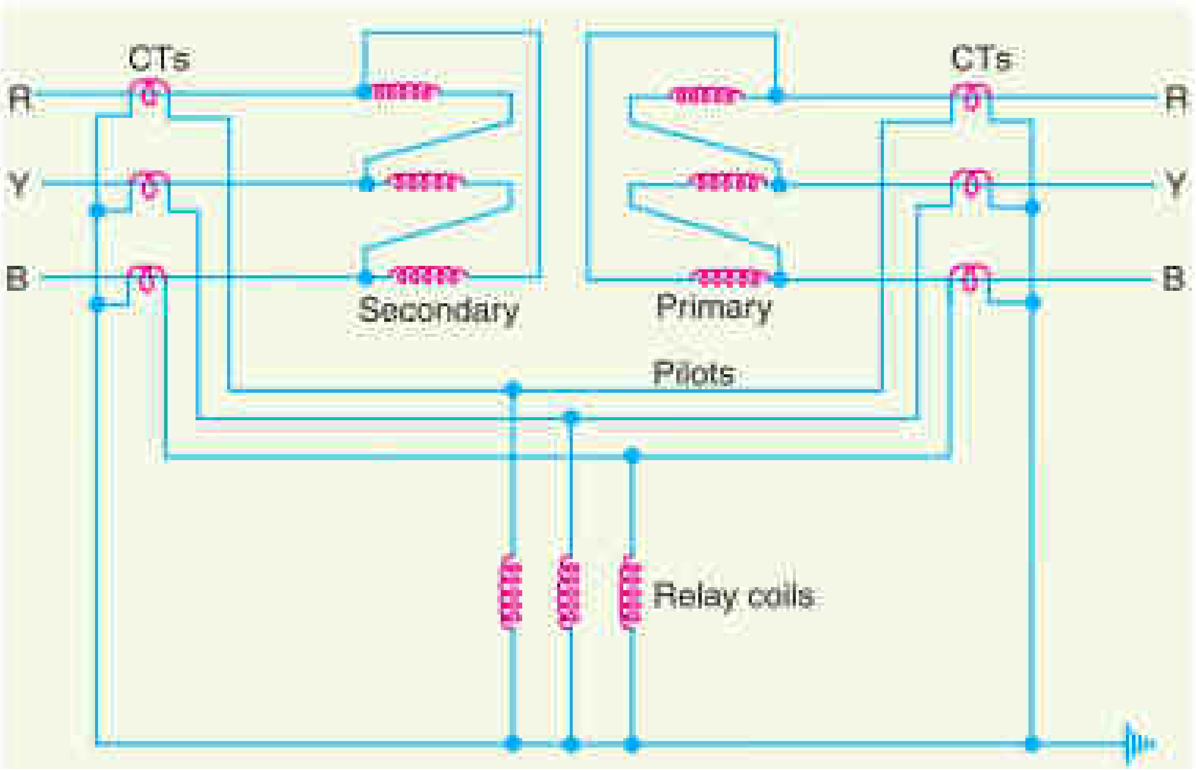
  The complicating features and their remedial measures are briefed below :
- (i) In a power transformer, currents in the primary and secondary are to be compared. As these two currents are usually different, therefore, the use of identical transformers (of same turn ratio) will give differential current and operate the relay even under no load conditions. The difference in the magnitude of currents in the primary and secondary of power transformer is compensated by different turn ratios of CTs. If T is the turn-ratio of power transformer, then turn ratio of CTs on the l.v. side is made T times that of the CTs on the h.v. side. Fulfilled this condition, the secondaries of the two CTs will carry identical currents under normal load conditions. Consequently, no differential current will flow through the relay and it remains inoperative.
- (ii) There is usually a phase difference between the primary and secondary currents of a 3-phase power transformer. Even if CTs of the proper turn-ratio are used, a differential current may flow through the relay under normal conditions and cause relay operation. The correction for phase difference is effected by appropriate connections of CTs

- (iii) Most transformers have means for tap changing which makes this problem even more difficult. Tap changing will cause differential current to flow through the relay even under normal operating conditions. The above difficulty is overcome by adjusting the turn-ratio of CTs on the side of the power transformer provided with taps.
- (iv) Another complicating factor in transformer protection is the magnetising in-rush current. Under normal load conditions, the magnetising current is very small. However, when a transformer is energised after it has been taken out of service, the magnetising or in-rush current can be extremely high for a short period. It appears as a fault current to differential relay and may cause relay operation.

Circulating Current Scheme for Transformer Protection

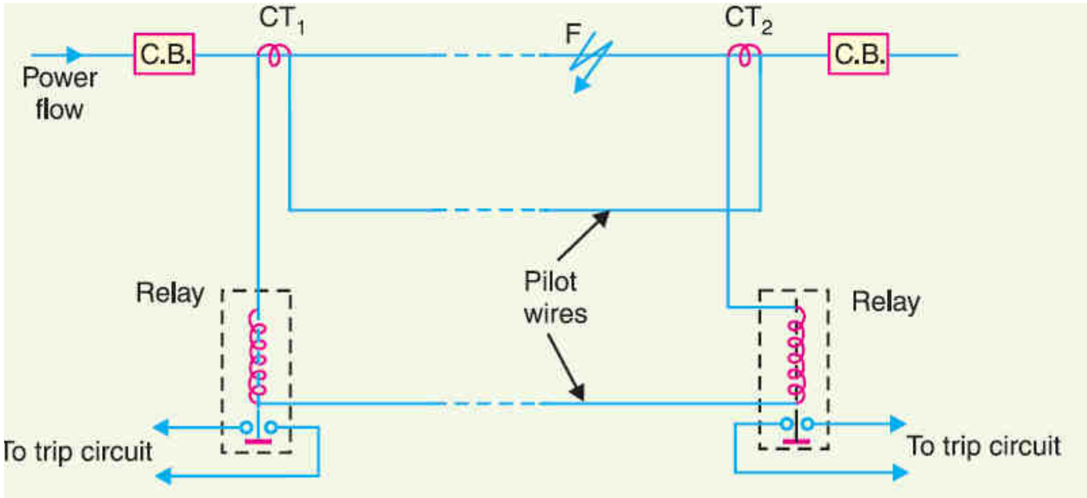
- CTs on the two sides of the transformer are connected in star. This compensates for the phase difference between the power transformer primary and secondary. The CTs on the two sides are connected by pilot wires and one relay is used for each pair of CTs.
- During normal operating conditions, the secondaries of CTs carry identical currents. Therefore, the currents entering and leaving the pilot wires at both ends are the same and no current flows through the relays. If a ground or phase-to-phase fault occurs, the currents in the secondaries of CTs will no longer be the same and the differential current flowing through the relay circuit will clear the breaker on both sides of the transformer. The-protected zone is limited to the region between CTs on the high-voltage side and the CTs on the low-voltage side of the power transformer.

- This scheme also provides protection for short-circuits between turns on the same phase winding. When a short-circuit occurs between the turns, the turn-ratio of the power transformer is altered and causes unbalance between current transformer pairs. If turn-ratio of power transformer is altered sufficiently, enough differential current may flow through the relay to cause its operation. However, such short-circuits are better taken care of by Buchholz relays.

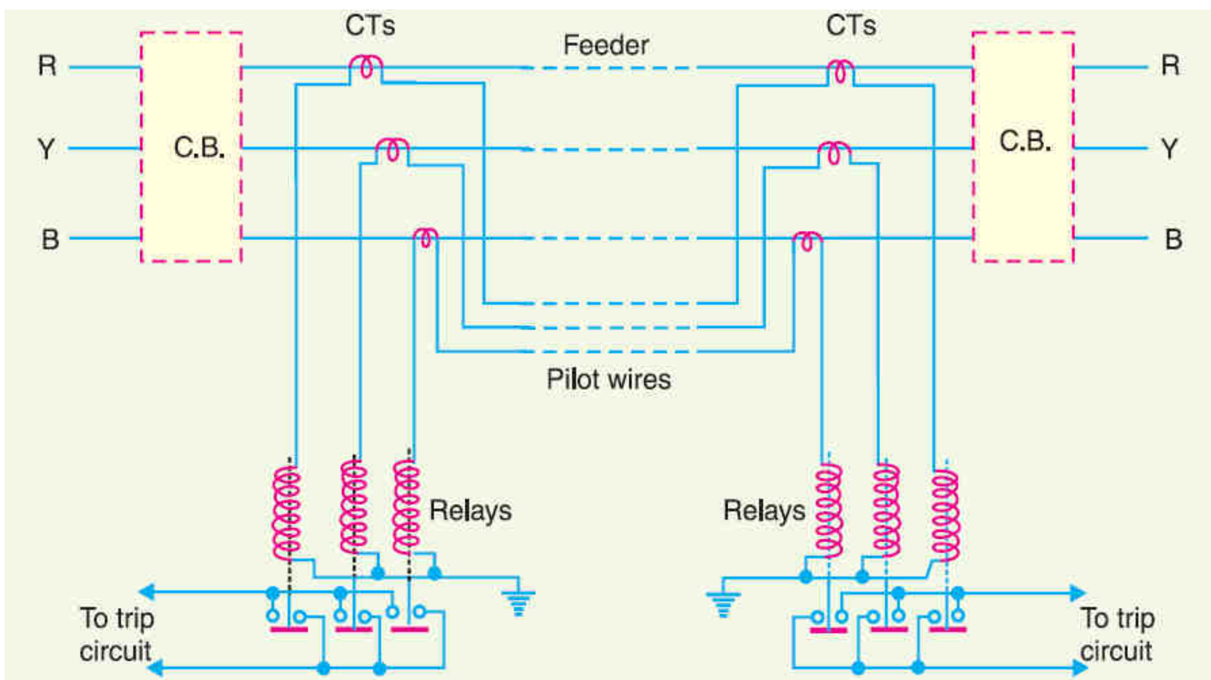


Differential pilot wire protection of Transmission lines

- The differential pilot-wire protection is based on the principle that under normal conditions, the current entering one end of a line is equal to that leaving the other end. As soon as a fault occurs between the two ends, this condition no longer holds and the difference of incoming and outgoing currents is arranged to flow through a relay which operates the circuit breaker to isolate the faulty line.
- **Merz-Price voltage balance system.** Fig.1 shows the single line diagram of Merz-Price voltage balance system for the protection of a 3-phase line. 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. Under healthy conditions, current entering the line at one-end is equal to that leaving it at the other end. Therefore, equal and opposite voltages are induced in the secondaries of the *CT*s at the two ends of the line. The result is that no current flows through the relays.
- Suppose a fault occurs at point *F* on the line as shown in Fig. 1. This will cause a greater current to flow through *CT*1 than through *CT*2. Consequently, their secondary voltages become unequal and circulating current flows through the pilot wires and relays. The circuit breakers at both ends of the line will trip out and the faulty line will be isolated. Fig. 2 shows the connections of Merz-Price voltage balance scheme for all the three phases of the line.



CT1
F
CT2
C.B.
C.B.
Power flow
Relay
Pilot wires
Relay
To trip circuit
To trip circuit



CTs
Feeder
CTs
R
Y
B
C.B.
C.B.
R
Y
B
Pilot wires
Relays
Relays
To trip circuit
To trip circuit

- **Advantages**

(*i*) This system can be used for ring mains as well as parallel feeders.

(*ii*) This system provides instantaneous protection for ground faults. This decreases the possibility of these faults involving other phases.

(*iii*) This system provides instantaneous relaying which reduces the amount of damage to overhead conductors resulting from arcing faults.

- **Disadvantages**

(*i*) Accurate matching of current transformers is very essential.

(*ii*) If there is a break in the pilot-wire circuit, the system will not operate.

(*iii*) This system is very expensive owing to the greater length of pilot wires required.

(*iv*) In case of long lines, charging current due to pilot-wire capacitance effects may be sufficient to cause relay operation even under normal conditions.

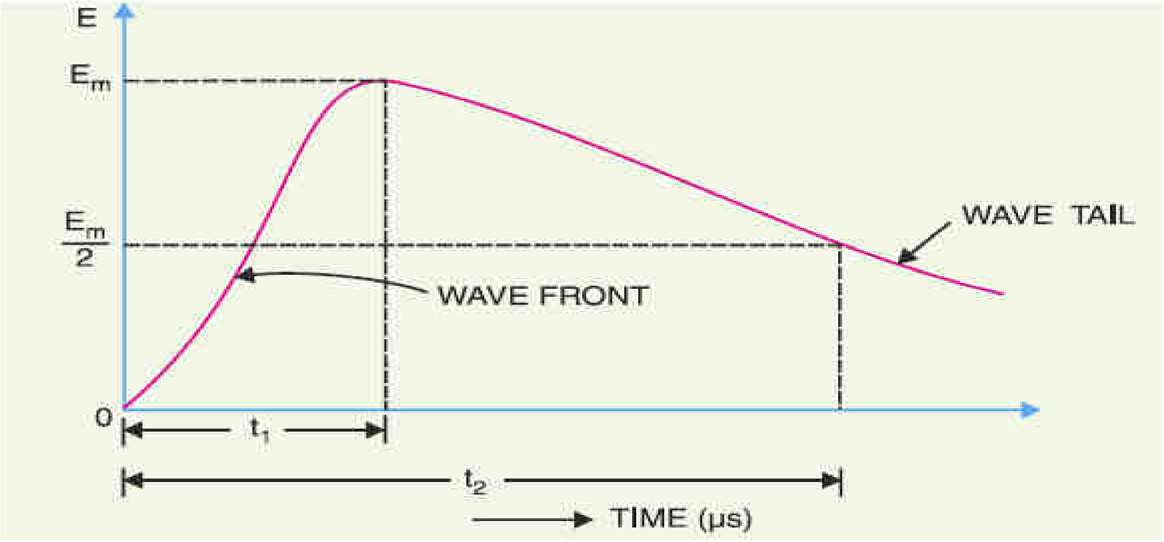
(*v*) This system cannot be used for line voltages beyond 33 kV because of constructional difficulties in matching the current transformers.

Voltage Surge

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

- Transients or surges are of temporary nature and exist for a very short duration (a few hundred μ*s*) but they cause overvoltages on the power system. They originate from switching and from other causes but by far the most important transients are those caused by lightning striking a transmission line. When lightning strikes a line, the surge rushes along the line, just as a flood of water rushes along a narrow valley when the retaining wall of a reservoir at its head suddenly gives way. In most of the cases, such surges may cause the line insulators (near the point where lightning has struck) to flash over and may also damage the nearby transformers, generators or other equipment connected to the line if the equipment is not suitably protected.

- Figure shows the wave-form of a typical lightning surge. The voltage build-up is taken along *y*-axis and the time along *x*-axis. It may be seen that lightning introduces a steep-fronted wave. The steeper the wave front, the more rapid is the build-up of voltage at any point in the network. In most of the cases, this build-up is comparatively rapid, being of the order of 1–5 μs. Voltage surges are generally specified in terms of *rise time *t*1 and the time *t*2 to decay to half of the peak value.



Causes of Overvoltages

- The overvoltages on a power system may be broadly divided into two main categories *viz*.
- **1. Internal causes**

(*i*) Switching surges **(*ii*)** Insulation failure **(*iii*)** Arcing ground **(*iv*)** Resonance

- **2. External causes** *i.e*. lightning

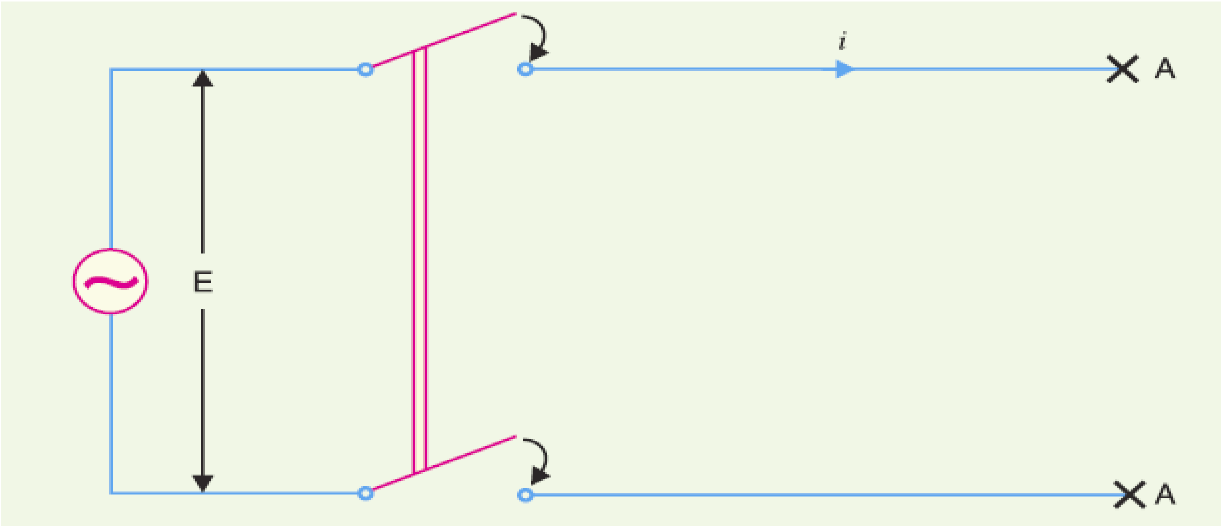
Internal causes do not produce surges of large magnitude. Generally, surges due to internal causes are taken care of by providing proper insulation to the equipment in the power system. However, surges due to lightning are very severe and may increase the system voltage to several times the normal value. If the equipment in the power system is not protected against lightning surges, these surges may cause considerable damage. In fact, in a power system, the protective devices provided against overvoltages mainly take care of lightning surges.

Internal Causes of Overvoltages

- Internal causes of overvoltages on the power system are primarily due to oscillations set up by the sudden changes in the circuit conditions. This circuit change may be a normal switching operation such as opening of a circuit breaker, or it may be the fault condition such as grounding of a line conductor.

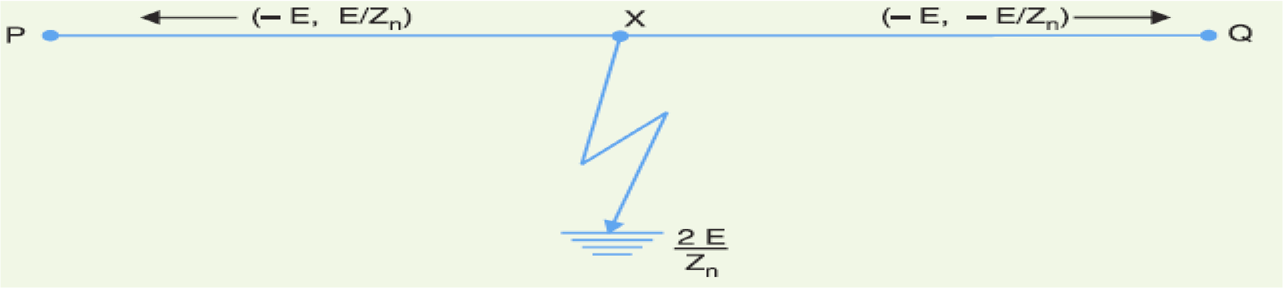
Internal causes of overvoltages.

- **1. Switching Surges.** The overvoltages produced on the power system due to switching operations are known as switching surges. A few cases are :
- **(*i*) Case of an open line.** During switching operations of an unloaded line, travelling waves are set up which produce overvoltages on the line. Consider an unloaded line being connected to a voltage source as shown in Figure.



- When the unloaded line is connected to the voltage source, a voltage wave is set up which travels along the line. On reaching the terminal point *A*, it is reflected back to the supply end without change of sign. This causes voltage doubling *i.e.* voltage on the line becomes twice the normal value. If E*r.m.s.* is the supply voltage, then instantaneous voltage which the line will have to withstand will be $2\sqrt{2}\ E$. This overvoltage is of temporary nature.
- **(*ii*) Case of a loaded line.** Overvoltages will also be produced during the switching operations of a loaded line. Suppose a loaded line is suddenly interrupted. This will set up a voltage of 2 *Zn I* across the break (*i.e.* switch) where *i* is the instantaneous value of current at the time of opening of line and *Zn* is the natural impedance of the line.
- **(*iii*) Current chopping.** Current chopping results in the production of high voltage transients across the contacts of the air blast circuit breaker. When breaking low currents (*e.g.* transformer magnetising current) with air-blast breaker, the powerful de-ionising effect of air-blast causes the current to fall abruptly to zero well before the natural current zero is reached. This phenomenon is called current chopping and produces high transient voltage across the breaker contacts. Overvoltages due to current chopping are prevented by resistance switching.

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



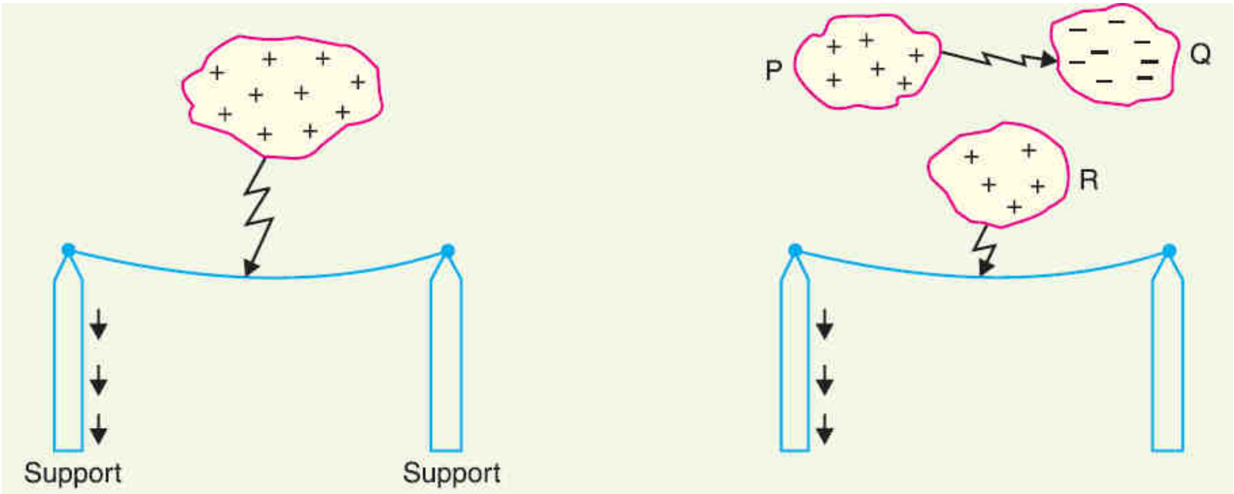
Suppose a line at potential E is earthed at point X. The earthing of the line causes two equal voltages of $-E$ to travel along XQ and XP containing currents $-E/Zn$ and $+E/Zn$ respectively. Both these currents pass through X to earth so that current to earth is $2\ E/Zn$.

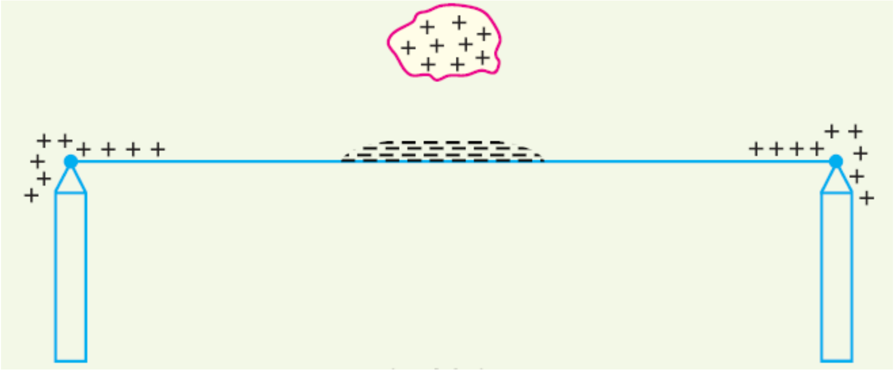
- **3. Arcing ground.** The arcing ground produces severe oscillations of three to four times the normal voltage. *The phenomenon of intermittent arc taking place in line-to-ground fault of a 3φ system with consequent production of transients is known as* **arcing ground.** The transients produced due to arcing ground are cumulative and may cause serious damage to the equipment in the power system by causing breakdown of insulation. Arcing ground can be prevented by earthing the neutral.
- **4. Resonance.** Resonance in an electrical system occurs when inductive reactance of the circuit becomes equal to capacitive reactance. Under resonance, the impedance of the circuit is equal to resistance of the circuit and the p.f. is unity. Resonance causes high voltages in the electrical system. In the usual transmission lines, the capacitance is very small so that resonance rarely occurs at the fundamental supply frequency. However, if generator *e.m.f.* wave is distorted, the trouble of resonance may occur due to 5th or higher harmonics and in case of underground cables too.

External cause of overvoltages: lightning

- *An electric discharge between cloud and earth, between clouds or between the charge centres of the same cloud is known as* **lightning.**
- Lightning is a huge spark and takes place when clouds are charged to such a high potential (+ve or −ve) with respect to earth or a neighbouring cloud that the dielectric strength of neighbouring medium (air) is destroyed.
- Types of Lightning Strokes
- **1.** Direct stroke **2.** Indirect stroke
- **1. Direct stroke.** In the direct stroke, the lightning discharge (*i.e.* current path) is directly from the cloud to the subject equipment *e.g*. an overhead line. From the line, the current path may be over the insulators down the pole to the ground. The overvoltages set up due to the stroke may be large enough to flashover this path directly to the ground. The direct strokes can be of two types *viz*.
- (*i*) Stroke *A* and (*ii*) stroke *B*.
- In stroke *A*, the lightning discharge is from the cloud to the subject equipment *i.e*. an overhead line in this case as shown in Fig i In stroke *B*, the lightning discharge occurs on the overhead line as a result of stroke *A* between the clouds as shown in Fig ii

- **2. Indirect stroke.** Indirect strokes result from the electrostatically induced charges on the conductors due to the presence of charged clouds. This is illustrated in Fig. iii A positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction. This negative charge, however, will be only on that portion of the line right under the cloud and the portions of the line away from it will be positively charged as shown in Fig.iii. The induced positive charge leaks slowly to earth *via* the insulators. When the cloud discharges to earth or to another cloud, the negative charge on the wire is isolated as it cannot flow quickly to earth over the insulators. The result is that negative charge rushes along the line is both directions in the form of travelling waves.





SURGE

- Surges, or transients, are brief overvoltage spikes or disturbances on a power waveform that can damage, degrade, or destroy electronic equipment within any home, commercial building, or manufacturing facility.

SURGE DIVERTER

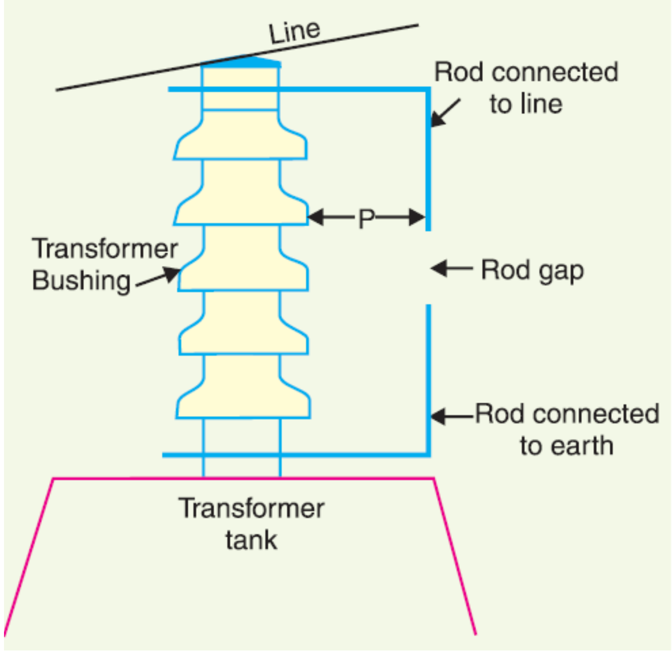
- *A* **lightning arrester** *or a* **surge diverter** *is a protective device which conducts the high voltage surges on the power system to the ground,* thus protecting sensitive electrical and electronic equipment.
- It consists of a spark gap in series with a non-linear resistor. One end of the diverter is connected to the terminal of the equipment to be protected and the other end is effectively grounded. The length of the gap is so set that normal line voltage is not enough to cause an arc across the gap but a dangerously high voltage will break down the air insulation and form an arc. The property of the non-linear resistance is that its resistance decreases as the voltage (or current) increases and vice-versa.
- **(*i*)** Under normal operation, the lightning arrester is off the line *i.e.* it conducts no current to earth or the gap is non-conducting.
- **(*ii*)** On the occurrence of overvoltage, the air insulation across the gap breaks down and an arc is formed, providing a low resistance path for the surge to the ground. In this way, the excess charge on the line due to the surge is harmlessly conducted through the arrester to the ground instead of being sent back over the line.

TYPES OF SURGE DIVERTER

- Rod gap
- Horn gap
- Protector tube or expulsion type surge diverter
- Valve type surge diverter

ROD GAP TYPE

- It is a very simple type of diverter and consists of two 1.5 cm rods, which are bent at right angles with a gap in between.
- One rod is connected to the line circuit and the other rod is connected to earth.
- The distance between gap and insulator must not be less than one third of the gap length so that the arc may not reach the insulator and damage it.
- Under normal operating conditions, the gap remains non-conducting.
- On the occurrence of a high voltage surge on the line, the gap sparks over and the surge current is conducted to earth.
- In this way excess charge on the line due to the surge is harmlessly conducted to earth.

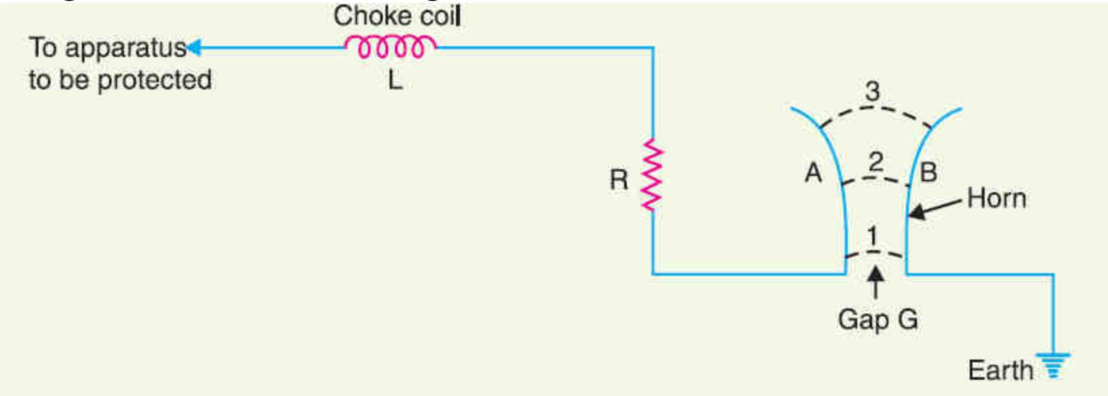


LIMITATIONS

- After the surge is over, the arc in the gap is maintained by the normal supply voltage, leading to short-circuit on the system.
- The rods may melt or get damaged due to excessive heat produced by the arc.
- The climatic conditions (e.g. rain, humidity, temperature etc.) affect the performance of rod gap arrester.
- The polarity of the surge also affects the performance of this arrester.

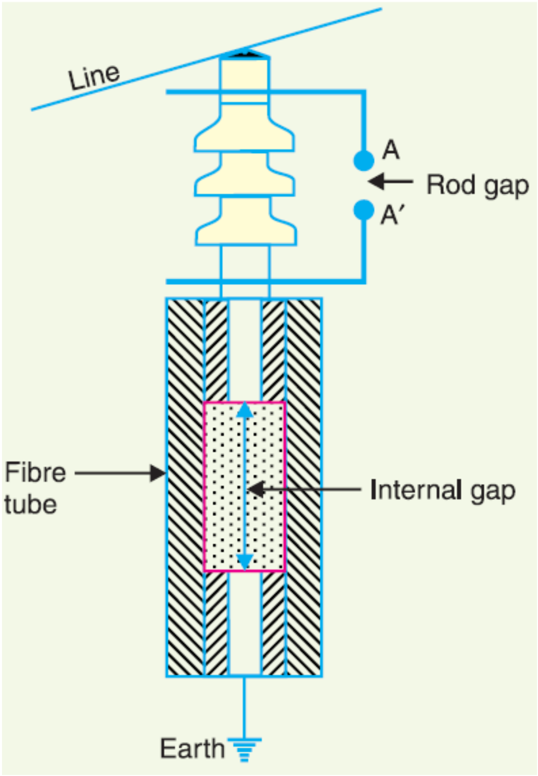
Horn gap arrester

- It consists of two horn shaped metal rods *A* and *B* separated by a small air gap. The horns are so constructed that distance between them gradually increases towards the top as shown.
- One end of horn is connected to the line through a resistance *R* and choke coil *L* while the other end is effectively grounded. The resistance *R* helps in limiting the follow current to a small value.
- The choke coil is so designed that it offers small reactance at normal power frequency but a very high reactance at transient frequency. Thus the choke does not allow the transients to enter the apparatus to be protected. The gap between the horns is so adjusted that normal supply voltage is not enough to cause an arc across the gap.
- Under normal conditions, the gap is non-conducting *i.e.* normal supply voltage is insufficient to initiate the arc between the gap. On the occurrence of an overvoltage, spark-over takes place across the small gap *G*. The heated air around the arc and the magnetic effect of the arc cause the arc to travel up the gap. The arc moves progressively into positions 1, 2 and 3. At some position of the arc (perhaps position 3), the distance may be too great for the voltage to maintain the arc. Consequently, the arc is extinguished. The excess charge on the line is thus conducted through the arrester to the ground.



EXPULSION TYPE SURGE DIVERTER

- This type of arrester is also called 'protector tube' and is commonly used on system operating at voltages up to 33kV.
- It essentially consists of a rod gap in series with a second gap enclosed within the fiber tube.
- The gap in the fiber tube is formed by two electrodes.
- The upper electrode is connected to rod gap and the lower electrode to the earth.
- On the occurrence of an overvoltage on the line, the series gap $A\ A'$ is spanned and an arc is struck between the electrodes in the tube. The heat of the arc vaporises some of the fibre of tube walls, resulting in the production of a neutral gas.
- In an extremely short time, the gas builds up high pressure and is expelled through the lower electrode which is hollow. As the gas leaves the tube violently, it carries away ionised air around the arc. This de-ionising effect is generally so strong that arc goes out at a current zero and will not be re-established.



ADVANTAGES

- They are not very expensive.
- They can be easily installed.
- They are improved form of rod gap arresters as they block the flow of power frequency follow currents.

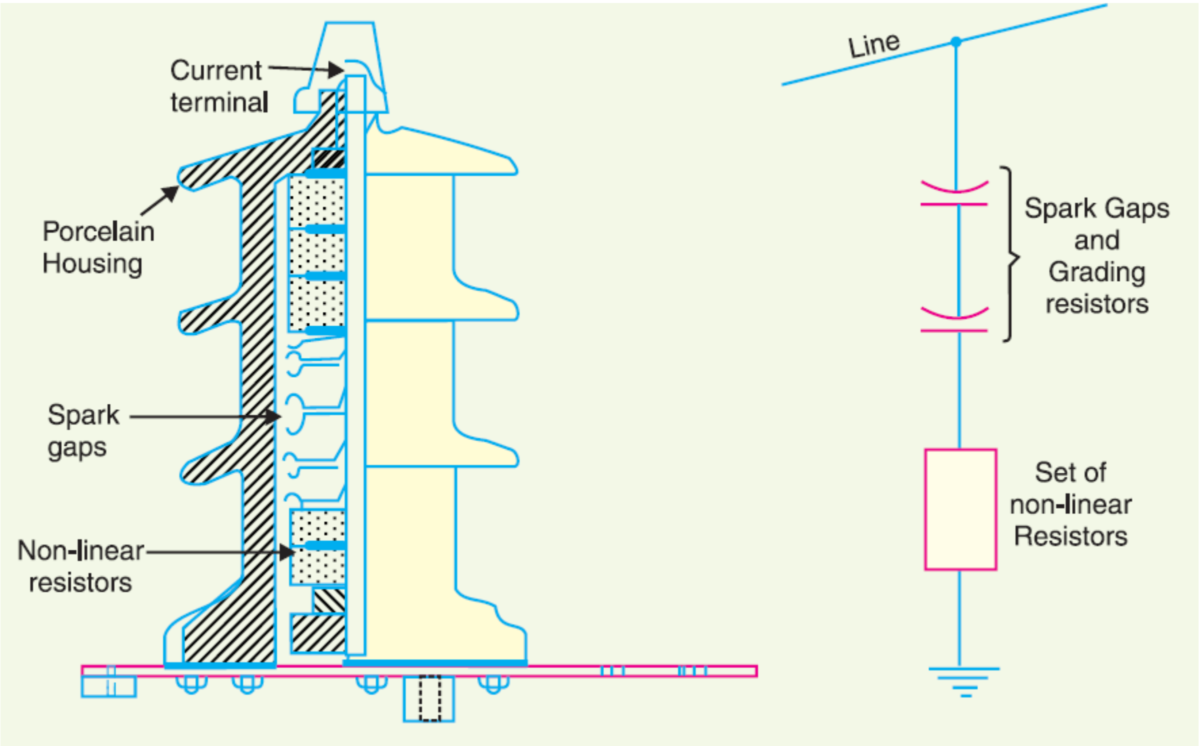
LIMITATIONS

- An expulsion type arrester can perform only limited number of operations as during each operation some of the fiber material is used up.
- This type of arrester cannot be mounted on enclosed equipment due to discharge of gases during operation.
- Due to the poor volt/amp characteristic of the arrester, it is not suitable for protection of expensive equipment.

VALVE TYPE ARRESTERS

- Valve type arresters incorporate non linear resistors and are extensively used on systems, operating at high voltages.
- It consists of two assemblies (i) series spark gaps and (ii) non-linear resistor discs
- The non-linear elements are connected in series with the spark gaps. Both the assemblies are accommodated in tight porcelain container.
- The spark gap is a multiple assembly consisting of a number of identical spark gaps in series.
- Each gap consists of two electrodes with fixed gap spacing. The spacing of the series gaps is such that it will withstand the normal circuit voltage.
- An over voltage will cause the gap to break down causing the surge current to ground via the non-linear resistors.
- The non-linear resistors have the property of offering a high resistance to current flow when normal system voltage is applied, but a low resistance to the flow of high surge currents.
- When the surge is over the non linear resistor assume high resistance to stop the flow of current.
- Under normal conditions, the normal system voltage is insufficient to cause the breakdown of air gap assembly.

- On the occurrence of an over voltage, the breakdown of the series spark gap takes place and the surge current is conducted to earth via the nonlinear resistances.
- Since the magnitude of surge current is very large, the nonlinear elements will offer a very low resistance to the passage of surge.
- The surge will rapidly go to earth instead of being sent back over the line.



ADVANTAGES

- They provide very effective protection against surges.
- They operate very rapidly taking less than a second
- The impulse ratio is practically unity.

LIMITATIONS

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

INSULATION COORDINATION

- Insulation Coordination is the process of determining the proper insulation levels of various components in a power system as well as their arrangements. It is the selection of an insulation structure that will withstand voltage stresses to which the system, or equipment will be subjected to, together with the proper surge arrester. The process is determined from the known characteristics of voltage surges and the characteristics of surge arresters.
- **Some common terms that must be known when performing an Insulation Coordination Study.**

1. <u>Basic Impulse Insulation Level (BIL)</u>

- This is the reference insulation level expressed as an impulse crest (or peak) voltage with a standard wave not longer than a **1.2 x 50 microsecond** wave. A **1.2 x 50 microsecond** wave means that the impulse takes 1.2 microseconds to reach the peak and then decays to 50% of the peak in 50 microseconds.

2. <u>Withstand Voltage</u>

- This is the BIL level that can repeatedly be applied to an equipment without flashover, disruptive charge or other electrical failure under test conditions.

3. <u>Chopped Wave Insulation Level</u>

- This is determined by using impulse waves that are of the same shape as that of the BIL waveform, with the exception that the wave is chopped after 3 microseconds. Generally, it is assumed that the Chopped Wave Level is 1.15 times the BIL level for oil filled equipment such as transformers.

4. <u>Critical Flashover Voltage</u>

- This is the peak voltage for a 50% probability of flashover or disruptive charge.

5. <u>Impulses Ratio</u>

- This is normally used for Flashover or puncture of insulation. It is the ratio of the impulse peak voltage to the value of the 60 Hz voltage that causes flashover or puncture. Or, it is the ratio of breakdown voltage at surge frequency to breakdown voltage at normal system frequency (60 Hz).