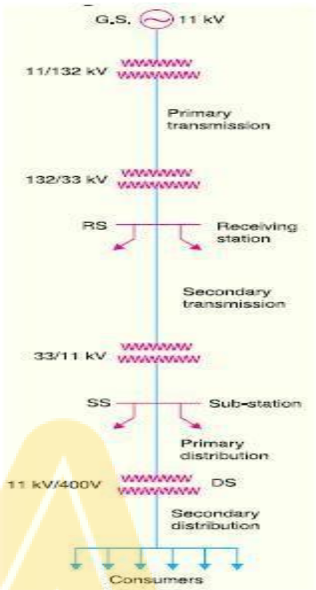
MODULE- 1: INTRODUCTION TO POWER SYSTEM

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

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

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

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

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

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

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.

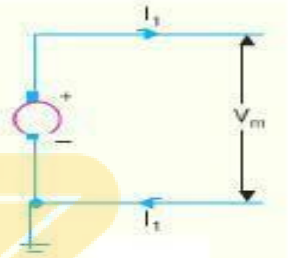
(ii) The distance (*l metres*) over which power is transmitted remains thesame.

(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_mPower 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

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

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

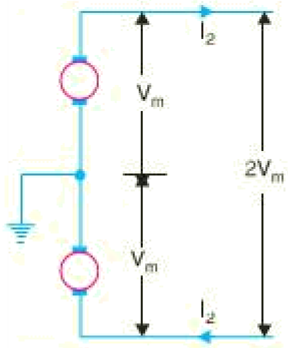
Volume of conductor material required

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

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 isV_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.

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

$$[\because R_2 = \rho\, l/a_2]$$

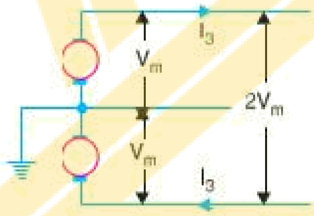
$$\therefore \qquad W = \frac{P^2 \rho\, l}{2a_2 V_m^2}$$

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.



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

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

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

Volume of conductor material required

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

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

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.

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

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

Volume of conductor material required

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

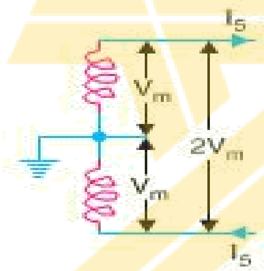
$$= \frac{2}{\cos^2\phi} \times \frac{4\,P^2\rho\,l^2}{W\,V_m^2}$$

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

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.,* V_m). Therefore, the maximum voltage between the two wires is $2V_m$. 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

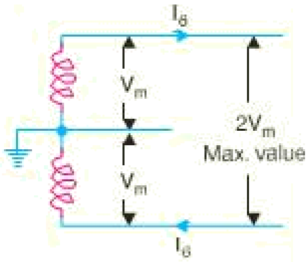
$$= 2\,a_5\,l = 2\left(\frac{P^2\rho\,l}{W\,V_m^2\cos^2\phi}\right)l = \frac{2\,P^2\rho\,l^2}{W\,V_m^2\cos^2\phi}$$

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

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

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.

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

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

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

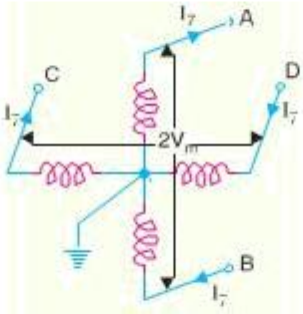
Assuming the area of X-section of neutral wire to be half that of the outer wire, Volume of conductor material required

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

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

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

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 $B = 2Vm$

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

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

$$= 4 a_7 l$$

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

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

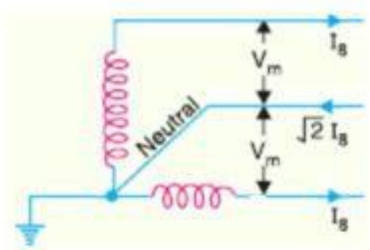
$$= \frac{K}{2\cos^2\phi} \qquad \left[\because K = \frac{4P^2 \rho l^2}{W V_m^2}\right]$$

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.

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

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

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

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

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

Volume of conductor material required

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

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

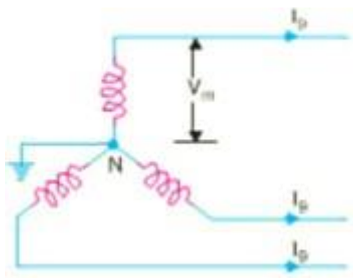
$$= \frac{1{\cdot}457}{\cos^2 \phi} K \qquad \left[\because K = \frac{4 P^2 \rho\, l^2}{W V_m^2}\right]$$

Hence, the volume of conductor material required for this system is $1{\cdot}457/\cos^2 \phi$ 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 = $P/3$

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



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

∴ 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

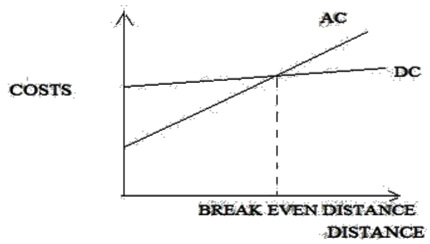
Investment Cost

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

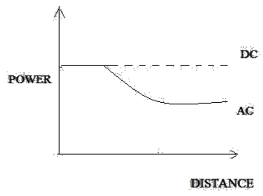


2. TechnicalPerformance

- 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.

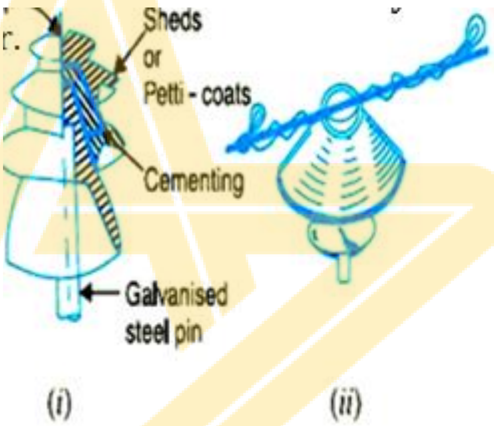
i) Pin Type Insulators

• 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

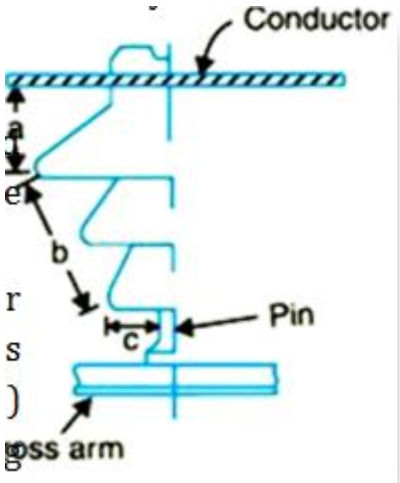


• Beyond operating voltage of 33kV, the pin type insulators become too bulky andhence uneconomical.

• 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.

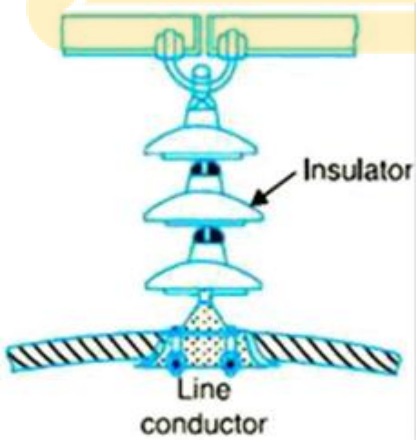


Fig.4.6

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

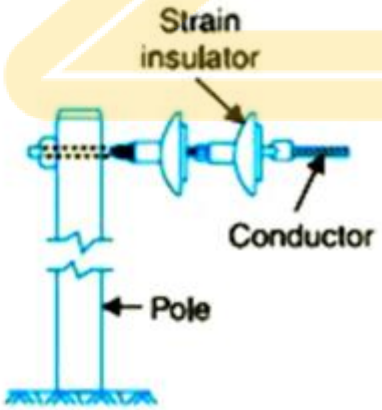
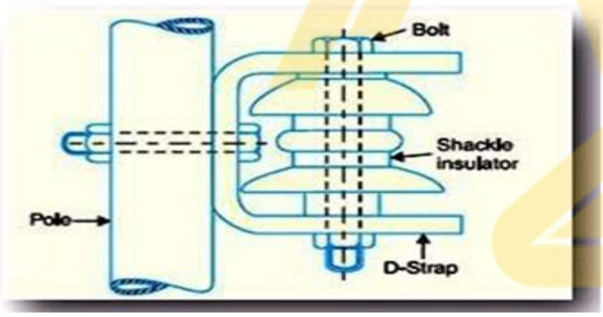
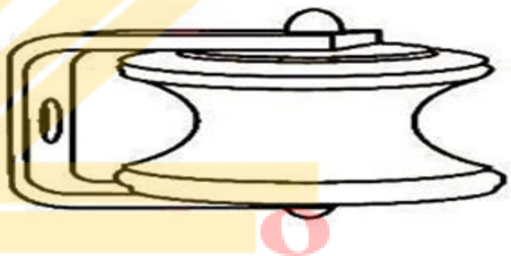


Fig.4.8

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.

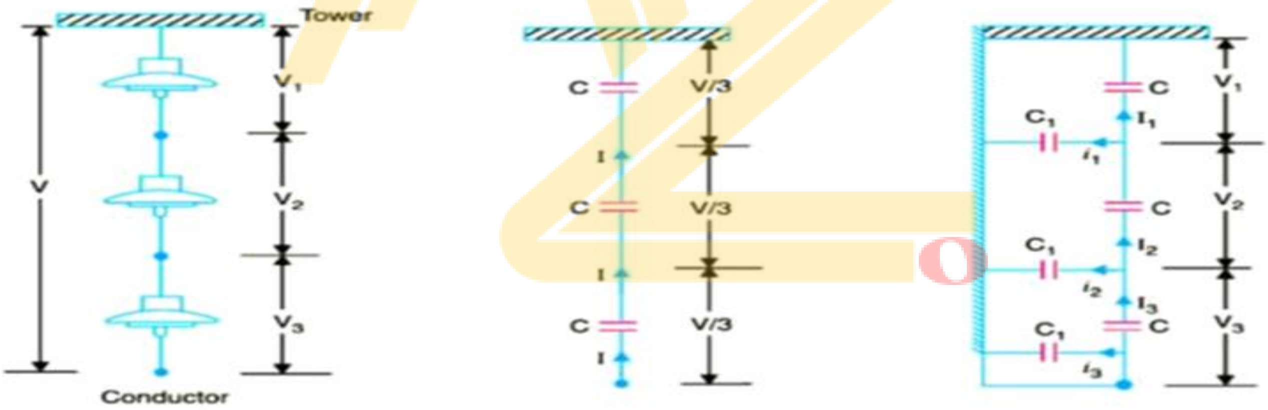
Fig.4.10

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.

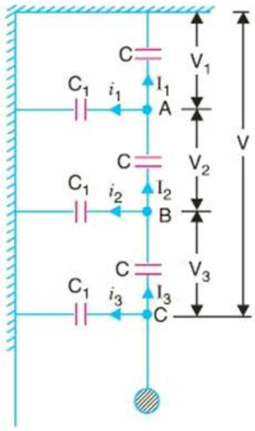


Fig. 4.12

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

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

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

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

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

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

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

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 $= \frac{\text{Voltage}}{\text{Capacitive reactance}}$

† 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.

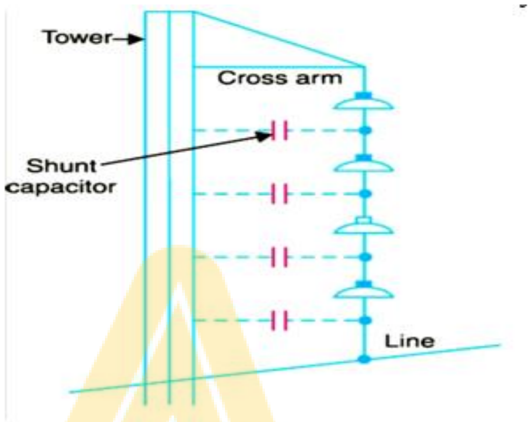


Fig.4.13

(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.

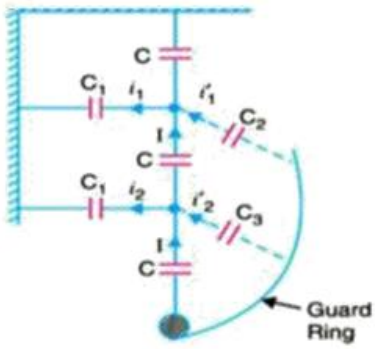
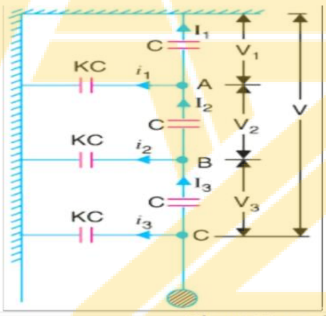


Fig.4.14

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.



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

Voltage across string, $V = 33/\sqrt{3} = 19{\cdot}05$ 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 $V_2 = 1{\cdot}11\ V_1$ ...(*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, $V_1 = 19{\cdot}05/3{\cdot}452 =$ **5·52 kV**

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

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

(*ii*) String efficiency $= \dfrac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \dfrac{19 \cdot 05}{3 \times 7 \cdot 4} \times 100 =$ **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 $$V2\omega C = V1\omega C + V1 K\omega C$$

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 $= \dfrac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \dfrac{37{\cdot}12}{3 \times 18{\cdot}12} \times 100 = 68{\cdot}28\%$

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

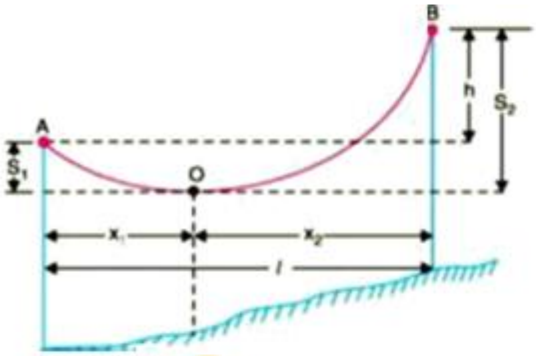


Fig.5.3

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

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

and

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

Also $\quad x_1 + x_2 = l \qquad \ldots(i)$

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

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

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

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

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

But $\quad S_2 - S_1 = h$

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

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

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

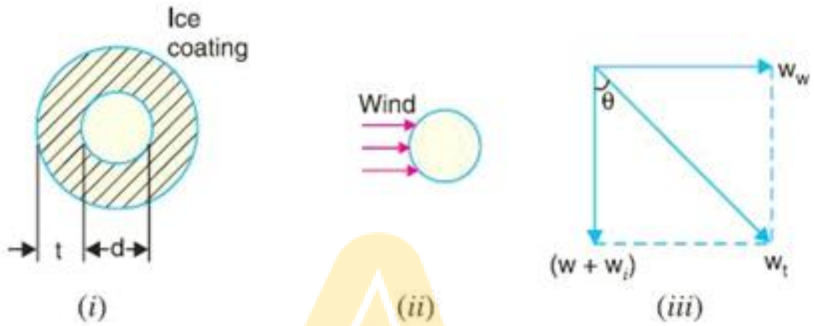


Fig.5.4

Total weight of conductor per unit length is

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

where

$$\begin{aligned} w &= \text{weight of conductor per unit length} \\ &= \text{conductor material density} \times \text{volume per unit length} \\ w_i &= \text{weight of ice per unit length} \\ &= \text{density of ice} \times \text{volume of ice per unit length} \\ &= \text{density of ice} \times \frac{\pi}{4}[(d+2t)^2 - d^2] \times 1 \\ &= \text{density of ice} \times \pi t (d+t)^* \\ w_w &= \text{wind force per unit length} \\ &= \text{wind pressure per unit area} \times \text{projected area per unit length} \\ &= \text{wind pressure} \times [(d+2t) \times 1] \end{aligned}$$

* 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

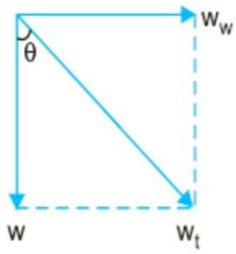
$= 9{\cdot}9 \times 2 \times 100 = 1980$ gm $= 1{\cdot}98$ kg

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 kgConductor diameter, d = 1·96 cm ; Ice coating thickness, t = 1·27 cm Working tension, T = 8060/2 = 4030kg

3

$$= \pi t\,(d + t) \times 100 \text{ cm}^3$$

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

Weight of ice per metre length of conductor is

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

kg Wind force/m length of conductor is

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

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

$$= 1{\cdot}755 \text{ kg}$$

Total weight of conductor per metre length of conductor is

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

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

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

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

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

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

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

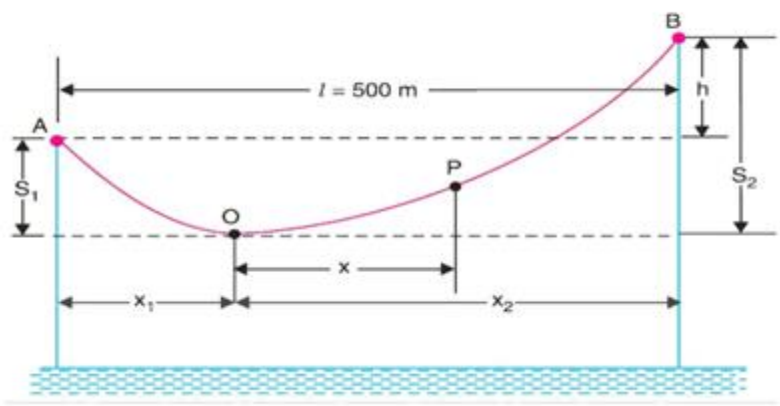
or Safety factor, $$f = \frac{8191 \times 8 \times 3{\cdot}92}{1{\cdot}875 \times (214)^2} = 3$$

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, $x1 + x2 = 500$m ...(*i*)



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

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

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

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

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

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

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, $\qquad x = 250 - x_1 = 250 - 122 = 128$ m

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