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Transmission and Distribution

Unit I : Transmission Line Parameters

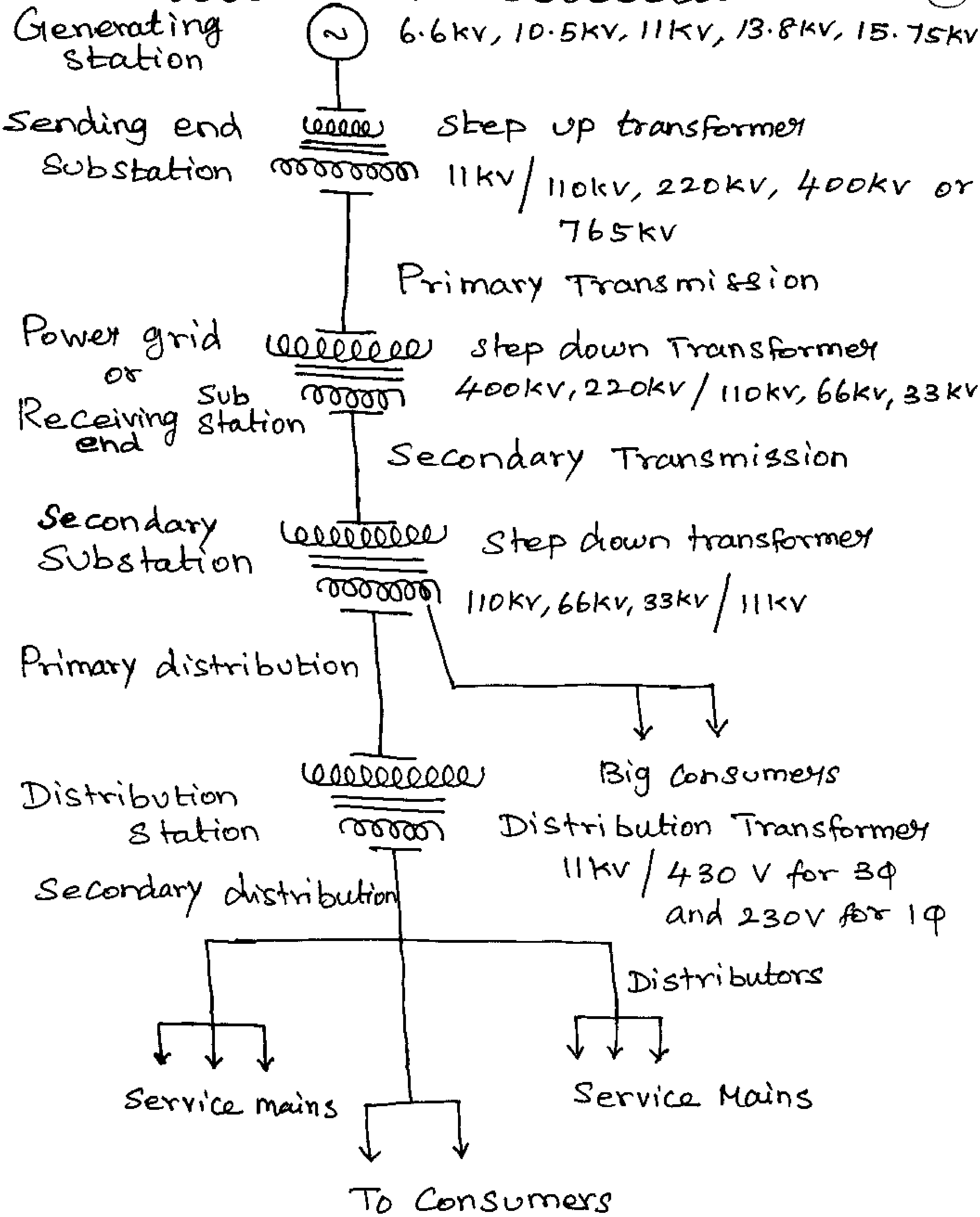
Structure of Power system – Parameters of single and three phase transmission lines with single and double circuits – Resistance, inductance and capacitance of solid, stranded and bundled Conductors, Symmetrical and unsymmetrical spacing and transposition – application of self and Mutual GMD, skin and Proximity effects – Typical Configurations, Conductor types and electrical parameters of EHV lines.

Structure of Power system:

An electrical Power system Consists of generation, transmission and distribution. The transmission system supply bulk Power and the distribution systems transfer electric Power to the Ultimate Consumers.

The generation of electrical energy is nothing but the Conversion of one form of energy into electrical energy. Electrical energy is generated in hydro, thermal and nuclear Power stations. Electrical energy is also generated from Non-renewable energy resources like Wind, Solar, waves, fossil fuels etc.

Structure of Power System



Generating Station:

The generating voltages are usually 6.6 kv, 10.5kv, 11kv, 13.8 kv, 15.75 kv etc. It may be any one type of Power Stations like Thermal, Hydro, Nuclear, Solar, Wind. Generator Converts mechanical energy into electrical energy.

Grid:

The interconnected transmission syste of a state or a region is called the grid. State grids are interconnected with the help of tie lines and form the regional grid.

Transmission system:

It interconnects two or more generating stations. It transmit the Bulk Power from generating Station to Power grid or substation. The transmission System can be diveded into Primary transmissi and Secondary transmission.

Primary Transmission:

If the generated Power is transmitted through transmission line without Stepping up the generated Voltage and line Current then the Power loss would be very high. so, th generated Voltage is stepped up to higher Valu by using step up transformer located in substat known as Sending end Substations near the generating stations.

The transmission of electric Power from generating station (sending end substation) to receivi end substation (Power grid) is called Primary transmission. Primary transmission Voltages are 110 220KV, 400KV, 765 KV. It uses 3φ, 3wire system.

Secondary Transmission:

The transmission of electr Power from receiving end substation (Grid) to Secondary substation is called Secondary tran-mission. At the receiving end substation, the voltag is stepped down to a value of 110kv, 66kv, 33kv using stepdown transformers. It uses 3φ, 3 wire system and the conductors used are called as feeders

Distribution System:

The Component of an electric Power system connecting all the Consumers in an are to the bulk Power sources is called a distribution sy A distribution station distributes the Power to domes commercial and industries. It can be divided into Primary and secondary distribution system.

Primary Distribution:

At the Secondary substations the voltage is stepped down to 11kv or 6.6kv using step down transformers. The Primary distributor forms the link between secondary substation and distribution substation. It uses 3φ, 3 wire system.

Secondary Distribution:

At the distribution substatic the voltage is stepped down to 430V for 3φ or 230V for 1φ using step down transformers. The distribution lines are drawn along the roads and service connections to the consumers are tapped off from the distributors. It uses 3φ, 4 wire system.

Parameters of single and three phase transmission line with single and double circu

Resistance, inductance and capacitance of solid:

Resistance:

It is opposition of transmission line Conductors to the flow of Current. It Causes a Power loss in the Conductor.

$$\text{Power Loss}, P_L = I^2 R$$

Line Resistance:

It is the opposition of line Conductors to Current flow. The real transmission loss mainly depends on resistance of transmission line.

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

R - Resistance of the Conductor

I - Current flowing through the Conductor

The resistance of the solid round Conductor at a Specified temperature.

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

Where

ρ - Resistivity of a Conductor

l - Length of a Conductor

a - Cross sectional area of a Conductor.

Inductance

It is defind as the flux linkages Per unit Current. The transmission line capacity Mainly depends on the inductance (L).

$$L = \frac{\Psi}{I} \text{ Henry}$$

Where ψ – Flux linkage, I – current

Capacitance:

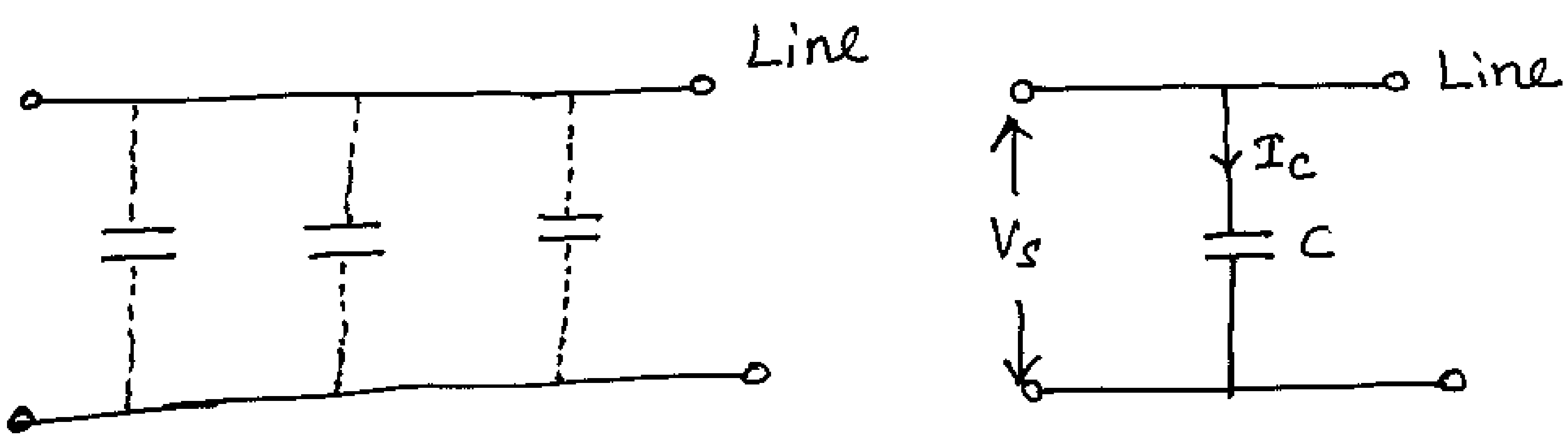
Any two Conducting media Separeted by an insulating Material Constitute a Capacitor.

Capacitance is defind as charge per Unit potential difference.

$$C = \frac{Q}{V} \text{ farad}$$

Shunt Capacitance:

It Causes a charging Current to flow in the line. It won't be Neglected for medium and long transmission lines.



Distributed Capacitor Lumped Capacitor

Inductance of a Single Conductor:

Let us consider the current through the conductor is uniformly distributed. A current carrying conductor produces a magnetic field concentric around the conductor.

Inductance "L" is defind as the ratio of total magnetic flux linkage (λ) to the current "I" for non magnetic material.

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

Where
λ – Flux linkages in weber-turns

Important Relations to be used:

$$\log_e A = \ln A$$

$$\ln A + \ln B = \ln (AB)$$

$$\ln A - \ln B = \ln \left(\frac{A}{B}\right)$$

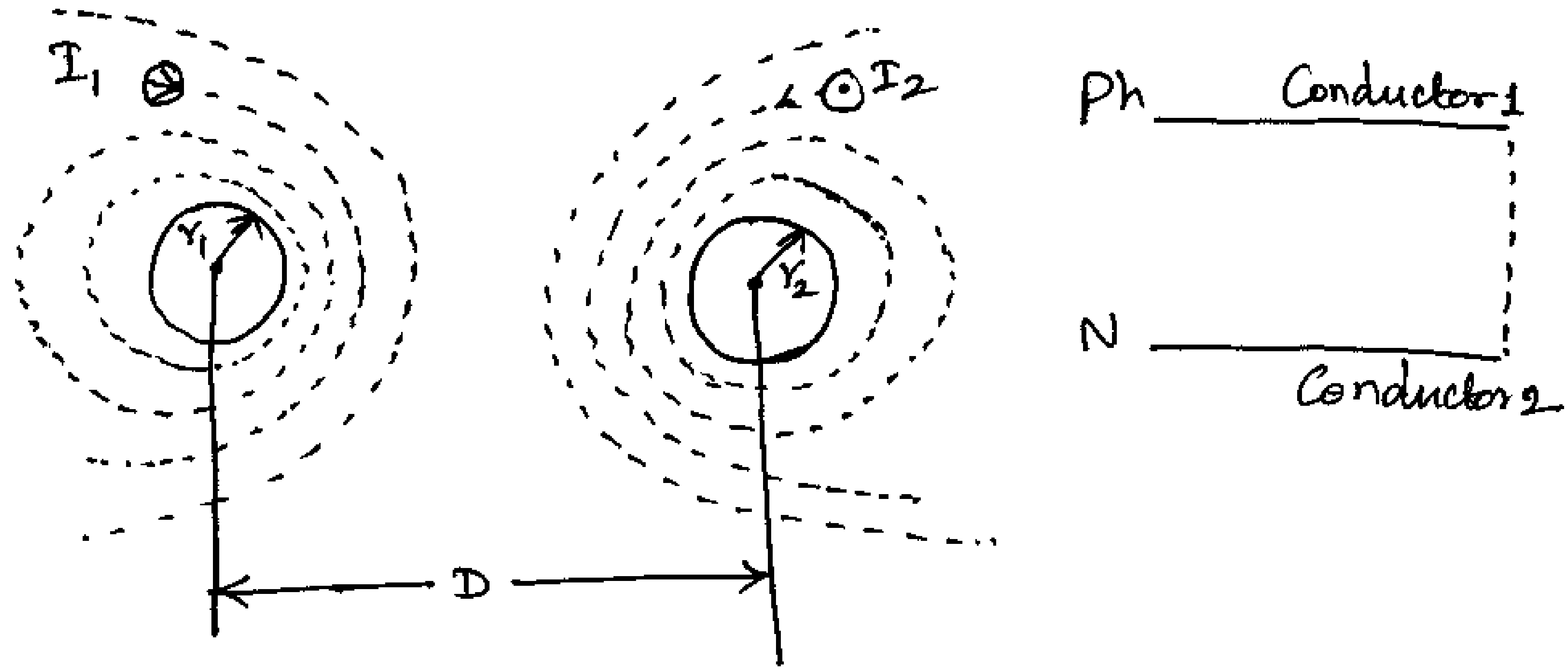
$$n \ln m = \ln m^n$$

$$\frac{1}{n} \ln m = \ln m^{1/n}$$

$$\ln A + \ln B + \ln C = \ln (ABC)$$

$$-\ln \left(\frac{1}{D}\right) = +\ln D$$

Inductance of Single phase lines :



Consider the cross section of two solid round conductor of a single phase line as shown in figure.

Let r_1, r_2 be the radius of phase and Neutral conductor.

Let D be the spacing between centre to centre of two conductors.

Let I_1, I_2 be the current carried by the phase and Neutral conductor.

Neutral conductor is the return conductor. Therefore the direction of current flowing in the neutral conductor is opposite to that of phase conductor.

$$\therefore I_2 = -I_1$$

Inductance of conductor 1 due to internal and External flux linkage.

$$\text{Total flux linkages, } \lambda_1 = \lambda_{1\,int} + \lambda_{1\,ext}$$

$$\lambda_1 = \frac{\mu_0 I}{8\pi} + \frac{\mu_0 I}{2\pi} \ln\left[\frac{D}{r_1}\right] \text{ Wb/m}$$

Total inductance of conductor 1, $L_1 = \frac{\lambda_1}{I}$

$$L_1 = \frac{\mu_0}{8\pi} + \frac{\mu_0}{2\pi} \ln\left[\frac{D}{r_1}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \ln\left(\frac{D}{r_1}\right)\right]$$

Where μ_0 is the Permeability of free Space (air)

Value of $\mu_0 = 4\pi \times 10^{-7}$ H/m

$$L_1 = \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \ln\left(\frac{D}{r_1}\right)\right]$$

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

$$= 2\times 10^{-7}\left(\ln e^{1/4} + \ln\frac{1}{r_1} + \ln D\right)$$

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

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

Let $r_1' = r_1 e^{-1/4}$

$$L_1 = 2\times 10^{-7}\left[\ln\frac{1}{r_1'} + \ln D\right]$$

$$L_1 = 2\times 10^{-7} \ln\left(\frac{D}{r_1'}\right) \text{ H/m}$$

Similarly for, Inductance of Conductor 2 is

$$L_2 = 2\times 10^{-7} \ln\left(\frac{D}{r_2'}\right) \text{ H/m}$$ where $r_2' = r_2 e^{-1/4}$

If $r_1 = r_2 = r$ and $L_1 = L_2 = L$

Inductance per phase per meter length of the line

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

Where $r' = re^{-1/4} = 0.7788r$

$$\text{Loop inductance} = 2L = 4\times10^{-7} \ln\left(\frac{D}{r'}\right)$$

Application of Self GMD:

Geometric Mean Radius or self GMD:

The term $r' = re^{-1/4} = 0.7788r$ is known as the self-geometric mean distance of a circle with radius r or self GMD and is denoted by GMR. GMR - Geometric mean radius

It is also denoted as D_s.

$$L = 2\times10^{-7} \ln\left(\frac{D}{r'}\right) = 2\times10^{-7} \ln\left[\frac{D}{0.7788r}\right]$$

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

Inductance per phase in mH/km $= 2\times10^{-7} \ln\left(\frac{D}{D_s}\right) \times \frac{1000}{10^{-3}}$

$$L = 2\times10^{-7} \ln\left(\frac{D}{r'}\right) \times 10^{6} = 0.2 \ln\left(\frac{D}{r'}\right) = 0.2 \ln\left(\frac{D}{0.7788r}\right)$$

$$L = 0.2 \ln\left(\frac{D}{r'}\right) \text{ mH/km}$$

Loop inductance $= 2L = 0.4 \ln\left(\frac{D}{r'}\right)$ mH/km

Reactance per phase in ohm/m $= 2\pi fL = 2\pi f \times 2\times10^{-7} \ln\left(\frac{D}{r'}\right)$ ohm/m

Problems for inductance of single phase Line: (11)

1. Find the loop inductance and reactance Per km of a single phase overhead line consisting of two Conductors, each 4.4755 cm diameter. The spacing between Conductor is 3m.

Given data: Diameter = 4.4755 cm

Distance, D = 3m

Formula used:

$$\text{Loop Inductance/km} = 0.4 \ln\left(\frac{D}{r'}\right) \text{ mH}$$

$$\text{Loop Reactance/km} = 2\pi f L = 2\pi f \times 0.4 \ln\left(\frac{D}{r'}\right) \Omega$$

$$\text{Radius}(r) = \frac{\text{Diameter}}{2} = \frac{4.4755}{2} = 2.23775 \text{ cm}$$

$$= 2.23775 \times 10^{-2} \text{ m}$$

$$\text{Loop inductance/km} = 0.4 \ln\left(\frac{3}{0.7788 \times 2.23775 \times 10^{-2}}\right)$$

$$L/\text{km} = ~~21.0296 \text{ mH}~~$$

$$= 2.0592 \text{ mH}$$

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2. A 1φ transmission line 35 km long Consists of two Solid round Conductors each having a diameter of 0.9 cm. The Conductor spacing is 2.5 m. What is the value of the inductance Per Conductor.

Given data: Length of transmission line = 35km

Conductor diameter = 0.9 cm

Conductor Spacing, D = 2.5 m

Formula used:

Inductance Per conductor $= 2\times10^{-7}\ln\left(\frac{D}{r'}\right)$

$r' = 0.7788\,r$

$r = \frac{0.9}{2}\times \text{cm} = 0.45\,\text{cm} = 0.45\times10^{-2}\,\text{m}$

$r' = 0.7788 \times 0.45 = 0.35\ \text{cm}$

Inductance Per conductor/km, $L = 0.2\ln\left(\frac{D}{r'}\right)$ mH

$L = 0.2\ln\left[\frac{2.5}{0.35\times10^{-2}}\right]$

$L/\text{km} = 1.313$ mH

For 35 km, $L = 35\times1.313 = 45.99$ mH

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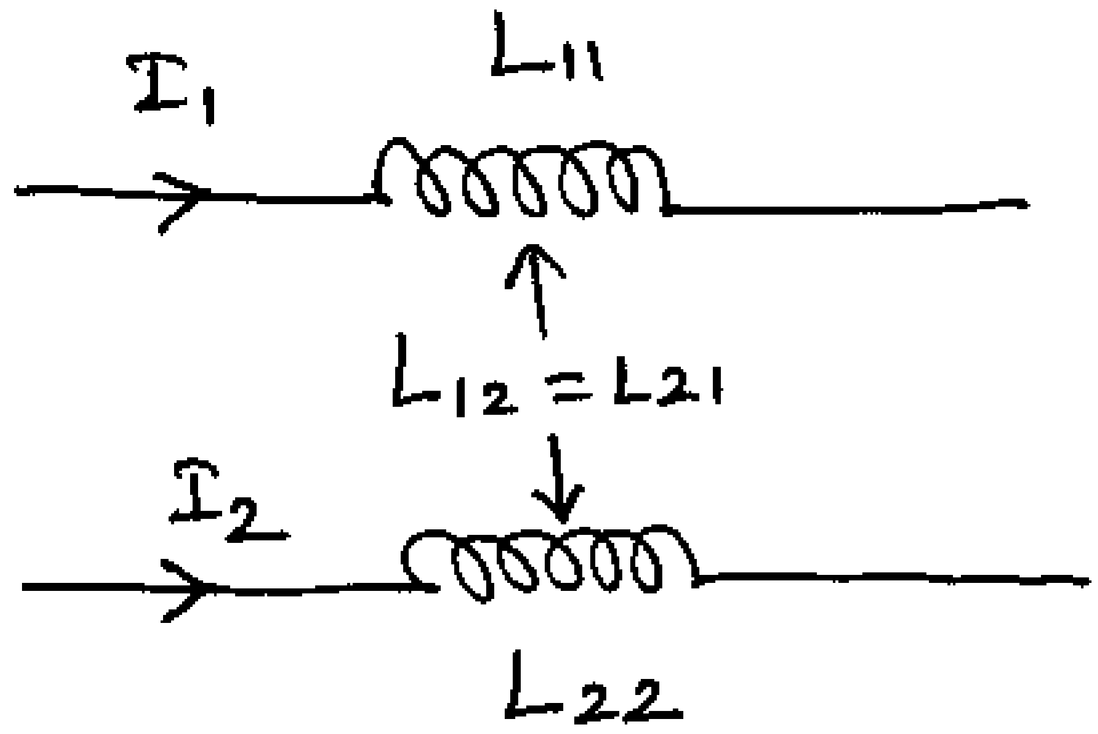
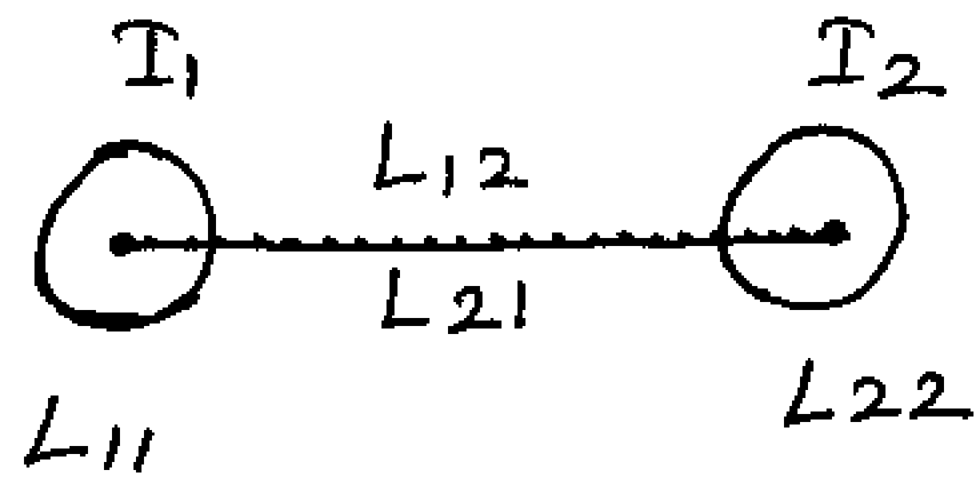
Flux linkages in terms of self and mutual inductances:





Let L_{11}, L_{22} be the self inductance

Let L_{12}, L_{21} be the mutual inductance

Let I_1, I_2 be the Current through the line

Let λ_1, λ_2 be the flux linkages

Flux linkage $\lambda_1 = L_{11} I_1 + L_{12} I_2$

$\lambda_2 = L_{21} I_1 + L_{22} I_2$

Since $I_2 = -I_1$, I_2 – Return Conductor Current

$$\lambda_1 = L_{11} I_1 - L_{12} I_1 \quad \text{— (1)}$$

$$\lambda_2 = -L_{21} I_2 + L_{22} I_2 \quad \text{— (2)}$$

$$\lambda_1 = 2 \times 10^{-7} I_1 \ln\left(\frac{D}{r_1'}\right)$$

$$\lambda_1 = 2 \times 10^{-7} I_1 \ln \frac{1}{r_1'} - 2 \times 10^{-7} I_1 \ln \frac{1}{D} \quad \text{— (3)}$$

$$\lambda_2 = 2 \times 10^{-7} I_2 \ln\left(\frac{D}{r_2'}\right)$$

$$= -2 \times 10^{-7} I_2 \ln \frac{1}{D} + 2 \times 10^{-7} I_2 \ln \frac{1}{r_2'} \quad \text{— (4)}$$

Equating the equations (1) & (3) and (2) & (4)

Self inductance of line 1, $L_{11} = 2 \times 10^{-7} \ln\left(\frac{1}{r_1'}\right)$

Self inductance of line 2, $L_{22} = 2 \times 10^{-7} \ln\left(\frac{1}{r_2'}\right)$

Mutual inductance $L_{12} = L_{21} = 2 \times 10^{-7} \ln\left(\frac{1}{D}\right)$

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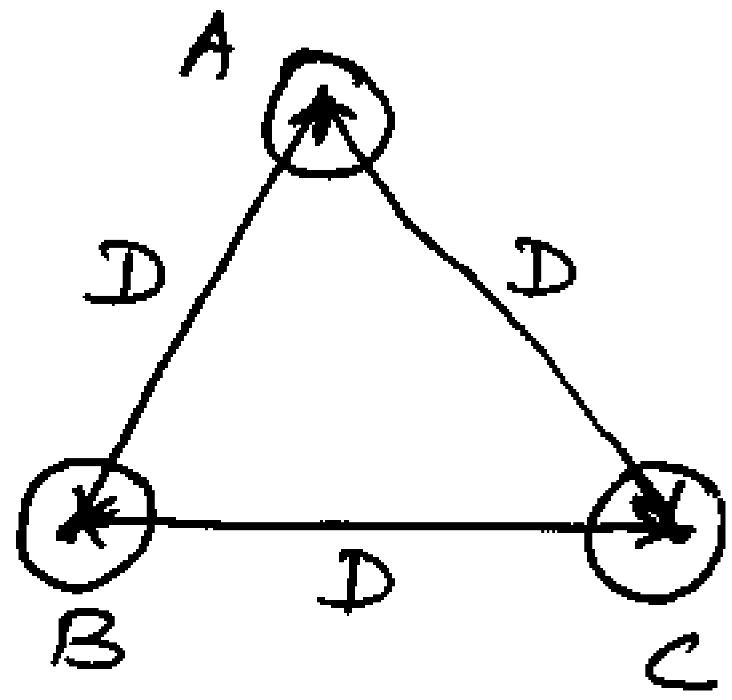
Inductance of 3φ Symmetrical Transmission Line: (14)

Symmetrical Line:



3φ Symmetrical Tr line

When the conductors are placed at equal spacing, they are called as symmetrical spacing or symmetrical line.

Consider one meter length of a 3φ transmission line is having three conductors A, B and C spaced in a triangular configuration as shown in figure.

Let I_A, I_B and I_C be the current through the conductors A, B and C respectively.

Let r be the radius of each conductors.

Let D be the distance between the conductors or spacing between the conductors.

$$D_{AB} = D_{BC} = D_{CA} = D \quad (\text{For symmetrical line})$$

Assuming balanced 3φ currents

$$I_A + I_B + I_C = 0$$

$$I_B + I_C = -I_A$$

Total flux linkages of phase 'A' conductor is

$$\lambda_A = L_{AA} I_A + L_{AB} I_B + L_{AC} I_C$$

$$\lambda_A = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r_1}\right) + I_B \ln\left(\frac{1}{D_{AB}}\right) + I_C \ln\left(\frac{1}{D_{AC}}\right)\right] \text{ wb/m}$$

$$\lambda_A = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r'}\right) + I_B \ln\left(\frac{1}{D}\right) + I_C \ln\left(\frac{1}{D}\right)\right]$$

$$\lambda_A = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r'}\right) + \ln\left(\frac{1}{D}\right)(I_B + I_C)\right]$$

$$\lambda_A = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r'}\right) - I_A \ln\left(\frac{1}{D}\right)\right] \quad \because [I_B + I_C = -I_A]$$

$$= 2\times10^{-7} I_A \left[\ln\left(\frac{1}{r'}\right) - \ln\left(\frac{1}{D}\right)\right]$$

$$= 2\times10^{-7} I_A \left[\ln\left(\frac{1}{r'}\right) + \ln D\right] \quad \because \left(-\ln\left(\frac{1}{D}\right) = \ln\left(\frac{1}{D^{-1}}\right) = \ln D\right)$$

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

Inductance per phase in M, $L_A = \frac{\lambda_A}{I_A} = 2\times10^{-7} \ln\left(\frac{D}{r'}\right)$ H/m

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

Inductance per phase per km

$$\boxed{L = 0.2 \ln\left(\frac{D}{r'}\right) \text{ mH/km}}$$

$$r' = re^{-1/4} = 0.7788r = GMR = D_s = \text{self GMD}$$

·x———————x·

Problems for 3φ Symmetrical Transmission line:

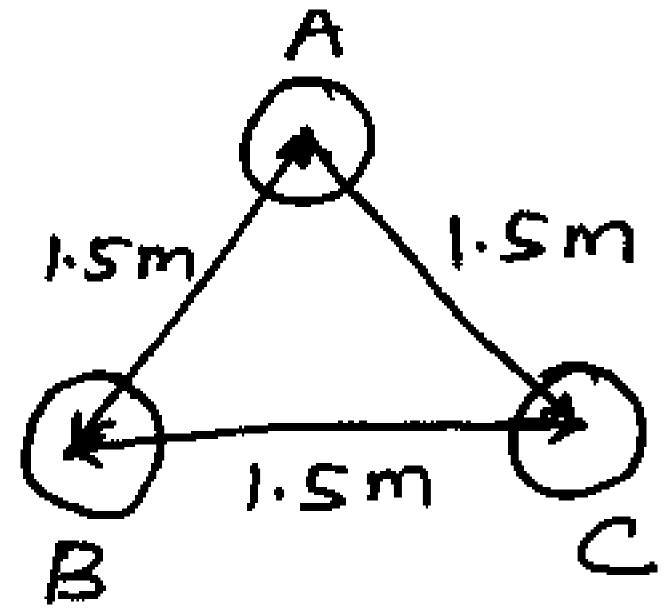
Determine the inductance of a 3 phase line, operating at 50 Hz and the conductors are arranged as shown in figure. The conductor diameter is 0.7 cm.

Given data:

Diameter = 0.7 cm

Distance, D = 1.5 m

$D_{AB} = 1.5m$, $D_{AC} = 1.5m$, $D_{BC} = 1.5m$



Formula used:

$$L = 0.2 \ln\left(\frac{D}{r'}\right) \text{ mH/km}$$

$$r' = 0.7788r$$

Solution:

$$\text{Radius} = \frac{\text{Diameter}}{2} = \frac{0.7}{2} = 0.35 \text{cm}$$

for symmetrical line $D_{AB} = D_{BC} = D_{CA} = D = 1.5m$

$$r' = 0.7788r = 0.7788 \times 0.35 = 0.27258 \text{ cm}$$

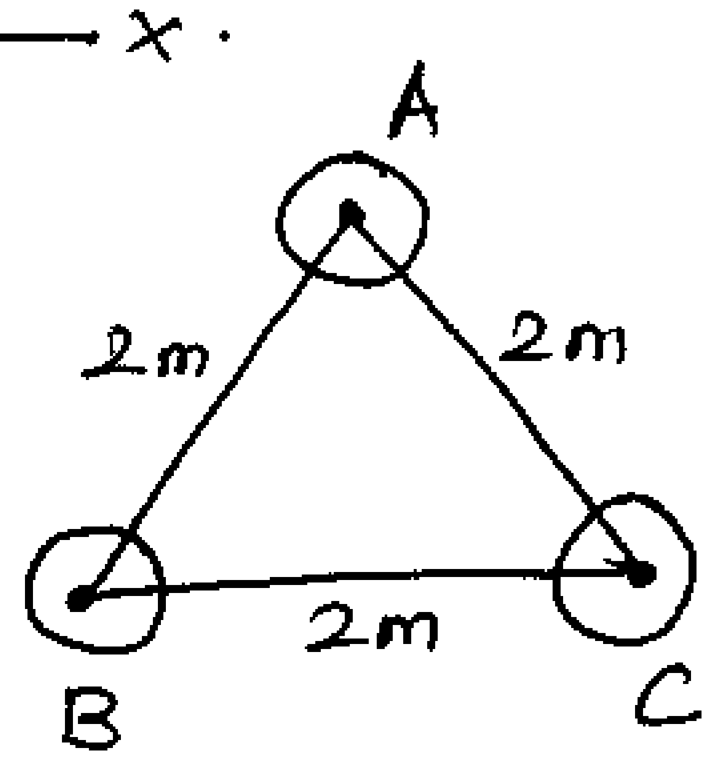
$$= 0.27258 \times 10^{-2} m$$

$$L = 0.2 \ln\left(\frac{1.5}{0.27258 \times 10^{-2}}\right)$$

$$\boxed{L = 1.262 \text{ mH/km}}$$

·x ——————————————— x·

A 3ϕ overhead transmission line has its Conductors arranged at the Corners of an equiletral triangle of 2m side. Calculate the inductance of each line Per km. Given that the radius of each Conduct is a 0.625 cm.



Given data:

$r = 0.625 cm = 0.00625 m$

Distance $D = 2 m$

Solution: Formula used

$$\text{Inductance/ph/km} = 0.2 \ln\left(\frac{D}{r'}\right) \text{ mH}$$

$r' = 0.7788 r$

$r' = 0.7788 \times 0.00625 = 4.8675 \times 10^{-3} m$

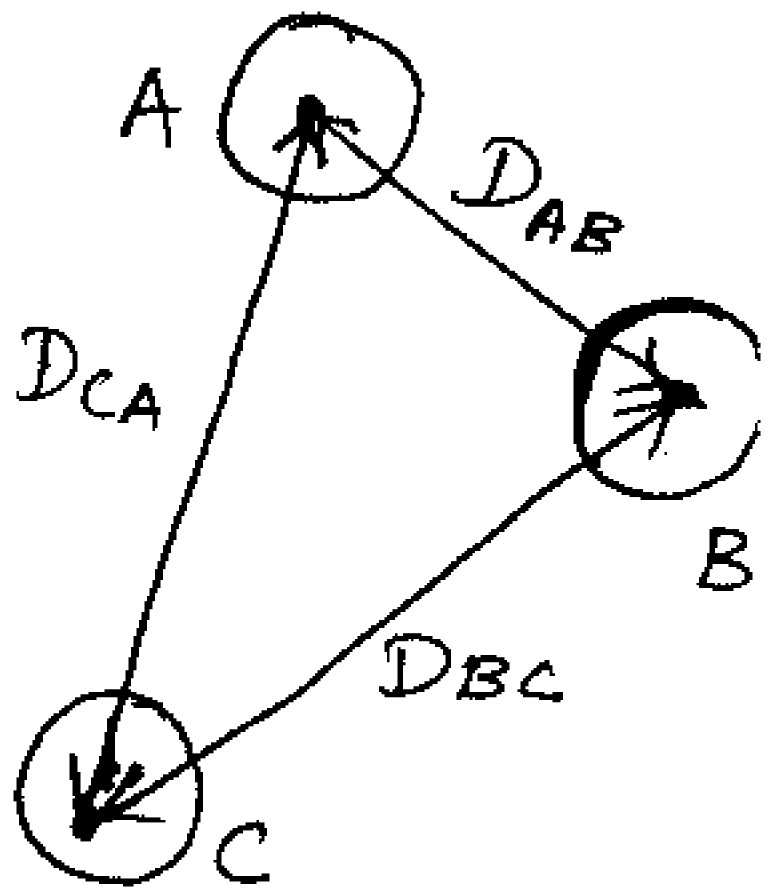
$$L = 0.2 \ln\left(\frac{2}{4.8675 \times 10^{-3}}\right)$$

$$\boxed{L/ph/km = 1.20366 \text{ mH}}$$

·x ——————— x·

Inductance of 3φ Unsymmetrical Transmission Line

Unsymmetrical Spacing or Line



When the conductors are placed at unequal spacing, they are called unsymmetrical transmission line

Let I_A, I_B and I_C be the current through the conductors A, B and C.

Consider one metre length of a 3φ line is having 3 conductors A, B and C spaced D_{AB}, D_{BC} and D_{CA} respectively.

Let 'r' be the radius of each Conductor

Assuming balanced Currents

$$I_A + I_B + I_C = 0$$

Flux linkages with conductor A,

$$\lambda_A = L_{AA} I_A + L_{AB} I_B + L_{AC} I_C$$

$$\lambda_A = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r'}\right) + I_B \ln\left(\frac{1}{D_{AB}}\right) + I_C \ln\left(\frac{1}{D_{AC}}\right)\right] \quad -(1)$$

Similarly flux linkages with Conductor B,

$$\lambda_B = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{D_{BA}}\right) + I_B \ln\left(\frac{1}{r'}\right) + I_C \ln\left(\frac{1}{D_{BC}}\right)\right] \quad -(2)$$

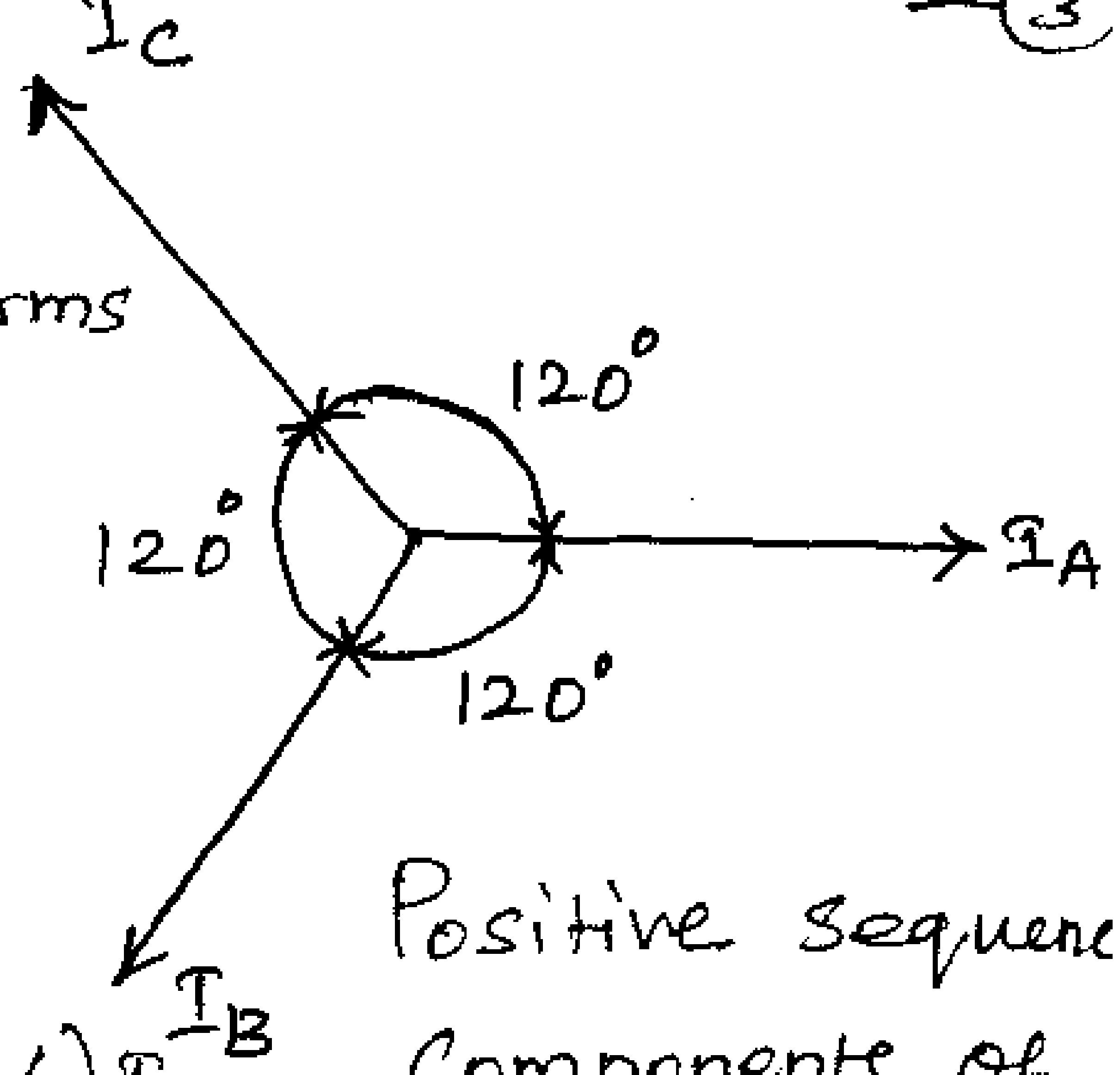
$$\lambda_B = L_{BA} I_A + L_{BB} I_B + L_{BC} I_C$$

Similarly flux linkages with Conductor C,

$$\lambda_C = L_{CA} I_A + L_{CB} I_B + L_{CC} I_C$$

$$\lambda_C = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{D_{CA}}\right) + I_B \ln\left(\frac{1}{D_{CB}}\right) + I_C \ln\left(\frac{1}{r'}\right)\right] \quad -(3)$$

The Phase Current I_B and I_C can be represented in terms of phase Current I_A



Positive sequence Components of Current

$$I_A = I_A \angle 0^\circ$$

$$I_B = I_A \angle -120^\circ$$

$$= I_A \angle 240 = (-0.5 - j0.866) I_A$$

$$= \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right) I_A$$

$$I_C = I_A \angle 120^\circ = (-0.5 + j0.866) I_A = \left(\frac{-1}{2} + \frac{j\sqrt{3}}{2}\right) I_A$$

Substituting I_B and I_C in equation ①, ② & ③

We get

$$\lambda_A = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r'}\right) + I_A\left(-\frac{1}{2} - \frac{j\sqrt{3}}{2}\right)\ln\left(\frac{1}{D_{AB}}\right) + I_A\left(-\frac{1}{2}+\frac{j\sqrt{3}}{2}\right)\ln\left(\frac{1}{D_{AC}}\right)\right]$$

Inductance of conductor A $= \dfrac{\lambda_A}{I_A}$

$$L_A = 2\times10^{-7}\left[\ln\frac{1}{r'} - \frac{1}{2}\ln\left(\frac{1}{D_{AB}}\right) - \frac{1}{2}\ln\left(\frac{1}{D_{AC}}\right) - \frac{j\sqrt{3}}{2}\ln\left(\frac{1}{D_{AB}}\right) + \frac{j\sqrt{3}}{2}\ln\left(\frac{1}{D_{AC}}\right)\right]$$

$$= 2\times10^{-7}\left[\ln\left(\frac{1}{r'}\right) - \left(\ln\left(\frac{1}{D_{AB}}\right)^{1/2} + \ln\left(\frac{1}{D_{AC}}\right)^{1/2}\right) - \frac{j\sqrt{3}}{2}\left(\ln\frac{1}{D_{AB}} + \ln D_{AC}\right)\right]$$

$$L_A = 2\times10^{-7}\left[\ln\frac{1}{r'} - \ln\frac{1}{\sqrt{D_{AB}\cdot D_{AC}}} - \frac{j\sqrt{3}}{2}\ln\left(\frac{D_{AC}}{D_{AB}}\right)\right] \text{ H/m}$$

Similarly,

$$L_B = 2\times10^{-7}\left[\ln\left(\frac{1}{r'}\right) - \ln\frac{1}{\sqrt{D_{BA}\cdot D_{BC}}} - \frac{j\sqrt{3}}{2}\ln\left(\frac{D_{BA}}{D_{BC}}\right)\right] \text{ H/m}$$

$$L_C = 2\times10^{-7}\left[\ln\left(\frac{1}{r'}\right) - \ln\frac{1}{\sqrt{D_{CA}\cdot D_{CB}}} - \frac{j\sqrt{3}}{2}\ln\left(\frac{D_{CB}}{D_{CA}}\right)\right] \text{ H/m}$$

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Transposition of Conductors:

To avoid the unbalancing effect due to unsymmetrical spacing, interchanging the conductor position at regular intervals along the line, so that each conductor occupy others position over an equal distance is called as Transposition of conductors.

The need of transposition is to get the inductances in all the three wires equal to get same voltage at the receiving end.

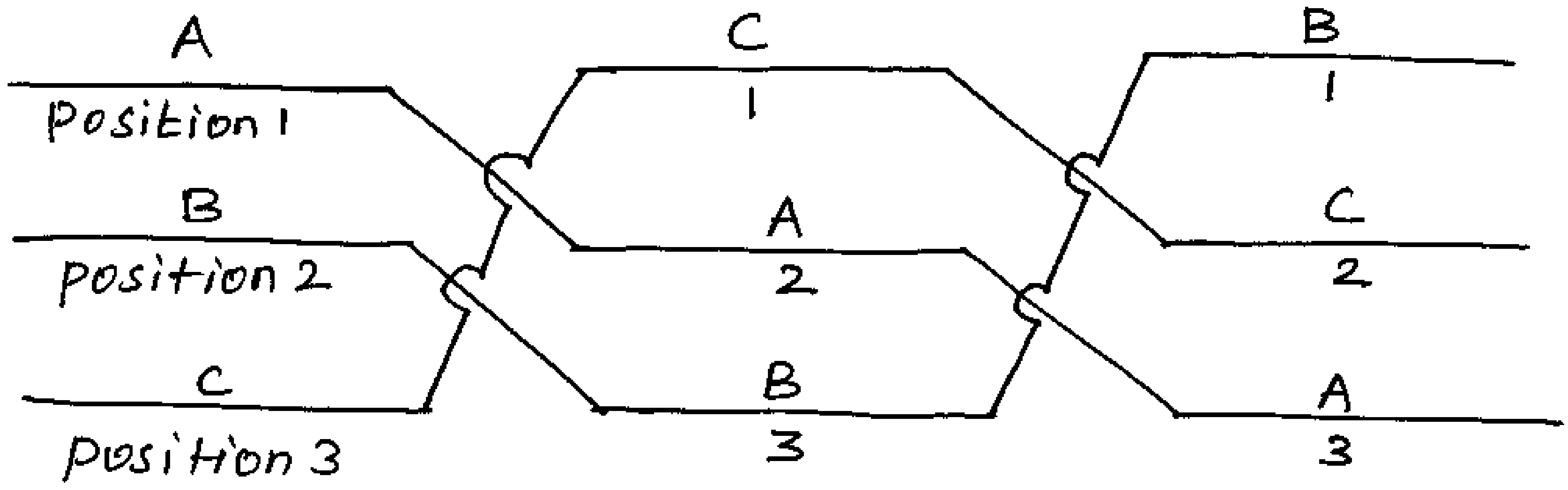
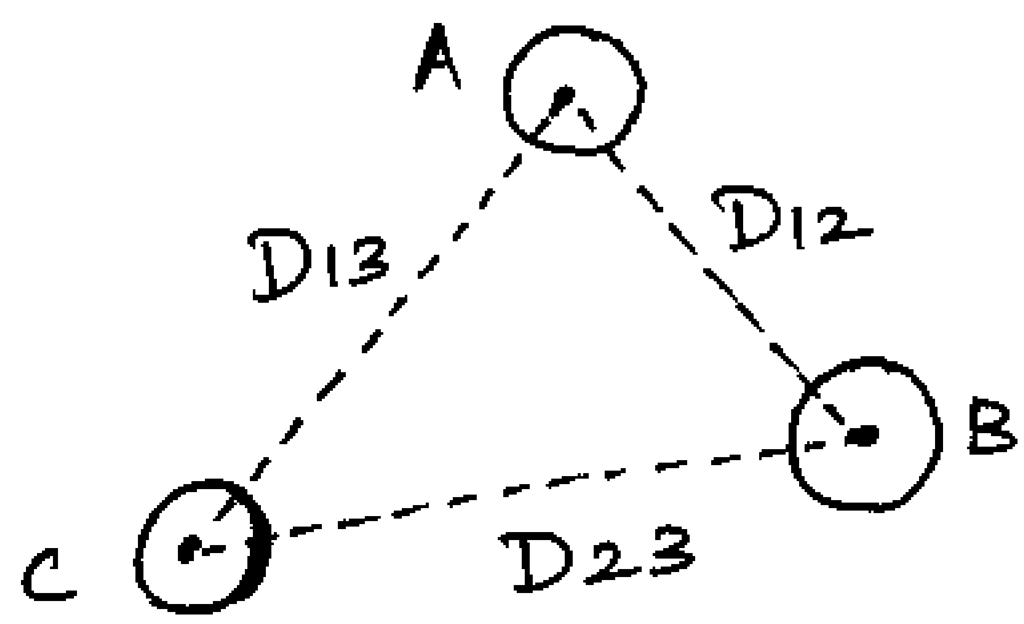


Fig: Transposition of Conductors



$D_{12} \neq D_{23} \neq D_{31}$

Flux linkages of Conductor A is in position 1, Conductor B is in position 2 and Conductor C is in position 3.

$$\lambda_A = L_{AA} I_A + L_{AB} I_B + L_{AC} I_C$$

$$\lambda_{A1} = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r1}\right) + I_B \ln\left(\frac{1}{D_{12}}\right) + I_C \ln\left(\frac{1}{D_{13}}\right)\right]$$

Flux linkages of Conductor A is in position 2, Conductor B is in position 3 and Conductor C is in position 1

$$\lambda_{A2} = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r1}\right) + I_B \ln\left(\frac{1}{D_{23}}\right) + I_C \ln\left(\frac{1}{D_{21}}\right)\right]$$

Flux linkages of Conductor A is in position 3, Conductor B is in position 1 and Conductor C is in position 2.

$$\lambda_{A3} = 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r'}\right) + I_B \ln\left(\frac{1}{D_{31}}\right) + I_C \ln\left(\frac{1}{D_{32}}\right)\right]$$

Average flux linkages of conductor A,

$$\lambda_A = \frac{\lambda_{A1}+\lambda_{A2}+\lambda_{A3}}{3}$$

$$\lambda_A = \frac{2\times10^{-7}}{3}\left[3I_A \ln\left(\frac{1}{r'}\right) + I_B \ln\left(\frac{1}{D_{12}\cdot D_{23}\cdot D_{31}}\right) + I_C \ln\left(\frac{1}{D_{13}D_{21}D_{32}}\right)\right]$$

$$= \frac{2\times10^{-7}}{3}\left[3I_A \ln\left(\frac{1}{r'}\right) + \ln\left(\frac{1}{D_{12}\cdot D_{23}\cdot D_{31}}\right)(I_B+I_C)\right]$$

Since $I_B + I_C = -I_A$

$$\lambda_A = \frac{2\times10^{-7}}{3}\left[3I_A \ln\left(\frac{1}{r'}\right) + \ln\left(\frac{1}{D_{12}D_{23}D_{31}}\right)(-I_A)\right]$$

$$= 2\times10^{-7}\left[I_A \ln\left(\frac{1}{r'}\right) - \frac{I_A}{3}\ln\left(\frac{1}{D_{12}D_{23}D_{31}}\right)\right]$$

$$= 2\times10^{-7} I_A\left[\ln\left(\frac{1}{r'}\right) - \ln\left(\frac{1}{D_{12}D_{23}D_{31}}\right)^{1/3}\right]$$

$$= 2\times10^{-7} I_A\left[\ln\left(\frac{1}{r'}\right) + \ln\left(D_{12}D_{23}D_{31}\right)^{1/3}\right]$$

$$= 2\times10^{-7} I_A \ln\left[\frac{(D_{12}\cdot D_{23}\cdot D_{31})^{1/3}}{r'}\right]$$

Inductance of phase A, $L_A = \frac{\lambda_A}{I_A}$

$$= 2\times10^{-7}\ln\left(\frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r'}\right)$$

$r' = D_S$, $D_M = \sqrt[3]{D_{12}D_{23}D_{31}}$

$$L = 2\times10^{-7} \ln\left(\frac{D_M}{D_s}\right) \; H/m$$

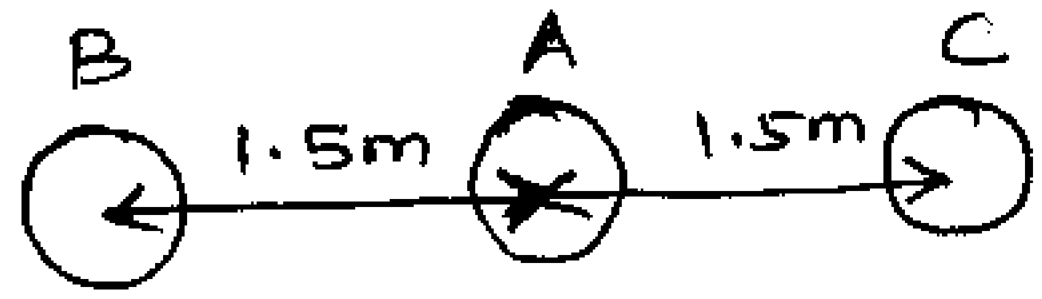
Mutual GMD:

Inductance of 3 phase unsymmetrical transposed line $L = 2\times10^{-7}\ln\left(\frac{D_M}{D_s}\right)$ H/m

Here $D_M = \sqrt[3]{D_{12}D_{23}D_{31}}$ is called

.x ——————— x.

Determine the inductance of a 3 phase line, operating at 50 Hz and the conductors are transposed and arranged as shown in figure. The conductor's diameter is 0.7 cm.



Given data:

Diameter = 0.7 cm

$D_{AB} = 1.5m \quad D_{AC} = 1.5m \quad D_{BC} = 3m$

Radius $= \frac{0.7}{2} = 0.35\,cm = 0.35\times10^{-2}\,m$

Solution:

$r' = D_s = 0.7788 r = 0.7788\times0.35\times10^{-2}$

$= 0.002725\, m$

Mutual GMD of the Conductor $(D_M) = [D_{AB}D_{BC}D_{CA}]$

$D_M = [1.5\times3\times1.5]^{1/3} = 1.8898\, m$

Formula used: $L = 2\times10^{-7} \ln\left(\frac{D_M}{D_S}\right)$ H/m

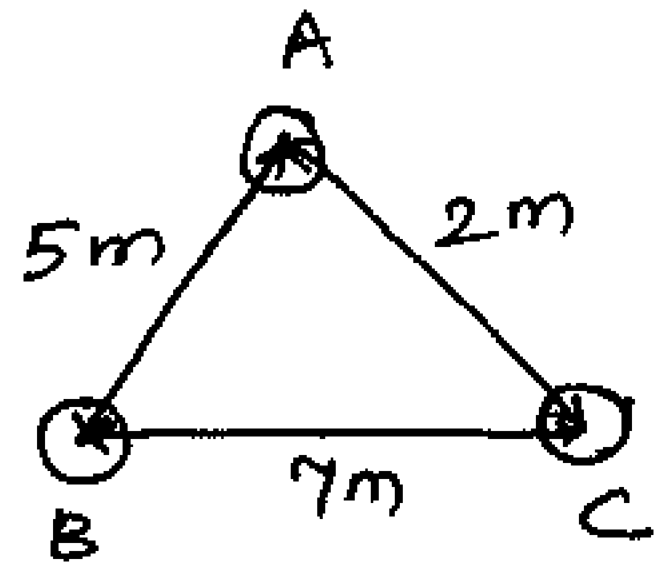
$$L = 2\times10^{-7} \ln\left[\frac{1.8898}{0.002725}\right] \text{ H/m}$$

$$L = 1.308\times10^{-6} \text{ H/m} = 1.308 \text{ mH/km}$$

Inductance Per km = 1.308×10^{-3} H/km

·x ———— x·

Calculate the inductance of a 3 phase line operating at 50 Hz and the conductors are transposed and arranged as shown in figure. The conductor diameter is 2.3222 cm.



Given data:

Conductor diameter $D = 2.3220$ cm

$D_{AB} = 5m$, $D_{BC} = 7m$, $D_{AC} = 2m$

Solution: $r = \frac{D}{2} = \frac{2.3220}{2} = 1.161 \text{ cm} = 0.01161 \text{ m}$

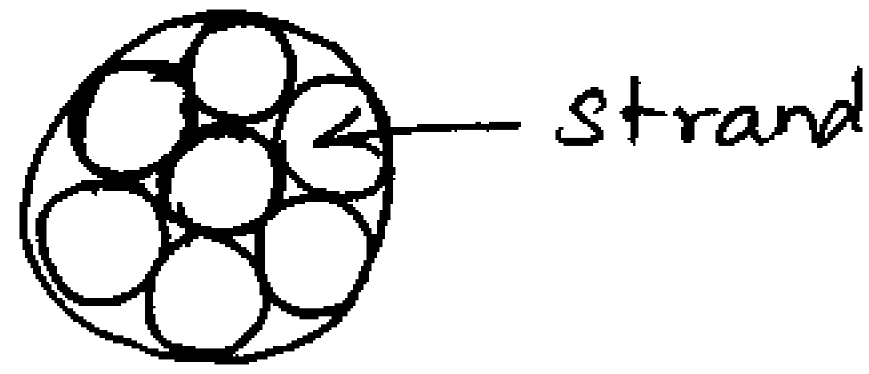
$$D_M = \text{Mutual GMD} = \sqrt[3]{D_{AB} D_{BC} D_{CA}} = \sqrt[3]{5\times7\times2}$$
$$= 4.1213 \text{ m}$$

$$D_s = re^{-1/4} = 0.7788\,r = 0.7788 \times 0.01161$$
$$r' = 9.04187\times10^{-3} \text{ m}$$

$$L = 0.2 \ln\frac{D_M}{D_s} \text{ mH/km} = 0.2 \ln\frac{4.1213}{9.04187\times10^{-3}}$$

$L/ph = 1.2244$ mH/km

Stranded Conductors:



Stranded Conductors touch each other, stranded conductors are composed of two or more elements or strands electrically in parallel with alternate layers spiralled in opposite direction to prevent undwinding. In this, there is one central wire and is surrounded by successive layers of wir containing 6, 18, 36 wires. 7 strand conductor is shown in figure.

Total number of strands $N = 3x^2 - 3x + 1$

Where x - Number of layers

Layer	Number of Strands
1	$3\times1 - 3\times1 + 1 = 1$
2	$3\times2^2 - 3\times2 + 1 = 7$
3	$3\times3^2 - 3\times3 + 1 = 19$
4	$3\times4^2 - 3\times4 + 1 = 37$

Material Used:

Aluminium

Advantages:

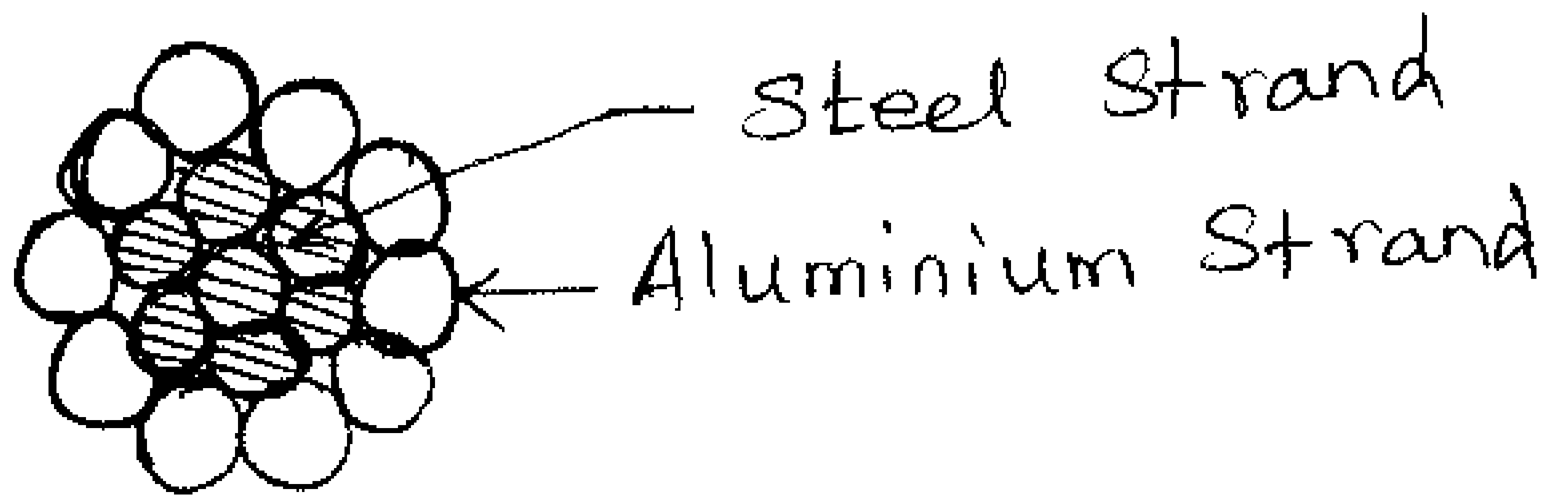
* Cheaper and lighter than copper
* Low density and low conductivity
* Increases flexibility

* Reduces [illegible] conductor surface, so tha

line is Corona free

ACSR (Aluminium Conductor Steel Reinforced)

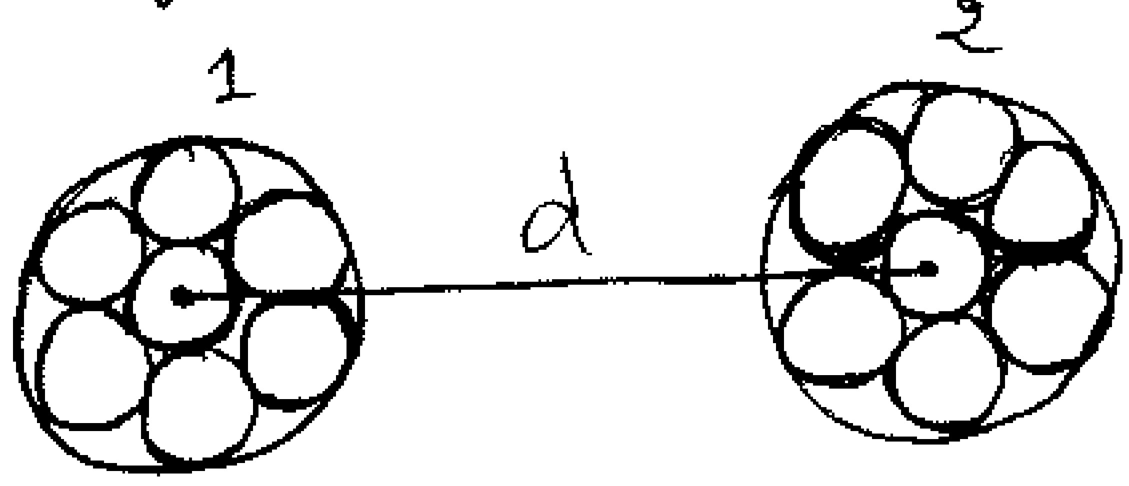
The low tensile Strength of aluminium Conductors is made up by providing central strand of high tensile strength galvanised steel core. such a Conductor is known as ACSR and is Commonly used in overhead transmission lines.



ASCR

Bundled Conductors:

A bundled Conductor is a Conductor made up of two or more subconductors and is used as one phase conductors. Bundled Conductors are separated from each other by 30 cm or more and conductors of each phase are connected by Connecting wires at particular length.



For the voltages more than 230KV line, it is not possible to use the round

Conductors due to excessive Corona loss. So, bundled Conductors are used. The subconduc within a bundle are separated by spacer dampers. Spacer dampers prevent Clashing.

Advantages:

* Reduces the line reactance due to increase in Self GMD Which improves the line Performa
* Increases the Power capability of the line
* Reduces Corona loss
* Reduces radio interference
* Reduces surge impedance
* Increases surge impedance loading

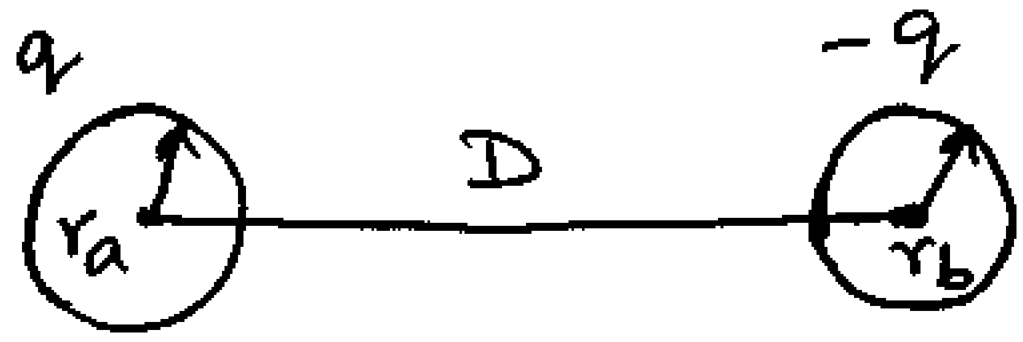
x ———————— x

Capacitance of single phase line:

Capacitance is defind as the ratio of charge on one Conductor to the potential difference between the Conductors.

$$C = \frac{q}{V}$$

Consider one meter length of a single phase line having radius r_a and r_b meter and separated by a distance D meters.



Let the charge per unit length of Conductor a be q

Let the charge per unit length of Conductor b be -q

Electric field intensity for Conductor 'a' due to Charge 'q'.

$$E_{ab} = \frac{q}{2\pi\varepsilon_0 x}$$

Voltage between Conductor A and B is

$$V_{AB(q)} = \int_{r_a}^{D} \frac{q}{2\pi\varepsilon_0 x} = \left[\frac{q}{2\pi\varepsilon_0} \ln x\right]_{r_a}^{D}$$

$$V_{AB(q)} = \frac{q}{2\pi\varepsilon_0} \ln\left(\frac{D}{r_a}\right)$$

Electric field intensity for conductor B due to Charge '-q'.

$$E_{BA(-q)} = \frac{-q}{2\pi\varepsilon_0 x}$$

$$V_{BA(-q)} = \int_{r_b}^{D} \frac{-q}{2\pi\varepsilon_0 x} = \left[\frac{-q}{2\pi\varepsilon_0} \ln x\right]_{r_b}^{D}$$

$$= \frac{-q}{2\pi\varepsilon_0} \ln\left(\frac{D}{r_b}\right)$$

$$V_{AB(-q)} = -V_{BA(-q)} = \frac{q}{2\pi\varepsilon_0} \ln\left(\frac{D}{r_b}\right)$$

Potential difference between Conductor a and b is

$$V_{AB} = V_{AB(q)} + V_{AB(-q)}$$

$$= \frac{q}{2\pi\varepsilon_0}\left[\ln\frac{D}{r_a} + \ln\frac{D}{r_b}\right]$$

$$= \frac{q}{2\pi\varepsilon_0}\ln\left(\frac{D^2}{r_a r_b}\right)$$

Capacitance per unit length between the Conductors

$$C_{AB} = \frac{q}{V_{AB}} = \frac{q}{\frac{q}{2\pi\varepsilon_0}\ln\left(\frac{D^2}{r_a r_b}\right)}$$

$$= \frac{2\pi\varepsilon_0}{\ln\left(\frac{D}{\sqrt{r_a r_b}}\right)^2}$$

$$= \frac{2\pi\varepsilon_0}{2\ln\left(\frac{D}{\sqrt{r_a r_b}}\right)} = \frac{\pi\varepsilon_0}{\ln\left(\frac{D}{\sqrt{r_a r_b}}\right)} \text{ F/m}$$

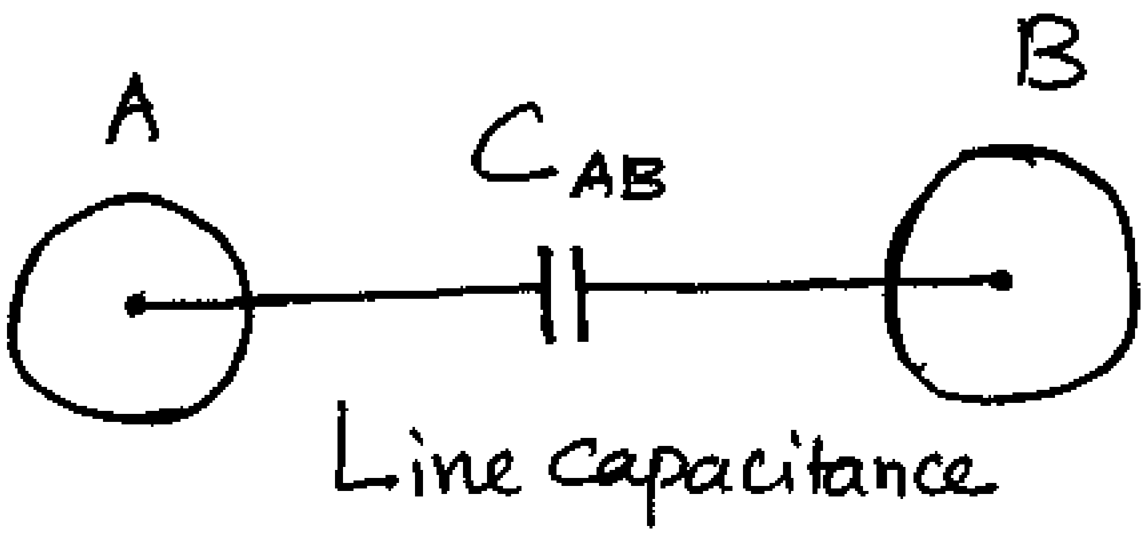
If $r_a = r_b = r$, then

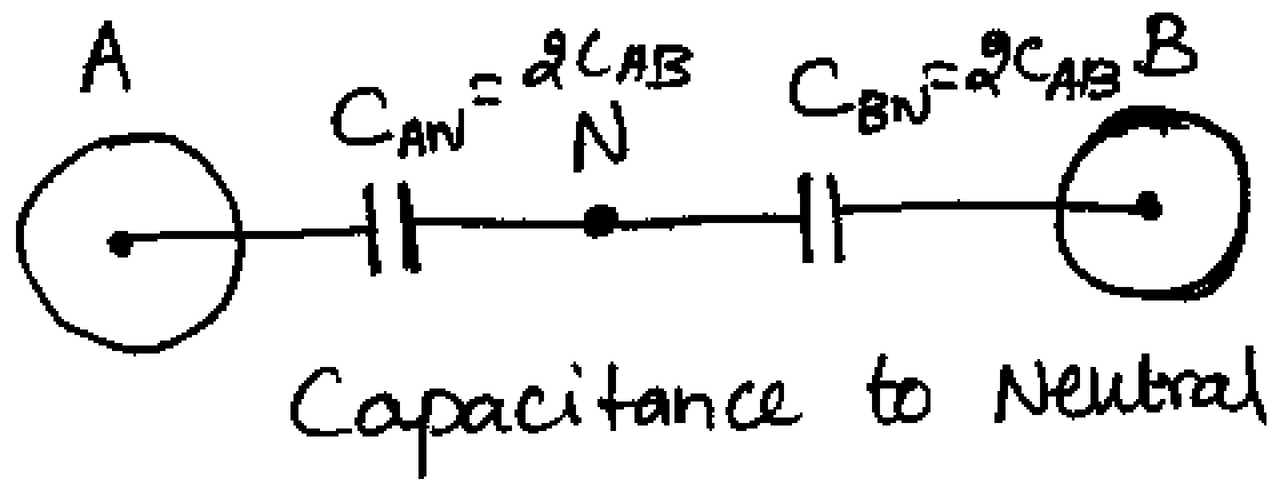
$$C_{AB} = \frac{\pi\varepsilon_0}{\ln\left(\frac{D}{r}\right)} \text{ F/m}$$

$$V_{AB} = \frac{q}{2\pi\varepsilon_0}\ln\left(\frac{D}{r}\right)$$

Where C_{AB} – Line to line Capacitance

Capacitance between Line and Neutral Conductors:





$$V_{AN} = V_{BN} = \frac{V_{AB}}{2}$$

The Potential difference between each Conductor and the ground or neutral is half the potential difference between the Conductors. Thus the Capacitance to ground or capacitance to neutral for the two wire line is twice the line to line Capacitance. Capacitance to neutral

$$C_{AN} = C_{BN} = 2C_{AB}$$

$$C_{AN} = 2C_{AB} = \frac{2\pi\varepsilon_0}{\ln\left(\frac{D}{r}\right)} \text{ F/m} \qquad \varepsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$$

$$C_{AN} = \frac{2\pi \times 8.85 \times 10^{-12}}{\ln\left(\frac{D}{r}\right)} \text{ F/m}$$

$$\boxed{C_{AN} = \frac{0.0556}{\ln\left(\frac{D}{r}\right)} \ \mu\text{F/km}}$$

Find the Capacitance Per km of a single phase overhead line consisting of two Conductors each 4.4755 cm diameter. The spacing is 3m.

- Given data:

Diameter = 4.4755 cm

Spacing D = 3m

Formula used:

$$C = \frac{0.0556}{\ln\left(\frac{D}{r}\right)} = \frac{0.0556}{\ln\left(\frac{3}{0.0223775}\right)}$$

$$r = \frac{\text{Diameter}}{2} = \frac{4.4755}{2} = 2.23775\ \text{cm}$$

$$= 0.0223775\ \text{m}$$

$$C = 0.01135\ \mu F/km$$

$$\boxed{C = 11.35\ nF/km}$$

Potential Difference in a multiconductor:

Consider 'n' Parallel long Conductors with Charges $q_1, q_2, \ldots\ldots, q_n$ Coulomb/m as shown in figure.

Assume Charge is Uniformly distributed

$$q_1 + q_2 + q_3 + \ldots\ldots + q_n = 0$$

Potential difference between Conductors 1 and 2 due to charge $q_1, q_2 \ldots\ldots, q_n$

$$V_{12}(q_1) = \frac{q_1}{2\pi\varepsilon_0} \ln\left(\frac{D_{12}}{D_{11}}\right) = \frac{q_1}{2\pi\varepsilon_0} \ln\left(\frac{D_{12}}{r}\right)$$

$$V_{12}(q_2) = \frac{q_2}{2\pi\varepsilon_0} \ln\left(\frac{D_{22}}{D_{21}}\right)$$

$$V_{12}(q_3) = \frac{q_3}{2\pi\varepsilon_0} \ln\left(\frac{D_{32}}{D_{31}}\right)$$

⋮

$$V_{12}(q_n) = \frac{q_n}{2\pi\varepsilon_0} \ln\left(\frac{D_{n2}}{D_{n1}}\right)$$

$$V_{12} = V_{12}(q_1) + V_{12}(q_2) + \cdots + V_{12}(q_n)$$

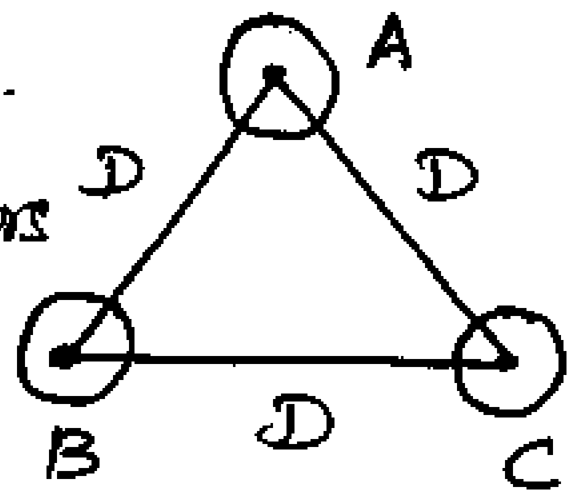
In general $V_{ij} = \frac{1}{2\pi\varepsilon_0} \sum_{k=1}^{n} q_k \ln\left(\frac{D_{kj}}{D_{ki}}\right)$

Capacitance of 3φ Symmetrical Tr Line:

Symmetrical Line:

When the conductors are placed at equal spacing, then they are called symmetrical line.

Consider one meter length of 3φ line with three long conductors A, B and C respectively.



Let 'r' be the radius of each conductor.

Let D be the distance between the conductors

Let q_a, q_b, q_c be the charge in Coulomb/m of each conductor.

Assuming charge is uniformly distributed

$$q_a + q_b + q_c = 0 \Rightarrow q_b + q_c = -q_a$$

$$V_{AB} = V_{AN} - V_{BN}$$

$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D_{AB}}{D_{AA}}\right) + q_b \ln\left(\frac{D_{BB}}{D_{BA}}\right) + q_c \ln\left(\frac{D_{CB}}{D_{CA}}\right)\right]$$

$$D_{AA} = D_{BB} = r$$

$$V_{AB} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D}{r}\right) + q_b \ln\left(\frac{r}{D}\right) + q_c \ln\left(\frac{D}{D}\right)\right]$$

Similarly

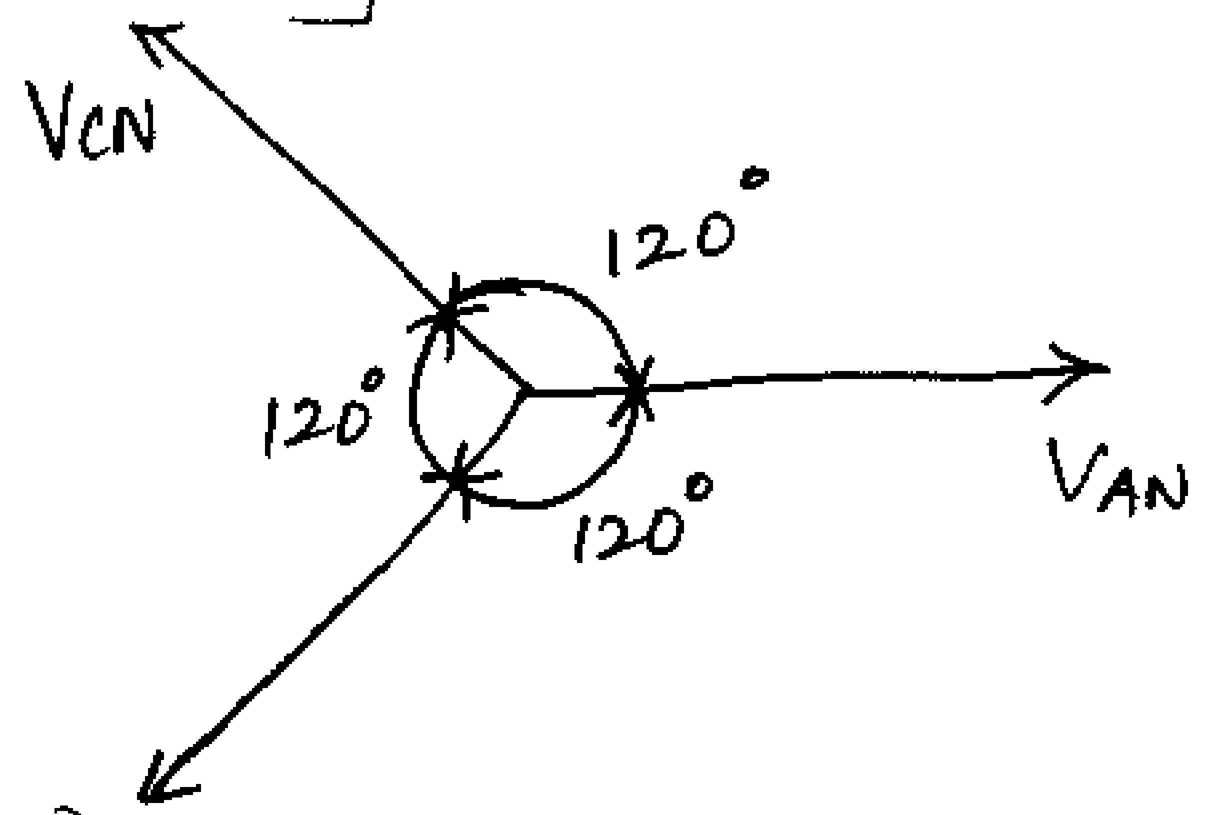
$$V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D}{r}\right) + q_b \ln\left(\frac{D}{D}\right) + q_c \ln\left(\frac{r}{D}\right)\right]$$

$$V_{AB}+V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln\left(\frac{D}{r}\right) + \ln\left(\frac{r}{D}\right)(q_b+q_c)\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln\left(\frac{D}{r}\right) + \ln\left(\frac{r}{D}\right)(-q_a)\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln\left(\frac{D}{r}\right) + q_a \ln\left(\frac{D}{r}\right)\right]$$

$$= \frac{1}{2\pi\varepsilon_0} 3q_a \ln\left(\frac{D}{r}\right)$$



For 3ϕ balanced circuit

$$V_{AN} = V_{AN}\angle 0^\circ = V_{AN}$$

$$V_{BN} = V_{AN}\angle -120^\circ = V_{AN}\left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)$$

$$V_{CN} = V_{AN}\angle 120^\circ = V_{AN}\left(-1/2 + j\sqrt{3}/2\right)$$

$$V_{AB} = V_{AN} - V_{BN} = V_{AN} + j0 - V_{AN}\left(-1/2 - j\frac{\sqrt{3}}{2}\right)$$

$$= \frac{3V_{AN}}{2} + \frac{j\sqrt{3}}{2} V_{AN}$$

$$V_{AC} = V_{AN} - V_{CN} = V_{AN} + j0 - V_{AN}\left(-1/2 + j\sqrt{3}/2\right)$$

$$= \frac{3}{2} V_{AN} - \frac{j\sqrt{3}}{2} V_{AN}$$

$$V_{AB} + V_{AC} = \frac{3V_{AN}}{2} + \frac{3V_{AN}}{2} = \frac{6V_{AN}}{2} = 3V_{AN}$$

$$V_{AN} = \frac{V_{AB}+V_{AC}}{3}$$

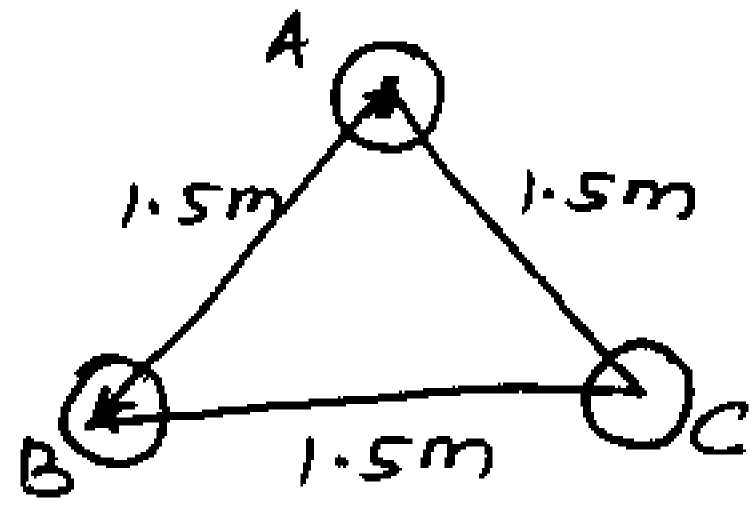
$$V_{AN} = \frac{1}{3} \times \frac{3q_a}{2\pi\varepsilon_0} \ln\left(\frac{D}{r}\right) = \frac{q_a}{2\pi\varepsilon_0} \ln\left(\frac{D}{r}\right)$$

Line to neutral capacitance

$$C_{AN} = \frac{q_a}{V_{AN}} = \frac{2\pi\varepsilon_0}{\ln\left(\frac{D}{r}\right)} \text{ F/m}$$

$$\boxed{C = \frac{0.0556}{\ln\left(\frac{D}{r}\right)} \ \mu\text{F/km}}$$

Determine the capacitance of a 3ϕ line operating at 50 Hz and the conductors are arranged as shown in figure. The conductor diameter is 0.7 cm.



Given data:

Diameter = 0.7 cm

$D_{AB} = 1.5m$, $D_{BC} = 1.5m$, $D_{CA} = 1.5m$

Solution: Formula used

$$\text{Capacitance per phase} = \frac{0.0556}{\ln\left(\frac{D}{r}\right)} \ \mu F/km$$

$$\text{Radius } r = \frac{\text{Diameter}}{2} = \frac{0.7}{2} = 0.35 \text{ cm}$$

$$D_{AB} = D_{BC} = D_{CA} = D = 1.5 \text{ m}$$

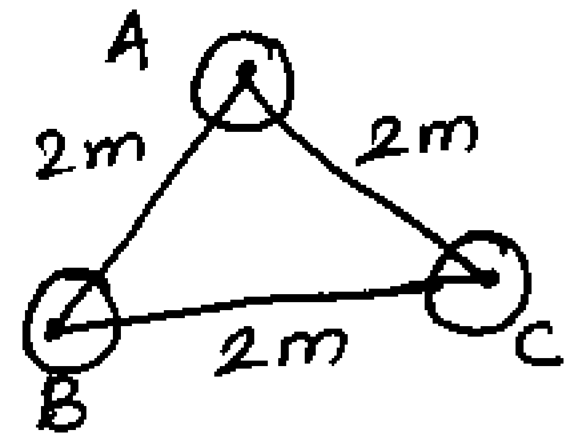
$$C = \frac{0.0556}{\ln\left(\frac{1.5}{0.35\times10^{-2}}\right)} \ \mu F/km$$

$$= 9.1742\times10^{-3} \ \mu F/km$$

$$\boxed{C/ph = 9.1742 \ nF/km}$$

·×——————×·

A 3ϕ overhead transmission line has its conductors arranged at the corners of an equilateral traingle of 2m side. Calculate the capacitance of each line conductor per km. Given that the radius of each conductor is 0.65 cm.



Given data: $D = 2$

$r = 0.65$ cm

Formula used: $$\text{Capacitance} = \frac{0.0556}{\ln\left(\frac{D}{r}\right)} \ \mu F/km$$

$$C = \frac{0.0556}{\ln\left(\frac{2}{0.65\times10^{-2}}\right)} = \frac{0.0556}{\ln\left(\frac{2}{0.00625}\right)} = 9.63885\times10^{-3} \ \mu F/km$$

$$\boxed{C = 9.63885 \ nF/km}$$

Capacitance of 3φ Unsymmetrical or Asymmetrical transposed Line:

When conductors are at unequal spacing, they are called asymmetrical transmission line.

Consider one metre length of 3φ line with three long conductors A, B, C respectively are transposed.

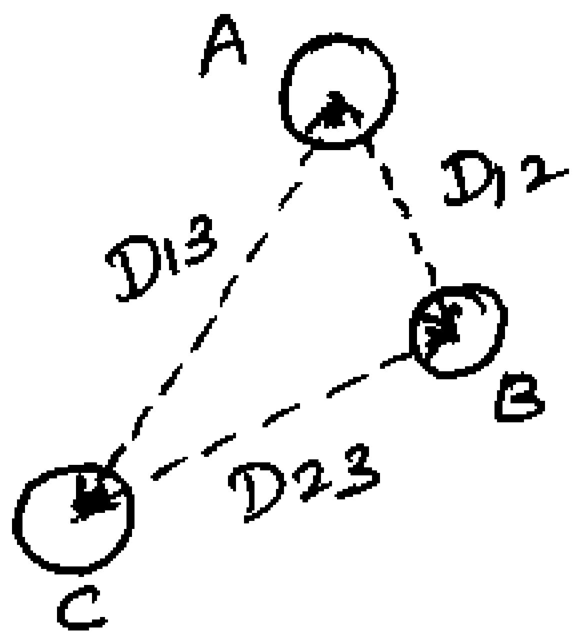
Let r be the radius of conductor

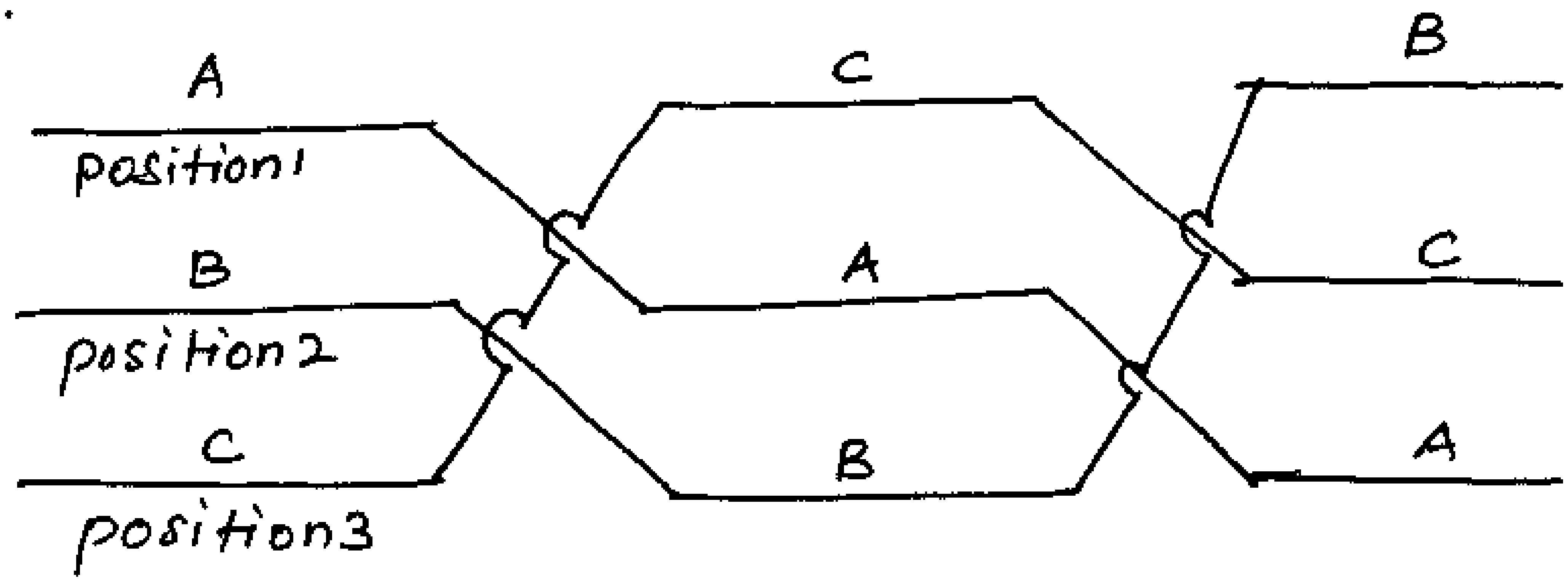
Let q_a q_b and q_c be the charge in Coulomb/m of each conductor

Let 'r' be the radius of conductor

Let q_a, q_b and q_c be the charge in coulomb/m of each conductor

Let D_{AB}, D_{BC}, D_{CA} be the distance between conductors a, b and c.





For phase A in position 1, B in position 2 and C in position 3

$$V_{AB1} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D_{12}}{r_a}\right) + q_b \ln\left(\frac{r_b}{D_{12}}\right) + q_c \ln\left(\frac{D_{23}}{D_{13}}\right)\right]$$

For phase A in position 2, B in position 3 and C in position 1

$$V_{AB2} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D_{23}}{r_a}\right) + q_b \ln\left(\frac{r_b}{D_{23}}\right) + q_c \ln\left(\frac{D_{13}}{D_{12}}\right)\right]$$

For phase A in position 3, B in position 1, C in position 2,

$$V_{AB3} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D_{13}}{r_a}\right) + q_b \ln\left(\frac{r_b}{D_{13}}\right) + q_c \ln\left(\frac{D_{12}}{D_{23}}\right)\right]$$

$$V_{AB} = \frac{V_{AB1} + V_{AB2} + V_{AB3}}{3}$$

Potential difference between conductors A and B

$$V_{AB} = \frac{1}{3}\left[\frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D_{12}D_{23}D_{13}}{r_a^3}\right) + q_b \ln\left(\frac{r_b^3}{D_{12}D_{23}D_{31}}\right) + q_c \ln\left(\frac{D_{12}D_{23}D_{13}}{D_{12}D_{23}D_{13}}\right)\right]\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\frac{(D_{12}D_{23}D_{13})^{1/3}}{r_a} + q_b \ln\frac{r_b}{(D_{12}D_{23}D_{31})^{1/3}} + q_c \ln 1\right]$$

If $r_a = r_b = r$, $V_{AB} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D_M}{r}\right) + q_b \ln\left(\frac{r}{D_M}\right)\right]$ — (1)

$$D_M = GMD = \sqrt[3]{D_{12}D_{23}D_{13}}$$

Similarly $V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[q_a \ln\left(\frac{D_M}{r}\right) + q_c \ln\left(\frac{r}{D_M}\right)\right]$ — (2)

Assuming uniformly distributed charges

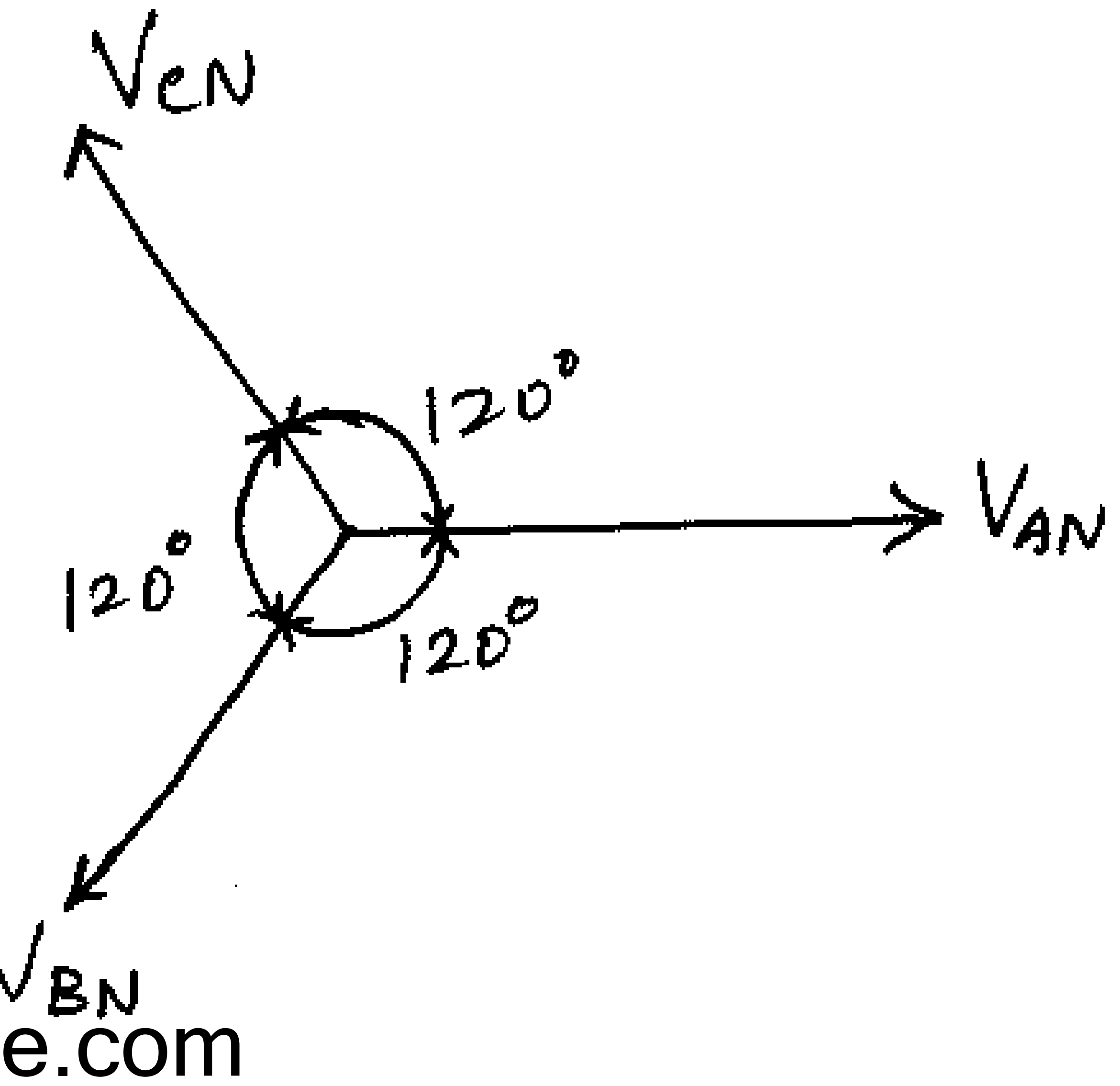
$$q_a + q_b + q_c = 0, \quad q_b + q_c = -q_a$$

$$V_{AB} + V_{AC} = \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln\left(\frac{D_M}{r}\right) + \ln\left(\frac{r}{D_M}\right)(q_b + q_c)\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln\left(\frac{D_M}{r}\right) + (-q_a)\ln\left(\frac{r}{D_M}\right)\right]$$

$$V_{AB} + V_{AC} = \frac{3q_a}{2\pi\varepsilon_0}\ln\left(\frac{D_M}{r}\right) \quad \text{— (3)}$$

For balanced 3ϕ circuit:



$$V_{AN} = V_{AN}\angle 0^\circ$$

$$V_{BN} = V_{AN}\angle -120^\circ = V_{AN}\left[-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right]$$

$$V_{CN} = V_{AN}\angle 120 = V_{AN}\left[-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right]$$

$$V_{AB} = V_{AN} - V_{BN} = \frac{3}{2} V_{AN} + \frac{j\sqrt{3}}{2} V_{AN}$$

$$V_{AC} = V_{AN} - V_{CN} = \frac{3}{2} V_{AN} - \frac{j\sqrt{3}}{2} V_{AN}$$

$$V_{AB} + V_{AC} = \frac{6V_{AN}}{2} = 3V_{AN}$$

$$V_{AN} = \frac{V_{AB} + V_{AC}}{3} \quad \text{——} \quad (4)$$

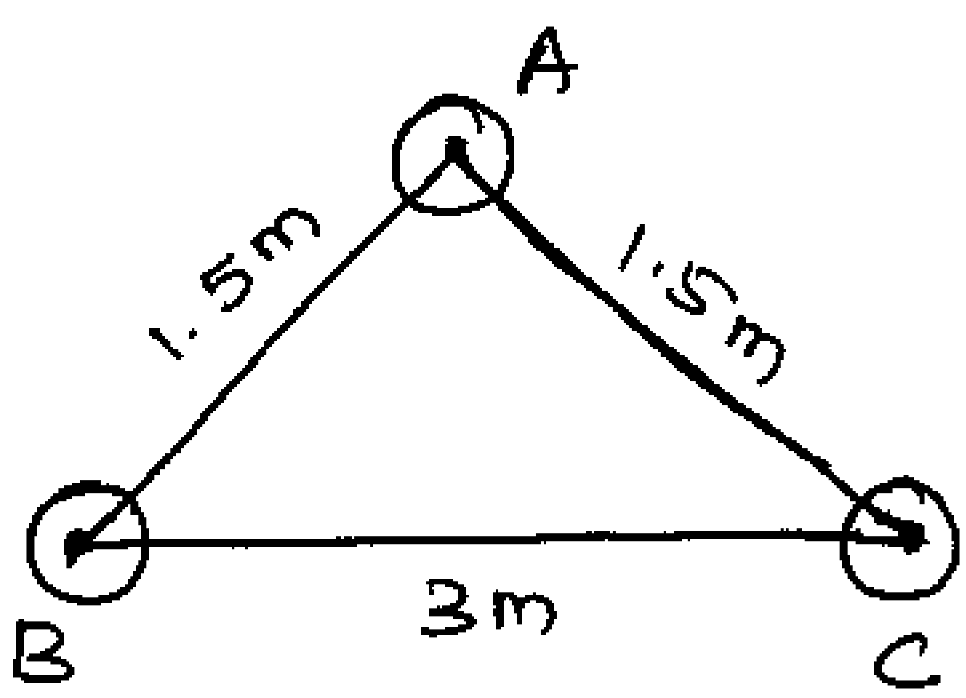
Substituting equation (3) ~~and~~ in equation (4), we get

$$V_{AN} = \frac{3q_a}{3 \times 2\pi\varepsilon_0} \ln\left(\frac{D_M}{r}\right) = \frac{q_a}{2\pi\varepsilon_0} \ln\left(\frac{D_M}{r}\right)$$

Capacitance per phase $C_{AN} = \frac{q_a}{V_{AN}} = \frac{2\pi\varepsilon_0}{\ln\left(\frac{D_M}{r}\right)}$ F/m

$$\boxed{C = \frac{0.0556}{\ln\left(\frac{D_M}{r}\right)} \ \mu F/km}$$

Determine the capacitance of 3φ line operating at 50Hz and the conductors are transposed and arrange as shown in figure. The conductor diameter is 0.7cm.



Given data: Diameter = 0.7 cm

$D_{AB} = 1.5m$, $D_{BC} = 3m$, $D_{AC} = 1.5m$

$$\text{Radius} = \frac{0.7}{2} = 0.35\,cm$$

$$\text{Mutual GMD } (D_M) = \left[D_{AB} D_{BC} D_{CA}\right]^{1/3}$$

$$= (1.5 \times 3 \times 1.5)^{1/3} = 1.8898\,m$$

$$D_M = 1.8898 \text{ m}$$

$$\text{Capacitance per phase} = \frac{0.0556}{\ln\left(\frac{D_M}{r}\right)} \ \mu F/km$$

$$= \frac{0.0556}{\ln\left(\frac{1.8898}{0.35\times10^{-2}}\right)} \ \mu F/km$$

$$C/ph = 8.8374 \times 10^{-3} \ \mu F/km$$

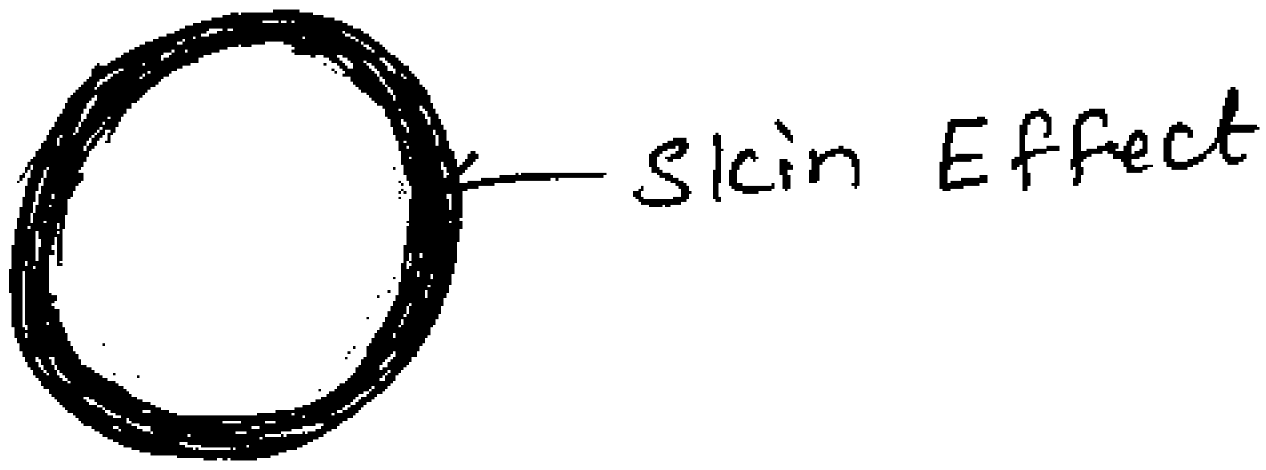
$$C/ph = 8.8374 \ nF/km$$

. x ———————— x .

Skin Effect:

The tendency of alternating current to concentrate near the surface of a conductor is called skin effect.

The direct current (DC) distribution in a conductor is uniform. But the alternating current distribution in a conductor is not uniform. The current density near the surface is more than near to the centre of the conductor. It is affected by the frequency of the current. If the frequency of current is more, the current distribution is more non uniform. This effect is called as skin effect. The effective cross sectiona area of the Conductor through which Current flow is reduced.

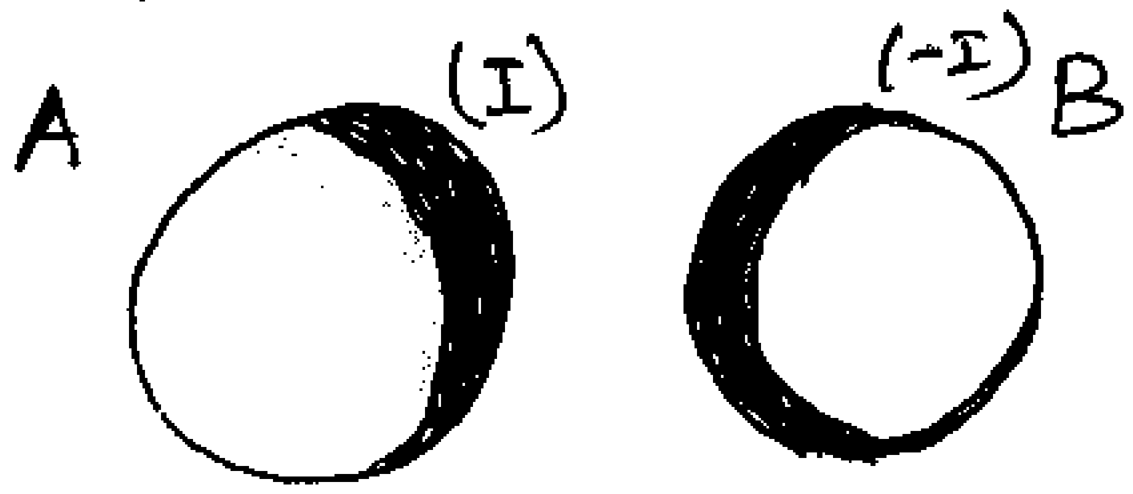


* Skin effect is negligible for frequency < 50 HZ and the conductor diameter < 1 cm

* Skin effect depends on the Conductor size, frequency, resistivity and Permeability of the Conductor material.

Proximity Effect:

The alternating magnetic flux in a Conductor caused by the current flowing in a neighbouring Conductor gives rise to circulating Currents which cause non uniformity of current and an apparent increase in the resistance of the Conductor. This phenomenon is known as proximity effect.



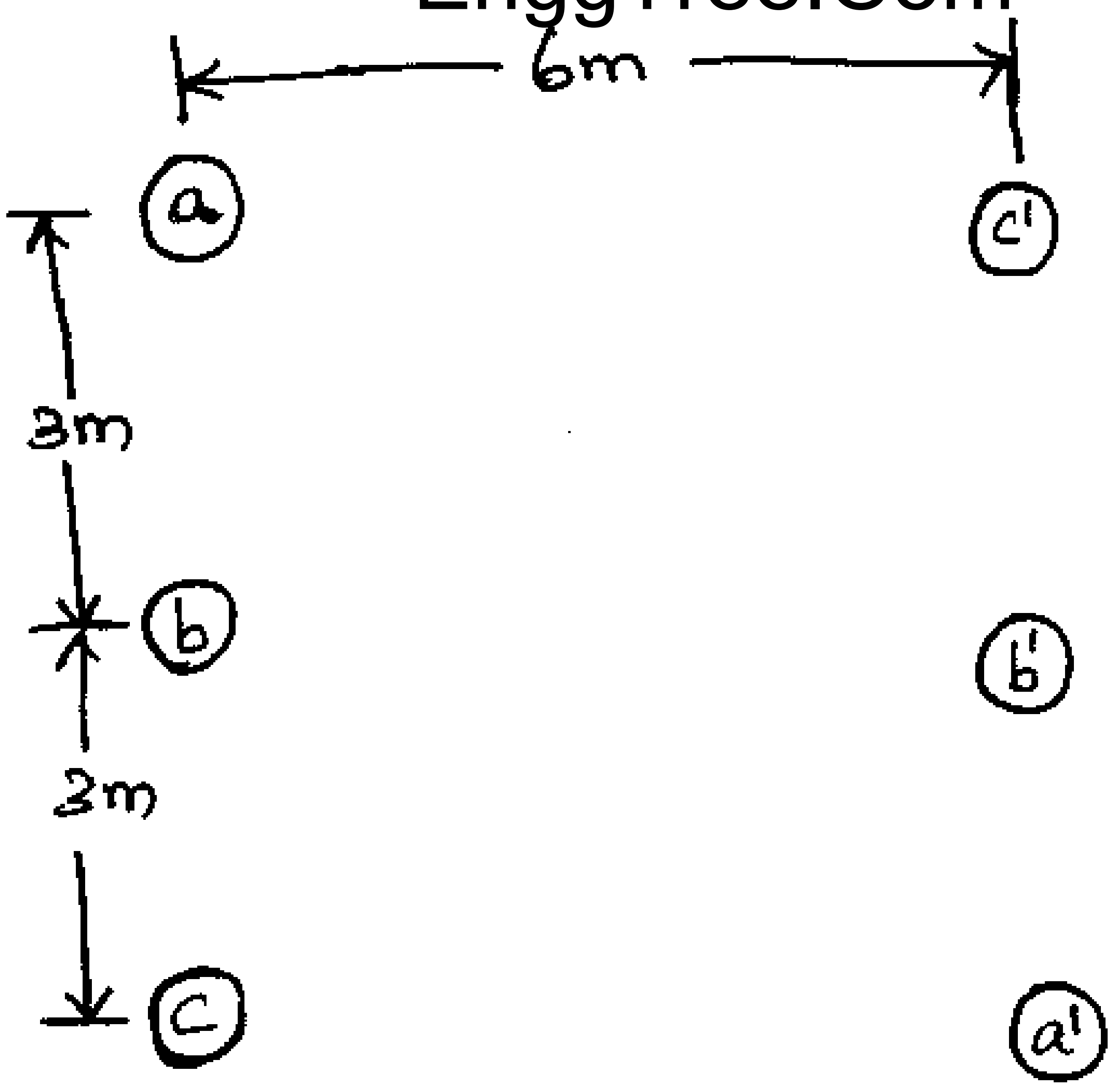
Let us consider two wire system as shown in figure. When conductor A carries current its flux links with the other conductor B. The flux linkages are nearer to the conductor A ie the shaded portion than the opposite side of B. If the current in the conductor B is opposite to the current in A, the current density will be more in the adjacent portion of the conductor. Due to this, the effective resistance of A.C is more than that of D.C.

Proximity effect is negligible in transmission lines and it is more pronounced in cable where the conductors are nearer to each other. It depends on the conductor size frequency, resistivity and permeability of the conductor material.

·x————x·

Problems for Double Circuit Line:

The figure below shows the spacings of a double circuit 3-phase overhead line. The phase sequence is ABC and the line is completely transposed. The conductor radius in 1.3 cm. Find the inductance per phase per kilometre.



G.M.R. of Conductor $= 1.3 \times 0.7788 = 1.01$ cm

Distance a to b' $= \sqrt{6^2+3^2} = 6.7$ m

Distance a to a' $= \sqrt{6^2+6^2} = 8.48$ m

Self GMD $D_s = \sqrt[3]{D_{s1} \times D_{s2} \times D_{s3}}$

Where D_{s1}, D_{s2} and D_{s3} represent the self GMD in position 1, 2, and 3 respectively.

Now $D_{s1} = \sqrt[4]{D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a}}$

$= \sqrt[4]{(1.01 \times 10^{-2}) \times (8.48) \times (1.01 \times 10^{-2}) \times (8.48)}$

$= 0.292\text{m} = D_{s3}$

$D_{s2} = \sqrt[4]{D_{bb} \times D_{bb'} \times D_{b'b'} \times D_{b'b}}$

$= \sqrt[4]{(1.01 \times 10^{-2}) \times (6) \times (1.01 \times 10^{-2}) \times (6)}$

$= 0.246$ m

$D_s = \sqrt[3]{0.292 \times 0.246 \times 0.292}$

$D_s = 0.275$ m

$$D_M = \sqrt[3]{D_{AB} \times D_{BC} \times D_{CA}}$$

$$D_{AB} = \sqrt[4]{D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'}}$$

$$= \sqrt[4]{3 \times 6.7 \times 6.7 \times 3}$$

$$= 4.48\,m = D_{BC}$$

$$D_{CA} = \sqrt[4]{D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'}}$$

$$= \sqrt[4]{6 \times 6 \times 6 \times 6}$$

$$= 6m$$

$$D_m = \sqrt[3]{4.48 \times 4.48 \times 6} = 4.94m$$

$$\boxed{D_M = 4.94m}$$

Inductance per phase per metre length

$$L = 10^{-7} \times 2 \log_e\left(\frac{D_M}{D_S}\right) = 2 \times 10^{-7} \ln(4.94/0.275)$$

$$= 5.7 \times 10^{-7} H$$

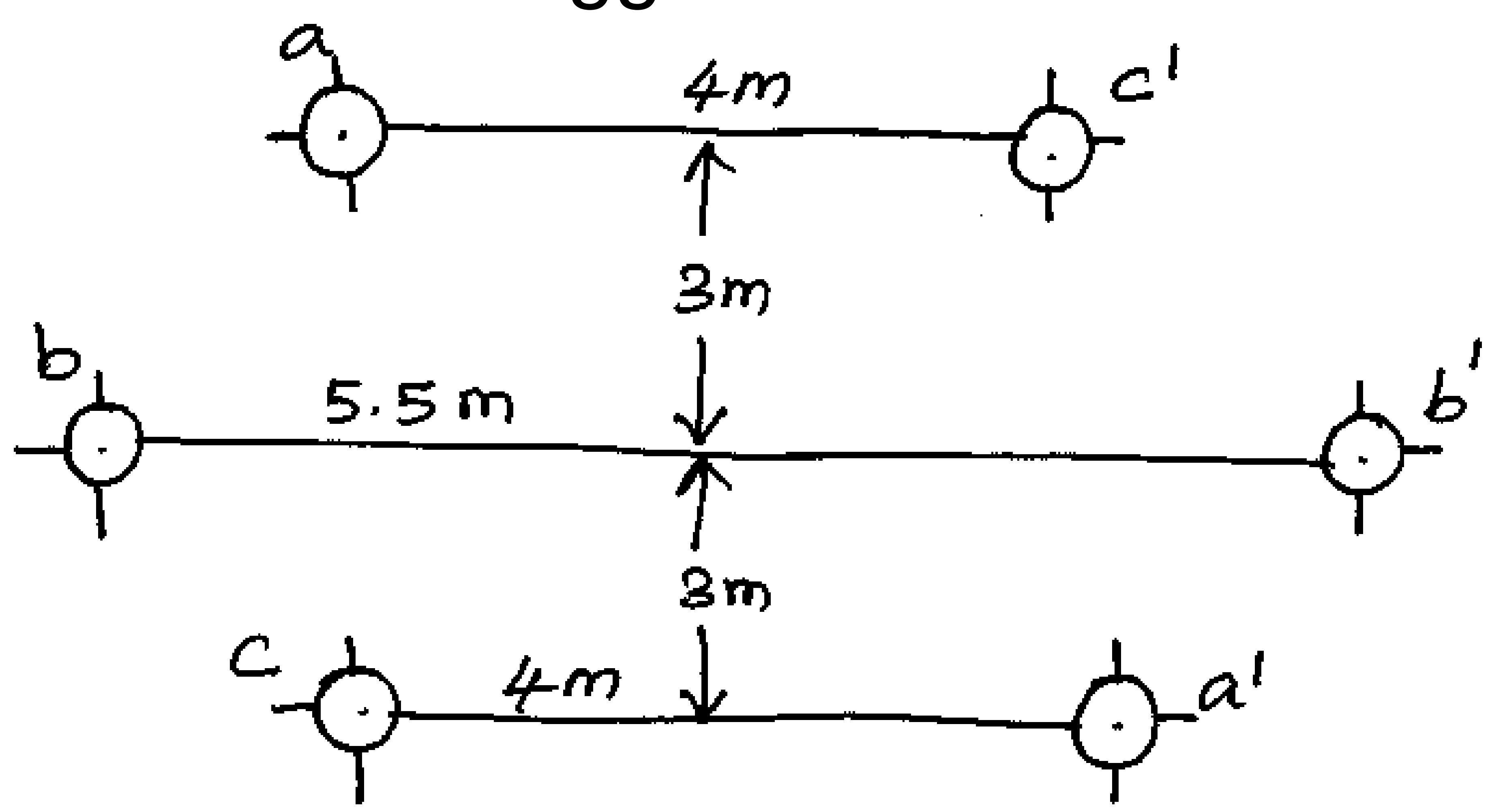
Inductance/phase/km $= 5.7 \times 10^{-7} \times 1000$

Inductance/km $= 0.57 \times 10^{-3} H$

$$\boxed{L = 0.57 mH}$$

·×————×·

Find the inductance per phase per km of double circuit 3 phase line shown in figure. The conductors are transposed and are of radius 0.75 cm each. The phase sequence is ABC.



GMR of Conductor $= 0.75 \times 0.7788 = 0.584$ cm

Distance a to b $= \sqrt{3^2 + (0.75)^2} = 3.1m$

Distance a to b' $= \sqrt{3^2 + (4.75)^2} = 5.62m$

Distance a to a' $= \sqrt{6^2 + 4^2} = 7.21m$

Self GMD

$$D_s = \sqrt[3]{D_{s1} \times D_{s2} \times D_{s3}}$$

Where

$$D_{s1} = \sqrt[4]{D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a}}$$

$$= \sqrt[4]{(0.584 \times 10^{-2}) \times (7.21) \times (0.584 \times 10^{-2}) \times (7.21)}$$

$$D_{s1} = 0.205m = D_{s3}$$

$$D_{s2} = \sqrt[4]{D_{bb} \times D_{bb'} \times D_{b'b'} \times D_{b'b}}$$

$$= \sqrt[4]{(0.584 \times 10^{-2}) \times (5.5) \times (0.584 \times 10^{-2}) \times 5.5}$$

$$D_{s2} = 0.18m$$

$$D_s = \sqrt[3]{0.205 \times 0.18 \times 0.205}$$

$$D_s = 0.195m$$

Mutual GMD

$$D_M = \sqrt[3]{D_{AB} \times D_{BC} \times D_{CA}}$$

$$D_M = \sqrt[3]{D_{AB} \times D_{BC} \times D_{CA}}$$

$$D_{AB} = \sqrt[4]{D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'}}$$

$$= \sqrt[4]{3.1 \times 5.62 \times 5.62 \times 3.1}$$

$$D_{AB} = 4.17m = D_{BC}$$

$$D_{CA} = \sqrt[4]{D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'}}$$

$$= \sqrt[4]{6 \times 4 \times 4 \times 6}$$

$$D_{CA} = 4.9m$$

$$D_M = \sqrt[3]{4.17 \times 4.17 \times 4.9}$$

$$D_M = 4.4m$$

$$\text{Inductance/phase/m} = 2 \times 10^{-7} \ln\left(\frac{D_M}{D_S}\right)$$

$$= 2 \times 10^{-7} \ln\left(\frac{4.4}{0.195}\right)$$

$$= 6.23 \times 10^{-7} H$$

$$= 0.623 \times 10^{-3} mH$$

$$\text{Inductance/phase/km} = 0.623 \times 10^{-3} \times 1000$$

$$L/km = 0.623 \, mH$$

x———————x

Typical Configurations, Conductor types and electrical Parameters of EHV lines:

Voltage	Name of Conductor	Strand/size of a strand	Diameter	Area of Cross section (mm^2)
		ACSR Conductor		
230kV	Kundah	42/3.5mm + 7/1.94mm (Aluminium) (Steel)	26.797	423.57
230kV	Zebra	54/3.18mm + 7/3.18mm (Aluminium) (Steel)	28.62	482.8

Voltage	Name of Conductor	Strand/size of a strand	Resistance Ω/km	Reactance Ω/km	Area of Cross section (mm^2)
110KV	Leopard	6/5.28mm + 7/1.76mm	0.236	0.446	80
	Tiger	30/2.36mm + 7/0.093mm	0.24	0.412	80
	Wolf	30/2.59mm + 7/0.102mm	0.199	0.408	95
	Lyna	30/2.79mm + 7/0.11mm	0.172	0.401	110
	Panther	30/3.0mm + 7/3.0mm	0.149	0.397	130
66KV	Racoon	6/4.09mm + 1/4.09mm	0.395	0.435	48
33KV	Copher	6/2.36mm + 1/2.36mm	1.185	0.413	16
	Weasel	6/2.59mm + 1/2.59mm	0.985	0.4085	20
	Ferret	6/3.0mm + 1/3.0mm	0.734	0.403	25
	Mink	6/3.66mm + 1/3.66mm	0.493	0.398	40
22KV	Squirrel	6/2.11mm + 1/2.1mm	1.486	0.4	13
11KV	Copher	6/2.36mm + 1/2.36mm	1.185	0.395	16
	Weasel	6/2.59mm + 1/2.59mm	0.985	0.392	20
	Ferret	6/3.0mm + 1/3.0mm	0.734	0.386	25
	Rabbit	6/3.35mm + 1/3.5mm	0.587	0.383	30

Dr. M. Ettappan

UNIT-II Modelling and Performance of Transmission Line:

Classification of overhead Transmission Line:

The transmission lines are classified into three types. They are

1. Short transmission line
2. Medium transmission line
3. Long transmission line

Short transmission line:

When the length of an overhead transmission line is upto about 50 km and the line voltage is less than 20 kV, then it is called 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.

* length upto 50 km
* Line Voltage < 20 kV

Medium transmission lines:

When the length of an overhead transmission line is about 50 km to 150km and the line voltage is moderatly high (>20kV <100kV), it is considered as a medium transmission line. Due to the sufficient length and voltage of the line, the capacitance effects are taken into account.

* Length is 50 to 150km
* Line voltage is between 20kv to 100kv

Long transmission line:

When the length of an overhead transmission line is more than 150km and the line voltage is above 100kv, it is considered as a long transmission line.

* Length is more than 150km
* Line voltage is above 100kv

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 (V_R) of the line is generally less than the sending end voltage (V_s). This voltage drop ($V_s - V_R$) in the line is expressed as a percentage of receiving end voltage V_R and is called voltage regulation.

The difference in voltage at the receivi 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.

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

Transmission Efficiency:

The Power obtained at the receivi end of a transmission line is generally less than the sending end Power due to losses in the line resistance.

The ration of receiving end Power to the sending end Power of a transmission line is known as the transmission efficiency of the line.

$$\%\text{age Transmission efficiency} = \frac{\text{Receiving end Powe}}{\text{Sending end Pow}} \times 1\text{C}$$

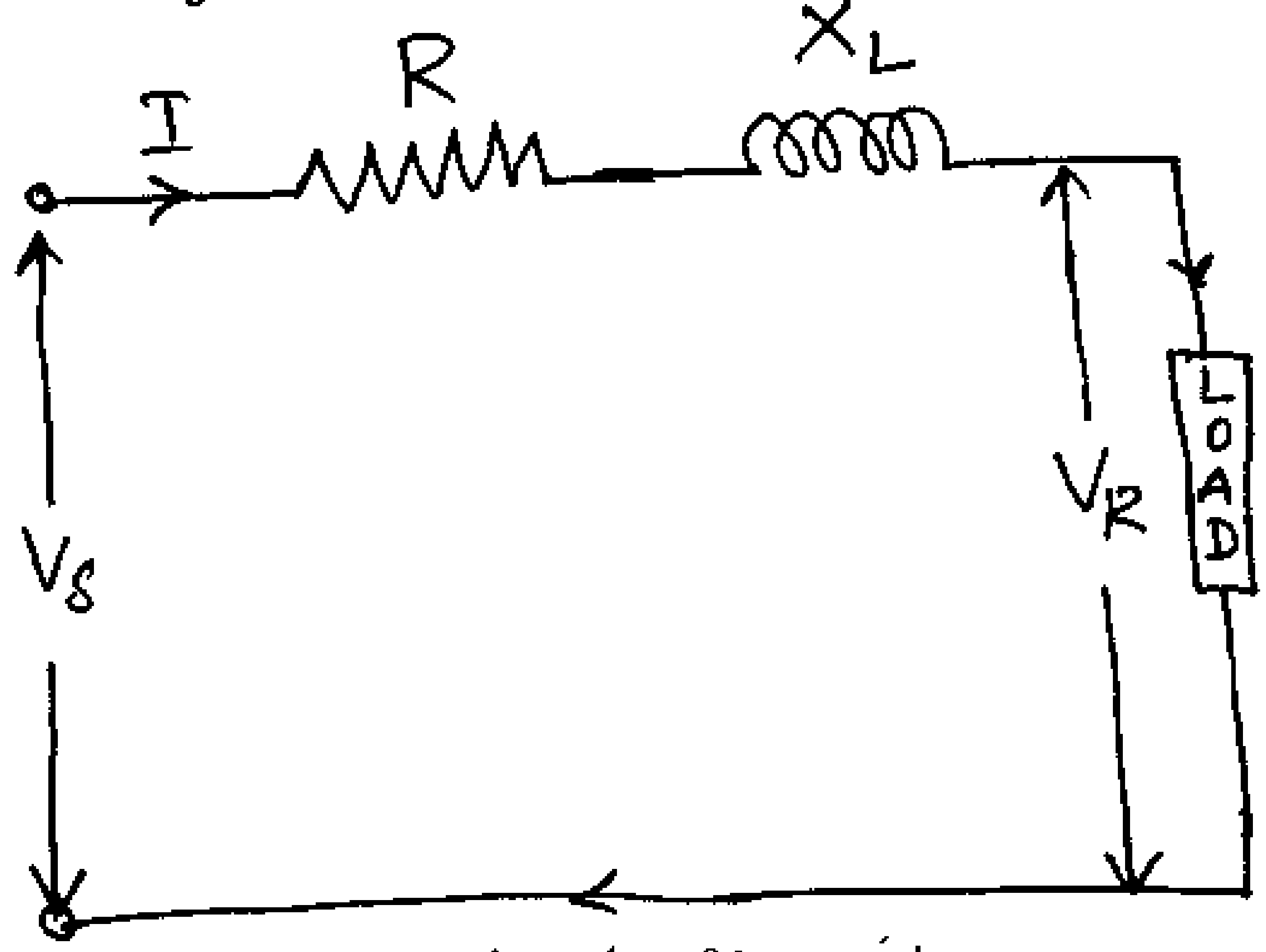
$$= \frac{V_R I_R \cos\phi_R}{V_s I_s \cos\phi_s} \times 100$$

-x———————x-

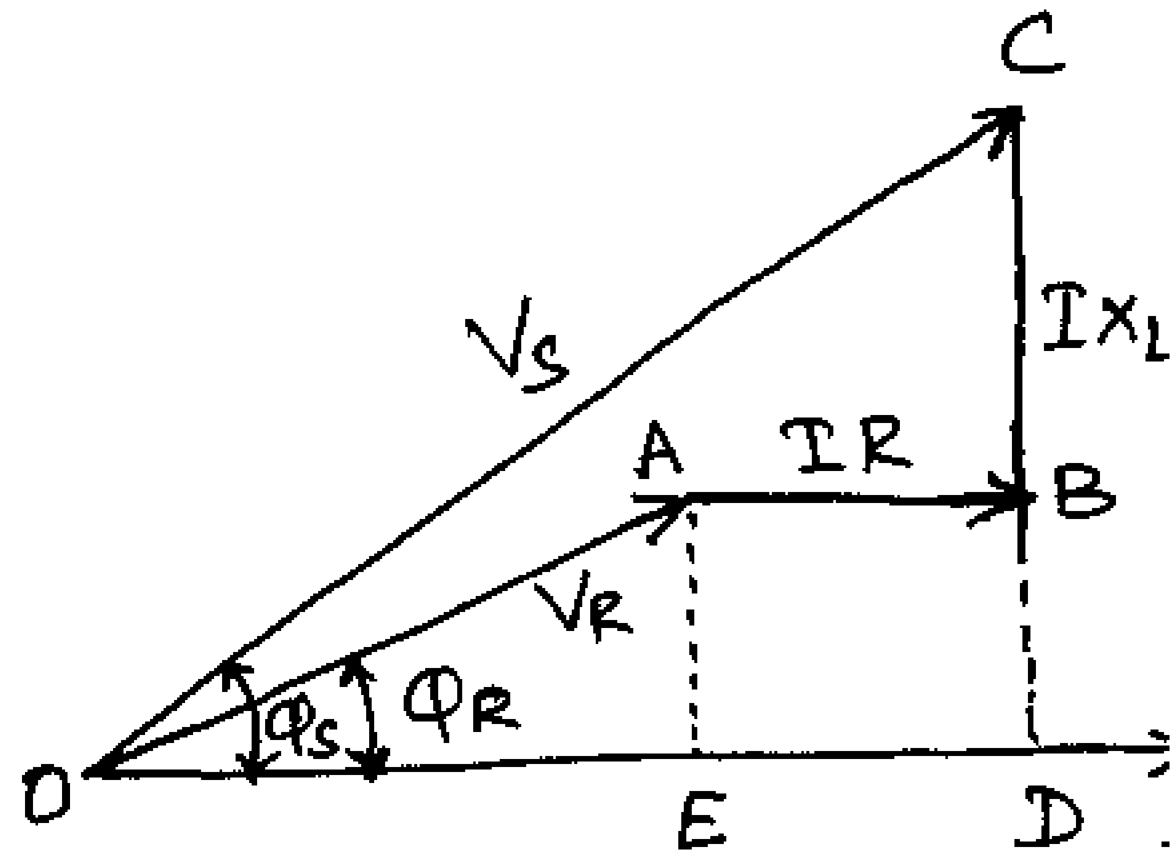
Performance of single phase short transmission Line:

The effects of line Capacitance are neglected for a short transmission line. Therefore while Studying the Performance of a 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 figure. Here the total line resistance and inductance are shown as Concentrated or lumped instead of being distributed.



Equivalent circuit



Phasor diagram

- I – load Current
- R – loop resistance
- X_L – loop reactance
- V_R – Receiving end Voltage
- $\cos\varphi_R$ – Receiving end Power factor
- V_s – Sending end Voltage
- $\cos\varphi_s$ – Sending end Power factor

Phasor diagram:

Current I is taken as the reference phasor. OA represents the receiving end voltage V_R leading I by φ_R. AB represents the drop IR in phase with I. BC represents the inductive drop IX_L and leads I by 90°. OC represents the sending end voltage V_S and leads I by φ_S.

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

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

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

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

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

$$\text{Sending end P.f } \cos\varphi_S = \frac{OD}{OC} = \frac{V_R \cos\varphi_R + IR}{V_S}$$

$$\text{Power delivered} = V_R I_R \cos\varphi_R$$

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

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

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

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

Solution in Complex notation:

It is often Convenient and Profitable to make the line calculations in Complex notation.

Taking $\vec{V_R}$ as the reference phasor, draw the phasor diagram as shown in figure. It is Clear that $\vec{V_S}$ is the phasor sum of $\vec{V_R}$ and $\vec{I}\vec{Z}$.

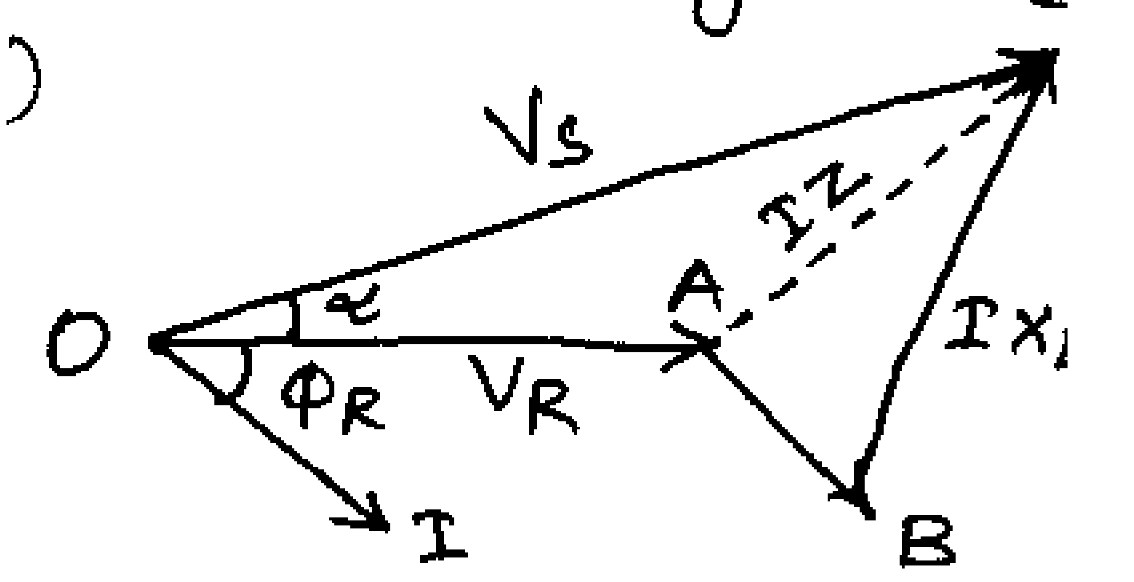
$\vec{V_R} = V_R + j0$

$\vec{I} = \vec{I}\angle -\varphi_R = I(\cos\varphi_R - j\sin\varphi_R)$

$\vec{Z} = R + jX_L$

$\vec{V_S} = \vec{V_R} + \vec{I}\vec{Z}$

Phasor Diagram



$$= (V_R + j0) + I(\cos\varphi_R - j\sin\varphi_R)(R + jX_L)$$

$$= (V_R + IR\cos\varphi_R + IX_L\sin\varphi_R) + j(IX_L\cos\varphi_R - IR\sin\varphi_R)$$

$$V_S = \sqrt{(V_R + IR\cos\varphi_R + IX_L\sin\varphi_R)^2 + (IX_L\cos\varphi_R - IR\sin\varphi_R)^2}$$

The second term under the root is quite small and can be neglected with reasonable accuracy. Therefore, approximate expression for V_s becomes

$$V_S = V_R + IR\cos\varphi_R + IX_L\sin\varphi_R$$

A single phase overhead transmission line delivers 1100kW at 33kV at 0.8 p.f lagging. The total resistance and inductive reactance of the line are 10Ω and 15Ω respectively. Determine (i) sending end voltage (ii) sending end Power factor (iii) Transmission efficiency

Given data:

$P = 1100\,kW$ $\quad R = 10\,\Omega$

$V_R = 33\,kV$ $\quad X_L = 15\,\Omega$

$p.f = 0.8$ lag

Find!

(i) V_s (ii) $\cos\phi_s$ (iii) Tr. η

Solution:

Load Power factor, $\cos\phi_R = 0.8$ lag

Total line impedance $\vec{Z} = R + jX_L = 10 + j15$

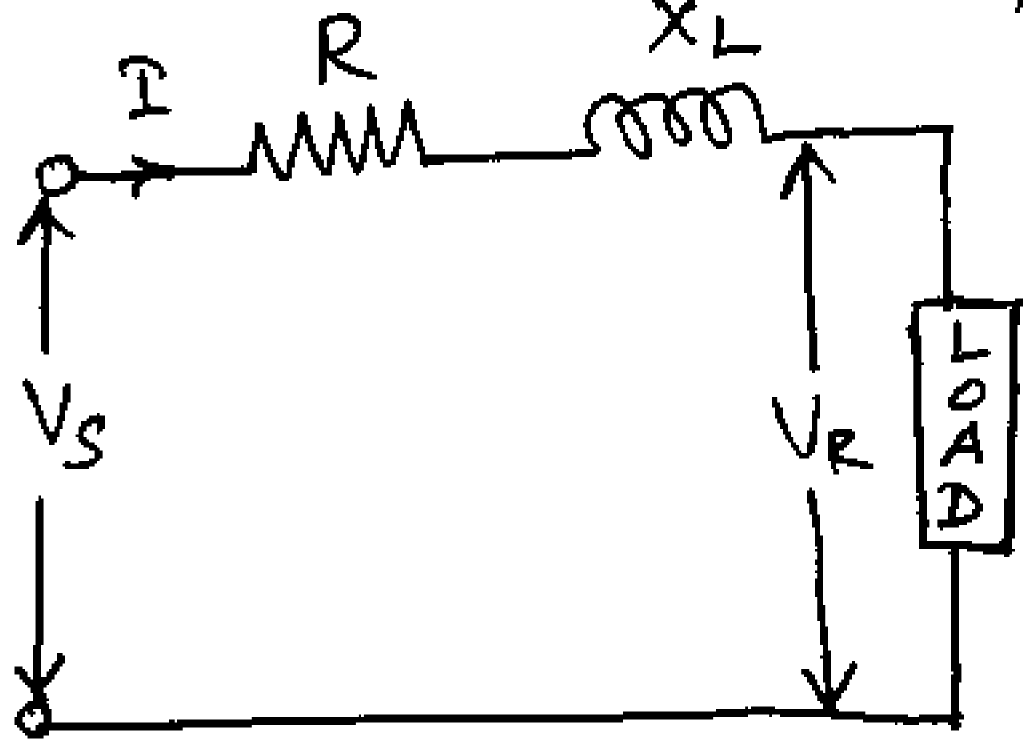
Receiving end voltage, $V_R = 33\text{kV} = 33{,}000\text{V}$

Line current, $I = \dfrac{\text{KW} \times 10^3}{V_R \cos\phi_R} = \dfrac{1100 \times 10^3}{33{,}000 \times 0.8}$

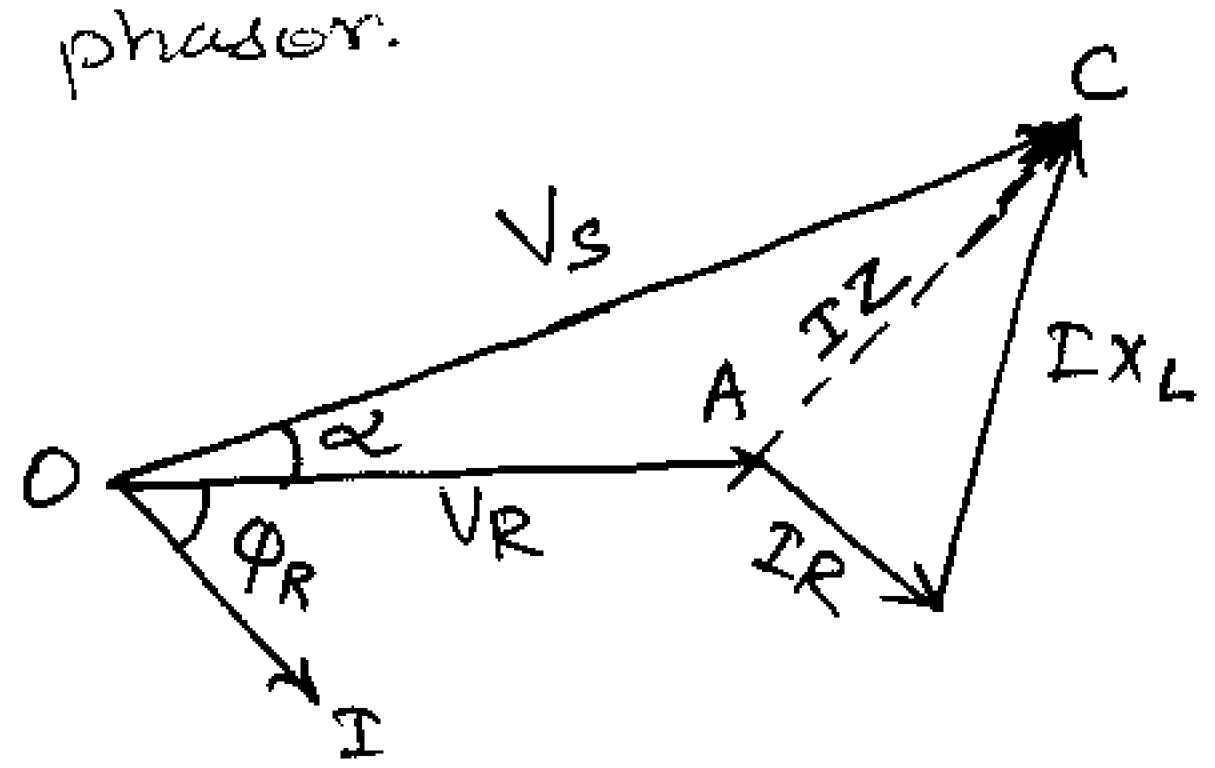
$$I = 41.67\text{ A}$$

$\cos\phi_R = 0.8$, $\phi_R = \cos^{-1}(0.8)$, $\phi_R = 36.66°$

$\sin\phi_R = 0.6$, Taking receiving end voltage $\vec{V_R}$ as the reference phasor.



Equivalent circuit



Phasor diagram

$\vec{V_R} = V_R + j0 = 33000\text{V}$

$\vec{I} = I(\cos\phi_R - j\sin\phi_R)$

$= 41.67(0.8 - j0.6) = 33.33 - j25$

Sending end voltage $\vec{V_s} = \vec{V_R} + \vec{I}\vec{Z}$

$= 33000 + (33.33 - j25.0)(10 + j15)$

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

$\vec{V_s} = 33{,}708 + j250$

Magnitude of $V_s = \sqrt{(33708.3)^2 + (250)^2}$

$$V_s = 33709\,V$$

Angle between $\vec{V_s}$ and $\vec{V_R}$ is

$$\alpha = \tan^{-1}\left(\frac{250}{33708.3}\right) = \tan^{-1}(0.0074)$$

$$\alpha = 0.42^\circ$$

Sending end Power factor angle is

$$\phi_s = \phi_R + \alpha = 36.87^\circ + 0.42^\circ = 37.29^\circ$$

Sending end P.f $\cos\phi_s = \cos 37.29 = 0.7956$ lag

Line losses $= I^2R = (41.67)^2 \times 10 = 17,364\,W$

$= 17.364\,kW$

output delivered $= 1100\,kW$

Power sent $= 1100 + 17.364 = 1117.364\,kW$

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

$$= \frac{1100}{1117.364} \times 100$$

$$\eta = 98.44\%$$

V_s and ϕ_s can also be calculated as follows

$$V_s = V_R + IR\cos\phi_R + IX_L\sin\phi_R$$

$$= 33,000 + 41.67 \times 10 \times 0.8 + 41.67 \times 15 \times 0.6$$

$$= 33,000 + 333.36 + 375.03$$

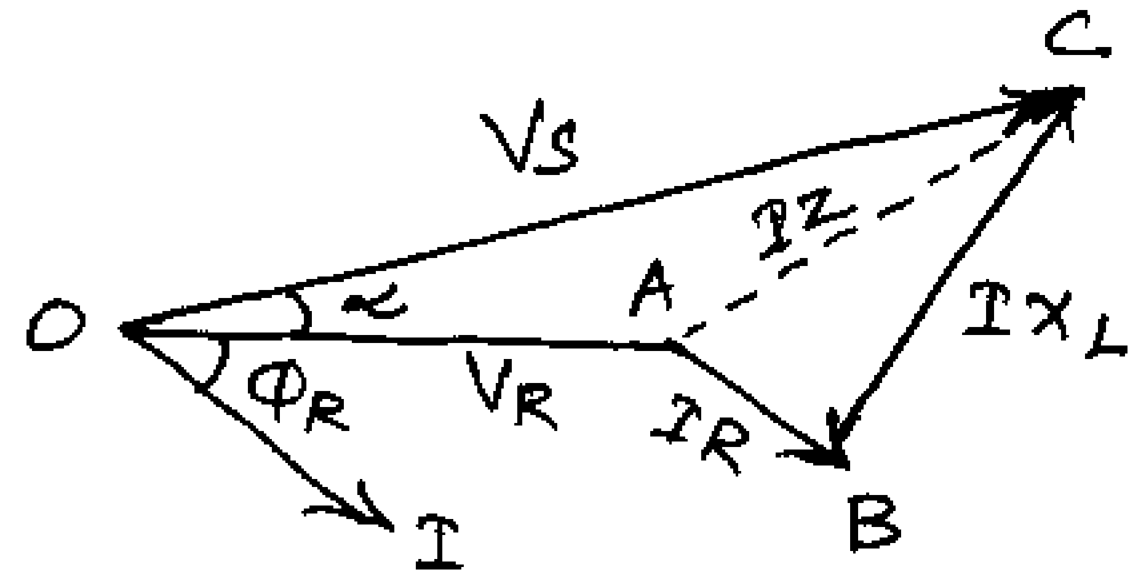
$$= 33708.39\,V$$

$$\cos\phi_s = \frac{V_R\cos\phi_R + IR}{V_s} = \frac{33000 \times 0.8 + 41.67 \times 10}{33708.39}$$

$$= \frac{26816.7}{33708.39} = 0.7958$$

An overhead 3 phase transmission line delivers 5000kw at 22kv at 0.8 p.f lagging. The resistance and reactance of each conductor is 4 Ω and 6 Ω respectively. Determine (i) Sending end voltage (ii) Percentage regulation (iii) Transmission Efficiency

Given data:



$P = 5000kw$ $R = 4 \Omega$

$V_R = 22kv$ $X_L = 6 \Omega$

$p.f = 0.8$ lag

Load Power factor, $\cos\phi_R = 0.8$ lagging

Receiving end Voltage/phase, $V_R = 22{,}000/\sqrt{3} = 12{,}700V$

Impedance/phase $\vec{Z} = 4 + j6$

Line current $I = \dfrac{5000 \times 10^3}{3 \times 12700 \times 0.8} = 164A$

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

Taking $\vec{V_R}$ as the reference phasor

$\vec{V_R} = V_R + j0 = 12700V$

$\vec{I} = I(\cos\phi_R - j\sin\phi_R) = 164(0.8 - j0.6) = 131.2 - j98.4$

(i) Sending end voltage per phase is

$$\vec{V_s} = \vec{V_R} + \vec{I}\vec{Z} = 12700 + (131.2 - j98.4)(4 + j6)$$

$$= 12700 + 524.8 + j787.2 - j393.6 + 590$$

$$\vec{V_s} = 13815.2 + j393.6$$

Magnitude of $V_s = \sqrt{(13815.2)^2 + (393.6)^2}$

$$\boxed{V_s = 13820.8V}$$

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

$= 23938V$

$$V_s = 23.938kV$$

(ii) % age Regulation $= \frac{V_S - V_R}{V_R} \times 100 = \frac{13820.8 - 12700}{12700} \times$

$$\% \text{ Regulation} = 8.825\%$$

Line losses $= 3I^2R = 3 \times (164)^2 \times 4 = 322752W$

$$\text{losses} = 322.752 \text{ kW}$$

Transmission efficiency $= \frac{5000}{5000 + 322.752} \times 100$

$$Tr.\ \eta = 93.94\%$$

·x————————x·

Medium Transmission Lines:

The Medium transmission line have sufficient length (50-150 km) and usually operate at voltages greater than 20kV, 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

(11)

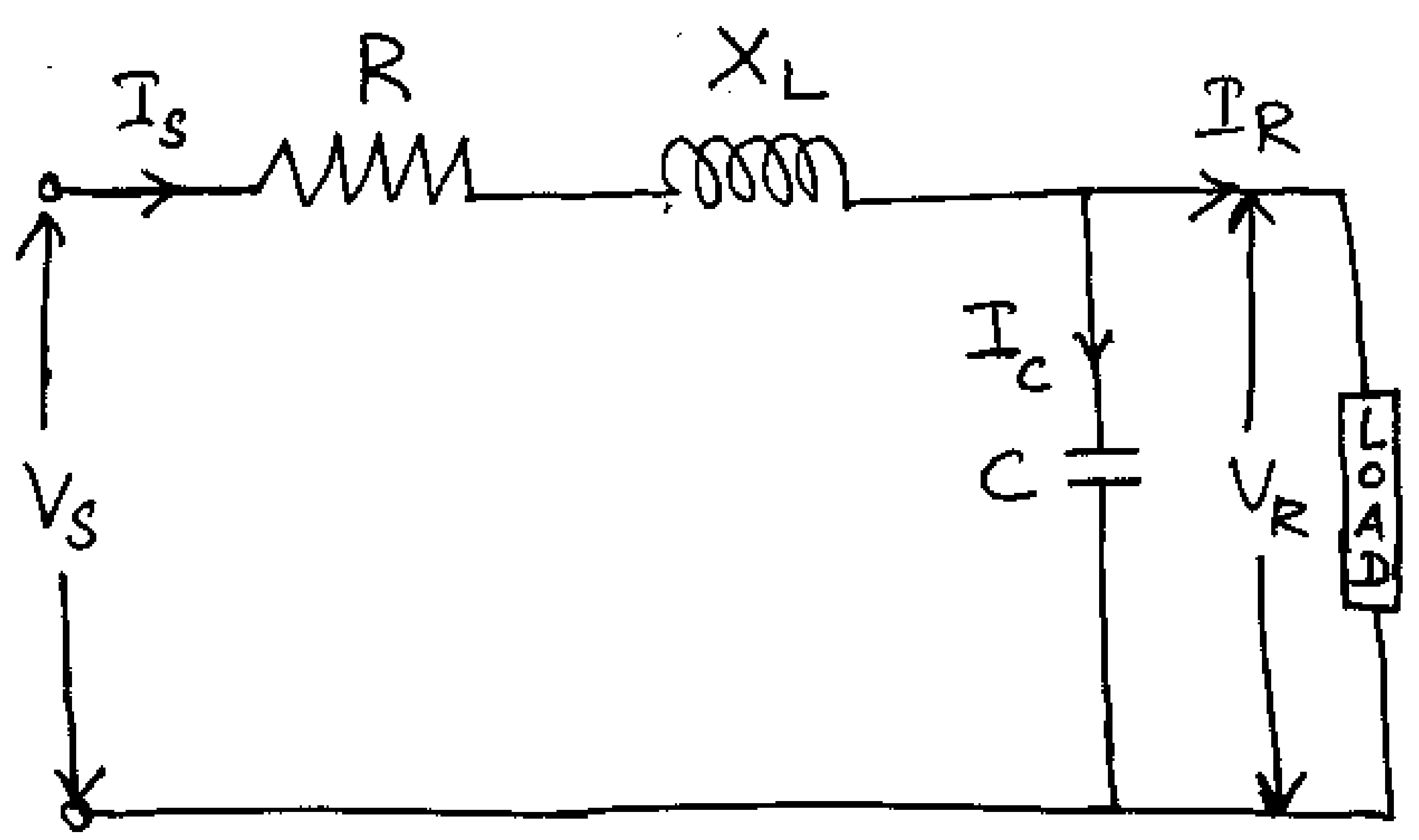
The most Commonly used methods for the Solution of medium transmission lines are (11)

(i) End Condenser method

(ii) Nominal T method

(iii) Nominal π method

End Condenser method:



In this method, the Capacitance of the line is lumped or Concentrated at the receiving or load end as shown in figure.

Let I_R = Load Current Per phase

R = Resistance per phase

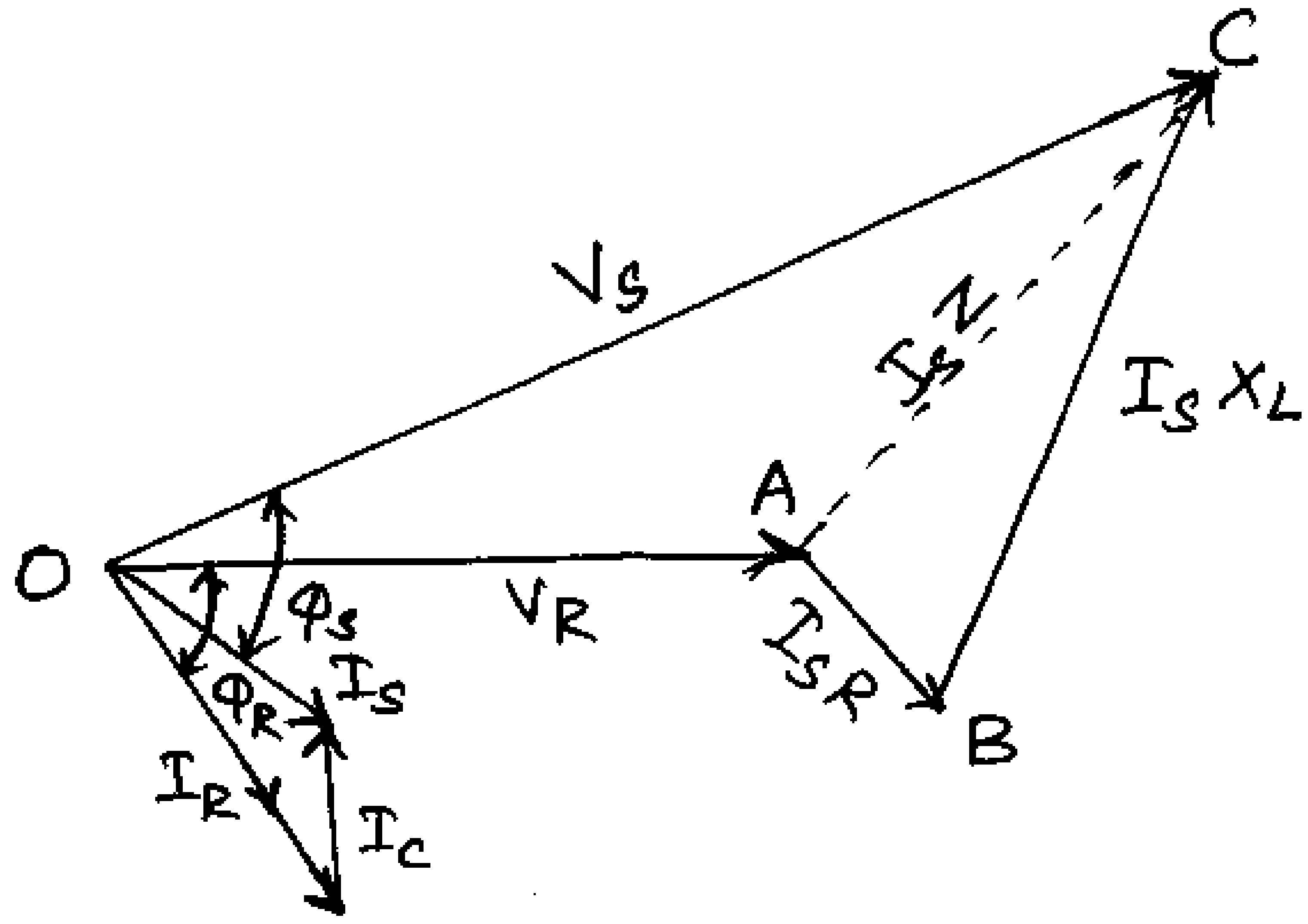
X_L = Inductive reactance Per phase

C = Capacitance per phase

$\cos\varphi_R$ = Receiving end Power factor

V_S = sending end Voltage

The phasor diagram for the circuit is shown in figure. Taking the receiving end voltage $\vec{V}_R$ as the reference phasor.



We have, $\vec{V}_R = V_R + j0$

Load current $\vec{I}_R = I_R(\cos\varphi_R - j\sin\varphi_R)$

Capacitive current $\vec{I}_C = j\vec{V}_R \omega C = j2\pi f C \vec{V}_R$

The sending end current $\vec{I}_S$ is the phasor sum of load current $\vec{I}_R$ and capacitive current $\vec{I}_C$ i.e.,

$$\vec{I}_S = \vec{I}_R + \vec{I}_C$$

$$= I_R(\cos\varphi_R - j\sin\varphi_R) + j2\pi f C V_R$$

$$= I_R\cos\varphi_R + j(-I_R\sin\varphi_R + 2\pi f C V_R)$$

$$= \vec{I}_S \vec{Z} = \vec{I}_S(R + jX_L)$$

Sending end voltage $\vec{V}_S = \vec{V}_R + \vec{I}_S\vec{Z}$

$$= \vec{V}_R + \vec{I}_S(R + jX_L)$$

Thus, the magnitude of sending end voltage V_S can b...

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

$$\%\ \text{Transmission Efficiency} = \frac{\text{Power delivered}}{\text{Power delivered} + \text{losses}} \times 100$$

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

x ———————— x

A medium single phase transmission line 100 km long has the following constants

Resistance/km = 0.25 Ω Reactance/km = 0.8 Ω

Susceptance/km = 14×10^{-6} siemen

Receiving end line voltage = 66,000 V

Assuming that the total capacitance of the line is localised at the receiving end alone, determine (i) the sending end current (ii) the sending end voltage (iii) regulation (iv) supply power factor

The line is delivering 15,000 kW at 0.8 power factor lagging. Draw the phasor diagram to illustrate your calculations.

Given Data:

$R = 0.25\ \Omega$ $X_L = 0.8\ \Omega$ $Y = 14 \times 10^{-6}$ siemen

$V_R = 66{,}000$ V $P = 15000$ kW, $\cos\phi_R = 0.8$ lag

Find: (i) I_S (ii) V_S (iii) Regulation (iv) $\cos\phi_S$

Total resistance $R = 0.25 \times 100 = 25\Omega$

Total reactance $X_L = 0.8 \times 100 = 80\Omega$

Total susceptance $Y = 14 \times 10^{-6} \times 100 = 14 \times 10^{-4}\,S$

Receiving end voltage $V_R = 66,000V$

Load Current $I_R = \dfrac{15000 \times 10^3}{66000 \times 0.8}$

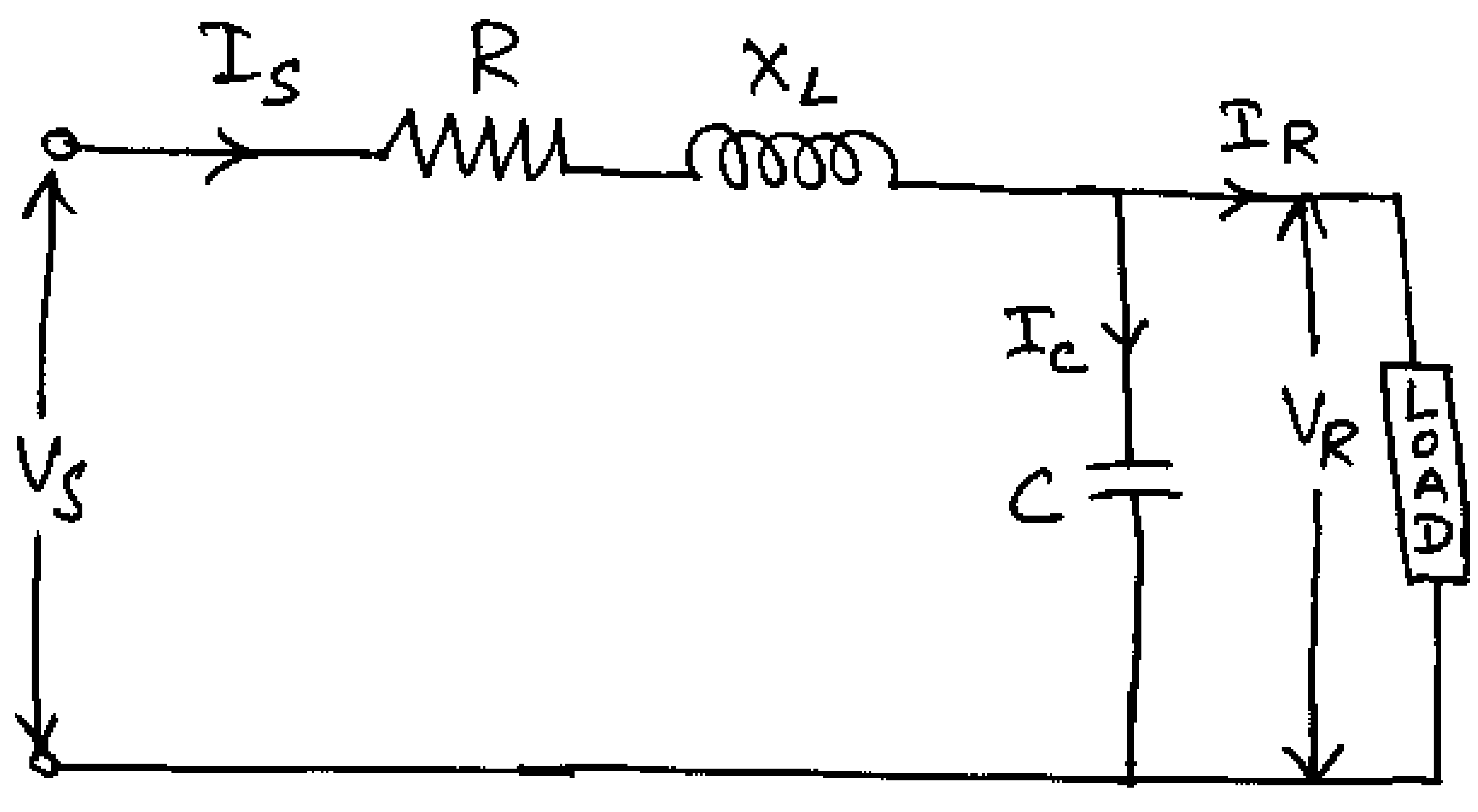
$$I_R = 284A$$

$\cos\varphi_R = 0.8 \quad \sin\varphi_R = 0.6$

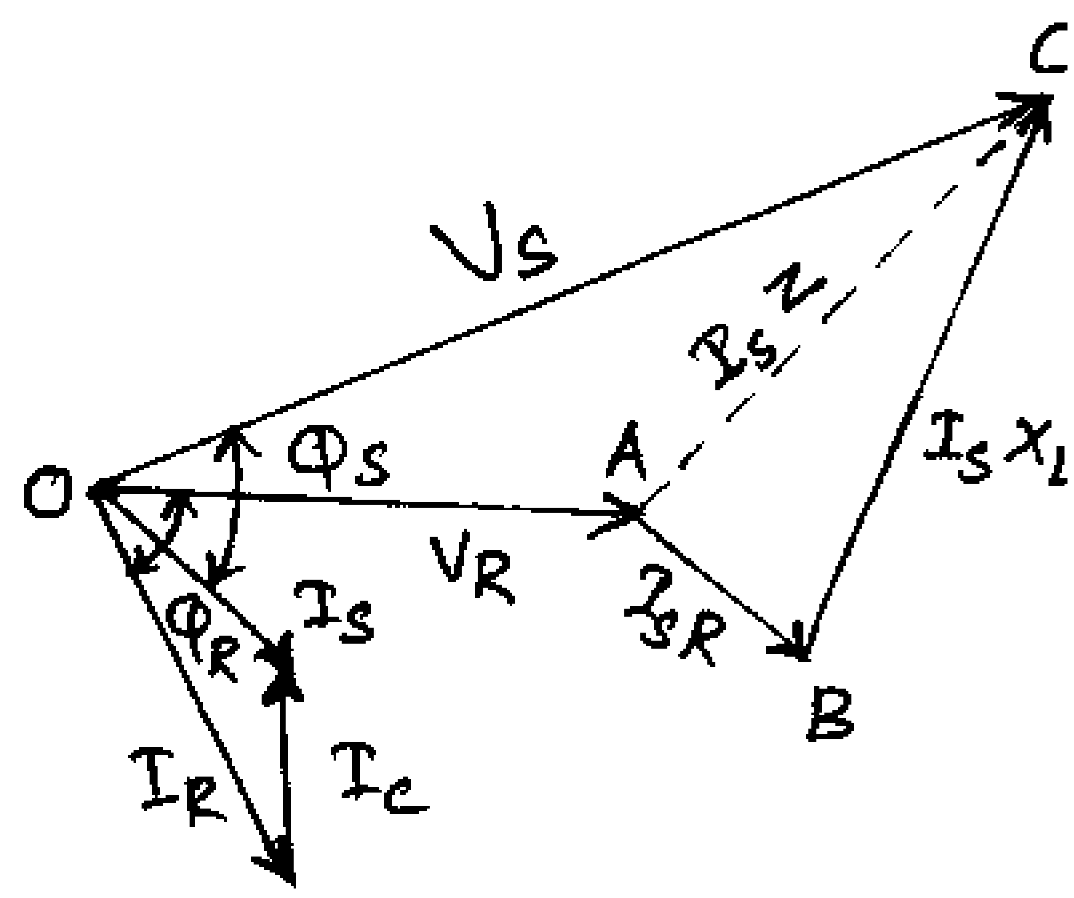
$\vec{V_R} = V_R + j0 = 66000V$

$\vec{I_R} = I_R(\cos\varphi_R - j\sin\varphi_R)$

$= 284(0.8 - j0.6) = 227 - j170$



Circuit diagram



Phasor diagram

Capacitive current $\vec{I_C} = jY \times V_R = j14 \times 10^{-14} \times 66000$

$= j92$

(i) Sending end Current $\vec{I_S} = \vec{I_R} + \vec{I_C}$

$\vec{I}_s = 227 - j170 + j92$

$= 227 - j78$

Magnitude of $I_s = \sqrt{(227)^2 + (78)^2} = 240\,A$

$$I_s = 240\,A$$

Voltage drop $= \vec{I}_s \vec{Z} = \vec{I}_s (R + jX_L)$

$= (227 - j78)(25 + j80)$

$= 5675 + j18160 - j1950 + 6240$

$= 11915 + j16210$

(ii) Sending end voltage

$\vec{V}_s = \vec{V}_R + \vec{I}_s \vec{Z} = 66{,}000 + 11915 + j16210$

$= 77915 + j16210$

Magnitude of $V_s = \sqrt{(77915)^2 + (16210)^2}$

$$V_s = 79583\,V$$

(iii) % Voltage regulation $= \dfrac{V_s - V_R}{V_R} \times 100$

$= \dfrac{79{,}583 - 66000}{66{,}000} \times 100$

Voltage regulation = 20.58 %

(iv) phase angle between $\vec{V_R}$ and $\vec{I_s}$ is

$$\theta_1 = \tan^{-1}\left(\frac{-78}{227}\right) = \tan^{-1}(-0.3436)$$

$$\boxed{\theta_1 = -18.96^\circ}$$

phase angle between $\vec{V_R}$ and $\vec{V_s}$ is

$$\theta_2 = \tan^{-1}\frac{16210}{77915} = \tan^{-1}(0.2036) = 11.50^\circ$$

Supply Power factor angle, $\varphi_s = 18.96^\circ + 11.50^\circ$

$$\boxed{\varphi_s = 30.46^\circ}$$

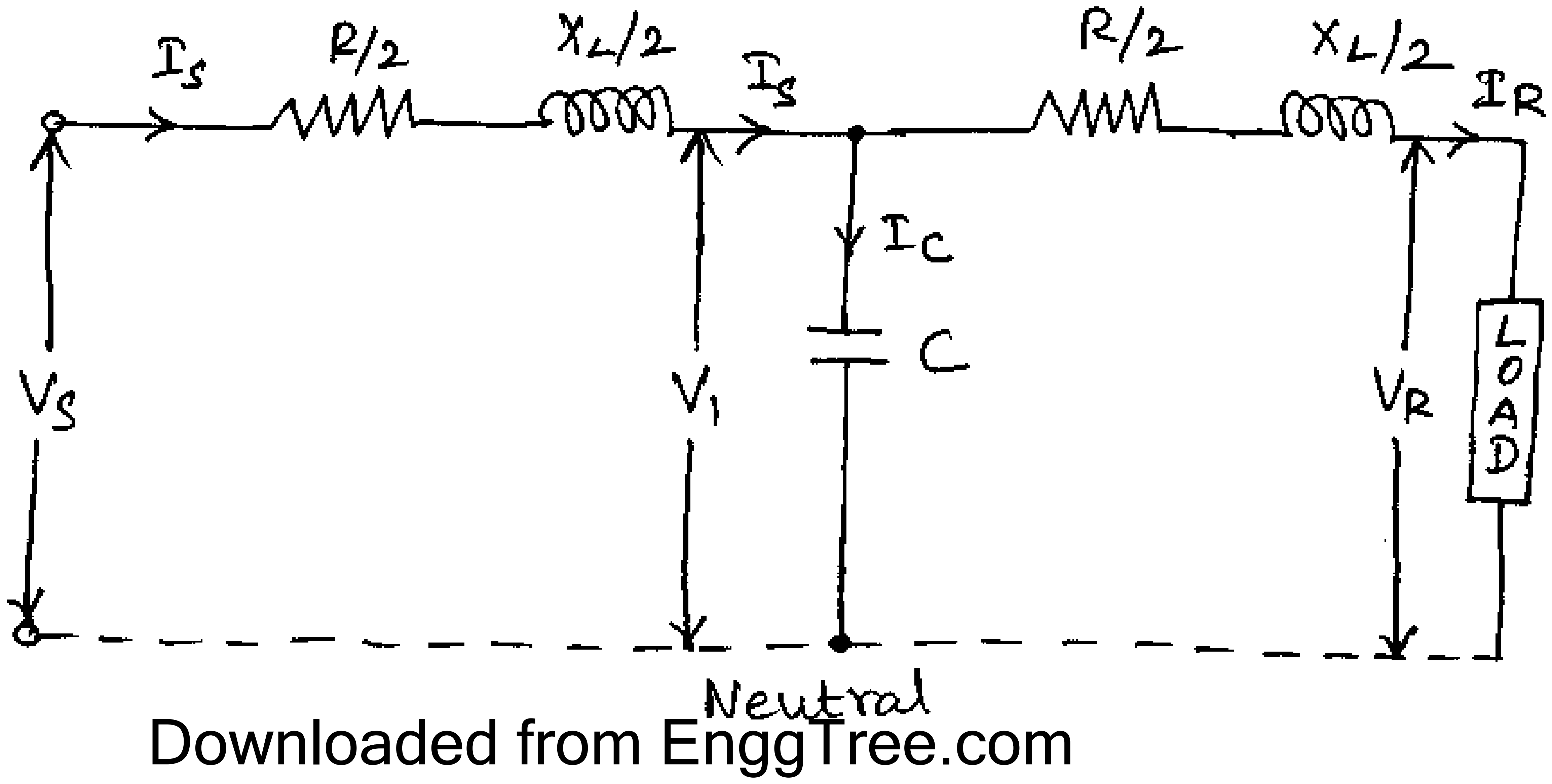
Supply Power factor $= \cos\varphi_s = \cos(30.46^\circ)$

$$\boxed{\cos\varphi_s = 0.86 \text{ lag}}$$

·×——————×·

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 figure. Therefore in this arrangement full charging current flows over half the line.



I_R = load current per phase R = Resistance/phase

X_L = Inductive reactance per phase

C = Capacitance per phase

V_S = Sending end voltage/phase

V_1 = Voltage across Capacitor C

$\cos\phi_R$ = Receiving end Power factor (lag)

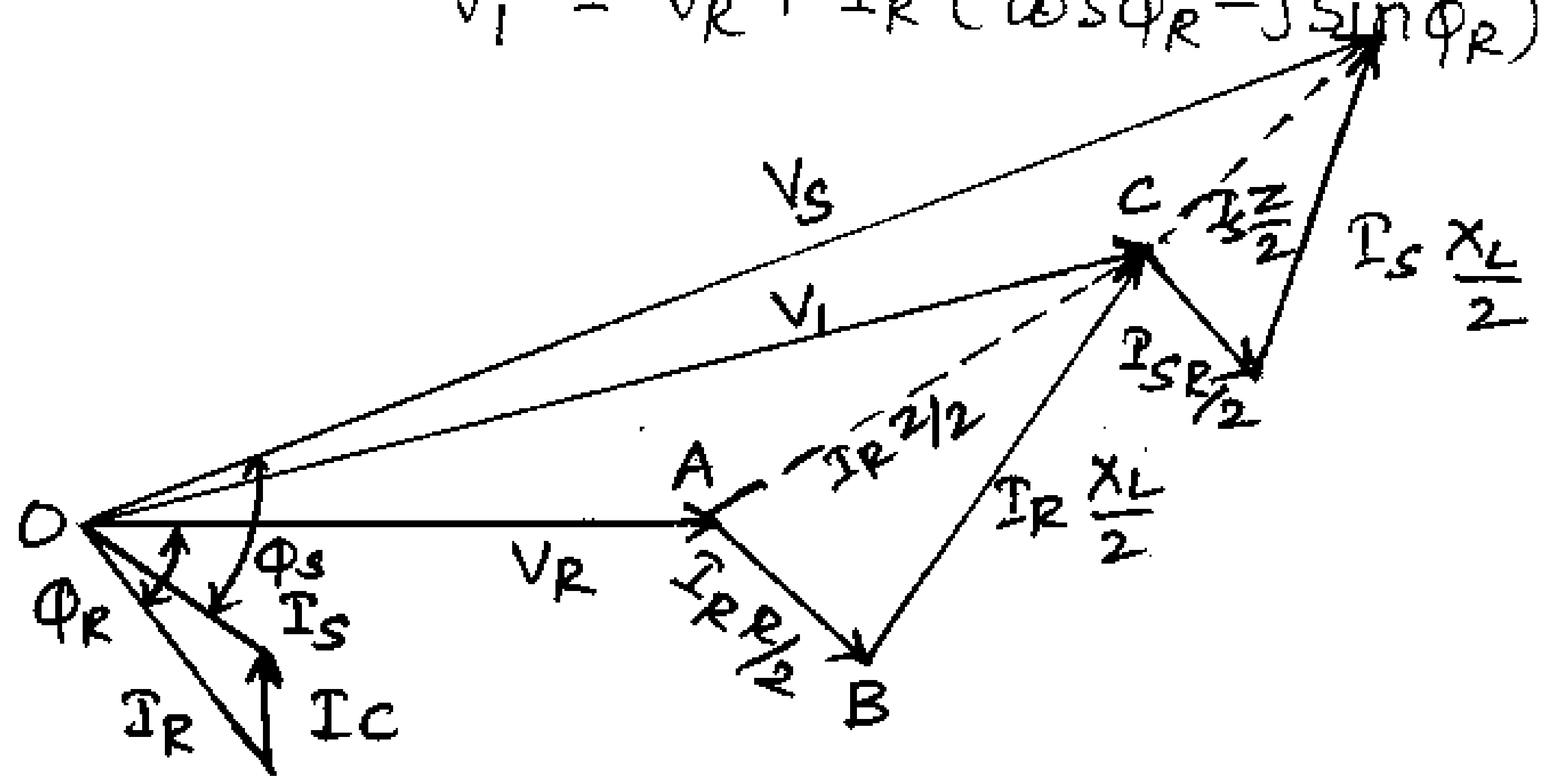
The phasor diagram for the circuit is shown in figure. Taking the receiving end voltage $\vec{V_R}$ as the reference phasor, we have

Receiving end voltage $\vec{V_R} = V_R + j0$

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

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

$$\vec{V_1} = V_R + I_R(\cos\phi_R - j\sin\phi_R)\left(\frac{R}{2} + j\frac{X_L}{2}\right)$$



Capacitive current $\vec{I_c} = j\omega C\vec{V_1} = j2\pi f C\vec{V_1}$

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

Sending end voltage $\vec{V_S} = \vec{V_1} + \vec{I_S}\frac{\vec{Z}}{2}$

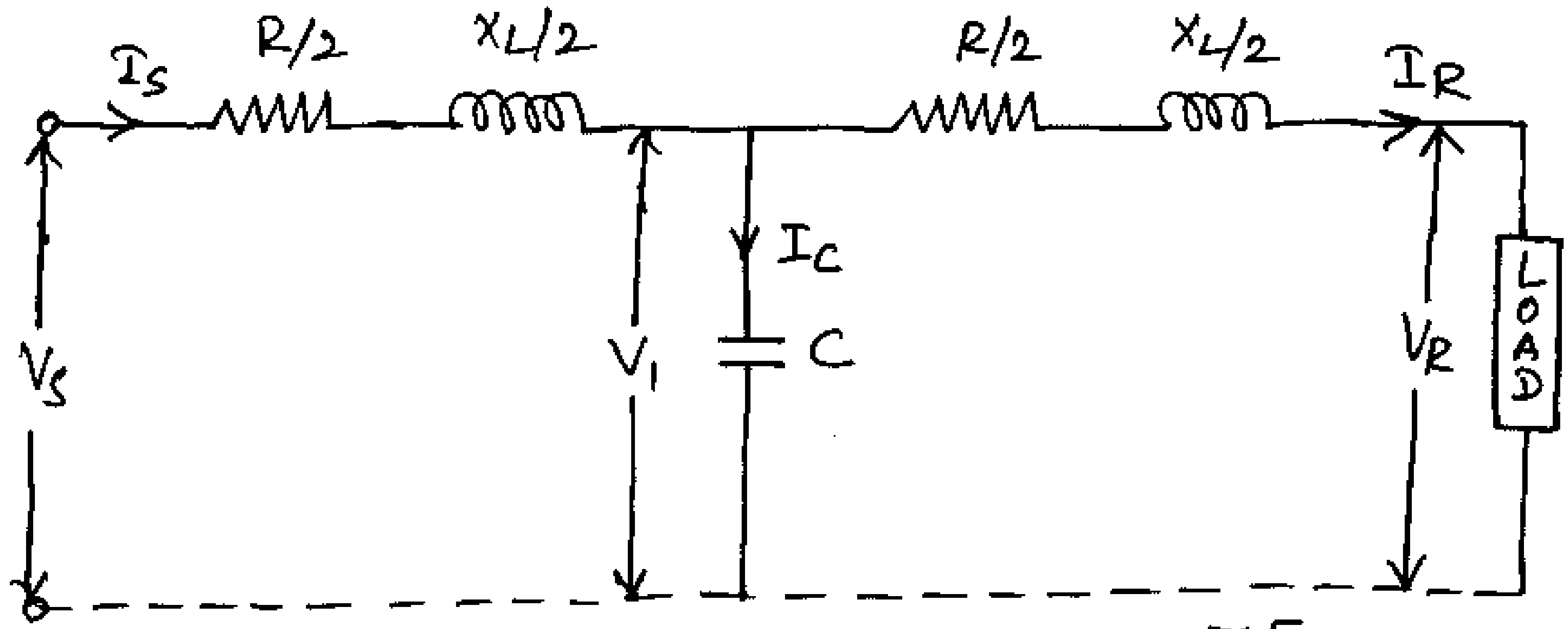
$$\vec{V_S} = \vec{V_1} + \vec{I_S}\left(\frac{R}{2} + j\frac{X_L}{2}\right)$$

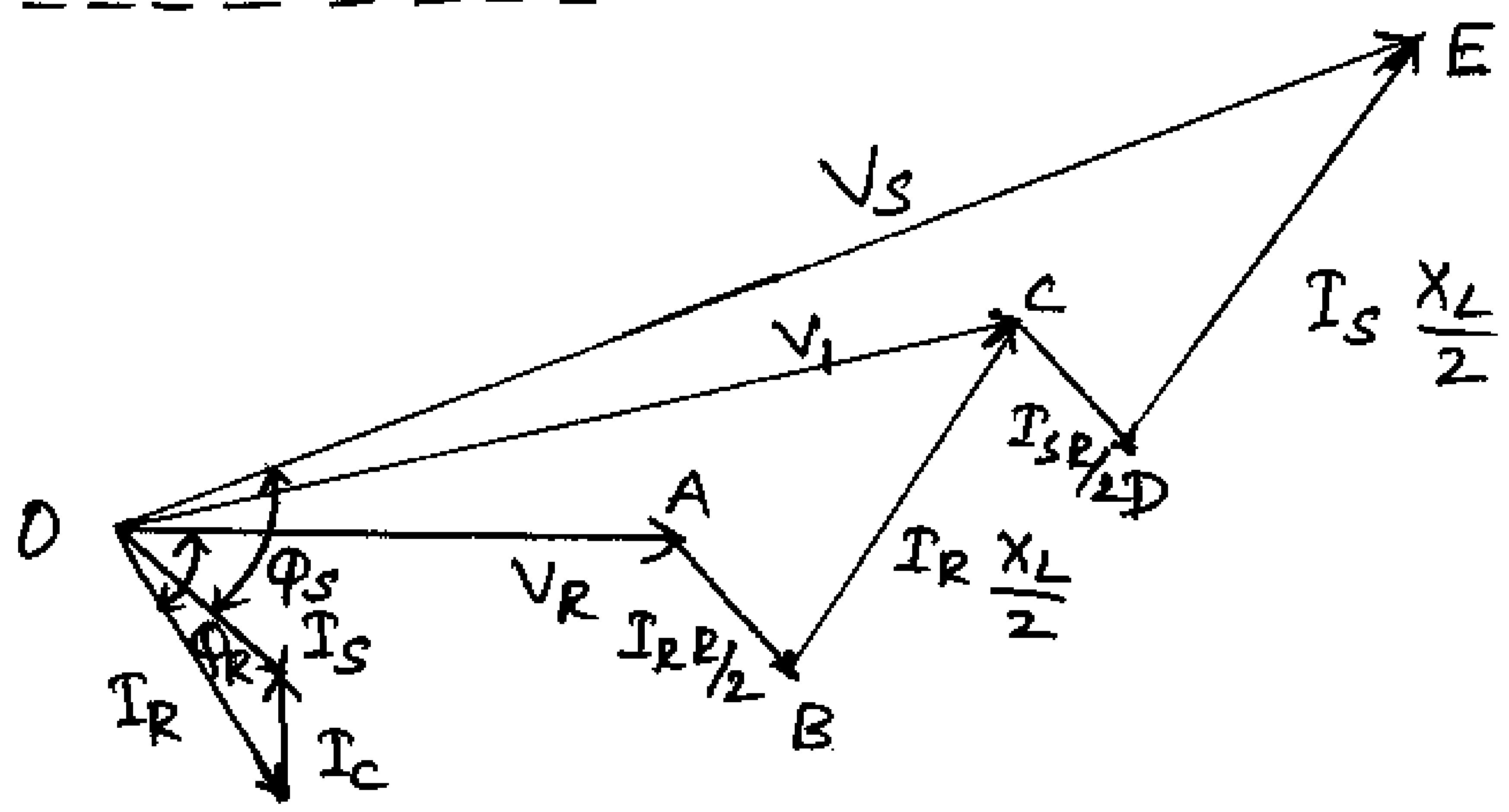
-x————————x-

A 3 phase 50Hz overhead transmission line 100km long has the following constants (18)

Resistance/km/phase = 0.1 Ω , Inductive reactance/km/phase = 0..
Capacitive susceptance/km/phase = 0.04×10^{-4} siemen

Determine (i) the sending end current (ii) sending end Voltage (iii) Sending end Power factor and (iv) transmission efficiency when supplying a balanced load of 10,000kw at 66kV, p.f. 0.8 lagging. Use nominal T method.





Total resistance/phase, $R = 0.1 \times 100 = 10\,\Omega$

Total reactance/phase, $X_L = 0.2 \times 100 = 20\,\Omega$

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

Receiving end voltage $V_R = 66000/\sqrt{3} = 38105\,V$

Load current, $I_R = \dfrac{10000 \times 10^3}{\sqrt{3}3 \times 66 \times 10^3 \times 0.8}$

$I_R = 109\,A$

$\cos\varphi_R = 0.8$; $\sin\varphi_R = 0.6$

Impedance Per phase $\vec{Z} = R + jX_L = 10 + j20$

Receiving end voltage $\vec{V_R} = V_R + j0 = 38,105\,V$

Load current, $\vec{I_R} = I_R(\cos\varphi_R - j\sin\varphi_R) = 109(0.8 - j0.6)$

$= 87.2 - j65.4$

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

$= 38,105 + (87.2 - j65.4)(5 + j10)$

$= 38,105 + 436 + j872 - j327 + 654$

$= 39,195 + j545$

Charging current $\vec{I_c} = jY\vec{V_1} = j4\times10^{-4}(39195 + j545)$

$= -0.218 + j15.6$

Sending end current $\vec{I_s} = \vec{I_R} + \vec{I_c}$

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

$= 87.0 - j49.8$

$= 100\angle{-29^\circ 47'}\,A$

$$\boxed{I_s = 100A}$$

Sending end voltage, $\vec{V_s} = \vec{V_1} + \vec{I_s}\,\vec{Z}/2$

$\vec{V_s} = (39,195 + j545) + (87.0 - j49.8)(5 + j10)$

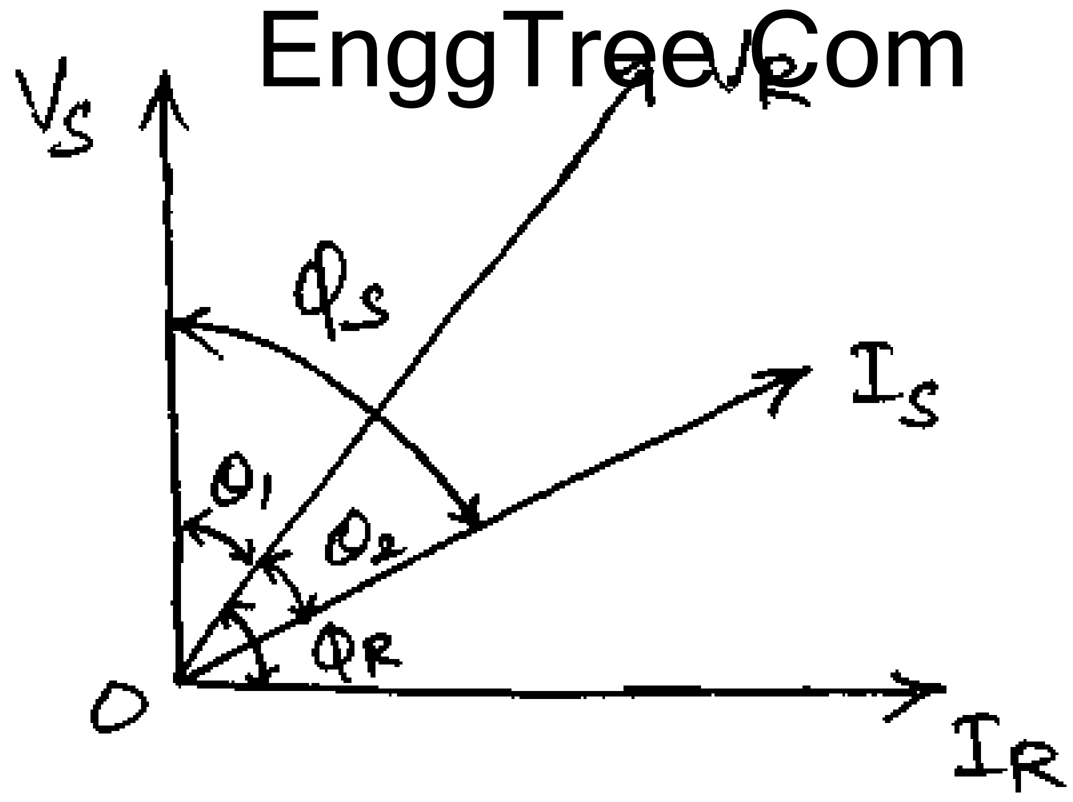
$= 39,195 + j545 + 434.9 + j870 - j249 + 498$

$= 40128 + j1170 = 40145\angle{1^\circ 40'}\,V$

Line value of Sending end voltage

$= 40145 \times \sqrt{3} = 69533$

$$\boxed{V_s = 69.533\,kV}$$



Referring to phasor diagram

θ_1 = angle between $\vec{V_R}$ and $\vec{V_S}$ = $1^\circ 40'$

θ_2 = angle between $\vec{V_R}$ and $\vec{I_S}$ = $29^\circ 47'$

ϕ_S = angle between $\vec{V_S}$ and $\vec{I_S}$

$= \theta_1 + \theta_2 = 1^\circ 40' + 29^\circ 47' = 31^\circ 27'$

$$\boxed{\phi_S = 31^\circ 27'}$$

Sending end Power factor, $\cos\phi_S = \cos 31^\circ 27'$

$$\boxed{\cos\phi_S = 0.853 \text{ lag}}$$

Sending end Power $= 3 V_S I_S \cos\phi_S$

$= 3 \times 40145 \times 100 \times 0.853$

$= 10273105$ W

$= 10273.105$ kW

Power delivered $= 10,000$ kW

Transmission efficiency $= \dfrac{10000}{10273.105} \times 100$

$$\boxed{\eta = 97.34\%}$$

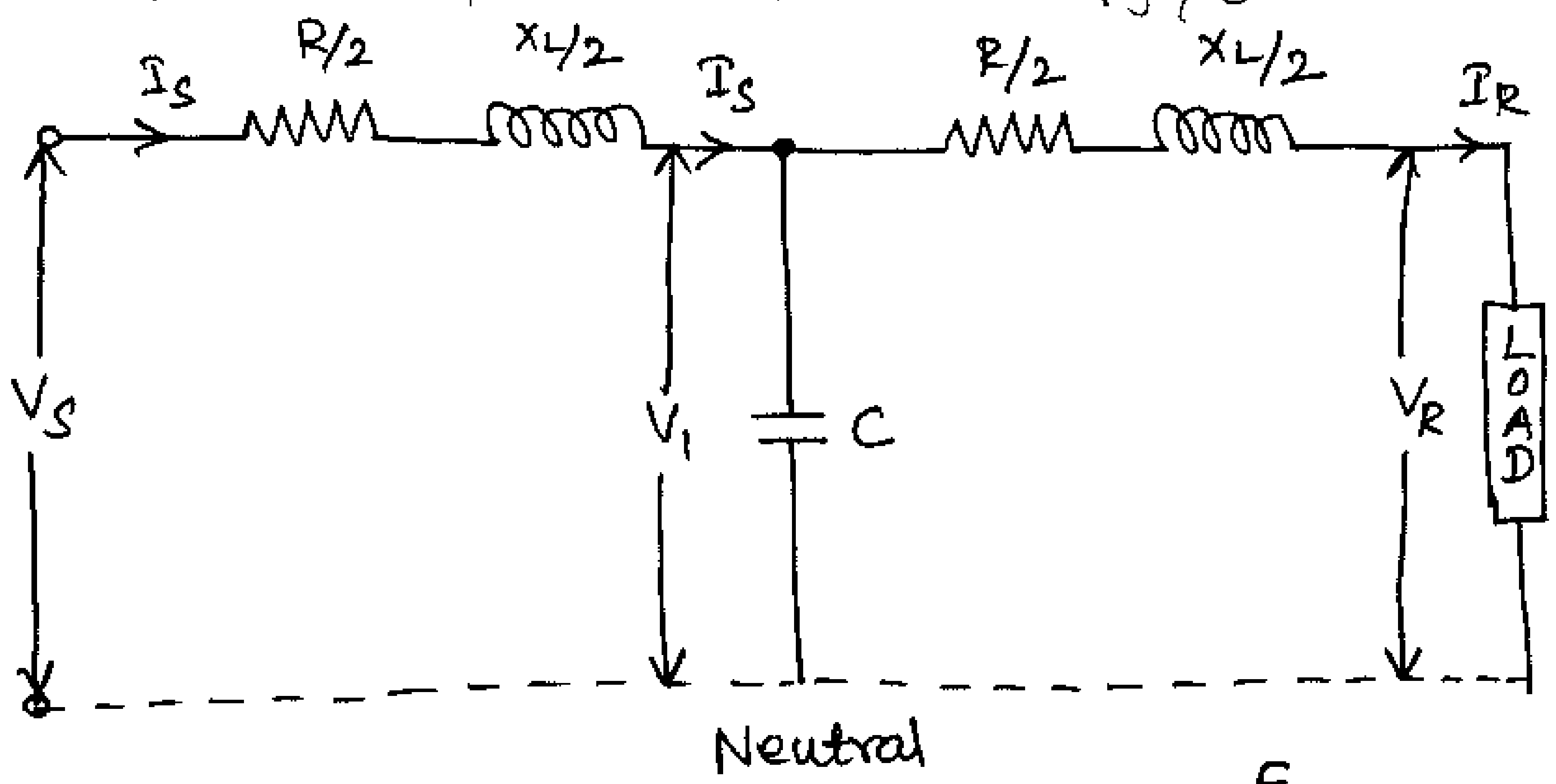
A 3 phase, 50 Hz transmission line 100 km long delivers 20 MW at 0.9 p.f lagging and at 110 kV. The resistance and reactance of the line per phase per km are 0.2 Ω and 0.4 Ω respectively, while capacitance admittance is 2.5×10^{-6} siemen/km/phase. Calculate
(i) the current and voltage at the sending end
(ii) Efficiency of transmission. Use nominal T method.

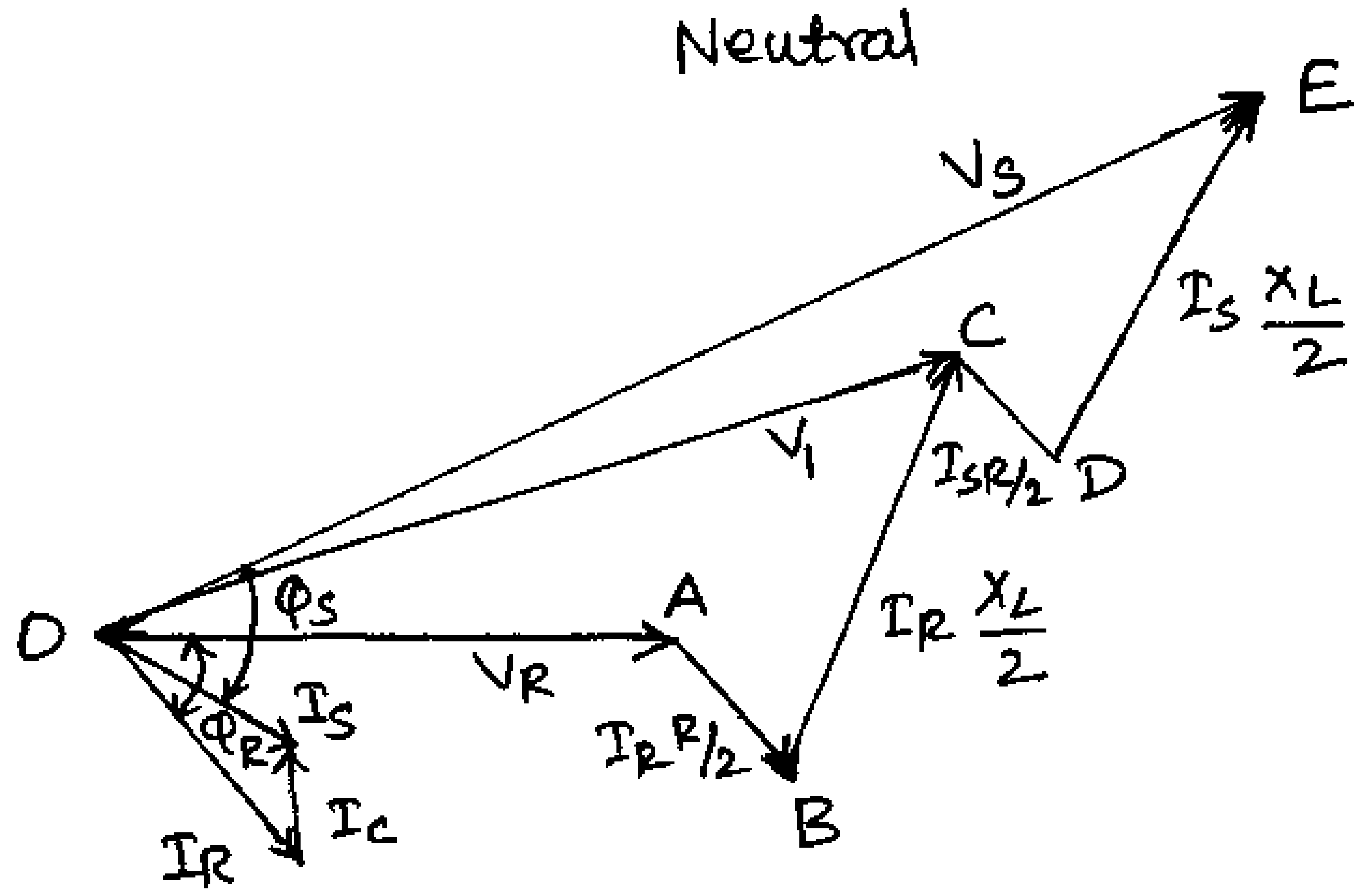
Total resistance/phase, $R = 0.2 \times 100 = 20\,\Omega$

Total reactance/phase, $X_L = 0.4 \times 100 = 40\,\Omega$

Total capacitance admittance/phase, $Y = 2.5 \times 10^{-6} \times 100 = 2.5 \times 1$

Phase impedance, $\vec{Z} = 20 + j40$





Receiving end voltage/phase, $V_R = 110 \times 10^3 / \sqrt{3} = 63508\,V$

Load current, $I_R = \dfrac{20 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0.9} = 116.6\,A$

$I_R = 116.6\,A$

$\cos\phi_R = 0.9 \quad \sin\phi_R = 0.435$

Taking receiving end voltage as the reference phasor

$$\vec{V}_R = V_R + j0 = 63508\,V$$

$$\boxed{V_R = 63508\,V}$$

$$\vec{I}_R = I_R(\cos\phi_R - j\sin\phi_R) = 116.6(0.9 - j0.435)$$

$$\boxed{\vec{I}_R = 105 - j50.7}$$

Voltage across C

$$\vec{V}_1 = \vec{V}_R + \vec{I}_R\,\vec{Z}/2 = 63508 + (105 - j50.7)(10+j2$$

$$= 63508 + (2064 + j1593)$$

$$\boxed{\vec{V}_1 = 65572 + j1593}$$

Charging current $\vec{I}_c = jY\vec{V}_1 = j2.5\times10^{-4}(65572 + j1593$

$$\boxed{\vec{I}_c = -0.4 + j16.4}$$

Sending end Current $\vec{I}_s = \vec{I}_R + \vec{I}_c$

$$\vec{I}_s = (105 - j50.7) + (-0.4 + j16.4)$$

$$= (104.6 - j34.3) = 110\angle{-18^\circ 9'}\,A$$

$$\boxed{I_s = 110\,A}$$

Sending end Voltage

$$\vec{V}_s = \vec{V}_1 + \vec{I}_s\,\vec{Z}/2$$

$$= (65572 + j1593) + (104.6 - j34.3)(10+j2$$

$$= 67304 + j3342$$

Magnitude of $V_s = \sqrt{(67304)^2 + (3342)^2}$

$$\boxed{V_s = 67387\,V}$$

Line value of Sending end Voltage

$$= 67387 \times \sqrt{3} = 116717 V$$

$$V_S = 116.717 \text{ kV}$$

Total line losses for the three phases

$$= 3 I_S^2 R/2 + 3 I_R^2 R/2$$

$$= 3 \times (110)^2 \times 10 + 3 \times (116.6)^2 \times 10$$

$$= 0.770 \times 10^6 W$$

$$= 0.770 \text{ MW}$$

Transmission efficiency

$$\eta = \frac{20}{20 + 0.770} \times 100$$

$$Tr\ \eta = 96.29\%$$

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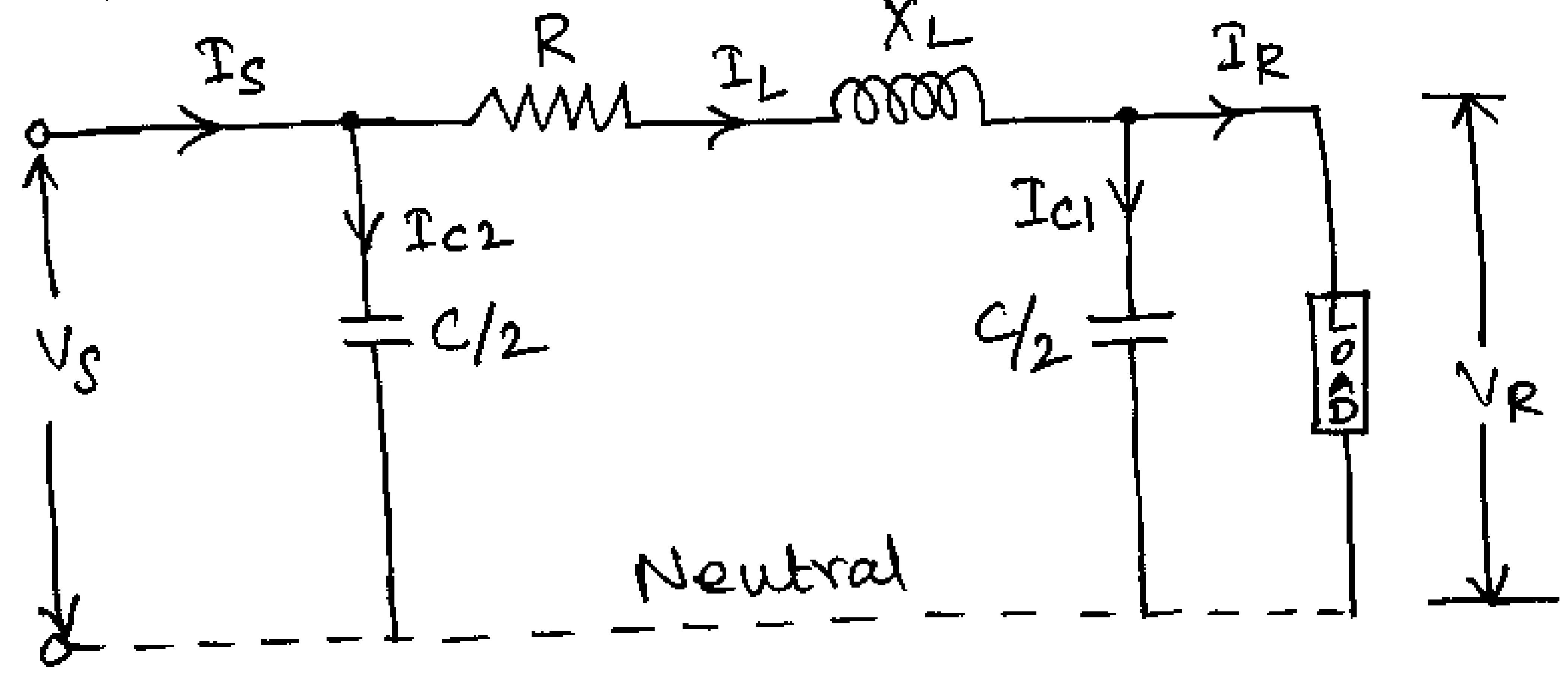
Nominal π Method:

In this method, capacitance of each conductor is divided into two halves, one half being lumped at the sending end and the other half at the receiving end as shown in figure.



I_R = Load current per phase

R = Resistance per phase

X_L = Inductive reactance per phase

C = Capacitance per phase

V_S = Sending end voltage per phase

$\cos\phi_R$ = Receiving end power factor (lag)

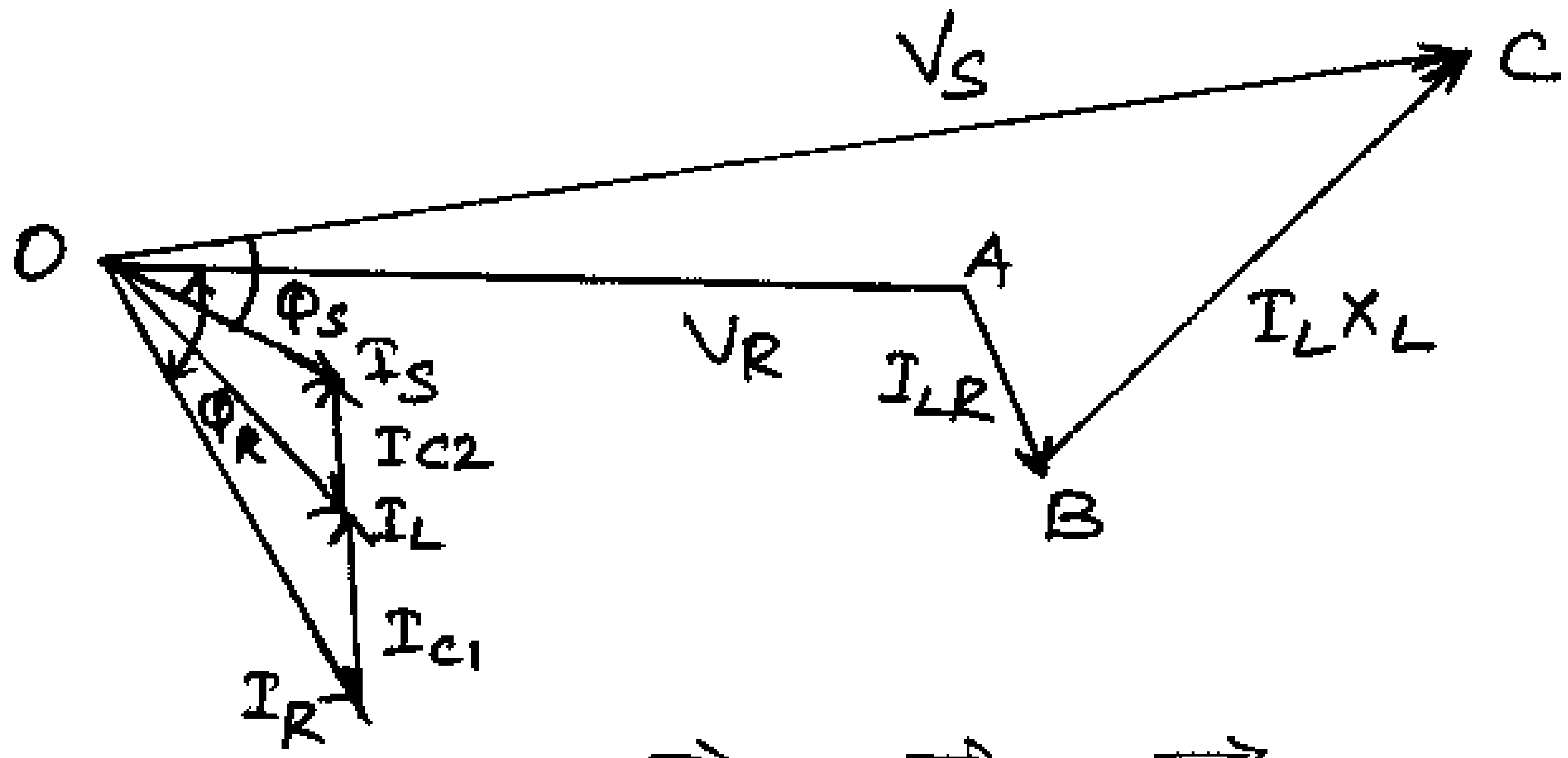
Taking the receiving end voltage as reference phasor

$$\vec{V_R} = V_R + j0$$

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, $\vec{I_S} = \vec{I_L} + \vec{I_{C2}}$

25

A 3 phase, 50 Hz, 150 km line has a resistance inductive reactance and capacitive shunt admittance of 0.1 Ω, 0.5 Ω and 3×10^{-6} S per km per phase. If the line delivers 50 MW at 110 kV and 0.8 p.f lagging determine the sending end voltage and current. Assume a nominal π circuit for the line.

Total resistance/phase $R = 0.1 \times 150 = 15\,\Omega$

Total reactance/phase $X_L = 0.5 \times 150 = 75\,\Omega$

Capacitive admittance/phase $Y = 3 \times 10^{-6} \times 150$

$= 45 \times 10^{-5}\,S$

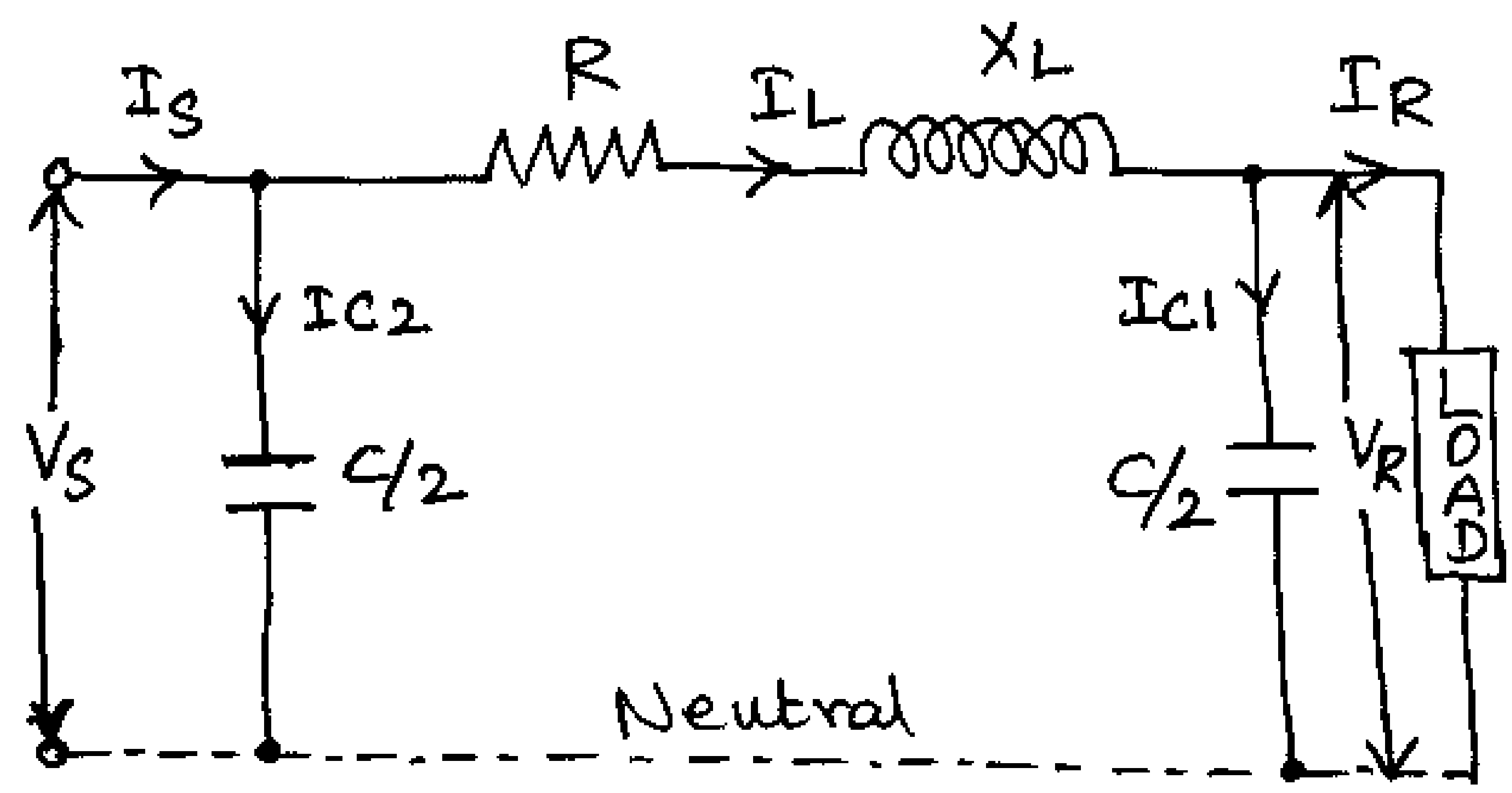
Receiving end voltage/phase, $V_R = 110 \times 10^3 / \sqrt{3}$

$\boxed{V_R = 63508\,V}$

Load Current, $I_R = \dfrac{50 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0.8}$

$\boxed{I_R = 328\,A}$

$\cos\phi_R = 0.8 \quad \sin\phi_R = 0.6$



$\vec{V_R} = V_R + j0 = 63508\,V$

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

$= 328(0.8 - j0.6)$

$= 262.4 - j196.8$

Charging current at the load end is

$$\vec{I}_{C1} = \vec{V}_R \, j \frac{Y}{2} = 63508 \times j \frac{45 \times 10^{-5}}{2}$$

$$\boxed{\vec{I}_{C1} = j14.3}$$

Line current $\vec{I}_L = \vec{I}_R + \vec{I}_{C1}$

$$= (262.4 - j196.8) + j14.3$$

$$\boxed{\vec{I}_L = 262.4 - j182.5}$$

Sending end voltage

$$\vec{V}_S = \vec{V}_R + \vec{I}_L \vec{Z} = \vec{V}_R + \vec{I}_L (R + jX_L)$$

$$= 63508 + (262.4 - j182.5)(15 + j75)$$

$$= 63508 + 3936 + j19680 - j2737.5 + 13687$$

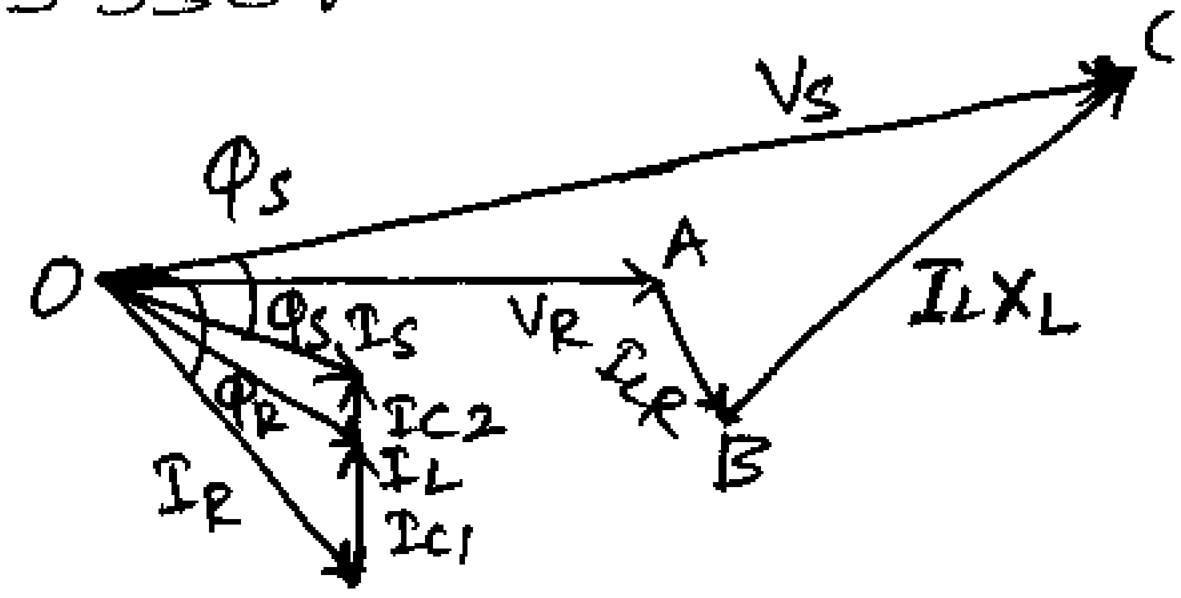
$$= 81131 + j16942.5$$

$$\boxed{\vec{V}_S = 82881 \angle 11^\circ 47' \, V}$$

Line to line sending end voltage

$$= 82881 \times \sqrt{3} = 143550 V$$

$$\boxed{V_S = 143.55 \, kV}$$



Charging current at the sending end is

$$I_{C2} = j \vec{V}_S \, Y/2 = (81131 + j16942.5) \, j \frac{45 \times 10^{-5}}{2}$$

$$\boxed{I_{C2} = -3.81 + j18.25}$$

Sending end Current $\vec{I}_S = \vec{I}_L + \vec{I}_{C2} = (262.4 - j182.5) + (-3.81 + j18.25)$

$$= 258.6 - j164.25$$

$$= 306 \angle -32.4^\circ A$$

$$\boxed{I_S = 306.4 A}$$

A 100 km long 3 phase 50Hz transmission line has following line constants (27)

Resistance/phase/km = 0.1Ω, Reactance/phase/km = 0.5Ω

Susceptance/phase/km = 10×10^{-6} S

If the line Supplies load of 20 mw at 0.9 P.f lagging at 66 kV at the receiving end, calculate by nominal π method.

(i) Sending end Power factor (ii) Regulation

(iii) Transmission Efficiency

Total Resistance/phase, $R = 0.1 \times 100 = 10\Omega$

Total Reactance/phase, $X_L = 0.5 \times 100 = 50\Omega$

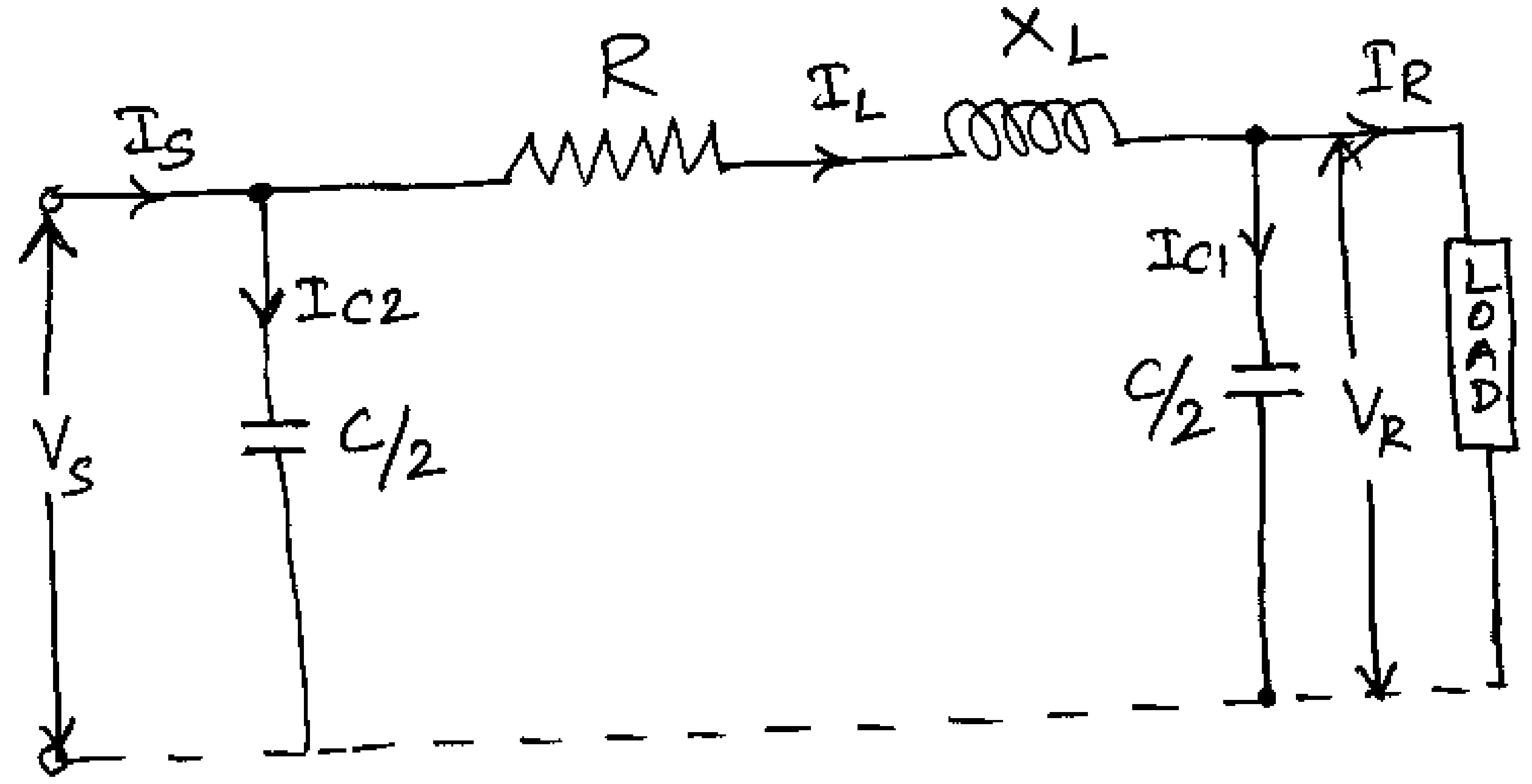
Susceptance/phase, $Y = 10 \times 10^{-6} \times 100 = 10 \times 10^{-4}$ S

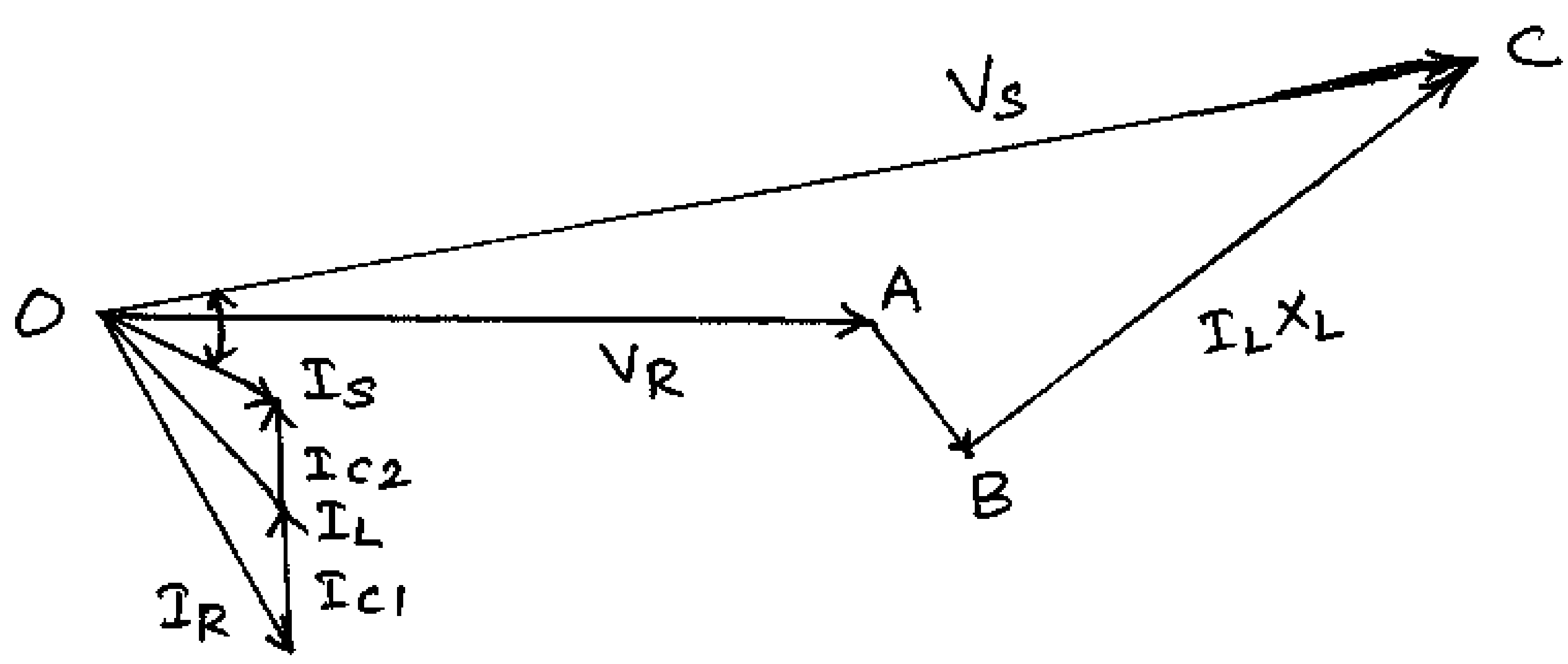
Receiving end voltage/phase $V_R = 66 \times 10^3/\sqrt{3} = 38105V$

Load Current $I_R = \dfrac{20 \times 10^6}{\sqrt{3} \times 66 \times 10^3 \times 0.9} = 195A$

$$\boxed{I_R = 195\,A}$$

$\cos\phi_R = 0.9$; $\sin\phi_R = 0.435$





Taking receiving end voltage as the reference pha

$$\vec{V}_R = V_R + j0$$

$$V_R = 38105\,V$$

Load current $\vec{I}_R = I_R(\cos\varphi_R - j\sin\varphi_R)$

$$= 195(0.9 - j0.435)$$

$$= 176 - j85$$

Charging current at the receiving end is

$$\vec{I}_{C1} = \vec{V}_R\, j\frac{Y}{2} = 38105 \times j\,\frac{10\times10^{-4}}{2}$$

$$\boxed{\vec{I}_{C1} = j19}$$

$$\vec{I}_L = \vec{I}_R + \vec{I}_{C1} = (176 - j85) + j19 = 176 - j66$$

$$\boxed{\vec{I}_L = 176 - j66}$$

Sending end Voltage $\vec{V}_S = \vec{V}_R + \vec{I}_L \vec{Z}$

$$= \vec{V}_R + \vec{I}_L(R + jX_L)$$

$$\vec{V}_S = 38105 + (176 - j66)(10 + j50)$$

$$= 38105 + (5060 + j8140)$$

$$= 43165 + j8140 = \underline{\underline{43925\angle 10.65^\circ\,V}}$$

Sending end line to line Voltage $= 43925 \times \sqrt{3}$

$$= 76 \times 10^3\,V$$

$$\boxed{V_S = 76\,kV}$$

Charging current at the sending end is

$$\vec{I}_{C2} = \vec{V}_s \, j \, Y/2 = (43165 + j8140)\, j \, \frac{10 \times 10^{-4}}{2}$$

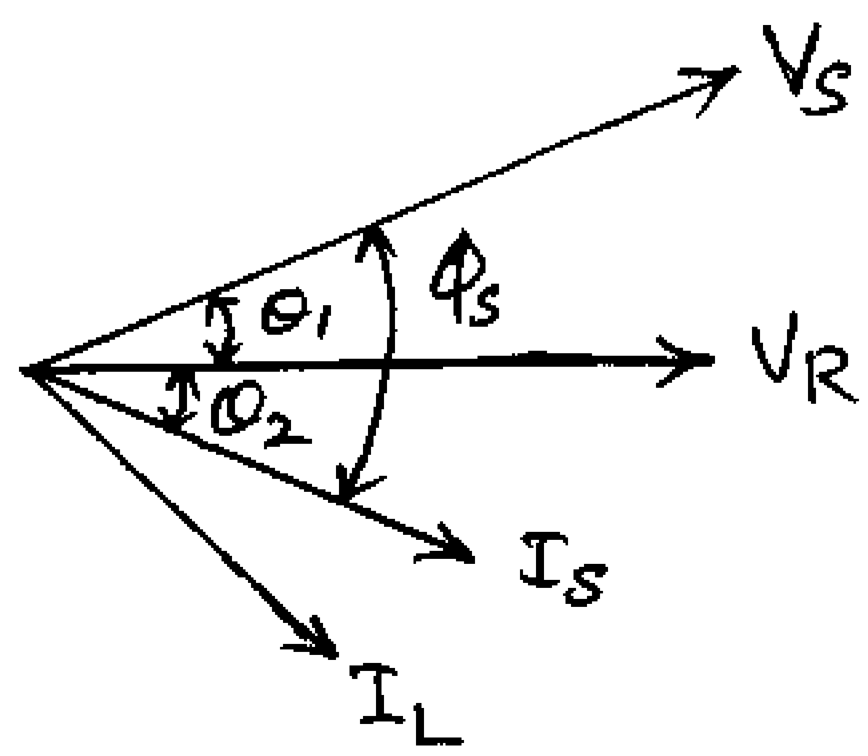
$$\vec{I}_{C2} = -4.0 + j\,2.16$$

Sending end current

$$\vec{I}_s = \vec{I}_L + \vec{I}_{C2} = (176 - j66) + (-4.0 + j\,21.6)$$

$$= 172 - j44.4$$

$$\boxed{\vec{I}_s = 177.6 \angle -14.5 \text{ A}}$$



(i) θ_1 = angle between $\vec{V}_R$ and $\vec{V}_s$

$$\boxed{\theta_1 = 10.65^\circ}$$

θ_2 = angle between $\vec{V}_R$ and $\vec{I}_s$

$$\boxed{\theta_2 = -14.5^\circ}$$

ϕ_s = angle between $\vec{V}_s$ and $\vec{I}_s$

$$= \theta_2 + \theta_1$$

$$= 14.5^\circ + 10.65^\circ$$

$$\boxed{\phi_s = 25.15^\circ}$$

Sending end P.f $\cos\phi_s = \cos 25.15^\circ$

$$\boxed{\cos\phi_s = 0.905 \text{ lag}}$$

(ii) % Voltage regulation $= \dfrac{V_s - V_R}{V_R} \times 100$

$$= \frac{43925 - 38105}{38105} \times 100$$

$$= 15.27\ \%$$

(iii) Sending end Power $= 3V_s I_s \cos\phi_s$

$= 3 \times 43925 \times 177.6 \times 0.905$

$= 21.18 \times 10^6$ W

$= 21.18$ MW

Transmission Efficiency $= 20/21.8 \times 100$

$\eta = 94\%$

·×———————×·

CORONA:

When the Potential difference is increas[ed], potential gradient is set up. If the potential gradient is above 30kV/1cm, the conductor gets ionised. The phenomenon of faint violet glow, hissing noise and production of ozone gas is known as Corona.

Formation of Corona:

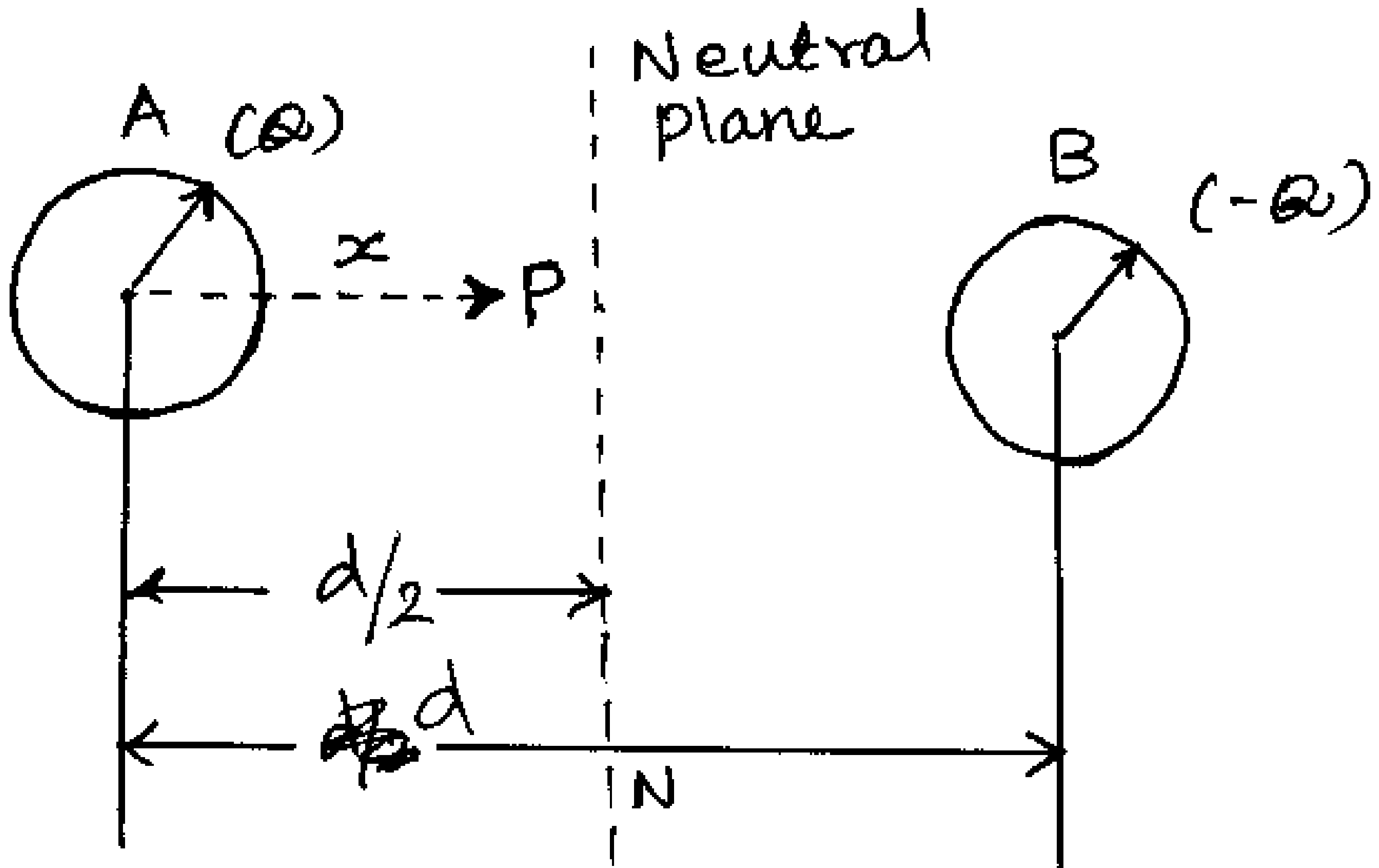
When the Potential gradient is less than 30kV/cm, there is no Corona formation. When the Potential gradient is greater than 30kV, the ions attain a sufficiently high velocity and strike each other and other neutral molecule, dislodge one or more electrons from this neutral molecule.

This produces a new electron and a positive ion which in turn are accelerated until they collide with other molecules and produce more ions. An ion avalanche results. Therefore a complete electric breakdown occurs and an arc is produced between the two electrodes.

Corona Power loss occurs in Power lines when Voltage exceeds 100 kV. Highly ionized air may cause flashover in the insulators or between phases causing damage to the equipment.

Critical Disruptive Voltage:

Consider a single phase transmission line as shown in figure.



Single phase transmission line

Let 'r' be the radius of conductor
Let 'd' be the spacing between the conductors
Let 'Q' be the charge density in col/m

Electric field intensity at P from the Centre of Conductor A (3

$$= \frac{Q}{2\pi\varepsilon_0 x}$$

Electric field intensity at P from the Centre of Conductor B.

$$= \frac{-Q}{2\pi\varepsilon_0 (d-x)}$$

Total electric field intensity (E_x)

$$= \frac{Q}{2\pi\varepsilon_0 x} + \frac{Q}{2\pi\varepsilon_0 (d-x)}$$

$$= \frac{Q}{2\pi\varepsilon_0}\left[\frac{1}{x} + \frac{1}{d-x}\right]$$

Let V' be the voltage of one Conductor with respect to neutral

$$\text{potential or Voltage} = \int_r^{d/2} E_x \, dx$$

$$= \int_r^{d/2} \frac{Q}{2\pi\varepsilon_0}\left[\frac{1}{x} + \frac{1}{d-x}\right] dx$$

$$= \frac{Q}{2\pi\varepsilon_0}\left\{[\ln x]_r^{d/2} - \ln [d-x]_r^{d/2}\right\}$$

$$= \frac{Q}{2\pi\varepsilon_0}\left\{\ln d/2 - \ln r - \ln d/2 + \ln (d-r)\right\}$$

$$V' = \frac{Q}{2\pi\varepsilon_0} \ln\left[\frac{d-r}{r}\right] \text{ Volt}$$

$$\Rightarrow \quad Q = V' \times \frac{2\pi\varepsilon_0}{\ln\left(\frac{d-r}{r}\right)}$$

Substitute in E_x, we get

$$E_x = V' \frac{2\pi\varepsilon_0}{\ln\left(\frac{d-r}{r}\right)} \times \frac{1}{2\pi\varepsilon_0}\left(\frac{1}{x} + \frac{1}{d-x}\right)$$

$$= \frac{V'}{\ln\left(\frac{d-r}{r}\right)} \times \frac{d}{x(d-x)}$$

Since $d >> r$, we get

$$E_x = \frac{V'}{\ln\left(\frac{d}{r}\right)} \cdot \frac{d}{x(d-x)}$$

Electric stress or gradient is maximum at the surface of the conductor (ie, $x = r$)

$$E_{max} \text{ or } g_{max} = \frac{V'}{\ln\left(\frac{d}{r}\right)} \cdot \frac{d}{r(d-r)}$$

Since $d >> r$ $\quad = \dfrac{V'd}{\ln\left(\frac{d}{r}\right) \cdot r \cdot d} = \dfrac{V'}{r\ln\left(\frac{d}{r}\right)}$

$$\Rightarrow V' = r\, E_{max} \ln\left(\frac{d}{r}\right)$$

Electric stress at which ionisation ie corona occurs under temperature at $25°C$ and 76 cm pressure

E_0 or $g_0 = 30$ kV/cm (max value)

$$V' = r g_0' \ln\left(\frac{d}{r}\right)$$

Dielectric strength at any temperature $t°C$ and

 Pressure

$$g_0' = g_0 \delta$$

$$V' = r g_0 \delta \ln\left(\frac{d}{r}\right)$$

Critical Disruptive Voltage:

The Potential difference between Conduct at which the electric field intensity at the Surface of the conductor exceeds the critical Value (ie, 30kV/cm) and occurs Corona is known as critical disruptive Voltage.

Usually stranded Conductors are used in transmission lines, therefore irregularity of surface occurs and also dust and dirt on the surface will reduce the break down Voltage. Therefore multiply the above expression by irregularity factor m_0.

∴ Critical disruptive Voltage

$$V_c = m_0 r g_0 \delta \ln\left(\frac{d}{r}\right) \text{ kV/ph}$$

Visual Critical Voltage:

At V_c, the Corona is not Visible. When the Voltage increases further at Some point, the Corona becomes visible i.e, the minimum phase Voltage at which Corona glow appears all along ... This Voltage is called as Visual Critical Voltage (V_v).

Electric stress or gradient Corresponding to V_v is g_v.

Distance between g_o and g_v = Energy distance

$$\therefore \quad g_v = g_o \delta \left[1 + \frac{0.03}{\sqrt{r\delta}}\right] \text{kV/cm}$$

$$\boxed{\text{Visual critical Voltage } V_v = m_v r g_v \ln\left(\frac{d}{r}\right)}$$

$$V_v = m_v r g_o \delta \left[1 + \frac{0.03}{\sqrt{rd}}\right] \ln\left(\frac{d}{r}\right) \text{kV}$$

·x ———————————— x·

Surge impedance:

It is defined as the square root of the ratio of series impedance (Z) to the shunt admittance (Y) is called as surge impedance of the line.

$$Z = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{L}{C}}$$

Surge impedance loading:

Surge impedance loading of the line is the maximum Power transmitted when a lossless line operating at its nominal Voltage, is terminated with a resistance equal to surge impedance of the line.

$$P_R = \frac{|V_{RL}|^2}{Z_C} \quad MW$$

Where

V_{RL} - Line voltage at the receiving end

Z_C - surge impedance $= \sqrt{L/C}$

P_R = surge impedance loading

·x———————— ————————x·

Attenuation Constant:

$\gamma = \alpha + j\beta$

γ = Propagation Constant

α = Attenuation Constant

β = phase Constant

The real part of the propagation Constant is the attenuation Constant and is denoted by α (alpha). It causes a signal amplitude to decrease along a transmission line. The natural units of the attenuation Constant are Nepers/meter, but we often Convert to dB/meter.

Attenuation Constant:

The attenuation Constant is the attenuation of an electromagnetic wave propagat through a medium per unit distance from the Source. It is the real part of the propagation Constant and is measured in nepers per metre.

Phase Constant:

In electromagnetic theory, the phas Constant is a Parameter or Coefficient. It is the imaginary component of the propogation Constan for a plane wave. It represents the change in phase per unit length along the path travelled by the wave at any instant and is equal to the real part of the angular wavenumber of the wave. It is represented by the symbol β and is measured in units of radians per unit length.

Propagation Constant:

The propagation Constant of a Sinusoid electromagnetic wave is a measure of the Change undergone by the amplitude and phase of the wave as it propagates in a given direction.

The quantity being measured can be the voltage, the current in a circuit, or a field vector such as electric field strength or flux density. The propagation constant itself measures the change per unit length.

TD – UNIT – III

Dr. M. Ettappan

Mechanical Design of Lines

Line supports

The supporting structures for overhead line conductors are various types of poles and towers called line supports. In general, the line supports should have the following properties.

* High mechanical strength to withstand the weight of conductors and wind loads etc.
* Light in weight without the loss of mechanical strength.
* Cheap in cost and economical to maintain
* Longer Life
* Easy accessibility of conductors for maintenance

The line supports used for transmission and distribution of electric Power are of various types including wooden poles, steel poles, R.C.C poles and lattice steel towers. The choice of supporting structure for a particular case depends upon the line span, X sectional area, line voltage cost and local conditions.

Types of Towers

The supporting structures for overhead line conductors are called towers.

Properties of Towers

* It should have high mechanical strength to withstand weight of conductor, wind and ice loads etc.
* Cost should be less and economical.
* It should have longer life
* Maintenance should be easier

The various types of towers are as follows

* Wooden poles
* Steel poles
* Rcc Poles
* Lattice steel towers

The types of towers depends on the line span (distance between towers), cross sectional area, line voltage etc.

1. Wooden poles:

These types of poles are used for the span length upto 50m and line voltages less than 20k. These poles are made up of seasonal wood (sal o Chir).

Advantages

* Cheap.
* It provides better insulation.
* It is used in distribution lines.

Disadvantages

* Tendency to rot below the ground level
* Life is small.
* Mechanical strength is lesser.
* It requires periodical inspection.

2. Steel poles:

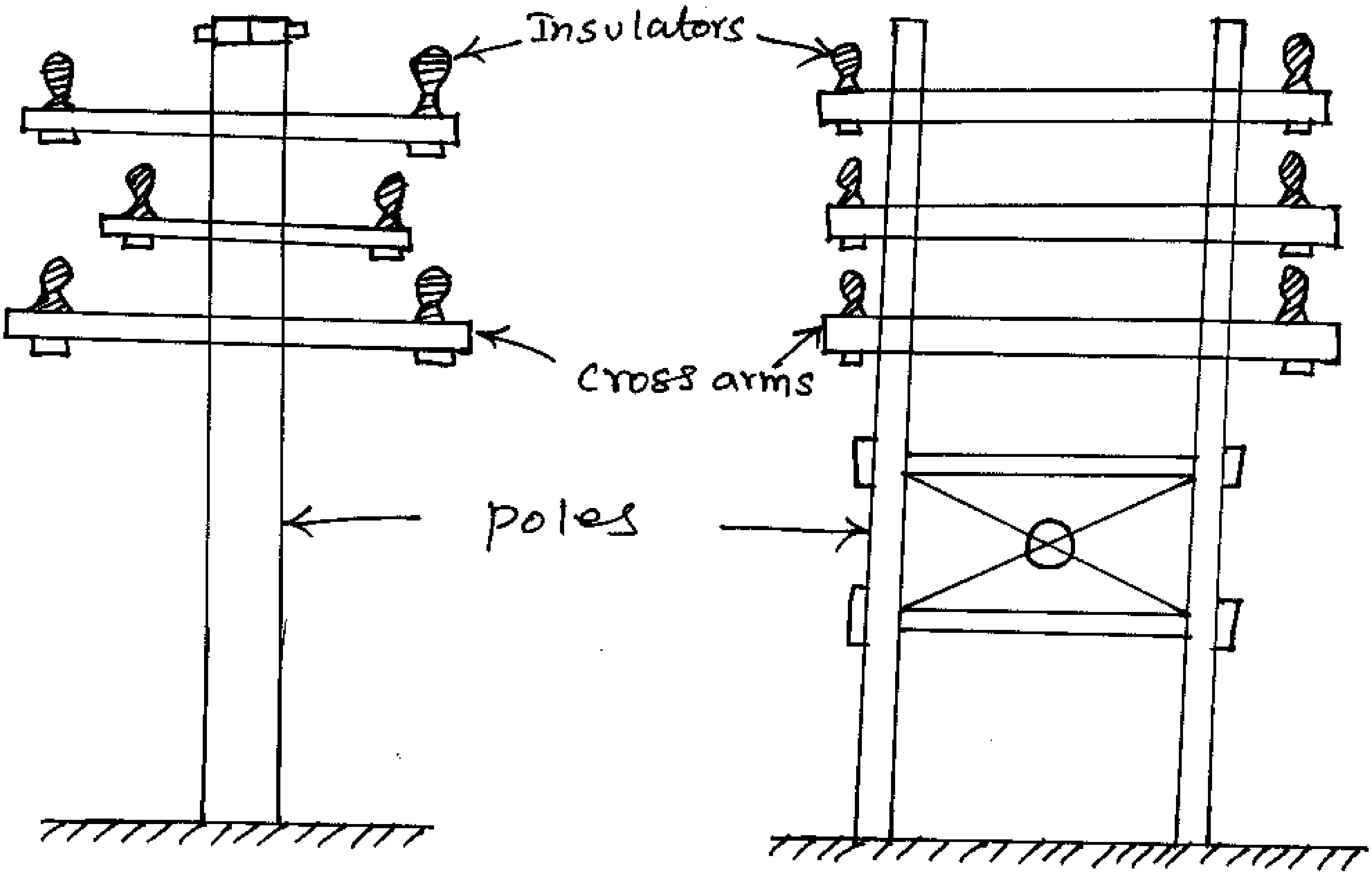
It is used instead of wooden poles. There are three types of steel poles.

a. Rail poles b. Tubular poles c. Rolled steel joints.

Advantages:

* Mechanical strength is more
* Life is long
* Span length is more compare than wooden poles.
* It is used in distribution line

Steel poles:



3. Reinforced Concrete poles:

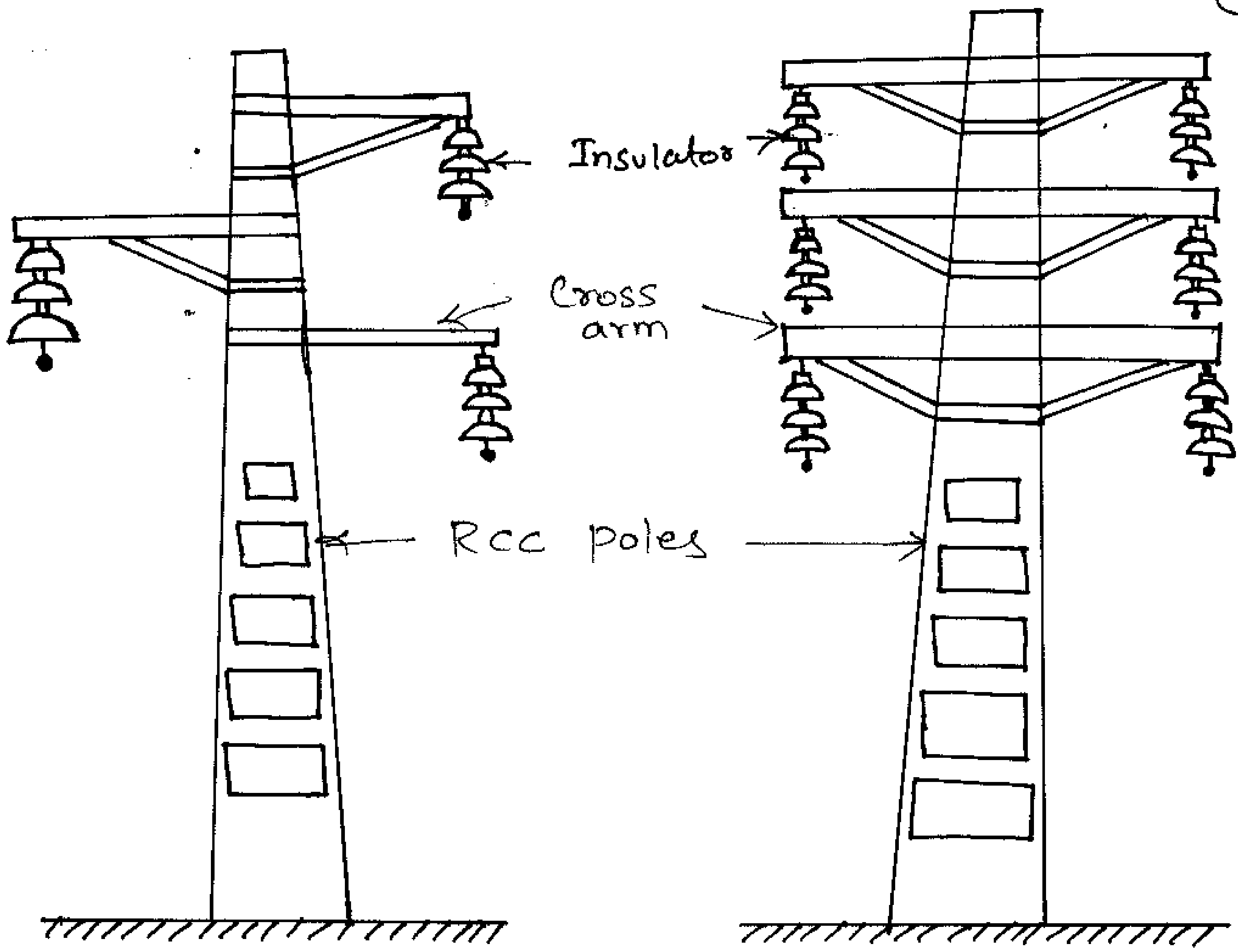
In many places of distribution lines, RCC Poles are used. It can be used up to a voltage of 11kV.

Advantages

* Mechanical strength is more
* Life is long
* Maintenance cost is less
* Better insulation property

Disadvantages

* High cost
* Weight is heavy, so transportation is not easy.

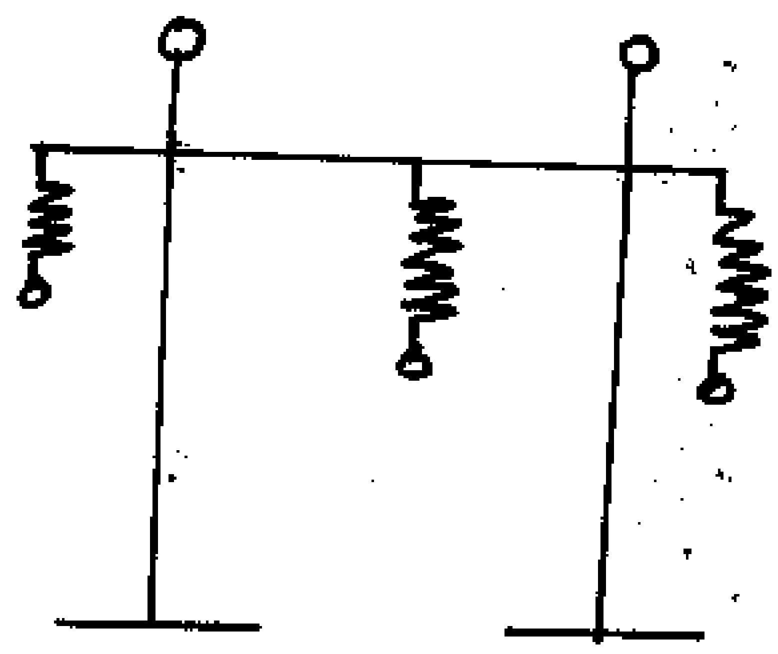


4. Steel Towers:

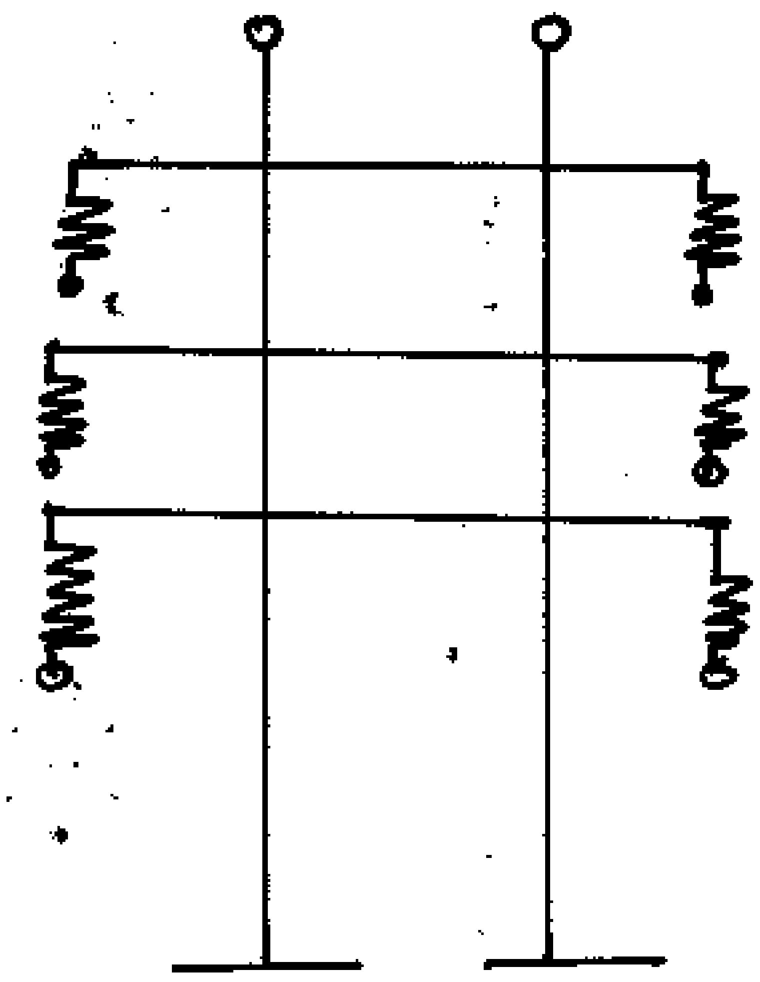
Steel towers are used for long distance transmission line. Tower footings are grounded by driving rods into earth.

a. Single phase circuits:

It can be either single circuit or double circuit. single circuit has one phase wire and one neutral wire but double circuit has two phase wires and two neutral wires. If failure of any one circuit occurs, another circuit can carry the Power.



Single circuit twin earth wire (33kv line)



Double ckt twin earth wire (66 kv Line)

Three phase circuits:

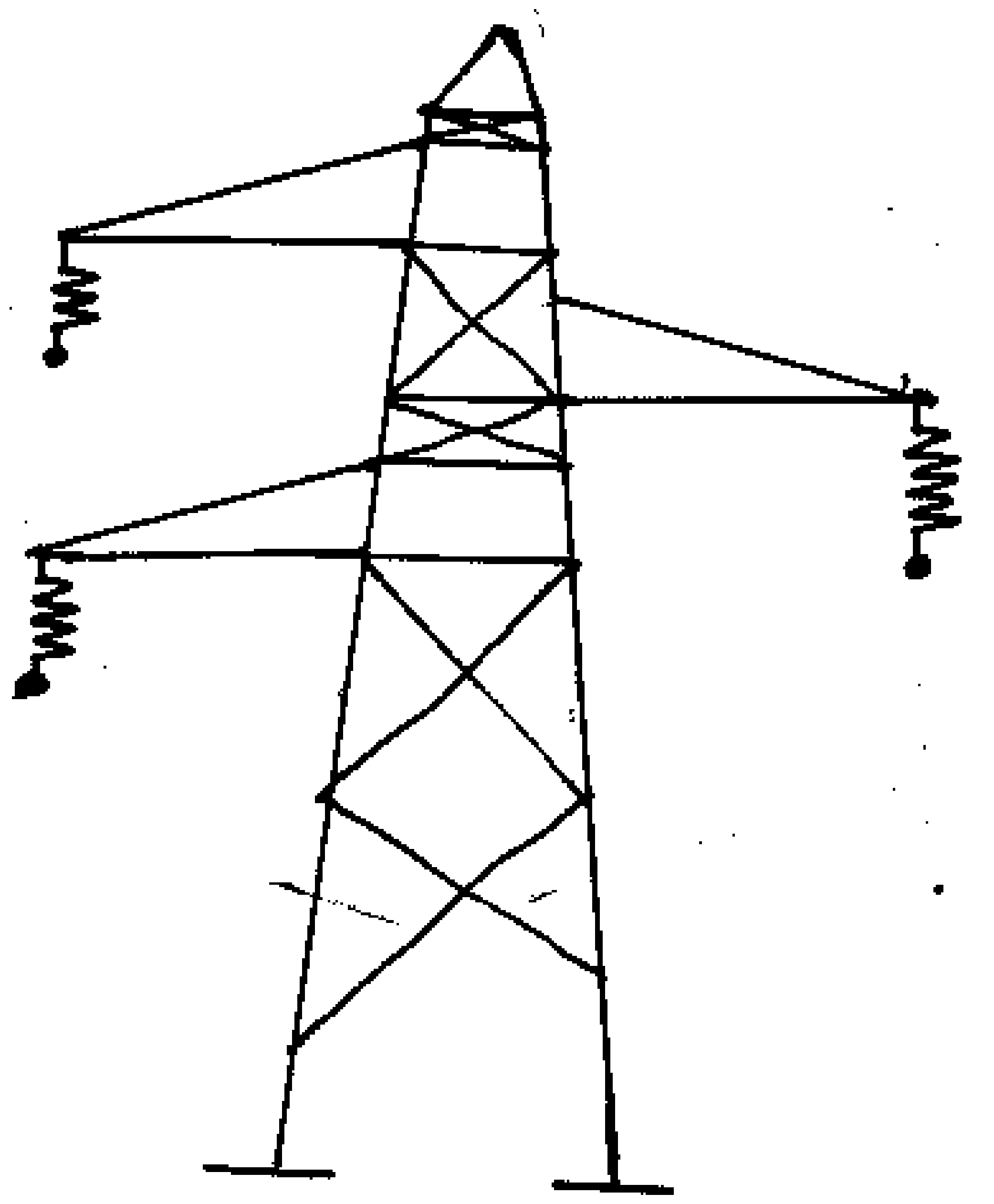
Three phase Circuits are used for voltages ranges from 440v to 765kv

The types of steel towers for three phase circuits are

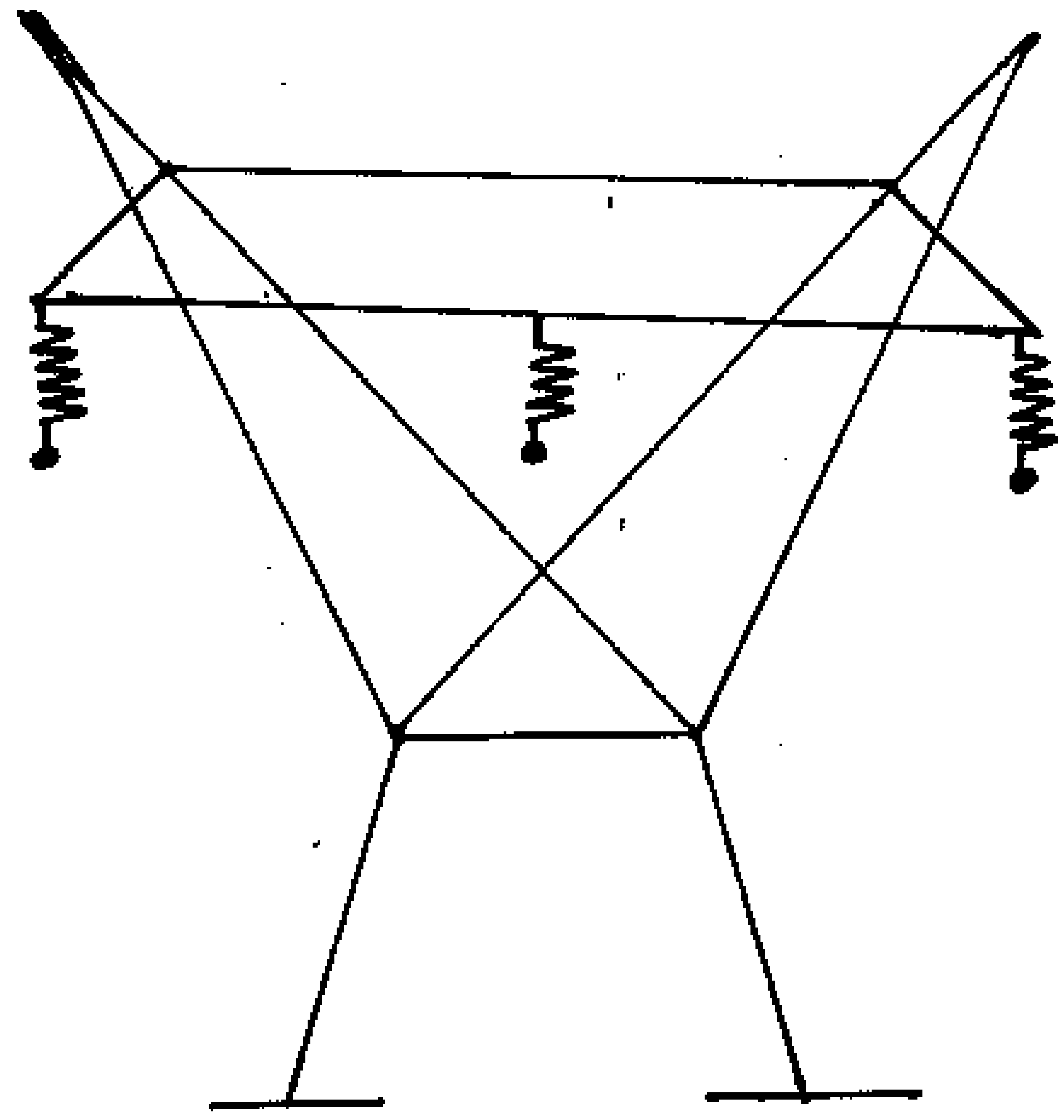
* Single circuit tower
* Double Circuit tower
* Double Circuit with bundled Conductor tower

Single circuit Tower:

* In this circuit, three Conductor are used
* In some circuits, conductors are arranged at the
* Corners of right angled triangle, so that distance between them are equal.
* If any faults occurs, interruption of supply takes place.



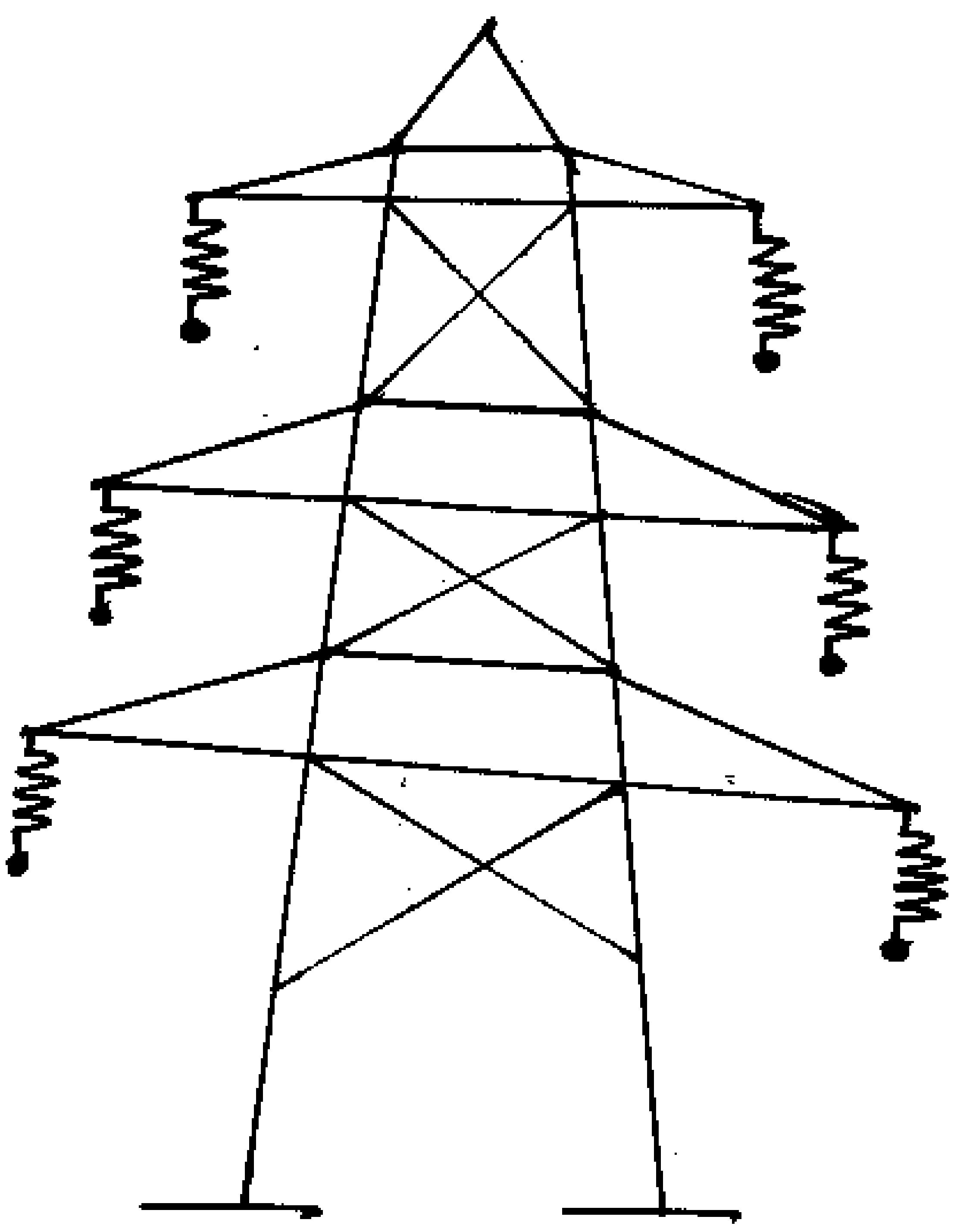
Single circuit single Earth wire (110kv)



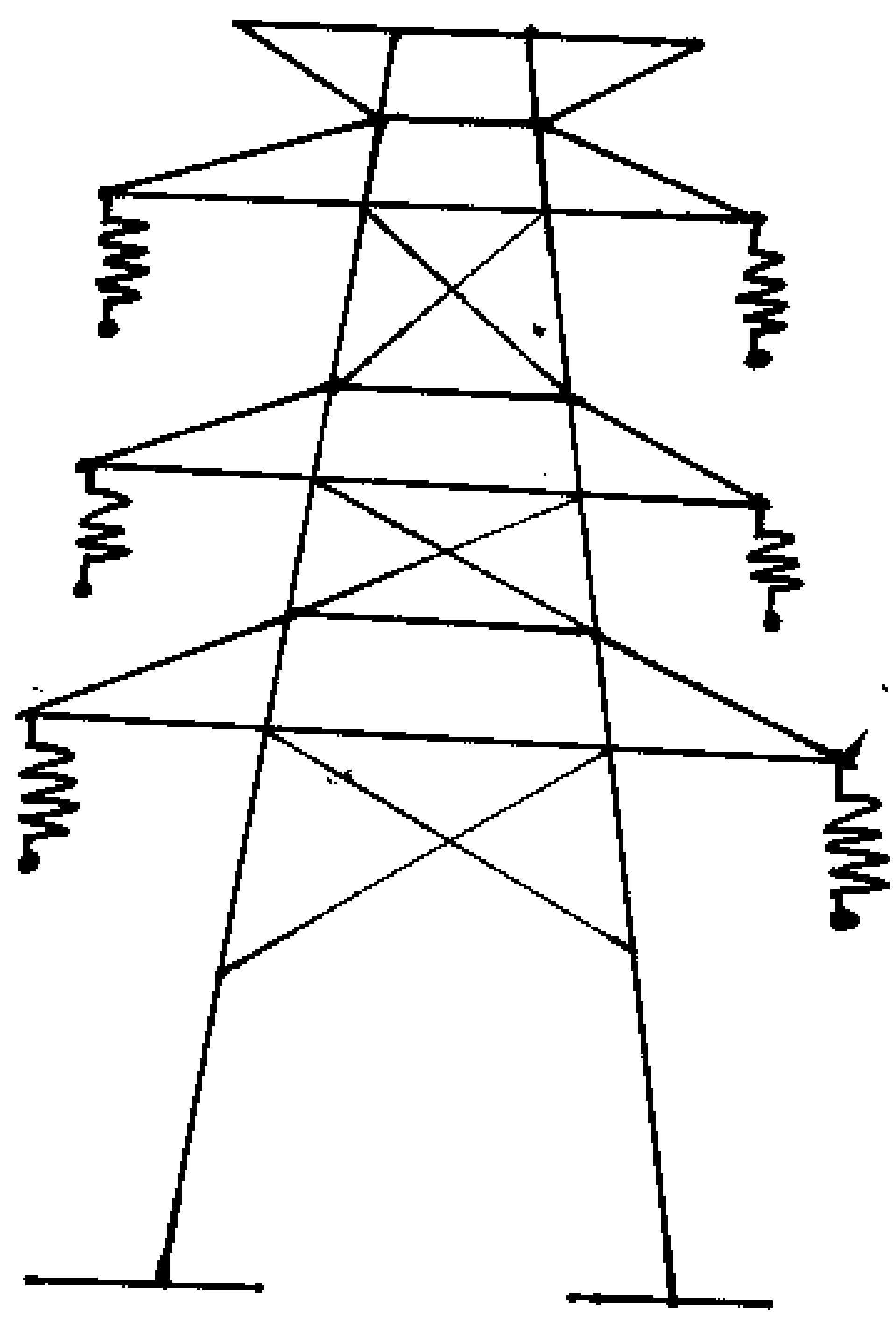
single circuit Double Earth wire (110kv)

Double circuit Tower:

* In this circuit six Conductors are used.
* If any fault occurs at one circuit, the Continuity of supply can be maintained by the other circuit.



Double circuit single earth wire (220kv Line)



Double ckt Double Earth wire (220kv Line)

Double circuit with bundled Conductor Tower:

* In this circuit, bundled Conductors are used
* These circuits can carry large amount of Power
* If any fault occurs at one circuit, the continuity of supply can be maintained by other circuit.

Advantages:

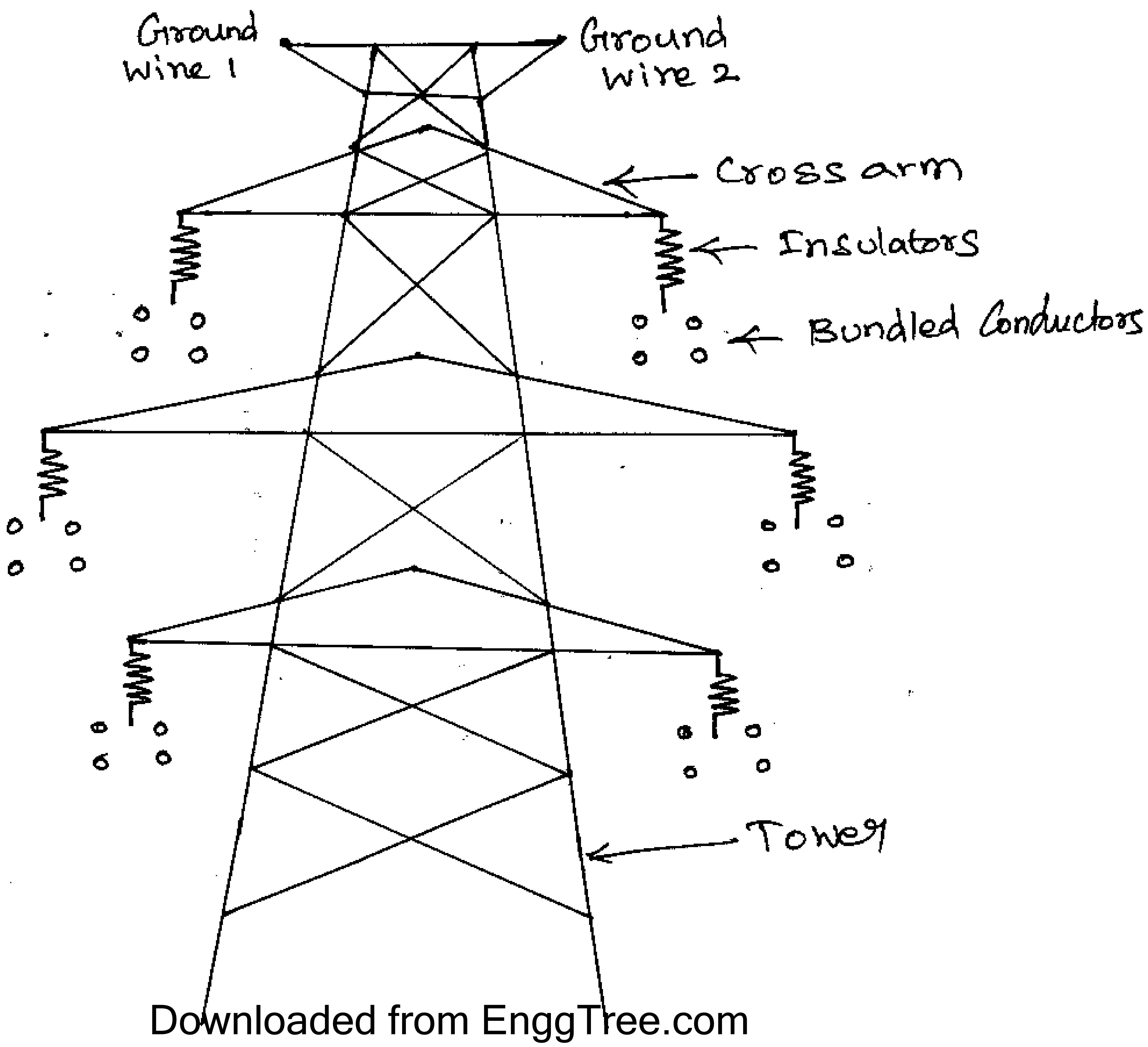
Mechanical strength is very high

Life is long

Used for longer span length

It can withstand all climatic conditions

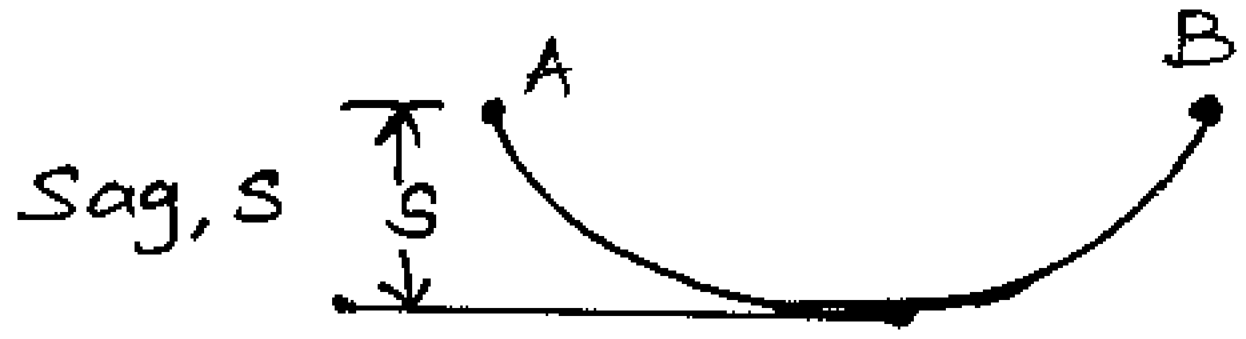
Due to longer span, insulation failure is reduce



Sag in overhead Lines

Sag:

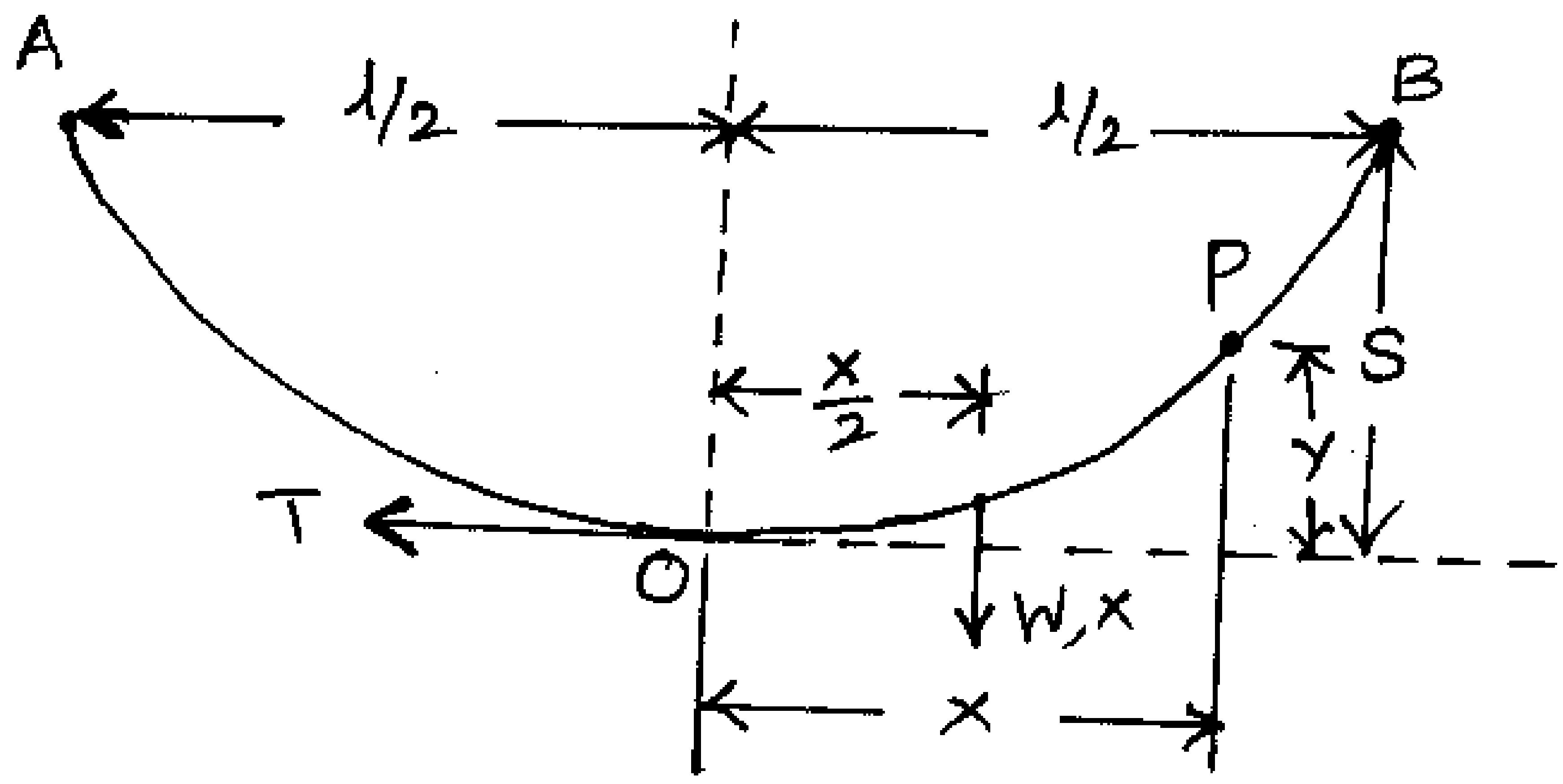
The difference in level between points of support and the lowest point on the conductor is called sag.



Calculation of sag:

(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 in figure. It can be proved that lowest point will be at the mid-span.



l = Length of span

W = weight per unit length of conductor

T = Tension in the conductor

Consider a point P on the conductor. Taking the lowest point O as the origin, let the coordinates of point P be x and y. The two forces acting on the portion OP of the Conductor are

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

b. The tension T acting at O

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

$$Ty = wx \frac{x}{2}$$

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

The maximum sag is represented by the value of y at either of the supports A and B.

At support A, $x = l/2$ and $y = S$

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

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

(ii) <u>When supports are at unequal levels:</u>

In hilly areas, we generally come across Conducto[r]s Suspended between supports at unequal levels. The figure shows a conductor suspended between two supports A and B which are at different levels.

The lowest point on the Conductor is O.

Let

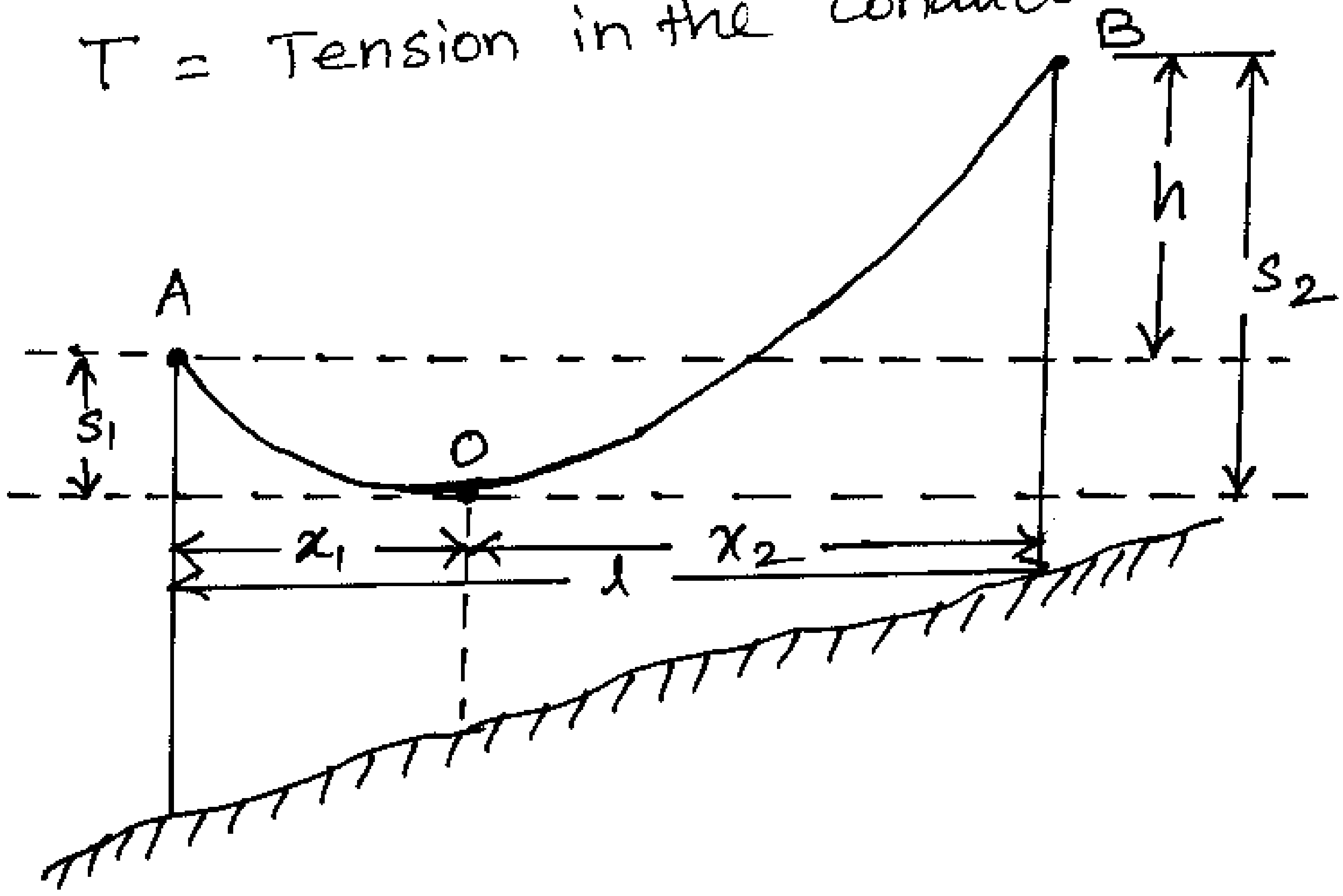
l = span length

h = Difference in levels between two supports

x_1 = Distance of Support at lower level from O

x_2 = Distance of Support at higher level from O

T = Tension in the Conductor.



If W is the weight per unit length of the Conductor, then

$$\text{Sag } s_1 = \frac{W x_1^2}{2T}$$

$$\text{Sag } s_2 = \frac{W x_2^2}{2T}$$

$$x_1 + x_2 = l$$

$$s_2 - s_1 = \frac{W}{2T}(x_2^2 - x_1^2)$$

$$= \frac{W}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$s_2 - s_1 = \frac{Wl}{2T}(x_2 - x_1) \qquad \because x_2 + x_1 = l$$

$$S_2 - S_1 = h$$

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

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

Substitute $x_1 = l - x_2$ in eqn (1) we get

$$x_2 - l + x_2 = \frac{2Th}{Wl}$$

$$2x_2 = \frac{2Th}{Wl} + l$$

$\div$ by 2 $\Rightarrow$

$$x_2 = \frac{Th}{Wl} + \frac{l}{2}$$

Substitute $x_2 = \frac{Th}{Wl} + \frac{l}{2}$ in eqn $x_1 + x_2 = l$

$$x_1 + \frac{Th}{Wl} + \frac{l}{2} = l$$

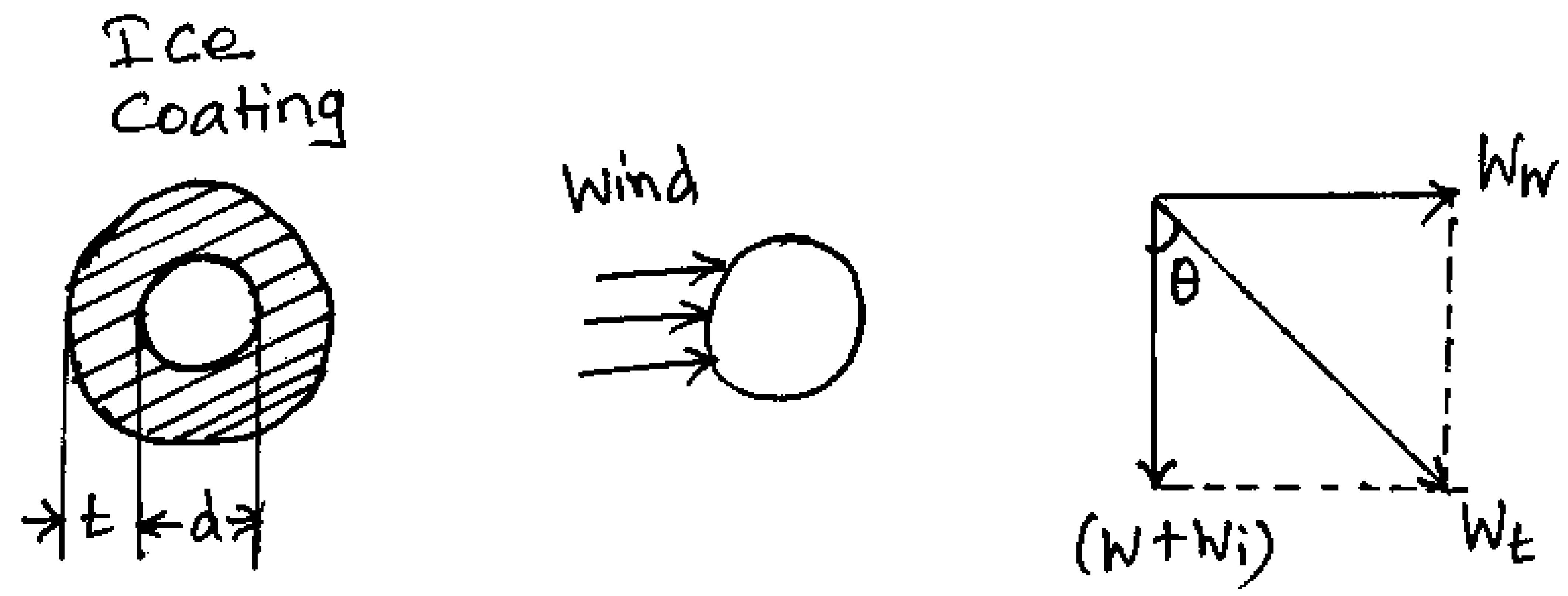
$$x_1 = l - \frac{l}{2} - \frac{Th}{Wl}$$

$$\boxed{x_1 = \frac{l}{2} - \frac{Th}{Wl}}$$

$$\boxed{x_2 = \frac{l}{2} + \frac{Th}{Wl}}$$

Effect of wind and ice loading:

The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. 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 ie 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 in figure.



$$W_t = \sqrt{(W+W_i)^2 + (W_w)^2}$$

W = weight of conductor per unit length
= Conductor material density x volume per unit length

W_i = weight of ice per unit length
= density of ice x volume of ice per unit length
= density of ice x $\pi t(d+t)$

W_w = Wind force per unit length

W_w = Wind pressure per unit area × Projected area per unit length

= Wind pressure × $(d + 2t)$

When the Conductor has wind and ice loading also, the following points may be noted.

The Conductor sets itself in a plane at an angle θ to the vertical where

$$\tan\theta = \frac{W_w}{W + W_i}$$

The sag in the Conductor is given by

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

Hence S represents the slant sag in a direction making an angle θ to the vertical.

The vertical sag $= S\cos\theta$

Problems for sag calculation:

① A 132 kV transmission line has the following data
Weight 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 requi is 10 metres.

Weight of Conductor/metre $W = 680/1000$

$$W = 0.68 kg$$

Tension, $T = \frac{\text{Ultimate strength}}{\text{Safety factor}} = \frac{3100}{2}$

$$T = 1550 kg$$

$l = 260 m$

$$Sag = \frac{wl^2}{8T} = \frac{0.68(260)^2}{8 \times 1550}$$

$$Sag = 3.7 m$$

Conductor should be supported at a height of

$10 + 3.7 = 13.7 m$

(2) A transmission line has a span of 150 m between level supports. The conductor has a cross sectional area of $2 cm^2$. The tension in the conductor is 2000 kg. If the specific gravity of the conductor material is $9.9 gm/cm^3$ and wind pressure is 1.5 kg/m. Calculate the sag and vertical sag.

Given data: span length, $l = 150 m$

Tension $T = 2000 kg$

Wind force/m, $W_w = 1.5 kg$

Weight of Conductor/m = Sp. Gravity × Volume of 1m Conductor

$= 9.9 \times 2 \times 100 = 1980\ gm$

$$W = 1.98\,kg$$

Total weight of 1m length of Conductor is

$$W_t = \sqrt{w^2 + w_w^2}$$

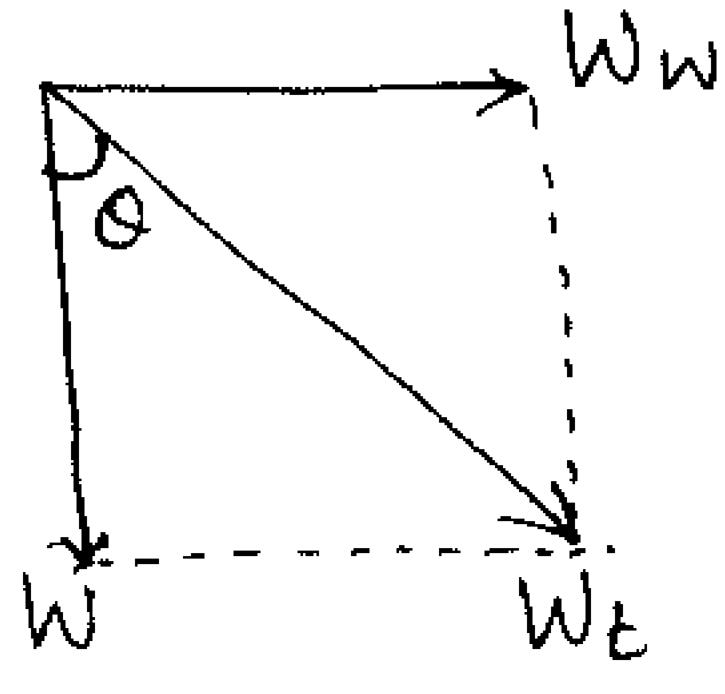
$$= \sqrt{(1.98)^2 + (1.5)^2}$$

$$W_t = 2.48\,kg$$

$$\text{Sag},\ S = \frac{W_t l^2}{8T} = \frac{2.48(150)^2}{8 \times 2000}$$

$$S = 3.48\,m$$

$$\tan\theta = \frac{W_w}{W} = 1.5/1.98$$



$\tan\theta = 0.76$

$\theta = \tan^{-1}(0.76)$

$\theta = 37.23^\circ$

Vertical sag $= S\cos\theta$

$= 3.48 \times \cos 37.23$

Vertical Sag = 2.77m

(3) A transmission line has a span of 200 meters between level supports. The conductor has a cross sectional area of 1.29 cm^2, weights 1170 kg/km and has a breaking stress of 4218 kg/cm^2. Calculate the sag for a safety factor of 5, allowing wind force/m length is 1.56 kg. What is the vertical sag? (17)

Given data: $l = 200\,m$ $a = 1.29\,cm^2$

$W = 1170\,kg/km$ Breaking stress $= 4218\,kg/cm^2$

Safety factor 5, $W_W = 1.56\,kg$

Find: Sag, Vertical sag

Weight of Conductor/m, $W = 1170/1000$

$$\boxed{W = 1.17\,kg}$$

Total weight $W_t = \sqrt{W^2 + W_W^2}$

$$W_t = \sqrt{(1.17)^2 + (1.56)^2}$$

$$\boxed{W_t = 1.95\,kg}$$

$$\text{Slant sag}, S = \frac{W_t l^2}{8T} = \frac{1.95 \times (200)^2}{8 \times 1088}$$

$$\boxed{S = 8.96\,m}$$

$$\tan\theta = W_W/W, \quad \theta = \tan^{-1}(W_W/W) = \tan^{-1}\left(\frac{1.56}{1.17}\right)$$

$\theta = 53.13°$

Vertical sag $= S\cos\theta = 8.96 \times \cos 53.13$

Vertical sag = 5.37m

(4) A transmission line has a span of 275 m between level supports. The conductor has an effective diameter of 1.96 cm and weights 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 a wind pressure of 3.9 gm/cm^2 of projected area, calculate sag for a safety factor 2. Weight of 1cc of ice is 0.91 gm.

Given data: $l = 275m$ $W = 0.865 \, kg/m$

$d = 1.96cm$ $t = 1.27 \, cm$

Ultimate strength = 8060 kg Wind pressure = 3.9 gm/cm

Safety factor = 2 Density of weight = 0.91 gm

Tension $T = 8060/2 = 4030 \, kg$

Volume of ice/m $= \pi t(d+t) \times 100 \, cm^3$

$= \pi \times 1.27 (1.96 + 1.27) \times 100$

$= 1288 \, cm^3$

Weight of ice/m $W_i = 0.91 \times 1288$

$= 1172 \text{ gm}$

$$W_i = 1.172 \text{ kg}$$

Wind force/m W_W = Wind pressure × d+2t ×100

$= 3.9 \times (1.96 + 2 \times 1.27) \times 100$

$= 1755 \text{ gm}$

$$W_W = 1.755 \text{ kg}$$

Total weight of Conductor/m

$$W_t = \sqrt{(w + W_i)^2 + (W_W)^2}$$

$$= \sqrt{(0.865 + 1.172)^2 + (1.755)^2}$$

$$W_t = 2.688 \text{ kg}$$

$$Sag = \frac{W_t l^2}{8T} = \frac{2.688 \times (275)^2}{8 \times 4030}$$

$$Sag = 6.3 \text{ m}$$

(5) An overhead line has a span of 150 m between level supports. The conductor has a cross sectional area of 2 cm². The ultimate strength is 5000 kg/cm² and safety factor is 5. The specific gravity of the material is 8.9 gm/cc. The wind pressure is 1.5 kg/m. Calculate the height of the conductor above the ground level at which it should be supported if a minimum clearance of 7 m is to be left between the ground and the conductor.

Given Data: Span length $l = 150\text{m}$ $W_W = 1.5\text{ kg/m}$

$a = 2\text{cm}^2$, Ultimate Strength $= 5000\text{ kg/cm}^2$

Safety factor $= 5$, Specific gravity $= 8.9\text{ gm/cc}$

Minimum clearance $= 7\text{m}$

Solution:

Weight of Conductor $W = 2 \times 100 \times 8.9$

$= 1780\text{ gm}$

$W = 1.78\text{ kg}$

$T = 5000 \times 2/5$

$T = 2000\text{ kg}$

$W_t = \sqrt{W^2 + W_W^2}$

$W_t = \sqrt{(1.78)^2 + (1.5)^2} = 2.33\text{ kg}$

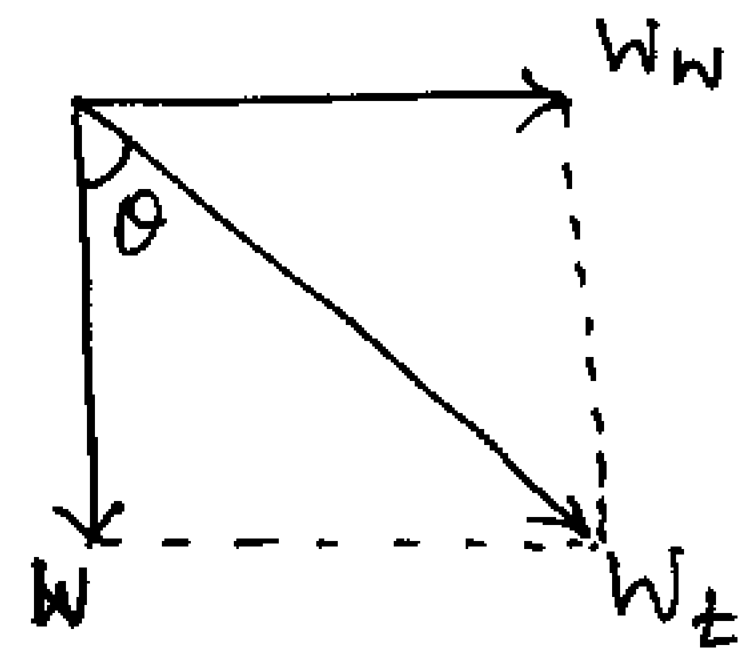
$W_t = 2.33\text{ kg}$

Slant Sag, $S = \frac{W_t l^2}{8T} = \frac{2.33 \times (150)^2}{8 \times 2000}$

$S = 3.28\text{m}$

Vertical sag $= \delta \cos\theta = 3.28 \times W/W_t$

$\because \cos\theta = \frac{W}{W_t}$ $\therefore$



Vertical sag $= 3.28 \times 1.78/2.33$

Vertical sag = 2.5 m

Conductor should be supported at height

$= 7 + 2.5 = 9.5$ m

(6) The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance between the tower is 500m. If the tension in the conductor is 1600kg, 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 tower can be considered to be at water level.

Given Data: $l = 500$m $W = 1.5$ kg $T = 1600$ kg

$h = 90 - 30 = 60$m

Solution: $x_1 + x_2 = 500$m —(1)

Sag $S_1 = \frac{W x_1^2}{2T}$ Sag $S_2 = \frac{W x_2^2}{2T}$

$$h = S_2 - S_1 = \frac{Wx_2^2}{2T} - \frac{Wx_1^2}{2T}$$

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

$$x_2 - x_1 = \frac{60 \times 2 \times 1600}{1.5 \times 500} = 256\,m$$

$$x_2 - x_1 = 256\,m \quad \text{--- (2)}$$

Adding the eqns (1) & (2)

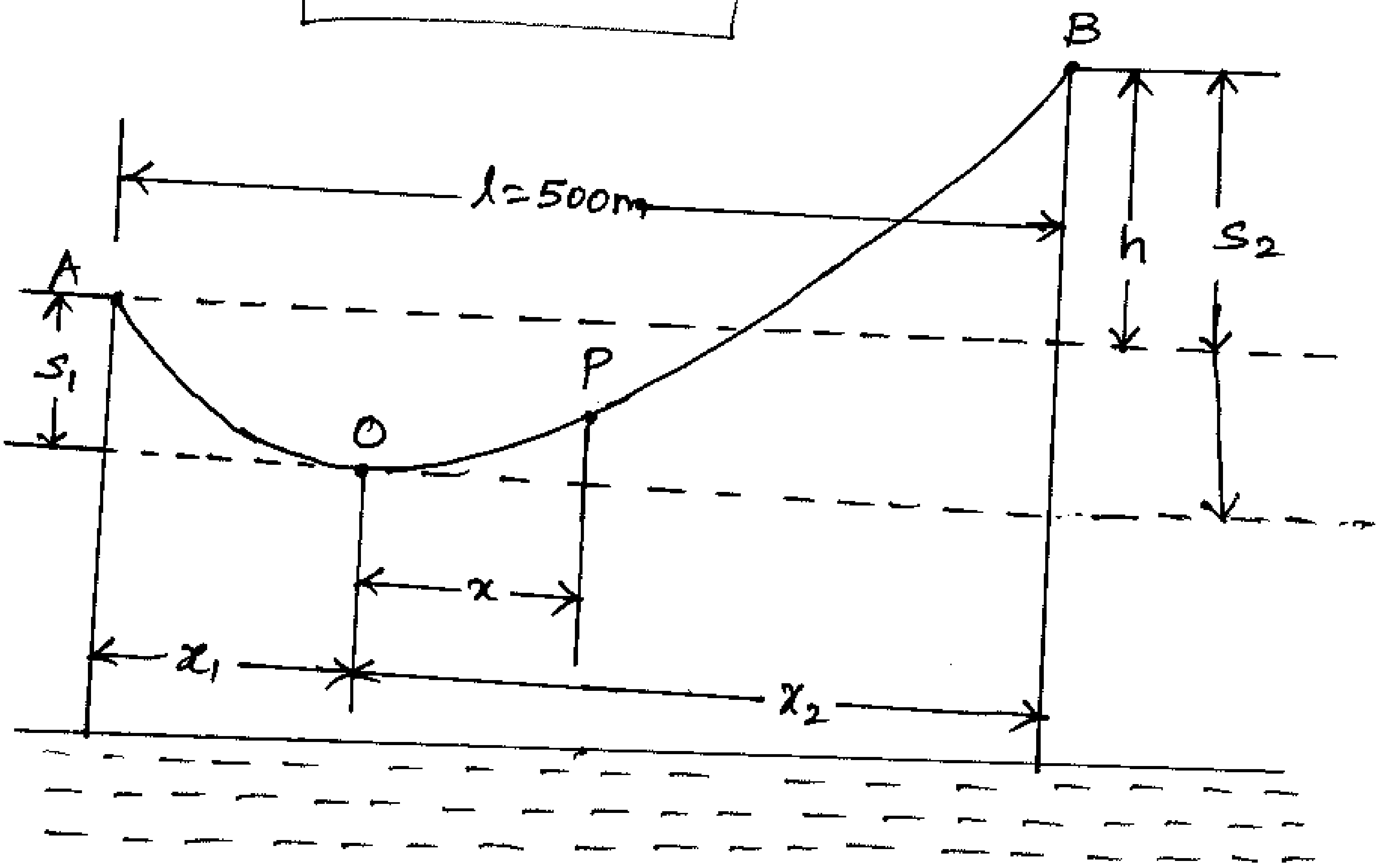
$$x_1 + x_2 + x_2 - x_1 = 500 + 256$$

$$2x_2 = 756, \quad \boxed{x_2 = 378\,m}$$

Substitute $x_2 = 378$ in eqn (1)

$$x_1 + 378 = 500, \quad x_1 = 500 - 378$$

$$\boxed{x_1 = 122\,m}$$



$$S_1 = \frac{Wx_1^2}{2T} = \frac{1.5 \times (122)^2}{2 \times 1600}$$

$$\boxed{S_1 = 7m}$$

Clearance of the lowest point o from water level

$= 30 - 7 = 23m$

Let the mid point P be at a distance x from the lowest point o.

$x = 250 - x_1 = 250 - 122 = 128m$

$$S_{mid} = \frac{Wx^2}{2T} = \frac{1.5\,(128)^2}{2 \times 1600}$$

$$\boxed{S_{mid} = 7.68m}$$

Clearance of mid point P from water level

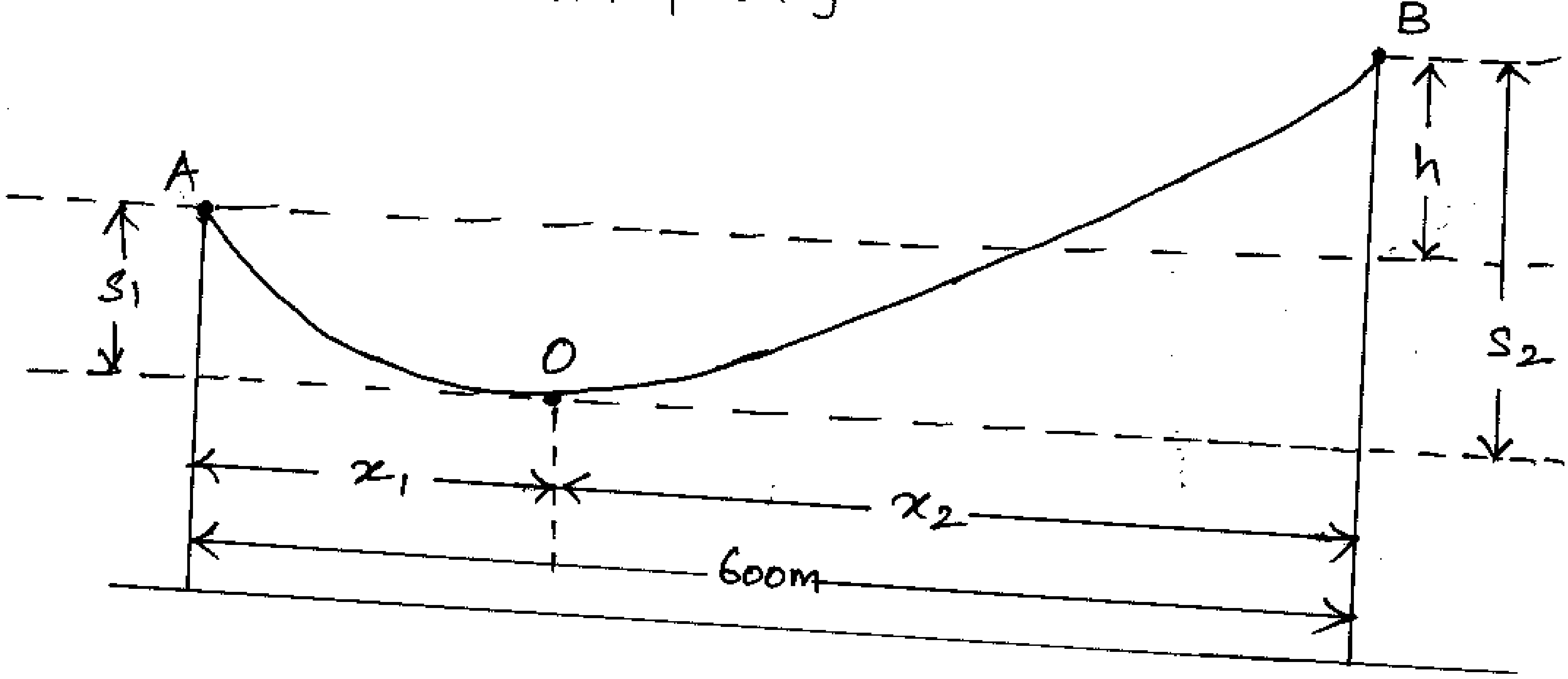
$= 23 + 7.68 = 30.68m$

(7) An overhead transmission line conductor having a parabolic configuration weight 1.925 kg/m. The area of cross section of the conductor is 2.2 cm² and the ultimate strength is 8000 kg/cm². The supports are 600 m apart having 15 m difference of levels. Calculate the sag from the taller of the two supports which must be allowed so that the factor of safety shall be 5. Assume that ice load is

1kg per metre run and there is no wind pressure.

Solution: $l = 600m$ $W_i = 1kg$, $h = 15m$

$W = 1.925 kg$



$$T = 8000 \times 2.2/5 = 3520kg$$

$$\boxed{T = 3520kg}$$

$$W_t = W + W_i = 1.925 + 1 = 2.925 kg$$

$$\boxed{W_t = 2.925 kg}$$

$$x_1 + x_2 = 600m \quad \text{— (1)}$$

$$h = S_2 - S_1 = \frac{W_t x_2^2}{2T} - \frac{W_t x_1^2}{2T}, \quad 15 = \frac{W_t}{2T}(x_2+x_1)(x_2-x$$

$$x_2 - x_1 = \frac{2 \times 15 \times 3520}{2.925 \times 600} = 60m$$

$$x_2 - x_1 = 60 \quad \text{— (2)} \quad \text{Adding eqns (1) \& (2)}$$

$$x_1 + x_2 + x_2 - x_1 = 600 + 60, \quad 2x_2 = 660$$

$$\boxed{x_2 = 330m}, \quad x_1 + x_2 = 600, \quad x_1 = 600 - 330$$

$$\boxed{x_1 = 270m}$$

Sag from the taller of the tower is

$$S_2 = \frac{W_t x_2^2}{2T} = \frac{2.925 (330)^2}{2 \times 3520} \quad \boxed{S_2 = 45.24m}$$

Insulators:

Insulators are the elements which Provide necessary insulation between line Conductors and Supports (tower) and thus prevent any leakage current from Conductors to earth.

Properties of a Good Insulator:

* It should be mechanically strong
* It must have very high Insulation resistance
* It should have high dielectric strength
* It should be able to withstand over voltage and Normal Working Voltage.
* It should be a Perfect homogeneous material.
* It should be non-porous
* It should not have any impurities like holes crakes etc.
* It should not be affected by the changes in the temperature.

Insulator materials:

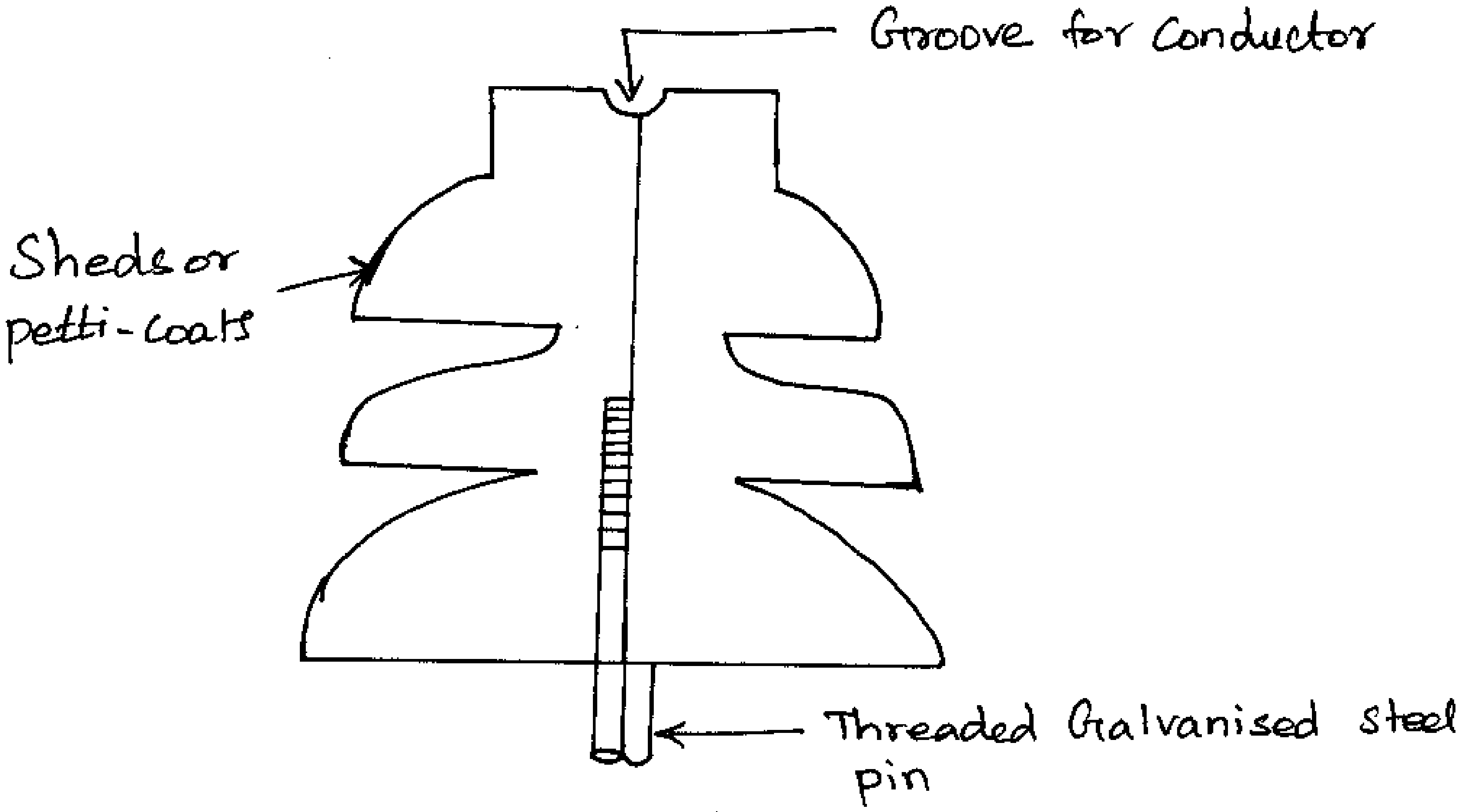
* Glazed porcelain insulator
* Glass insulator
* Synthetic insulator

Types of Insulator:

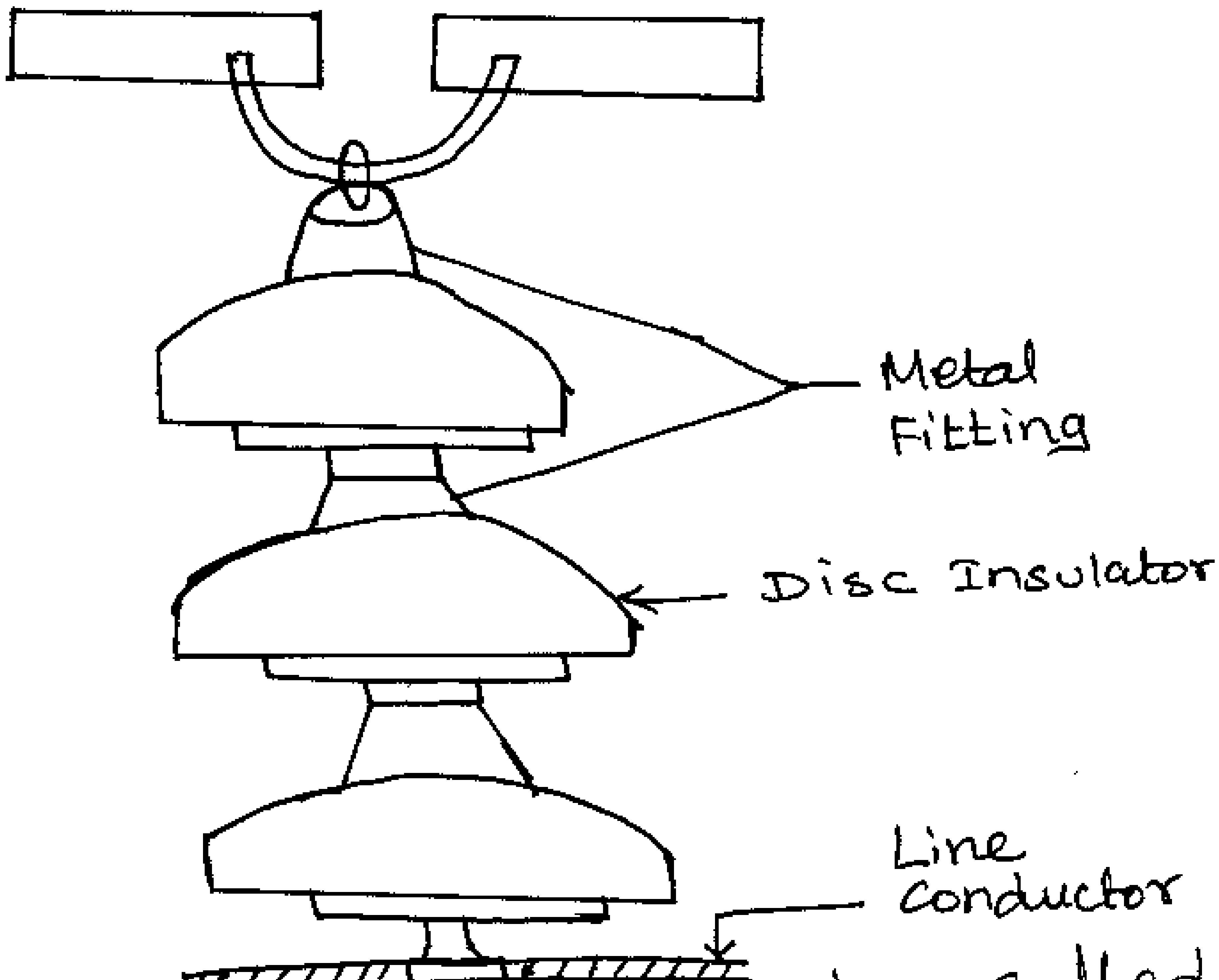
1. Pin Type Insulator
2. Suspension type Insulator
3. Strain Insulator
4. Shackle Insulator
5. Stay Insulator
6. Stack Insulator

Pin Type Insulator:

Pin type insulators are secured to the cros arm on the pole. The conductor is bound into a groove on the top of the insulator. An adequate length of leakage path is obtained by providing insulator with 2 or 3 petticoats or rain sheds. These are so designed that even when outer surface of insulator is wet due to rain, sufficie leakage reactance is still given by the inner dry surfaces. Pin type insulators are normally used for 11kv. But it can also be used upto 33kv for transmission and distribution.



Suspension Type Insulator



* This type of insulator is otherwise called as disc or string insulators.

* As Pin type insulators cannot be used for Voltages > 50 kV.

* Suspension type insulators are used whose Cost is less at high Voltages.

* They Consists of number of porcelain discs Connected in series by metal links in the form of a string.
* Conductor is suspended at bottom end of String.
* Other end of String is secured to the cross arm of tower.
* The number of discs in series depend upon working Voltage.
* Each unit or disc is designed for 11kv.

Advantages:

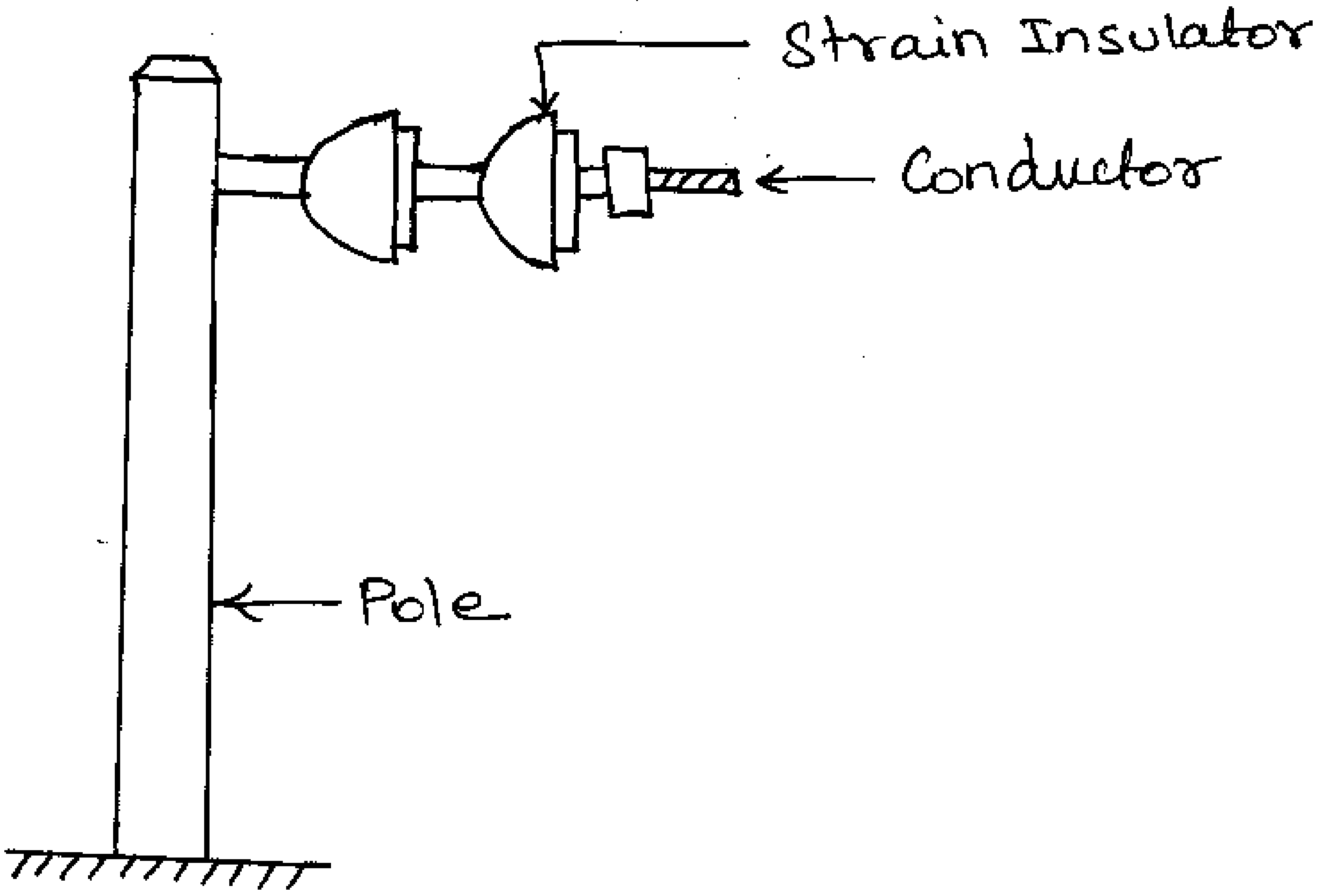
* Economical for voltage above 33kv
* Failure of any unit can be replaced without changing the whole String.
* Flexible in extension of voltage rating by adding more units.
* Since line is suspended flexibly, mechanical stresses are reduced.

Strain Insulators:

* These insulators are used to take the tension of the conductors at terminations of the line and at angle positions where there is a change in direction of the line.
* A Shackle insulator is suitable for light low

Voltage lines.

* But for high voltage, a string of suspension insulator is necessary.
* When tension in line is exceedingly high as at long river spans, two or more strings are used in parallel.
* The discs of a strain insulator are same as suspension insulator except that they are in a vertical plane.

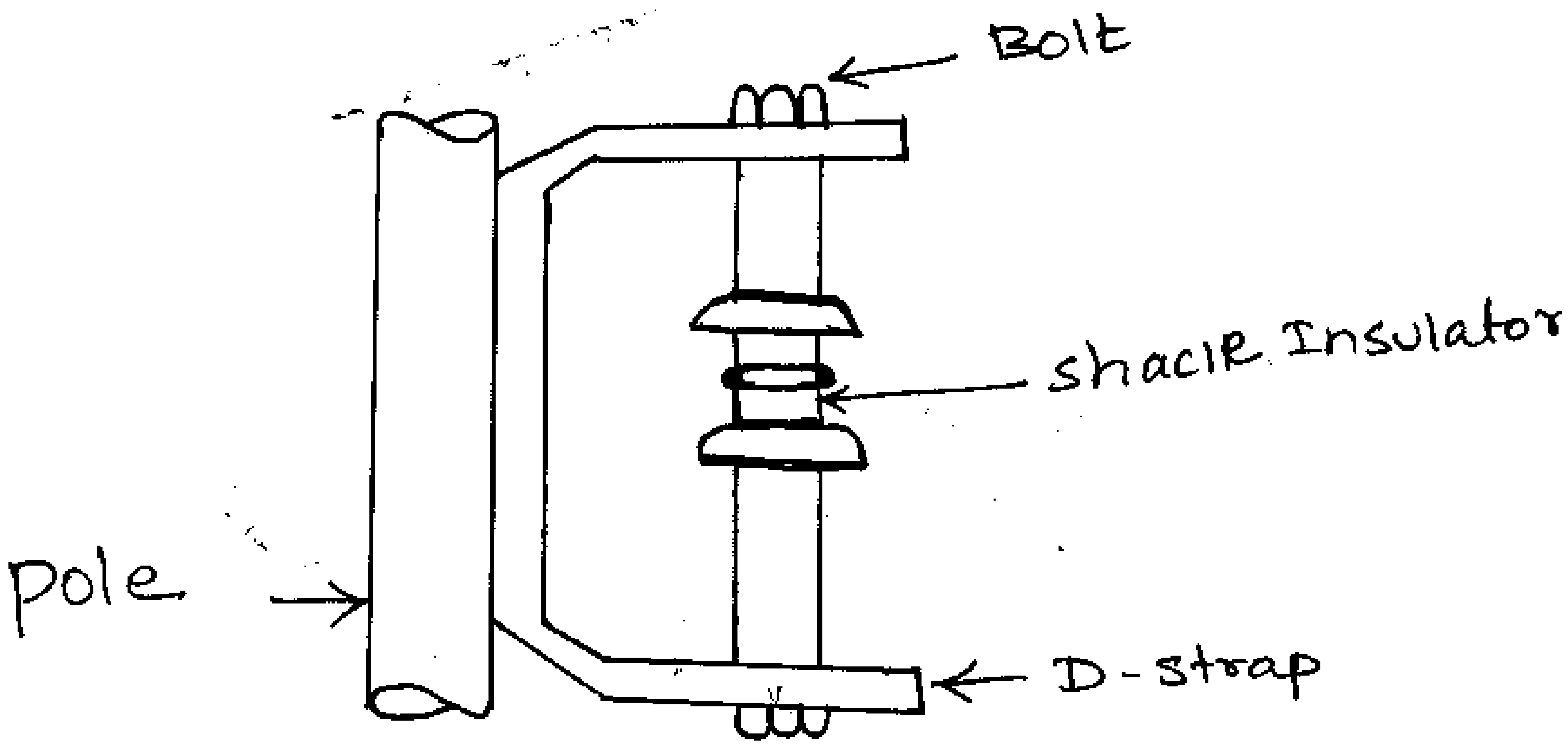


Shackle Insulators or Spool Insulators:

* In earlier days, shackle insulators were used as strain insulator.
* But nowadays, they are used for low voltage distribution lines.
* Shackle insulators can be used in either horizontal position or in vertical position.

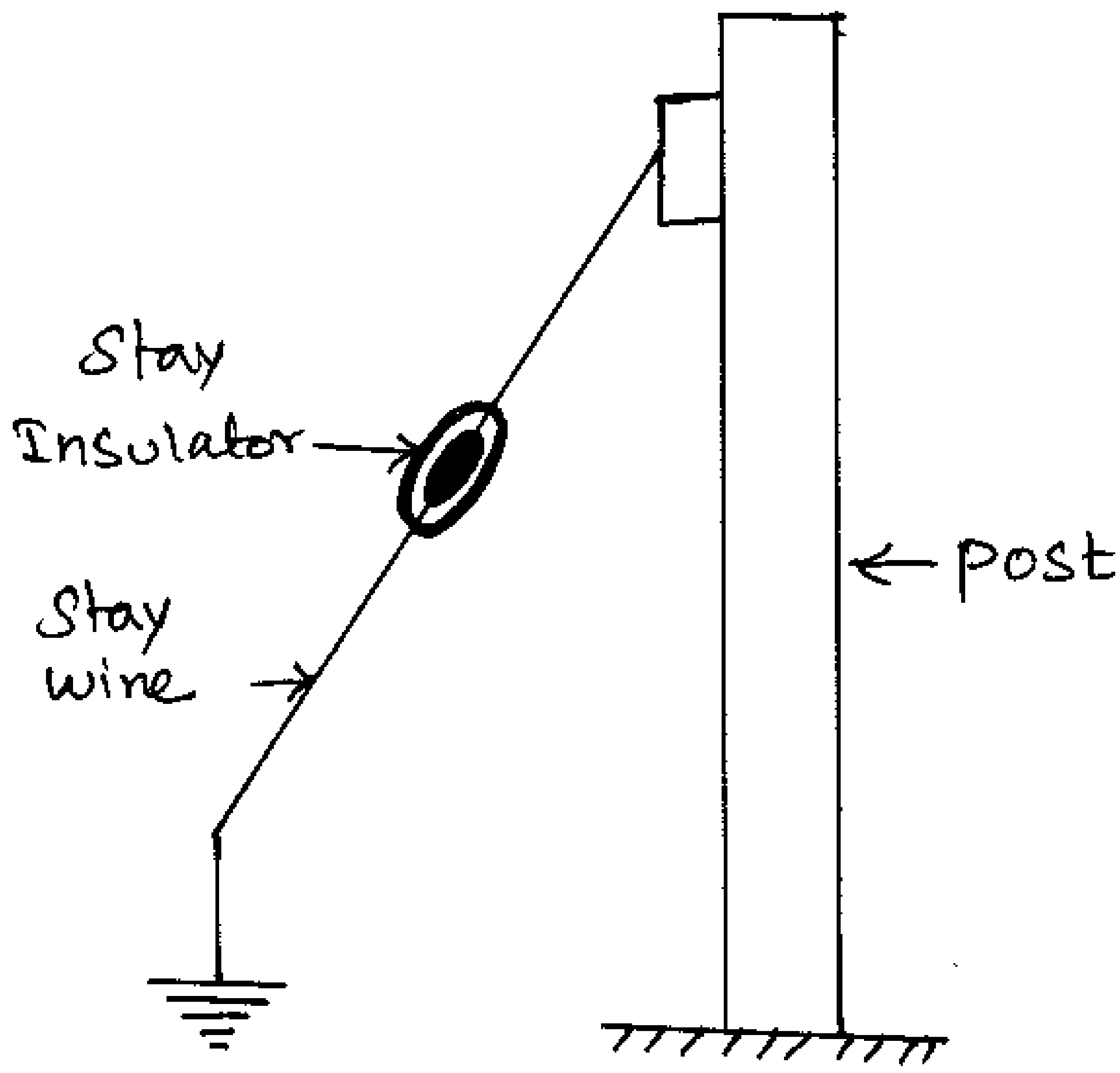
* They can directly fixed to pole with a bolt or to the cross arm.
* The conductor in groove is fixed with a soft binding wire.

~~Stay Insulators or Egg insulators~~:



Stay or Egg Insulators:

* The stay wire or guy wire is used to support the dead end Poles and keep the poles in its position.
* The insulator used in the stay wire is called as stay insulator.
* The shape of this insulator is egg, so it is called as egg insulator.
* It is also used to avoid leakage current flows through the lower Part of the stay wire.



Stack Insulators:

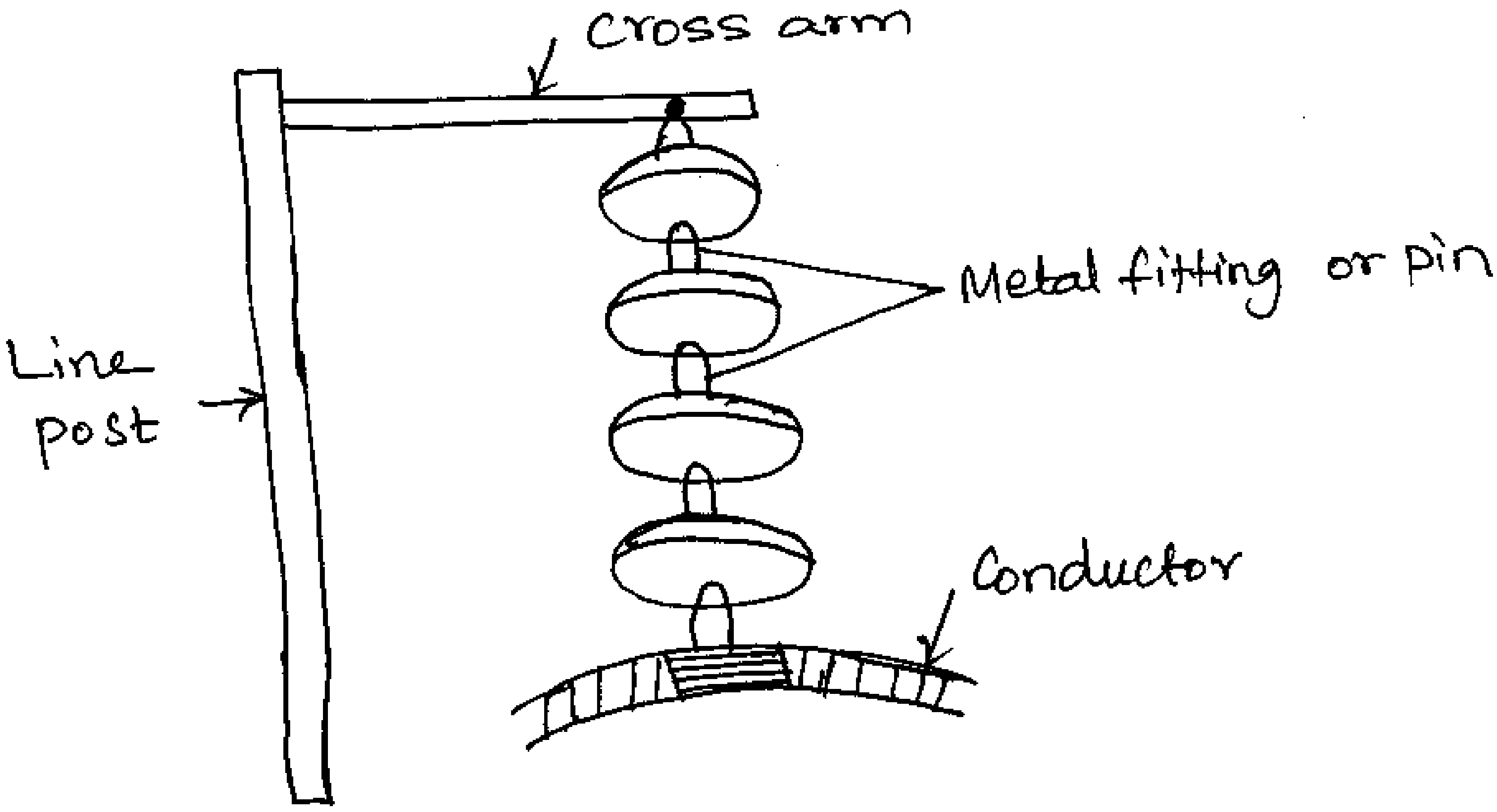
* Nowadays, these insulators are used for a Voltage above 110 kV.
* In this type, the discs are arranged as a stack.
* These type of insulators are easy to handle.

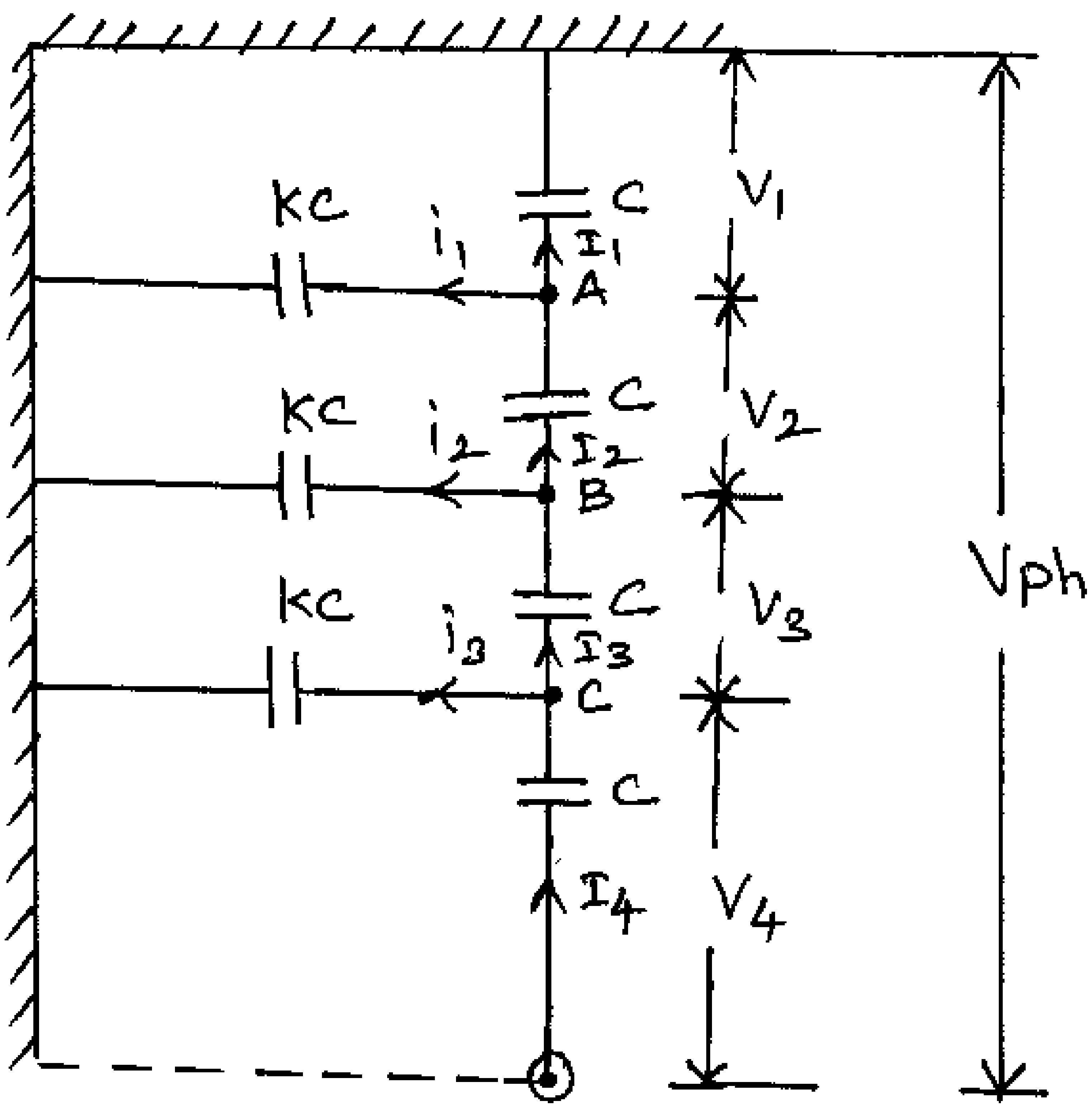
x————x

Voltage Distribution in Insulator string:

Consider a string having suspension insulators Assume the string Consists of four insulators in series which are separated by metal fittings. Thus the insulator forms a Capacitor 'C' called as Self Capacitance. In addition to this, there will be Capacitance between each metal fittings and earth i.e line support. In this Capacitance air acts as a dielectric and is called as ground Capacitance or mutual capacitance.

The number of discs depend on the operating Voltage i.e one disc for every 11kV. The Voltage across the discs are not uniformly distributed because of the Capacitance between metal fittings and the tower structure.





$$K = \frac{\text{Ground Capacitance}}{\text{self capacitance}} = \frac{kc}{c}$$

Reactance of self capacitance $X_c = \frac{1}{wc}$

Reactance of the ground capacitance

$$= \frac{1}{wkc}$$

Current flowing throug top insulator $I_1 = \frac{V_1}{X_c} = V_1 wc$

$$i_1 = V_1 wkc$$

$$I_2 = V_2 wc \qquad i_2 = (V_1 + V_2) wkc$$

$$I_3 = V_3 wc \qquad i_3 = (V_1 + V_2 + V_3) wkc$$

Apply KCL at Node A $\quad I_2 = I_1 + i_1$

$$V_2 wc = V_1 wc + V_1 wkc$$

$$\boxed{V_2 = V_1 (1 + k)}$$

Apply KCL at Node B

$$I_3 = I_2 + i_2$$

$$V_3 wc = V_2 wc + (V_1 + V_2) wkc$$

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

$$V_3 = V_1 (1+k) + [V_1 + V_1 (1+k)] k$$

$$= V_1 [1 + k + k + k + k^2]$$

$$\boxed{V_3 = V_1 [1 + 3k + k^2]}$$

Apply KCL at Node C:

$$I_4 = I_3 + i_3$$

$$V_4 \omega C = V_3 \omega C + (V_1+V_2+V_3)\omega k C$$

$$V_4 = V_3 + (V_1+V_2+V_3)k$$

$$V_4 = V_1(1+3k+k^2) + [V_1 + (1+k)V_1 + (1+3k+k^2)V_1]k$$

$$= V_1[1+3k+k^2+k+k+k^2+k+3k^2+k^3]$$

$$\boxed{V_4 = V_1[1+6k+5k^2+k^3]}$$

$$\boxed{V_{ph} = V_1+V_2+V_3+V_4}$$

Line Voltage $V_L = \sqrt{3} \times V_{ph}$

The Voltage drop across the insulator nearest to the Power Conductor is maximum and it goes on decreasing towards the Cross arm.

$$\boxed{V_4 > V_3 > V_2 > V_1}$$

String Efficiency

String efficiency is defind as the ratio of total Voltage across the string to the product of number of units and the voltage across the unit nearest to the line Conductor.

$$\text{String efficiency } \eta = \frac{\text{Voltage across the string } (V_{ph})}{\text{Number of Insulator} \times \text{Voltage across the unit nearest to the Power Conductor}}$$

η, String Efficiency = $\dfrac{V_{ph}}{n \times \text{Voltage across the insulator nearest to the line}}$

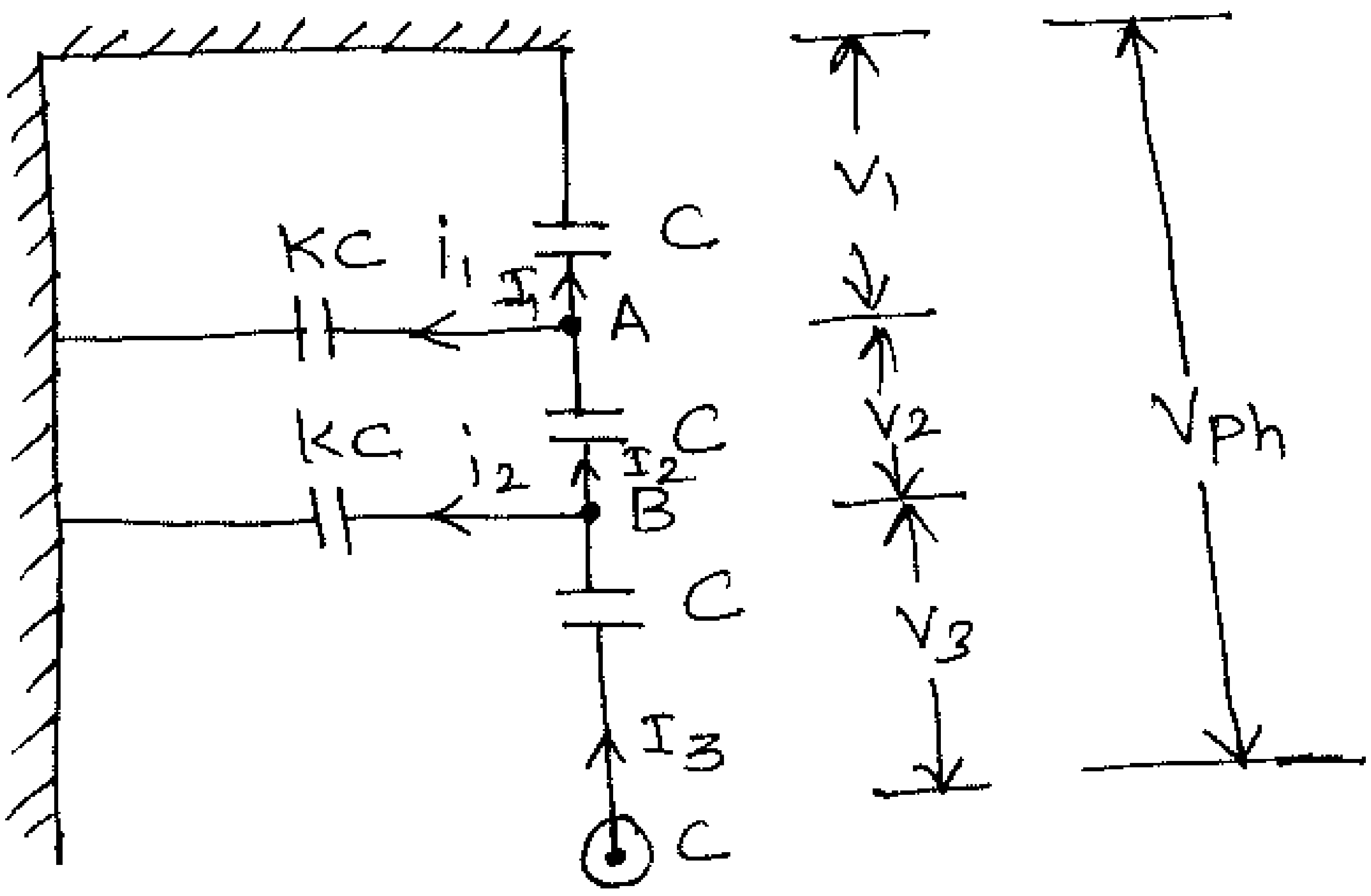
Problems for Voltage Distribution in insulator string

① . A 3 phase overhead transmission line is being Supported by three disc insulator. The potential across top unit and middle unit are 8KV and 11KV respectively. Calculate

(a) Ratio of capacitance between pin and earth to the self capacitance.

(b) Line Voltage

(c) String efficiency



Given: $V_1 = 8KV \quad V_2 = 11KV$

$I_1 = V_1 wc \qquad i_1 = V_1 wKc$

$I_2 = V_2 wc \qquad i_2 = (V_1+V_2) wKc$

$I_3 = V_3 wc$

Let k be the ratio of capacitance between meta[l] fitting and earth to self capacitance.

$$K = \frac{\text{Ground Capacitance}}{\text{self capacitance}} = \frac{kC}{C}$$

Apply KCL to junction A

$$I_2 = I_1 + i_1$$

$$V_2 wC = V_1 wC + V_1 kwC$$

$$V_2 = V_1 + V_1 K$$

$$V_2 = V_1 (1+k)$$

$$1+K = \frac{V_2}{V_1}$$

$$K = \frac{V_2}{V_1} - 1 = \frac{11}{8} - 1 = 0.375$$

$$\boxed{K = 0.375}$$

Applying KCL to junction B

$$I_3 = I_2 + i_2$$

$$V_3 wC = V_2 wC + (V_1 + V_2) wKC$$

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

$$V_3 = 1\$ + (08 + 11) * 0.375$$

$$= 8 + 19 \times 0.375$$

$$\boxed{V_3 = 15.125 \text{ kV}}$$

$$V_{ph} = V_1 + V_2 + V_3 = 8 + 11 + 15.125$$

$$V_{ph} = 34.125\,kV$$

Line voltage $= \sqrt{3} \times V_{ph} = \sqrt{3} \times 34.125$

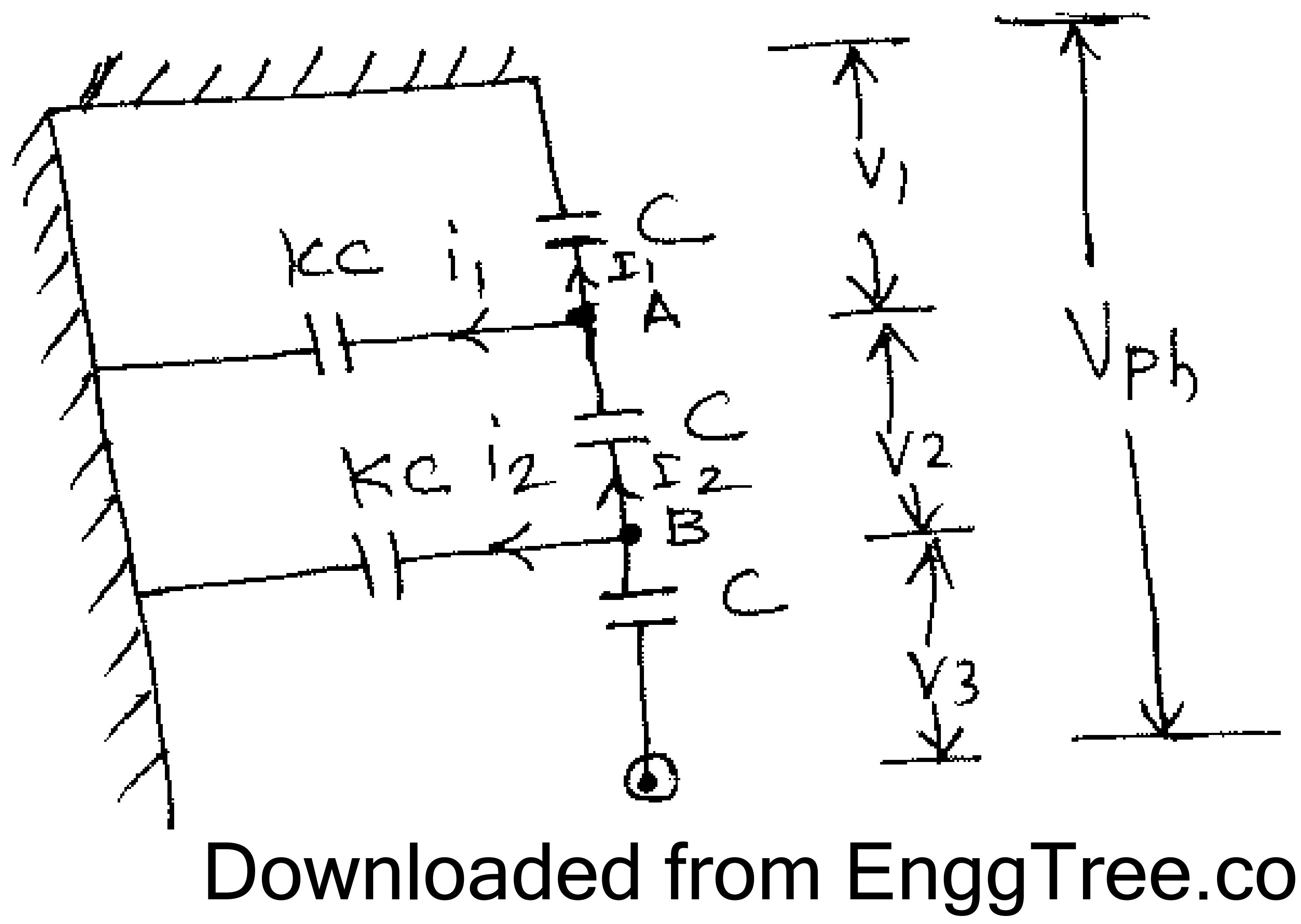
$$\text{Line Voltage} = 59.106\,kV$$

$$\text{String efficiency} = \frac{V_{ph}}{N \times V_3}$$

$$= \frac{34.125}{3 \times 15.125} \times 100$$

$$\eta = 75.2\%$$

(2) An insulator string consists of three units, having a safe working voltage of 20kV. The ratio of self to shunt capacitance is 6:1. Determine the line voltage and string efficiency.



Given data:

$$V_3 = 20kV$$

$$\frac{C}{KC} = \frac{6}{1}$$

$$K = \frac{1}{6}, \quad \boxed{K = 0.1666}$$

$$V_3 = V_1(1 + 3k + k^2)$$

$$V_1 = \frac{V_3}{1+3k+k^2} = \frac{20}{(0.1666)^2 + 3\times 0.1666 + 1}$$

$$\boxed{V_1 = 13.093kV}$$

$$V_2 = (1+k)V_1 = (1 + 0.1666)\times 13.093$$

$$\boxed{V_2 = 15.274 kV}$$

$$V_{ph} = V_1 + V_2 + V_3 = 13.093 + 15.274 + 20$$

$$\boxed{V_{ph} = 48.367 kV}$$

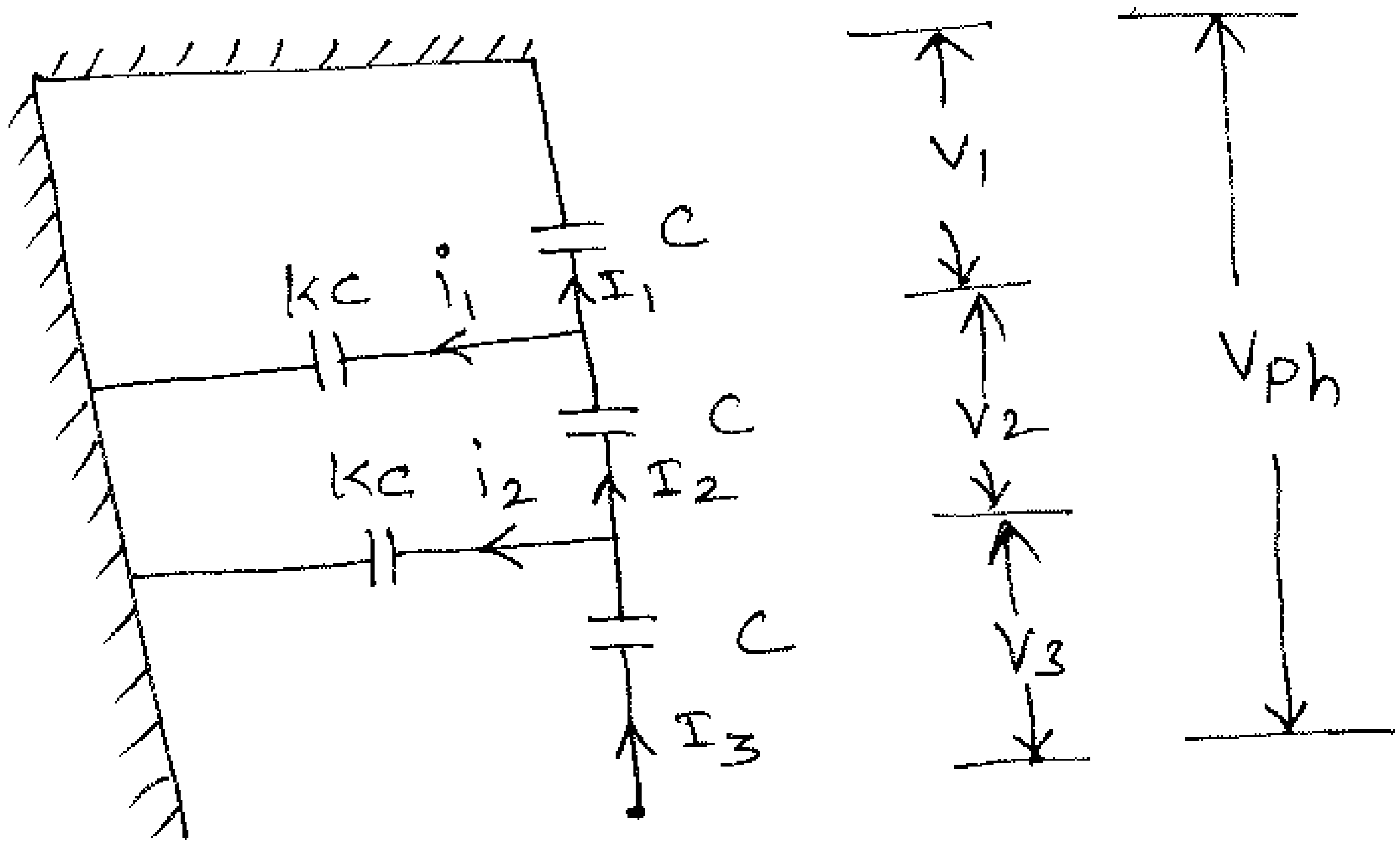
$$\text{Line Voltage} = \sqrt{3} \times V_{ph} = \sqrt{3} \times 48.367$$

$$\boxed{\text{Line voltage} = 83.774 kV}$$

$$\text{String efficiency } \eta = \frac{V_{ph}}{n \times V_3} = \frac{V_{ph}}{3 \times V_3} = \frac{48.367}{3 \times 20}$$

$$\boxed{\eta = 80.6\%}$$

(3) In a 33kV overhead line, there are three units in the string of insulators. If the capacitance (39) between each insulator Pin and earth is 11 % of Self capacitance of each insulator, find the distribution of voltage over 3 insulator and string efficiency. Draw the equivalent circuit.



$V_L = 33KV$

$V_{ph} = \frac{33}{\sqrt{3}} = 19.05KV$

$KC = \frac{11}{100} C$

$K = \frac{11}{100}$ $\boxed{K = 0.11}$

$V_2 = V_1(1+K)$

$= (1+0.11)V_1$

$\boxed{V_2 = 1.11 V_1}$

$$V_3 = V_1(1+3k+k^2)$$

$$= V_1(1+3\times0.11+(0.11)^2)$$

$$\boxed{V_3 = 1.3421V_1}$$

$$V_{ph} = V_1+V_2+V_3$$

$$19.05 = V_1+1.11V_1+1.3421V_1$$

$$19.05 = 3.4521V_1$$

$$V_1 = \frac{19.05}{3.4521} = 5.518\ kV$$

$$\boxed{V_1 = 5.518\ kV}$$

$$V_2 = 1.11V_1 = 1.11\times5.518$$

$$\boxed{V_2 = 6.125\ kV}$$

$$V_3 = 1.3421V_1 = 1.3421\times5.518$$

$$\boxed{V_3 = 7.406\ kV}$$

String efficiency, $\eta = \dfrac{V_{ph}}{3\times V_3} = \dfrac{19.05}{3\times7.406}$

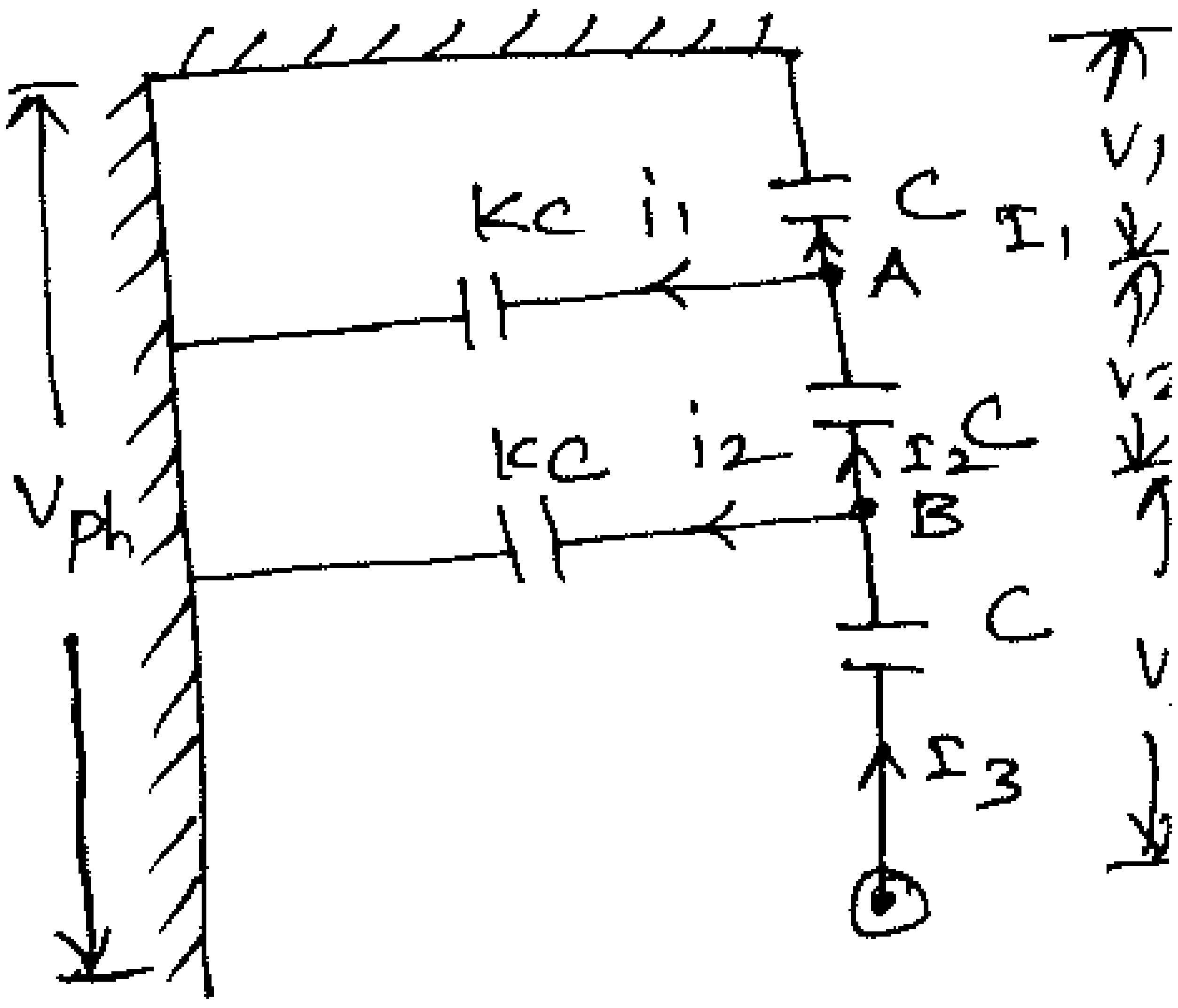
$$\boxed{\eta = 85.74\ \%}$$

(4). Each line of a three phase system is suspended by a string of three similar insulator. If the voltage across the line unit is 20kV. Calculate the line to neutral voltage and string efficiency. Assume that the shunt capacitance between each Insulator and earthed metal work of the tower be 1/10th of the capacitance of the insulator.

Given data:

$V_3 = 20\,kV$

$KC = \frac{1}{10} C$



Find: V_L & η

$K\not{C} = \frac{1}{10} \not{C}$

$\boxed{K = 0.1}$

$V_3 = V_1 (1 + 3K + K^2)$

$V_1 = \frac{20}{1 + 0.1 \times 3 + (0.1)^2}$

$\boxed{V_1 = 15.267\,kV}$

$V_2 = (1+K) V_1$

$= (1 + 0.1) V_1 = 1.1 V_1$

$V_2 = 1.1 \times 15.267$

$V_2 = 16.794$ kV

$V_{ph} = V_1 + V_2 + V_3$

$= 15.267 + 16.794 + 20$

$V_{ph} = 52.061$ kV

Line Voltage $= \sqrt{3} \times V_{ph} = \sqrt{3} \times 52.061$

Line Voltage $= 90.172$ kV

String efficiency $\eta = \dfrac{V_{ph}}{n \times V_3} = \dfrac{52.06}{3 \times 20}$

$\eta = 86.77\%$

(5). A 3φ overhead line is supported by the units of Post insulators, each having string of 3 pin type insulators. The Voltage across a unit nearest to line is 11 kV. Voltage across middle unit is 8.5 kV. Find the ratio of shunt to series Capacitance, line Voltage and String efficiency.

Given data: $V_3 = 11$ kV, $V_2 = 8.5$ kV

$V_2 = V_1(1+K)$

$$8.5 = V_1(1+k) \quad \cdots\cdots (1)$$

$$V_3 = V_1(1+3k+k^2)$$

$$11 = V_1(1+3k+k^2) \quad \cdots\cdots (2)$$

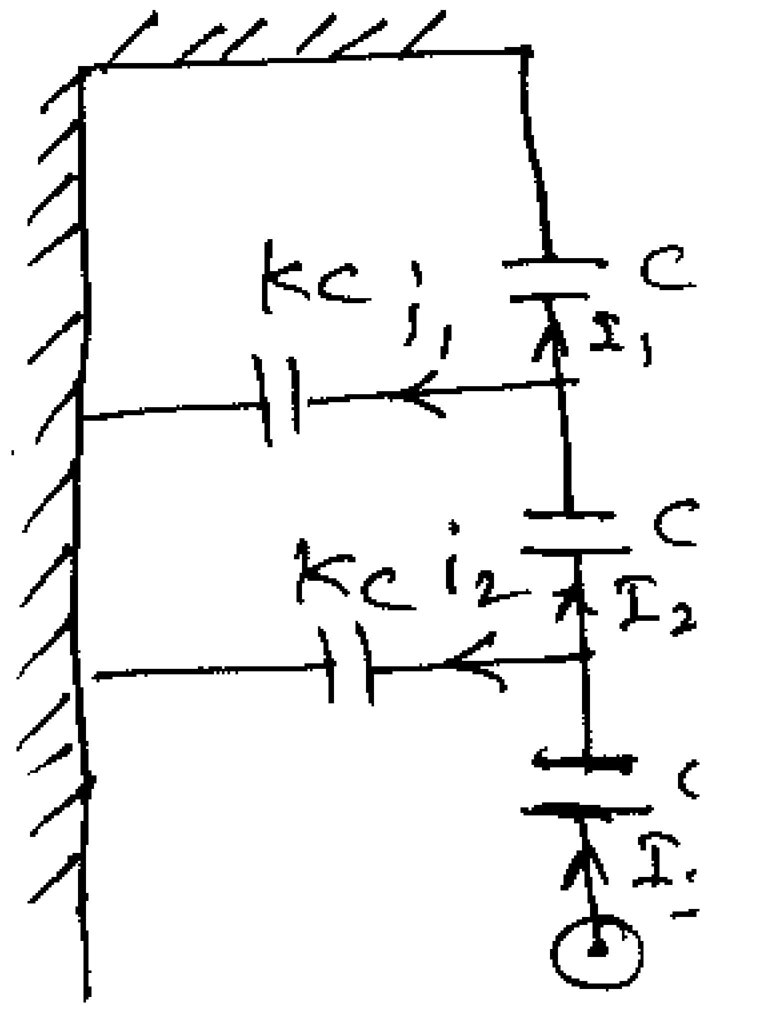
$$(2) \div (1) \Rightarrow \frac{11}{8.5} = \frac{V_1(1+3k+k^2)}{V_1(1+k)}$$

$$11 + 11k = 8.5 + (8.5 \times 3)k + 8.5k^2$$

$$8.5k^2 + 14.5k - 2.5 = 0$$

$$K = \frac{-14.5 \pm \sqrt{(14.5)^2 + 4(2.5)(8.5)}}{2 \times 8.5}$$

$$K = \frac{-14.5 \pm 17.18}{2 \times 8.5}$$



$$K = 0.1578 \text{ (or } -1.8635$$

K is positive, $K = 0.1578$

$$8.5 = V_1(1+K)$$

$$V_1 = \frac{8.5}{1+K} = \frac{8.5}{1+0.1578}$$

$$\boxed{V_1 = 7.342 \text{ kV}}$$

$$V_{ph} = V_1 + V_2 + V_3 = 7.342 + 8.5 + 11$$

$$\boxed{V_{ph} = 26.842} \text{ kV}$$

Line voltage, $V_L = \sqrt{3}\, V_{ph} = \sqrt{3} \times 26.842$

$$\boxed{V_L = 46.492 \text{ kV}}$$

$$\text{String efficiency} = \frac{V_{ph}}{3 \times V_3} \times 100$$

$$= \frac{26.842}{3 \times 11} \times 100$$

$$\boxed{\eta = 81.34\%}$$

(6) An insulation string for 66kv line has 4 discs. shunt capacitance between each joint and metal work is 12.5% of capacitance of each disc. Find voltage across the different disc and string efficiency.

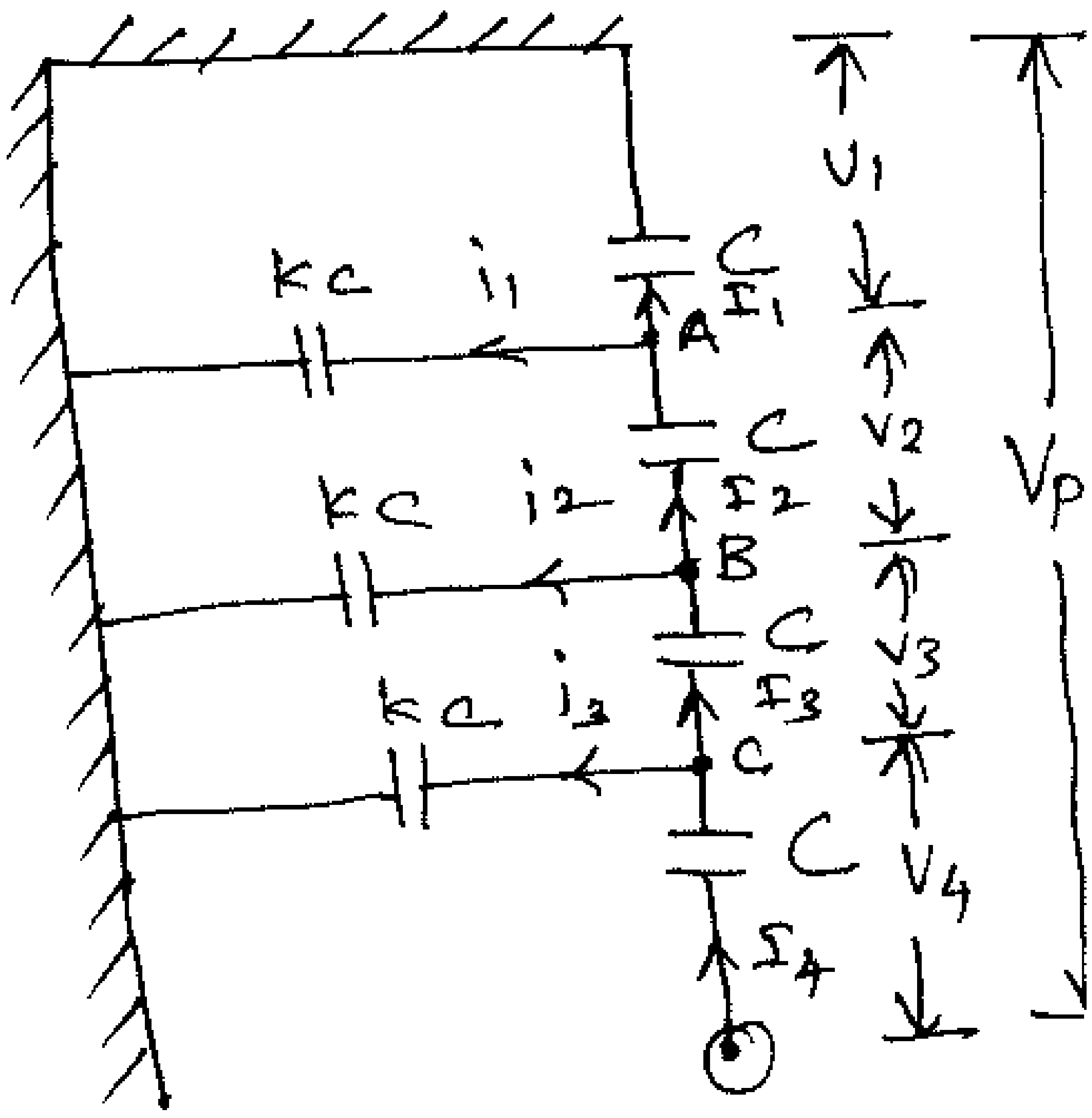
Given data: $V_L = 66kv$, $Kc = 12.5\% C$

$$V_{ph} = \frac{66}{\sqrt{3}} kv = 38.105 kv$$

$Kc = 12.5\% C$

$$\frac{kc}{c} = \frac{12.5}{100}$$

$$\boxed{k = 0.125}$$



$V_2 = V_1(1+k)$

$V_2 = V_1(1+0.125)$

$$\boxed{V_2 = 1.125 V_1}$$

$V_3 = V_1(1+3k+k^2)$

$= V_1[1+3 \times 0.125 + (0.125)^2]$

$$\boxed{V_3 = 1.39 V_1}$$

$$V_4 = (1 + 6k + 5k^2 + k^3)V_1$$

$$= V_1\left(1 + 6\times 0.125 + 5(0.125)^2 + (0.125)^3\right)$$

$$\boxed{V_4 = 1.83V_1}$$

$$V_{ph} = V_1 + V_2 + V_3 + V_4$$

$$= V_1 + 1.125V_1 + 1.39V_1 + 1.83V_1$$

$$V_{ph} = 5.345V_1$$

$$V_1 = \frac{38.105}{5.345}$$

$$\boxed{V_1 = 7.129\,kV}$$

$$V_2 = 1.125 \times 7.129$$

$$\boxed{V_2 = 8.02\,KV}$$

$$V_3 = 1.39V_1$$

$$= 1.39 \times 7.129$$

$$\boxed{V_3 = 9.912\,KV}$$

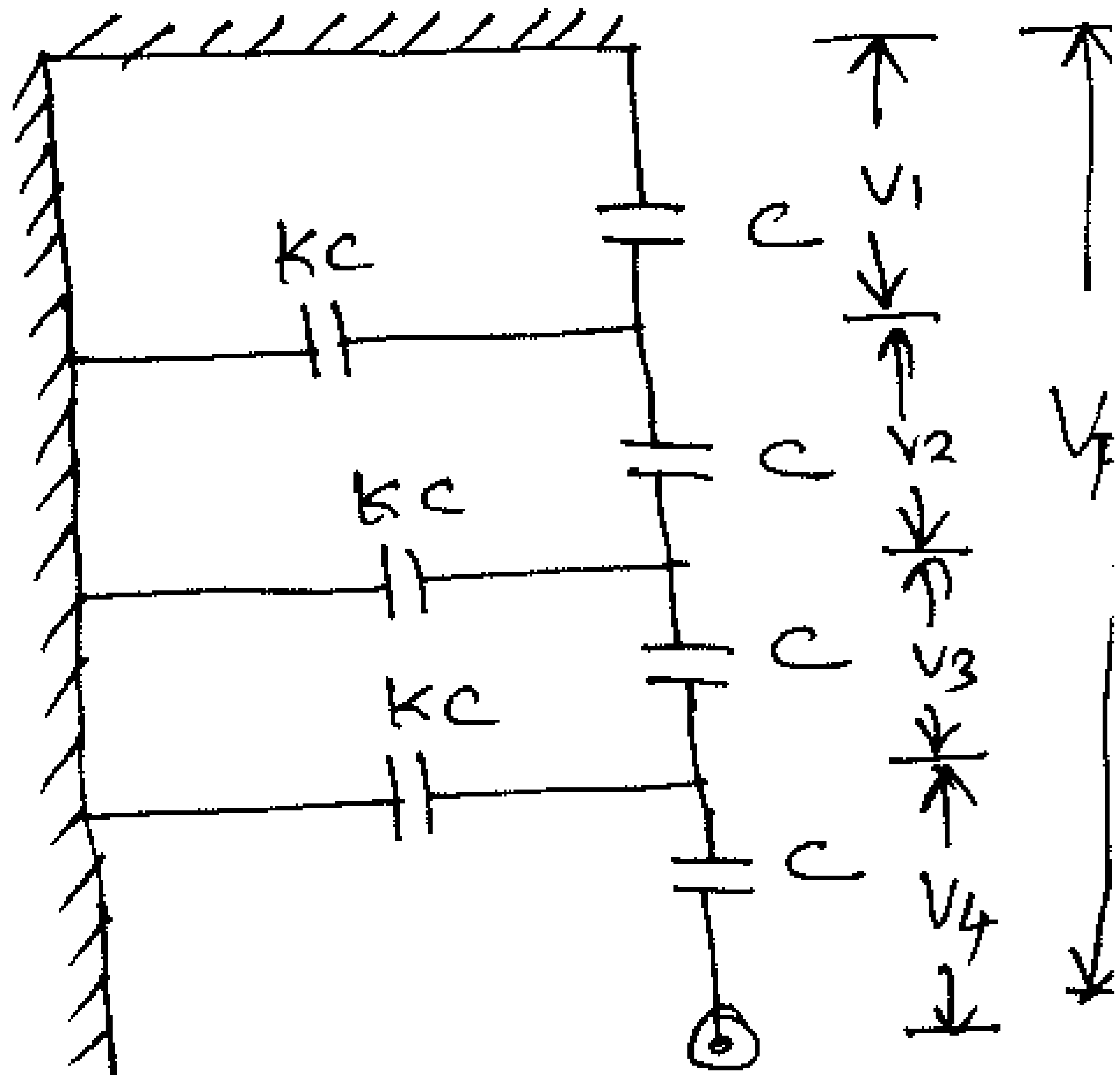
$$V_4 = 1.83V_1 = 1.83 \times 7.129$$

$$\boxed{V_4 = 13.045}$$

$$\text{String efficiency} = \frac{V_{ph}}{4 \times V_4} \times 100 = \frac{38.105}{4 \times 13.045} \times 100$$

$$\boxed{\eta = 73.03\%}$$

(7) A 3φ overhead line is supported on 4 disc suspension insulator. The voltage across the 2nd and 3rd discs are 13.8 kV and 15.2 kV respectively. Calculate line voltage and mention the nearest standard voltage in practice and string efficiency.



Given data:

$V_2 = 13.8\,kV, \quad V_3 = 15.2\,kV$

Find: V_L, η

Solution: $V_2 = V_1(1+k)$

$13.8 = V_1(1+k)$ — (1)

$V_3 = V_1(1+3k+k^2)$

$V_3 = 15.2$

$15.2 = V_1(1+3k+k^2)$ — (2)

$\frac{(2)}{(1)} \Rightarrow \frac{15.2}{13.8} = \frac{V_1(1+3k+k^2)}{V_1(1+k)}$

$15.2k + 15.2 = 13.8 + 41.4k + 13.8k^2$

$13.8k^2 + 26.2k - 1.4 = 0$

$a = 13.8, \; b = 26.2, \; c = -1.4$

$k = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

$k = 0.052$ or -1.311

$\boxed{k = 0.052}$

substitute $k = 0.052$ in equation (1) we get

$V_1(1+0.052) = 13.8$

$V_1 = \frac{13.8}{1.052}$, $\boxed{V_1 = 13.1183\ kV}$

$V_4 = V_1(1+6K+5K^2+K^3)$

$V_4 = 13.1183[1+6\times(0.052)+5(0.052)^2+(0.052)^3]$

$\boxed{V_4 = 17.39\ KV}$

$V_{ph} = V_1+V_2+V_3+V_4$

$= 13.118+13.8+15.2+17.391$

$\boxed{V_{ph} = 59.509\ kV}$

$V_L = \sqrt{3}\times V_{ph} = \sqrt{3}\times 59.09$

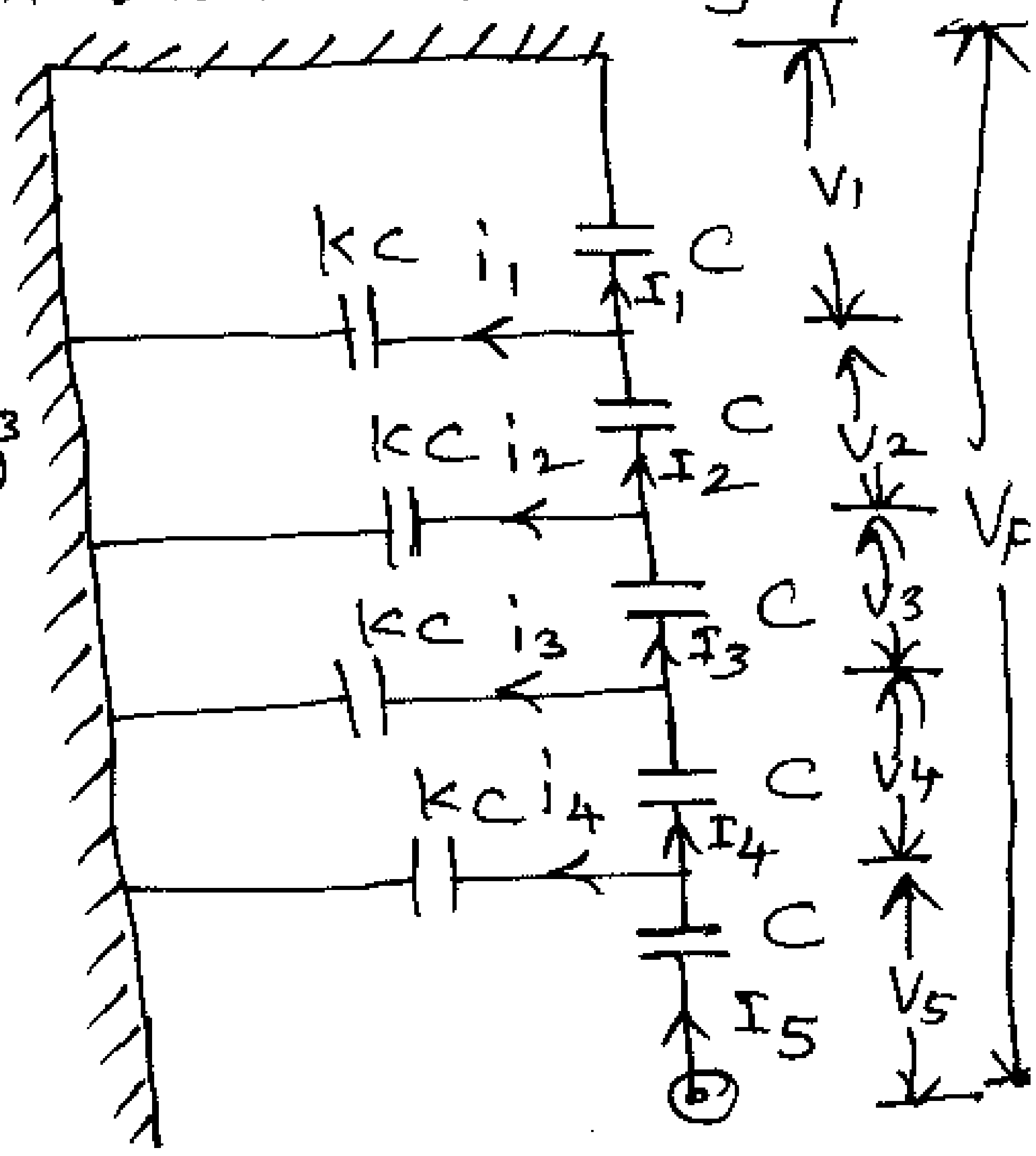
$\boxed{V_L = 103.07\ KV}$

% String efficiency $= \frac{V_{ph}\times 100}{4\times V_4}$

$\eta = \frac{59.509}{4\times 17.39}\times 100$

$\boxed{\eta = 85.54\ \%}$

(8) A String insulator has 5 units and voltage across the insulator nearest to the Conductor is 11 kV. The self capacitance of unit is 10 times the capacitance of metal fitting to earth. Find the voltage across each disc and string η.



$V_5 = 11\,kV$, $k = \frac{1}{10} = 0.1$

$V_5 = V_1(1 + 10k + 15k^2 + 7k^3 + k^4)$

$= V_1[1 + 10(0.1) + 15(0.1)^2 + 7(0.1)^3 + (0.1)^4]$

$V_5 = 2.1571\,V_1$

$V_1 = \frac{V_5}{2.1571} = \frac{11}{2.1571}$

$\boxed{V_1 = 5.1\,kV}$

$V_2 = V_1(1+k) = V_1(1+0.1) = 1.1V_1 = 1.1 \times 5.1$

$\boxed{V_2 = 5.61\,kV}$

$V_3 = V_1(1 + 3k + k^2) = V_1[1 + 3(0.1) + (0.1)^2] = 1.31V_1$

$V_3 = 1.31 \times 5.1 = 6.681\,kV$

$\boxed{V_3 = 6.681\,kV}$

$V_4 = V_1(1 + 6k + 5k^2 + k^3) = V_1(1 + 6\times0.1 + 5\times0.1 + 0.1^3)$

$= 1.651V_1 = 1.651 \times 5.1$

$\boxed{V_4 = 8.4201\,kV}$

$V_{ph} = V_1 + V_2 + V_3 + V_4 + V_5 = 5.1 + 5.61 + 6.681 + 8.42 + 11$

$\boxed{V_{ph} = 36.811\,kV}$

$$V_L = \sqrt{3} \times V_{ph} = \sqrt{3} \times 36.811$$

$$V_L = 63.756 kV$$

$$\eta = \frac{V_{ph}}{n \times V_5} = \frac{36.811}{5 \times 11} \times 100$$

$$\eta = 66.92\%$$

Improvement of String Efficiency

The following three methods are used to improve String efficiency of insulators or to equalize the potential across each unit.

a. By using longer Cross arms

b. By Grading of Insulators

c. By using guard ring or static Shielding

By using Longer Cross Arm

String efficiency depends on the Value of k.

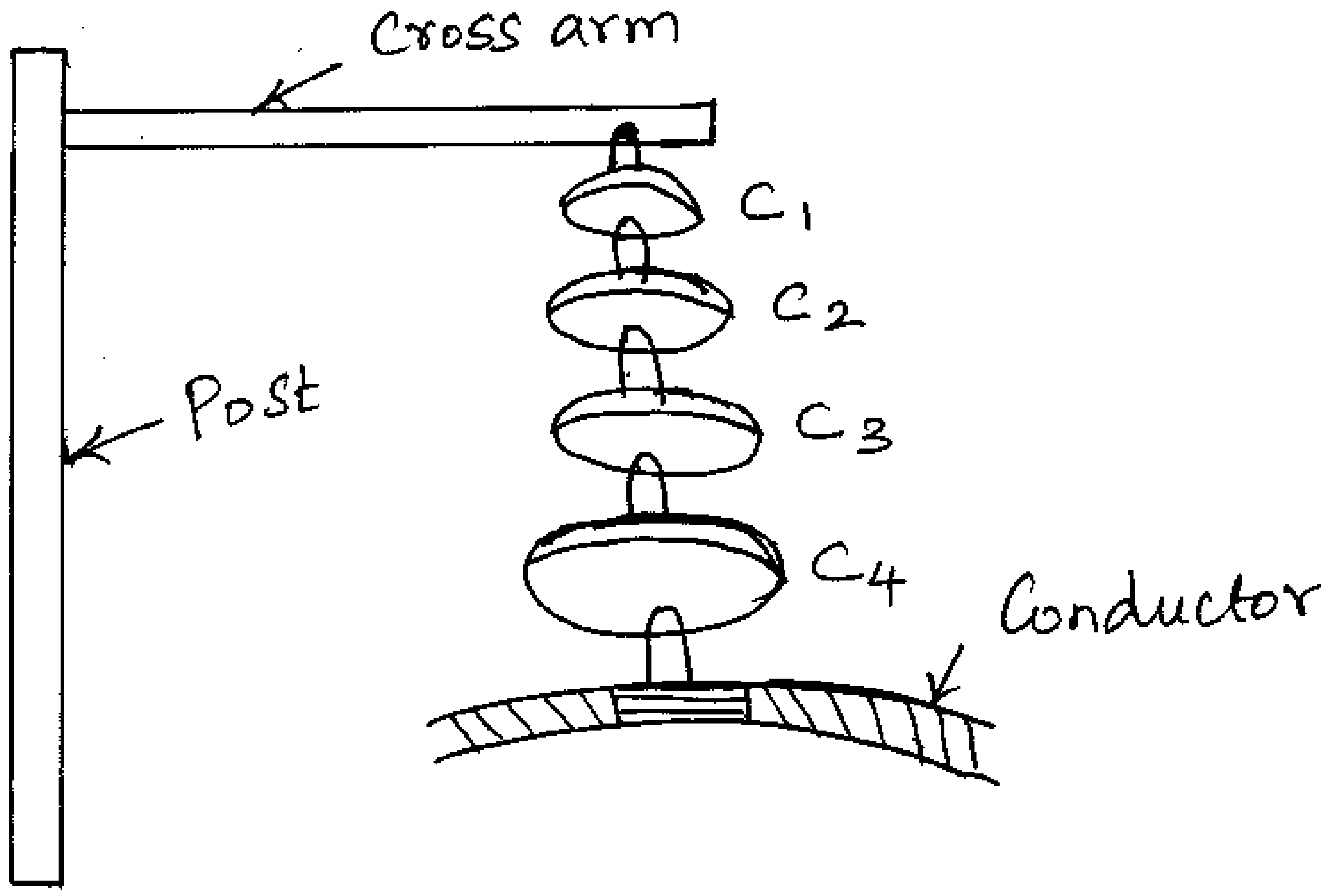
$$k = \frac{\text{Shunt Capacitance}}{\text{Self Capacitance}} = \frac{kc}{c} =$$

The Value of K can be decreased by reducing the value of Shunt Capacitance. So the String efficiency increases and the Voltage distribution is more.

To reduce C_{sh}, the distance of conductor from tower must be increased. However increasing the cross arm length beyond certain value is not economical. So the value of K cannot be reduced to less than 0.1.

By Grading the insulators:

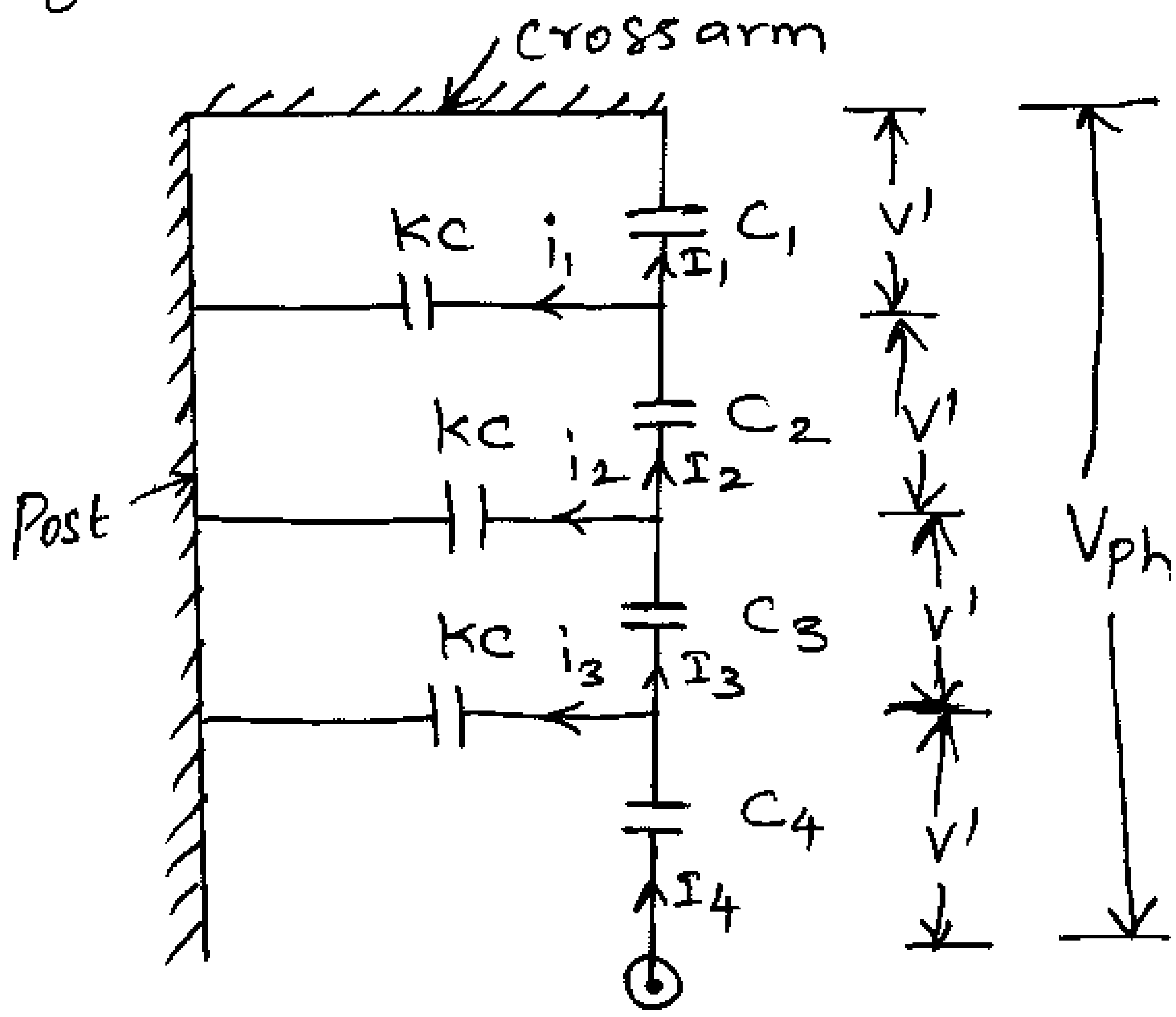
Unequal distribution of voltage occurs because of leakage current from the metal fitting (Pin) to the tower structure. If the self capacitance of the insulators is so graded that the top unit has the minimum capacitance while the bottom unit has the maximum capacitance, the voltage across each unit can be equalized.



Let C_1 be the self capacitance of the top unit. Let C_2, C_3, C_4 be the self capacitance of second, third, fourth units from the top.

$C_4 > C_3 > C_2 > C_1$

Let 'V' be the Voltage across each unit



$I_1 = V'wC_1$

$I_2 = V'wC_2$

$I_3 = V'wC_3$

$I_4 = V'wC_4$

$i_1 = V'wkc$

$i_2 = (V'+V')wkc$

$= 2V'wkc$

$i_3 = (V'+V'+V')wkc$

$= 3V'wkc$

Applying KCL to junction A

$I_2 = I_1 + i_1$

$V'wC_2 = V'wC_1 + V'wkc$

$$\boxed{C_2 = C_1 + kc}$$

Applying KCL to Junction B

$I_3 = I_2 + i_2$

$V'wC_3 = V'wC_2 + 2V'wkc$

$V'wC_3 = V'w(C_2 + 2kc)$

$$\boxed{C_3 = C_2 + 2kc}$$

Applying KCL to junction C

$$I_4 = I_3 + i_3$$

$$V'\omega C_4 = V'\omega C_3 + 3V'\omega kc$$

$$V'\omega C_4 = V'\omega (C_3 + 3kc)$$

$C_4 = C_3 + 3kc$
$C_{n+1} = C_n + nkc$

If the capacitance of one unit is fixed, the capacitance of other units can be found.

Disadvantages:

Different size units are required for grading the insulators. This requires large stocks of different sized units, which is uneconomical and impractical. This method is used only for very high voltage lines.

Problems for Grading of Insulator:

(1) A suspension type insulator is having 4 units and the value of pin to earth capacitance is c. If the capacitance of top unit is 6c, find the capacitance of each unit to make the string efficiency 100%.

Apply KCL at junction A,

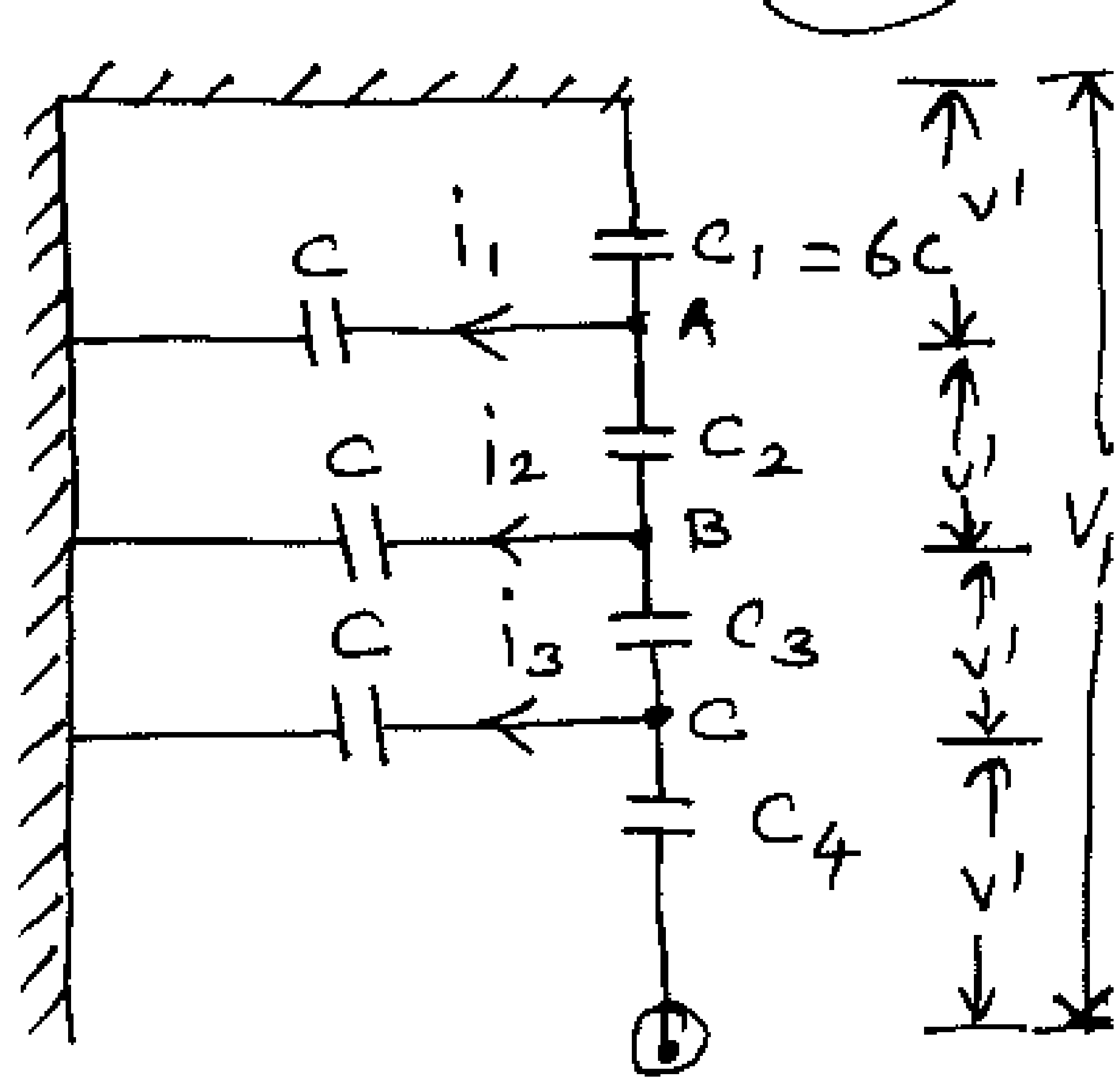
$$I_2 = I_1 + i_1$$

$V'\omega C_2 = V'\omega C_1 + V'\omega C$

$C_2 = C_1 + C$

$C_2 = 6C + C$

$\boxed{C_2 = 7C}$



Apply KCL at junction B,

$I_3 = I_2 + i_2$

$V'\omega C_3 = V'\omega C_2 + 2V'\omega C$

$V'\omega C_3 = V'\omega \times 7C + 2V'\omega C$

$\boxed{C_3 = 9C}$

Applying KCL at junction C

$I_4 = I_3 + i_3$

$V'\omega C_4 = V'\omega C_3 + 3V'\omega C$

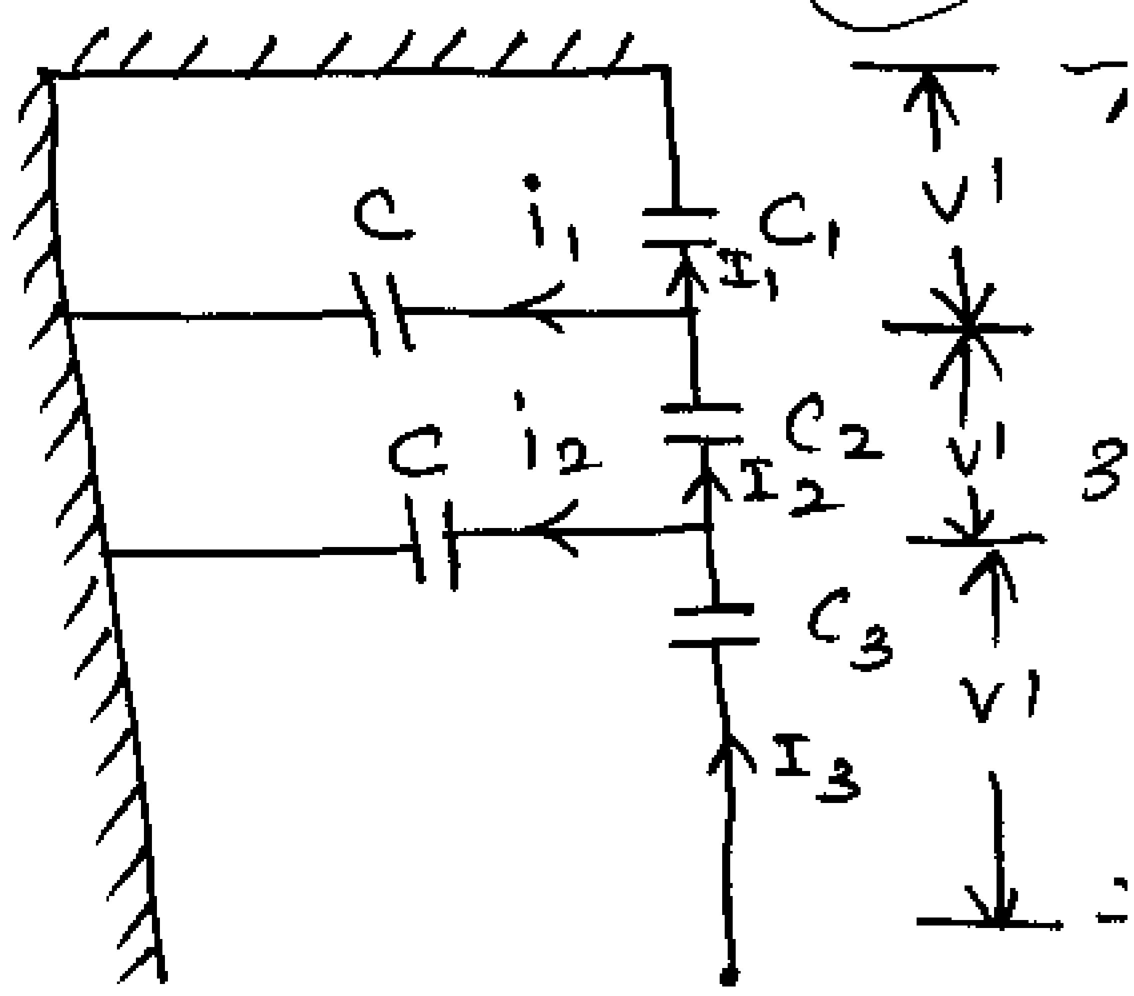
$\boxed{C_4 = C_3 + 3C}$

$C_4 = 9C + 3C$

$\boxed{C_4 = 12C}$

(2) A suspension type insulator is having 3 units and the value of pin to earth capacitance is C. If the capacitance of top unit is 5C, find the capacitance of each unit to make the string efficie[ncy] 100%.

A 100% string efficiency means that the voltage across each disc is same. It can be done by grading of Insulators.



String efficiency $\eta = \frac{V_{ph}}{3V'}$

$= \frac{3V'}{3V'} \times 100$

$kc = c$

$= 100\%$

$C_1 = 5C$ $\quad C_{n+1} = C_n + nkC$

$C_2 = C_1 + 1kc$, $C_2 = 5c + c$

$C_2 = 6C$

$C_3 = C_2 + 2c$, $C_3 = 8C$

(3) A String of 8 Suspension insulator is to be graded to obtain uniform distribution of voltage across the String. If the Capacitance of the top unit is 10 times the capacitance to ground of each unit. Determine the capacitance of the remaining 7 units.

$C_{n+1} = C_n + nKC$

At Junction A, $I_2 = I_1 + i_1$

$C_2 = C_1 + C = 10c + c = 11C$

$C_2 = 11C$

At Junction B, $I_3 = I_2 + i_1$

$C_3 = C_2 + 2C$

$= 11C + 2C$

$$\boxed{C_3 = 13C}$$

At Junction C, $I_4 = I_3 + i_3$

$C_4 = C_3 + 3C$

$= 13C + 3C = 16C$

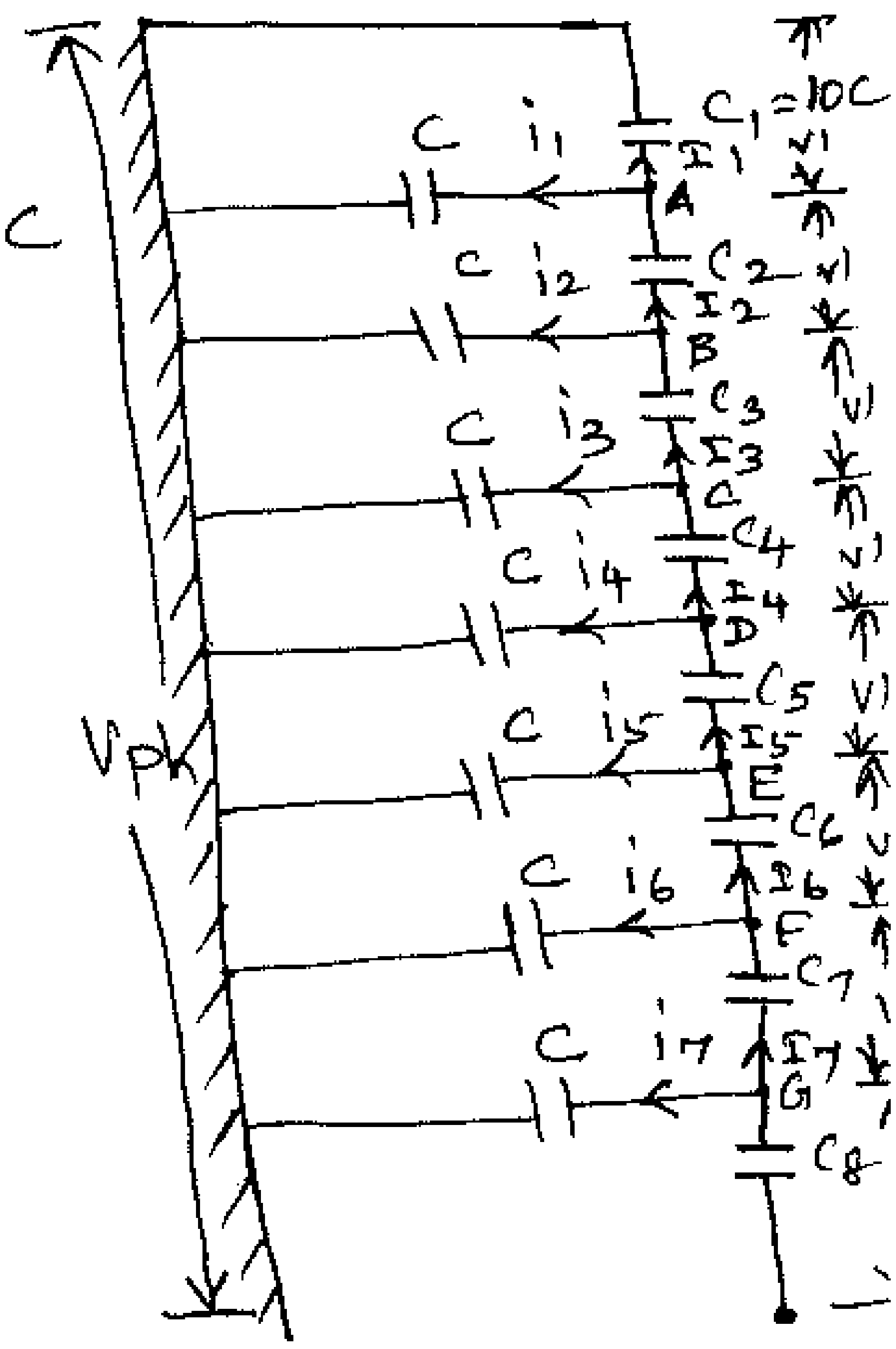
$$\boxed{C_4 = 16C}$$

At Junction D, $I_5 = I_4 + i_4$

$C_5 = C_4 + 4C$

$= 16C + 4C$

$$\boxed{C_5 = 20C}$$



At Junction E, $I_6 = I_5 + i_5$

$C_6 = C_5 + 5C$

$= 20C + 5C$

$$\boxed{C_6 = 25C}$$

At Junction F, $I_7 = I_6 + i_6$

$C_7 = C_6 + 6C$

$= 25C + 6C$

$$\boxed{C_7 = 31C}$$

At Junction G, $I_8 = I_7 + i_7$, $C_8 = C_7 + 7C$

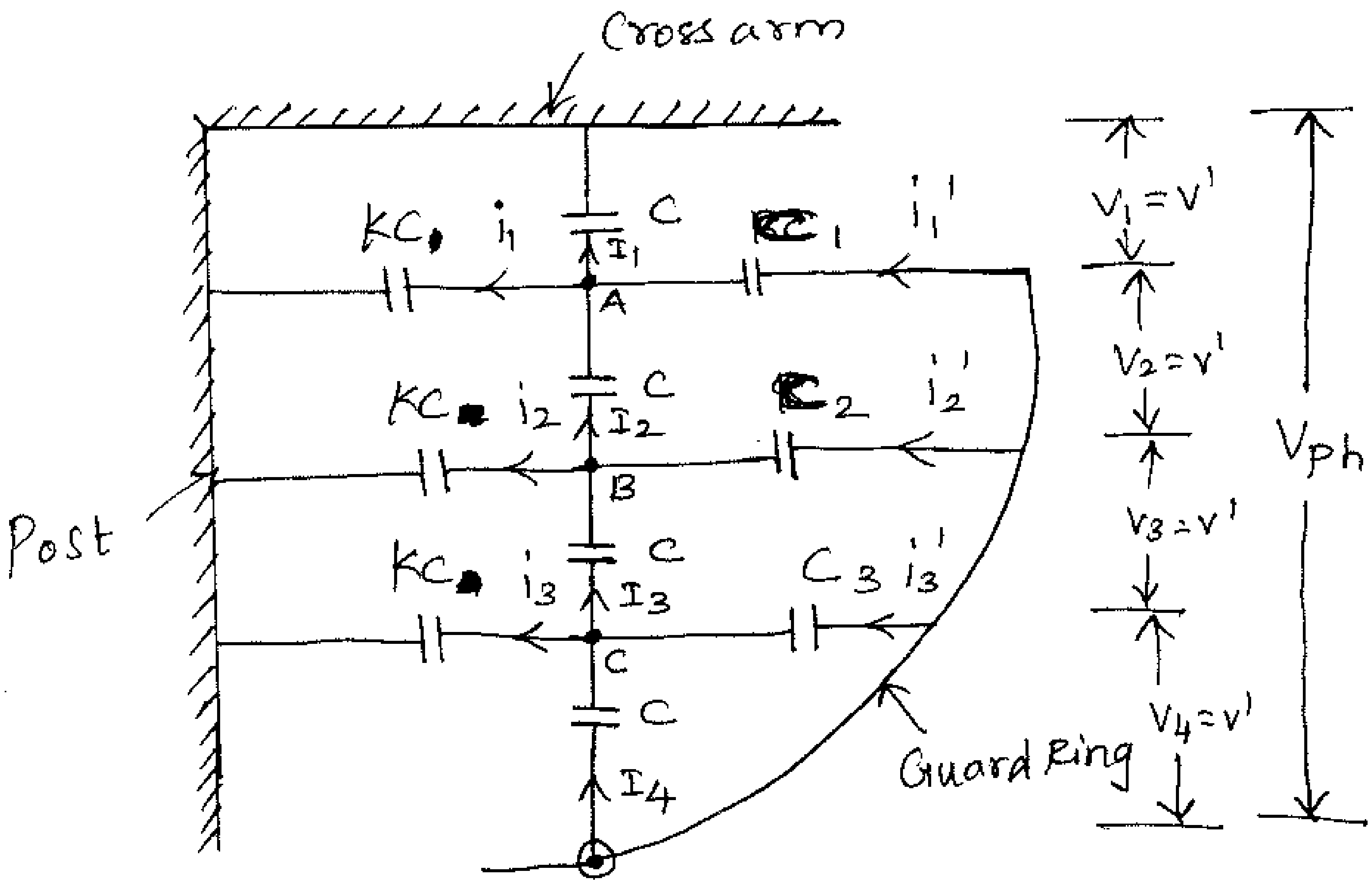
$= 31C + 7C$

$$\boxed{C_8 = 38C}$$

Guard Ring (static shielding):

A guard ring is a metal ring of large diameter electrically connected to the line and it surrounds the bottom insulator.

The ring increases the capacitance between the Metal fittings and the line and the charging Current flows. This charging current has to cancel exactly the Pin to tower charging currents. so that the same current flows through the identecal insulator units. Therefore, Voltage across each unit is same.



Consider a string of four units

Let C be the self capacitance of each unit

Let KC be the ground Capacitance

Let C1, C2, C3 be the capacitance between each Metal fitting and guard ring.

Let V be the potential across each unit.

The design of the ring should be such that this gives capacitance between metal fittings and line which will cancel the charging current through the ground capacitance.

$$i_1 = i_1' \quad i_2 = i_2' \quad i_3 = i_3'$$

$$I_1 = I_2 = I_3 = I_4 = I$$

Applying KCL to junction A

$$I_2 + i_1' = I_1 + i_1$$

$$I + i_1' = I + i_1$$

$$i_1' = i_1$$

$$3V'wC_1 = V'wKC$$

$$3C_1 = KC, \quad \boxed{C_1 = \frac{KC}{3}}$$

Applying KCL to junction B,

$$I_3 + i_2' = I_2 + i_2$$

$$I + i_2' = I + i_2$$

$$i_2' = i_2$$

$$2V'wC_2 = 2V'wKC$$

$$\boxed{C_2 = KC}$$

Applying KCL to junction E

$$I_4 + i_3' = I_3 + i_3$$

$$I + i_3' = i_3 + I$$

$$i_3' = i_3 \qquad 3V'\omega KC = V'\omega C_3$$

$$\boxed{C_3 = 3KC}$$

$$\boxed{C_x = \frac{xKC}{n-x}}$$

Where n – Total number of insulators

Advantages:

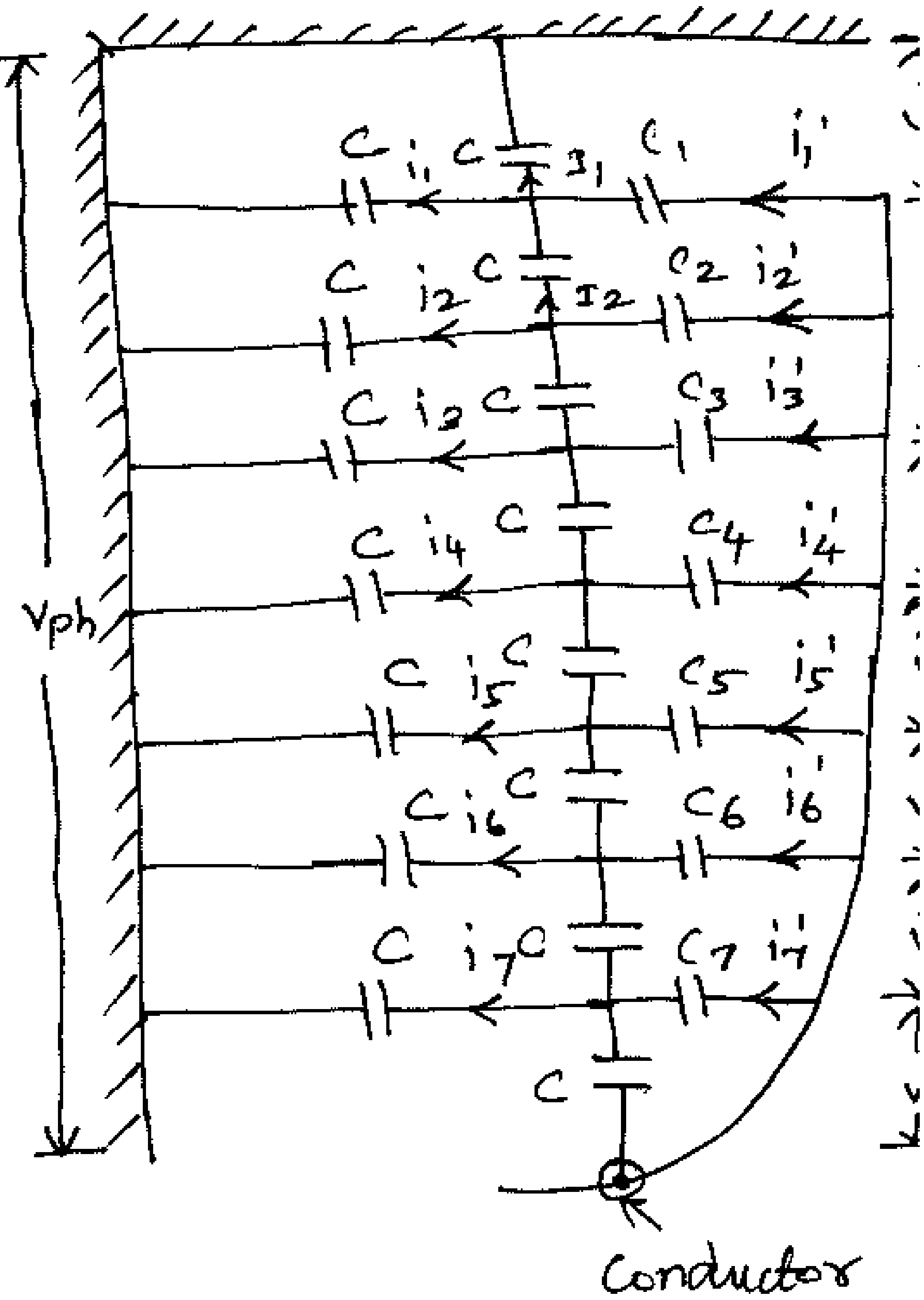
* Voltage drop across each unit is same
* If the guard ring is used with arcing horn, it will protect the insulator string from flashover under abnormal conditions.

Problems for guard Ring:

① A string of eight suspension insulators is to be fitted with a guard ring. If the Pin to earth capacitances are all equal to c, find the values of line to Pin capacitances that would give a uniform voltage distribution over the string.

Applying KCL at Point A

$$I_2 + i_1' = I_1 + i_1$$



$7V'\omega C_1 = V'\omega C$

$$C_1 = \frac{C}{7}$$

At Point B

$i_2' = i_2$

$6V'\omega C_2 = 2V'\omega C$

$$C_2 = \frac{2}{6}C = C/3$$

At Point C $\quad i_3' = i_3$

$5V'\omega C_3 = 3V'\omega C$

$$C_3 = \frac{3}{5}C$$

At Point D $\quad i_4' = i_4$

$4V'\omega C_4 = 4V'\omega C$

$$C_4 = C$$

At Point E, $\quad i_5' = i_5$

$3V'\omega C_5 = 5V'\omega C$

$$C_5 = \frac{5}{3}C$$

At Point F, $\quad i_6' = i_6$

$2V'\omega C_6 = 6V'\omega C$

$$C_6 = \frac{6}{2}C = 3C$$

At Point G

$i_7' = i_7$

$V'\omega C_7 = 7V'\omega C$

$$C_7 = 7C$$

(2) A suspension type insulator is having 6 units and the value of pin to earth capacitance is c. Find the line to pin capacitances to equalize the voltage across each unit.

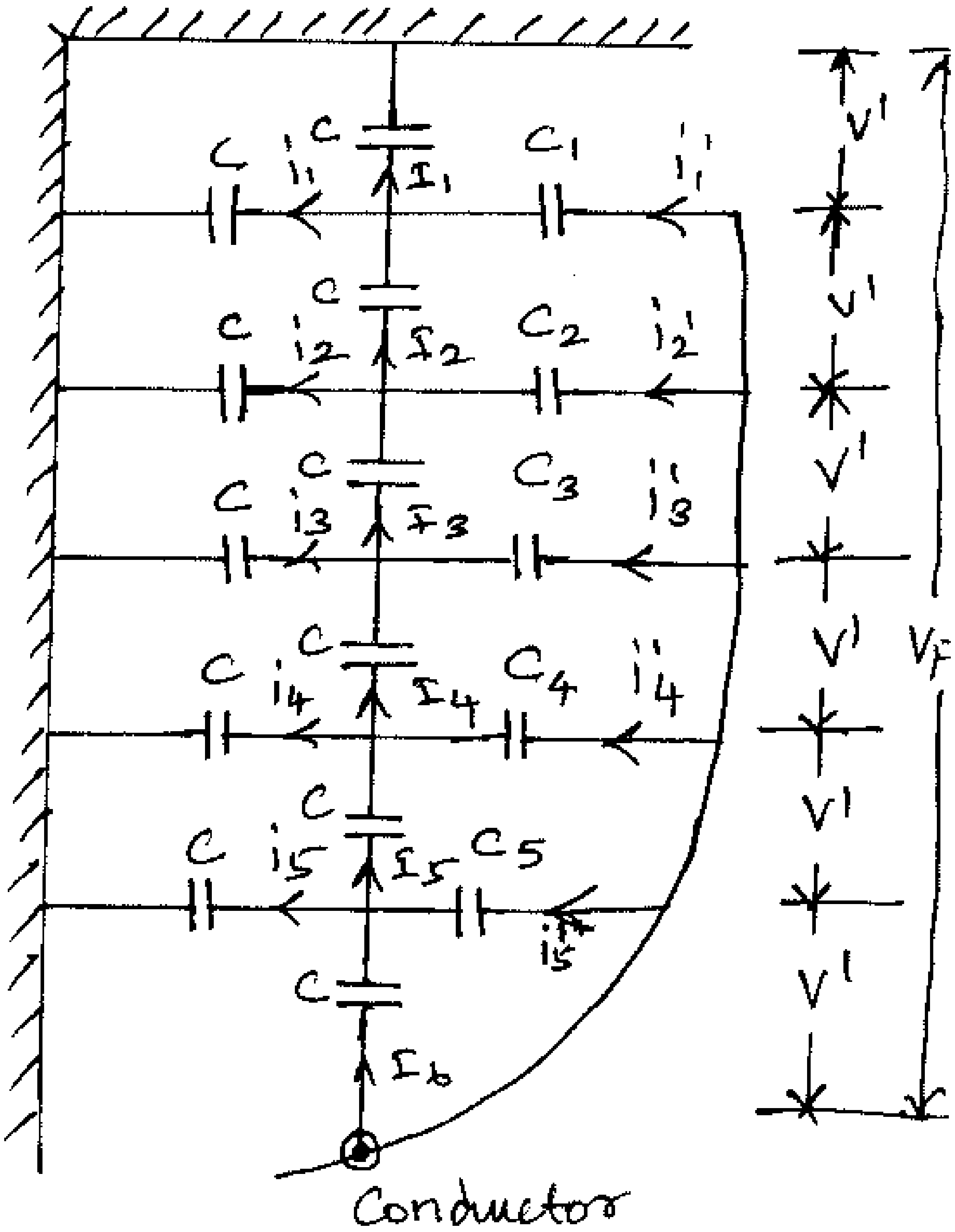
Apply KCL at Point A

$I_2 + i_1' = I_1 + i_1$

$i_1' = i_1$

$5V'\omega C_1 = V'\omega C$

$$C_1 = \frac{C}{5}$$



Apply KCL at Point B

$I_3 + i_2' = I_2 + i_2$

$i_2' = i_2$

$4V'\omega C_2 = 2V'\omega C$

$C_2 = \frac{2C}{4}$

$$C_2 = \frac{C}{2}$$

Apply KCL at Point C

$I_4 + i_3' = I_3 + i_3$

$i_3' = i_3$

$3V'\omega C_3 = 3V'\omega C$

$$C_3 = C$$

Apply KCL at Point D

$I_5 + i_4' = I_4 + i_4$

$i_4' = i_4$

$2V'\omega C_4 = 4V'\omega C$

$$C_4 = 2C$$

Apply KCL at Point E

$I_6 + i_5' = I_5 + i_5$

$i_5' = i_5$

$V'\omega C_5 = 5V'\omega C$

$$C_5 = 5C$$

③ A 3 unit insulator is fitted with a guard Ring. The capacitances of the link pins to metal work and guard ring can be assumed to be 20% and 8% of the capacitance of each unit. Determine the String efficiency.

$$C_1 = C_2 = 8\% \text{ of } C = 0.08C$$

$$KC = 20\% \text{ of } C = 0.2C$$

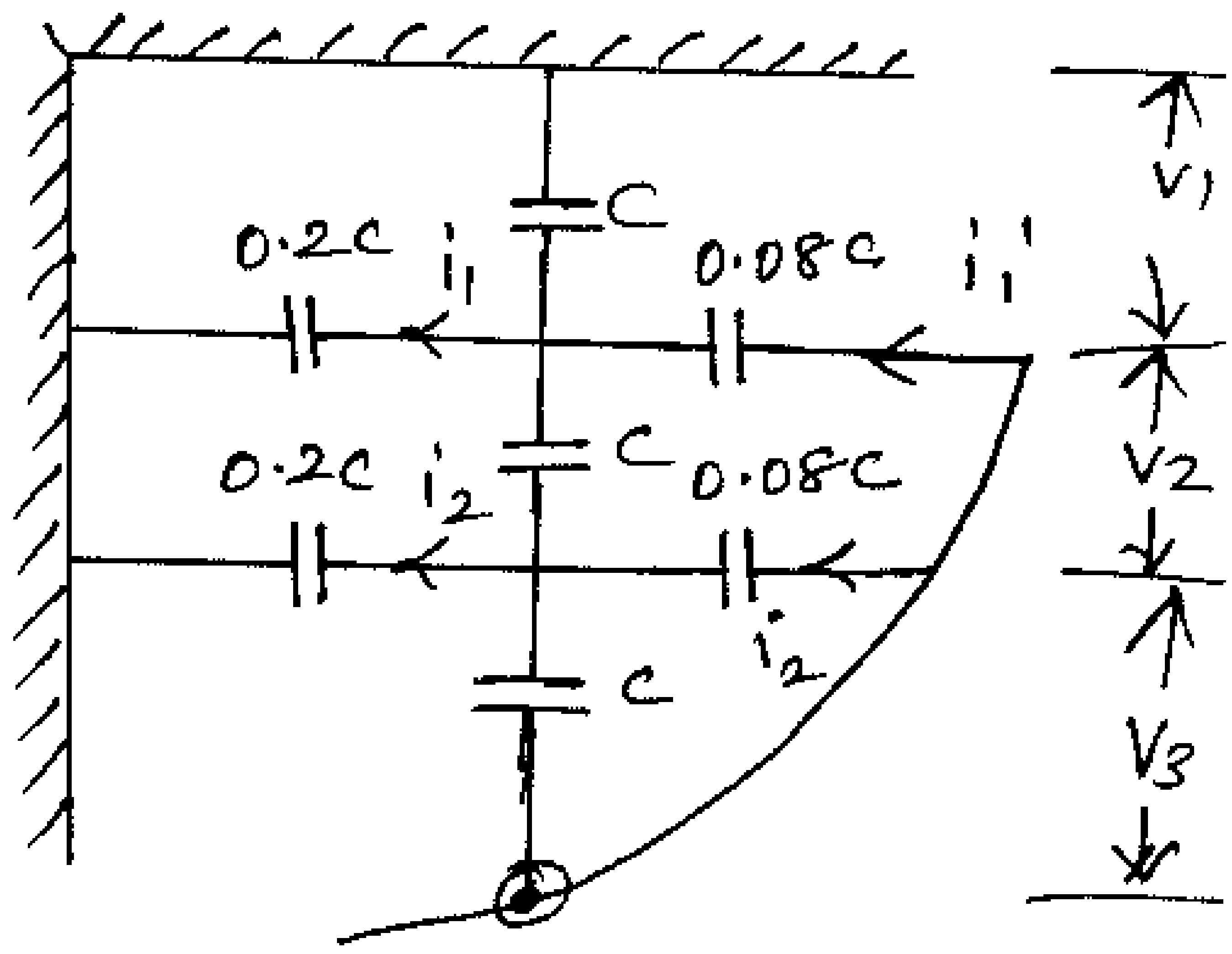
Apply KCL at point A

$$I_2 + i_1' = I_1 + i_1$$

$$V_2 \omega C + (V_2 + V_3)\omega \times 0.08C = V_1 \omega C + V_1 \omega\, 0.2C$$

$$0.08V_3 = 1.2V_1 - 1.08V_2$$

$$V_3 = 15V_1 - 13.5V_2 \quad —①$$



Apply KCL at Point B

$$I_3 + i_2' = I_2 + i_2$$

$$V_3 \omega C + V_3 \omega \times 0.08C = V_2 \omega C + (V_1 + V_2)\omega \times 0.2C$$

$$1.08V_3 = 1.2V_2 + 0.2V_1$$

$$V_3 = 1.111V_2 + 0.185V_1 \quad —②$$

Equating the eqns ① and ② we get

$$V_3 = 15V - 13.5V_2 = 1.111V_2 + 0.185V_1$$

$$14.611V_2 = 14.815V_1$$

$$\boxed{V_2 = 1.014V_1}$$

Substituting ~~equation~~ $V_2 = 1.014 V_1$ in eqn ①
we get

$$V_3 = 15V_1 - 13.5(1.014 V_1)$$

$$= 15V_1 - 13.688 V_1$$

$$\boxed{V_3 = 1.3115 V_1}$$

$$V_{ph} = V_1 + V_2 + V_3 = V_1 + 1.014V_1 + 1.3115 V_1$$

$$\boxed{V_{ph} = 3.3255 V_1}$$

$$\text{String Efficiency} = \frac{V_{ph}}{3V_3} = \frac{3.3255V_1}{3.13115V_1}$$

$$\boxed{\eta = 84.52\%}$$

·×————————×·

④ A String of 3 insulator is fitted with a guard ring. The capacitance of link to metal work and guard ring can be assum to be 10%. and 4%. of the capacitance of each unit. Determine voltage distribution and string efficiency.

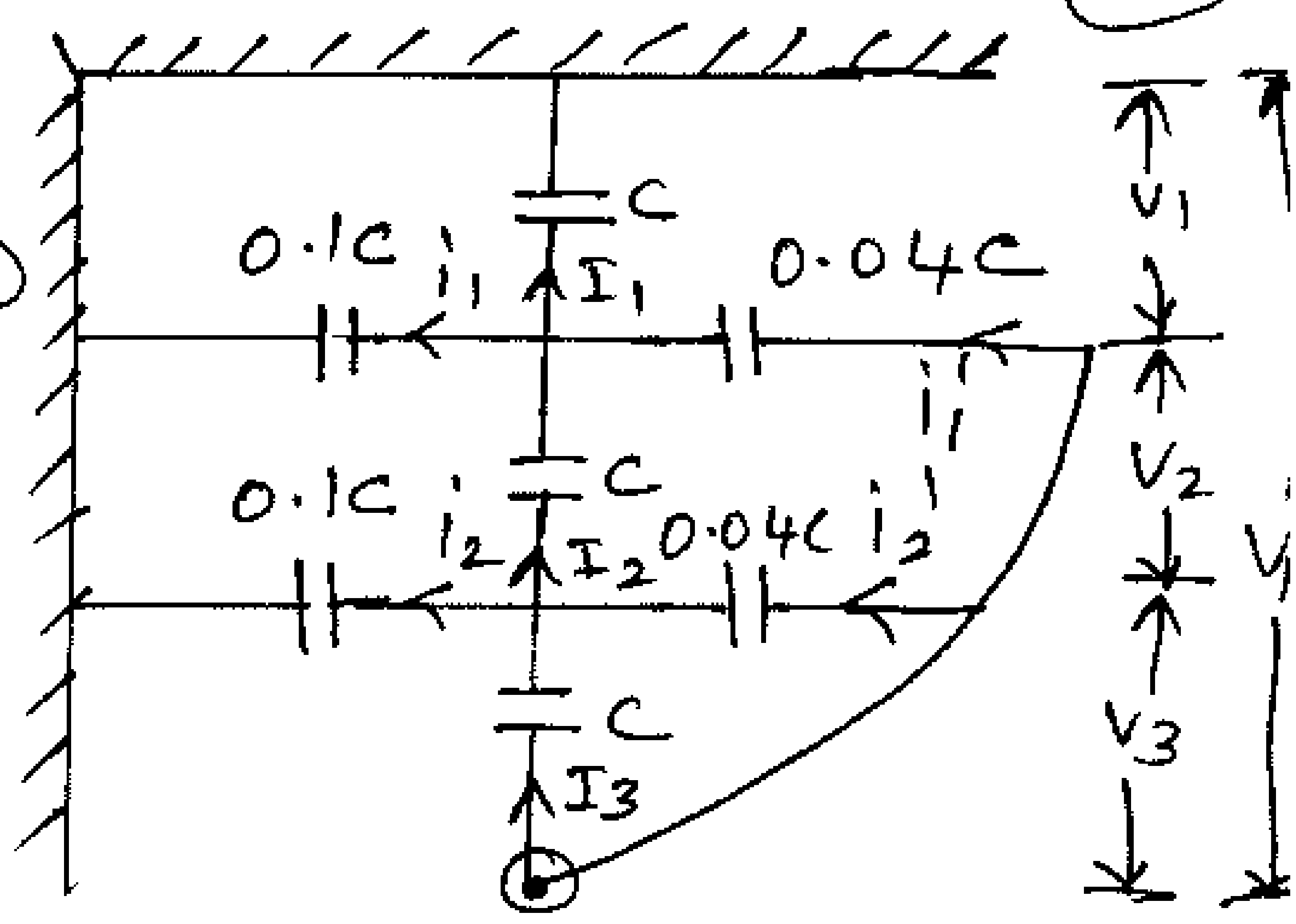
Apply KCL at node A

$$I_2 + i_1' = I_1 + i_1$$

$$V_2 \omega C + (V_2 + V_3)\omega 0.04C = V_1 \omega C + V_1 \omega C 0.1$$

$1.1V_1 - 1.04V_2 = 0.04V_3$

$27.5V_1 - 26V_2 = V_3$ — (1)



Apply KCL at node B

$I_3 + i_2' = I_2 + i_2$

$V_3\omega C + V_3\omega(0.04C)$

$= V_2\omega C + (V_1 + V_2)\omega(0.1C)$

$1.04V_3 = 0.1V_1 + 1.1V_2$

$V_3 = 0.0962V_1 + 1.05769V_2$ — (2)

Equating the Eqns (1) & (2), we get

$27.5V_1 - 26V_2 = 0.0962V_1 + 1.05769V_2$

$27.5V_1 - 0.0962V_1 = 1.05769V_2 + 26V_2$

$27.05769V_2 = 27.4038V_1$

$$V_2 = \frac{27.4038V_1}{27.05769}$$

$$\boxed{V_2 = 1.01279V_1}$$

Substituting the value of V_2 in eqn (1), we get

$V_3 = 27.5V_1 - 26(1.013V_1)$

$V_3 = 1.1674V_1$ $\quad V_{ph} = V_1 + V_2 + V_3$

$$\boxed{V_{ph} = 3.1802V_1}$$

$$\eta = \frac{V_{ph}}{3V_3} \times 100 = \frac{3.1802V_1}{3 \times 1.1674V_1} \times 100$$

$$\boxed{\eta = 90.81\%}$$

Testing of Insulators

Insulators are the elements which provide necessary insulation between line conductor and supports and thus prevent any leakage current from conductors to earth.

The tests that are normally conducted are

(i). Type Tests:

* These test are intended to prove or check the design features and the quality.
* Type tests are done on samples when new designs or design changes are introuduced.

(ii) Sample Tests:

* It is a meachanical test
* These tests are conducted to prove the quality of Insulators, Insulator material type and Mechanical properties of insulators.

(iii) Routine Tests:

The routine test are intended to check the quality of the individual test piece.

The routine tests are done to ensure the reliability of the individual test objects and quality and consistency of the materials.

The following tests are to be conducted for testing insulators

a. Mechanical test
b. Electrical Insulation test
c. Environmental test
d. Temporary cycle test
e. Corona and Interference test

(a) Mechanical test

Mechanical tests are Performed to prove the quality, type of insulating material.

The important Mechanical test are as follows

Tensile Strength:

The insulators should bear the tensile force 2.5 times that of maximum tensile load is applied for one minute.

Compression test:

The insulators should not have any porous.

Torsional test:

The insulator should withstand when twisting moment is applied to insulators for one Minute.

Bending Minimum Test:

It is Conducted only for Pin type insulators. The insulators should not be damaged when

Mounted on a Steel Pin and 2.5 times the maximu Working load is applied for one Minute.

Mechanical Vibration test:

The insulators should not be damaged when oscillations are applied for one minute.

(b) Electrical Insulation test (or) High Voltage tests

(i) Power frequency test (ii) Impulse test

Power frequency Test

(i) Dry and Wet flashover Tests

(ii) Dry Flash over Test

(iii) Wet withstand Test

(iv) Wet and Dry withstand Test.

(i) Dry and Wet flashover Tests:

In these tests, the A.C Voltage of Power frequency is applied across the insulators and increased at a uniform rate of about 2 Percent Per second of 75% of the estimated test Voltage.

(ii) Dry Flash over Test

If the test is conducted under normal conditions without any rain or Precipitation it is called dry flash over test.

(iii) Wet Flash over Voltage or wet withstand Test

If the test is carried under conditions of artificial rain, it is called wet flash over test or wet withstand Test.

(iv) Wet and Dry withstand Tests

In these test, the test voltage is applied under dry and wet conditions for a period of one minute with an insulator mounted as in service conditions. The test piece should withstand the specified voltage.

Impulse Test:

(i) Impulse withstand voltage Test

This test is done by applying standard impulse voltage of 1/50 μ sec wave under dry conditions with both positive and negative polarities of the wave.

(ii) 50% Dry impulse Flash over Test

50% Dry impulse flash over test is done by applying standard impulse voltage of specified value under dry condition with both positive and negative polarities of the wave.

C. Environmental Test or pollution Test

pollution tests are important because of the following types of pollutions

(i) Dust, micro organisms, bird secretions, flies.
(ii) Industrial smoke, petroleum vapours, dusts and other deposits
(iii) Coastal pollution
(iv) Desert pollution
(v) In polar countries, Ice and fog deposits at high altitudes.

(d) Temporary cycle Test:

The glaze of the insulator should not be damaged. During this test, the insulator is heated in water at 70°c for one hour and cooled in water at 7°c immediately for another hour and tests are repeated and then dried.

(e) Corona and Radio interference test

When the potential gradient exceeds 30 kv/cm, then corona discharge occurs around the transmission line. If any communication line is provided near the transmission line, the inductive interference takes place. This can be avoided by

* By providing grading of insulators
* By increasing the size of conductors
* By using smooth surface

Chennai Institute of Technology
Department of Electrical and ElectronicsEngineering
EE3401-Transmission and Distribution
UNIT-IV-UNDER GROUND CABLES

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 fulfill the following necessary requirements:**

(i) The conductor used in cables should be tinned stranded copper or aluminum 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.

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 followingProperties**

(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.

(v) Non-inflammable.

(vi) Low cost so as to make the underground system a viable proposition.

(vii) Unaffected by acids and alkalies 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 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.

Varnished cambric

It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as empire tape. The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent. As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.

Polyvinyl chloride (PVC)

This insulating material is a synthetic compound. It is obtained from the polymerization of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gell and renders the material plastic over the desired range of temperature. Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over VIR in extreme environmental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations.

CONSTRUCTION OF THREE CORE CABLE:

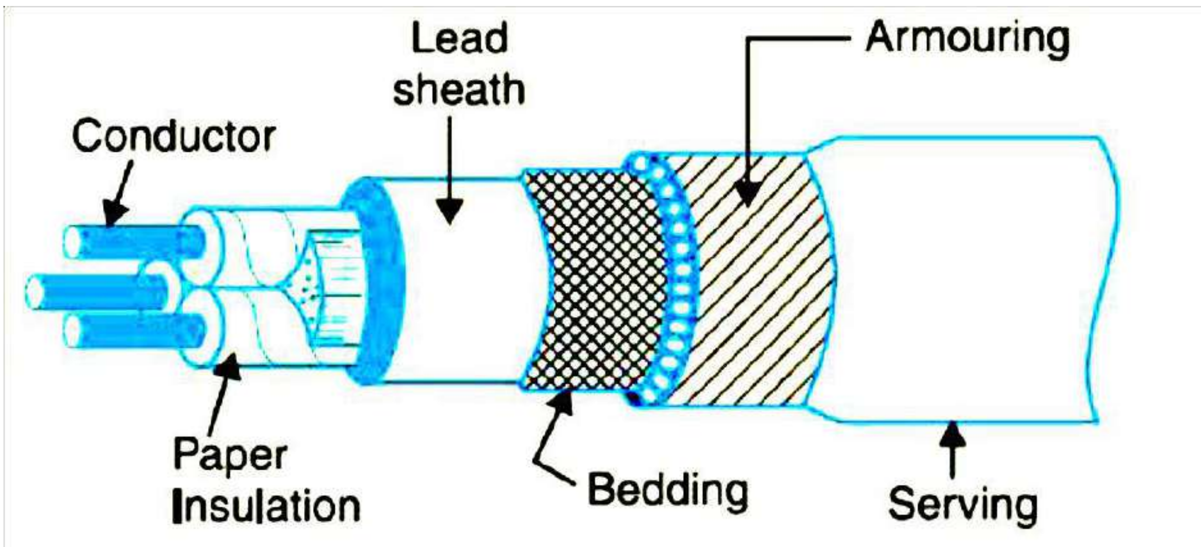


Fig1: Construction of three Core Cable

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 3-phase service. The conductors are made of tinned copper or aluminum 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 alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminum 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.

TYPES OF CABLES

Cables for underground service may be classified in two ways according to

(i) the type of insulating material used in their manufacture

(ii)the voltage for which they are manufactured.

However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups:

Low-tension (L.T.) cables — upto 1000 V
High-tension (H.T.) cables — upto 11,000 V
Super-tension (S.T.) cables — from 22 kV to 33 kV
Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV
Extra super voltage cables — beyond 132 kV

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be

(i) single-core (ii) two-core (iii) three-core (iv) four-core etc.

For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand. Fig. shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (up to 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

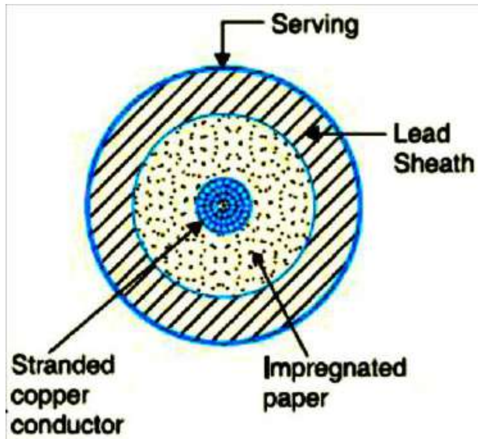


Fig2: Construction of a single-core low tension cable

Cable For 3-Phase

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or three single core cables may be used. For voltages upto 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables areused. The following types of cables are generally used for 3-phase service

1. Belted cables — upto 11 kV
2. Screened cables — from 22 kV to 66 kV
3. Pressure cables — beyond 66 kV.

1. Belted Cables

These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV. Fig.3 shows the constructional details of a 3-core belted cable. The cores are insulated from each other by layers of impregnated paper.

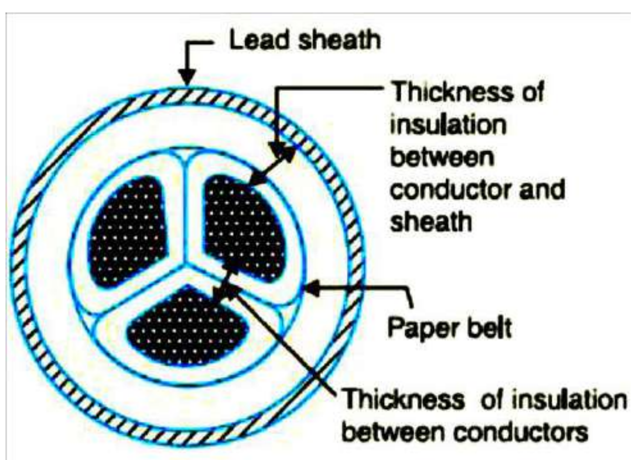


Fig.3 Constructional details of a 3-core belted cable

Another layer of impregnated paper tape, called paper belt is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of non circular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure).The belted type construction is suitable only for low and medium voltages as the electro static stresses developed in the cables for these voltages are more or less radial i.e., across the insulation. However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation. As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment. In order to overcome this difficulty, screened cables are used where leakage currents are conducted to earth through metallic screens.

2.Screened Cables

These cables are meant for use up to 33 kV, but in particular cases their use may be extended to operating voltages up to 66 kV. Two principal types of screened cables are H-type cables and S.L. type cables.

(i)H-type Cables

This type of cable was first designed by H. Hochstetler and hence the name. Fig4. shows the constructional details of a typical 3-core, H-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminum foil. The cores are laid in such a way that metallic screens

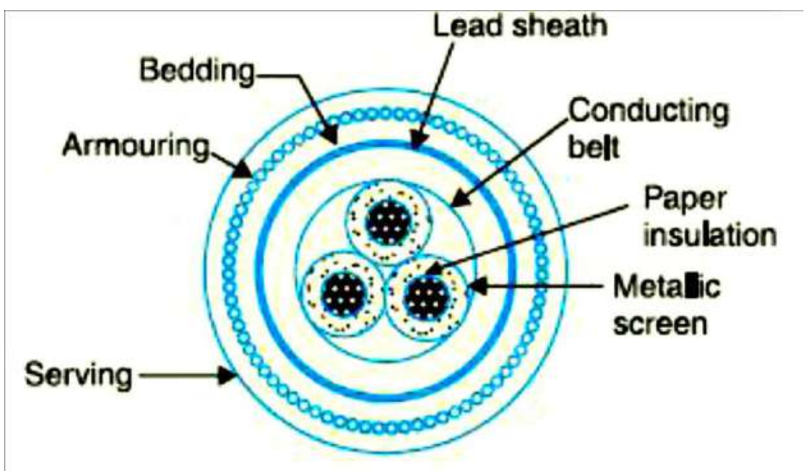
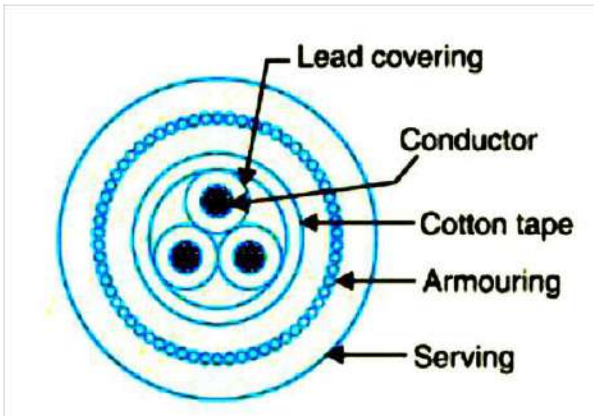


Fig4: 3-core, H-type cable

make contact with one another. An additional conducting belt (copper woven fabric tape) is wrapped round the three cores. The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced. Two principal advantages areclaimed for *H*-type cables. Firstly, the perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation. Secondly, the metallic screens increase the heat dissipating power of the cable.

(ii) S.L.Type cables

Fig.5 shows the constructional details of a 3-core S.L. (separate lead) type cable. It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over H-type cables. Firstly, the separate sheaths minimize the possibility of core-to-core breakdown. Secondly, bending of cables becomes easy due to the elimination of overall lead sheath. However, the disadvantage is that the three lead sheaths of S.L. cable are much thinner than the single sheath of H-cable and, therefore, call for greater care in manufacture.



3. Pressure cables

For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids. When the operating voltages are greater than 66 kV, pressure cables are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables viz oil-filled cables and gas pressure cables are commonly used.

(i)Oil-filled cables.

In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the cable. Oil under pressure compresses the layers of paper insulation and is forced in to any voids that may have formed between the layers. Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV up to 230 kV. Oilfilled cables are of three types viz., single-core conductor channel, single-core sheath channel and three-core filler-space channels.

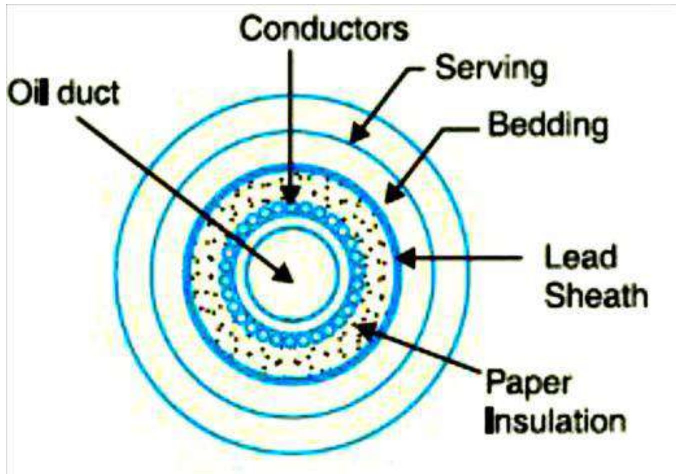
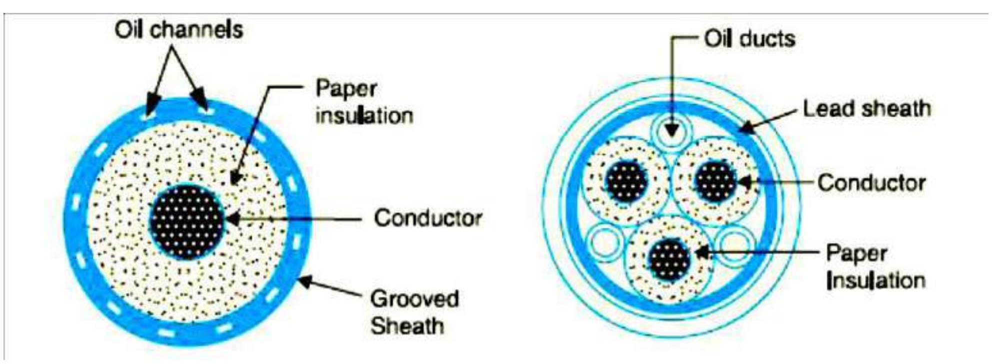


Fig. shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the center by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation. The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in thereservoir. However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel. The disadvantage of this type of cable is that the channel is at the middle of the cable and is at full voltage *w.r.t.* earth, so that a very complicated system of joints is necessary. Fig. shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in them etallic sheath as shown. In the 3-core oil-filler cable shown in Fig. the oil ducts are located in the filler spaces. These channels are composed of perforated metalribbon tubing and are at earth potential.



(ii)Gas Pressure Cable

The voltage required to set up ionization inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionization can be altogether eliminated. At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.

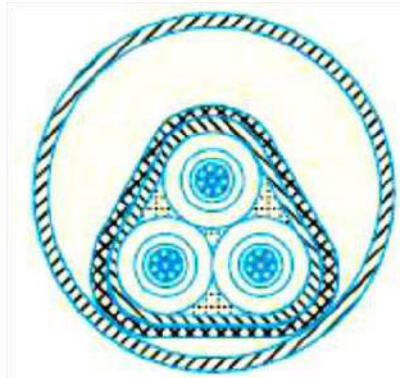


Fig Shows the section of external pressure cable designed by Hochstetler, Vogal and Bowden. The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable. The triangular section reduces the weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane. The sheath is protected by a thin metal tape. The cable is laid in a gas-tight steel pipe. The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres. The gas pressure produces radial compression and closes the voids that may have formed between the layers of paper insulation. Such cables can carry more load current and operate at higher voltages than a normal cable. Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. However, it has the disadvantage that the overall cost is very high.

Insulation Resistance:

The cable Conductor is provided with a suitable thickness of insulating material in order to prevent leakage current. The ~~Path~~ opposition offered by insulation to leakage current is known as insulation resistance of the cable. This value should be very high.

Consider a single core cable of conductor

Let 'r' be the radius of conductor

Let R be the radius of internal sheath

Let l be the length of the cable

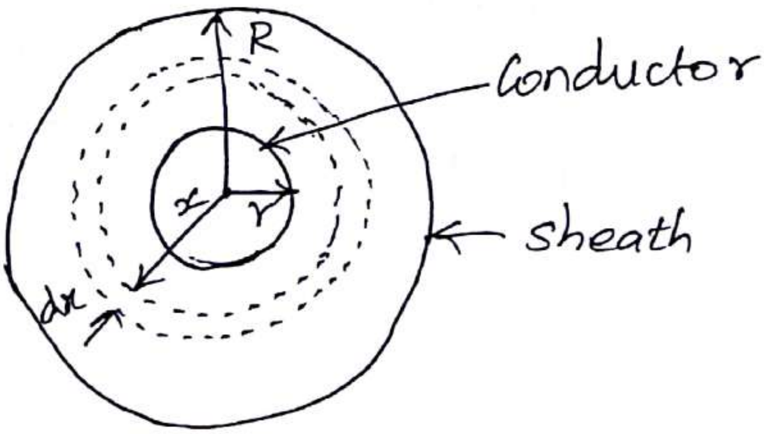
Let ρ be the resistivity of the insulating material

Consider a very small layer of insulation of thickness dx with radius x.

Surface area of cylinder $= 2\pi x l$

Insulation resistance of thickness dx at radius x

$$dR_{ins} = \frac{\rho}{2\pi x l} dx$$



Insulation resistance of whole cable (2)

$$R_{ins} = \int_r^R \frac{\rho}{2\pi x l} dx$$

$$= \frac{\rho}{2\pi l} \int_r^R \frac{1}{x} dx = \frac{\rho}{2\pi l} \left[\ln x\right]_r^R$$

$$= \frac{\rho}{2\pi l} \left[\ln R - \ln r\right] = \frac{\rho}{2\pi l} \ln\left[\frac{R}{r}\right]$$

length is inversly proportional to insulation resistance. When length increases, insulation resistance decreases.

If $l = 1\,m$ then,

$$R_{ins} = \frac{\rho}{2\pi} \ln\left[\frac{R}{r}\right] \; \Omega/m$$

In General

$$R_{ins} = \frac{\rho}{2\pi l} \ln\left[\frac{R}{r}\right] \; \Omega/m$$

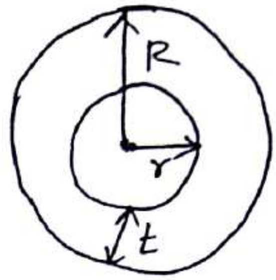
Problem (1) An insulation resistance of single core cable is 500 MΩ/km, Diameter of core is 3 mm and resistivity of insulation is 5×10^{12} Ωm. Find Insulation thickness

Given Data: $l = 1\,km = 1000\,m$ $R_{ins} = 500\,M\Omega$

$d = 3\,mm$, $\rho = 5\times10^{12}\,\Omega\text{-}m$

(3)

Let R be the internal Sheath radius (Insulation Radius)



Insulation Resistance

$$R_{ins} = \frac{\rho}{2\pi l} \ln\left(\frac{R}{r}\right)$$

$$\ln\left(\frac{R}{r}\right) = \frac{2\pi l \times R_{ins}}{\rho} = \frac{2\pi \times 1000 \times 500 \times 10^{6}}{5 \times 10^{12}}$$

$$\ln\left(\frac{R}{r}\right) = 0.6283 , \left(\frac{R}{r}\right) = e^{0.6283} = 1.874$$

$$R = 1.874 \times r = 1.874 \times 1.5 \times 10^{-3}$$

$$R = 2.812 \times 10^{-3} m = 2.812 mm$$

$$R = 2.812 mm$$

Insulation thickness $t = R - r = (2.812 - 1.5) mm$

$$t = 1.312 mm = 1.312 \times 10^{-3} m$$

(2) A Single Core cable has a length of 2km and Conductor diameter of 28 mm and an insulation thickness of 6mm. The resistivity of dielectric is $7.3 \times 10^{12}\ \Omega m$ a. Determine the insulation resistance of the cable, b) The resistance to be increased by 15%. Calculate the additional thickness of insulation.

Given data: $l = 2km = 2000m$, $d = 28mm$

$t = 6mm$, $\rho = 7.3 \times 10^{12}\ \Omega m$

Conductor radius, $r = \frac{28}{2} = 14mm$

Insulation thickness, $t = 6mm$

$$\rho = 7.3 \times 10^{12} \, \Omega m$$

Insulation Sheath radius $R = r + t = 14 + 6$

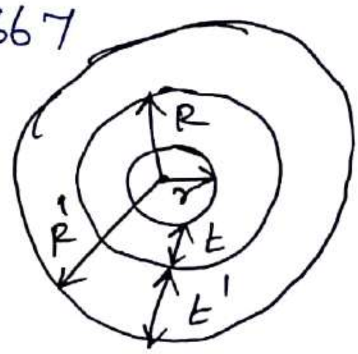
$$R = 20mm$$

Insulation resistance $R_{ins} = \frac{\rho}{2\pi l} \ln\left[\frac{R}{r}\right]$

$$R_{ins} = \frac{7.3 \times 10^{12}}{2\pi \times 2000} \ln\left[\frac{20 \times 10^{-3}}{14 \times 10^{-3}}\right]$$

$$= 580.915 \times 10^{6} \times 0.35667$$

$$R_{ins} = 207.2 \, M\Omega$$



Rins is increased by 15%.

$$R_{ins} = R_{ins} + \frac{15}{100} R_{ins} = 1.15 R_{ins}$$

$$= 1.15 \times 207.2 = 238.28 \, M\Omega$$

Let t' be the additional insulation thickness

Let R' be the New Sheath radius

$$R' = r + t + t'$$

$$R'_{ins} = \frac{\rho}{2\pi l} \ln\left[\frac{R'}{r}\right]$$

$$238.28 \times 10^{6} = \frac{7.3 \times 10^{12}}{2\pi \times 2000} \ln\left[\frac{R'}{14 \times 10^{-3}}\right]$$

$$\ln\left[\frac{R'}{14\times10^{-3}}\right] = \frac{238.28\times10^{6}\times2\pi\times2000}{7.3\times10^{12}}$$

$$= 0.41$$

$$\frac{R'}{14\times10^{-3}} = e^{0.41} = 1.507$$

$$R' = 1.507\times14\times10^{-3}$$

$$R' = 0.021m, \quad \boxed{R' = 21mm}$$

$$R' = r+t+t'$$

$$21 = 14+6+t' \quad t' = 21-20$$

$$\boxed{t' = 1mm}$$

Additional insulation thickness = 1mm

(3) A single core cable has a conductor diameter of 26 mm, has an insulation thickness of 4mm and an insulation resistance of 425 MΩ/km. What thickness of similar material would be needed for 36 mm diameter cable in order to have an insulation resistance of 850 MΩ/km.

$d = 26mm \quad r = \frac{26}{2} = 13mm = 13\times10^{-3}m$

$t = 4mm = 4\times10^{-3}m$ Radius of sheath $R = r+t$

$R = 13+4 = 17mm = 17\times10^{-3}m$

$R_{ins} = 425\ M\Omega/km$ (6)

Since similar material is used, ρ is same

$$R_{ins} = \frac{\rho}{2\pi l} \ln\left[\frac{R}{r}\right]$$

$$425\times10^{6} = \frac{\rho}{2\pi l} \ln\left[\frac{17\times10^{-3}}{13\times10^{-3}}\right]$$

$$\frac{\rho}{2\pi l} = \frac{425\times10^{6}}{0.268} = 1584.26\times10^{6} \quad \text{—①}$$

Second Conductor diameter = 36 mm

$$r_1 = \frac{36}{2} = 18\,mm = 18\times10^{-3}\,m$$

$$R_{ins1} = 850\ M\Omega/km$$

$$R_{ins1} = \frac{\rho}{2\pi l} \ln\left[\frac{r_1+t}{r_1}\right] \quad \text{—②}$$

Equating the eqns ① & ②

$$850\times10^{6} = 1584.26\times10^{6} \ln\left[\frac{18\times10^{-3}+t_1}{18\times10^{-3}}\right]$$

$$\ln\left[\frac{18\times10^{-3}+t_1}{18\times10^{-3}}\right] = \frac{850\times10^{6}}{1584.26\times10^{6}} = 05365$$

$$\frac{18\times10^{-3}+t_1}{18\times10^{-3}} = e^{0.5365} = 1.71$$

$$1.8\times10^{-3}+t_1 = 18\times10^{-3}\times1.71 = 0.0308$$

$$t_1 = 0.0308 - 18\times10^{-3} = 0.0128\,m$$
$$= 12.8\,mm$$

Additional insulation thickness = 12.8 mm

Capacitance of a single Core cable:

Since the single core cable has an earthed metallic sheath, there is an electric field between the Conductor and Sheath.

Let Q Coulomb per metre length be the charge per metre on the surface of the Conductor.

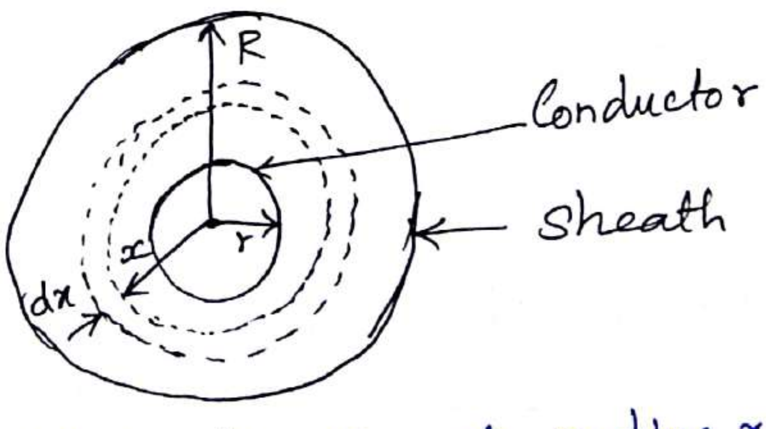
Let D_x be the electric flux density

Surface area of cylinder $= 2\pi x l$

$$D_x \text{ at radius } x = \frac{\text{flux}}{\text{Area}} = \frac{Q}{2\pi x l}$$

Assume length is 1m

$$D_x = \frac{Q}{2\pi x} \text{ Col}/m^2$$



Electric field intensity E_x at radius x

$$\frac{D_x}{\varepsilon} = \frac{D_x}{\varepsilon_0 \varepsilon_r} = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x}$$

ε_r – Relative Permittivity

ε_0 – 8.854×10^{-12} F/m

Potential difference between the core and sheath

$$V = \int_r^R E_x \, dx = \int_r^R \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x} dx = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \left[\ln x\right]_r^R$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \left[\ln x\right]_r^R = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \left[\ln R - \ln r\right]$$

$$V = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \ln\left[\frac{R}{r}\right] \text{ volts}$$

Capacitance between core and sheath is

$$C = \frac{Q}{V} \qquad C = \frac{Q \cdot 2\pi \varepsilon_0 \varepsilon_r}{Q \ln\left[\frac{R}{r}\right]} \text{ F/m}$$

$$C = \frac{2\pi \varepsilon_0 \varepsilon_r}{\ln\left[\frac{R}{r}\right]} \text{ F/m}$$

$$C = \frac{2\pi \times 8.854 \times 10^{-12} \cdot \varepsilon_r}{\ln\left[\frac{R}{r}\right]} \text{ F/m}$$

(1) A 11 KV, 3 phase underground feeder, 2 km long uses three single core cables. The diameter of each Conductor is 28 mm and an insulation thickness of 4.4 mm and the relative permitivity of 4. Determine (a) Capacitance of the cable per phase, b) Charging Current per phase, c) Total Charging

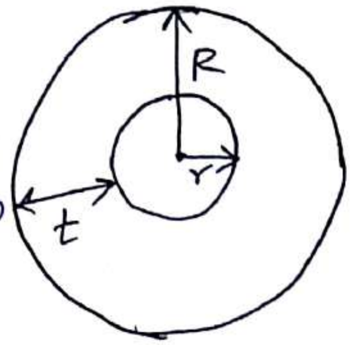
KVAR. Length = 2km

= 2000m

Conductor diameter = 28 mm

Conductor radius $r = \frac{28}{2} = 14 mm$

$t = 4.4 mm$



$\varepsilon_r = 4$, Internal sheath radius

$R = r + t = 14 + 4.4$

$= 18.4 \text{ mm}$

$$\text{Capacitance} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left[\frac{R}{r}\right]} \text{ F/m}$$

$$= \frac{2\pi \times 8.85 \times 10^{-12} \times 4}{\ln\left[\frac{18.4 \times 10^{-3}}{14 \times 10^{3}}\right]}$$

$$= \frac{2.2242 \times 10^{-10}}{0.2733} = 8.138 \times 10^{-10}$$

$$C = 0.8138 \text{ nF/m}$$

Length of cable = 2 km

Capacitance per phase $= 81.38 \times 10^{-9} \times 2 \times 1000$

$= 1.627 \times 10^{-6}$

$$C = 1.627 \mu F$$

b) Charging current I per phase $= V_{ph} \cdot 2\pi f C$

$V_L = 11 kV$, $V_{ph} = \frac{11}{\sqrt{3}} = 6.35 kV$

$I = 6.35 \times 10^3 \times 2 \times \pi \times 50 \times 1.627 \times 10^{-6}$

$I/\text{phase} = 3.247 \text{ Amp}$

c) Total Charging VAR for 3phase $= 3 \times V_{ph} \cdot I$

$= 3 \times 6.35 \times 10^3 \times 3.247$

$= 61855.35 \text{ VAR}$

$= 61.855 \text{ KVAR}$

(2) Calculate charging current and capacitance of a single core cable used on 3ϕ 66kV system. Core diameter is 12 cm and an impregnated paper thickness of 8 cm. Length of cable is 1km. Relative Permeability of Insulation may be 5 and frequency is 50 Hz.

$V_L = 66\text{kV}, \; V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{66}{\sqrt{3}} = 38.1051 \text{ kV}$

$d = 12\text{cm} \quad r = \frac{d}{2} = \frac{12}{2} = 6\text{cm}$

$R = r + t = 6 + 8 = 14\text{cm}, \; l = 1\text{km} \quad \varepsilon_r = 5$

$f = 50\text{Hz}$

Capacitance of Single Core Cable is given by

$$C = \frac{2\pi \varepsilon_0 \varepsilon_r l}{\ln\left[\frac{R}{r}\right]} = \frac{2\pi \times 8.854 \times 10^{-12} \times 5 \times 1 \times 10^3}{\ln\left(\frac{14 \times 10^{-2}}{6 \times 10^{-2}}\right)}$$

$C = 3.283 \times 10^{-7} \text{ F}$

Charging Current $I = \frac{V}{X_C} = WCV_{ph}$

$= 2\pi f C V_{ph}$

$I = 2\pi \times 50 \times 3.283 \times 10^{-7} \times 38.105 \times 10^{3}$

$I = 3.93\,A$

Capacitance Grading:

The Process of achieving uniformity in the dielectric stress by using two or more layers of dielectrics having different Permittivities and Placing dielectrics have larger Permittivities near to the conductor.

If the dielectric stress is same throught the insulating material, then the utilization factor is maximum.

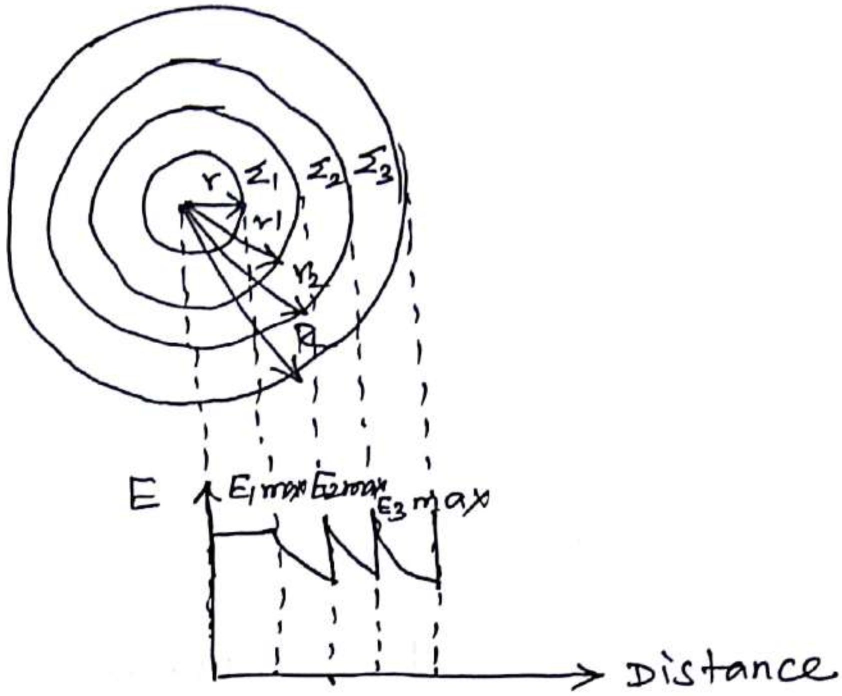
Let r be the radius of the conductor

Let r_1, r_2 be the radius of first and second layers of insulation.

Let R be the radius of the internal sheath

Let $\varepsilon_1, \varepsilon_2$ and ε_3 be the Permittivity of the three different dielectric material

Let $E_{1max}, E_{2max}, E_{3max}$ be the maximum Stress of three different dielectric materials



Case (i) : Same safety factor

Let the safety factor be F for all the materials. Electric stress at the surface of the conductor.

$$E_1 max = \frac{Q}{2\pi\varepsilon_0\varepsilon_1 r} \times F \Rightarrow Q = \frac{E_1 max}{F} \frac{2\pi\varepsilon_0\varepsilon_1}{r}$$

Electric stress at the radius r_1,

$$E_2 max = \frac{Q}{2\pi\varepsilon_0\varepsilon_2 r_1} \times F \Rightarrow Q = \frac{E_2 max}{F} \times 2\pi\varepsilon_0\varepsilon_2 r_1$$

Electric stress at the radius r_2

$$E_3 max = \frac{Q}{2\pi\varepsilon_0\varepsilon_3 r_2} \times F \Rightarrow Q = \frac{E_3 max}{F} \times 2\pi\varepsilon_0\varepsilon_3 r_2$$

Equating Q, we get

$$\frac{E_{1max} 2\pi \varepsilon_0 \varepsilon_1 r}{F} = \frac{E_{2max} 2\pi \varepsilon_0 \varepsilon_r r_1}{F} = \frac{E_{3max} 2\pi \varepsilon_0 \varepsilon_3 r_2}{F}$$

$$E_{1max} \varepsilon_1 r = E_{2max} \varepsilon_2 r_1 = E_{3max} \varepsilon_3 r_2$$

Since $r < r_1 < r_2$

$\varepsilon_1 E_{1max} > \varepsilon_2 E_{1max} > \varepsilon_3 E_{3max}$, We know

$\varepsilon_1 > \varepsilon_2 > \varepsilon_3$

Operating voltage of the cable

$$V = \int_r^{r_1} E_{1max}\, dx + \int_{r_1}^{r_2} E_{2max}\, dx + \int_{r_2}^{R} E_{3max}\, dx$$

$$= \int_r^{r_1} \frac{Q}{2\pi \varepsilon_0 \varepsilon_1 x} dx + \int_{r_1}^{r_2} \frac{Q}{2\pi \varepsilon_0 \varepsilon_2 x} dx + \int_{r_2}^{R} \frac{Q}{2\pi \varepsilon_0 \varepsilon_3 x} dx$$

$$= \frac{Q}{2\pi \varepsilon_0} \left[\frac{1}{\varepsilon_1} \ln\left(\frac{r_1}{r}\right) + \frac{1}{\varepsilon_2} \left(\frac{r_2}{r_1}\right) + \frac{1}{\varepsilon_3} \ln\left(\frac{R}{r_2}\right) \right]$$

$$= \frac{Q}{2\pi \varepsilon_0} \left[\frac{r}{\varepsilon_1 r} \ln\left(\frac{r_1}{r}\right) + \frac{r_1}{\varepsilon_2 r_1} \ln\left(\frac{r_2}{r_1}\right) + \frac{r_2}{\varepsilon_3 r_2} \ln\left(\frac{R}{r_2}\right) \right]$$

Replacing Q in terms of Emax, we get

$$V = E_{1max}\, r \ln\left[\frac{r_1}{r}\right] + E_{2max}\, r_1 \ln\left[\frac{r_2}{r_1}\right] + E_{3max}\, r_2 \ln\left(\frac{R}{r_2}\right)$$

$$V = E_{1max} \times r \ln\left(\frac{r_1}{r}\right) + E_{1max} \frac{\varepsilon_1 r}{\varepsilon_2 r} \times r_1 \ln\left(\frac{r_2}{r_1}\right) + E_{1max} \frac{\varepsilon_1 r}{\varepsilon_3 r_2} \times r_2 \ln\left(\frac{R}{r_2}\right) \Big]$$

$$V = E_{1max}\left\{ r \ln\left[\frac{r_1}{r}\right] + \frac{\varepsilon_1}{\varepsilon_2} r \ln\left[\frac{r_2}{r_1}\right] + \frac{\varepsilon_1}{\varepsilon_3} r \ln\left[\frac{R}{r_2}\right] \right\} \quad (14)$$

Case (ii): Same maximum Stress:

If all the materials are subjected to the same maximum stress, the stresses at r, r_1 and r_2 should be same.

$$E_{max} = E_{1max} = E_{2max} = E_{3max}$$

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_1 r} = \frac{Q}{2\pi\varepsilon_0\varepsilon_2 r_1} = \frac{Q}{2\pi\varepsilon_0\varepsilon_3 r_2}$$

$$\boxed{\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2}$$

$$r < r_1 < r_2, \quad \varepsilon_1 > \varepsilon_2 > \varepsilon_3$$

Operating Voltage $V = V_1 + V_2 + V_3$

$$= E_{1max}\, r \ln\left(\frac{r_1}{r}\right) + E_{2max}\, r_1 \ln\left(\frac{r_2}{r_1}\right) + E_{3max}\, r_2 \ln\left(\frac{R}{r_2}\right)$$

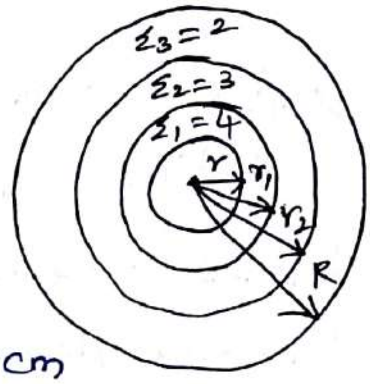
$$E_{1max} = E_{2max} = E_{3max}$$

$$\boxed{V = E_{max}\left[r \ln\left(\frac{r_1}{r}\right) + r_1 \ln\left(\frac{r_2}{r_1}\right) + r_2 \ln\left(\frac{R}{r_2}\right)\right]}$$

If the cable is homogeneous dielectric

$$\boxed{V' = E_{max} \cdot r \ln\left[\frac{R}{r}\right]}$$

(1) A cable is graded with three dielectrics of permittivities 4, 3 and 2. The maximum permissible potential gradient for all dielectrics is same and equals to 30 kV/cm. The core diameter is 1.5 cm and internal sheath diameter is 5.5 cm. Determine the working voltage. (15)



$\varepsilon_1 = 4$ $\varepsilon_2 = 3$, $\varepsilon_3 = 2$

$E_{max} = 30$ kV/cm

Core diameter = 1.5 cm

Internal sheath diameter = 5.5 cm

$r = \frac{1.5}{2} = 0.75$ cm $\quad R = \frac{5.5}{2} = 2.75$ cm

Since potential gradient is same

$E_{1max} = E_{2max} = E_{3max} = 30$ kV/cm

$r\varepsilon_1 = r_1\varepsilon_2 = r_2\varepsilon_3$

$r\varepsilon_1 = r_1\varepsilon_2 \quad r_1 = \frac{\varepsilon_1 r}{\varepsilon_2} = \frac{4 \times 0.75}{3} = 1$ cm

$r\varepsilon_1 = r_2\varepsilon_3$, $r_2 = \frac{\varepsilon_1 r}{\varepsilon_3} = \frac{4 \times 0.75}{2} = 1.5$ cm

$$V = E_{max}\left[r \ln\left(\frac{r_1}{r}\right) + r_1 \ln\left(\frac{r_2}{r_1}\right) + r_2 \ln\left(\frac{R}{r_2}\right)\right]$$

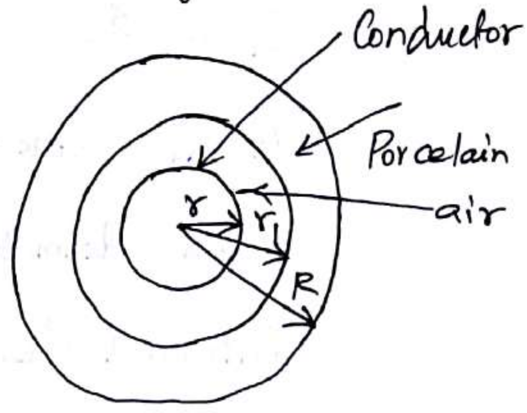
$$= 30\left[0.75 \ln\left[\frac{1}{0.75}\right] + 1 \ln\left[\frac{1.5}{1}\right] + 1.5 \ln\left[\frac{2.75}{1.5}\right]\right]$$

$$= 30\left[0.75 \times 0.2877 + 0.4055 + 1.5 \times 0.606\right]$$

$= 30 \times 1.530 = 45.912$ kV $\quad V_{rms} = \frac{V}{\sqrt{2}} = \frac{45.914}{\sqrt{2}}$

Working voltage $= 32.465$ kV

(2) A Conductor of 1cm diameter passes centrally through a porcelain cylinder of internal diameter 2 cm and external diameter 7 cm. The cylinder is surrounded by a tightly fitted metal sheath. The permittivity of porcelain is 5 and the peak voltage gradient in air must not exceed 34 kV/cm. Determine the maximum safe working voltage.



Conductor diameter = 1 cm

Radius $r = \frac{1}{2} = 0.5$ cm

$E_{1max} = 34$ kV/cm

Internal diameter $d_1 = 2$ cm

External diameter $D = 7$ cm $r_1 = \frac{2}{2} = 1$ cm

$R = \frac{7}{2} = 3.5$ cm , $\varepsilon_1 = 1$ (air) $\varepsilon_2 = 5$ (porcelain)

Let Q be the charge per unit length of the Conductor

$$E_{1max} = \frac{Q}{2\pi\varepsilon_0\varepsilon_1 r} \qquad E_{2max} = \frac{Q}{2\pi\varepsilon_0\varepsilon_2 r_1}$$

$$\frac{(2)}{(1)} \Rightarrow \frac{E_{2max}}{E_{1max}} = \frac{r\varepsilon_1}{r_1\varepsilon_2}, \quad E_{2max} = E_{1max}\frac{\varepsilon_1 r}{\varepsilon_2 r_1}$$

$E_{2max} = 3.4$ kV/cm

Peak Permissible voltage $V = E_{1max}\, r \ln\left(\frac{r_1}{r}\right) + E_{2max}\, r_1 \ln\left(\frac{R}{r_1}\right)$

$$V = 34 \times 0.5 \ln\left(\frac{1}{0.5}\right) + 3.4 \times 1 \ln\left(\frac{3.5}{1}\right)$$

$V = 16.04$ kV (peak)

Working Voltage $V_{rms} = \frac{V}{\sqrt{2}} = \frac{16.04}{\sqrt{2}} = 11.34$ kV

Chennai Institute of Technology
Department of Electrical and Electronics Engineering
EE3401-Transmission and Distribution
UNIT V-DISTRIBUTION SYSTEMS

DISTRIBUTION SYSTEMS

The electrical energy produced at the generating station is conveyed to the consumers through a network of transmission and distribution systems. In general, distribution system is that part of power system which distributes power to the consumers for utilization.

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.

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 tapings 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 tapings are taken for supply to the consumers. The current through a distributor is not constant because tapings 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 main is generally a small cable which connects the distributor to the consumers' terminals.

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) DC Distribution system (b) AC Distribution system

Now-a-days, AC 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 construction 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 current. 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 AC power at high voltage and utilize it at a safe potential. High transmission and distribution voltages have greatly reduced the current in the conductors and the resulting line losses.

The AC 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 low-voltage 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

ii) Secondary distribution system

It is that part of a.c. distribution system. The secondary distribution employs 400/230V, 3-phase, 4 wire 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 400V and power is delivered by 3-phase, 4-wire a.c. system. The voltage between any two phases is 400V and between any phase and neutralize 230V. The single phase domestic loads are connected between anyone phase and the neutral, whereas 3-phase 400V motor loads are connected across3- phase lines directly.

D.C. DISTRIBUTION

It is a common knowledge that electric power is almost exclusively generated, transmitted and distributed as a.c. However, for certain applications, d.c. supply is absolutely necessary. For instance, d.c. supply is required for the operation of variable speed machinery (d.c. motors), for electro-chemical work and for congested areas where storage battery reserves are necessary. For this purpose, a.c. power is converted into d.c. power at the substation by using converting machinery e.g., mercury arc rectifiers, rotary converters and motor-generator sets. The d.c. supply from the substation may be obtained in the form of

(i) 2-wire (ii) 3-wire for distribution.

(i) 2-wire d.c. system.

As the name implies, this system of distribution consists of two wires. One is the outgoing or positive wire and the other is the return or negative wire. The loads such as lamps, motors etc. are connected in parallel between the two wires.

(ii) 3-wire d.c. system.

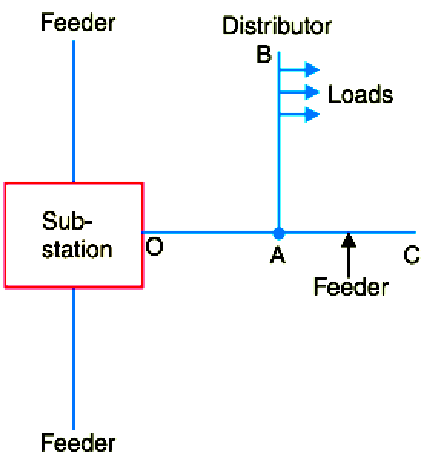
It consists of two outers and a middle or neutral wire which is earthed at the substation. The voltage between the outers is twice the voltage between either outer or neutral wire. Loads requiring high voltage (e.g., motors) are connected across the outers, whereas lamps and heating circuits requiring less voltage are connected between either outer and the neutral.

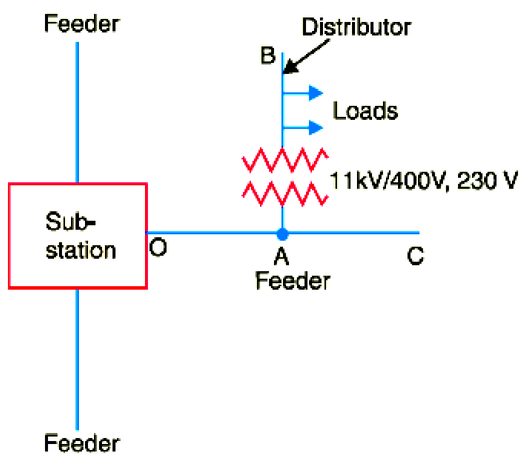
CONNECTION SCHEMES OF DISTRIBUTION SYSTEM

All distribution of electrical energy is done by constant voltage system. In practice, the following distribution circuits are generally used.

(i) Radial System.

In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Fig. shows a single line diagram of a radial system for d.c. distribution where a feeder OC supplies a distributor A B at point A. Obviously, the distributor is fed at one end only i.e., point A is this case. Fig (ii) shows a single line diagram of radial system for a.c. distribution. The radial system is employed only when power is generated at low voltage and the substation is located at the centre of the load.





This is the simplest distribution circuit and has the lowest initial cost. However, it suffers from the following drawbacks

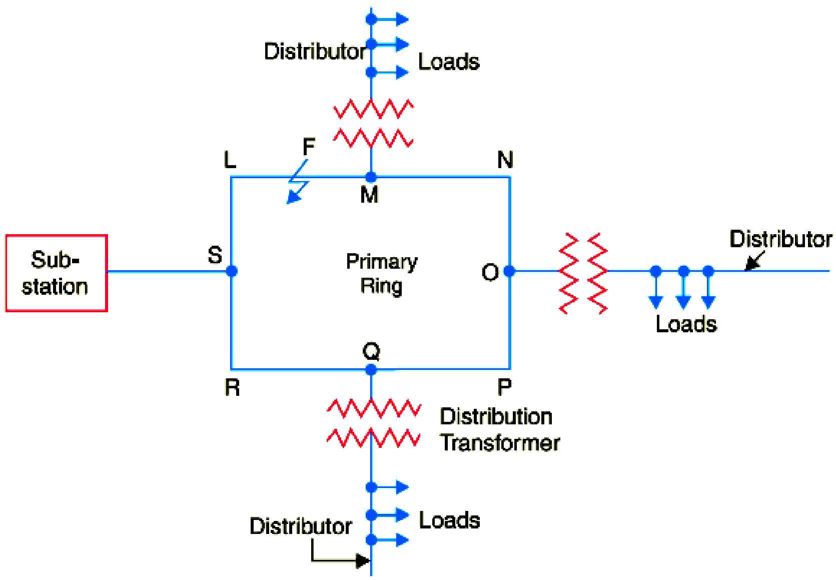
(a) The end of the distributor nearest to the feeding point will be heavily loaded.

(b) The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the substation.

(c) The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes. Due to these limitations, this system is used for short distances only.

(ii) Ring main system.

In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation. Fig.shows the single line diagram of ring main system for a.c. distribution where substation supplies to the closed feeder LMNOPQRS.



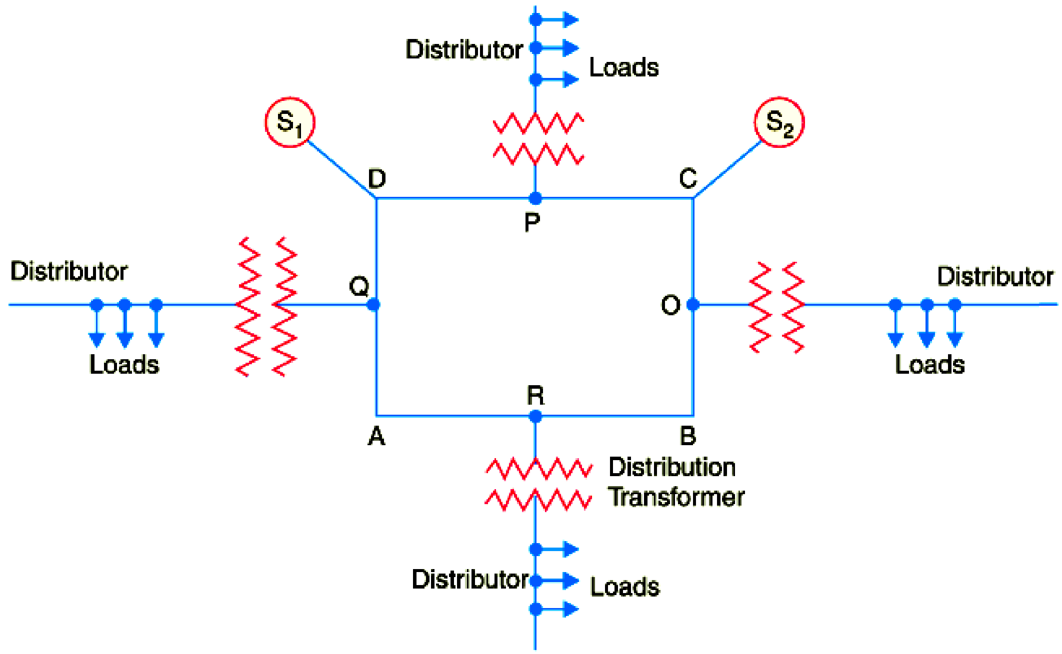
The distributors are tapped from different points M, O and Q of the feeder through distribution transformers. The ring main system has the following advantages

(a) There are less voltage fluctuations at consumer's terminals.

(b) The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the feeder SRQPONM.

(iii) Interconnected system.

When the feeder ring is energized by two or more than two generating stations or substations, it is called inter-connected system. Fig. 12.10 shows the single line diagram of interconnected system where the closed feeder ring ABCD is supplied by two substations S and S at points D and C respectively.



Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers. The interconnected system has the following advantages

(a) It increases the service reliability.

(b) Any area fed from one generating station during peak load hours can be fed from the other generating station. This reduces reserve power capacity and increases efficiency of the system.

COMPARISON BETWEEN OVERHEAD AND UNDERGROUND SYSTEM

The distribution system can be overhead or underground. Overhead lines are generally mounted on wooden, concrete or steel poles which are arranged to carry distribution transformers in addition to the conductors. The underground system uses conduits, cables and manholes under the surface of streets and sidewalks. The choice between overhead and underground system depends upon a number of widely differing factors. Therefore, it is desirable to make a comparison between the two.

(i) Public safety.

The underground system is more safe than overhead system because all distribution wiring is placed underground and there are little chances of any hazard.

(ii) Initial cost.

The underground system is more expensive due to the high cost of trenching, conduits, cables, manholes and other special equipment. The initial cost of an underground system may be five to ten times than that of an overhead system.

(iii) Flexibility.

The overhead system is much more flexible than the underground system. Underground system manholes, duct lines etc., are permanently placed once installed and the load expansion can only be met by laying new lines. However, on an overhead system, poles, wires, transformers etc., can be easily shifted to meet the changes in load conditions.

(iv) Faults.

The chances of faults in underground system are very rare as the cables are laid underground and are generally provided with better insulation.

(v) Appearance.

The general appearance of an underground system is better as all the distribution lines are invisible. This factor is exerting considerable public pressure on electric supply companies to switch over to underground system.

(vi) Fault location and repairs.

In general, there are little chances of faults in an underground system. However, if a fault does occur, it is difficult to locate and repair on this system. On an overhead system, the conductors are visible and easily accessible so that fault locations and repairs can be easily made.

(vii) Current carrying capacity and voltage drop.

An overhead distribution conductor has a considerably higher current carrying capacity than an underground cable conductor of the same material and cross-section. On the other hand, underground cable conductor has much lower inductive reactance than that of an overhead conductor because of closer spacing of conductors.

(viii) Useful life.

The useful life of underground system is much longer than that of an overhead system. An overhead system may have a useful life of 25 years, whereas an underground system may have a useful life of more than 50 years.

(ix) Maintenance cost.

The maintenance cost of underground system is very low as compared with that of overhead system because of less chances of faults and service interruptions from wind, ice, lightning as well as from traffic hazards.

(x) Interference with communication circuits.

An overhead system causes electromagnetic interference with the telephone lines. The power line currents are superimposed on speech currents, resulting in the potential of the communication channel being raised to an undesirable level. However, there is no such interference with the underground system.

It is clear from the above comparison that each system has its own advantages and disadvantages. However, comparative economics (i.e.,annual cost of operation) is the most powerful factor influencing the choice between underground and overhead system. The greater capital cost of underground system prohibits its use for distribution. But sometimes non-economic factors (e.g., general appearance, public safety etc.) exert considerable influence on choosing underground system. In general, overhead system is adopted for distribution and the use of underground system is made only where overhead construction is impracticable or prohibited by local laws.

Substation - introduction

The assembly of apparatus used to change some characteristic (e.g. voltage, a.c. to d.c., frequency, p.f. etc.) of electric supply is called a sub-station. Sub-stations are important part of power system. The continuity of supply depends to a considerable extent upon the successful operation of sub-stations. It is, therefore, essential to exercise utmost care while designing and building a sub-station. The following are the important points which must be kept in view while laying out a sub-station

(i) It should be located at a proper site. As far as possible, it should be located at the centre of gravity of load.

(ii) It should provide safe and reliable arrangement. For safety, consideration must be given to the maintenance of regulation clearances, facilities for carrying out repairs and maintenance, abnormal occurrences such as possibility of explosion or fire etc. For reliability, consideration must be given for good design and construction, the provision of suitable protective gear etc.

(iii) It should be easily operated and maintained.

(iv) It should involve minimum capital cost.

Classification of Sub-Stations

There are several ways of classifying sub-stations. However, the two most important ways of classifying them are according to (1) service requirement and (2) constructional features.

1.According to service requirement

A sub-station may be called upon to change voltage level or improve power factor or convert a.c. power into d.c. power etc. According to the service requirement, sub-stations may be classified into :

(i)Generating sub-stations.

Generating substations are located near the generatingplants. The generating voltages are 11kv or 6.6 kv and need to be stepped up to the transmission in the range of 110kv, 220kv and 400kv, so that the power loss will be reduced and large amount of power can be transmitted over long distance.

(ii) Grid substations

Grid substations are located in the intermediate points between the generating stations and load centers. Load centers receive all the information from the generating stations and to ensure corrective actions. The main purpose of these substations is to provide connections of low voltage line, some compensating devices etc.

(iii) Secondary substations

These substations are connected with the main grid substations with the help of secondary transmission lines. The voltages at these substations are stepped down to the primary distribution voltage or sub transmission voltage such as 11kv or 6.6 kv. Some large factories are directly connected to these substations.

(iv) Distribution substation

Distribution substations are connected between primary and secondary distribution. The primary distribution voltages such as 11kv or 6.6 kv is to be stepped down to the supply voltage 400 V for three phase and 230 V for single phase. These substations are transfer power to the consumer through distributors and service mains.

(v) Switching sub-stations

These sub-stations do not change the voltage level i.e. incoming and outgoing lines have the same voltage. However, they simply perform the switching operations of power lines.

(vi) Power factor correction sub-stations.

Those sub-stations which improve the power factor of the system are called power factor correction sub-stations. Such sub-stations are generally located at the receiving end of transmission lines. These sub-stations generally use synchronous condensers as the power factor improvement equipment.

(vii) Frequency changer sub-stations

Those sub-stations which change the supply frequency are known as frequency changer sub-stations. Such a frequency change may be required for industrial utilization.

(viii) Converting sub-stations

Those sub-stations which change a.c. power into d.c. power are called converting sub-stations. These sub-stations receive a.c. power and convert it into d.c power with suitable apparatus to supply for such purposes as traction, electroplating, electric welding etc.

(ix) Industrial sub-stations

Those sub-stations which supply power to individual industrial concerns are known as industrial sub-stations.

2. According to constructional features

A sub-station has many components (e.g. circuit breakers, switches, fuses, instruments etc.) which must be housed properly to ensure continuous and reliable service. According to constructional features, the sub-stations are classified as

(i) Indoor sub-station

(ii) Outdoor sub-station

(iii) Underground sub-station

(iv) Pole-mounted sub-station

(i) Indoor sub-stations

For voltages upto 11 kV, the equipment of the sub-station is installed indoor because of economic considerations. However, when the atmosphere is contaminated with impurities, these sub-stations can be erected for voltages upto 66 kV.

(ii) Outdoor sub-stations

For voltages beyond 66 kV, equipment is invariably installed out- door. It is because for such voltages, the clearances between conductors and the space required for switches, circuitbreakers and other equipment becomes so great that it is not economical to install the equipment indoor.

(iii) Underground sub-stations

In thickly populated areas, the space available for equipment and building is limited and the cost of land is high. Under such situations, the sub-station is created underground.

(iv) Pole-mounted sub-stations

This is an outdoor sub-station with equipment installed over- head on H-pole or 4-pole structure. It is the cheapest form of sub-station for voltages not exceeding 11kV (or 33 kV in some cases). Electric power is almost distributed in localities through such sub- stations. For complete discussion on pole-mounted sub-station,

METHODS OF GROUNDING

GROUNDING - INTRODUCTION

In power system, grounding or earthing means connecting frame of electrical equipment (non-current carrying part) or some electrical part of the system (e.g. neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth i.e. soil. This connection to earth may be through a conductor or some other circuit element (e.g. are resistor, a circuit breaker etc.) depending up on the situation, grounding or earthing offers two principal advantages. First, it provides protection to the power system. For example, If the neutral point of a star-connected system is grounded through a circuit breaker and phase to earth fault occurs on any one line, a large fault current will flow through the circuit breaker. The circuit breaker will open to isolate the faulty line. This protects the power system from the harmful effects of the fault. Secondly, earthing of electrical equipment ensures the safety of the persons handling the equipment. For example, if insulation fails, there will be a direct contact of the live conductor with the metallic part (i.e. frame) of the equipment. Any person in contact with the metallic part of this equipment will be subjected to a dangerous electrical shock which can be fatal. In this chapter, we shall discuss the importance of grounding or earthing in the line of power system with special emphasis on neutral grounding.

Concept of Grounding

The process of connecting the metallic frame (i.e. non-current carrying part) of electrical equipment or some electrical part of the system (e.g. neutral point in a star- connected system, one conductor of the secondary of a transformer etc.) to earth (i.e. soil) is called grounding or earthing. It is strange but true that grounding of electrical systems is less understood aspect of power system. Nevertheless, it is a very important subject. If grounding is done systematically in the line of the power system, we can effectively prevent accidents and damage to the equipment of the power system and at the same time continuity of supply can be maintained. Grounding or earthing may be classified as:(i) Equipment grounding (ii) System grounding. Equipment grounding deals with earthing the non-current-carrying metal parts of the electrical equipment. On the other hand, system grounding means earthing some part of the electrical system e.g. earthing of neutral point of star-connected system in generating stations and substations.

Neutral Grounding

The process of connecting neutral point of 3-phase system to earth (i.e. soil) either directly or through some circuit element is called neutral grounding. Neutral grounding provides protection to personal and equipment. It is because during earth fault, the current path is completed through the earthed neutral and the protective devices (e.g. a fuse etc.) operate to isolate the faulty conductor from the rest of the system. This point is illustrated in Fig.

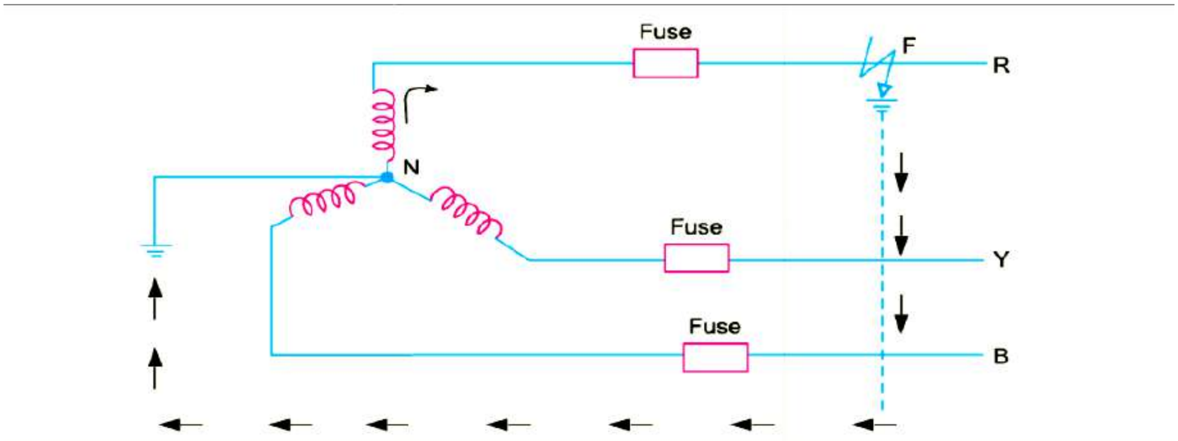


Fig. shows a 3-phase, star-connected system with neutral earthed. Suppose a single line to ground fault occurs in line R at point F. This will cause the current to flow through ground path as shown in Fig.1. Note that current flows from R phase to earth, then to neutral point N and back to R-phase. Since the impedance of the current path is low, a large current flows through this path. This large current will blow the fuse in R-phase and isolate the faulty line R. This will protect the system from the harmful effects of the fault. One important feature of grounded neutral is that the potential difference between the live conductor and ground will not exceed the phase voltage of the system i.e. it will remain nearly constant.

Advantages of Neutral Grounding

The following are the advantages of neutral grounding

(i) Voltages of the healthy phases do not exceed line to ground voltages i.e. they remain nearly constant.

(ii) The high voltages due to arcing grounds are eliminated.

(iii) The protective relays can be used to provide protection against earth faults. In case earth fault occurs on any line, the protective relay will operate to isolate the faulty line.

(iv) The over voltages due to lightning are discharged to earth.

(v) It provides greater safety to personnel and equipment.

(vi) It provides improved service reliability.

(vii) Operating and maintenance expenditures are reduced

Methods of Neutral Grounding

The methods commonly used for grounding the neutral point of a 3-phase system are :

(i) Solid or effective grounding

(ii) Resistance grounding

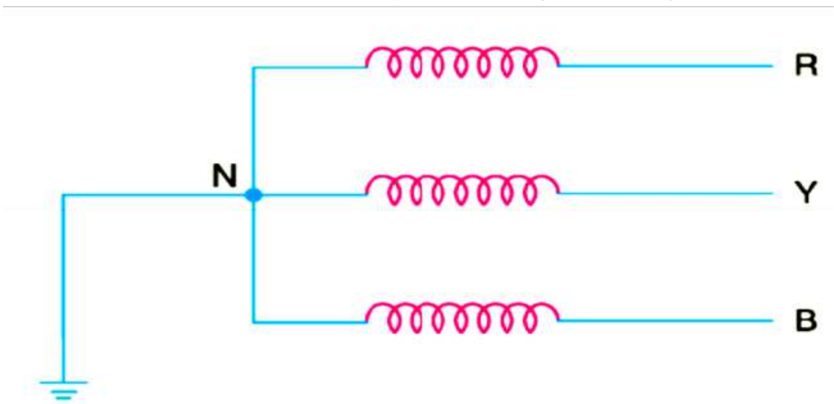
(iii) Reactance grounding

(iv) Peterson-coil grounding

The choice of the method of grounding depends upon many factors including the size of the system, system voltage and the scheme of protection to be used.

(i)Solid Grounding

When the neutral point of a 3-phase system (e.g. 3- phase generator, 3-phase transformer etc.) is directly connected to earth (i.e. soil) through a wire of negligible resistance and reactance, it is called solid grounding or effective grounding. Fig. shows the solid grounding of the neutral point. Since the neutral point is directly connected to earth through a wire, the neutral point is held at earth potential under all conditions. Therefore, under fault conditions, the voltage of any conductor to earth will not exceed the normal phase voltage of the system.



Advantages

The solid grounding of neutral point has the following advantages:

(i) The neutral is effectively held at earth potential.

(ii)When earth fault occurs on any phase, the resultant capacitive current IC is in phase opposition to the fault current IF . The two currents completely cancel each other. Therefore, no arcing ground or over-voltage conditions can occur.

(iii)When there is an earth fault on any phase of the system, the phase to earth voltage of the faulty phase becomes zero.

(iv) It becomes easier to protect the system from earth faults which frequently occur on the system. When there is an earth fault on any phase of the system, large fault current flows between the fault point and the grounded neutral. This permits the easy operation of earth fault relay.

Disadvantages

The following are the disadvantages of solid grounding :

(i) Since most of the faults on an overhead system are phase to earth faults, the system has to bear a large number of severe shocks. This causes the system to become unstable.

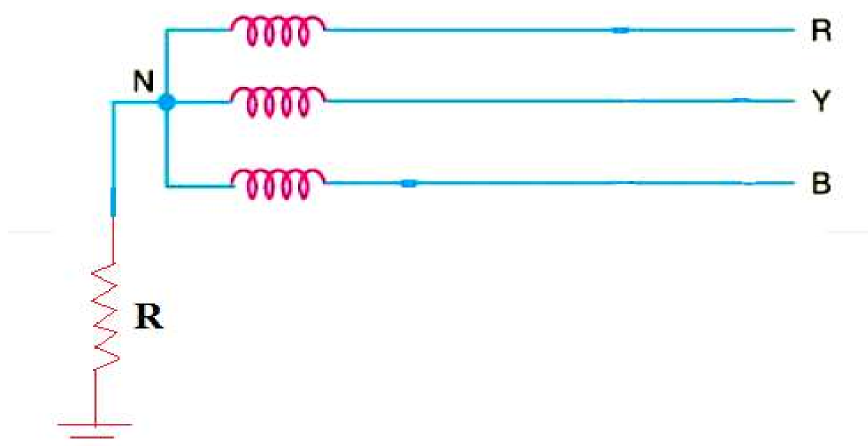
(ii) The solid grounding results in heavy earth fault currents. Since the fault has to be cleared by the circuit breakers, the heavy earth fault currents may cause the burning of circuit breaker contacts.
(iii) The increased earth fault current results in greater interference in the neighboring communication lines.

Applications

Solid grounding is usually employed where the circuit impedance is sufficiently high so as to keep the earth fault current within safe limits. This system of grounding is used for voltages up to 33 kV with total power capacity not exceeding 5000 kVA.

(ii)Resistance Grounding

In order to limit the magnitude of earth fault current, it is a common practice to connect the neutral point of a 3-phase system to earth through a resistor. This is called resistance grounding. When the neutral point of a 3-phase system (e.g. 3-phase generator, 3- phase transformer etc.) is connected to earth (i.e. soil) through a resistor, it is called resistance grounding. Fig.shows the grounding of neutral point through a resistor R . The value of R should neither be very low nor very high. If the value of earthing resistance R is very low, the earth fault current will be large and the system becomes similar to the solid grounding system. On the other hand, if the earthing resistance R is very high, the system conditions become similar to ungrounded neutral system. The value of R is so chosen such that the earth fault current is limited to safe value but still sufficient to permit the operation of earth fault protection system. In practice, that value of R is selected that limits the earth fault current to 2 times the normal full load current of the earthed generator or transformer.



Advantages

The following are the advantages of resistance earthing:
i)The earth fault current is small due to the presence of earthing resistance. Therefore, interference with communication circuits is reduced.
ii)It improves the stability of the system.

Disadvantages

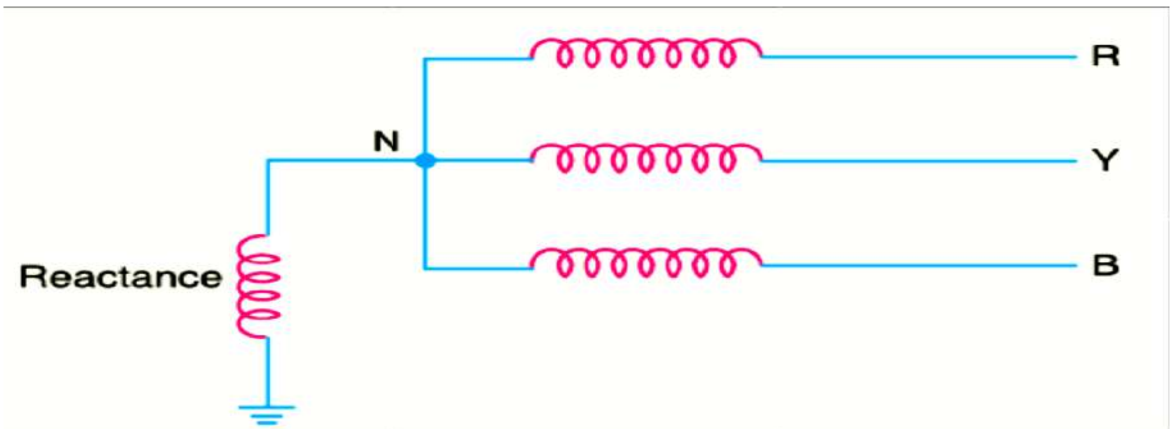
The following are the disadvantages of resistance grounding

(i) Since the system neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.
(ii)This system is costlier than the solidly grounded system.
(iii)A large amount of energy is produced in the earthing resistance during earth faults. Sometimes it becomes difficult to dissipate this energy to atmosphere.

Applications

It is used on a system operating at voltages between 2.2 kV and 33 kV with power source capacity more than 5000 kVA.

(iii)Reactance Grounding



In this system, a reactance is inserted between the neutral and ground as shown in Fig. The purpose of reactance is to limit the earth fault current. By changing the earthing reactance, the earth fault current can to changed to obtain the conditions similar to that of solid grounding. This method is not used these days because of the following.

Disadvantages

(i) In this system, the fault current required to operate the protective device is higher than that of resistance grounding for the same fault conditions.
(ii)High transient voltages appear under fault conditions.

(iv) Arc Suspension Grounding (Or Resonant Grounding)

We have seen that capacitive currents are responsible for producing arcing grounds. These capacitive currents flow because capacitance exists between each line and earth. If inductance L of appropriate value is connected in parallel with the capacitance of the system, the fault current IF flowing through L will be in phase opposition to the capacitive current IC of the system. If L is so adjusted that IL= Ic then resultant current in the fault will be zero. This condition is known as resonant grounding. When the value of L of arc suppression coil is such that the fault current IF exactly balances the capacitive current Ic, it is called resonant grounding.

Advantages

The Peterson coil grounding has the following advantages:

(i) The Peterson coil is completely effective in preventing any damage by an arcing ground.

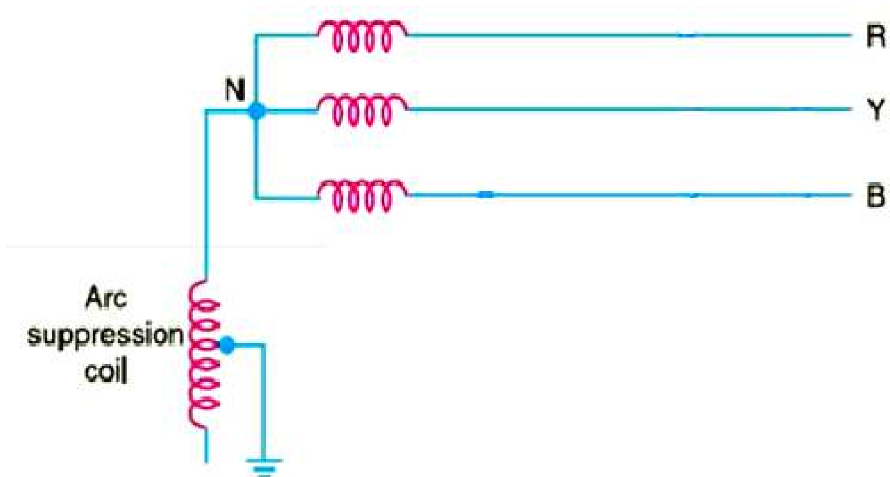
(ii) The Peterson coil has the advantages of ungrounded neutral system.

Disadvantages

The Peterson coil grounding has the following disadvantages.

(i) Due to varying operational conditions, the capacitance of the network changes from time to time. Therefore, inductance L of Peterson coil requires readjustment.

(ii) The lines should be transposed.



HVDC Transmission System

The massive transmission of electricity in the form of DC over long distances by means of submarine cables or overhead transmission line is the high voltage direct current transmission. This type of transmission is preferred over HVAC transmission for very long distance when considering the cost, losses and many other factors. The names Electrical superhighway or Power superhighway are often used for **HVDC**.

We know that AC power is generated in the generating station. This should first be converted into DC. The conversion is done with the help of rectifier. The DC power will flow through the overhead lines. At the user end, this DC has to be converted into AC. For that purpose, an inverter is placed at the receiving end.

Thus, there will be a rectifier terminal in one end of HVDC substation and an inverter terminal in the other end. The power of the sending end and user end will be always equal (Input Power = Output Power).

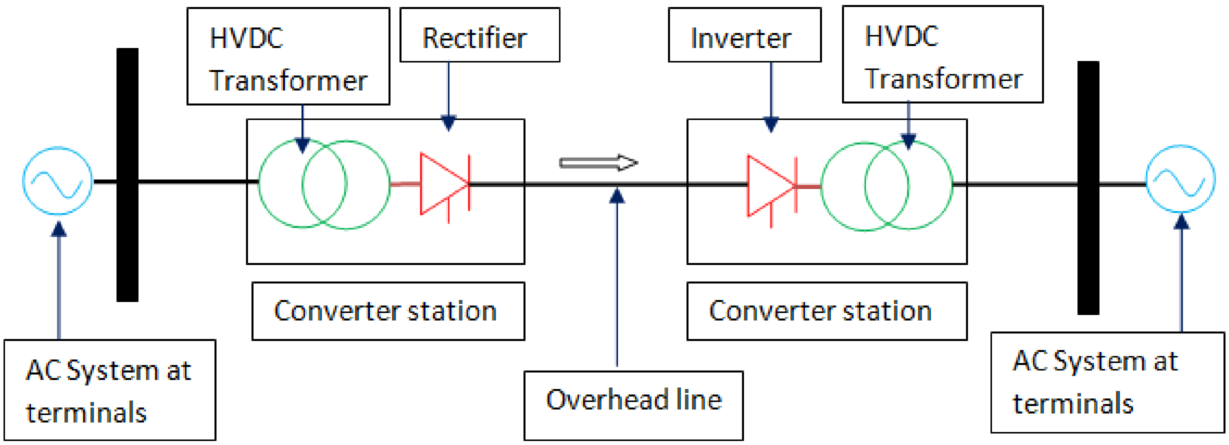


Figure 1: HVDC Substation Layout

When there are two converter stations at both ends and a single transmission line is termed as two terminal DC systems. When there are two or more converter stations and DC transmission lines is termed as multi-terminal DC substation.

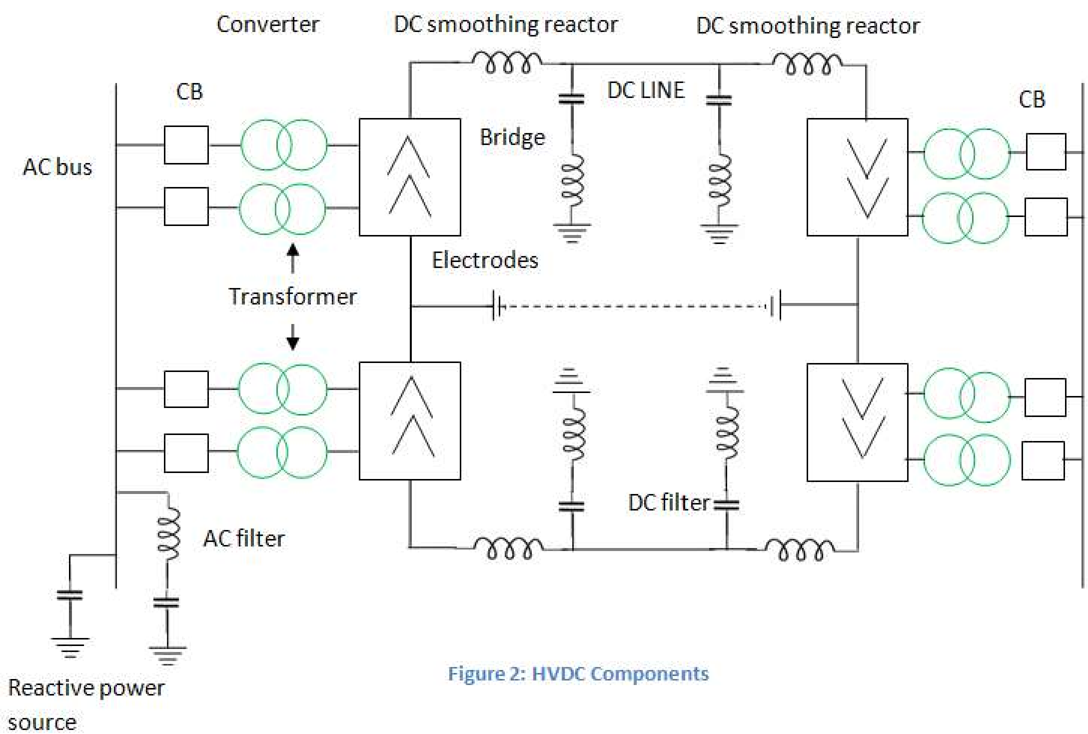


Figure 2: HVDC Components

The components of the **HVDC Transmission** system and its function are explained below.
Converters: The AC to DC and DC to AC conversion are done by the converters. It includes transformersand valve bridges.
Smoothing Reactors: Each pole consist of smoothing reactors which are of inductorsconnected in series with the pole. It is used to avoid commutation failures occurring in inverters, reduces

harmonics and avoids discontinuation of current for loads.
Electrodes: They are actually conductors which are used to connect the system to the earth.
Harmonic Filters: It is used to minimize the harmonics in voltage and current of the converters used.
DC Lines: It can be cables or overhead lines.
Reactive Power Supplies: The reactive power used by the converters could be more than 50% of the total transferred active power. So the shunt capacitors provide this reactive power.
AC Circuit Breakers: The fault in the transformer is cleared by the circuit breakers. It also used to disconnect the DC link.

The classification (types) of HVDC links.

Mono Polar Links

Single conductor is required and water or ground act as the return path. If the earth resistivity is high, metallic return is used.

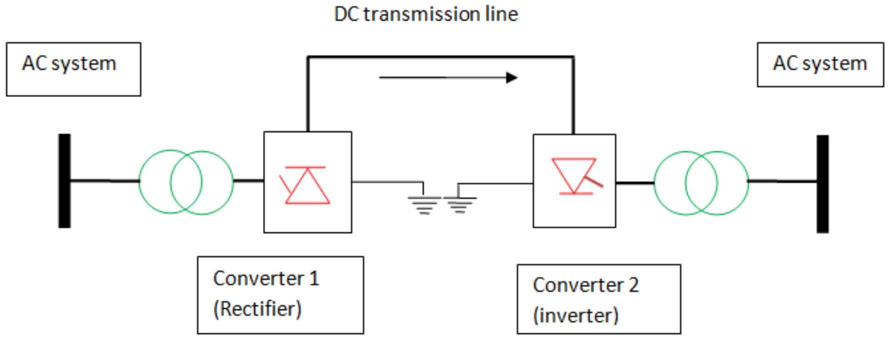


Figure 3: Mono Polar Link

Bipolar Links

Double converters of same voltage rating are used in each terminal. The converter junctions are grounded.

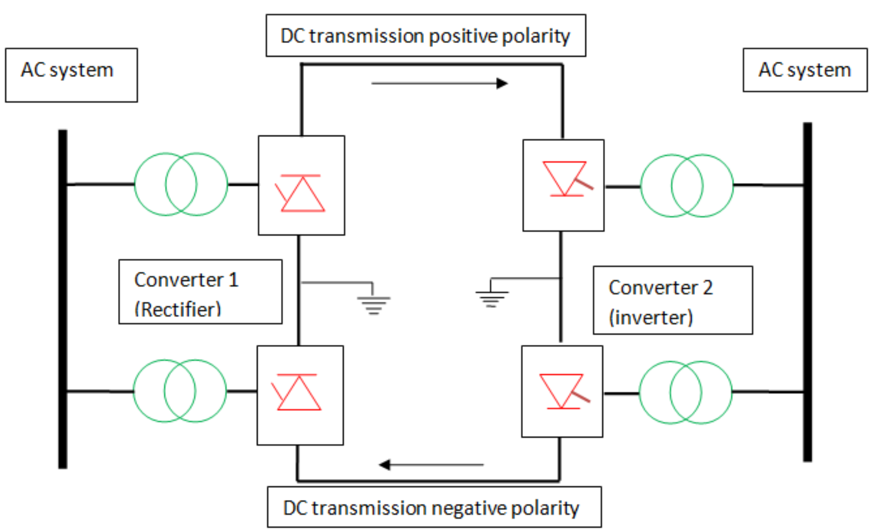


Figure 4: Bipolar Link

Homo Polar Links

It consists of more than two conductors which is having equal polarity generally negative. Ground is the return path.

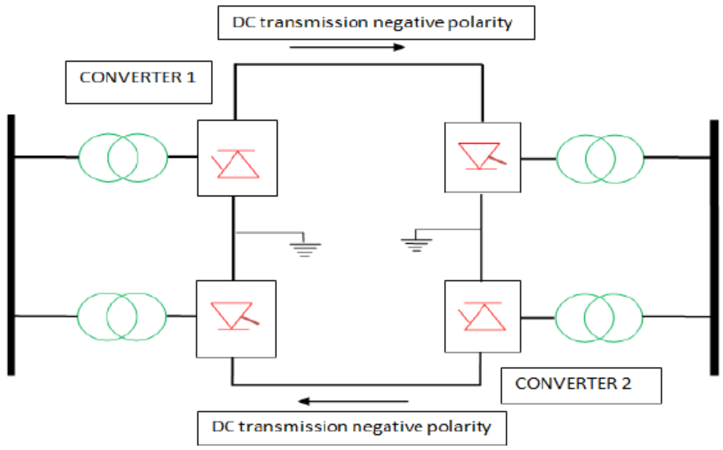


Figure 5: Homo Polar Link

Comparison of both HVAC and HVDC Transmission System

HVDC Transmission System	HVAC Transmission System
Low losses.	Losses are high due to the skin effect and corona discharge
Better Voltage regulation and Control ability.	Voltage regulation and Control ability is low.
Transmit more power over a longer distance.	Transmit less power compared to a HVDC system.
Less insulation is needed.	More insulation is required.
Reliability is high.	Low Reliability.
Asynchronous interconnection is possible.	Asynchronous interconnection is not possible.
Reduced line cost due to fewer conductors.	Line cost is high.
Towers are cheaper, simple and narrow.	Towers are bigger compared to HVDC.

Economic Distance for HVDC transmission lines

DC lines are cheaper than the AC lines, but the cost of DC terminal equipment is very high as compared to AC terminal cables (shown in the graph below). Thus, the initial cost is high in HVDC transmission system, and it is low in the AC system.

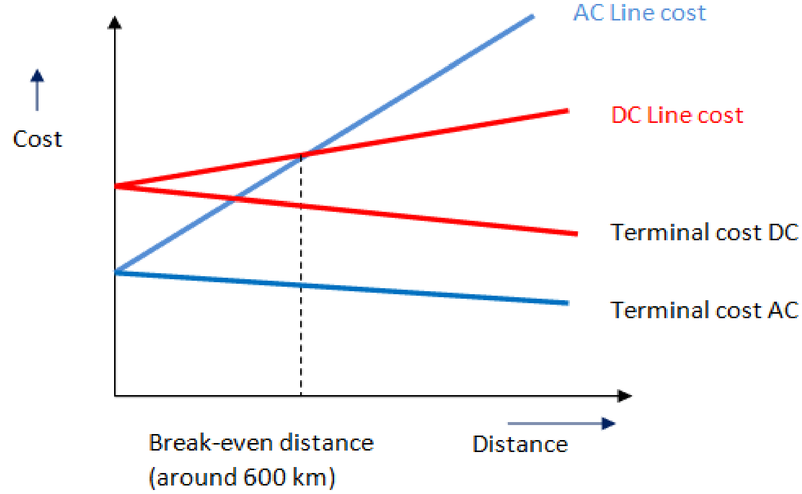
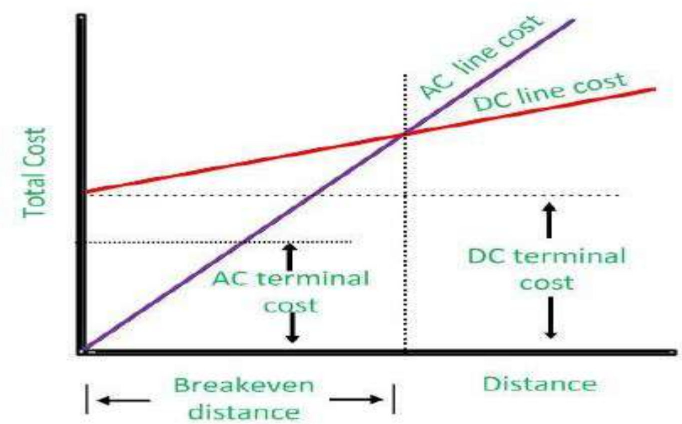


Figure 6: Comparison of Cost of HVDC and HVAC



Comparision of the costs of AC and DC transmission

The point where two curves meet is called the **breakeven distance**. Above the breakeven distance, the HVDC system becomes cheaper. Breakeven distance changes from 500 to 900 km in overhead transmission lines.

Advantages of HVDC transmissions

1. A lesser number of conductors and insulators are required thereby reducing the cost of the overall system.
2. It requires less phase to phase and ground to ground clearance.
3. Their towers are less costly and cheaper.
4. Lesser corona loss is less as compared to HVAC transmission lines of similar power.

5. Power loss is reduced with DC because fewer numbers of lines are required for power transmission.
6. The HVDC system uses earth return. If any fault occurs in one pole, the other pole with ‘earth returns’ behaves like an independent circuit. This results in a more flexible system.
7. The HVDC has the asynchronous connection between two AC stations connected through an HVDC link; i.e., the transmission of power is independent of sending frequencies to receiving end frequencies. Hence, it interconnects two substations with different frequencies.
8. Due to the absence of frequency in the HVDC line, losses like skin effect and proximity effect does not occur in the system.
9. It does not generate or absorb any reactive power. So, there is no need for reactive power compensation.
10. The very accurate and lossless power flows through DC link.

Disadvantages of HVDC transmission

1. Converter substations are placed at both the sending and the receiving end of the transmission lines, which result in increasing the cost.
2. Inverter and rectifier terminals generate harmonics which can be reduced by using active filters which are also very expensive.
3. If a fault occurs in the AC substation, it may result in a power failure for the HVDC substation placed near to it
4. Inverter used in converter substations have limited overload capacity.
5. Circuit breakers are used in HVDC for circuit breaking, which is also very expensive.
6. It does not have transformers for changing the voltage levels.
7. Heat loss occurs in converter substation, which has to be reduced by using the active cooling system.
8. HVDC link itself is also very complicated.

Conclusion

Considering all the advantages of DC, it seems that HVDC lines are more proficient than AC lines. But, the initial cost of HVDC substation is very high and their substation equipment is quite complicated.Thus, for long distance transmission it is preferable that power is generated in AC, and for transmission, it is converted into DC and then again converted back into AC for final use. This system is economical and also improves the efficiency of the system.

Application of HVDC Transmission

- Undersea and underground cables
- AC network interconnections
- Interconnecting Asynchronous system

FACTS

FACTS is an Flexible Alternating Current Transmission System.Dr.Narain.G.Hingorani is a father of facts concept. Facts devices are used to provide controllability, stability and power transfer capability of AC transmission system.

Flexible AC Transmission System (FACTS) is an integrated concept based on power electronic switching converters and dynamic controllers to enhance the system utilization and power transfer capacity as well as the stability, security, reliability and power quality of AC system interconnections. FACTS is a collection of thyristor-based controllers, including phase shifters, advanced static VAR compensator, dynamic brake, modulator series capacitor, load tap changer, fault current limiter, and perhaps other that have yet to be invented.

Objectives of FACTS

1. Rapid control of reactive power flow.
2. Improves the voltage profile
3. Secure loading of lines.
4. Improve power transfer capability.

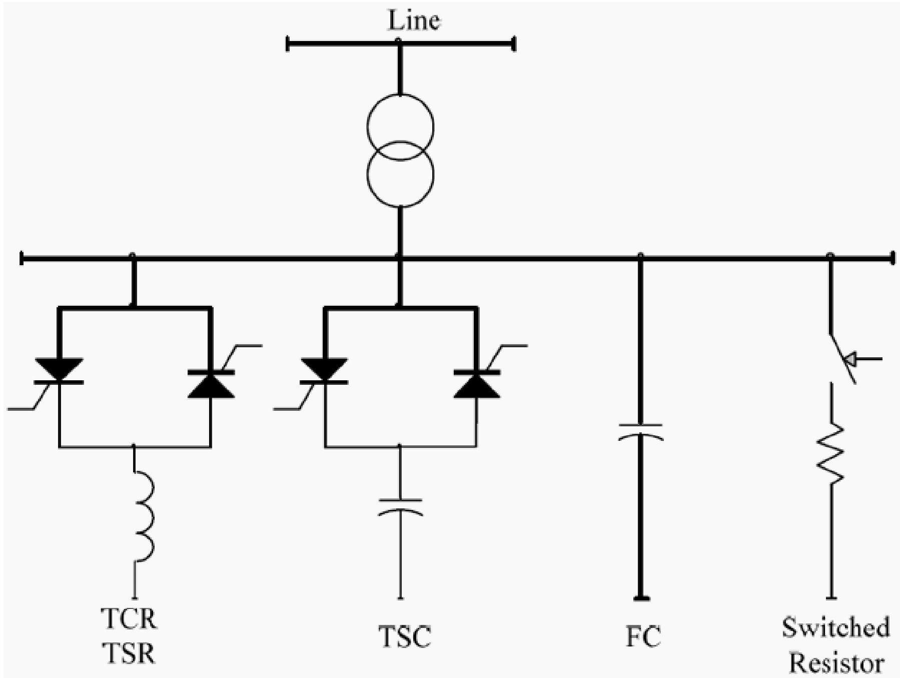
Advantages of FACTS

1. Improves transient Stability and Dynamic stability
2. Improved steady state stability
3. Reduced financial costs
4. Increase the system security
5. Improve power transfer capability.
6. Reduces power system oscillations

STATIC VAR COMPENSATOR(SVC)

Static VAR Compensator (SVC) The Static VAR Compensator (SVC) is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids. The SVC regulates voltage at its terminals by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the SVC generates reactive power (SVC capacitive). When system voltage is high, it absorbs reactive power (The variation of reactive power is performed by switching three-phase capacitor banks and inductor banks connected on the secondary side of a coupling transformer. Each capacitor bank is switched on and off by three thyristor switches (Thyristor Switched Capacitor or TSC). Reactors are either switched on-off (Thyristor Switched Reactor or TSR) or phase-controlled (Thyristor Controlled Reactor or TCR).

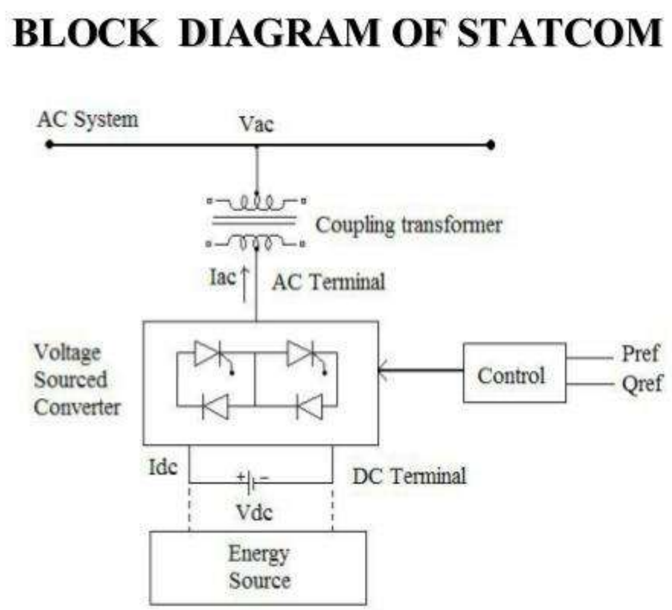
This device provides reactive power quickly to HV transmission lines thus enhancing the line performance. The word “static” indicates that it has no moving part such as circuit breakers. This SVC device was designed for impedance matching so that power system come closer to unity power factor. If the reactive load of power system is leading, the SVC will consume VARs mainly using thyristor controlled reactors, however if the load is lagging, the capacitor banks are switched in automatically offering greater control of system voltage.



A SVC is an electrical device for providing fast acting reactive power on high-voltage electricity transmission networks. SVCs are part of the FACTS device family and regulating voltage and stabilizing the system. Unlike a synchronous condenser which is a rotating electrical machine a SVC has no significant moving parts and prior to the invention of the SVC power factor compensation was the preserve of large rotating machines such as synchronous condensers or switched capacitor banks. The SVC is an automated impedance matching device designed to bring the system closer to unity power factor. SVCs are used in two main situations: Connected to the power system, to regulate the transmission voltage. Connected near large industrial loads, to improve power quality. In transmission applications the SVC is used to regulate the grid voltage. If the power system's reactive load is capacitive (leading) the SVC will use thyristor controlled reactors to consume vars from the system lowering the system voltage. Under inductive (lagging)conditions the capacitor banks are automatically switched on thus providing a higher system voltage and by connecting the thyristor-controlled reactor which is continuously variable along with a capacitor bank step and the net result is continuously-variable leading or lagging power. In industrial applications SVCs are typically placed near high and rapidly varying loads such as arc furnaces where they can smooth flicker voltage.

Static Compensator (STATCOM)

A STATCOM or static Compensator is a shunt connected device used on AC transmission systems and is a good alternative of conventional static VAR compensator. It belongs to the second generation of FACTS family and is based on power electronics voltage source converters (VSC). As it is connected in parallel it is also called shunt connected controller. The output current of STATCOM can be regulated autonomously without any regard for the system voltage, independent of the detail that it is inductive or capacitive. Usually it is used to support voltage regulation and in power networks of reduced power factor. It can provides dynamic stability and active AC power when connected to source, but most commonly it is used to provide voltage stability in power system. Figure shows circuit diagram of static compensator (STATCOM) without energy storage.



The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating and/ or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM considered is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer). The dc voltage is provided by an energy-storage capacitor and a STATCOM can improve power-system performance in such areas as the following.

1. The dynamic voltage control in transmission and distribution systems
2. The power-oscillation damping in power-transmission systems
3. The transient stability
4. The voltage flicker control.

5. The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source.

Advantages of STATCOM

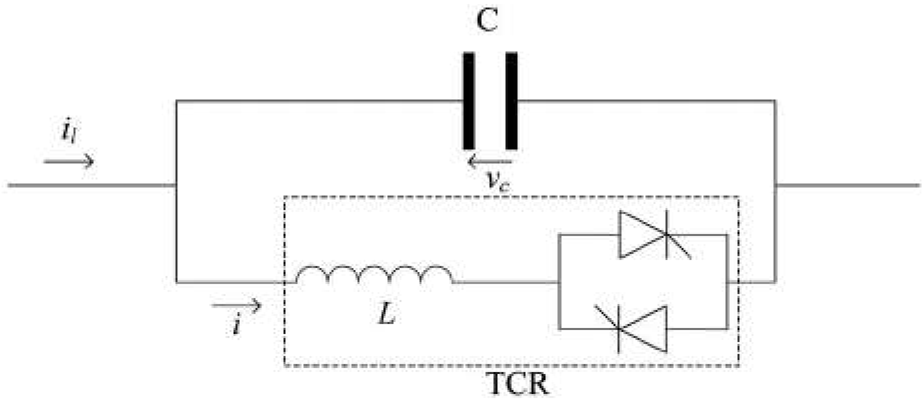
1. It occupies a small footprint, for it replaces passive banks of circuit elements by compact electronic converters.
2. It offers modular, factory-built equipment, thereby reducing site work and commissioning time.
3. It uses encapsulated electronic converters, thereby minimizing its environmental impact.

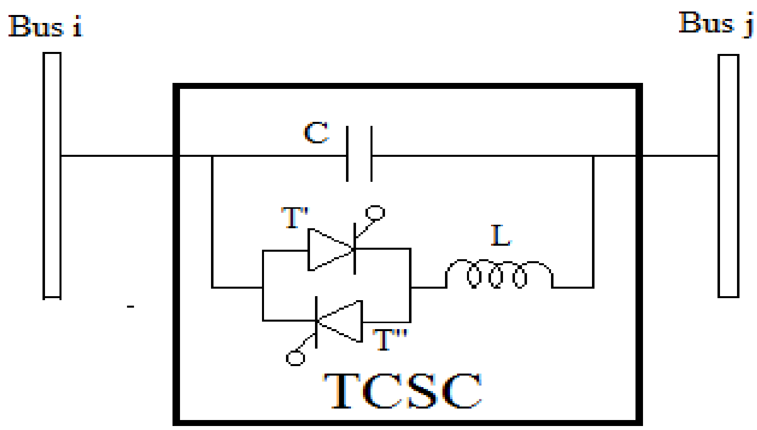
Thyristor Controlled Series Capacitor (TCSC)

TCSC is a power electronic based system and Thyristor Switched Capacitor is connected in series with a bidirectional thyristor valve. The TCSC can control power flow, mitigate sub-synchronous resonance, improve transient stability, damp out power system oscillations resulting increase of power transfer capability. A single diagram of TCSC shows two modules connected in series and there can be one or more module depending on the requirement to reduce the costs and TCSC may be used in conjunction with fixed series capacitors. Nowadays TCSC is being included in some of the transmission systems and the basic circuit of a TCSC in one of the phase is shown in the fig.controls the current through the reactor. The forward-looking thyristor has firing angle 90 – 180 and firing the thyristors at this time results in a current flow through the inductor that is opposite to the capacitor current and in this loop current increases the voltage across the capacitor. Further the loop current increases as firing angle decreases from 180. The different compensation levels are obtained by varying the firing angle of the reactor-circuit-thyristor.

APPLICATION OF TCSC:

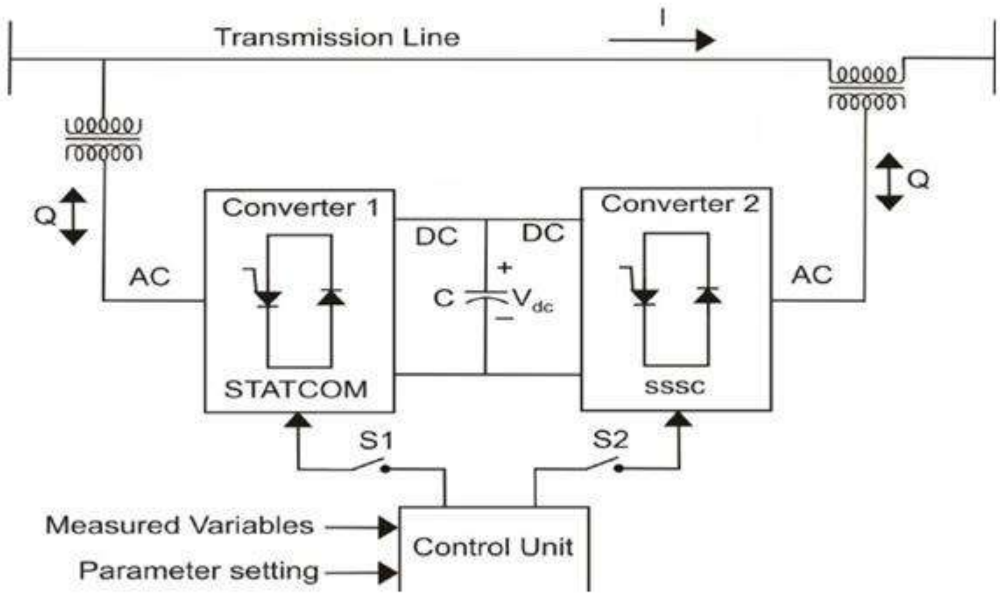
Thyristor-controlled series capacitors (TCSCs) can be used for several power system performance enhancements, namely, the improvement in system stability, the damping of power oscillations, the alleviation of sub synchronous resonance (SSR), and the prevention of voltage collapse. The effectiveness of TCSC controllers is dependent largely on their proper placement within the carefully selected control signals for achieving different functions. Although TCSCs operate in highly nonlinear power-system environments, linear-control techniques are used extensively for the design of TCSC controllers.





UNIFIED POWER FLOW CONTROLLER (UPFC)

The UPFC is the most versatile member of FACTS family using power electronics to control power flow on power grids. The UPFC uses a combination of a shunt controller (STATCOM) and a series controller (SSSC) interconnected through a common DC bus.This FACTS topology provides much more flexibility than the SSSC for controlling the line active and reactive power because active power can now be transferred from the shunt converter to the series converter through the DC bus.It can independently and very rapidly control both real- and reactive power flows in a transmission.One VSC converter 1 is connected in shunt with the line through a coupling transformer; the other VSC converter 2 is inserted in series with the transmission line through an interface transformer. The dc voltage for both converters is provided by a common capacitor bank.In this process, the series converter exchanges both real and reactive power with the transmission line. Although the reactive power is internally generated/ absorbed by the series converter, the real-power generation/ absorption is made feasible by the dc-energy–storage device that is, the capacitor. The shunt-connected converter 1 is used mainly to supply the real-power demand of converter 2, which it derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus. Thus the net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers. In addition, the shunt converter functions like a STATCOM and independently regulates the terminal voltage of the interconnected bus by generating/ absorbing a requisite amount of reactive power.



VOLTAGE CONTROL METHODS

The voltage of the power system may vary with the change in load. The voltage is normally high at light load and low at the heavy-load condition. For keeping the voltage of the system in limits, some additional equipment requires which increase the system voltage when it is low and reduces the voltage when it is too high. The following are the methods used in the power system for controlling the voltage.

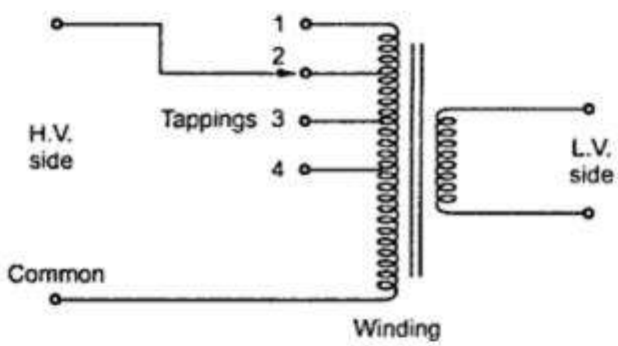
1. On – Load Tap Changing Transformer
2. Off – Load Tap Changing transformer
3. Shunt Reactors
4. Synchronous Condenser
5. Shunt Capacitor
6. Static VAR System (SVS)

Controlling the system voltage by the help of shunt inductive element is known as shunt compensation. The shunt compensation is of two types, i.e., the static shunt compensation and the synchronous compensation. In static shunt compensation, the shunt reactor, shunt capacitor and static VAR system are used, whereas the shunt compensation uses the synchronous phase modifier. The methods used for controlling the voltage are explained below in details.

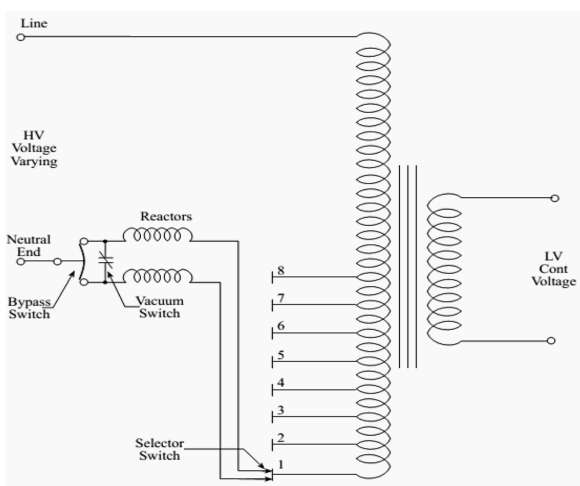
Voltage Control by Tap changing in transformers:

The voltage control of transmission and distribution systems is obtained basically by tap-changing Tap changers are either on-load or off load tap changers. By changing the turns ratio of the transformer the voltage ratio and the secondary voltage is changed and voltage control is obtained. Tap changing is widely used voltage control method employed at every voltage level.

1. Off – Load Tap Changing Transformer – In this method, the voltage is controlled by changing the turn ratio of the transformer. The transformer is disconnected from the supply before changing the tap. The tap changing of the transformer mostly donemanually.



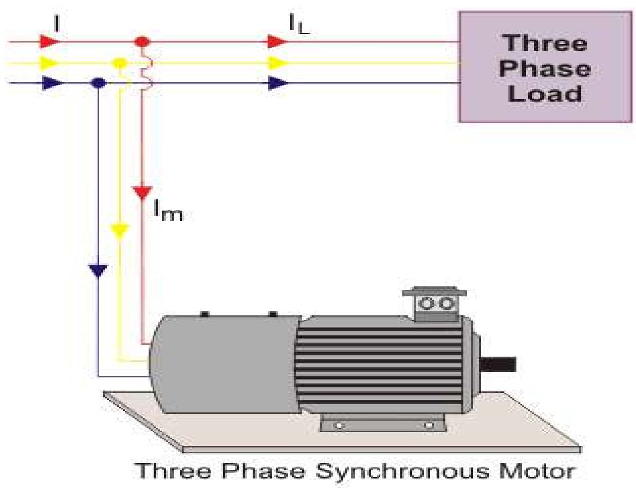
2. On – Load Tap Changing Transformer – This arrangement is used for changing the turn ratio of the transformer for regulating the system voltage when the transformer delivers the load. Most of the power transformer is provided with on-load tap changer.



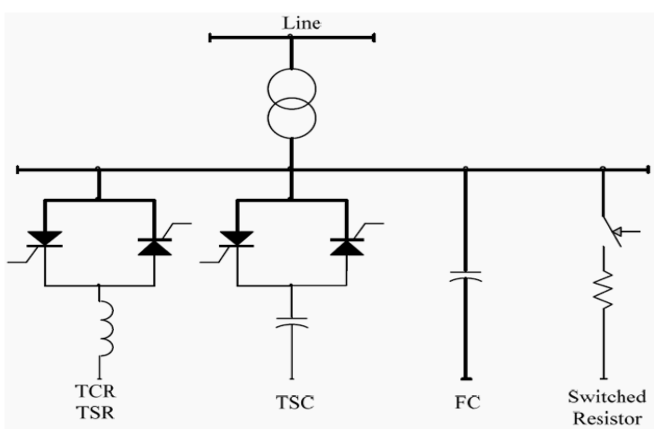
3. Shunt Reactor – The shunt reactor is the inductive current element which is connected between the line and neutral. The shunt reactor compensates the inductive current from the transmission line or underground cables. It is mainly used in the long distance EHV and UHV transmission lines for reactive power control.The shunt reactors are used in the sending end substation, receiving end substation and in the intermediate substation of long EHV and UHV line. In the long transmission line, the shunt reactor is connected at the distance of 300 Km to limit the voltage at an intermediate point.

4. Shunt Capacitors – The shunt capacitors are the capacitors connected in parallel with the line. It is installed at the receiving end substation, distribution substations and in the switching substations. The shunt capacitor injected the reactive volt-ampere to the line. It is placed in the three phase bank.

5. Synchronous Condenser – The synchronous condenser is the synchronous motor running without a mechanical load. It is connected with the load at receiving the end of the line. The synchronous condenser absorbs or generates the reactive power by varying the excitation of the field winding. It keeps the voltage constant at any condition of the load and also improves the power factor.



6. StaticVar Systems (SVS) – The static VAR compensator inject or absorb the inductive VAR to the system when the voltage becomes higher or lower than the reference value. In static VAR compensator, the thyristor is used as switching device in place of circuit breakers. Nowadays, the thyristor switching is used in the system in place of mechanical switching because thyristor switching is faster and provides transient free operation by controlling the switching.



METHODS OF POWER FACTOR IMROVEMENT

Power Factor Improvement

The term power factor comes into picture in AC circuits only. Mathematically it is cosine of the phase difference between source voltage and current. It refers to the fraction of total power (apparent power) which is utilized to do the useful work called active power.

Power factor = Active Power/Apparent Power

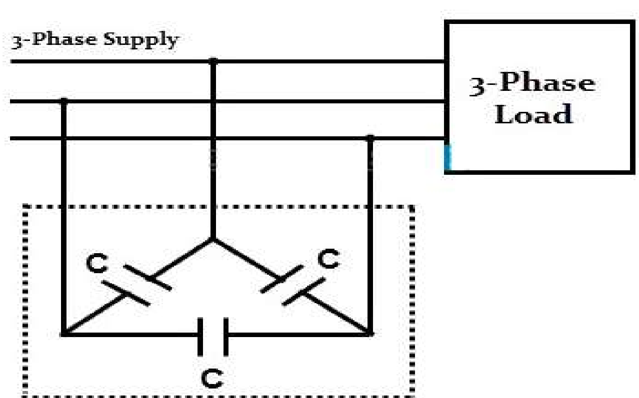
Need for Power Factor Improvement

- Real power is given by P = VIcosφ. To transfer a given amount of power at certain voltage, the electrical current is inversely proportional to cosφ. Hence higher the pf lower will be the current flowing. A small current flow requires less cross sectional area of conductor and thus it saves conductor and money.
- From above relation we saw having poor power factor increases the current flowing in conductor and thus copper loss increases. Further large voltage drop occurs in alternator, electrical transformer and transmission and distribution lines which gives very poor voltage regulation.
- Further the KVA rating of machines is also reduced by having higher power factor as, Hence, the size and cost of machine also reduced. So, electrical power factor should be maintained close to unity.

Methods of Power Factor Improvement

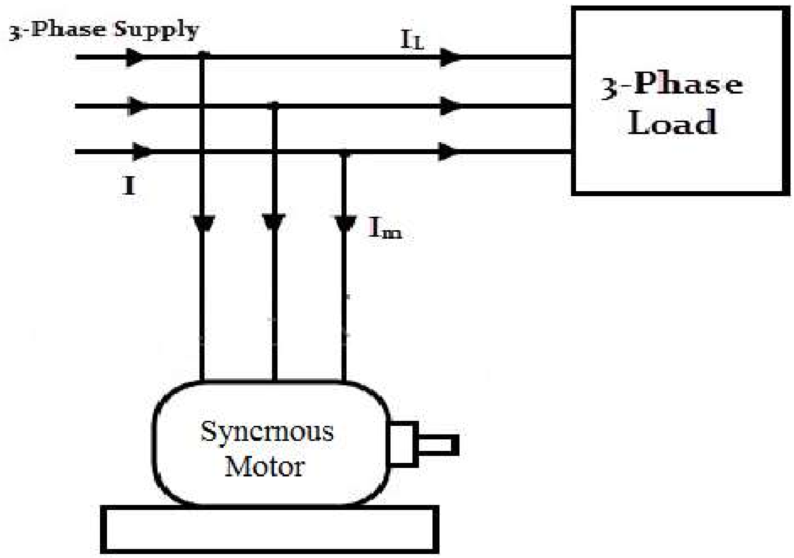
Capacitors:

Improving power factor means reducing the phase difference between voltage and current. Since majority of loads are of inductive nature, they require some amount of reactive power for them to function. This reactive power is provided by the capacitor or bank of capacitors installed parallel to the load. They act as a source of local reactive power and thus less reactive power flows through the line. Basically they reduces the phase difference between the voltage and current.



- **SynchronousCondenser:**

  They are 3 phase synchronous motor with no load attached to its shaft. The synchronous motor has the characteristics of operating under any power factor leading, lagging or unity depending upon the excitation. For inductive loads, synchronous condenser is connected towards load side and is overexcited. This makes it behave like a capacitor. It draws the lagging current from the supply or supplies the reactive power.



- **PhaseAdvancer:**

  This is an ac exciter mainly used to improve pf of induction motor. They are mounted on shaft of the motor and is connected in the rotor circuit of the motor. It improves the power factor by providing the exciting ampere turns to produce required flux at slip frequency. Further if ampere turns are increased, it can be made to operate at leading power factor.