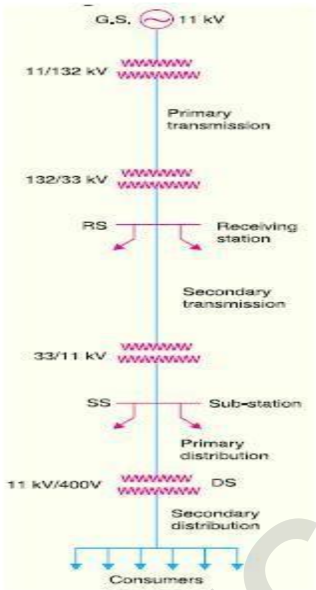
MODULE- 1: INTRODUCTION TO POWER SYSTEM

Structure of electric power system: Generation, Transmission and Distribution. Advantages of high voltage transmission: HVAC, EHVAC, UHVAC and HVDC. Inter connection. Feeders, distributors & service mains

1. Explain with neat sketch, the structure of power system.



Introduction

- An electric power supply system consists of three principal components, the power station, transmission lines and distribution system.
- Electric power is generated at power stations, which are located at favorable places, generally quite away from the consumer.
- It is then transmitted over large distances to load centres with the help of conductors known as transmission lines. Finally, it is distributed to a large number of small and big consumers through a distribution network.
- The electric supply system can be broadly classified into (*i*) d.c. or a.c. system (*ii*) overhead or underground system. Now-a- days, 3-phase, 3-wire a.c. system is universally adopted for generation and transmission of electric power as an economical proposition. However, distribution of electric power is done by 3-phase, 4-wire a.c. system.
- The underground system is more expensive than the overhead system. Therefore, in our country, overhead system is mostly adopted for transmission and distribution of electric power.
- The large network of conductor between the power station and the consumers can be broadly divided into two parts; viz; Transmission and distribution system.
- Each part can further be subdivided into two, primary transmission and secondary transmission and primary distribution and secondary distribution.

1. **Generatingstation:**

i) Generating station represents the generating station, where electric power isproduced by 3 phase alternator operating inparallel.
ii) The usual generation voltage is 11kV. The power generated at this voltage is stepped upto 132 kV, 220kV, 400kV.
iii) As the transmission of electric power at high voltages have so many advantages, viz; saving of conducting material, high transmission efficiency and less sineloss.

2. **PrimaryTransmission:**

i) The electric power at high voltage (say 132 kV) is transmitted by 3 phase, 3 wire i) The primary transmission line terminates at the receiving station, which usually lies at the outsides of the city at the receiving station, the voltage is reduced is reduced to 33 kV by 3 phase, 3 wire over head system to various sub stations located at the strategic points in the city. This forms secondary transmission.

1. Primary Distribution:

i) The secondary transmission line terminates at the sub station where voltage is reduced from 33 kV to 11 kV 3 phase 3 wire.

ii) The 11 kV line runs along the important roadsides of the city. This forms the primary Distribution.

2. Secondary Distribution:

i) The electric power from primary distribution line is delivered to distribution sub stations.

ii) These sub stations are located near the consumer localities and step down the voltage to 400 V and between any phase and neutral is 230V.

iii) The 3 phase residential lighting load is connected between any one phase and neutral whereas 3 phase 400V motor loads are connected across 3 phase lines directly.

(v) Has less corona loss and reduced interference with communication circuits.

(vii) The high voltage d.c. transmission is free from the dielectric losses, particularly in the case of cables.

(viii) In d.c. transmission, there are no stability problems and synchronising difficulties.

Disadvantages:

(i) Electric power cannot be generated at high d.c. voltage due to commutation problems.

(ii) The d.c. voltage cannot be stepped up for transmission of power at high voltages.

(iii)The d.c. switches and circuit breakers have their own limitations. Overhead system to the outskirts of the city. This form the primary transmission.

2. Explain the advantages and disadvantages of EHVAC transmission system.

Advantages of High Transmission Voltage

(i) Reduces volume of conductor material

(ii) Increases transmission efficiency

(iii) Decreases percentage line drop.

(i) Reduces volume of conductor material.

V = line voltage in volts

$\cos\varphi$ = power factor of the load

l = length of the line in metres

R = resistance per conductor in ohms ρ

= resistivity of conductor material

a = area of X-section of conductor

$$\text{Load current, } I = \frac{P}{\sqrt{3}\, V \cos\phi}$$

$$\text{Resistance/conductor, } R = \rho l/a$$

$$\text{Total power loss, } W = 3I^2 R = 3\left(\frac{P}{\sqrt{3}\, V\cos\phi}\right)^2 \times \frac{\rho l}{a}$$

$$= \frac{P^2 \rho l}{V^2 \cos^2\phi\, a}$$

$$\therefore \quad \text{Area of X-section, } a = \frac{P^2 \rho l}{W V^2 \cos^2\phi}$$

Total volume of conductor material required

$$= 3\, a\, l = 3\left(\frac{P^2 \rho\, l}{W V^2 \cos^2\phi}\right) l$$

$$= \frac{3 P^2 \rho l^2}{W V^2 \cos^2\phi} \qquad \ldots(i)$$

It is clear from exp. (*i*) that for given values of *P*, *l*, ρ and *W*, the volume of conductor material required is inversely proportional to the square of transmission voltage and power factor. In other words, the greater the transmission voltage, the lesser is the conductor material required

(ii) Increases transmission efficiency

$$\text{Input power} = P + \text{Total losses}$$

$$= P + \frac{P^2 \rho\, l}{V^2 \cos^2\phi\, a}$$

Assuming J to be the current density of the conductor, then,

$$a = I/J$$

$$\therefore \quad \text{Input power} = P + \frac{P^2 \rho\, l\, J}{V^2 \cos^2\phi\, I} = P + \frac{P^2 \rho\, l\, J}{V^2 \cos^2\phi} \times \frac{1}{I}$$

$$= P + \frac{P^2\, \rho\, l\, J}{V^2 \cos^2\phi} \times \frac{{}^{*}\sqrt{3}\, V \cos\phi}{P}$$

$$= P + \frac{\sqrt{3}\, P\, J\, \rho\, l}{V \cos\phi} = P\left[1 + \frac{\sqrt{3}\ J\, \rho\, l}{V\cos\phi}\right]$$

$$\text{Transmission efficiency} = \frac{\text{Output power}}{\text{Input power}} = \frac{P}{P\left[1 + \frac{\sqrt{3}\ J\rho\, l}{V\cos\phi}\right]} = \frac{1}{\left[1 + \frac{\sqrt{3}\ J\rho\, l}{V\cos\phi}\right]}$$

$$= {}^{**}\left[1 - \frac{\sqrt{3}\ J\rho\, l}{V\cos\phi}\right] \text{ approx.} \qquad \ldots(ii)$$

As J, ρ and l are constants, therefore, transmission efficiency increases when the line voltage is increased.

(iii) Decreases percentage line drop

$$\text{Line drop} = I\,R = I \times \frac{\rho\, l}{a}$$

$$= I \times \rho\, l \times J/I = \rho\, l\, J \qquad [\because a = I/J]$$

$$\text{\%age line drop} = \frac{J\rho\, l}{V} \times 100 \qquad \ldots(iii)$$

As J, ρ and l are constants, therefore, percentage line drop decreases when the transmission voltage increases.

Limitations of high transmission voltage. From the above discussion, it might appear advis- able to use the highest possible voltage for transmission of power in a bid to save conductor material. However, it must be realised that high transmission voltage results in

(i) The increased cost of insulating the conductors

(ii) The increased cost of transformers, switchgear and other terminal apparatus.

Therefore, there is a limit to the higher transmission voltage which can be economically employed in a particular case. This limit is reached when the saving in cost of conductor material due to higher voltage is offset by the increased cost of insulation, transformer, switchgear etc.

3. Derive the expression for Volume of copper conductor material required for DC and AC Distributors. Comparison of Conductor Material in Overhead system:

In comparing the relative amounts of conductor material necessary for different systems of transmission, similar conditions will be assumed in each case *viz*.,

(i) Same power (*P watts*) transmitted by eachsystem.

(ii) The distance (*l metres*) over which power is transmitted remains thesame.

(iii) The line losses (W watts) are the same in eachcase.

(iv) The maximum voltage between any conductor and earth (V_m) is the same in eachcase.

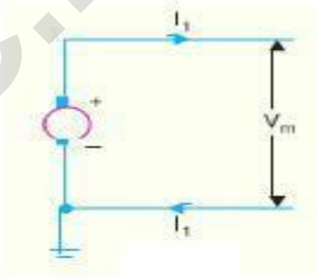
1. **Two-wire d.c. system with one conductorearthed**

In the 2-wire d.c. system, one is the outgoing or positive wire and the other is the return or negative wire as shown in Fig.1.2. The load is connected between the two wires.

Max. voltage between conductors=

V_m Power to be transmitted = P

Load current, $I_1 = P/V_m$



If R1 is the resistance of each line conductor, then,

$$R_1 = l/a_1$$

wherea1 is the area of X-section of the conductor

$$\text{Line losses,} \quad W = 2I_1^2 R_1 = 2\left(\frac{P}{V_m}\right)^2 \rho \frac{l}{a_1}$$

$$\therefore \quad \text{Area of X-section, } a_1 = \frac{2P^2\rho l}{W V_m^2}$$

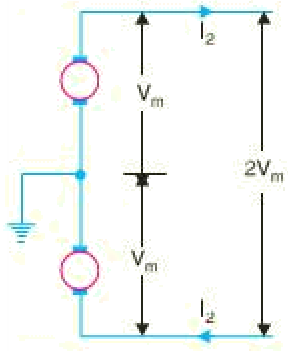
Volume of conductor material required

$$= 2a_1 l = 2\left(\frac{2P^2\rho l}{W V_m^2}\right) l = \frac{4P^2\rho l^2}{W V_m^2}$$

It is a usual practice to make this system as the basis for comparison with other systems. Therefore, volume of conductor material required in this system shall be taken as the basic quantity *i.e.*

$$\frac{4P^2\rho l^2}{W V_m^2} = K \text{ (say)}$$

2. **Two-wire d.c. system with mid-point earthed.** Fig.1.3 shows the two-wire d.c. system with mid-point earthed. The maximum voltage between any conductor and earth is V_m so that maximum voltage between conductors is $2V_m$.



Load current, I2= P/2Vm

Let a_2 be the area of X-section of the conductor.

$$\text{Line losses, } W = 2I_2^2\,R_2 = 2\left(\frac{P}{2\,V_m}\right)^2 \times \frac{\rho l}{a_2}$$
$$[\because R_2 = \rho\, l/a_2]$$

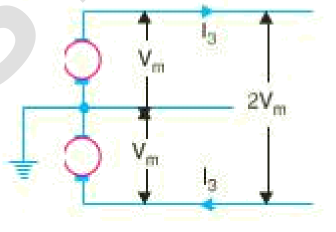
$$\therefore \qquad W = \frac{P^2 \rho\, l}{2a_2\,V_m^2}$$

Hence, the volume of conductor material required in this system is *one-fourth* of that required in a two-wire d.c. system with one conductor earthed

3. **Three-wire d.c. system.** In a 3-wire d.c. system, there are two outers and a middle or neutral wire which is earthed at the genera - tor end as shown in Fig. 1.4. If the load is balanced, the current in the neutral wire is zero. Assuming balancedloads,

   Load current, $I3 = P/2Vm$

   Let a3 be the area of X-section of each outer wire.



$$\text{Line losses, } W = 2I_3^{\,2} R_3 = 2\left(\frac{P}{2\,V_m}\right)^2 \times \rho\,\frac{l}{a_3} = \frac{P^2\rho\, l}{2\,V_m^2\,a_3}$$

$$\therefore \qquad \text{Area of X-section, } a_3 = \frac{P^2\rho\, l}{2\,W\,V_m^2}$$

Assuming the area of X-section of neutral wire to be half that of the outer wire,

Volume of conductor material required

$$= 2{\cdot}5\,a_3\,l = 2{\cdot}5\left(\frac{P^2\rho\, l}{2\,W\,V_m^2}\right)l = \frac{2{\cdot}5}{2}\left(\frac{P^2\rho\, l^2}{W\,V_m^2}\right)$$

$$= \frac{5}{16}K \qquad \left[\because K = \frac{4P^2\rho l^2}{W\,V_m^2}\right]$$

Hence the volume of conductor material required in this system is 5/16th of what is required for a 2-wire d.c. system with one conductor earthed.

4. **Single phase 2-wire a.c. system with one conductor earthed.** Fig. 1.5. shows a single phase 2-wire a.c. system with one conductor earthed. The maximum voltage between conductors is Vm so that r.m.s. value of voltage between them is √ . Assuming the load power factor to be cos ϕ,

$$\text{Load current, } I_4 = \frac{P}{(V_m/\sqrt{2})\cos\phi} = \frac{\sqrt{2}\,P}{V_m\cos\phi}$$

Let a_4 be the area of X-section of the conductor.

$$\therefore \quad \text{Line losses, } W = 2 I_4^2 R_4 = 2\left(\frac{\sqrt{2}\,P}{V_m\cos\phi}\right)^2 \times \frac{\rho l}{a_4} = \frac{4P^2\rho l}{\cos^2\phi\, V_m^2\, a_4}$$

$$\therefore \quad \text{Area of X-section, } a_4 = \frac{4P^2\rho l}{\cos^2\phi\, W V_m^2}$$

Volume of conductor material required

$$= 2 a_4 l = 2\left(\frac{4P^2\rho l}{V_m^2 W\cos^2\phi}\right) l$$

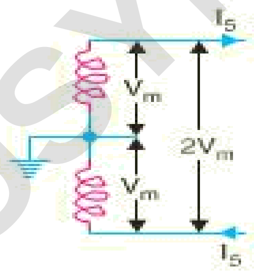
$$= \frac{2}{\cos^2\phi} \times \frac{4P^2\rho l^2}{W V_m^2}$$

$$= \frac{2K}{\cos^2\phi} \qquad \left[\because K = \frac{4P^2\rho l^2}{W V_m^2}\right]$$

Hence the volume of conductor material required in this system is 2/cos2ϕtimes that of 2-wire d.c. system with the one conductor earthed.

5. **Single phase 2-wire system with mid-point earthed.** Fig. 1.6. shows a single phase a.c. system with mid point earthed. The two wires possess equal and opposite voltages to earth

   (*i.e.,* Vm). Therefore, the maximum voltage between the two wires is $2Vm$. The r.m.s. value of voltage between conductors is Assuming the power factor of the loadto be cosϕ,



$$\text{Load current, } I_5 = \frac{P}{\sqrt{2}\,V_m\cos\phi}$$

Let a_5 be the area of X-section of the conductor.

$$\text{Line losses, } W = 2 I_5^2 R_5 = 2\left(\frac{P}{\sqrt{2}\,V_m\cos\phi}\right)^2 R_5$$

$$\therefore \quad W = \frac{P^2\rho l}{a_5 V_m^2\cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_5 = \frac{P^2\rho l}{W V_m^2\cos^2\phi}$$

Volume of conductor material required

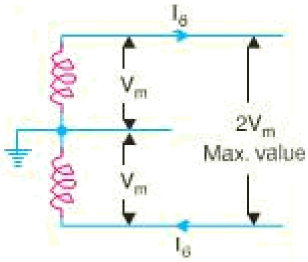
$$= 2 a_5 l = 2\left(\frac{P^2\rho l}{W V_m^2\cos^2\phi}\right) l = \frac{2P^2\rho l^2}{W V_m^2\cos^2\phi}$$

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

$$= \frac{K}{2\cos^2\phi} \qquad \left[\because K = \frac{4P^2\rho l^2}{W V_m^2}\right]$$

Hence the volume of conductor material required in this system is 1/2 cos2 ϕtimes that of 2-wire d.c. system with one conductor earthed.

1. Single phase, 3-wire system. The single phase 3-wire system is identical in principle with 3-wire d.c. system. The system consists of two outers and neutral wire taken from the mid-point of the phase winding as shown in Fig. 1.7. If the load is balanced, the current through the neutral wire is zero. Assuming balancedload,



Max. voltage between conductors = 2 Vm

R.M.S. value of voltage between conductors $= 2V_m / \sqrt{2} = \sqrt{2}V_m$

If the p.f of the load is cos ϕ, then,

$$\text{Load current, } I_6 = \frac{P}{\sqrt{2}\, V_m \cos\phi}$$

Let a_6 be the area of X-section of each outer conductor.

$$\text{Line losses, } W = 2 I_6^2 R_6 = 2\left(\frac{P}{\sqrt{2}\, V_m \cos\phi}\right)^2 \times \frac{\rho l}{a_6}$$

$$= \frac{P^2 \rho l}{a_6 V_m^2 \cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_6 = \frac{P^2 \rho l}{W V_m^2 \cos^2\phi}$$

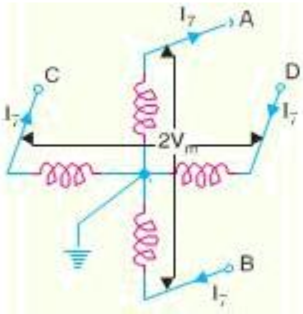
Assuming the area of X-section of neutral wire to be half that of the outer wire, Volume of conductor material required

$$= 2{\cdot}5\, a_6 l = 2{\cdot}5\left(\frac{P^2 \rho l}{W V_m^2 \cos^2\phi}\right) l = \frac{2\cdot 5\, P^2 \rho l^2}{W V_m^2 \cos^2\phi}$$

$$= \frac{2\cdot 5}{\cos^2\phi} \times \frac{P^2 \rho l^2}{W V_m^2}$$

$$= \frac{5K}{8\cos^2\phi} \qquad \left[\because K = \frac{4P^2 \rho l^2}{W V_m^2}\right]$$

2. Two phase, 4-wire a.c. system. As shown in Fig. 1.8. the four wires are taken from the ends of the two-phase windings and the mid-points of the two windings are connected together. This system can be considered as two independent single phase systems, each trans- mitting one half of the totalpower.



Max. voltage between outers A and B $=2Vm$

R.M.S. value of voltage $= 2V_m/\sqrt{2} = \sqrt{2}\,V_m$

Power supplied per phase (*i.e.*, by outers A and B) $= P/2$

Assuming p.f. of the load to be $\cos\phi$,

$$\text{Load current, } I_7 = \frac{P/2}{\sqrt{2}\,V_m\cos\phi} = \frac{P}{2\sqrt{2}\,V_m\cos\phi}$$

Let a_7 be the area of X-section of one conductor.

$$\text{Line losses, } W = 4\,I_7^2\,R_7 = 4\left(\frac{P}{2\sqrt{2}\,V_m\cos\phi}\right)^2 \times \frac{\rho\,l}{a_7}$$

$$\therefore \quad W = \frac{P^2\,\rho\,l}{2a_7\,V_m^2\cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_7 = \frac{P^2\,\rho\,l}{2\,W\,V_m^2\cos^2\phi}$$

$\therefore$ Volume of conductor material required

$$= 4\,a_7\,l$$

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

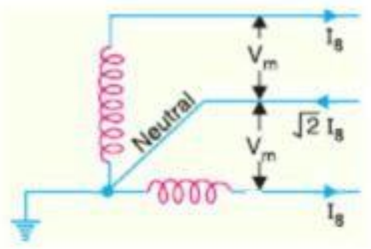
$$= \frac{1}{2\cos^2\phi} \times \frac{4P^2\,\rho\,l^2}{W\,V_m^2}$$

$$= \frac{K}{2\cos^2\phi} \qquad \left[\because K = \frac{4P^2\,\rho\,l^2}{W\,V_m^2}\right]$$

Hence, the volume of conductor material required for this system is $1/2\cos^2\phi$ times that of 2- wire d.c. system with one conductor earthed.

3. Two-phase, 3-wire system. Fig. 1.9. shows two-phase, 3-wire a.c. system. The third or neutral wire is taken from the junction of two-phase windings whose voltages are in quadrature with each other.Obviously, each phase transmits one half of the total power. The R.M.S. voltage between outgoing conductor and neutral

$$\therefore \quad \text{Current in each outer, } I_8 = \frac{P/2}{\frac{V_m}{\sqrt{2}}\cos\phi} = \frac{P}{\sqrt{2}\, V_m \cos\phi}$$



$$\text{Current in neutral* wire} = \sqrt{I_8^2 + I_8^2} = \sqrt{2} I_8$$

Assuming the current density to be constant, the area of X-section of the neutral wire will be times that of either of the outers. Current in the neutral wire is the phasor sum of currents in the outer wires. Now, the currents in the outers are in quadrature (*i.e.*, 90 degree apart) with each other.Since the neutral wire carries √ times the current in each of the outers, its X-section must be increased in the same ratio to maintain the same current density.

$$\therefore \quad \text{Resistance of neutral wire} = \frac{R_8}{\sqrt{2}} = \frac{\rho l}{\sqrt{2}\, a_8}$$

$$\text{Line losses, } W = 2 I_8^2 R_8 + \left(\sqrt{2}\, I_8\right)^2 \frac{R_8}{\sqrt{2}} = I_8^2 R_8 \left(2 + \sqrt{2}\right)$$

$$= \left(\frac{P}{\sqrt{2}\, V_m \cos\phi}\right)^2 \times \frac{\rho l}{a_8}\left(2 + \sqrt{2}\right)$$

$$\therefore \quad W = \frac{P^2 \rho l}{2\, a_8 V_m^2 \cos^2\phi}\left(2 + \sqrt{2}\right)$$

$$\therefore \quad \text{Area of X-section, } a_8 = \frac{P^2 \rho l}{2W V_m^2 \cos^2\phi}\left(2 + \sqrt{2}\right)$$

Volume of conductor material required

$$= 2\, a_8 l + \sqrt{2}\, a_8 l = a_8 l \left(2 + \sqrt{2}\right)$$

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

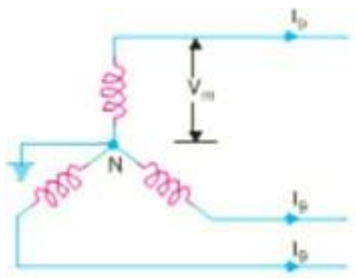
$$= \frac{1 \cdot 457}{\cos^2\phi} K \qquad \left[\because K = \frac{4P^2 \rho l^2}{W V_m^2}\right]$$

Hence, the volume of conductor material required for this system is $1\cdot457/\cos^2\phi$ times that of 2-wire d.c. system with one conductor earthed.

4. 3-Phase, 3-wire system. This system is almost universally adopted for transmission of electricpower.The3-phase,3wire system may be star connected or delta connected.Fig.1.10 shows 3-phase, 3-wire star connected system. The neutral point N is earthed. The same result will be obtained if Δ-connected system is considered.

Power transmitted per phase = $P/3$

Load current per phase, $I_9 = \dfrac{P/3}{\left(V_m/\sqrt{2}\cos\phi\right)} = \dfrac{\sqrt{2}\,P}{3\,V_m\cos\phi}$



Let a_9 be the area of X-section of each conductor.

$$\text{Line losses, } W = 3\,I_9^2\,R_9 = 3\left(\frac{\sqrt{2}\,P}{3\,V_m\cos\phi}\right)^2\frac{\rho\,l}{a_9} = \frac{2\,P^2\,\rho\,l}{3\,a_9\,V_m^2\cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_9 = \frac{2\,P^2\,\rho\,l}{3\,W\,V_m^2\cos^2\phi}$$

Volume of conductor material required

$$= 3\,a_9\,l = 3\left(\frac{2\,P^2\,\rho\,l}{3\,W\,V_m^2\cos^2\phi}\right)l = \frac{2\,P^2\,\rho\,l^2}{W\,V_m^2\cos^2\phi}$$

$$= \frac{0{\cdot}5\,K}{\cos^2\phi} \qquad \left[\because K = \frac{4P^2\,\rho\,l^2}{W\,V_m^2}\right]$$

Hence, the volume of conductor material required for this system is 0·5/cos2ϕtimes that required for 2-wire d.c. system with one conductor earthed.

10. 3-phase, 4-wire system. In this case, 4th or neutral wire is taken from the neutral point as shown in Fig.1.11 The area of X-section of the neutral wire is generally one-half that of the line conductor. If the loads are balanced, then current through the neutral wire is zero. Assuming balanced loads and p.f. of the load as cosϕ,

Line losses, W = Same as in 3 phase, 3-wire

$\therefore$ Volume of conductor material required

$$= 3{\cdot}5\,a_{10}\,l = 3{\cdot}5\left(\frac{2\,P^2\,\rho\,l}{3\,W\,V_m^2\cos^2\phi}\right)\times l$$

$$= \frac{7\,P^2\,\rho\,l^2}{3\,W\,V_m^2\cos^2\phi} = \frac{7}{3\cos^2\phi}\times\frac{P^2\rho\,l^2}{W\,V_m^2}$$

$$= \frac{7\,K}{12\cos^2\phi} \qquad \left[\because K = \frac{4P^2\,\rho\,l^2}{W\,V_m^2}\right]$$

4. Compare EHVAC and HVDC transmission system.

Comparison of HVDC and EHVAC Transmission

The relative merits of the two modes of transmission which need to be considered by a system is based on the following factors:

1. Economics oftransmission
2. Technicalperformance
3. Reliability

1. Economics of transmission

(i) Investment cost

(ii) Operational cost

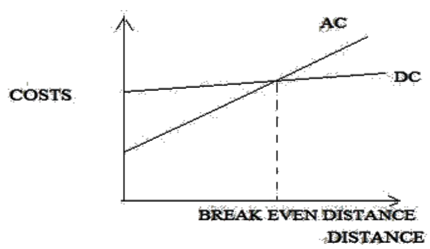
Investment Cost

It includes cost of right of way, transmission towers, conductors, insulators and terminal equipment.

Operational Cost

Mainly includes the cost of losses.

- The characteristics of insulators vary with the type of voltage applied.
- DC line can carry power with two conductors whereas AC needs three conductors.
- For a given power level, DC line requires less Right of Way, simpler and cheaper towers and reduced conductor and insulator costs.
- Power losses are also reduced in DC as there are only two conductors.
- Absence of skin effect with DC is also beneficial in reducing power losses.
- Corona effects tend to be less significant on DC conductors than for AC
- AC tends to be more economical for less than breakeven distance and costlier for longer distances
- Breakeven distances can vary from 500 to 800km in overhead lines depending on the per unit line costs

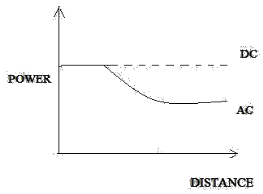


2. TechnicalPerformance

- Full control over powertransmitted.
- Ability to enhance transient and dynamic stability in associated ACnetworks.
- Fast control to limit fault currents in DC lines. This makes it feasible to avoidDC breakers.

Stability Limits

- Power transfer in AC lines is dependent on the angle difference between voltagephasors at twoends.
- Maximum power transfer is limited by the considerations of steady state and transient stability



Voltage Control

- Voltage control in AC is complicated by line charging and inductive voltagedrops.
- Voltage profile in AC is relatively flat only for a fixed level of power transfer corresponding to surge impedanceloading.
- Voltage profile varies with theloading
- Reactive power requirements increase with the increase in linelengths
- DC converter stations require reactive power related to the line loadings, the line itself does not require reactivepower.

Line Compensation

- AC line requires shunt and series compensation in long distance transmission, mainly to overcome the problems of line charging and stabilitylimitations
- Increase in power transfer and voltage control is possible through the use of staticVAR systems
- In AC cable transmission, it is necessary to provide shunt compensation at regular intervals. It is a serious problem in undergroundcables.

Problems of AC Interconnection

- When two power systems are connected through AC ties, the automatic generation control of both systems have to be coordinated using tie line power and frequency signals.
- Even with coordinated control of interconnected systems, the operation of AC ties can be problematic due to presence of large power oscillations which can lead to frequent tripping, increase in fault level, transmission of disturbances from one system toanother
- Controllability of power flow in DC lines eliminates all the aboveproblems.

Ground Impedance

- In AC transmission the existence of ground current cannot be permitted in steady-state due to high magnitudes of ground impedance which will not only affect efficient power transfer but also telephoneinterference
- This is negligible for DC currents and a DC link can operate using one conductorwith ground return

- While operating in mono polar mode, the AC network feeding the DC converterstation operates with balanced voltages andcurrents.

3. Reliability

- Reliability of DC system is quite good and comparable to that ofAC
- Performance of thyristor values is much more reliable than mercury arc values and further developments in devices, control and protection is likely to improve the reliability

Applications of HVDC Transmission.

- Long distance bulk powertransmission
- Underground or under watercables
- Asynchronous interconnection of AC system operating at different frequencies or where independent control of system isdesired
- Control and stabilization of power flows in AC ties in an integrated powersystem.
- Testing of HVAC cables of longlength
- Electrostatic precipitation of aching in thermal powerplants
- Electrostaticpainting
- Cement industry and Communicationsystems

Distribution System

That part of power system which distributes electric power for local use is known as distribution system. In general, the distribution system is the electrical system between the substation fed by the Transmission system and the consumer's meters. It generally consists of feeders, distributors, and service mains. Fig. 12.1 shows the single line diagram of a typical low tension distribution system. i) Feeders A feeder is a conductor which connects the sub-station (or localized generating station) to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

(ii)Distributor

A distributor is a conductor from which tappings are taken for supply to the consumers. In Fig. AB, BC, CD and DA are the distributors. The current through a distributor is not constant because tappings are taken at various places along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 6% of rated value at the consumers' terminals.

(iii)Service mains

A service mains is generally a small cable which connects the distributor to the consumers' terminals.

A brief introduction to types of supporting structures and line conductors- convectional conductors; Aluminium conductor steel reinforced (ACSR), all-aluminum alloy conductor (AAAC) and All-aluminium conductor (AAC).

High temperature conductors; Thermal resistant aluminium alloy (ATI), super thermal resistant aluminium alloy (ZTAI), Gap type thermal resistant aluminium alloy Conductor steel reinforced (GTACSR), gap type super thermal resistant aluminium alloy conductor steel reinforced (GZTACSR). Bundle conductor and its advantages. Importance of sag, sag calculation- supports at same and different levels, effects of wind and ice. Line vibration and vibration dampers. Overhead line protection against lightening ground wires.

Aluminium conductor steel reinforced: Aluminium conductor steel-reinforced cable (ACSR) is a type of high-capacity, high-strength stranded conductor typically used in overhead power lines. The outer strands are high-purity aluminium, chosen for its good conductivity, low weight and low cost. The center strand is steel for additional strength to help support the weight of the conductor. Steel is higher strength than aluminium which allows for increased mechanical tension to be applied on the conductor. Steel also has lower elastic and inelastic deformation (permanent elongation) due to mechanical loading (e.g. wind and ice) as well as a lower coefficient of thermal expansion under current loading. These properties allow ACSR to sag significantly less than all-aluminium conductors As per the International Electrotechnical Commission (IEC) and The CSA Group (formerly the Canadian Standards Association or CSA) naming convention, ACSR is designated A1/S1AGap-type ZT-aluminum conductor steel reinforced (GZTACSR) uses heat-resistant aluminum over a steel core. A small annular Gap is maintained between a high-strength steel core and the first layer of aluminum alloy strands. The gap between the first layer trapezoidal shaped aluminum strands and the steel core is filled with high thermal resistant grease. The principle of the Gap type conductor is that it can be tensioned on the steel core alone during erection. This results in a conductor with a knee-point at the erection temperature. Above the knee point conductor will have a thermal expansion equal to that of steel, while below the knee point temperature it is that of a comparable ACSR. This construction allows for low sag properties above the erection temperature and good strength below the thermal knee point. Presence of heat resistant Zirconium aluminum alloy makes the conductor suitable for continuous operation at elevated temperature (up to 210oC) without affecting its mechanical and electrical properties. A bundle conductor is a conductor made up of two or more sub-conductors and is used as one phase conductor. For voltages greater than 220 kV it is preferable to use more than one conductor per phase which is known as Bundle conductor. There are many advantages of using bundled conductors in transmission lines. Bundled conductors are primarily employed to reduce the corona loss and radio interference. However they have several advantages: Bundled conductors per phase reduces the voltage gradient in the vicinity of the line. Thus reduces the possibility of the corona discharge.

1. Explain with neat sketch, the different types of insulators.

Types of Insulator

There are mainly three types of insulator likewise

(i) Pin Insulator

(ii) Suspension Insulator

(iii) StrayInsulator

In addition to that there are other two types of electrical insulator available mainly for low voltage application, i.e stay insulator and shackle insulator.

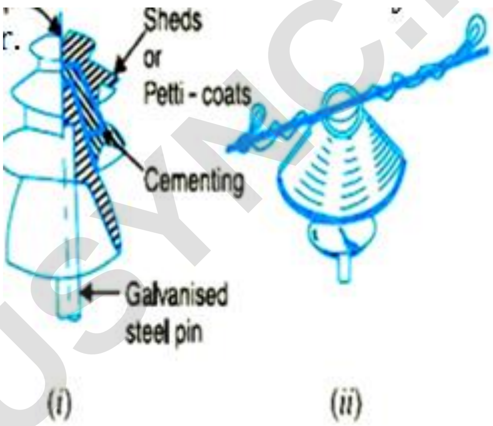
i) Pin Type Insulators

• The pin type insulator is secured to the cross-arm on the pole. There is a groove on the upper end of the insulator for housing the conductor.

• The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor.

• Pin type insulators are used for transmission and distribution of electric power at voltages up to33 kV.

Fig.4.4

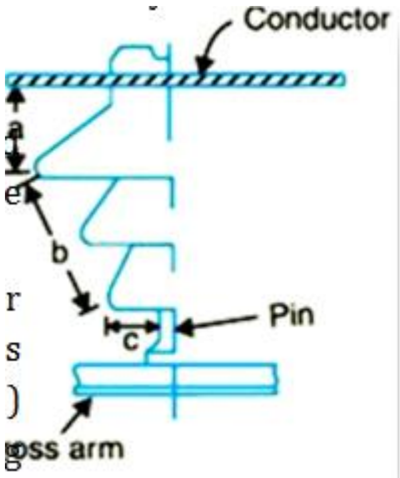


• Beyond operating voltage of 33kV, the pin type insulators become too bulky andhence uneconomical.

• Insulators are required to withstand both mechanical and electrical stresses. The latter type is primarily due to line voltage and may cause the breakdown of the insulator.

• The electrical breakdown of the insulator can occur either by flash-over or puncture. In flashover, an arc occurs between the line conductor and insulator pin (i.e., earth) and the discharge jumps across the air gaps, following shortest distance.

• Figure 4.5 shows the arcing distance (i.e. a + b + c) for the insulator. In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced Fig.4.5 by the arc destroys the insulator.



• In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat.

• In practice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flashover voltage is known as safety factor.

2. Suspension Type

• For high voltages (>33 kV), it is a usual practice to use suspension typeinsulators shown in Figure.

• Consist of a number of porcelain discs connected in series by metal links in the form of a string.

• The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross- arm of the tower.

• Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage.

• For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

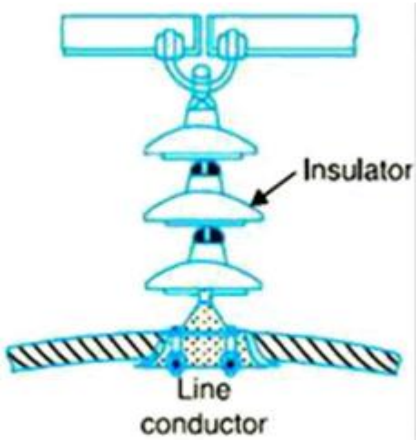


Fig.4.6

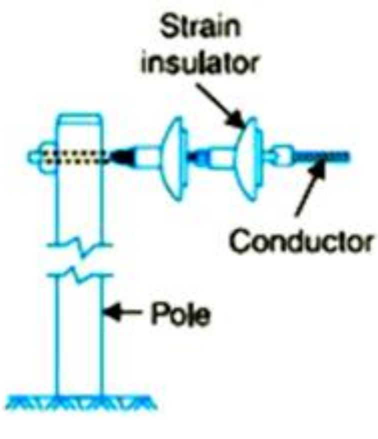
Advantages of suspension type:

- Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.
- Each unit or disc of suspension type insulator is designed for low voltage, usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in series.

- If anyone disc is damaged, the whole string does not become useless because the damaged disc can be replaced.
- The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.
- In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.
- The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

3. Strain Insulators:

- When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used.
- For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in Figure.4.7
- The discs of strain insulators are used in the vertical plane.
- When the tension in lines is exceedingly high, at long river Fig.4.7spans,two or more strings are used in parallel



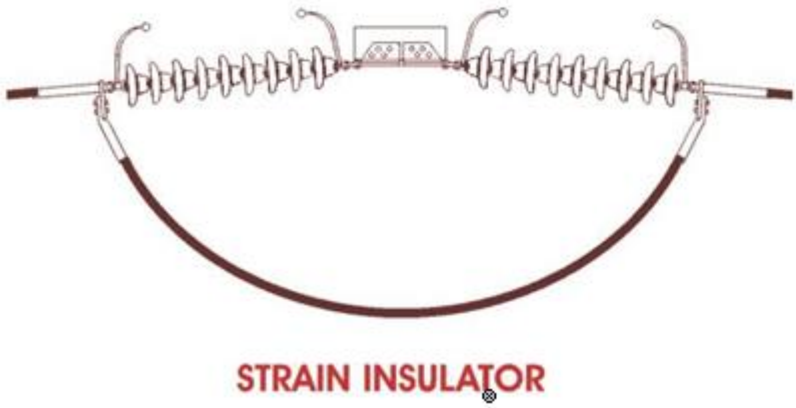
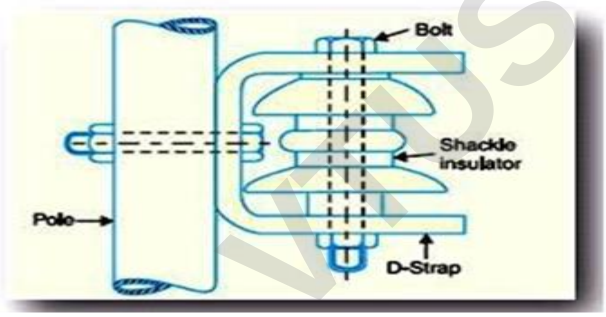
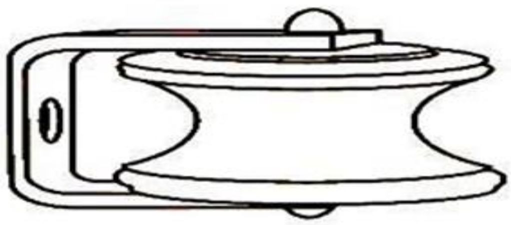


Fig.4.8

4. Shackle Insulators

- In early days, the shackle insulators were used as strain insulators. But now a day, they are frequently used for low voltage distribution lines.
- Suchinsulatorscanbeusedeitherinahorizontalpositionorinaverticalposition.They can be directly fixed to the pole with a bolt or to the cross arm.





5. Stay Insulator

For low voltage lines, the stays are to be insulated from ground at a height. The insulator used in the stay wire is called as the **stay insulator** and is usually of porcelain and is so designed that in case of breakage of the insulator the guy-wire will not fall to the ground. There are several methods of increasing the string efficiency or improving voltage distribution across different units of a string.

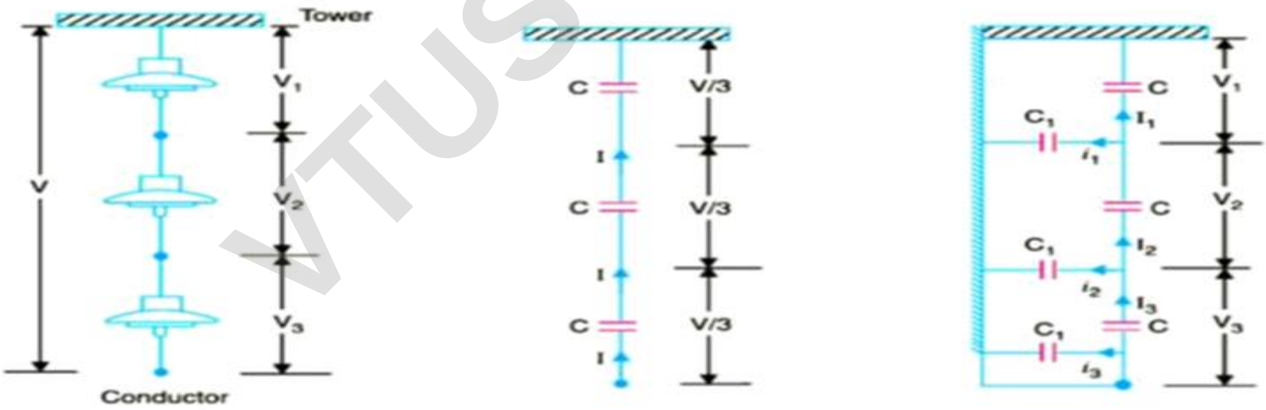
Fig.4.10

2. **Derive the expression for voltage distribution in insulator string and string efficiency. (ND13) Potential Distribution over Suspension Insulator String**

- A string of suspension insulators consists of a number of porcela in discs connected in series through metallic links. Fig.4.11(i) shows 3-disc string of suspension insulators.
- The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor C as shown in Fig.(ii) This is known as mutual capacitance.

If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same i.e., V/3 as shown infig4.11.(ii)

- However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as shunt capacitanceC1.
- Due to shunt capacitance, charging current is not the same through all the discs of the string Therefore, voltage across each disc will be different.
- Obviously, the disc nearest to the line conductor will have the maximum voltage. Thus referring to Fig V3 will be much more than V2 orV1.



The following points may be noted regarding the potential distribution over a string of suspension insulators:

- The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the presence of shunt capacitance.
- The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.
- The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured. Therefore, means must be provided to equalize the potential across each unit.
- If the voltage impressed across the string were d.c., then voltage across each unit would be the same. It is because insulator capacitances are ineffective ford..

String Efficiency

- As stated above, the voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs. The disc nearest to the conductor has much higher potential than the other discs.
- Thisunequalpotentialdistributionisundesirableandisusuallyexpressed intermsof string efficiency.
- The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as string efficiency i.e.,

$$\text{String efficiency} = \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc nearest to conductor}}$$

where n = number of discs in the string.

String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution. Thus 100% string efficiency is an ideal case for which the voltage across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible.

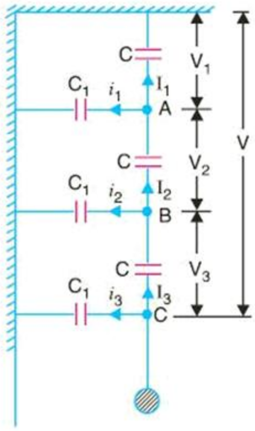


Fig. 4.12

Mathematical Expression. Fig. Shows the equivalent circuit for a 3-disc string. Let us suppose that self-capacitance of each disc is C. Let us further assume that shunt capacitance C1 is some fraction K of self-capacitance i.e., C1 =KC. Starting from the cross-arm or tower, the voltage across each unit is V1,V2 and V3 respectively as shown.

Applying Kirchhoff's current law to node *A*, we get,

$$I_2 = I_1 + i_1$$

or $$V_2 \omega C^* = V_1 \omega C + V_1 \omega C_1$$

or $$V_2 \omega C = V_1 \omega C + V_1 \omega K C$$

$\therefore$ $$V_2 = V_1 (1 + K) \quad ...(i)$$

Applying Kirchhoff's current law to node *B*, we get,

$$I_3 = I_2 + i_2$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2)\, \omega C_1 \dagger$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2)\, \omega K C$$

or $$V_3 = V_2 + (V_1 + V_2) K$$

$$= KV_1 + V_2 (1 + K)$$

$$= KV_1 + V_1 (1 + K)^2 \qquad [\because V_2 = V_1 (1 + K)]$$

$$= V_1 [K + (1 + K)^2]$$

$\therefore$ $$V_3 = V_1 [1 + 3K + K^2] \quad ...(ii)$$

Voltage between conductor and earth (*i.e.*, tower) is

$$V = V_1 + V_2 + V_3$$
$$= V_1 + V_1(1+K) + V_1(1+3K+K^2)$$
$$= V_1(3+4K+K^2)$$
$$\therefore \quad V = V_1(1+K)(3+K) \quad \text{...(iii)}$$

From expressions (*i*), (*ii*) and (*iii*), we get,

$$\frac{V_1}{1} = \frac{V_2}{1+K} = \frac{V_3}{1+3K+K^2} = \frac{V}{(1+K)(3+K)} \quad \text{...(iv)}$$

$$\therefore \text{Voltage across top unit, } V_1 = \frac{V}{(1+K)(3+K)}$$

$$\text{Voltage across second unit from top, } V_2 = V_1(1+K)$$
$$\text{Voltage across third unit from top, } V_3 = V_1(1+3K+K^2)$$
$$\text{\%age String efficiency} = \frac{\text{Voltage across string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100$$
$$= \frac{V}{3 \times V_3} \times 100$$

* Note that current through capacitor = $\dfrac{\text{Voltage}}{\text{Capacitive reactance}}$

† Voltage across second shunt capacitance C_1 from top = $V_1 + V_2$. It is because one point of it is connected to *B* and the other point to the tower.

Following Points May Be Noted From The Above Mathematical Analysis

(i) If K = 0•2 (Say), then from exp. (iv), we get, V2 = 1•2 V1 and V3 = 1•64 V1. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(ii) The greater the value of K (= C1/C), the more non-uniform is the potential across the discs and lesser is the string efficiency.

(iii) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one

3.Describe the various methods to improve string efficiency. (ND12, ND15, MJ16)

Methods of Improving String Efficiency

• It has been seen above that potential distribution in a string of suspension insulators is not uniform. The maximum voltage appears across the insulator nearest to the line conductor and decreases progressively as the cross arm is approached.

•Iftheinsulationofthehigheststressedinsulatorbreaksdownorflashovertakesplace, the breakdown of other units will take place in succession.

• This necessitates equalizing the potential across the various units of the string i.e. to improve the string efficiency. The various methods for this purpose are:

• The value of string efficiency depends upon the value of K i.e., ratio of shunt capacitance to mutual capacitance. The lesser the value of K, the greater is the string efficiency and more uniform is the voltage distribution.

• The value of K can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased i.e., longer cross-arms should be used.

•However, limitations of cost and strength of tower do not allow the use of very long cross-arms. In practice, K = 0•1 is the limit that can be achieved by this method.

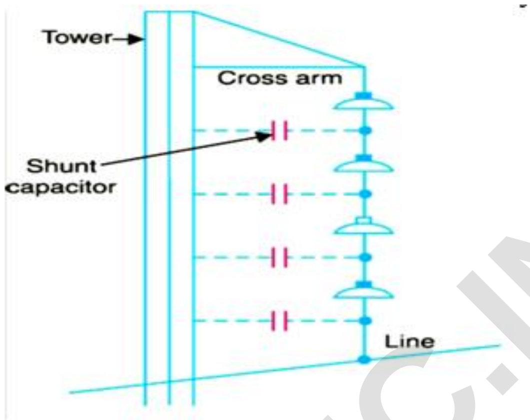


Fig.4.13

(II) By Grading The Insulators

•In this method, insulators of different dimensions are so chosen that each has a different capacitance.

• The insulators are capacitance graded i.e. they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (i.e., nearest to conductor) is reached. Since voltage is inversely proportional to capacitance, this method tends to equalize the potential distribution across the units in the string.

• This method has the disadvantage that a large number of different-sized insulators are required.

• However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line conductor.

(III) By Using A Guard Ring

• The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig

• The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents i1, i2 etc. are equal to metal fitting line capacitance currents i′1, i′2etc.

• The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.

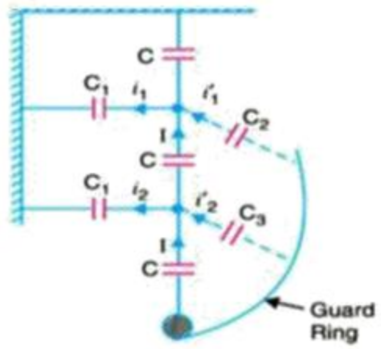
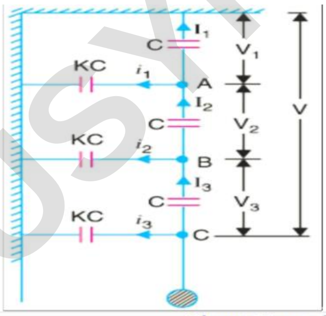


Fig.4.14

4. In a 33 kV overhead line, there are three units in the string of insulators. If the capacitance between each insulator pin and earth is 11% of self-capacitance of each insulator, find (i) the distribution of voltage over 3 insulators and (ii) string efficiency. (ND12)

Solution.Fig: shows the equivalent circuit of string insulators. Let V1, V2 and V3 be the voltage across top, middle and bottom unit respectively. If C is the self-capacitance of each unit, then KC will be the shunt capacitance.



$$K = \frac{\text{Shunt Capacitance}}{\text{Self - capacitance}} = 0.11$$

$$\text{Voltage across string, } V = 33/\sqrt{3} = 19{\cdot}05 \text{ kV}$$

At Junction A

$$I_2 = I_1 + i_1$$

or $$V_2 \omega C = V_1 \omega C + V_1 K \omega C$$

or $$V_2 = V_1(1+K) = V_1(1+0{\cdot}11)$$

or $$V_2 = 1{\cdot}11\, V_1 \qquad \ldots(i)$$

At Junction B

$$I_3 = I_2 + i_2$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2) K \omega C$$

or $$V_3 = V_2 + (V_1 + V_2) K$$

$$= 1{\cdot}11 V_1 + (V_1 + 1{\cdot}11\, V_1)\, 0{\cdot}11$$

$\therefore$ $$V_3 = 1{\cdot}342\, V_1$$

(*i*) Voltage across the whole string is

$$V = V_1 + V_2 + V_3 = V_1 + 1{\cdot}11\, V_1 + 1{\cdot}342\, V_1 = 3{\cdot}452\, V_1$$

or $$19{\cdot}05 = 3{\cdot}452\, V_1$$

$\therefore$ Voltage across top unit, $V_1 = 19{\cdot}05/3{\cdot}452 = \mathbf{5{\cdot}52\ kV}$

Voltage across middle unit, $V_2 = 1{\cdot}11\, V_1 = 1{\cdot}11 \times 5{\cdot}52 = \mathbf{6.13\ kV}$

Voltage across bottom unit, $V_3 = 1{\cdot}342\, V_1 = 1{\cdot}342 \times 5{\cdot}52 = \mathbf{7.4\ kV}$

(*ii*) $$\text{String efficiency} = \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{19\cdot05}{3 \times 7\cdot4} \times 100 = \mathbf{85.8\%}$$

6. A 3-phase transmission line is being supported by three disc insulators. The potentials across top unit (i.e., near to the tower) and middle unit are 8 kV and 11 kV respectively. Calculate (i) the ratio of capacitance between pin and earth to the self- capacitance of each unit (ii)the line voltage and (iii) string efficiency. (ND11)

Solution.The equivalent circuit of string insulators is the same as shown in previous Fig.It is given that V1 = 8 kV and V2 = 11 kV.

(i) Let K be the ratio of capacitance between pin and earth to self-capacitance. If C farad is the self-capacitance of each unit, then capacitance between pin and earth = KC. Applying Kirchoff's current law to Junction A,

$$I2 = I1 + i1$$

or $$V2\omega C = V1\omega C + V1K\omega C$$

or $$V2 = V1\,(1 + K)$$

$$\therefore \quad K = \frac{V_2 - V_1}{V_1} = \frac{11-8}{8} = 0{\cdot}375$$

(ii) Applying Kirchoff's current law to Junction B,

$$I_3 = I_2 + i_2$$

or $$V_3\,\omega\,C = V_2\,\omega\,C + (V_1 + V_2)\,K\,\omega\,C$$

or $$V_3 = V_2 + (V_1 + V_2)\,K = 11 + (8 + 11) \times 0{\cdot}375 = 18{\cdot}12 \text{ kV}$$

Voltage between line and earth $= V_1 + V_2 + V_3 = 8 + 11 + 18{\cdot}12 = 37{\cdot}12$ kV

$\therefore$ Line Voltage $= \sqrt{3} \times 37{\cdot}12 = 64{\cdot}28$ **kV**

(iii) String efficiency $$= \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{37{\cdot}12}{3 \times 18{\cdot}12} \times 100 = 68.28\%$$

PERFORMANCE TEST OF INSULATOR

Temperature Cycle Test of Insulator

• The insulator is first heated in water at 70oC for onehour.

• Then this insulator immediately cooled in water at 7oC for another onehour.

• This cycle is repeated for three times.

• After completion of these three temperature cycles, the insulator is dried andthe glazing of insulator is thoroughly observed.

• After this test there should not be any damaged or deterioration in the glaze of the insulator surface

Puncture Voltage Test of Insulator

• The insulator is first suspended in an insulating oil.

• Then voltage of 1.3 times of flash over voltage, is applied to the insulator.

• A good insulator should not puncture under this condition

Porosity Test of Insulator

• The insulator is first broken in to pieces.

• Then These broken piece of insulator are immersed in 0.5% alcohol solution of fuchsine dye under pressure of about 140.7 kg / cm2 for 24hours.

• After that the sample are removed and examine.

• The presence of as light porosity in the material is indicated by adeeppenetration of the dye in to it.

Mechanical Strength Test of Insulator

• The insulator is applied by 2½ times the maximum working strength for about one minute.

• The insulator must be capable of sustaining this much mechanical stress for one minute without any damage in it.

ROUTINE TEST OFINSULATOR

• Eachoftheinsulatormustundergothefollowingroutinetestbeforetheyare recommended for using at site.

Proof Load Test of Insulator

• Inproofloadtestofinsulator,aloadof20%inexcessofspecifiedmaximum working load is applied for about one minute to each of the insulator.

• Theinsulatorwithitsgalvanizedorsteelfittingsissuspendedintoacoppersulfate solution for one minute.

• Then the insulator is removed from the solution and wiped,cleaned.

• Again it is suspended into the copper sulfate solution for one minute.

• The process is repeated for four times.

• Then it should be examined and there should not be any disposition of metal onit.

1. Derive the expression for calculation of sag i)when supports are equal ii) When supports are not equal iii) Effect of ice and wind

Calculation of Sag

• In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits. The tension is governed by conductor weight, effects of wind, ice loading and temperature variations.

- It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength i.e., minimum factor of safety in respect of conductor tension should be2.
- Sag and tension of a conductor are calculated when

(i) supports are at equal level sand (ii) supports are at unequal levels.

(i) When supports are at equal levels.

- Consider a conductor between two equilevel supports A and B with O as the lowest point as shown inFig.5.2.
- It can be proved that lowest point will be at a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig. It can be proved that lowest point will be at themid-span.
- A conductor between two equilevel supports A and B with O as the lowest point as shown inFig.
- It can be proved that lowest point will beat the mid-span.

Let

l = Length of span

w = Weight per unit length of conductor Fig.5.2 T = Tension in the conductor.

- Consider a point P on the conductor. Taking the lowest pointO as the origin, let the co- ordinates of point P be x and y.
- Assuming that the curvature is so small that curved length is equal to its horizontal projection (i.e., OP = x), the two forces acting on the portion OP of the conductor are:

(a) The weight wx of conductor acting at a distance x/2 fromO.

(b) The tension T acting at O.

Equating the moments of above two forces about point O, we get,

(ii) When supports are at unequal levels.

In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig.5.3 shows a conductor suspended between two supports A and B which are at different levels. The lowest point on the conductor is O .

Let

l = Span length

h = Difference in levels between two supports

x 1 = Distance of support at lower level (i.e., A) from O x 2 = Distance of support at higher level (i.e. B) from O T = Tension in the conductor

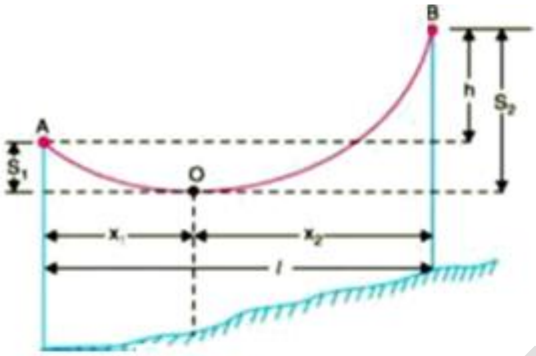


Fig.5.3

If w is the weight per unit length of the conductor, then,

$$\text{Sag } S_1 = \frac{w x_1^2}{2T}^{*}$$

$$\text{and} \qquad \text{Sag } S_2 = \frac{w x_2^2}{2T}$$

$$\text{Also} \qquad x_1 + x_2 = l \qquad \ldots(i)$$

$$^{*}\, y = \frac{w x^2}{2T}$$

At support A, $x = x_1$ and $y = S_1$.

$$\therefore \qquad S_1 = \frac{w x_1^2}{2T}$$

$$\text{Now} \qquad S_2 - S_1 = \frac{w}{2T}[x_2^2 - x_1^2] = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \qquad S_2 - S_1 = \frac{w\,l}{2T}(x_2 - x_1) \qquad [\because x_1 + x_2 = l]$$

$$\text{But} \qquad S_2 - S_1 = h$$

$$\therefore \qquad h = \frac{w\,l}{2T}(x_2 - x_1)$$

$$\text{or} \qquad x_2 - x_1 = \frac{2\,Th}{w\,l} \qquad \ldots(ii)$$

Solving exps. (i) and (ii), we get,

$$x_1 = \frac{l}{2} - \frac{T\,h}{w\,l}$$

$$x_2 = \frac{l}{2} + \frac{T\,h}{w\,l}$$

Having found x_1 and x_2, values of S_1 and S_2 can be easily calculated.

EFFECT OF WIND AND ICE LOADING

- The above formulae for sag are true only in still air and at normal temperature whenthe conductor is acted by its weightonly.
- However, in actual practice, a conductor may have ice coating and

simultaneously subjected to wind pressure. The weight of ice acts vertically downwards i.e. , in the same direction as the weight of conductor.

- The force due to the wind is assumed to act horizontally i.e ., at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown infig.5.4

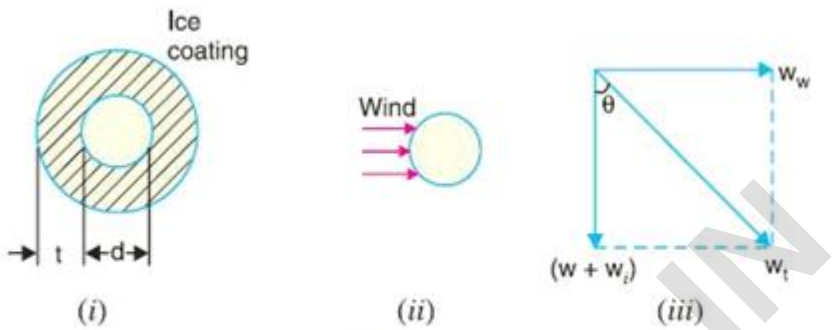


Fig.5.4

Total weight of conductor per unit length is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

where w = weight of conductor per unit length
= conductor material density × volume per unit length

w_i = weight of ice per unit length
= density of ice × volume of ice per unit length
= density of ice × $\frac{\pi}{4}[(d+2t)^2 - d^2] \times 1$
= density of ice × $\pi t (d+t)$*

w_w = wind force per unit length
= wind pressure per unit area × projected area per unit length
= wind pressure × $[(d + 2t) \times 1]$

* Volume of ice per unit length = $\frac{\pi}{4}[(d+t)^2 - d^2] \times 1 = \frac{\pi}{4}[4dt + 4t^2] = \pi t (d+t)$

When the conductor has wind and ice loading also, the following points may be noted : i)The conductor sets itself in a plane at an angle to the vertical where

$$\tan\theta = \frac{w_w}{w + w_i}$$

ii) The sag in the conductor is givenby

$$S = \frac{w_t l^2}{2T}$$

Hence S represents the slant sag in a direction making an angle to the vertical. If no specific mention is made in the problem, then slant slag is calculated by using the above formula.

(iii). The vertical sag=Scosθ

2.A 132 kV transmission line has the following data:

Wt. of conductor = 680 kg/km ; Length of span = 260 m Ultimate strength = 3100 kg ; Safety factor = 2

Calculate the height above ground at which the conductor should be supported. Ground clearance required is 10 metres

Solution.

Wt. of conductor/metre run, $w = 680/1000 = 0{\cdot}68$ kg

Working tension, $T = \dfrac{\text{Ultimate strength}}{\text{Safety factor}} = \dfrac{3100}{2} = 1550$ kg

Span length, $l = 260$ m

$$\therefore \quad \text{Sag} = \frac{w\,l^2}{8T} = \frac{0\cdot 68 \times (260)^2}{8 \times 1550} = 3\cdot 7 \text{ m}$$

∴ Conductor should be supported at a height of 10 + 3·7 = **13·7 m**

5. A transmission line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm². The tension in the conductor is 2000 kg. If the specific gravity of the conductor material is 9·9 gm/cm³ and wind pressure is 1·5 kg/m length, calculate the sag. What is the vertical sag?

Solution.

Span length, $l = 150$ m; Working tension, $T = 2000$ kg

Wind force/m length of conductor, $w_w = 1{\cdot}5$ kg

Wt. of conductor/m length, w = Sp. Gravity × Volume of 1 m conductor

$= 9{\cdot}9 \times 2 \times 100 = 1980$ gm $= 1{\cdot}98$ kg

Total weight of 1 m length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot 98)^2 + (1\cdot 5)^2} = 2\cdot 48 \text{ kg}$$

$$\therefore \quad \text{Sag, } S = \frac{w_t\, l^2}{8T} = \frac{2\cdot 48 \times (150)^2}{8 \times 2000} = \mathbf{3\cdot 48 \text{ m}}$$

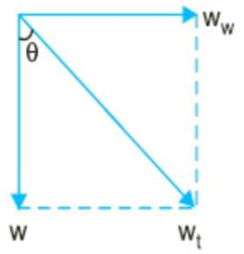
This is the value of slant sag in a direction making an angle θ with the vertical. Referring to Fig. the value of θ is given by ;

$$\tan\theta = w_w/w = 1\cdot 5/1\cdot 98 = 0\cdot 76$$

$$\therefore \quad \theta = \tan^{-1} 0\cdot 76 = 37\cdot 23°$$

$$\therefore \quad \text{Vertical sag} = S\cos\theta$$

$$= 3\cdot 48 \times \cos 37\cdot 23° = \mathbf{2\cdot 77 \text{ m}}$$



6. **A transmission line has a span of 275 m between level supports. The conductor has an effective diameter of 1·96 cm and weighs 0·865 kg/m. Its ultimate strength is 8060 kg. If the conductor has ice coating of radial thickness 1·27 cm and is subjected to awind pressure of 3·9 gm/ cm² of projected area, calculate sag for a safety factor of 2. Weight of 1 c.c. of ice is 0·91 gm.**

Solution.

Spanlength, l = 275m; Wt. of conductor/m length, w = 0·865 kg Conductor diameter, d = 1·96 cm ; Ice coating thickness, t = 1·27 cm Working tension, T = 8060/2 = 4030kg

3

$$= \pi t\,(d + t) \times 100 \text{ cm}$$

$$= \pi \times 1·27 \times (1·96 + 1·27) \times 100 = 1288 \text{ cm}^3$$

Weight of ice per metre length of conductor is

$$w_i = 0·91 \times 1288 = 1172 \text{ gm} = 1·172$$

kg Wind force/m length of conductor is

$$w_w = [\text{Pressure}] \times [(d + 2t) \times 100]$$

$$= [3·9] \times (1·96 + 2 \times 1·27) \times 100 \text{ gm} = 1755 \text{ gm}$$

$$= 1·755 \text{ kg}$$

Total weight of conductor per metre length of conductor is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

$$= \sqrt{(0·865 + 1·172)^2 + (1·755)^2} = 2·688 \text{ kg}$$

* Working stress $= \dfrac{\text{Ultimate Strength}}{\text{Safety factor}} = \dfrac{4218}{5}$

∴ Working Tension, T = Working stress × conductor area = 4218 × 1·29/5

$$\therefore \quad \text{Sag} = \frac{w_t\, l^2}{8T} = \frac{2·688 \times (275)^2}{8 \times 4030} = 6·3 \text{ m}$$

7. **A transmission line has a span of 214 metres between level supports.The conductors have a cross-sectional area of 3·225 cm². Calculate the factor of safety under the following conditions :Vertical sag = 2·35m;Wind pressure = 1·5 kg/m run Breaking Stress=2540kg/cm2 Wt. of conductor = 1·125 kg/m run.**

Solution.

Here, $l = 214$ m ; $w = 1{\cdot}125$ kg ; $w_w = 1{\cdot}5$ kg

Total weight of one metre length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1{\cdot}125)^2 + (1{\cdot}5)^2} = 1{\cdot}875 \text{ kg}$$

If f is the factor of safety, then,

$$\text{Working tension, } T = \frac{\text{Breaking stress} \times \text{conductor area}}{\text{safety factor}} = 2540 \times 3{\cdot}225/f = 8191/f \text{ kg}$$

$$\text{Slant Sag, } S = \frac{\text{Vertical sag}}{{}^{*}\cos\theta} = \frac{2{\cdot}35 \times 1{\cdot}875}{1{\cdot}125} = 3{\cdot}92 \text{ m}$$

Now $$S = \frac{w_t\, l^2}{8T}$$

or $$T = \frac{w_t\, l^2}{8\,S}$$

$\therefore$ $$\frac{8191}{f} = \frac{1{\cdot}875 \times (214)^2}{8 \times 3{\cdot}92}$$

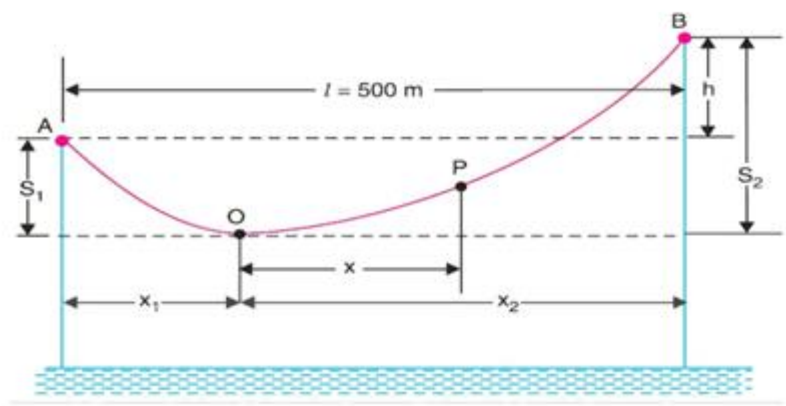
or Safety factor, $$f = \frac{8191 \times 8 \times 3{\cdot}92}{1{\cdot}875 \times (214)^2} = 3$$

8. The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance between the towers is 500 m. If the tension in the conductor is 1600 kg, find the minimum clearance of the conductor and water and clearance mid-way between the supports. Weight of conductor is 1.5 kg/m. Bases of the towers can be considered to be at water level.

Solution. Fig. shows the conductor suspended between two supports A and B at different levels with O as the lowest point on the conductor.

Here, l = 500 m ; w = 1•5 kg ; T = 1600kg. Difference in levels between supports, h = 90 □ 30 = 60 m. Let the lowest point O of the conductor be at a distance x1 from the support at lower level (i.e., support A) and at a distance x2 from the support at higher level (i.e., support B).

Obviously, $x1 + x2 = 500\text{m}$ ...(*i*)



Now $\quad \text{Sag } S_1 = \dfrac{w x_1^2}{2T}$ and $\text{Sag } S_2 = \dfrac{w x_2^2}{2T}$

$$\therefore \quad h = S_2 - S_1 = \frac{w x_2^2}{2T} - \frac{w x_1^2}{2T}$$

or $$60 = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \quad x_2 - x_1 = \frac{60 \times 2 \times 1600}{1 \cdot 5 \times 500} = 256 \text{ m} \qquad ...(ii)$$

Solving exps. (*i*) and (*ii*), we get, $x_1 = 122$ m; $x_2 = 378$ m

Now, $$S_1 = \frac{w x_1^2}{2T} = \frac{1 \cdot 5 \times (122)^2}{2 \times 1600} = 7 \text{ m}$$

Clearance of the lowest point *O* from water level

$$= 30 - 7 = \mathbf{23\ m}$$

Let the mid-point *P* be at a distance *x* from the lowest point *O*.

Clearly, $$x = 250 - x_1 = 250 - 122 = 128 \text{ m}$$

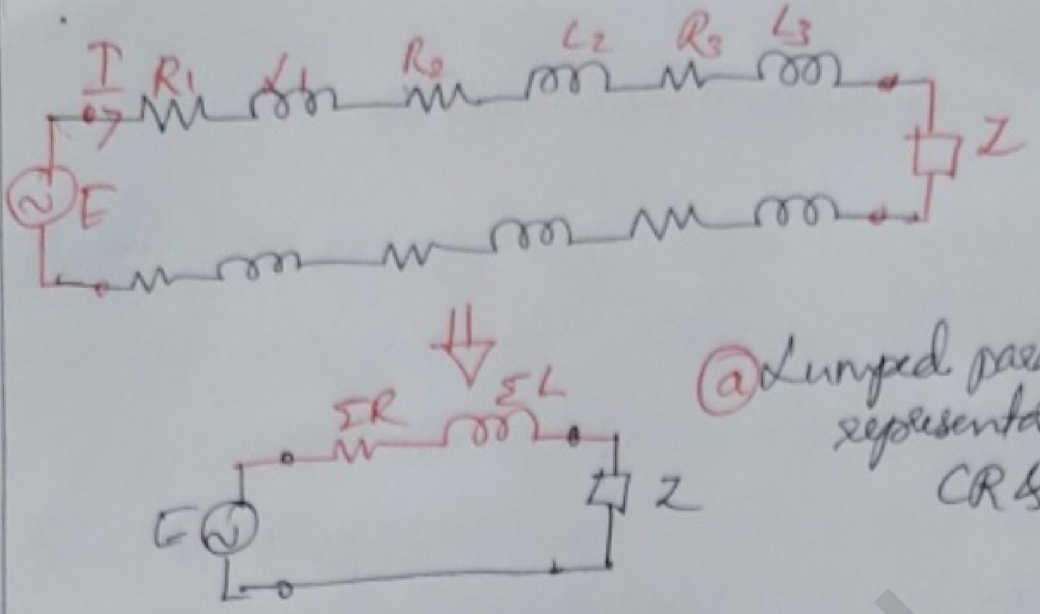
Sag at mid-point *P*, $$S_{mid} = \frac{w x^2}{2T} = \frac{1 \cdot 5 \times (128)^2}{2 \times 1600} = 7 \cdot 68 \text{ m}$$

Module-2

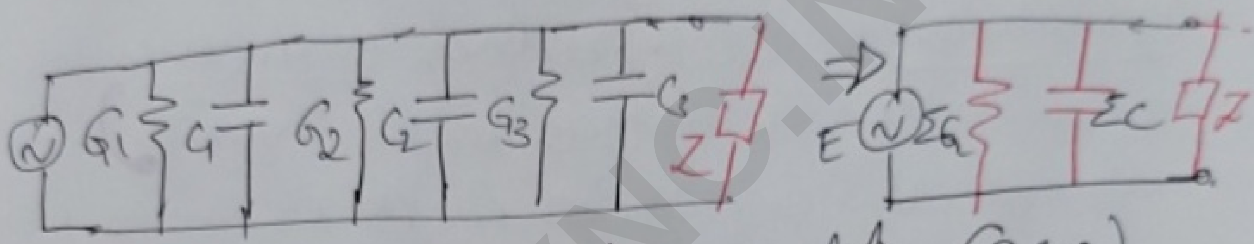
Transmission Line Parameters

* The electrical power generated in the generating station is transmitted with the help of transmission lines which are normally overhead.
* Transmission lines are basically circuits with distributed constants i.e., resistance, inductance, capacitance & ~~shunt capacitance~~ conductance (which is mostly due to leakage over the insulators) is almost always neglected in power transmission lines), are distributed along the whole length of line.
* The performance of these transmission lines is dependent on all these parameters. These parameters are uniformly distributed along the length of transmission line.
* The efficiency & voltage regulation whether it is good & poor is determined from these constants.
* Each small length at any section of the line will have its own values & concentration of all such parameters for the complete length of line into a single one is not possible.
* Some circuits which may have distributed parameters can be conveniently analysed by lumping the parameters

1

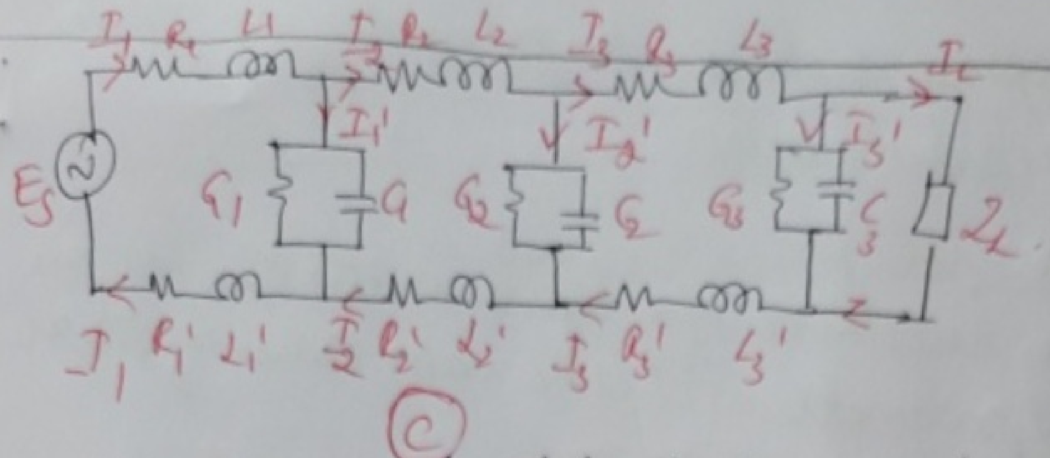


(a) Lumped parameter representation (R & L)

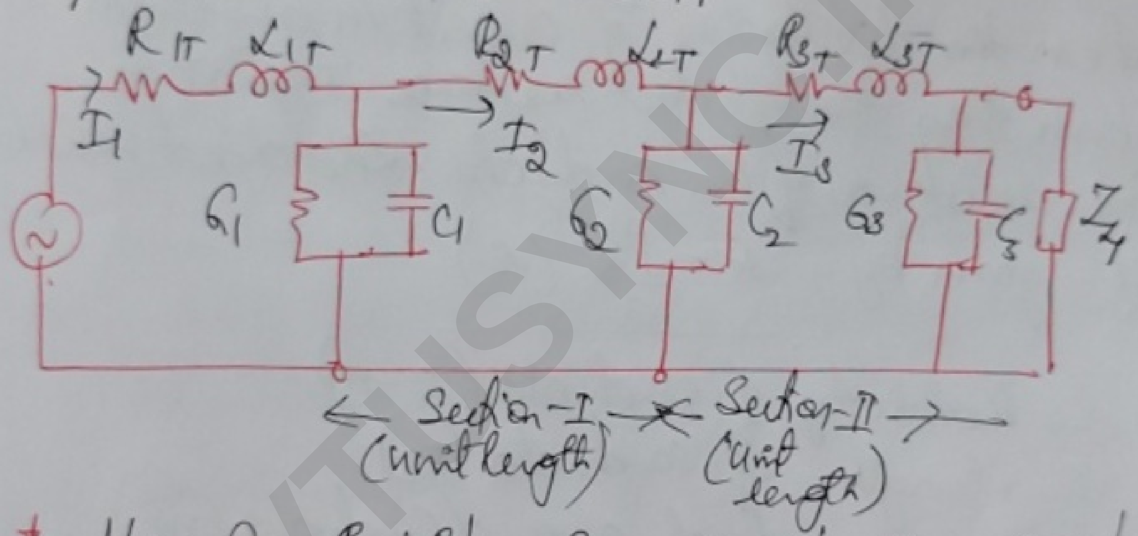


(b) Lumped parameter representation (G & C)

* Thus the series elements of resistance & inductance as shown in (a) can be considered equivalent as the same current is passing through each element of R & L.
* ll'ly circuits shown in (b) are equivalent for the same voltage is applied across each conductance & capacitance element.
* If the element are distributed as shown (c) then the elements cannot be lumped as the same current is not flowing through the series element & voltage across different elements changes from one section to other.



* The line is divided into large number of small sections of unit length. The upper & lower part of each section carries same current. Hence we have the equivalent circuit as shown.



* Here $R_{1T} = R_1 + R_1'$; $R_{2T} = R_2 + R_2'$; $R_{3T} = R_3 + R_3'$,
$L_{1T} = L_1 + L_1'$; $L_{2T} = L_2 + L_2'$; $L_{3T} = L_3 + L_3'$ etc

* The resistance per unit length of the line is say R.
where $R_{1T} = R_{2T} = R_{3T} = R$ Ω/m.
we have $L_{1T} = L_{2T} = L_{3T} = \ldots L$ H/m.
$G_1 = G_2 = \ldots G$ ℧/m
$C_1 = C_2 = \ldots C$ F/m.

In case of 2 wire transmission system the line parameters are expressed on Loop basis.

②

In a 3phase systems the parameters are represented on per conductor basis.

Resistance

The resistance of a transmission line is an important parameter as it is the main cause of power loss in a transmission line.

Effective resistance of a conductor is given by.

$$R = \frac{\text{Powerloss in conductor}}{I^2} (\Omega)$$

when the distribution of current in a conductor is uniform then the effective resistance is equal to d.c. resistance of the conductor. This direct resistance is given by. $R = \frac{\rho l}{a} (\Omega)$

$\rho \rightarrow$ Resistivity of conductor (Ω-m)

$l \rightarrow$ length of conductor (m)

$a \rightarrow$ cross-sectional area of conductor (m^2)

Inductance

Inductance of a conductor exists due to the flux distribution inside the conductor as well as the flux distribution outside the conductor.

1 The alternating flux produced by the alternating current when flowing through a conductor, links with the conductor.

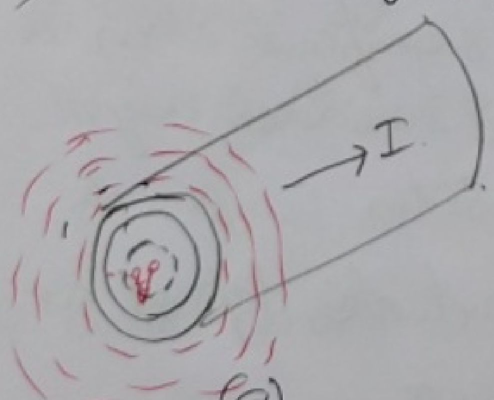
• The charge on the conductors at any point increases & decreases with increase & decrease of the instantaneous value of the voltage between the conductors at that point.

Inductance of a Conductor.

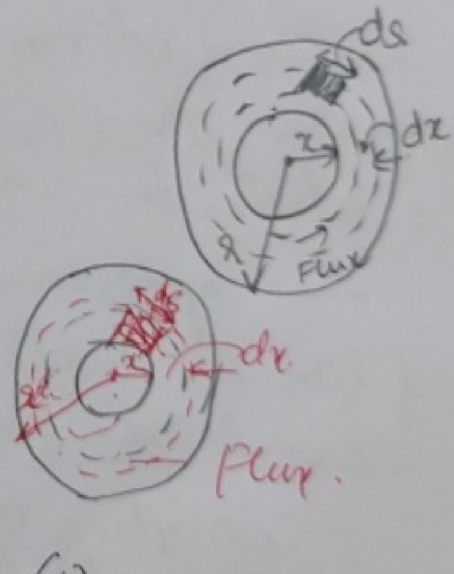
★ A current carrying conductor produces concentric magnetic flux lines around the conductor. If the current varies with time, the magnetic flux changes & a voltage is induced.

★ Inductance of a conductor it is necessary to calculate as in any magnetic circuit with permeability 'μ', the following factors are required

a) Magnetic field intensity (H)
b) Magnetic field density (B)
c) Flux linkage (Ψ)



(a)



(b)

An infinitely long, solid cylindrical conductor with radius 'r', carry current 'I' as shown.

The conductor possesses inductance due to these flux linkage. The flux linkage (ψ) per ampere (I) is called the inductance (L). i.e., $\boxed{L = \frac{\psi}{I}}$ wb-turns/A.

Self inductance $L = \frac{\psi}{I}$ $[\psi = N\phi_m.]$

whereas the mutual inductance is given by.

$$\boxed{M_{12} = \frac{\psi_{12}}{I_2}}$$ [ψ_{12} → flux linkage from '1 to 2'].

Capacitance:

when any 2 conductors are separated by an insulating material it will form a capacitor. In case of OHTL, air acts as an insulating medium (dielectric medium) between 2 conductors. The dielectric medium forms a capacitance between the conductors & between the conductor & ground.

The capacitance is not significant when the length of line is small & hence is considered only for line length greater than 80km.

Capacitance between 2 conductors, defined as charge per unit potential difference

$$\therefore \; C = \frac{Q}{V} \; F.$$

where, Q → charge (C)
V → potential diff (V)

Line Conductor

* magnetic field will be established due to this current. The magnetic flux lines will change inside the conductor which will contribute to induced voltage & hence inductance. The magnetic field lines are exist outside the conductor also.

* We assume that the return path for the current in this conductor is far away & the magnetic field of the conductor is not affected. The lines of flux are concentric with the conductor.

The m.m.f. in ampere-turns around any closed path is equal to the current in amperes enclosed by the path. Thus we have

MMF = N.I

$$\text{m.m.f.} \Rightarrow \oint H \cdot ds = I \quad , \quad H \to \text{magnetic field intensity AT/m}$$

Let the magnetic field intensity at a point 'x' m from the centre of the conductor be H_x. This is constant at all points as field is symmetrical.

$$\therefore \quad \oint ds \Rightarrow 2\pi x.$$

As H_x is constant, $H_x 2\pi x = I_x$ i.e. $\boxed{H_x = \frac{I_x}{2\pi x}}$

As current density is uniform, [$J = I/A \to$ current density]

$$\frac{I_x}{\pi x^2} \Rightarrow \frac{I}{\pi R^2}.$$

(4)

$$\text{i.e., } I_x = \frac{I}{\pi R^2} \times \pi x^2 \Rightarrow \frac{I x^2}{R^2} \quad \therefore \boxed{I_x = \frac{x^2}{R^2} I}$$

$$\therefore H_x = \frac{1}{2\pi x}\left(\frac{x^2}{r^2}\right) I$$

$$\boxed{H_x \Rightarrow \frac{x}{2\pi r^2} I \quad A\text{-}T/m}$$

$\therefore$ Flux density $\boxed{B_x \Rightarrow \mu H_x \Rightarrow \frac{\mu x I}{2\pi r^2}}$

For the element having thickness 'dx', the flux will be product of B_x & Area of cross section, normal to flux lines. $[\phi = B \cdot A]$

$\therefore$ This area is 'dx' times axial length. If the axial length considered is 1m then the flux per meter of length is,

$$d\phi \Rightarrow B_x \times A \Rightarrow \frac{\mu x}{2\pi r^2} I \cdot x (dx \times 1)$$

$$d\phi \Rightarrow \frac{\mu I}{2\pi r^2} x \cdot dx$$

This flux links with current I_x. Hence flux linkage per meter length of conductor is given by,

$$d\psi \Rightarrow \frac{x^2}{r^2} d\phi$$

$$\Rightarrow \frac{x^2}{r^2} \times \frac{\mu I}{2\pi r^2} \cdot x\, dx$$

$$d\psi \Rightarrow \frac{\mu I x^3}{2\pi r^4} dx$$

To find the total flux linkage inside the conductor

$$\psi_{int} \Rightarrow \int_0^r d\psi$$

$$\therefore \psi_{int} \Rightarrow \int_0^r \frac{\mu I}{2\pi r^4} x^3 \, dx. \qquad \int x^n = \frac{x^{n+1}}{n+1}$$

$$\Rightarrow \left(\frac{\mu I}{2\pi r^4}\right) \int_0^r x^3 \, dx \qquad x^3 \Rightarrow \frac{x^4}{4}$$

$$\Rightarrow \frac{\mu I}{2\pi} \left[\frac{x^4}{4} \right]_0^r \left(\frac{1}{r^4}\right)$$

$$\Rightarrow \frac{\mu I}{2\pi r^4} \left[\frac{r^4}{4} - 0 \right]$$

$$\boxed{\psi_{int} \Rightarrow \frac{\mu I}{8\pi} \text{ wb-turns/m.}}$$

But $\mu \Rightarrow \mu_0 \mu_r$; $\mu_0 \Rightarrow$ permeability of free space $\Rightarrow 4\pi \times 10^{-7}$ H/m

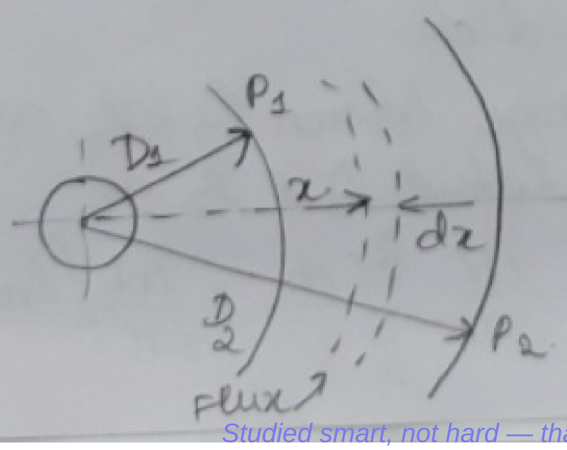
$$\therefore \psi_{int} \Rightarrow \frac{\mu_0 \mu_r I}{8\pi} \Rightarrow \frac{(4\pi \times 10^{-7}) \times \mu_r I}{8\pi} \Rightarrow \frac{1}{2} \times 10^{-7} \mu_r I$$

For non-magnetic material, $\mu_r = 1$; hence

$$\boxed{\psi_{int} \Rightarrow \frac{1}{2} \times 10^{-7} I}$$

$$\boxed{\therefore L_{int} \Rightarrow \frac{\psi_{int}}{I} \Rightarrow \frac{10^{-7}}{2} \text{ H/m}}$$

Inductance of conductor due to the External flux.



* Flux linkages of an isolated conductor which lies between two points P_1 & P_2 distant D_1 & D_2 respectively from the

5

centre of the conductor. As the flux paths are concentric circles around the conductor all the flux between P_1 & P_2 lies within the concentric cylindrical surfaces passing through points P_1 & P_2.

* The conductor shown in the fig. carries current 'I'. The flux paths are concentric circles;

* Consider a tubular element which is 'x' m from centre of conductor. The field intensity at this point is H_x:

* The m.m.f. around the element is

$$\text{m.m.f.} \Rightarrow \oint H_x \, ds \Rightarrow I$$

$$\therefore H_x (2\pi x) = I$$

Flux density at this point is given by

$$B_x \Rightarrow \mu H_x \Rightarrow \frac{\mu I}{2\pi x} \; wb/m^2$$

The flux in the tubular element is given by,

$$d\phi \Rightarrow B_x \times (dx \times 1) \text{ [as axial length of 1m is considered]}$$

$$\therefore d\phi \Rightarrow \frac{\mu I}{2\pi x} \cdot dx$$

* The flux linkages $d\psi$ per meter are equal to $d\phi$ since flux external to the conductor links all the current in the conductor.

* The total flux linkage between P_1 & P_2 are obtained ~~as~~ between distances D_1 & D_2 as

$$\psi_{12} \Rightarrow \int_{D_1}^{D_2} \frac{\mu I}{2\pi x} dx \Rightarrow \frac{\mu I}{2\pi} \int_{D_1}^{D_2} \frac{dx}{x} \Rightarrow \frac{\mu I}{2\pi} \left[\ln(x) \right]_{D_1}^{D_2}$$

$\therefore \psi_{12} = \frac{\mu_0 \mu_r I}{2\pi} \ln\left(\frac{D_2}{D_1}\right).$

$$\boxed{\psi_{12} \Rightarrow 2\times10^{-7} I \ln\left(\frac{D_2}{D_1}\right)}$$

The inductance due to flux linkages included between P_1 & P_2 only is, $\boxed{L_{12} \Rightarrow \frac{\psi_{12}}{I} \Rightarrow 2\times10^{-7} \ln\left(\frac{D_2}{D_1}\right).}$

* ~~If the total flux linkages is~~

If the external flux is considered to be extended from the surface of conductor to infinity then the total flux linkage is given by,

$$\psi_{12} \Rightarrow \int_r^{\infty} \frac{\mu_0 I}{2\pi x} dx.$$

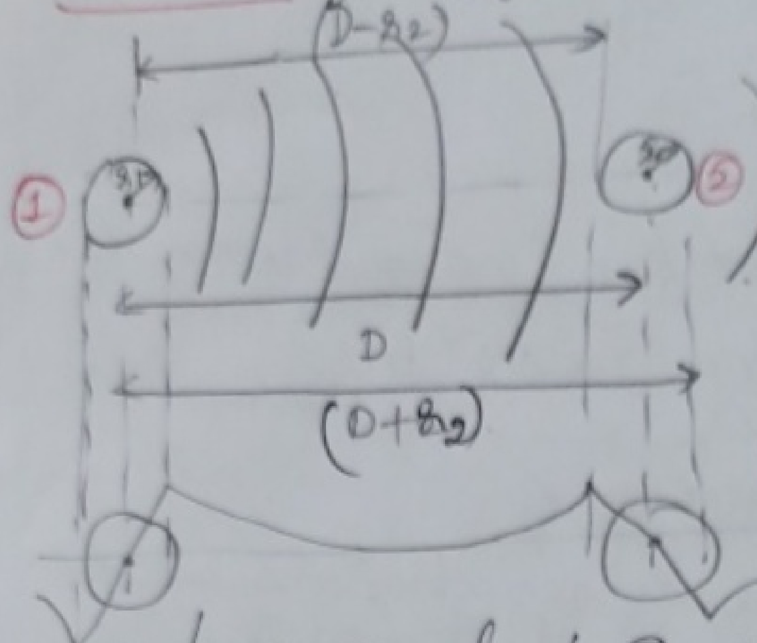
$\therefore$ Overall flux linkages is given by

$$\boxed{\psi_T \Rightarrow \frac{\mu_0 I}{2\pi} + \int_r^{\infty} \frac{\mu_0 I}{2\pi x} dx}$$

$$\boxed{\psi_T \Rightarrow \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right]}$$ //

6

Inductance of a Single Phase. Two wire Line.



* Fig shows a single phase 2 wire line.
* One conductor is the return circuit of the other.
* A line of flux set up by the current in conductor 1 at a distance equal to or greater than $(D+r_2)$ from the centre of conductor 1 links with zero net current (since conductor 1 & 2 carry equal currents in opposite directions). So no voltage is induced in the circuit for points so located.
* In a single phase circuit we have

$$I_1 + I_2 = 0$$

$$\therefore I_2 = -I_1$$ (neglecting the effect of earth's magnetic field).

* Consider only the flux linkages of the circuit caused by current in conductor 1.
* The flux line set up by the current flowing in conductor 1 at a distance equal to or greater than $(D+r_2)$ from the centre of conductor 1 does not link the circuit & hence, is not responsible for inducing any voltage in the circuit, [as $I_2 = -I_1$].

* The external flux from r_1 to $(D-r_2)$ links all the current I_1 in cond^r 1. Over the surface of conductor 2, i.e, between $(D-r_2)$ & $(D+r_2)$, the external flux links a current whose magnitude is progressively reduces from I_1 to zero, because of -ve current in cond^r 2.

* The total inductance of the current carrying in cond^{r} 1 can be calculated by assuming $D >> (r_1 \& r_2)$. Under this condition it can be assumed that flux from $(D-r_2)$ to the centre of cond^r '2' links current I_1 & flux from the centre of cond^r 2 to $(D+r_2)$ links zero current.

* Thus the inductance due to current in conductor '1' can be calculated by,

$$L_{12} = 2\times10^{-7} \ln\left(\frac{D_2}{D_1}\right) \text{ H/m}$$

$$L_{12} \Rightarrow 2\times10^{-7} \ln\left(\frac{D}{r_1}\right) \text{ H/m} \quad (\because \text{external flux})$$

w.r.t. internal flux,

$$L_{1(int)} \Rightarrow \frac{1}{2}\times10^{-7} \text{ H/m}$$

$$\therefore L_{1T} = L_{1int} + L_{12} \Rightarrow \frac{1}{2}\times10^{-7} + 2\times10^{-7}\left(\ln\frac{D}{r_1}\right)$$

$$= (2\times)\frac{10^{-7}}{2}\left[\frac{1}{4} + 2\ln\left(\frac{D}{r_1}\right)\right] \text{ H/m}$$

$$\therefore L_1 = 2\times10^{-7}\left[\ln e^{1/4} \ln\left(\frac{D}{r_1}\right)\right] \text{ where } \ln e^{(1/4)} = \frac{1}{4} \quad (1)$$

$$\Rightarrow 2\times10^{-7} \ln\left(\frac{D}{e^{-1/4} r_1}\right)$$

$$\Rightarrow 2\times10^{-7} \ln\left(\frac{D e^{1/4}}{r_1}\right)$$

Consider $r_1' = r_1 e^{-1/4}$ then, we have

$$\boxed{L_1 = 2\times10^{-7} \ln\left(\frac{D}{r_1'}\right)} \text{ H/m} \quad \{ r_1' = 0.7788 r_1$$

$r_1' \rightarrow$ radius of an imaginary (or) fictitious conductor assumed to have no internal flux, applicable for solid round conductors.

Similarly, conductor 2 carries current in opposite direction to that of cond 1.

Inductance of conductor 2 due to current in second conductor is given by,

$$\boxed{L_2 = 2\times10^{-7} \ln\left(\frac{D}{r_2'}\right) \text{ H/m}}$$

$\therefore$ The total inductance is given by $L = L_1 + L_2$.

$$\boxed{L_T \Rightarrow 4\times10^{-7} \ln\left(\frac{D}{r'}\right)} \quad [\text{If } r_1' = r_2' = r'.]$$

$$\boxed{L_T \Rightarrow 4\times10^{-4} \ln\left(\frac{D}{r'}\right) \text{ H/km}}$$

This value of inductance which is due to flux linkages caused by current in both conductors (one of which is the return path for the current in the other) is sometimes called Inductance per loop length

Loop inductance is double the inductance per conductor in a single phase line [$L_{a} = 2L_c$].

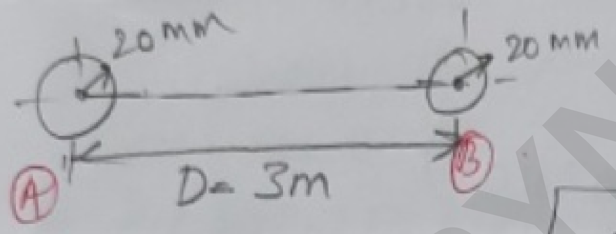
Examples:

1. A 2 conductor 1-phase line operates at 50Hz. The diameter of each conductor is 20mm & the spacing between the conductor is 3m. Calculate

(a) the inductance of each conductor per km.

(b) the loop inductance of the line per km.

(c) the inductive reactance per km.



$r' \Rightarrow 0.7788 r$

$\Rightarrow (0.7788 \times 10 \times 10^{-3})$

$\boxed{r' \Rightarrow 7.788 \text{ mm}}$

(a) Inductance of each conductor $L_c = 2 \times 10^{-7} \ln\left(\frac{D}{r'}\right)$

$L_c \Rightarrow 2 \times 10^{-7} \ln\left(\frac{3}{7.788 \times 10^{-3}}\right)$

$\Rightarrow 1.1909 \ \mu H/m$

$\boxed{L_c \Rightarrow 1.1909 \text{ mH/km}}$

(b) Total loop inductance $\Rightarrow L = 2L_c$

$\Rightarrow 2.38 \text{ mH/km}$

(c) Inductive reactance, $X_L = 2\pi f L$.

$\Rightarrow 0.7483 \Omega$

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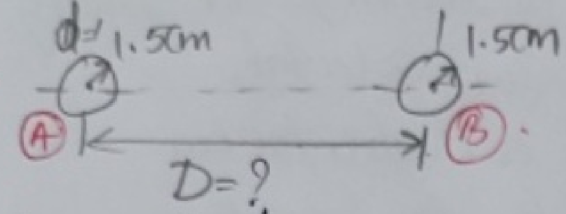
2) A single phase overhead line 25km long is to be constructed of conductor 1.5cm diameter. Calculate the maximum spacing between the conductors in order that the loop inductance of conductor is not more than 0.08H.

Soln



Length of transmission line is 25km = 25000m.

Loop inductance per meter of transmission line $= \frac{0.08}{25000} \Rightarrow 3.2 \times 10^{-6} H$

$r' \Rightarrow 0.7788 r$

$= (0.7788 \times 0.75 \times 10^{-2})$

$\boxed{r' \Rightarrow 5.841 mm}$

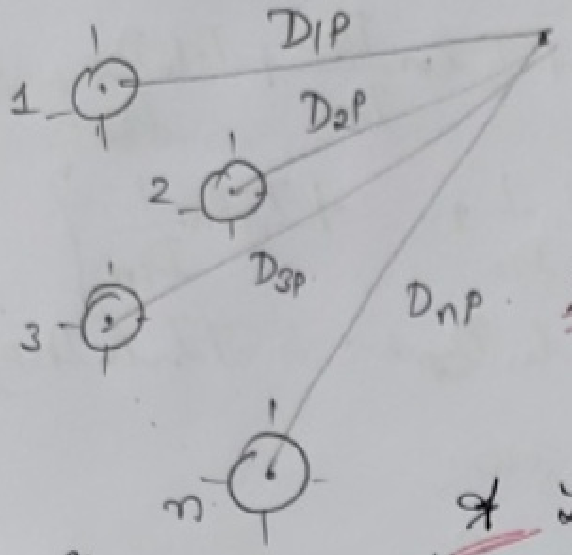
As

$L \Rightarrow 4 \times 10^{-7} \left(\frac{D}{r'}\right)$

$(3.2 \times 10^{-6}) = 4 \times 10^{-7} \ln\left(\frac{D}{5.841 \times 10^{-3}}\right)$

$\therefore \boxed{D \Rightarrow 17.411 m}$ //

Flux linkages of one conductor in a Group.



* Consider a composite conductor which is made up of two or more strands which are in parallel.

* The sum of the currents in all the conductors is zero.

* The conductors 1, 2, 3, .. n (a). carry the currents $I_1, I_2, \ldots I_n$. Let the distances of the the conductors from a point P be $D_{1P}, D_{2P}, \cdots D_{nP}$ respectively.

* Let ψ_{1P_1} be flux linkages of conductor 1 due to its own current I_1 due to internal & external flux. The flux beyond point 'P' is excluded.

$$\psi_{1P_1} = 2\times10^{-7}\left[\frac{I_1}{2} + 2I_1 \ln\frac{D_{1P}}{r_1}\right]$$

$$\Rightarrow I_1 (2\times10^{-7}) \left[\ln\left(\frac{D_{1P}}{r_1'}\right)\right]$$

$$\therefore \psi_{1P_1} \Rightarrow (2\times10^{-7}) I_1 \ln\left(\frac{D_{1P}}{r_1'}\right) \quad H/m$$

Now, ψ_{1P_2} is the flux linkage of conductor 1 due to current 'I_2' is equal to flux produced by 'I_2' between the point P & conductor 1.

$$\boxed{\psi_{1P_2} \Rightarrow 2\times10^{-7} I_2 \ln\left(\frac{D_{2P}}{D_{12}}\right) \quad H/m} \qquad (9)$$

||ly flux linkages ψ_{1p} with conductor 1 due to all the conductors in the group;

$$\psi_{1p} \Rightarrow 2\times10^{-7}\left[I_1 \ln\frac{D_{1p}}{r_1'} + I_2 \ln\frac{D_{2p}}{D_{12}} + I_3 \ln\frac{D_{3p}}{D_{13}} + \dots + I_n \ln\frac{D_{np}}{D_{1n}}\right]$$

$$\Rightarrow (2\times10^{-7})\left[I_1 \ln\frac{1}{r_1'} + I_2 \ln\frac{1}{D_{12}} + \dots + I_n \ln\frac{1}{D_{1n}}\right.$$
$$\left. + (I_1 \ln D_{1p} + I_2 \ln D_{2p} + \dots + I_n \ln D_{np}\right].$$

As sum of all current is zero.

$$I_1 + I_2 + \dots + I_n = 0.$$

$$I_n = -(I_1 + I_2 + I_3 + \dots + I_{n-1}).$$

$$\therefore \psi_{1p} \Rightarrow 2\times10^{-7}\left[I_1 \ln\frac{1}{r_1'} + I_2 \ln\frac{1}{D_{12}} + \dots + I_n \ln\frac{1}{D_{1n}} + \right.$$
$$\left. I_1 \ln D_{1p} + I_2 \ln D_{2p} + \dots (-I_1 - I_2 \dots - I_{n-1}) \ln D_{np}\right]$$

$$\psi_{1p} \Rightarrow 2\times10^{-7}\left[I_1 \ln\frac{1}{r_1'} + I_2 \ln\frac{1}{D_{12}} + \dots + I_n \frac{1}{D_{1n}} + I_1 \ln\left(\frac{D_{1p}}{D_{np}}\right)\right.$$
$$\left. + I_2\left(\frac{D_{2p}}{D_{np}}\right) + \dots + I_{n-1} \ln\left(\frac{D_{n-1p}}{D_{np}}\right)\right]$$

If pt. $\underline{P}$ is at infinite distance such that ratios.

$$\frac{D_{1p}}{D_{np}}, \frac{D_{2p}}{D_{np}} \dots \rightarrow \underline{1}$$

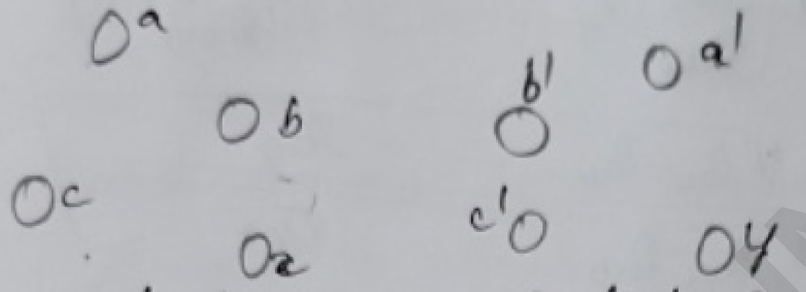
$$\therefore \ln\left(\frac{D_{1p}}{D_{np}}\right), \ln\left(\frac{D_{2p}}{D_{np}}\right), \dots \Rightarrow 0 \quad [\text{as } \ln 1 = 0]$$

$$\therefore \psi_{1p} \Rightarrow 2\times10^{-7}\left[I_1 \ln\frac{1}{D_{11}} + I_2 \ln\frac{1}{D_{12}} + I_3 \ln\frac{1}{D_{13}} + \dots + I_n \ln\frac{1}{D_{1n}}\right]$$

where $x_1' \Rightarrow D_{11}$,

$$\therefore \psi_{1p} \Rightarrow 2\times10^{-7}\left[\sum_{i=1}^{i=n} I_i \ln\frac{1}{D_{1i}}\right] \text{ wbT/m}$$

Inductance of composite Conductor Lines.



Conductor-P   Conductor-Q

$\log x^n \Rightarrow n \log x$

* Consider a 1-phase 2 wire system. It consists of 2 Conductors say P & Q which are composite Conductors.

* Conductor-P is consisting of x-identical parallel filaments. Each of the filaments carries a current of (I/x). Conductor Q consists of y filament with each filament carrying a current of $-(I/y)$.

* The flux linkages of filament 'a' due to all current in all the filaments is given by.

$$\psi_a \Rightarrow (2\times10^{-7})\left[\frac{I}{x}\ln\left(\frac{1}{D_{aa}}\right)+\frac{I}{x}\ln\frac{1}{D_{ab}}+\cdots+\frac{I}{x}\ln\frac{1}{D_{ax}}\right]$$

$$+(2\times10^{-7})\left[\frac{-I}{y}\ln\frac{1}{D_{aa'}}+\frac{-I}{y}\ln\frac{1}{D_{ab'}}+\frac{-I}{y}\ln\frac{1}{D_{ac'}}+\cdots+\frac{-I}{y}\ln\frac{1}{D_{ay}}\right]$$

$$\Rightarrow (2\times10^{-7})\,\frac{I}{x}\left[\ln\frac{1}{D_{aa}}+\ln\frac{1}{D_{ab}}+\cdots+\ln\frac{1}{D_{ax}}\right]$$

$$-(2\times10^{-7})\frac{I}{y}\left[\ln\frac{1}{D_{aa'}}+\ln\frac{1}{D_{ab'}}+\cdots+\ln\frac{1}{D_{ay}}\right]$$

As $\left[\log x^n \Rightarrow n\log x\right]$

$$\Rightarrow (2\times10^{-7})\, I\left[\ln\left(\frac{1}{D_{aa}}\right)^{\frac{1}{x}}+\cdots+\ln\left(\frac{1}{D_{ax}}\right)^{1/x}\right]$$

$$+(2\times10^{-7})I\left[\ln\left(\frac{1}{D_{aa'}}\right)^{\frac{1}{y}}+\cdots+\ln\left(\frac{1}{D_{ay}}\right)^{1/y}\right]$$

$$\psi_a \Rightarrow (2\times10^{-7})\, I\left[\ln\frac{\sqrt[y]{D_{aa'}D_{ab'}\cdots D_{ay}}}{\sqrt[x]{D_{aa}D_{ab}\cdots D_{ax}}}\right]$$

∴ The inductance of the filament 'a' is given by.

$$L_a=\frac{\psi_a}{I/x}\Rightarrow\frac{(2x\times10^{-7})\cancel{I}}{\cancel{I}}\times\ln\left(\frac{\sqrt[y]{D_{aa'}D_{ab'}\cdots D_{ay}}}{\sqrt[x]{D_{aa}D_{ab}\cdots D_{ax}}}\right)$$

$$\boxed{L_a\Rightarrow(2\times10^{-7})\times x\times\ln\left(\frac{\sqrt[y]{D_{aa'}D_{ab'}\cdots D_{ay}}}{\sqrt[x]{D_{aa}D_{ab}\cdots D_{ax}}}\right)}$$

The average value of inductance of the filaments of conductor P is

$$L_{av}\Rightarrow\frac{L_a+L_b+L_c+\cdots+L_x}{x}$$

Inductance of conductor 'P' is given by

$$L_P\Rightarrow\frac{L_{av}}{x}\Rightarrow\frac{L_a+L_b+\cdots+L_x}{x^2}$$

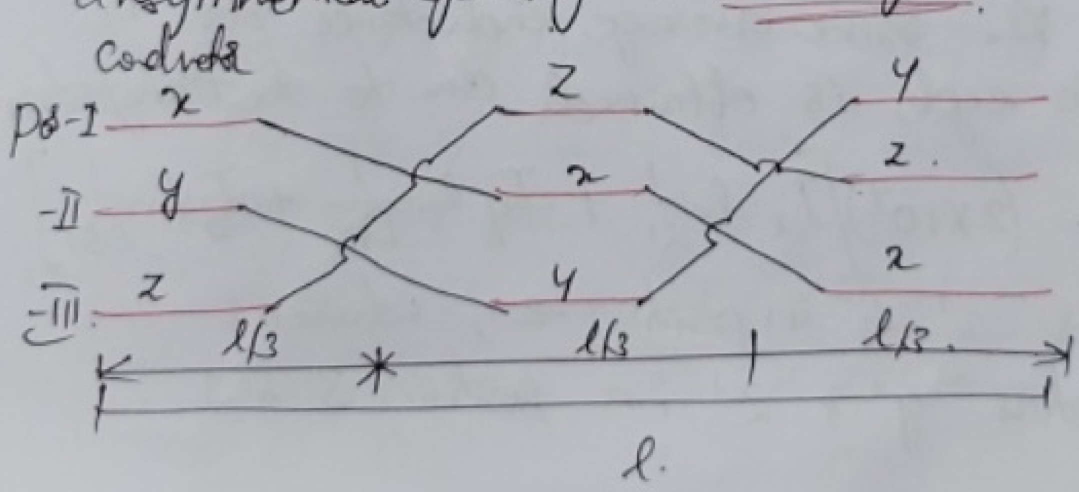
$$\therefore\ \boxed{L_P\Rightarrow(2\times10^{-7})\ln\frac{\sqrt[xy]{(D_{aa'}D_{ab'}\cdots D_{ay})(D_{ba'}D_{bb'}\cdots D_{by})\cdots(D_{xa'}\cdots D_{xy})}}{\sqrt[x^2]{(D_{aa}D_{ab}\cdots D_{ax})(D_{ba}D_{bb}\cdots D_{bx})\cdots(D_{xa}D_{xb}\cdots D_{xx})}}}$$

Transposition of transmission lines are normally done to prevent interference with neighbouring telephone lines. The transposition arrangement of high voltage lines helps to reduce the system power loss.

A transposition is developed for single circuit tower using same tension tower with reduced deviation angle. The transposition tower is designed to allow the physical crossing (or) swapping of conductors at a specific point along the transposition arrangements (ACC, ACB, BCA, etc).

Transposition of transmission lines are used to transpose the phase conductors in three sections in such a way that each phase by rotation occupies each of the three phase positions in a circuit.

Inductance of a Three-phase Line with Unsymmetrical Spacing but Transposed.



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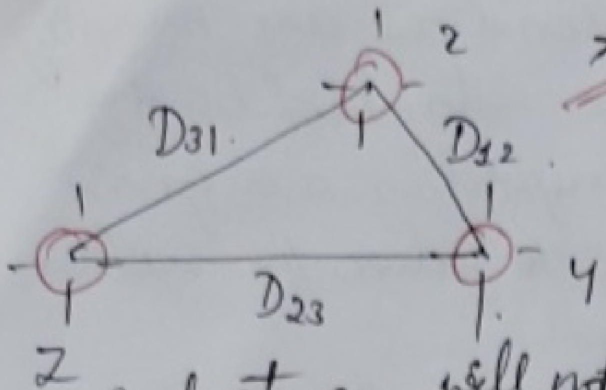


* If a three phase line having three conductors but not spaced equilaterally the flux linkage & corresponding inductance will not be same in each phase.

* Due to this different inductance per phase there is unbalance in the circuit though the currents in each phases are balanced.

* The drops in the three phases due to these inductances are observed to be different. To achieve balanced under this case, transposition of transmission line is preferred after a certain fixed distance.

* Flux linkages of conductor 'x' which is in position-1 whereas conductor y & z are in positions 2 & 3 respectively.

The conductors in the individual phases are danoted by x, y & z where the positions are given by 1, 2 & 3. The same average inductance over the complete cycle is obtained due to the transposition.

In posi-I $\psi_{x_1} = (2\times10^{-7})\left[I_x \ln\frac{1}{x'} + I_y \ln\frac{1}{D_{12}} + I_z \ln\frac{1}{D_{31}}\right]$

whereas conductor 'x' is in position-2, conductors 'y' & 'z' in position 3 & 1.

$$\therefore \psi_{x_2} = 2\times10^{-7}\left[I_x \ln\frac{1}{x'} + I_y \ln\frac{1}{D_{23}} + I_z \ln\frac{1}{D_{12}}\right]$$

||y in x^{n} position ③.

$$\psi_{x_3} \Rightarrow 2\times10^{-7}\left[I_x \ln\frac{1}{x'} + I_y \ln\frac{1}{D_{31}} + I_z \ln\frac{1}{D_{23}}\right]$$

The average value of flux linkage of conductor 'x' is,

$$\psi_x = \frac{\psi_{x_1}+\psi_{x_2}+\psi_{x_3}}{3}$$

$$\psi_x \Rightarrow \frac{2\times10^{-7}}{3}\left[3I_x \ln\frac{1}{x'} + I_y \ln\frac{1}{D_{12}D_{23}D_{31}} + I_z \ln\frac{1}{D_{12}D_{23}D_{31}}\right]$$

$$\Rightarrow \frac{2\times10^{-7}}{3}\left[3I_x \ln\frac{1}{x'} + (I_y+I_z)\ln\frac{1}{D_{12}D_{23}D_{31}}\right]$$

Inductance of Three Phase Lines with more than one circuit

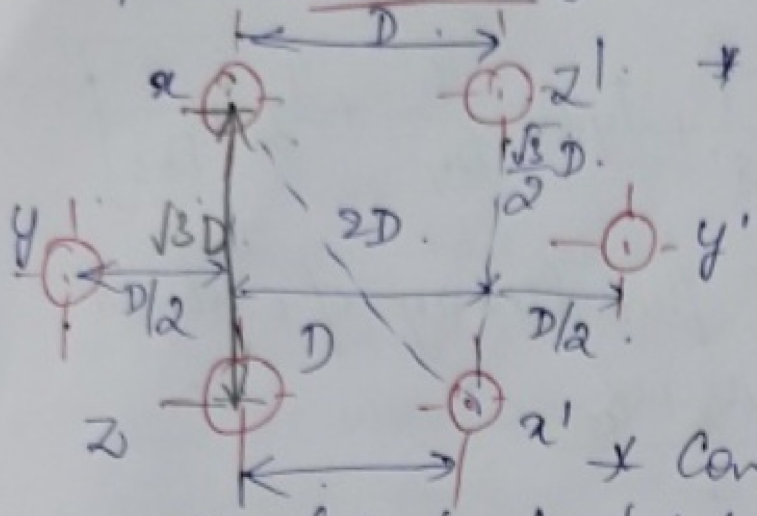
If there are more than one circuit in parallel then it is desired that the equivalent circuit should have low inductance. It can be achieved by low value of 'D_m' & high value of 'D_s'.

The use of double circuit increases the reliability of the power supply.

x O	O z'	x O	O x'
y O	O y'	y O	O y'
z O	O x'	z O	O z'
I		II	

②

Inductance of Three Phase Double circuit with Symmetrical spacing.



* Consider the three phase double circuit with the conductors placed at the vertices of a regular hexagon as shown.

* Conductors x, y & z belong to one circuit & x', y' & z' belong to another circuit.

Here $D_{xz} = \sqrt{3}D \Rightarrow D_{x'z'}$

$$D_{xy} = D_{yz} \Rightarrow \sqrt{\frac{3D^2}{4}+\frac{D^2}{4}} \Rightarrow \underline{D}$$

i.e., $D_{x'y'} = D_{z'y'} \Rightarrow D$.

$$D_{xy'} \Rightarrow \sqrt{\left(\frac{\sqrt{3}D}{2}\right)^2 + \left(D+\frac{D}{2}\right)^2} \Rightarrow \sqrt{\frac{3D^2}{4}+D^2+\frac{D^2}{4}+D^2} \Rightarrow \frac{[illegible]}{4}$$

$$\boxed{D_{xy'} \Rightarrow \sqrt{3D^2} \Rightarrow \sqrt{3}D}$$

$$D_{xx'} \Rightarrow 2D.$$

Flux linkage of conductor x due to currents in other phases,

$$\psi_x = 2\times10^{-7}\left[I_x\left(\ln\frac{1}{r'}+\ln\frac{1}{D_{xx'}}\right)+I_y\left(\ln\frac{1}{D_{xy}}+\ln\frac{1}{D_{xy'}}\right) + I_z\left(\ln\frac{1}{D_{xz}}+\ln\frac{1}{D_{xz'}}\right)\right]$$

$$= 2\times10^{-7}\left\{ I_x\left(\ln\frac{1}{x'}+\ln\frac{1}{2D}\right) + I_y\left\{\ln\frac{1}{D}+\ln\frac{1}{\sqrt{3}D}\right\} + I_z\left(\ln\frac{1}{\sqrt{3}D}+\ln\frac{1}{D}\right)\right\}$$

$$\Rightarrow 2\times10^{-7}\left[I_x\ln\left(\frac{1}{x'}\right)+\ln\left(\frac{1}{2D}\right) + (I_y+I_z)\left\{\ln\frac{1}{D}+\ln\frac{1}{\sqrt{3}D}\right\}\right]$$

As $I_x+I_y+I_z=0$.

$$I_y+I_z \Rightarrow -I_x.$$

$$\psi_x \Rightarrow 2\times10^{-7}\left\{I_x\ln\left(\frac{1}{x'}\right)+\ln\left(\frac{1}{2D}\right)\right\} - I_x\left(\ln\frac{1}{D}+\ln\frac{1}{\sqrt{3}D}\right)\Big\}$$

$$\Rightarrow 2\times10^{-7}\left[\left\{I_x\left(\frac{1}{2Dx'}\right)\right\} - I_x\left\{\ln\left(\frac{\sqrt{3}D}{D}\right)\right\}\right]$$

$$= 2\times10^{-7}\, I_x \ln\left(\frac{\sqrt{3}D}{2x'}\right) \text{ Wb/m}$$

$$\boxed{L_x \Rightarrow \frac{\psi_x}{I_x} = 2\times10^{-7}\ln\left(\frac{\sqrt{3}D}{2x'}\right) \text{ H/m}}$$

As conductor are in parallel, Inductance of each phase $\Rightarrow \frac{1}{2}$ Inductance per conductor.

$$\Rightarrow \frac{1}{2}L_x$$

$$\boxed{L_{x\,\text{phase}} \Rightarrow 10^{-7}\ln\left(\frac{\sqrt{3}D}{2x'}\right) \text{ H/m}}$$

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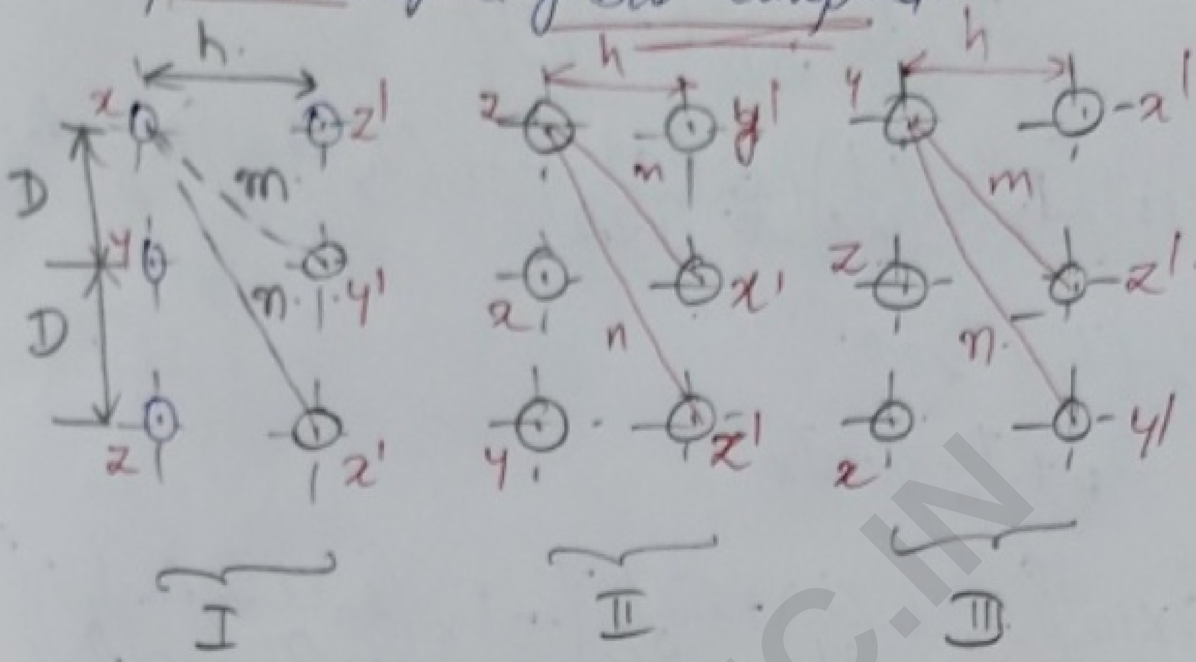
Inductance of Three-Phase Double circuit with Unsymmetrical spacing but transposed.



Consider a three phase double circuit having conductors usually transposed with unsymmetrical spaced. Each conductor occupies the position of other conductors after certain length (or) distance of transmission line.

Flux linkage of conductor 'x' in position - I

$$\psi_{x_1} \Rightarrow 2\times10^{-7}\Big[I_x\left(\ln\frac{1}{r'}+\ln\frac{1}{n}\right)+I_y\ln\left(\frac{1}{D}+\ln\frac{1}{m}\right)$$
$$+I_z\left(\ln\frac{1}{2D}+\ln\left(\frac{1}{h}\right)\right)\Big]$$

IIly $\psi_{x_2} \Rightarrow 2\times10^{-7}\Big[I_x\ln\left(\frac{1}{r'}+\ln\frac{1}{h}\right)+I_y\left(\ln\frac{1}{D}+\ln\frac{1}{m}\right)$
$$+I_z\left(\ln\left\{\frac{1}{D}+\ln\frac{1}{m}\right)\right)\Big]$$

$$\psi_{x_3} \Rightarrow (2\times10^{-7})\left[I_x\left(\ln\frac{1}{r'}+\ln\frac{1}{n}\right)+I_y\left(\ln\frac{1}{2D}+\ln\frac{1}{h}\right) + I_z\left(\ln\frac{1}{D}+\ln\frac{1}{m}\right)\right]$$

we have $\psi_x = \dfrac{\psi_{x_1}+\psi_{x_2}+\psi_{x_3}}{3}$

$$\therefore \psi_x \Rightarrow \frac{2\times10^{-7}}{3}\left[3 I_x\ln\frac{1}{r'} + I_x\ln\frac{1}{n^2h} + I_y\ln\frac{1}{2D^3} + I_y\ln\frac{1}{m^2h} + I_z\ln\frac{1}{2D^3} + I_z\ln\frac{1}{m^2h}\right]$$

As $I_x+I_y+I_z=0$, $(I_y+I_z) = -I_x$.

$$\psi_x \Rightarrow \frac{2\times10^{-7}}{3}\left[3I_x\ln\frac{1}{r'} + I_x\ln\frac{1}{n^2h} + (I_y+I_z)\left(\ln\frac{1}{m^2h}+\ln\frac{1}{2D^3}\right)\right]$$

$$\Rightarrow 2\times10^{-7}\left[I_x\left(\ln\frac{1}{r'}+\ln\left(\frac{1}{n^2h}\right)^{1/3}\right) - I_x\ln\frac{1}{m^{2/3}h^{1/3}} - I_x\ln\frac{1}{2^{1/3}D^{3/3}}\right]$$

$$\Rightarrow (2\times10^{-7})I_x\left[\ln\left(\frac{1}{r' n^{2/3}h^{1/3}}\right) - \ln\left(\frac{1}{(m^2h\,2D^3)^{1/3}}\right)\right]$$

$$\Rightarrow 2\times10^{-7} I_x \ln\frac{2^{1/3}D\, m^{2/3}h^{1/3}}{r' n^{2/3} h^{1/3}} \Rightarrow (2\times10^{-7}) I_x \ln\left(2^{1/3}\left(\frac{D}{r'}\right)\left(\frac{m}{n}\right)^{2/3}\right)$$

$$\therefore \boxed{L_x \Rightarrow \frac{\psi_x}{I_a} \Rightarrow (2\times10^{-7})\left[\ln 2^{1/3}\left(\frac{D}{r'}\right)\left(\frac{m}{n}\right)^{2/3}\right] \text{ H/m}}$$

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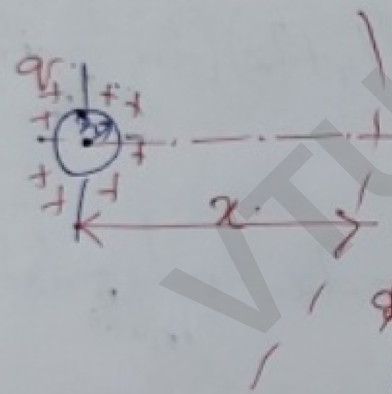
Inductance of each phase $\Rightarrow \frac{1}{2}L_x \Rightarrow 10^{-7}\left[\ln 2^{1/3}\left(\frac{D}{r'}\right)^{1/2}\left(\frac{m}{n}\right)^{1/3}\right]$ H/m

* Capacitance of Transmission Line.

* Due to the potential difference between the conductors we have to take into account the capacitance of transmission line. The capacitance causes the line to be charged similar to the plates of capacitor when potential difference is applied to it.

* Electric Potential at single charged conductor.

The Electric potential at a point due to a charge is measured by the work done in bringing unit +ve charge from infinity to that point.



* Consider a long straight cylindrical conductor placed in uniform medium such as air as shown.
* It carries a charge along its entire length given by '+q' C/m.

* The electric flux lines of this charged conductor are radial & uniformly placed.
* Electric flux density at a distance 'x' from the conductor i.e., along cylindrical surface of radius 'x' meters.

The electric flux density on the surface is equal to the flux leaving the conductor per meter of length divided by the surface area in an axial length of 1m with radius 'x'-m.

$$\therefore D \Rightarrow \frac{q}{2\pi x \times 1} \Rightarrow \frac{q}{2\pi x} \quad C/m^2 \rightarrow \text{Electric flux density.}$$

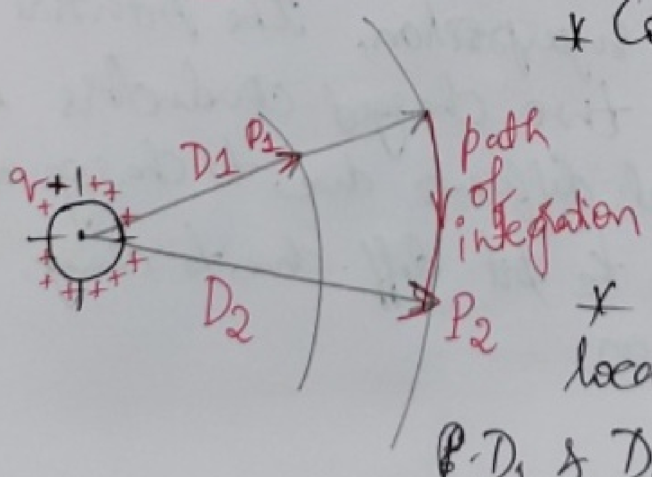
If D is divided by the permittivity of the medium. (ϵ) then we get electric field intensity (E)..

$$E \Rightarrow \frac{D}{\epsilon} \Rightarrow \frac{q}{2\pi\epsilon x} \quad V/m.$$

As $x \to \infty$, the value of $E \to 0$. Thus the pot. diff. b/n the conductor & neutral plane at infinity distance where E & 'V' is zero is given by,

$$\boxed{V = \int_x^{\infty} \frac{q\, dx}{2\pi\epsilon x} \Rightarrow \frac{q}{2\pi\epsilon}\int_x^{\infty} \frac{dx}{x}} \quad \epsilon = \epsilon_0.$$

potential of a conductor in a group of Charged Conductors



* Consider a long straight wire carrying positive charge of 'q' c/m.

* Consider 2 points P_1 & P_2 located at a distances of D_1 & D_2 from centre of wire.

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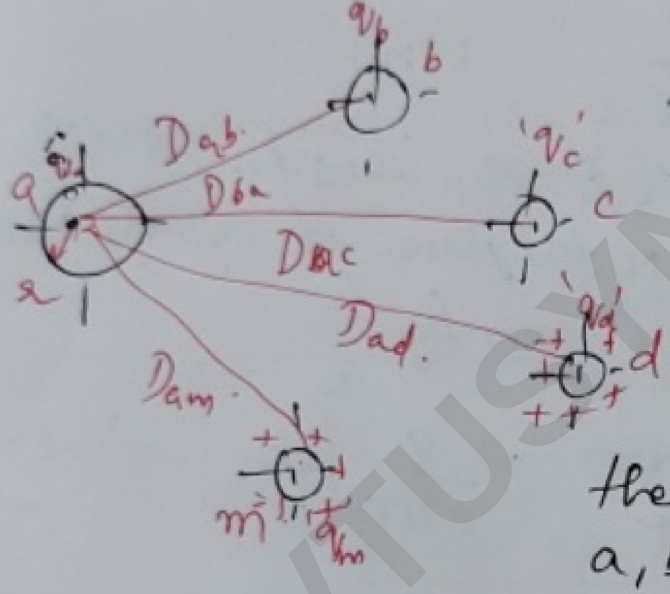
If a certain charge 'q' is moved from P_1 to P_2. Energy is expended which is voltage drop.

The voltage drop between P_1 & P_2 is,

$$V_{12} \Rightarrow \int_{D_1}^{D_2} E \cdot dx \Rightarrow \int_{D_1}^{D_2} \frac{q}{2\pi\epsilon x} dx \Rightarrow \frac{q}{2\pi\epsilon} \int_{D_1}^{D_2} \frac{dx}{x}$$

$$\boxed{V_{12} \Rightarrow \frac{q}{2\pi\epsilon} \ln\left(\frac{D_2}{D_1}\right)}$$



* Consider a system of 'm' conductors having radius 'r' m forming a circuit.

* Let q_a, q_b, q_c - - q_m be the charge /meter on the a, b, - - m conductors.

* Let D_{ab}, D_{bc}, - - D_{am} be the spacing of conductors b, c, d, - - m from 'a'.

* By the principle of superposition, the potential difference between two charged conductors is equal to the potential difference due to charge on 1st condr alone plus the pot. diff. due to charge on 2nd condr, & so on, - -

The potential difference between conductors 'a' & 'b' is given by.

$V_{ab} \Rightarrow$ pot. diff between 'a' & 'b' due to charge 'q_a' on a + pot. diff b/n 'a' & 'b' due to charge 'q_b' on b + — - -

$$V_{ab} \Rightarrow \frac{q_a}{2\pi\epsilon} \ln\left(\frac{D_{ab}}{r_a}\right) + \frac{q_b}{2\pi\epsilon} \ln\left(\frac{r_b}{D_{ba}}\right) + \frac{q_c}{2\pi\epsilon} \ln\left(\frac{D_{cb}}{D_{ca}}\right) + \cdots + \frac{q_m}{2\pi\epsilon} \ln\left(\frac{D_{mb}}{D_{ma}}\right)$$

we have $r_a = r_b = r$.

$$V_{ab} \Rightarrow \frac{q_a}{2\pi\epsilon} \ln\left(\frac{D_{ab}}{r}\right) + \frac{q_b}{2\pi\epsilon} \ln\left(\frac{r}{D_{ba}}\right) + \frac{q_c}{2\pi\epsilon} \ln\left(\frac{D_{cb}}{D_{ca}}\right) + \cdots + \frac{q_m}{2\pi\epsilon} \ln\left(\frac{D_{mb}}{D_{ma}}\right) \rightarrow (A)$$

||ly pot. diff between Cond^r 'a' & 'c' is given by.

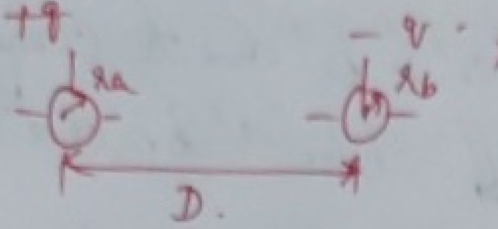
$$V_{ac} \Rightarrow \frac{q_a}{2\pi\epsilon}\left[\ln\frac{D_{ac}}{r} + q_b \ln\frac{D_{bc}}{D_{ba}} + q_c \ln\frac{r}{D_{ca}} + \cdots + q_m \ln\frac{D_{mc}}{D_{ma}}\right]$$

$$V_{am} \Rightarrow \frac{1}{2\pi\epsilon}\left[q_a \ln\frac{D_{am}}{r} + q_b \ln\frac{D_{bm}}{D_{ba}} + q_c \ln\frac{D_{cm}}{D_{ca}} + \cdots + q_m \ln\frac{r}{D_{ma}}\right] \rightarrow (B)$$

(16)

Under normal working conditions $q_a + q_b + q_c + \cdots + q_m = 0$

Capacitance of Single phase Line



* Capacitance between 2 condrs. of a 2 wire line is the charge on the conductor per unit value of potential diff between them. Capacitance of the line per unit length is given by.

$$\therefore \boxed{C = \frac{q}{V}} \text{ F/m}$$

* Consider a 1-phase OHTL consisting of 2 condrs 'a' & 'b' which are seperated by 'D' distance. The charge on each conductors are respectively '+q' & '-q' c/m.

* The Voltage drop V_{ab} is given by

$$V_{ab} \Rightarrow (V_{ab} \text{ due to } +q) + (V_{ab} \text{ due to } -q)$$

$$\Rightarrow \frac{q}{2\pi\epsilon} \ln\left(\frac{D}{r_a}\right) + \frac{-q}{2\pi\epsilon} \ln\left(\frac{r_b}{D}\right)$$

$$\Rightarrow \frac{q}{2\pi\epsilon}\left[\ln\frac{D}{r_a} - \ln\left(\frac{r_b}{D}\right)\right]$$

$$V_{ab} \Rightarrow \frac{q}{2\pi\epsilon} \ln\left(\frac{D^2}{r_a r_b}\right)$$

$\therefore$ The cap. b/n the conductors,

$$C_{ab} \Rightarrow \frac{q}{V_{ab}} \Rightarrow \frac{2\pi\epsilon}{\ln\left(\frac{D^2}{r_a r_b}\right)} = \frac{2\pi\epsilon_0\epsilon_r}{\ln\left(\frac{D^2}{r_a r_b}\right)}$$

For air, $\epsilon_r = 1$,

$$\therefore C_{ab} \Rightarrow \frac{2\pi\epsilon_0}{\ln\left(\frac{D^2}{r_a r_b}\right)}$$

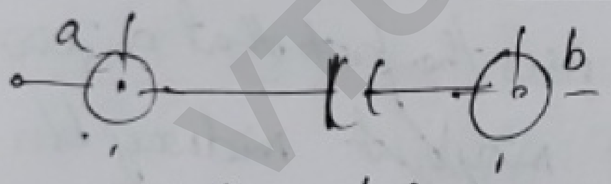
If $r_a = r_b = r$, then, $C_{ab} \Rightarrow \frac{2\pi\epsilon_0}{\ln\left(\frac{D}{r}\right)^2} \Rightarrow \frac{2\pi\epsilon_0}{2\ln\left(\frac{D}{r}\right)}$

$$\therefore C_{ab} \Rightarrow \frac{\pi\epsilon_0}{\ln\left(\frac{D}{r}\right)} \text{ F/m.}$$

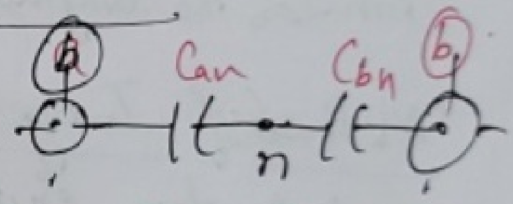
$$\boxed{C_{an} \Rightarrow \frac{\pi\epsilon_0 \times 10^3}{\ln\left(\frac{D}{r}\right)} \text{ F/km.}}$$

If Cap. between one of the cond^rs & neutral point

$$C_n = C_{an} = C_{bn} \Rightarrow \frac{2\pi\epsilon_0}{\ln(D/r)} \text{ F/m.}$$



(a) line-to line cap.



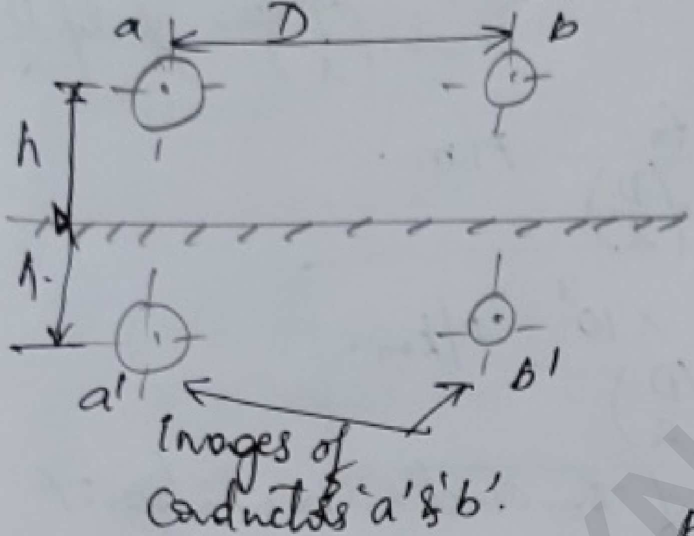
$C_{an} = C_{bn} = 2C_{ab}$

(b) Line to neutral cap.

Effect of Earth on Capacitance of Transmission Lines

The earth can be assumed to behave like an infinite, perfectly conducting plane. Due to this, electric field of the line is changed.

∴ The effect of earth, can be calculated from the 'Method of Images' (Lord Kelvin). If 2 conductors carry equal & opposite charges, then there exists a zero potential plane half way between the conductors.



* It is assumed that the field between a single charged conductor & the perfectly conducting plane, the earth is identical with the field which would be produced by replacing the conducting plane by the hypothetical conductor similar to original condr.

'Method of Images' → uses the fact that a zero potential plane exists at ~~midpoint~~ midway b/n the 2 long parallel & oppositely charged condrs (+q & -q).

* A fictitious conductor is placed below each condr of the same size & shape as the overhead conductor lying below the original conductor at a distance equal to twice the distance of the condr above the plane of ground.

This fictitious conductor is called image conductor. Having the charge opposite to that of overhead condr.

The voltage V_{ab} is given as

$$V_{ab} \Rightarrow \frac{1}{2\pi\epsilon}\left[q_a \ln\left(\frac{D}{r}\right) + q_b \ln\left(\frac{r}{D}\right)\right] + \frac{1}{2\pi\epsilon}\left\{-q_a \ln \frac{\sqrt{D^2+4h^2}}{2h} - q_b \ln \frac{2h}{\sqrt{D^2+4h^2}}\right\}$$

$$\Rightarrow \frac{1}{2\pi\epsilon}\left\{q_a \ln \frac{2h \cdot D}{r\sqrt{D^2+4h^2}} + q_b \ln \frac{r\sqrt{D^2+4h^2}}{2hD}\right\}$$

But $q_b = -q_a$.

$$\Rightarrow \frac{1}{2\pi\epsilon}\left\{q_a\left[\ln \frac{4h^2D^2}{r^2(D^2+4h^2)}\right] \Rightarrow \frac{q_a}{2\pi\epsilon} \ln\left[\frac{D^2}{r^2\left(1+\frac{D^2}{4h^2}\right)}\right]\right.$$

$$\Rightarrow \frac{1}{2\pi\epsilon} \times 2q_a \ln\left[\frac{D}{r\sqrt{\left(1+\frac{D^2}{4h^2}\right)}}\right]$$

$$V_{ab} \Rightarrow \frac{q_a}{\pi\epsilon} \ln\left(\frac{D}{r\sqrt{1+\frac{D^2}{4h^2}}}\right)$$

$$\therefore \boxed{C_{ab} \Rightarrow \frac{q_a}{V_{ab}} \Rightarrow \frac{\pi\epsilon}{\ln\left(\frac{D}{r\sqrt{1+\frac{D^2}{4h^2}}}\right)}}$$

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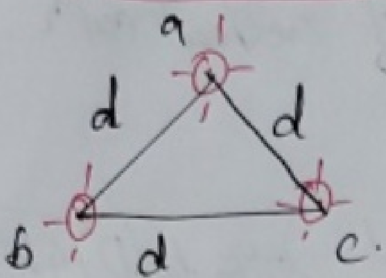
Capacitance of a 3-phase Line with Equilateral Spacing.



* Consider the three conductors a, b & c. of 3phase OHTL having the charges q_a, q_b & q_c respectively. as shown.

* Let the conductors be separated by a distance of 'd' m from each other (as shown).

* The radius of each conductor is say 'r'. The Voltage V_{ab} of the Three phase line due to only charges on conductors 'a' & 'b', is given by.

$$V_{ab} \Rightarrow \frac{1}{2\pi\epsilon}\left[q_a \ln\left(\frac{d}{r}\right) + q_b \ln\left(\frac{r}{d}\right)\right] \rightarrow (1)$$

Voltage V_{ab} due to only charge 'q_c' is zero as uniform charge distribution over the surface of the conductor is equivalent to a concentrated charge at the centre of conductor.

$$\therefore V_{ab} = \frac{q_c}{2\pi\epsilon} \ln\left(\frac{d}{d}\right) \rightarrow (2)$$

Considering all the 3 charges in writing the voltage equation we have,

$$V_{ab} \Rightarrow \frac{1}{2\pi\epsilon}\left[q_a \ln\left(\frac{d}{r}\right) + q_b \ln\left(\frac{r}{d}\right) + q_c \ln\left(\frac{d}{d}\right)\right] - (3)$$

$$|||^{ly}\ V_{ac} \Rightarrow \frac{1}{2\pi\epsilon}\left[q_a \ln\left(\frac{d}{r}\right) + q_b \ln\left(\frac{d}{d}\right) + q_c \ln\left(\frac{r}{d}\right)\right] \rightarrow (4)$$

(3) + (4), $V_{ab}+V_{ac} \Rightarrow \frac{1}{2\pi\epsilon}\left[2q_a \ln\left(\frac{d}{r}\right)+(q_b+q_c)\ln\left(\frac{r}{d}\right)\right]$ → (5)

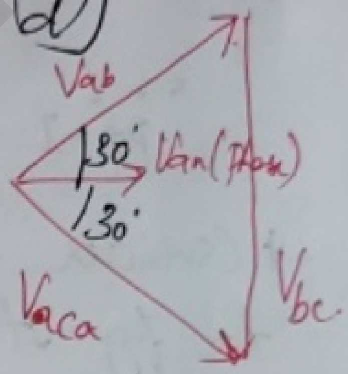
The voltages are sinusoidal & expressed as the phasors.
∴ In the absence of other charges, sum of charges is zero.

$$q_a+q_b+q_c=0$$

$$\therefore (q_b+q_c) = -q_a \rightarrow (6)$$

$$\therefore V_{ab}+V_{ac} \Rightarrow \frac{1}{2\pi\epsilon}\left[2q_a \ln\left(\frac{d}{r}\right) - q_a \ln\left(\frac{r}{d}\right)\right]$$

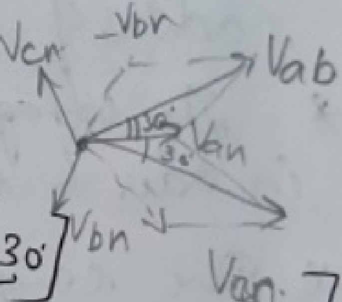
$$\Rightarrow \frac{q_a}{2\pi\epsilon}\left[3q_a \ln\left(\frac{d}{r}\right)\right]$$



For any balanced 3-phase line

$$V_{ab} \Rightarrow \sqrt{3}\, V_{an}\angle 30^\circ \quad [\dot{V}_L = \sqrt{3} V_{ph}]$$

$$V_{ac} \Rightarrow \sqrt{3}\, V_{an}\angle -30^\circ$$



$$\therefore V_{ab}+V_{ac} \Rightarrow V_{an}\left[\sqrt{3}\angle 30^\circ + \sqrt{3}\angle -30^\circ\right]$$

$$\Rightarrow \sqrt{3}\, V_{an}\left[0.866+j0.5+0.866-j0.5\right]$$

$$\Rightarrow \sqrt{3}\, V_{an} \times \left(\frac{\sqrt{3}}{2}+\frac{\sqrt{3}}{2}\right)$$

$$\boxed{V_{ab}+V_{ac} \Rightarrow 3V_{an}}$$

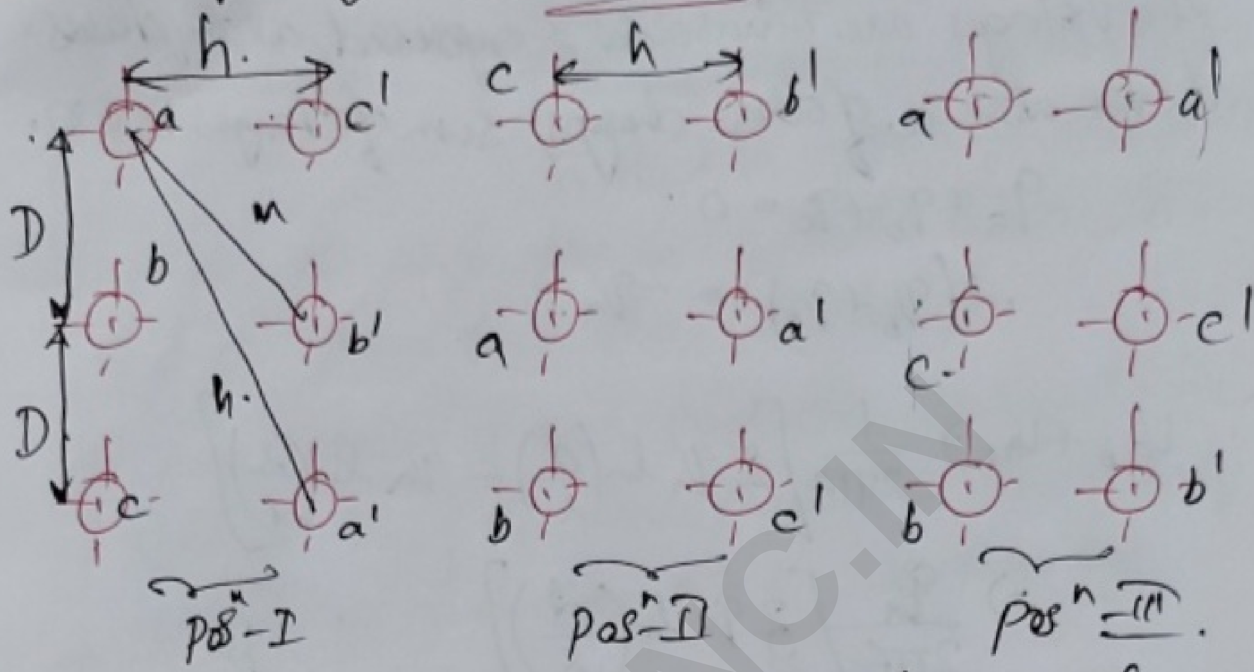
$$\boxed{\therefore C_{an} \Rightarrow \frac{2\pi\epsilon}{\ln\left(\frac{d}{r}\right)} \text{ F/m}}$$

$$\therefore 3V_{an} \Rightarrow \frac{3q_a}{2\pi\epsilon}\ln\left(\frac{d}{r}\right)$$

$$\therefore V_{an} \Rightarrow \frac{q_a}{2\pi\epsilon}\ln\left(\frac{d}{r}\right).$$

(19)

Capacitance of 3-phase Double circuit with Unsymmetrical spacing but Transposed.



* Consider the arrangement of conductors shown in the fig. It consists of 3phase double circuit. The radius of each conductor 'r'.
* The voltage between phases 'a' & 'b' can be calculated in order to calculate capacitance.
* One complete cycle of transposition is shown in fig.

In position - I

$$V_{ab_1} \Rightarrow \frac{1}{2\pi\epsilon}\left\{ q_a\left(\ln\frac{D}{r}+\ln\frac{m}{n}\right) + q_b\left(\ln\frac{r}{D}+\ln\frac{h}{m}\right) + q_c\left(\ln\frac{D}{2D}+\ln\frac{m}{h}\right)\right\} \rightarrow (1)$$

In position - II

$$V_{ab_2} \Rightarrow \frac{1}{2\pi\epsilon}\left\{ q_a\left[\ln\frac{D}{r}+\ln\frac{m}{h}\right] + q_b\left(\ln\frac{r}{D}+\ln\frac{h}{m}\right) + q_c\left(\ln\frac{2D}{D}+\ln\frac{h}{m}\right)\right\} \rightarrow (2)$$

In position III.

$$V_{ab_3} \Rightarrow \frac{1}{2\pi\epsilon}\left\{ q_a\left(\ln\frac{2D}{r} + \ln\frac{h}{n}\right) + q_b\left(\ln\frac{r}{2D} + \ln\frac{n}{h}\right) + q_c\left(\ln\frac{D}{D} + \ln\frac{m}{m}\right)\right\} \rightarrow (3)$$

$$\therefore V_{ab} \Rightarrow \frac{1}{3}\left[V_{ab_1} + V_{ab_2} + V_{ab_3}\right] \rightarrow (4)$$

$$\Rightarrow \frac{1}{6\pi\epsilon}\left\{ q_a\left(\ln\frac{2D^3}{r^3} + \ln\frac{m^2h}{n^2h}\right) + q_b\left(\ln\frac{r^3}{2D^3} + \ln\frac{n^2h}{m^2h}\right) + q_c\left(\ln\frac{2D^3}{2D^3} + \ln\frac{m^2h}{m^2h}\right)\right\}$$

$$V_{ab} \Rightarrow \frac{1}{6\pi\epsilon}\left\{ q_a \ln\frac{2D^3m^2}{r^3n^2} + q_b \ln\frac{r^3n^2}{2D^3m^2}\right\} \rightarrow (5)$$

Similarly potential between phases 'a' & 'c' can be calculated as

$$V_{ac} \Rightarrow \frac{1}{6\pi\epsilon}\left[q_a \ln\frac{2D^3m^2}{r^3n^2} + q_c \ln\frac{r^3n^2}{2D^3m^2}\right] \rightarrow (6)$$

As $V_{ab} + V_{ac} \Rightarrow 3V_{an}$.

$$\therefore 3V_{an} \Rightarrow \frac{1}{6\pi\epsilon}\left[2q_a \ln\frac{2D^3m^2}{r^3n^2} + (q_b+q_c)\ln\frac{r^3n^2}{2D^3m^2}\right] \rightarrow (7)$$

As $q_a + q_b + q_c = 0$, $(q_b + q_c) \Rightarrow -q_a$.

$$\therefore V_{an} \Rightarrow \frac{1}{6\pi\epsilon}\left\{ q_a \ln\frac{2D^3m^2}{r^3n^2}\right\}$$

Cap per phase $\Rightarrow 2C_{an}$.

$$\therefore \boxed{C_{an} \Rightarrow \frac{q_a}{V_{an}} \Rightarrow \frac{2\pi\epsilon}{\ln\left\{2^{1/3}(D/r)(m/n)^{2/3}\right\}}} \rightarrow (8)$$

Methods of Arrangement of conductors

There are various methods of arranging the conductors over the line supports.

i) Single phase circuits.

There are 2 types of arrangements in single phase circuit. For Eg Single circuit & double circuit.

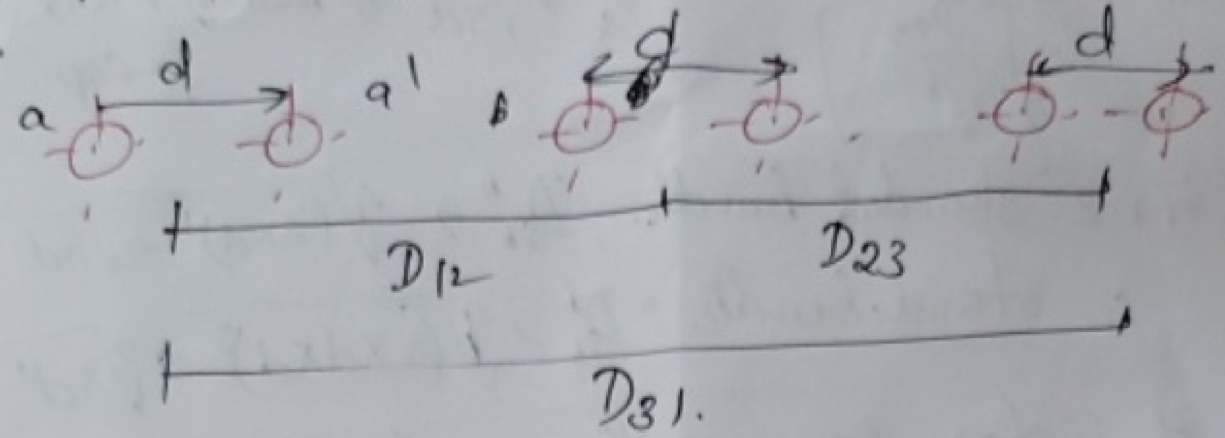
2) In double circuits there are again 2 subtypes

(a) horizontal disposition

(b) Vertical disposition.

Single circuit arrangement	Double circuit arrangement
1) This type of arrangement is less dangerous during repair work	1) The type of arrangement is comparatively dangerous.
2) From continuity of supply point of view, the circuit is less reliable.	2) w.r.t. continuity of supply, the circuit is much reliable
3). It requires lesser foundation & less weight of steel tower member.	3). It requires more foundation as the structure is of heavier members. The height of tower is more
4) The spacing of conductors required is greater	4) The spacing of Conductors required is lesser.
5) As spacing of conductors is high the reactance is high	5) As spacing of conductors is less, the reactance is low

Capacitance of System with Bundled Conductors



* Fig. shows the arrangement of one bundle conductors. The conductors of any one bundle are in parallel & charge per bundle is assumed to divide equally b/w the conductors of bundle.

* If charge of phase 'a' is 'q_a' then charge on each of the conductors a' & d' will be $q_a/2$. Same is the case with remaining 2 phases.

$$V_{ab} \Rightarrow \frac{1}{2\pi\epsilon}\left[\frac{q_a}{2}\left(\ln\frac{D_{12}}{r} + \ln\frac{D_{12}}{d}\right) + \frac{q_b}{2}\left(\ln\frac{r}{D_{12}} + \ln\frac{d}{D_{12}}\right) + \frac{q_c}{2}\ln\left(\frac{D_{23}}{D_{31}} + \ln\frac{D_{23}}{D_{31}}\right)\right]$$

$$\Rightarrow \frac{1}{2\pi\epsilon}\left[\frac{q_a}{2}\ln\left(\frac{D_{12}}{\sqrt{rd}}\right) + q_b\ln\left(\frac{\sqrt{rd}}{D_{12}}\right) + q_c\ln\left(\frac{D_{23}}{D_{31}}\right)\right]$$

similar to (unsymmetrical spacing)

$$\therefore C_{an} \Rightarrow \frac{2\pi\epsilon}{\ln\left(\frac{D_{eq}}{\sqrt{rd}}\right)} \text{ F/m.}$$

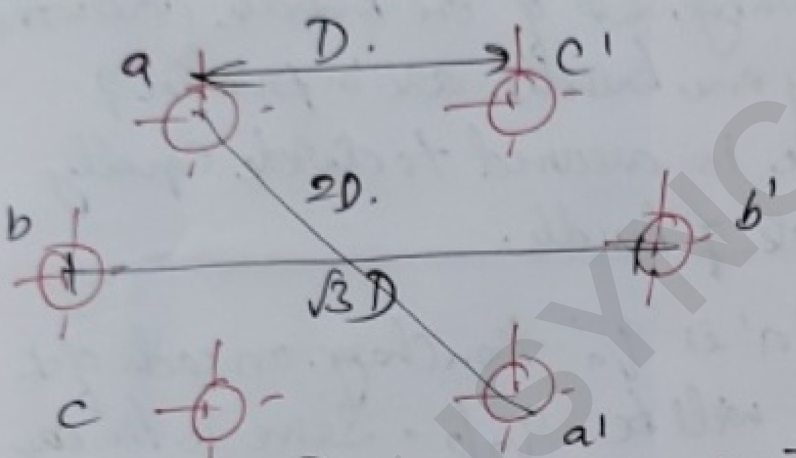
$$C_{an} \Rightarrow \frac{2\pi\epsilon}{\ln\left[\frac{D_{eq}}{D_{sc}^{b}}\right]}$$

$D_{sc}^{b} \Rightarrow \sqrt{rd} \Rightarrow$ modified GMR for cap.

For 2-stranded bundle, $D_{sb}^{b} \Rightarrow \sqrt[4]{(r\times d)^2} = \sqrt{rd}$.

3-strand bundle $\Rightarrow D_{sb}^{b} \Rightarrow \sqrt[9]{(r\times d\times d)^3} \Rightarrow \sqrt[3]{rd^2}$.

Cap. of 3-phase line with more than one circuit



The voltage between phases 'a' & 'b' is given by.

$$V_{ab} \Rightarrow \frac{1}{2\pi\epsilon}\left\{ q_a\left[\ln\left(\frac{D}{r}\right)+\ln\frac{\sqrt{3}D}{2D}\right] + q_b\left[\ln\left(\frac{r}{D}\right)+\ln\left(\frac{2D}{\sqrt{3}D}\right)\right] + q_c\left[\ln\left(\frac{D}{\sqrt{3}D}\right)+\ln\left(\frac{\sqrt{3}D}{D}\right)\right]\right\}$$

$$\Rightarrow \frac{1}{2\pi\epsilon}\left[q_a \ln\left(\frac{\sqrt{3}D}{2r}\right) + q_b \ln\left(\frac{2r}{\sqrt{3}D}\right) + 0\right]$$

Ily $V_{ac} \Rightarrow \frac{1}{2\pi\epsilon}\left[q_a \ln\frac{\sqrt{3}D}{2r} + q_c \ln\frac{2r}{\sqrt{3}D}\right]$

As $V_{ab} + V_{ac} \Rightarrow 3V_{an}$ for 3 phase A.C, $q_b + q_c = -q_a$

$$3V_{an} \Rightarrow \frac{3q_a}{2\pi\epsilon}\ln\left(\frac{\sqrt{3}D}{2r}\right)$$

$\therefore V_{an} \Rightarrow \frac{q_a}{2\pi\epsilon} \ln\left(\frac{\sqrt{3}D}{2r}\right)$ V/m

$\therefore$ Capacitance $C_{an} = \frac{q_a}{V_{an}} \Rightarrow \frac{2\pi\epsilon}{\ln\left(\frac{\sqrt{3}D}{2r}\right)}$ F/m

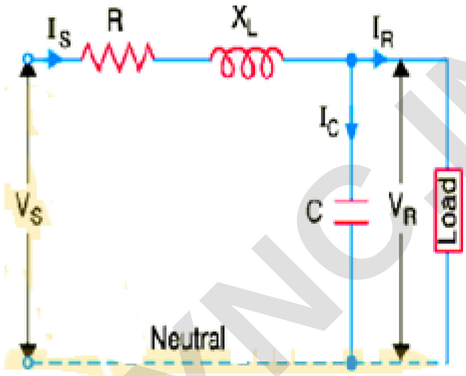
Cap. of each phase $\Rightarrow 2 C_{an}$

$$\Rightarrow \frac{4\pi\epsilon}{\ln\left(\frac{\sqrt{3}D}{2r}\right)} \text{ F/m.}$$

MODULE 3

MODELLING AND PERFORMANCE OF TRANSMISSION LINES

Classification of lines - short line, medium line and long line - equivalent circuits, phasor diagram, attenuation constant, phase constant, surge impedance; transmission efficiency and voltage regulation, real and reactive power flow in lines, Power - circle diagrams, surge impedance loading, methods of voltage control; Ferranti effect.



CLASSIFICATION OF LINES

The important considerations in the design and operation of a transmission line are the determination of voltage drop, line losses and efficiency of transmission. These values are greatly influenced by the line constants R, L and C of the transmission line. For instance the voltage drop in the line depends upon the values of above three line constants. Similarly, the resistance of transmission line conductors is the most important cause of power loss in the line and determines the transmission efficiency. In this chapter, we shall develop formulas by which we can calculate voltage regulation, line losses and efficiency of transmission lines. These formulas are important for two principal reasons. Firstly, they provide an opportunity to understand the effects of the parameters of the line on bus voltages and the flow of power. Secondly, they help in developing an overall understanding of what is occurring on electric power system.

CLASSIFICATION OF OVERHEAD TRANSMISSION LINES

A transmission line has *three constants R, L and C distributed uniformly along the whole length of the line. The resistance and inductance form the series impedance. The capacitance existing between conductors for 1-phase line or from a conductor to neutral for a 3phase line forms a shunt path throughout the length of the line. Therefore, capacitance effects introduce complications in transmission line calculations. Depending upon the manner in which capacitance is taken into account, the overhead transmission lines are classified as :

(i) Short transmission lines. When the length of an overhead transmission line is upto about 50 km and the line voltage is comparatively low (< 20 kV), it is usually considered as a short transmission line. Due to smaller length and lower voltage, the capacitance effects are small and hence can be neglected. Therefore, while studying the performance of a short transmission line, only resistance and inductance of the line are taken into account.

(ii) Medium transmission lines. When the length of an overhead transmission line is about 50-150 km and the line voltage is moderately high (>20 kV < 100 kV), it is considered as a medium transmission line. Due to sufficient length and voltage of the line, the capacitance effects are taken into account. For purposes of calculations, the distributed capacitance of the line is divided and lumped in the form of condensers shunted across the line at one or more points.

(iii) Long transmission lines. When the length of an overhead transmission line is more than 150 km and line voltage is very high (> 100 kV), it is considered as a long transmission line. For the treatment of such a line, the line constants are considered uniformly distributed over the whole length of the line and rigorous methods are employed for solution. It may be emphasised here that exact solution of any transmission line must consider the fact that the constants of the line are not lumped but are distributed uniformly throughout the length of the line. However, reasonable accuracy can be obtained by considering these constants as lumped for short and medium transmission lines.

Important Terms

While studying the performance of a transmission line, it is desirable to determine its voltage regulation and transmission efficiency. We shall explain these two terms in turn.

(i) Voltage regulation. When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (VR) of the line is generally less than the sending end voltage (VS). This voltage drop (Vs −V R) in the line is expressed as a percentage of receiving end voltage V and is called voltage regulation.

The difference in voltage at the receiving end of a transmission line **between conditions of no load and full load is called **voltage regulation** and is expressed as a percentage of the receiving end voltage.

(ii) Transmission efficiency. The power obtained at the receiving end of a transmission line is generally less than the sending end power due to losses in the line resistance. The ratio of receiving end power to the sending end power of a transmission line is known as the **transmission efficiency** of the line

PERFORMANCE OF SINGLE PHASE SHORT TRANSMISSION LINES

As stated earlier, the effects of line capacitance are neglected for a short transmission line. Therefore, while studying the performance of such a line, only resistance and inductance of the line are taken into account. The equivalent circuit of a single phase short transmission line is shown in Fig.

Here, the total line resistance and inductance are shown as concentrated or lumped instead of being distributed. The circuit is a simple a.c. series circuit.

Let I = load current

R = loop resistance i.e., resistance of both conductors

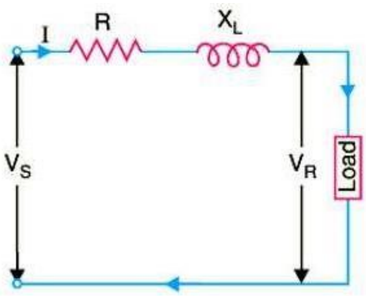
XL= loop reactance

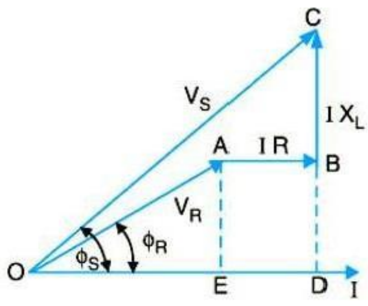
VR = receiving end voltage

cosφR = receiving end power factor (lagging)

VS= sending end voltage

cosφS= sending end power factor





The *phasor diagram of the line for lagging load power factor is shown in Fig. From the right angled triangle ODC, we get,

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

or

$$V_S^2 = (OE + ED)^2 + (DB + BC)^2$$

$$= (V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2$$

$$\therefore \quad V_S = \sqrt{(V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2}$$

(*i*) $$\text{\%age Voltage regulation} = \frac{V_S - V_R}{V_R} \times 100$$

(*ii*) $$\text{Sending end } p.f., \cos \phi_S = \frac{OD}{OC} = \frac{V_R \cos \phi_R + IR}{V_S}$$

(*iii*) $$\text{Power delivered} = V_R I_R \cos \phi_R$$

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

$$\text{Power sent out} = V_R I_R \cos \phi_R + I^2 R$$

$$\text{\%age Transmission efficiency} = \frac{\text{Power delivered}}{\text{Power sent out}} \times 100$$

$$= \frac{V_R I_R \cos \phi_R}{V_R I_R \cos \phi_R + I^2 R} \times 100$$

An approximate expression for the sending end voltage Vs can be obtained as follows. Draw S perpendicular from B and C on OA produced as shown in Fig. Then OC is nearly equal to OF

$$OC = OF = OA + AF = OA + AG + GF$$

$$= OA + AG + BH$$

$$V_s = V_R + IR \cos \varphi_R + I X_L \sin \varphi_R$$

THREE-PHASE SHORT TRANSMISSION LINES

For reasons associated with economy, transmission of electric power is done by 3-phase system. This system may be regarded as consisting of three single phase units, each wire transmitting one-third of the total power. As a matter of convenience, we generally analyse 3phase system by considering one phase only. Therefore, expression for regulation, efficiency etc. derived for a single phase line can also be applied to a 3-phase system. Since only one phase is considered, phase values of 3-phase system should be taken. Thus, Vs and VR are the phase voltages, whereas R and XL are the resistance S and inductive reactance per phase respectively.

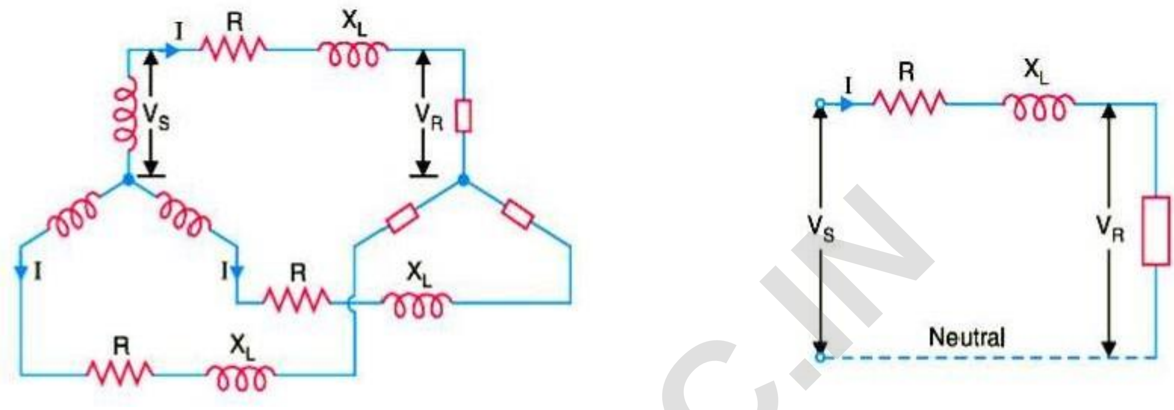


Fig (i) shows a Y-connected generator supplying a balanced Y-connected load through a transmission line. Each conductor has a resistance of R Ω and inductive reactance of X Ω. Fig.(ii) shows one phase separately. The calculations can now be made in the same way as for a single phase line.

MEDIUM TRANSMISSION LINES

In short transmission line calculations, the effects of the line capacitance are neglected because such lines have smaller lengths and transmit power at relatively low voltages (< 20 kV). However, as the length and voltage of the line increase, the capacitance gradually becomes of greater importance.

Since medium transmission lines have sufficient length (50-150 km) and usually operate at voltages greater than 20 kV, the effects of capacitance cannot be neglected. Therefore, in order to obtain reasonable accuracy in medium transmission line calculations, the line capacitance must be taken into consideration.

The capacitance is uniformly distributed over the entire length of the line. However, in order to make the calculations simple, the line capacitance is assumed to be lumped or concentrated in the form of capacitors shunted across the line at one or more points. Such a treatment of localising the line capacitance gives reasonably accurate results. The most commonly used methods (known as localised capacitance methods) for the solution of medium transmissions lines are :**(i) End condenser method**

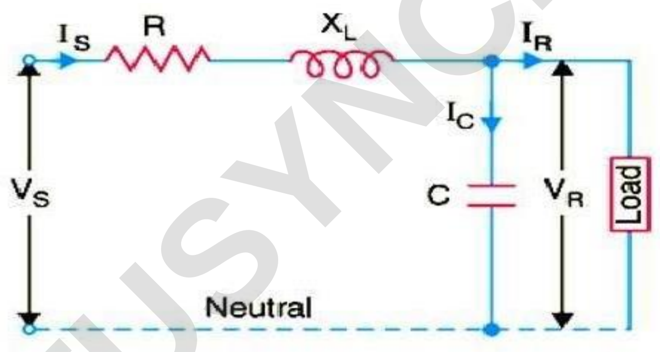
(ii) Nominal T method

(iii) Nominal π method.

Although the above methods are used for obtaining the performance calculations of medium lines, they can also be used for short lines if their line capacitance is given in a particular problem.

End Condenser Method

In this method, the capacitance of the line is lumped or concentrated at the receiving or load end as shown in Fig.This method of localising the line capacitance at the load end overestimates the effects of capacitance. In Fig, one phase of the 3-phase transmission line is shown as it is more convenient to work in phase instead of line-to-line values.



Let

I R= load current per phase

R = resistance per phase

XL= inductive reactance per phase

C = capacitance per phase

cosφR= receiving end power factor (lagging)

VS= sending end voltage per phase

The *phasor diagram for the circuit is shown in Fig Taking the receiving end voltage VR as the reference phasor,

we have, $V_R = V_R + j\,0$

Load current, $\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$

Capacitive current, $\vec{I_C} = j\,\vec{V_R}\,\omega C = j\,2\pi f C\,\vec{V_R}$

The sending end current Isis the phasor sum of load current IR and capacitive current IC i.e.

$$\vec{I_S} = \vec{I_R} + \vec{I_C}$$
$$= I_R(\cos\phi_R - j\sin\phi_R) + j\,2\pi f C\, V_R$$
$$= I_R\cos\phi_R + j(-I_R\sin\phi_R + 2\pi f C V_R)$$
$$= \vec{I_S}\,\vec{Z} = \vec{I_S}\,(R + jX_L)$$
$$\vec{V_S} = \vec{V_R} + \vec{I_S}\,\vec{Z} = \vec{V_R} + \vec{I_S}\,(R + jX_L)$$

Thus, the magnitude of sending end voltage V_S can be calculated.

$$\%\ \text{Voltage regulation} = \frac{V_S - V_R}{V_R} \times 100$$

$$\%\ \text{Voltage transmission efficiency} = \frac{\text{Power delivered / phase}}{\text{Power delivered / phase + losses / phase}} \times 100$$
$$= \frac{V_R I_R \cos\phi_R}{V_R I_R \cos\phi_R + I_S^2 R} \times 100$$

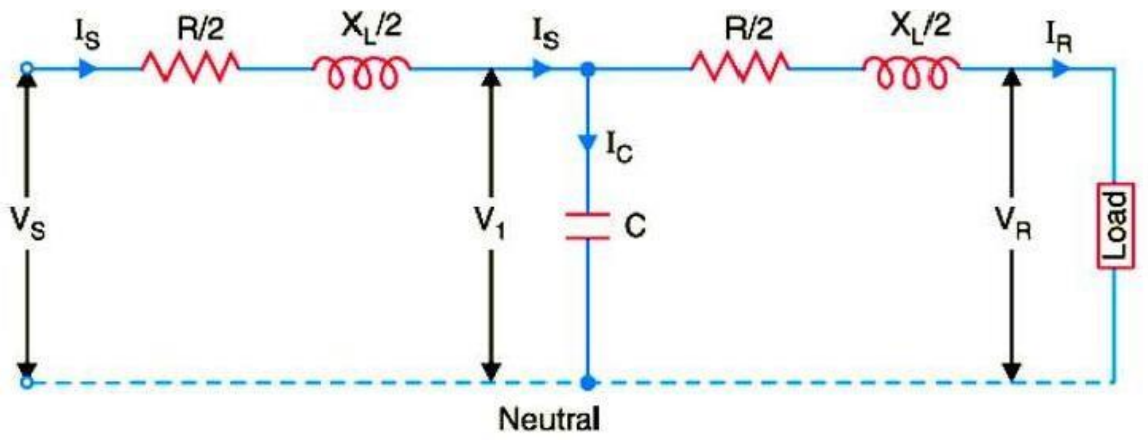
Limitations Although end condenser method for the solution of medium lines is simple to work out calculations, yet it has the following drawbacks :

(i) There is a considerable error (about 10%) in calculations because the distributed capacitance has been assumed to be lumped or concentrated.

(ii) This method overestimates the effects of line capacitance.

ii) Nominal T Method

In this method, the whole line capacitance is assumed to be concentrated at the middle point of the line and half the line resistance and reactance are lumped on its either side as shown in Fig.Therefore, in this arrangement, full charging current flows over half the line. In Fig. one phase of 3-phase transmission line is shown as it is advantageous to work in phase instead of line-to-line values.



Let

IR = load current per phase ;

R = resistance per phase

XL = inductive reactance per phase ;

C = capacitance per phase

cosφR = receiving end power factor (lagging) ;

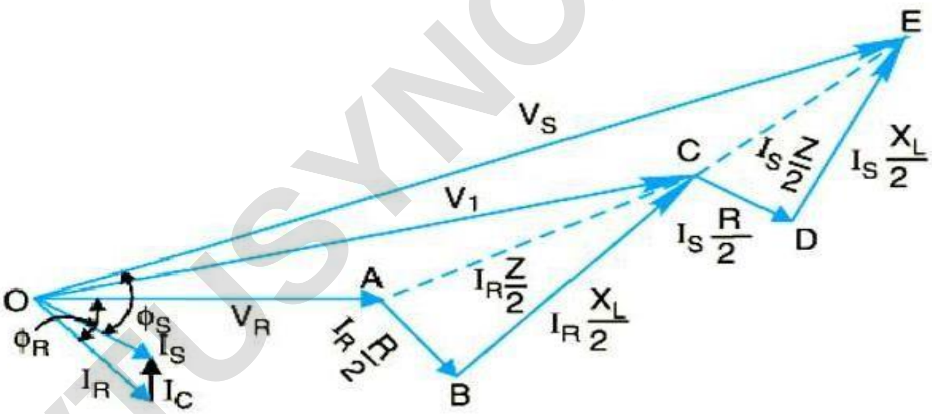
VS= sending end voltage/phase

V1 = voltage across capacitor C

The *phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage VR as the reference phasor, we have,

Receiving end voltage, $\vec{V_R} = V_R + j\,0$

Load current, $\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$



Voltage across C, $\vec{V_1} = \vec{V_R} + \vec{I_R}\,\vec{Z}/2$

$$= V_R + I_R(\cos\phi_R - j\sin\phi_R)\left(\frac{R}{2} + j\frac{X_L}{2}\right)$$

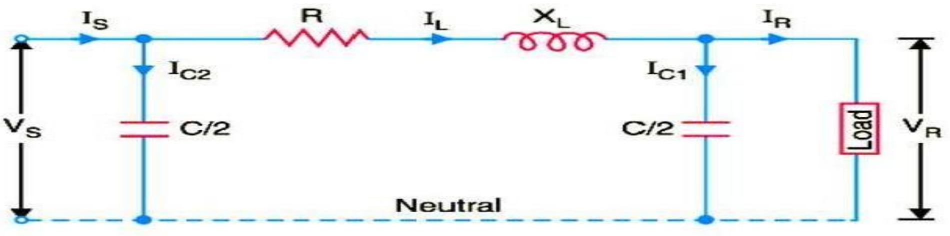
Capacitive current, $\vec{I_C} = j\,\omega\,C\,\vec{V_1} = j\,2\pi f\,C\,\vec{V_1}$

Sending end current, $\vec{I_S} = \vec{I_R} + \vec{I_C}$

Sending end voltage, $\vec{V_S} = \vec{V_1} + \vec{I_S}\,\frac{\vec{Z}}{2} = \vec{V_1} + \vec{I_S}\left(\frac{R}{2} + j\frac{X_L}{2}\right)$

iii) Nominal π Method

In this method, capacitance of each conductor (i.e., line to neutral) is divided into two halves; one half being lumped at the sending end and the other half at the receiving end as shown in Fig. It is obvious that capacitance at the sending end has no effect on the line drop. However, its charging current must be added to line current in order to obtain the total sending end current



Let

IR = load current per phase

R = resistance per phase

XL = inductive reactance per phase

C = capacitance per phase

cosφR = receiving end power factor (lagging)

VS= sending end voltage per phase

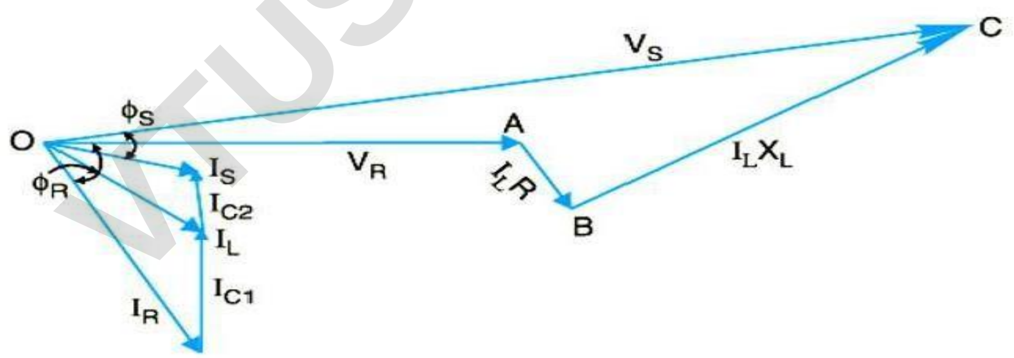
The *phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage as the reference phasor, we have,

$$\vec{V_R} = V_R + j\,0$$

Load current, $\vec{I_R} = I_R\,(\cos\phi_R - j\sin\phi_R)$

Charging current at load end is

$$\vec{I_{C1}} = j\,\omega\,(C/2)\,\vec{V_R} = j\,\pi\,f\,C\,\vec{V_R}$$



Line current, $\vec{I_L} = \vec{I_R} + \vec{I_{C1}}$

Sending end voltage, $\vec{V_S} = \vec{V_R} + \vec{I_L}\,\vec{Z} = \vec{V_R} + \vec{I_L}\,(R + jX_L)$

Charging current at the sending end is

$$\vec{I_{C2}} = j\,\omega\,(C/2)\,\vec{V_S} = j\,\pi\,f\,C\,\vec{V_S}$$

∴ Sending end current, $\vec{I_S} = \vec{I_L} + \vec{I_{C2}}$

LONG TRANSMISSION LINES

It is well known that line constants of the transmission line are uniformly distributed over the entire length of the line. However, reasonable accuracy can be obtained in line calculations for short and medium lines by considering these constants as lumped. If such an assumption of lumped constants is applied to long transmission lines (having length excess of about 150 km), it is found that serious errors are introduced in the performance calculations. Therefore, in order to obtain fair degree of accuracy in the performance calculations of long lines, the line constants are considered as uniformly distributed throughout the length of the line. Rigorous mathematicaltreatment is required for the solution of such lines. Fig shows the equivalent circuit of a 3-phase long transmission line on a phase-neutral basis. The whole line length is divided into n sections, each section having line constants 1 /n th of those for the whole line. The following points may by noted :

(i) The line constants are uniformly distributed over the entire length of line as is actually the case.

(ii) The resistance and inductive reactance are the series elements.

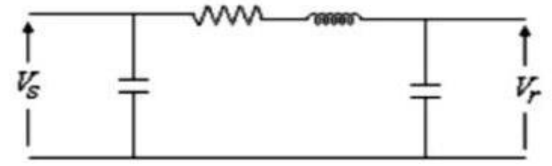
(iii) The leakage suspectance (B) and leakage conductance (G) are shunt elements. The leakage suspectance is due to the fact that capacitance exists between line and neutral. The leakage conductance takes into account the energy losses occurring through leakage over theinsulators or due to corona effect between conductors. Admittance $= \sqrt{G^2 + B^2}$.

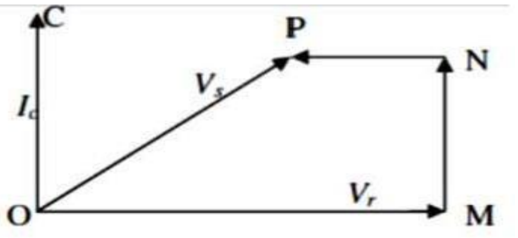
(iv) The leakage current through shunt admittance is maximum at the sending end of the line and decreases continuously as the receiving end of the circuit is approached at which point its value is zero.

FERRANTI EFFECT

A long transmission line draws a substantial quantity of charging current. If such a line is open circuited or very lightly loaded at the receiving end, the voltage at receiving end may become greater than voltage at sending end. This is known as Ferranti Effect and is due to the voltage drop across the line inductance (due to charging current) being in phase with the sending end voltages. Therefore both capacitance and inductance is responsible to produce this phenomenon The capacitance (and charging current) is negligible in short line but significant in medium line and appreciable in long line. Therefore this phenomenon occurs in medium and long lines.

Represent line by equivalent π model.





Line capacitance is assumed to be concentrated at the receiving end.

OM = receiving end voltage Vr

OC = Current drawn by capacitance = Ic

MN = Resistance drop

NP = Inductive reactance drop

Therefore;

OP = Sending end voltage at no load and is less than receiving end voltage (Vr)

Since, resistance is small compared to reactance; resistance can be neglected in calculating Ferranti effect.

From π model,

$$V_s = \left(1+\frac{YZ}{2}\right)V_r + ZI_r$$

For open circuit line; Ir = 0

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

or; $$V_s - V_r = \left(1+\frac{YZ}{2}\right)V_r - V_r = V_r\left(1+\frac{YZ}{2}-1\right)$$

or; $$V_s - V_r = \left(\frac{YZ}{2}\right)V_r = \frac{(j\omega Cl)(r+j\omega L)l}{2}V_r$$

Neglecting resistance;

$$V_s - V_r = \frac{-V_r \omega^2 l^2 LC}{2}$$

Substituting the value in above equation;

$$LC = \frac{1}{(3\times10^5)^2}$$

$$V_s - V_r = \frac{-V_r \omega^2 l^2}{2\,(3\times10^5)^2}$$

$$\therefore \quad V_s - V_r = \frac{-V_r \omega^2 l^2 \times 10^{-10}}{18}$$

$$\boxed{\therefore\ V_s = V_r\left[1 - \frac{\omega^2 l^2 \times 10^{-10}}{18}\right]}$$

Now, from above expression;

$$\left[1 - \frac{\omega^2 l^2 \times 10^{-10}}{18}\right] < 1$$

$$V_s < V_r \qquad or; \quad V_r > V_s$$

i.e. receiving end voltage is greater than sending end voltage and this effect is called Ferranti Effect. It is valid for open circuit condition of long line.

MODULE 4

CORONA

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called critical disruptive voltage, the conductors are surrounded by a faint violet glow called corona.

The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. The higher the voltage is raised, the larger and higher the luminous envelope becomes, and greater are the sound, the power loss and the radio noise. If the applied voltage is increased to breakdown value, a flash-over will occur between the conductors due to the breakdown of air insulation If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductor, otherwise the rough points will appear brighter. With d.c. voltage, there is difference in the appearance of the two wires. The positive wire has uniform glow about it, while the negative conductor has spotty glow.

Theory of corona formation

Some ionisation is always present in air due to cosmic rays, ultraviolet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionised particles and neutral molecules. When p.d. is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons. When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which is turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cumulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

Factors Affecting Corona

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. The following are the factors upon which corona depends:

(i)Atmosphere

As corona is formed due to ionisation of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

(ii) Conductor size.

The corona effect depends upon the shape and conditions of the conductors. The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona that a solid conductor.

(iii) Spacing between conductors.

If the spacing between the conductors is made very large as compared to their diameters, there may not be any corona effect. It is because larger distance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.

(iv) Line voltage.

The line voltage greatly affects corona. If it is low, there is no change in the condition of air surrounding the conductors and hence no corona is formed. However, if the line voltage has such a value that electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

Advantages and Disadvantages of Corona

Corona has many advantages and disadvantages. In the correct design of a high voltage overhead line, a balance should be struck between the advantages and disadvantages.

Advantages

(i) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.

(ii) Corona reduces the effects of transients produced by surges.

Disadvantages

(i) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.

(ii) Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.

(iii) The current drawn by the line due to corona is non-sinusoidal and hence no sinusoidal voltage drop occurs in the line. This may cause inductive interference with neighbouring communication lines.

Methods of Reducing Corona Effect

It has been seen that intense corona effects are observed at a working voltage of 33 kV or above. Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33 kV and higher voltages otherwise highly ionized air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment. The corona effects can be reduced by the following methods

(i) By increasing conductor size.

By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced. This is one of the reasons that ACSR conductors which have a larger cross-sectional area are used in transmission lines.

(ii) By increasing conductor spacing

By increasing the spacing between conductors, the voltage at which corona occurs is raised and hence corona effects can be eliminated. However, spacing cannot be increased too much otherwise the cost of supporting structure (e.g., bigger cross arms and supports) may increase to a considerable extent.

UNDERGROUND CABLES

An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover. Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must full fill the following necessary requirements:

(i) The conductor used in cables should be tinned stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

(ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.

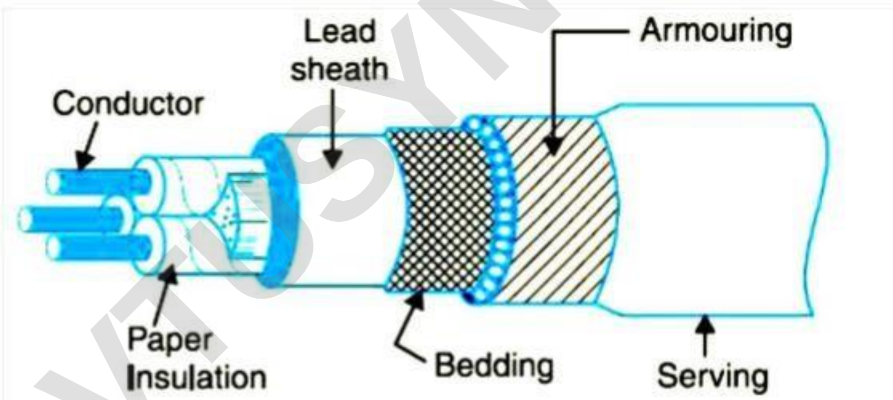
(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

(iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.

(v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

CONSTRUCTION OF CABLES

Fig shows the general construction of a 3-conductor cable. The various parts are



a) Cores or Conductors

A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3- conductor cable shown in Fig. is used for 3phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

b) Insulation

Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

c) Metallic sheath.

In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalise) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig.

d) Bedding.

Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

e) Armouring.

Over the bedding, armouring is provided which consists of one or two layers of galvanized steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

f) Serving.

In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as serving. It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from Mechanical injury.

INSULATING MATERIALS FOR CABLES

The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance. In general, the insulating materials used in cables should have the following

Properties

(i) High insulation resistance to avoid leakage current.

(ii) High dielectric strength to avoid electrical breakdown of the cable. (

(iii) High mechanical strength to withstand the mechanical handling of cables.

(iv) Non-hygroscopic i.e., it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.

(v) Non-inflammable.

(vi) Low cost so as to make the underground system a viable proposition.

(vii) Unaffected by acids and alkalise to avoid any chemical action. No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at. The principal insulating materials used in cables are rubber, vulcanized India rubber, impregnated paper, varnished cambric and polyvinyl chloride.

Rubber

Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is 1017 cm. Although pure rubber has reasonably high insulating properties, it suffers form some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38ºC), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

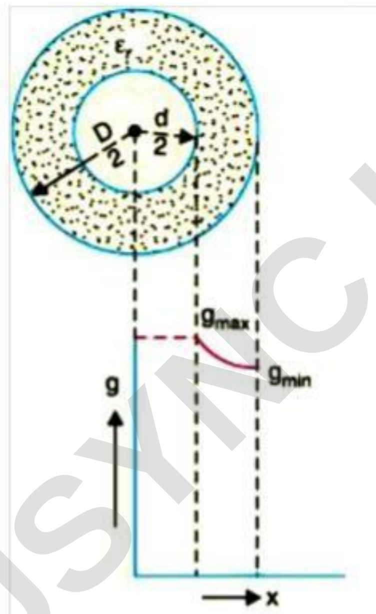
Vulcanised India Rubber (V.I.R.)

It is prepared by mixing pure rubber with mineral matter such as zinc oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150ºC. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

Impregnated paper

It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or naphthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed. If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar. Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a few joints. For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus. However, for smaller installations, where the lengths are small and joints are required at a number of places, VIR cables will be cheaper and durable than paper insulated cables.

Dielectric Stress In Cable



Under operating conditions, the insulation of a cable is subjected to electrostatic forces. This is known as dielectric stress. The dielectric stress at any point in a cable is in fact the potential gradient (or electric intensity) at that point. Consider a single core cable with core diameter d and internal sheath diameter D. As proved in Art 8, the electric intensity at a point x metres from the centre of the cable is

$$E_x = \frac{Q}{2\pi \varepsilon_o \varepsilon_r x} \text{ volts/m}$$

By definition, electric intensity is equal to potential gradient. Therefore, potential gradient g at a point x meters from the Centre of cable is

$$g = E_x$$

or $$g = \frac{Q}{2\pi \varepsilon_o \varepsilon_r x} \text{ volts/m} \qquad ...(i)$$

As proved, potential difference V between conductor and sheath is

$$V = \frac{Q}{2\pi\varepsilon_o\varepsilon_r}\log_e\frac{D}{d} \text{ volts}$$

or

$$Q = \frac{2\pi\varepsilon_o\varepsilon_r V}{\log_e\frac{D}{d}} \qquad ...(ii)$$

Substituting the value of Q from exp. (ii) in exp. (i), we get,

$$g = \frac{\frac{2\pi\varepsilon_o\varepsilon_r V}{\log_e D/d}}{2\pi\varepsilon_o\varepsilon_r x} = \frac{V}{x\log_e\frac{D}{d}} \text{ volts/m} \qquad ...(iii)$$

It is clear from exp. (iii) that potential gradient varies inversely as the distance x. Therefore, potential gradient will be maximum when x is minimum i.e., when x = d/2 or at the surface of the conductor. On the other hand, potential gradient will be minimum at x = D/2 or at sheath surface. Maximum potential gradient is

$$g_{max} = \frac{2V}{d\log_e\frac{D}{d}} \text{ volts/m} \qquad [\text{Putting } x = d/2 \text{ in exp. } (iii)]$$

Minimum potential gradient is

$$g_{min} = \frac{2V}{D\log_e\frac{D}{d}} \text{ volts/m} \qquad [\text{Putting } x = D/2 \text{ in exp. } (iii)]$$

$$\therefore \qquad \frac{g_{max}}{g_{min}} = \frac{\frac{2V}{d\log_e D/d}}{\frac{2V}{D\log_e D/d}} = \frac{D}{d}$$

The variation of stress in the dielectric is shown in Fig.14. It is clear that dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from the conductor. It may be noted that maximum stress is an important consideration in the design of a cable. For instance, if a cable is to be operated at such a voltage that maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of at least 5 kV/mm, otherwise breakdown of the cable will become inevitable.

GRADING OF CABLES

The process of achieving uniform electrostatic stress in the dielectric of cables is known as grading of cables.

It has already been shown that electrostatic stress in a single core cable has a maximum value (gmax) at the conductor surface and goes on decreasing as we move towards the sheath. The maximum voltage that can be safely applied to a cable depends upon gmax i.e., electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of dielectric must be more than g max .If a dielectric of high strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily over strong.

The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size.

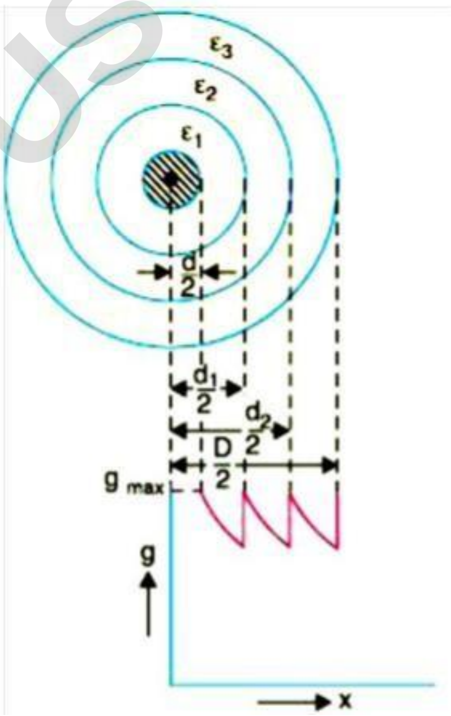
Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables. The following are the two main methods of grading of cables:

(i) Capacitance grading

(ii) Intersheath grading

(i) Capacitance Grading

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as capacitance grading



In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity r of any layer is inversely proportional to its distance from the center.

Under such conditions, the value of potential gradient any point in the dielectric is constant and is independent of its distance from the centre. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. However, ideal grading requires the use of an infinite number of dielectrics which is an impossible task. In practice, two or three dielectrics are used in the decreasing order of permittivity, the dielectric of highest permittivity being used near the core. The capacitance grading can be explained beautifully by referring to Fig. There are three dielectrics of outer diameter d1, d2 and D and of relative permittivity 1, 2 and 3 respectively. If the permittivity are such that 1 > 2 > 3 and the three dielectrics are worked at the same maximum stress, then,

$$\frac{1}{\varepsilon_1 d} = \frac{1}{\varepsilon_2 d_1} = \frac{1}{\varepsilon_3 d_2}$$

$$\text{or} \quad \varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g\, dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi \varepsilon_0 \varepsilon_1 x} dx$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_1} \log_e \frac{d_1}{d} = \frac{g_{max}}{2} d \log_e \frac{d_1}{d} \left[\because \ \frac{Q}{2\pi \varepsilon_0 \varepsilon_1} = \frac{g_{max}}{2} d \right]$$

Similarly, potential across second layer (V2) and third layer (V3) is given by

$$V_2 = \frac{g_{max}}{2} d_1 \log_e \frac{d_2}{d_1}$$

$$V_3 = \frac{g_{max}}{2} d_2 \log_e \frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$= \frac{g_{max}}{2} \left[d \log_e \frac{d_1}{d} + d_1 \log_e \frac{d_2}{d_1} + d_2 \log_e \frac{D}{d_2} \right]$$

$$V' = \frac{g_{max}}{2} d \log_e \frac{D}{d}$$

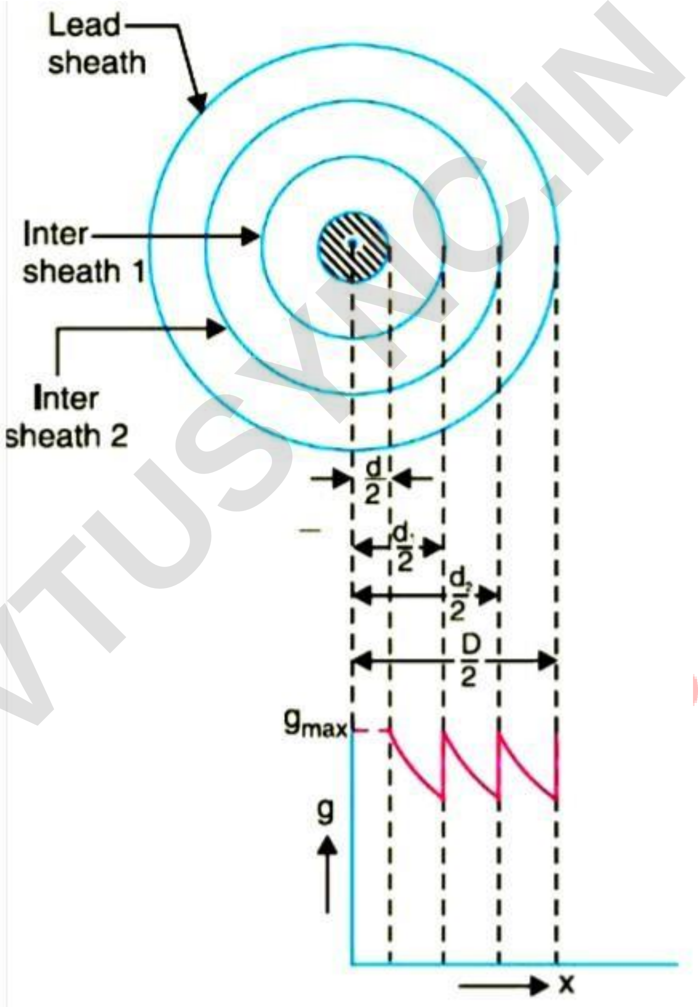
$$V = \frac{g_{1max}}{2} d \log_e \frac{d_1}{d} + \frac{g_{2max}}{2} d_1 \log_e \frac{d_2}{d_1} + \frac{g_{3max}}{2} d_2 \log_e \frac{D}{d_2}$$

If the cable had homogeneous dielectric, then, for the same values of d, D and gmax, the permissible potential difference between core and earthed sheath would have been

$$V' = \frac{g_{max}}{2} d \log_e \frac{D}{d}$$

(ii) Intersheath Grading

In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic inters heaths between the core and lead sheath. The inter sheaths are held at suitable potentials which are in between the core potential and earth potential. This arrangement improves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.



Consider a cable of core diameter d and outer lead sheath of diameter D. Suppose that two inters heaths of diameters d1 and d2 are inserted into the homogeneous dielectric and maintained at some fixed potentials. Let V1,V2 and V3 respectively be the voltage between core and intersheath 1, between inter sheath 1 and 2 and between inter sheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each inter sheath, therefore, each sheath can be treated like a homogeneous single core cable Maximum stress between core and inter sheath 1 is

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}}$$

Similarly,

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}}$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same i.e.,

$$g_{1max} = g_{2max} = g_{3max} = g_{max} \text{ (say)}$$

$$\therefore \quad \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase i.e. Voltage between conductor and earthed lead sheath is

$$V = V_1 + V_2 + V_3$$

Inter sheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the inter sheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable losses in the inter sheaths due to charging currents. For these reasons, inter sheath grading is rarely used.

MODULE 5

Distribution System

That part of power system which distributes electric power for local use is known as distribution system. In general, the distribution system is the electrical system between the substation fed by the Transmission system and the consumer's meters. It generally consists of feeders, distributors, and service mains.

CLASSIFICATION OF DISTRIBUTION SYSTEMS

A distribution system may be classified according to ;

i) **Nature of current**

According to nature of current, distribution system may be classified as

a) d.c. Distribution system
b) a.c. Distribution system

Now-a-days, a.c. system is universally adopted for distribution of electric power as it is simpler and more economical than direct current method

ii) **Type of construction**

According to type of construction distribution system may be classified as

a) Overhead system
b) Underground system.

The overhead system is generally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the underground system is used at places where overhead con struction is impracticable or prohibited by the local laws

(iii) **Scheme of connection**

According to scheme of connection, the distribution system may be classified as

a) Radial system
b) Ring main system

c) Inter-connected system

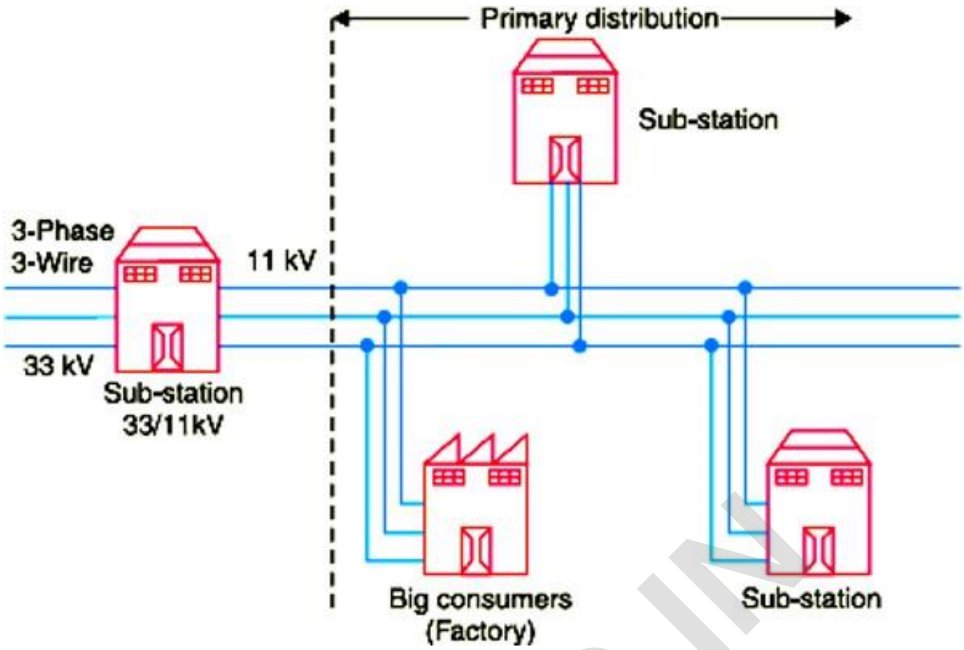
AC DISTRIBUTION

Now-a-days electrical energy is generated, transmitted and distributed in the form of alternating cur-rent. One important reason for the widespread use of alternating current in preference to direct current is the fact that alternating voltage can be conveniently changed in magnitude by means of a transformer. Transformer has made it possible to transmit a.c. power at high voltage and utilise it at a safe potential. High transmission and distribution voltages have greatly reduced the current in the conductors and the resulting line losses. There is no definite line between transmission and distribution according to voltage or bulk capacity. However, in general, the a.c. distribution system is the electrical system between the step- down substation fed by the transmission system and the consumers' meters. The a.c. distribution system is classified into

i. primary distribution system and
ii. Secondary distribution system.

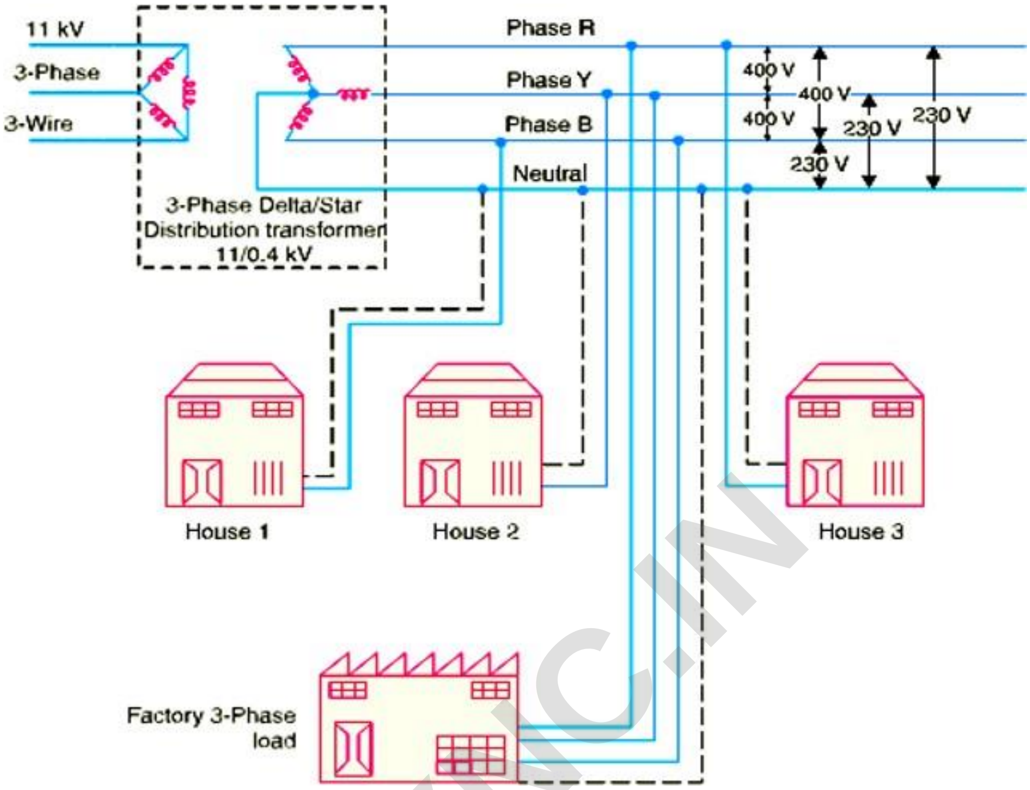
i) Primary distribution system.

It is that part of a.c. distribution system which operates at voltages somewhat higher than general utilization and handles large blocks of electrical energy than the average lowvoltage consumer uses. The voltage used for primary distribution depends upon the amount of power to be conveyed and the distance of the substation required to be fed. The most commonly used primary distribution voltages are 11 kV, 6·6 kV and 3·3 kV. Due to economic considerations, primary distribution is carried out by 3- phase, 3-wire system Fig. shows a typical primary distribution system Electric power from the generating station is transmitted at high voltage to the substation located in or near the city.



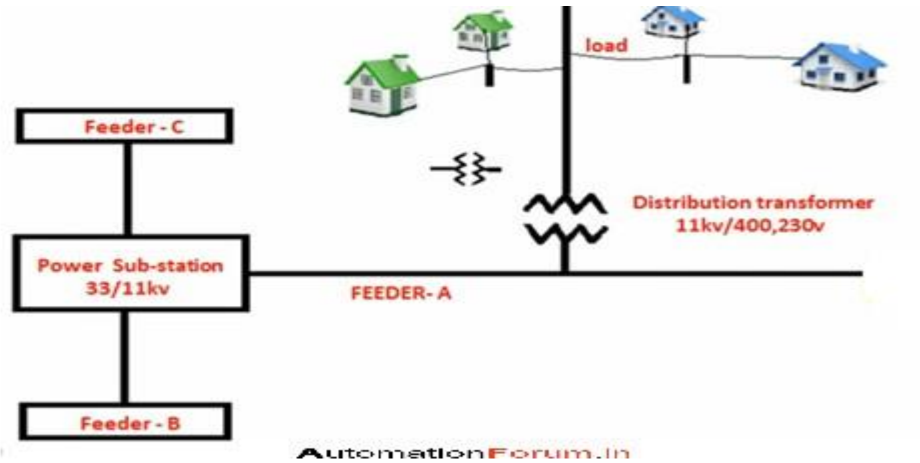
ii) Secondary distribution system

It is that part of a.c. distribution system. The secondary distribution employs 400/230V, 3phase, 4wire system. Fig shows a typical secondary distribution system. The primary distribution circuit delivers power to various substations, called distribution sub-stations. The substations are situated near the consumers' localities and contain step-down transformers. At each distribution substation, the voltage is stepped down to 400Vandpowerisdeliveredby 3-phase, 4wire a.c. system. The voltage between any two phasesis 400V and between any phase and neutralize 230V.The single phase domestic loads are connected between any one phase and the neutral, where as 3phase 400V motor loadsareconnectedacross3- phase lines directly.



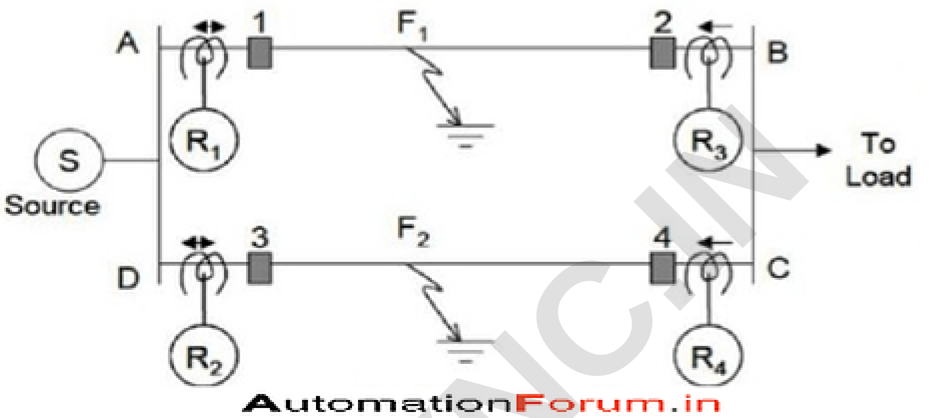
RADIALFEEDERS

It is used for many distribution processes it is really cheap and simple it is only used when the substation or the generating stations are located at the center of the consumers in this type feeder will radiate from the generating stations or substations and it will reach the distributors at one end. Thus the power flow is in one direction



Parallel feeder

There is a disadvantage in radial feeders if there is any fault occur during the transmission there will be no supply for many customers so this can be changed by using parallel feeder if there is any fault occurs only one line of the feeder will be affected the other will do the work the cost is high due to increase in feeder number it can be used to transfer heavy loads



Interconnected distribution system:

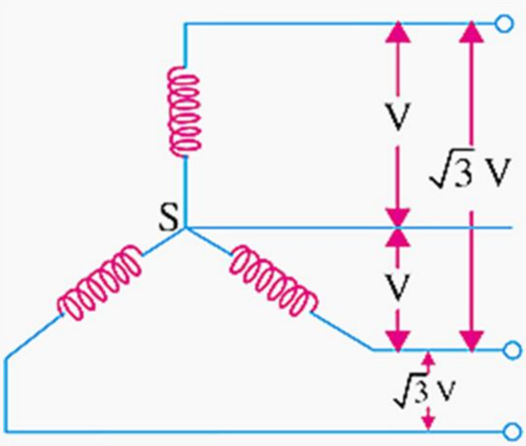
When a ring main feeder is energized by two or more substations or generating stations, it is called as an interconnected distribution system. This system ensures reliability in an event of transmission failure. Also, any area fed from one generating stations during peak load hours can be fed from the other generating station or substation for meeting power requirements from increased load.

Distribution of AC power

AC power transmission is always at high voltage and mostly by **3-phase system**. The use of single-phase system is limited to single-phase electric railways. Single-phase power transmission is used only for short distances and for relatively low voltages.

Three-phase, 4-wire system

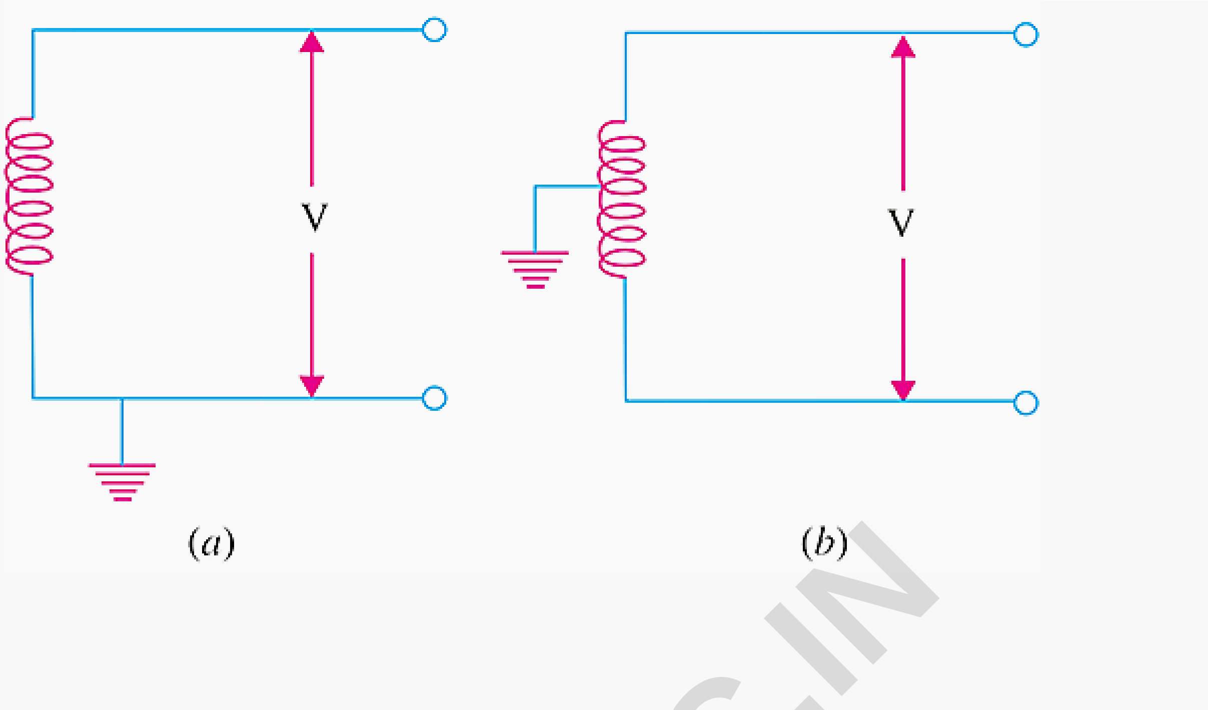
The 4th or neutral wire is taken from the star point of the star-connection as shown in Figure 6 and is of half the cross-section of the outers or line conductors. If V is the voltage of each winding, then line voltage is **3 V**. Usually, phase voltage i.e. voltage between any outer and the neutral for a symmetrical system is **230V** so that the voltage between any two lines or outers is **3×230=400V**.



Single-phase residential lighting loads or single-phase motors which run on **230 V** are connected between the neutral and any one of the line wires. These loads are connected symmetrically so that line wires are loaded equally. Hence, the resultant current in the neutral wire is **zero or at least minimum.**The three phase induction motors requiring higher voltages of 400 V or so are put across the lines directly.

Single-phase, 2-wire System

It is shown in Figure 1 (a) and (b). In Figure 1 (a), one of the two wires is earthed whereas in Figure 1 (b) **mid-point of the phase winding is earthed**.



What happens when neutral wire is disconnected?

When the neutral wire in a 3 – phase, 4 – wire system is disconnected, the loads which are connected between any two line conductors and the neutral are get connected in series and the potential difference across the combined load becomes equal to the line voltage. The potential difference across each load is changed according to the rating of theload

Illustration: The effect of disconnecting neutral wire in a 3 – phase 4 -wire system can be explained more clearly by the following illustration:

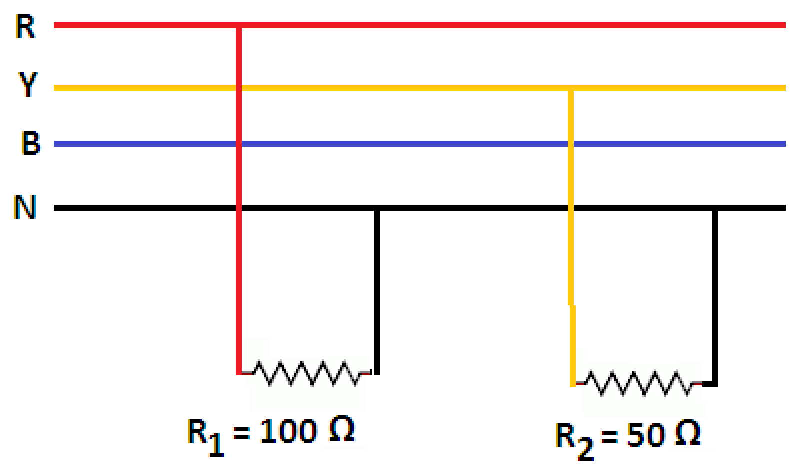


Figure A

Suppose a resistance of 100 Ω is connected between R – phase and neutral and a resistance of 50 Ω is connected between Y – phase and neutral in a 3 – phase, 4 wire supply as shown in Figure (a). The simplified diagram is shown in Figure (b).

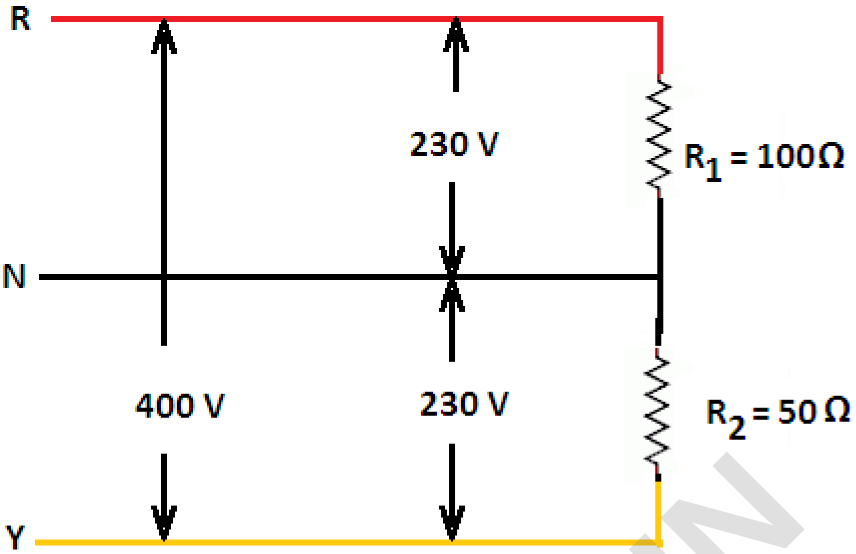


Figure B

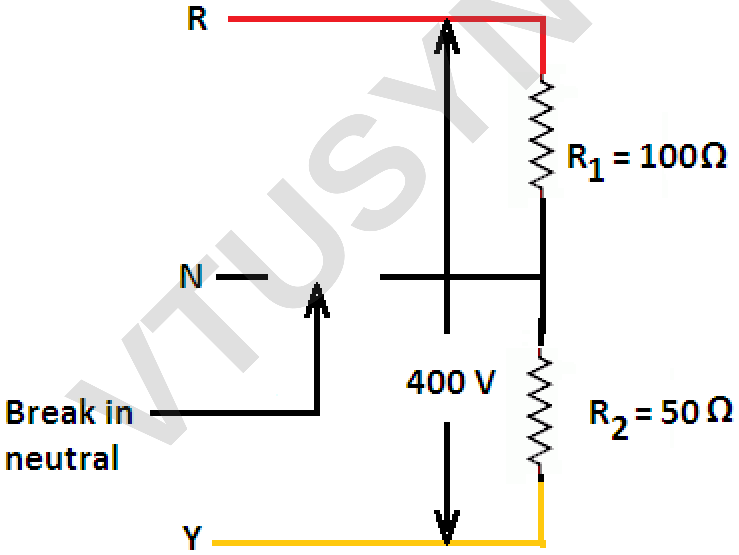


Figure C

If the neutral wire is disconnected, the two loads R_1 and R_2 are get connected in series and the potential difference across them becomes equal to the line voltage i.e. 400 V.

Therefore,

current through loads, $I = V_L/(R_1 + R_2)$

$= 400/(100 + 50) = 2.67$ A

Therefore,

potential difference across the resistance $R_1 = I*R_1$

$= 2.67*100 = 267$ V

Similarly,

potential difference across the resistance $R_2 = I*R_2$

$= 2.67*50 = 133$ V

It is clear from the above illustration that if the neutral wire is disconnected in a 3 – phase, 4 – wire system the potential difference across the high resistive load is increased and the potential difference across the low resistive load is decreased. In this process, the voltage across the high resistive load may rise more than the designed value and may damage the high resistive load.

Reliability and Quality of Distribution System:

Definition of Reliability: **Reliability** of a power **distribution system** is defined as the ability to deliver uninterrupted service to customer. **Distribution system reliability** indices can be presented in many ways to reflect the **reliability** of individual customers, feeders and **system** oriented indices related to substation.

Limitation of Distributed System

Distributed System is a collection of self-governing computer systems efficient of transmission and cooperation among each other by the means of interconnections between their hardware and software. It is a collection of loosely coupled processor that appears to its users a single systematic system. Distributed systems has various limitations such as in distributed system there is not any presence of a global state. This differentiates distributed system computing from databases in which a steady global state is maintained.

Distributed system limitations have the impact on both design and implementation of distributed systems.

POWER QUALITY

Good **power quality** saves money and energy. Direct savings to consumers come from lower energy cost and reactive power tariffs. Indirect savings are gained by avoiding circumstances such as damage and premature aging of equipment, loss of production or loss of data and work. Mainly the power quality problems are-high harmonic in distribution system, low power factor, voltage transients, voltage flicker, active power and reactive power. Due to poor power quality the performance of various sensitive loads is very poor. Power Quality Standards: An Industry Update. Power quality is a worldwide issue, and keeping related standards current is a never-ending task. It typically takes years to push changes through the process Most of the ongoing work by the IEEE in harmonic standards development has shifted to modifying Standard 519-1992.

DC Distribution Calculation:

In addition to the methods of feeding discussed above, a DC Distribution Calculation may have

1. **concentrated loading**
2. **uniform loading**
3. **both concentrated and uniform loading.**

The concentrated loads are those which act on particular points of the distributor. A common example of such loads is that tapped off for domestic use. On the other hand, distributed loads are those which act uniformly on all points of the distributor. Ideally, there are no distributed loads. However, a nearest example of distributed load is a large number of loads of same wattage connected to the DC Distribution Calculation at equal distances.

In DC Distribution Calculation, one important point of interest is the determination of point of minimum potential on the distributor. The point where it occurs depends upon the loading conditions and the method of feeding the distributor. The distributor is so designed that the minimum potential on it is not less than 6% of rated voltage at the consumer's terminals. In the next sections, we shall discuss some important cases of d.c. distributors separately.

DC Distributor Fed at one End—Concentrated Loading:

Fig. 13.5 shows the single line diagram of a 2-wire d.c. distributor AB fed at one end A and having concentrated loads I_1, 1_2, 1_3 and 1_4 tapped off at points C, D, E and F respectively.

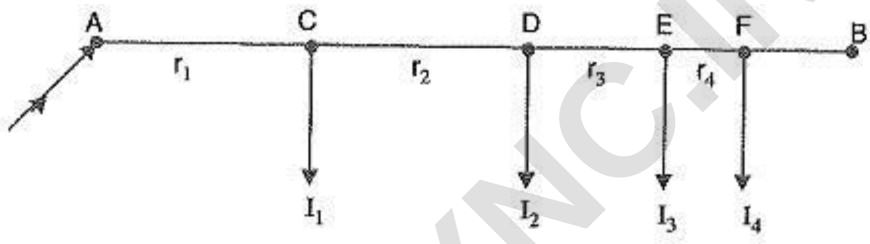


Fig. 13.5

Let r_1, r_2, r_3 and r_4 be the resistances of both wires (go and return) of the sections AC, CD, DE and EF of the distributor respectively.

$$
\begin{aligned}
&\text{Current fed from point } A && = I_1 + I_2 + I_3 + I_4 \\
&\text{Current in section } AC && = I_1 + I_2 + I_3 + I_4 \\
&\text{Current in section } CD && = I_2 + I_3 + I_4 \\
&\text{Current in section } DE && = I_3 + I_4 \\
&\text{Current in section } EF && = I_4 \\
&\text{Voltage drop in section } AC && = r_1 (I_1 + I_2 + I_3 + I_4) \\
&\text{Voltage drop in section } CD && = r_2 (I_2 + I_3 + I_4) \\
&\text{Voltage drop in section } DE && = r_3 (I_3 + I_4) \\
&\text{Voltage drop in section } EF && = r_4 I_4
\end{aligned}
$$

Total voltage drop in the DC Distribution Calculation is

Total voltage drop in the DC Distribution Calculation is

$$= r_1 (I_1 + I_2 + I_3 + I_4) + r_2 (I_2 + I_3 + I_4) + r_3 (I_3 + I_4) + r_4 I_4$$

Uniformly Loaded Distributor Fed at One End:

Fig 13.11 shows the single line diagram of a 2-wire d.c. distributor AB fed at one end A and loaded uniformly with i amperes per metre length. It means that at every 1 m length of the distributor, the load tapped is i amperes. Let l metres be the length of the distributor and r ohm be the resistance per metre run.

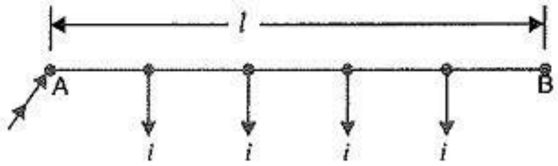


Fig. 13.11

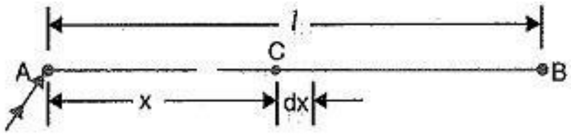


Fig. 13.12

Consider a point C on the distributor at a distance x metres from the feeding point A as shown in Fig. 13.12. Then current at point C is

$$= i\,l - i\,x \text{ amperes} = i\,(l - x) \text{ amperes}$$

Now, consider a small length dx near point C. Its resistance is r dx and the voltage drop over length dx is

$$dv = i\,(l - x)\,r\,dx = i\,r\,(l - x)\,dx$$

Total voltage drop in the distributor upto point C is

$$v = \int_0^x i\,r\,(l - x)\,dx = i\,r\left(l\,x - \frac{x^2}{2}\right)$$

The voltage drop upto point B (i.e. over the whole distributor) can be obtained by putting x = l in the above expression.

Voltage drop over the distributor AB

$$= i\,r\left(l \times l - \frac{l^2}{2}\right)$$

$$= \frac{1}{2}\,i\,r\,l^2 = \frac{1}{2}\,(i\,l)\,(r\,l)$$

$$= \frac{1}{2}\,I\,R$$

$$i\,l = I\text{, the total current entering at point } A$$

$$r\,l = R\text{, the total resistance of the distributor}$$

Thus, in a uniformly loaded distributor fed at one end, the total voltage drop is equal to that produced by the whole of the load assumed to be concentrated at the middle point.

Distributor Fed at Both Ends — Concentrated Loading:

Whenever possible, it is desirable that a long distributor should be fed at both ends instead of at one end only, since total voltage drop can be considerably reduced without increasing the cross-section of the conductor. The two ends of the distributor may be supplied with (i) equal voltages (ii) unequal voltages.

1. **Two ends fed with equal voltages:** Consider a distributor AB fed at both ends with equal voltages V volts and having concentrated loads I_1, I_2, I_3, I_4 and I_5 at points C, D, E, F and G respectively as shown in Fig. 13.14. As we move away from one of the feeding points, say A, p.d. goes on decreasing till it reaches the minimum value at some load point, say E, and then again starts rising and becomes V volts as we reach the other feeding point B.

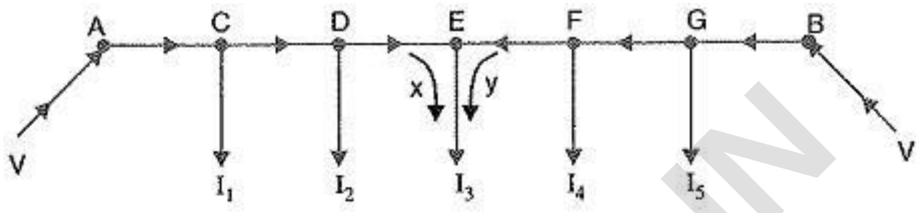


Fig. 13.14

All the currents tapped off between points A and E (minimum p.d. point) will be supplied from the feeding point A while those tapped off between B and E will be supplied from the feeding point B. The current tapped off at point E itself will be partly supplied from A and partly from B. If these currents are x and y respectively, then,

$$I_3 = x + y$$

Therefore, we arrive at a very important conclusion that at the point of minimum potential, current comes from both ends of the DC Distribution Calculation.

(i) Point of minimum potential. It is generally desired to locate the point of minimum potential. There is a simple method for it. Consider a distributor AB having three concentrated loads I_1, I_2 and I_3 at points C, D and E respectively. Suppose that current supplied by feeding end A is I_A. Then current distribution in the various sections of the distributor can be worked out as shown in Fig. 13.15 (i). Thus

$$I_{AC} = I_A\,; \qquad I_{CD} = I_A - I_1$$
$$I_{DE} = I_A - I_1 - I_2\,; \qquad I_{EB} = I_A - I_1 - I_2 - I_3$$

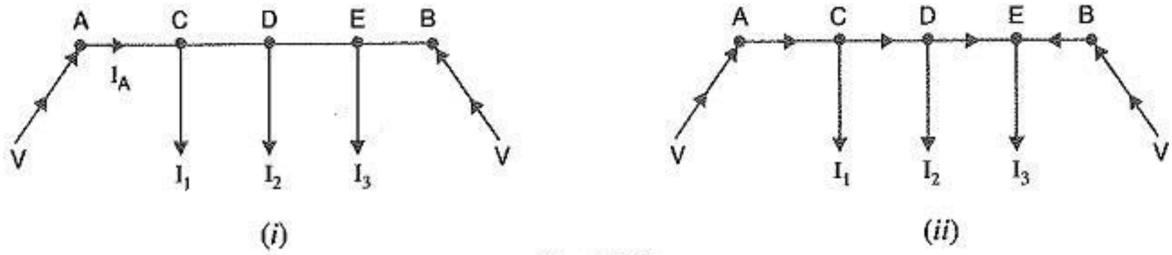


Fig. 13.15

Voltage drop between A and B = Voltage drop over AB

or $\quad V - V = I_A R_{AC} + (I_A - I_1) R_{CD} + (I_A - I_1 - I_2) R_{DE} + (I_A - I_1 - I_2 - I_3) R_{EB}$

From this equation, the unknown I_A can be calculated as the values of other quantities are generally given. Suppose actual directions of currents in the various sections of the distributor are indicated as shown in Fig. 13.15 (ii). The load point where the currents are coming from both sides of the distributor is the point of minimum potential i.e. point E in this case

(ii) Two ends fed with unequal voltages. Fig. 13.16 shows the distributor AB fed with unequal voltages ; end A being fed at V_1 volts and end B at V_2 volts. The point of minimum potential can be found by following the same procedure as discussed above. Thus in this case,

Voltage drop between A and B = Voltage drop over AB

or $\quad V_1 - V_2$ = Voltage drop over AB

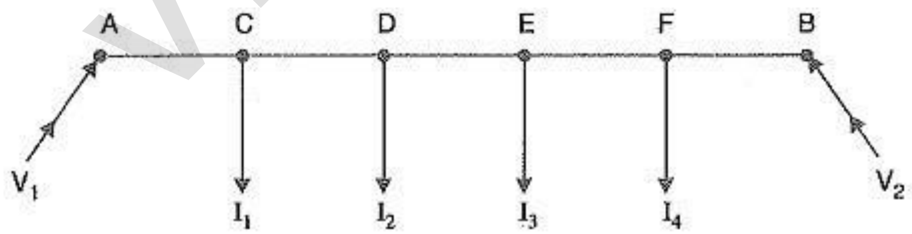


Fig. 13.16

Uniformly Loaded Distributor Fed at Both Ends:

We shall now determine the voltage drop in a uniformly loaded distributor fed at both ends. There can be two cases viz the distributor fed at both ends with

(i) equal voltages (ii) unequal voltages.

The two cases shall be discussed separately.

(i) Distributor fed at both ends with equal voltages. Consider a distributor AB of length l metres, having resistance r ohms per metre run and with uniform loading of i amperes per metre run as shown in Fig. 13.24. Let the DC Distribution Calculation be fed at the feeding points A and B at equal voltages, say V volts. The total current supplied to the distributor is i l. As the two end voltages are equal, therefore, current supplied from each feeding point is i l/2 i.e.

Current supplied from each feeding point

$$= \frac{i\,l}{2}$$

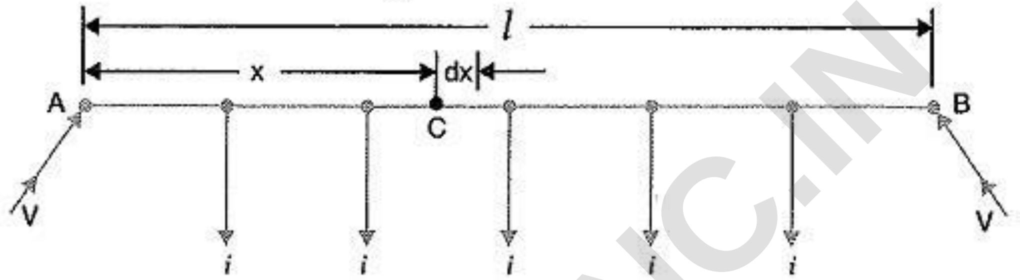


Fig. 13.24

Consider a point C at a distance x metres from the feeding point A. Then current at point C is

$$= \frac{i\,l}{2} - i\,x = i\left(\frac{l}{2} - x\right)$$

Now, consider a small length dx near point C. Its resistance is r dx and the voltage drop over length dx is

$$dv = i\left(\frac{l}{2} - x\right) r\,dx = i\,r\left(\frac{l}{2} - x\right) dx$$

$$\text{Voltage drop upto point } C = \int_0^x i\,r\left(\frac{l}{2} - x\right) dx = i\,r\left(\frac{l\,x}{2} - \frac{x^2}{2}\right)$$

$$= \frac{i\,r}{2}\left(l\,x - x^2\right)$$

Obviously, the point of minimum potential will be the mid-point. Therefore, maximum voltage drop will occur at mid-point i.e. where x =l/2.

$$\text{Max. voltage drop} = \frac{i\,r}{2}\left(l\,x - x^2\right)$$

$$= \frac{i\,r}{2}\left(l \times \frac{l}{2} - \frac{l^2}{4}\right) \qquad \text{[Putting } x =$$

$$= \frac{1}{8}\,i\,r\,l^2 = \frac{1}{8}(i\,l)(r\,l) = \frac{1}{8}\,I\,R$$

$i\,l$ = I, the total current fed to the distributor from both ends

$r\,l$ = R, the total resistance of the distributor

$$\text{Minimum voltage} = V - \frac{I\,R}{8}\ \text{volts}$$

(ii) Distributor fed at both ends with unequal voltages. Consider a distributor AB of length (metres having resistance r ohms per metre run and with a uniform loading of i amperes per metre run as shown in Fig. 13.25. Let the DC Distribution Calculation be fed from feeding points A and B at voltages V_A and V_B respectively.

Suppose that the point of minimum potential C is situated at a distance x metres from the feedingvpoint A. Then current supplied by the feeding point A will be i x.

$$\text{Voltage drop in section } AC = \frac{i\,r\,x^2}{2}\ \text{volts}$$

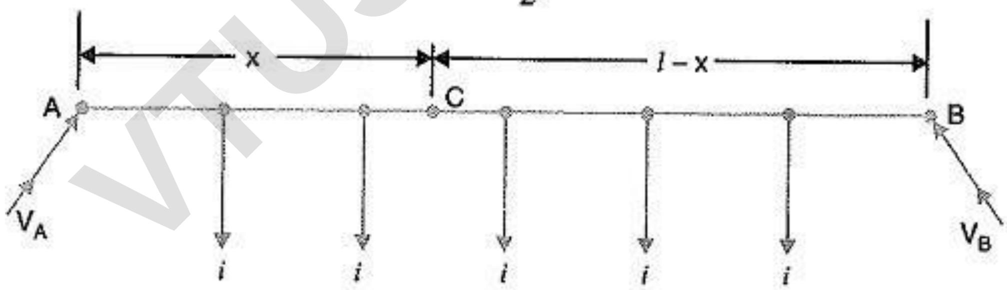


Fig. 13.25

As the distance of C from feeding point B is (1— x), therefore, current fed from B is i (l – x).

$$\text{Voltage drop in section } BC = \frac{i\,r\,(l-x)^2}{2}\ \text{volts}$$

$$\text{Voltage at point } C,\ V_C = V_A - \text{Drop over } AC$$

$$= V_A - \frac{i\,r\,x^2}{2} \qquad \ldots(i)$$

$$\text{Also, voltage at point } C,\ V_C = V_B - \text{Drop over } BC$$

$$= V_B - \frac{i\,r\,(l-x)^2}{2} \qquad \ldots(ii)$$

From equations (i) and (ii), we get,

$$V_A - \frac{i\,r\,x^2}{2} = V_B - \frac{i\,r\,(l-x)^2}{2}$$

Solving the equation for x, we get,

$$x = \frac{V_A - V_B}{i\,r\,l} + \frac{l}{2}$$

As all the quantities on the right hand side of the equation are known, therefore, the point on the distributor where minimum potential occurs can be calculated.