

20

Capacitance of Two-wire Line

- Name: Average capacitance of 20 pF/m.
- Per conductor: $C = \frac{2\pi k_e}{\ln(2D/d)}$
- Per conductor: $C = \frac{2\pi k_e}{\ln(2D/d)} \cdot \frac{1}{2} \cdot \frac{1}{2} = \frac{\pi k_e}{\ln(2D/d)}$
- Per conductor: $C = \frac{\pi k_e}{\ln(2D/d)} \cdot \frac{1}{2} \cdot \frac{1}{2} = \frac{\pi k_e}{\ln(2D/d)}$
- Per conductor: $C = \frac{\pi k_e}{\ln(2D/d)} \cdot \frac{1}{2} \cdot \frac{1}{2} = \frac{\pi k_e}{\ln(2D/d)}$
- Per conductor: $C = \frac{\pi k_e}{\ln(2D/d)} \cdot \frac{1}{2} \cdot \frac{1}{2} = \frac{\pi k_e}{\ln(2D/d)}$

21

$$V_{AB} = V_{AB} + \frac{1}{2} (V_{AB} + V_{BC}) + (V_{BC} + V_{CA}) + (V_{CA} + V_{AB})$$

$$\frac{1}{2} (V_{AB} + V_{BC}) = \frac{1}{2} \cdot \frac{1}{2} (V_{AB} + V_{BC})$$

$$\frac{1}{2} (V_{BC} + V_{CA}) = \frac{1}{2} \cdot \frac{1}{2} (V_{BC} + V_{CA})$$

$$\frac{1}{2} (V_{CA} + V_{AB}) = \frac{1}{2} \cdot \frac{1}{2} (V_{CA} + V_{AB})$$

$$\text{Again, } V_{AB} + V_{BC} = 2(V_{AB} + V_{BC}) \quad (1)$$

$$\text{So, from eqns (1) & (2),}$$

$$2(V_{AB} + V_{BC}) = \frac{1}{2} (V_{AB} + V_{BC}) + \frac{1}{2} (V_{BC} + V_{CA}) + \frac{1}{2} (V_{CA} + V_{AB}) \quad (3)$$

22

$$2(V_{AB} + V_{BC}) = \frac{1}{2} (V_{AB} + V_{BC}) + \frac{1}{2} (V_{BC} + V_{CA}) + \frac{1}{2} (V_{CA} + V_{AB})$$

$$\text{Hence, line to neutral capacitance } C_{LN} = \frac{1}{2} (V_{AB} + V_{BC})$$

$$\frac{1}{2} (V_{BC} + V_{CA}) = \frac{1}{2} \cdot \frac{1}{2} (V_{BC} + V_{CA})$$

$$\text{line to ground } C_{LG} = \frac{1}{2} (V_{AB} + V_{BC})$$

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Effect of Earth on Capacitance

- In discussion so far effect of earth has been neglected.
- It has been assumed that the conductors are situated in free space.
- Actually, the conductors Run parallel to the ground.
- Earth is assumed to behave like an infinite, perfectly conducting plane.
- Its presence therefore modifies the electric field of the line.
- This causes change in capacitance.

24

- Consider a circuit consisting of a single overhead conductor with return path through the earth.
- If the conductor carries a charge of q coulombs, then earth also has the same charge with opposite sign.
- Thus, a potential difference exists between the conductor and the earth.

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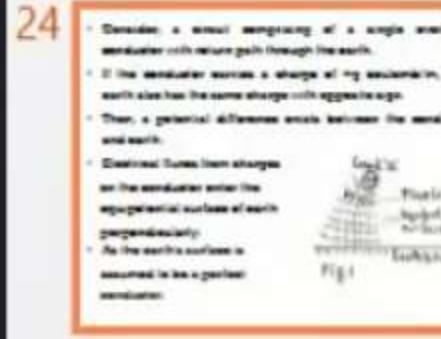
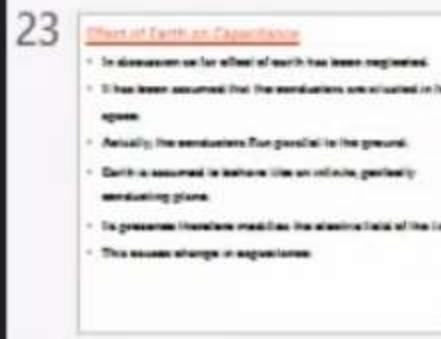
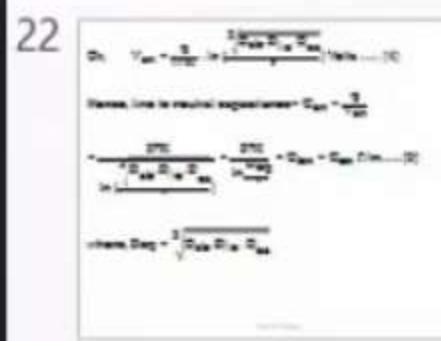
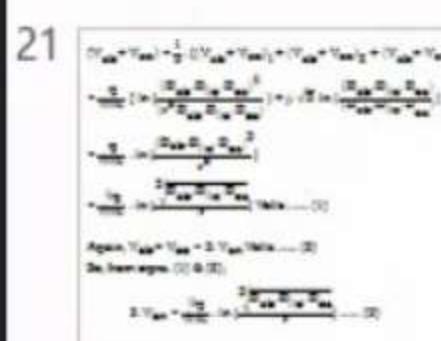
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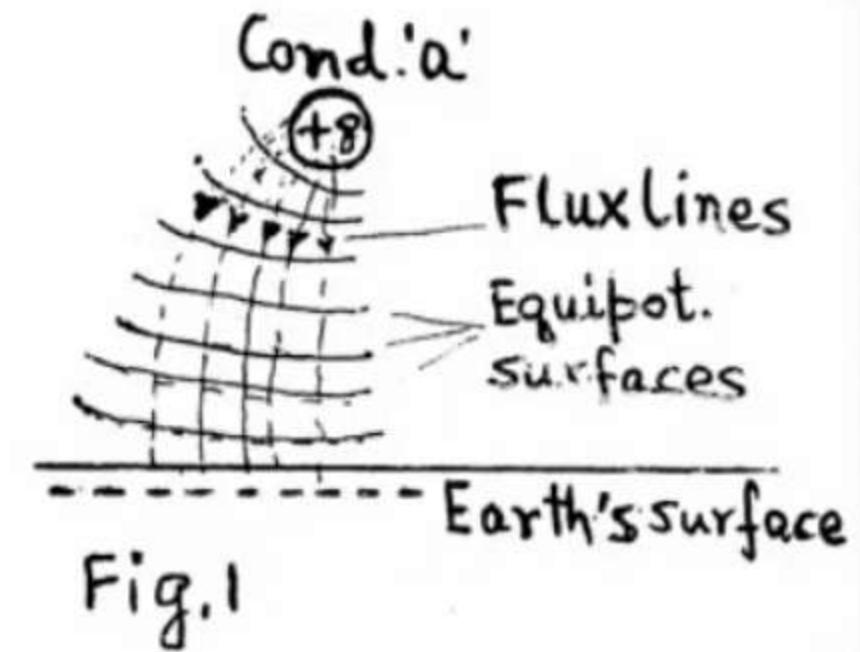
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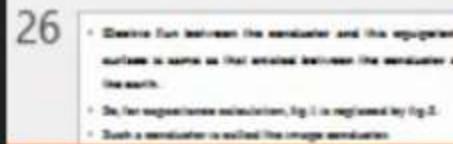
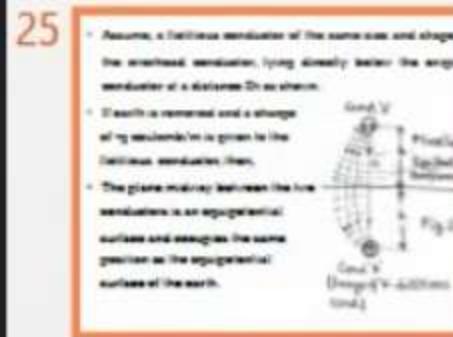
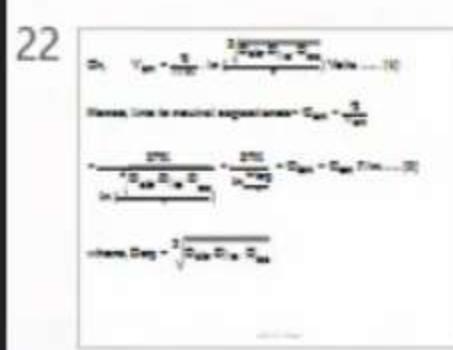


- Consider, a circuit comprising of a single overhead conductor with return path through the earth.
- If the conductor carries a charge of $+q$ coulomb/m, then earth also has the same charge with opposite sign.
- Then, a potential difference exists between the conductor and earth.
- Electrical fluxes from charges on the conductor enter the equipotential surface of earth perpendicularly.
- As the earth's surface is assumed to be a perfect conductor.

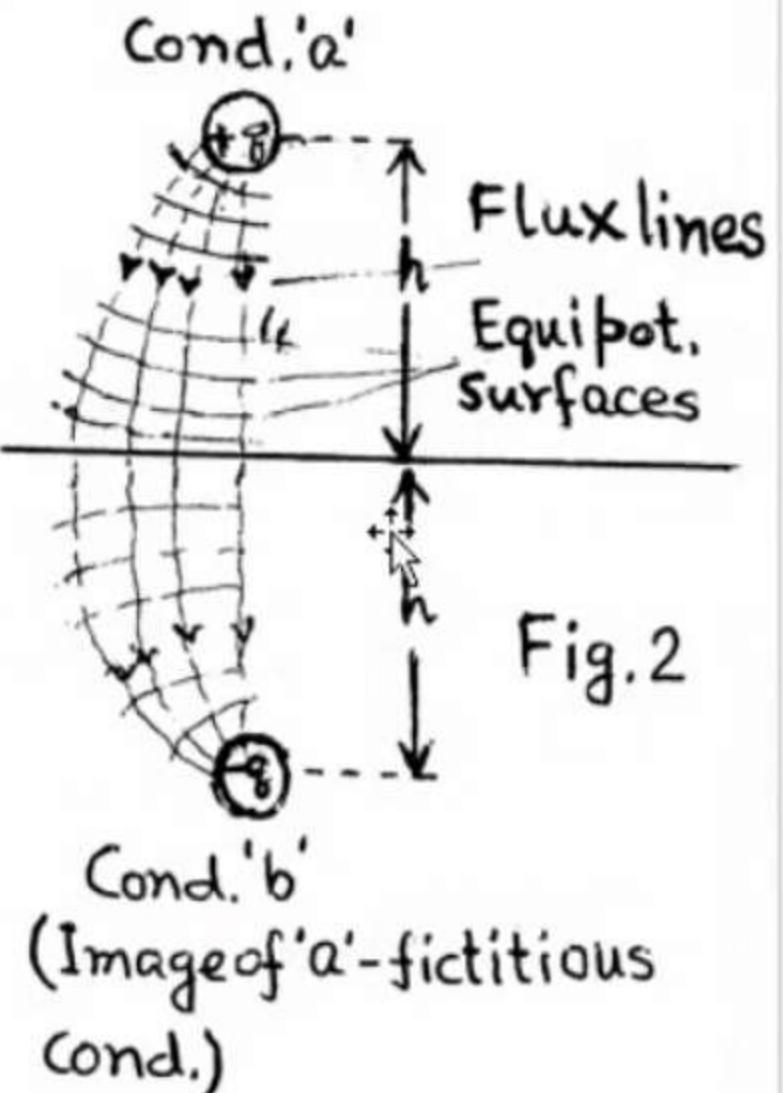


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- Assume, a fictitious conductor of the same size and shape as the overhead conductor, lying directly below the original conductor at a distance $2h$ as shown.
- If earth is removed and a charge of $-q$ coulomb/m is given to the fictitious conductor, then,
- The plane midway between the two conductors is an equipotential surface and occupies the same position as the equipotential surface of the earth.



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23

- In discussion we find that there has been no change.
- It has been assumed that the conductors are situated in free space.
- Assume the conductors are parallel to the ground.
- Define a Gaussian surface in the conductor itself.
- Assuming plane.
- In presence of conductor no source field of the source.
- This source charge is represented.

24

- Consider a coaxial arrangement of two concentric conductors with uniform charge density throughout the earth.
- If the outer conductor carries a charge of q , then inner conductor will have the same charge with opposite sign.
- Then, a Gaussian surface would surround the inner conductor and earth.
- Consider Gauss Law application.
- We can evaluate using the high-gauge law of electric field.
- The potential difference between the two conductors is zero.
- This process may be extended for more than one conductor.

25

- Assume a Gaussian surface passes through the two conductors.
- The outermost conductor (top) is neutral because the charges cancel each other.
- If both are charged and a charge q is distributed on the outer conductor, then the inner conductor will have the same charge with opposite sign.
- The Gaussian surface passes through the two conductors.
- The potential difference between the two conductors is zero.
- This process may be extended for more than one conductor.

26

- Gauss Law between the conductor and the equipotential surface is same as that existed between the conductor and the earth.
- So the potential difference is equal to that in fig. 2.
- Since a conductor is excess the charge carrier.
- This process may be extended for more than one conductor.
- Here, the potential difference between conductors a and b (image of a) is,

$$V_{ab} = 2 V_{an} = \frac{1}{2\pi k} \left[q_a \ln \frac{D_{ab}}{D_{aa}} + q_b \ln \frac{D_{bb}}{D_{ba}} \right]$$

$$= \frac{q}{2\pi k} \left[\ln \frac{2h}{r} - \ln \frac{r}{2h} \right] = \frac{2q}{2\pi k} \cdot \ln \frac{2h}{r} \dots\dots(1)$$

27

- A Gaussian surface passes through the two conductors.
- The outermost conductor (top) is neutral because the charges cancel each other.

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24

- Consider a small capacitor of a single earthed conductor with return path through the earth.
- If the conductor carries a charge of q coulombs, then earth also has the same charge with opposite sign.
- Then, a potential difference exists between the conductor and earth.
- Charge due to charges on the conductor enter the equipotential surface of earth perpendicularly.
- As the earth's surface is assumed to be a perfect conductor.

Fig. 1

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- Assume a fictitious conductor of the same size and shape as the earthed conductor, lying directly below the original conductor at a distance $2r$ as shown.
- It carries a negative charge of $-q$ coulombs given to the fictitious conductor.
- The potential difference between the two conductors is an exponential function of the separation distance as the equipotential surfaces of the earth.

Fig. 2

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- Charge due between the conductor and the equipotential surface is same as that existed between the conductor and the earth.
- By the superposition principle, Eq. 2 is replaced by Eq. 3.
- Such a conductor is called the image conductor.
- This process may be extended for more than one conductor.
- Here, we potential difference between conductors is zero & its image as well.

$$\text{V}_{an} = 2 \text{V}_{ce} = \frac{1}{2\pi K} \left[q_1 \ln \frac{2r}{r_1} + q_2 \ln \frac{2r}{r_2} \right]$$

$$= \frac{1}{2\pi K} \left[\ln \frac{2r}{r_1} - \ln \frac{r_1}{2r} \right] \leq \frac{1}{2\pi K} \ln \frac{1}{2} = 0$$

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$\Delta V_{an} = \frac{1}{2\pi K} \ln \frac{2r}{r_1}$ (2)

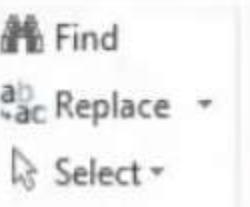
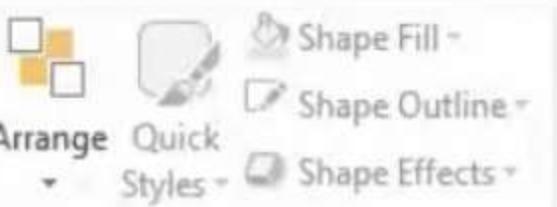
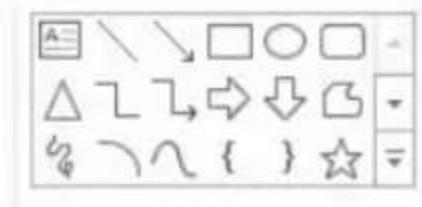
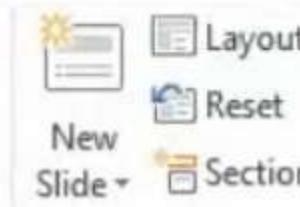
(i.e., Capacitance to ground = $C_{an} = \frac{1}{2\pi K} \ln \frac{2r}{r_1}$)

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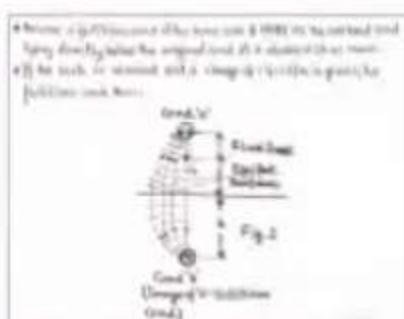
How $V_{an} = \frac{1}{2\pi K} \ln \frac{2r}{r_1}$ (2)

$$\text{Or, } V_{an} = \frac{q}{2\pi K} \ln \frac{2r}{r} \text{ Volts} \dots\dots (2)$$

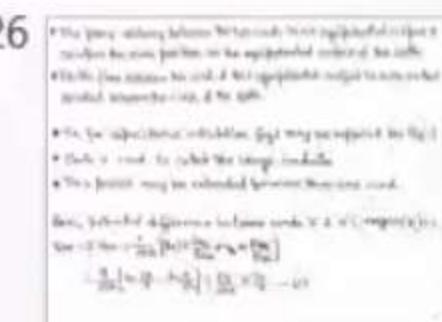
$$\text{So, Capacitance to ground} = C_{an} = \frac{q}{V_{an}} = \frac{2\pi K}{\ln \frac{2r}{r}} \text{ F/m} \dots\dots (3)$$



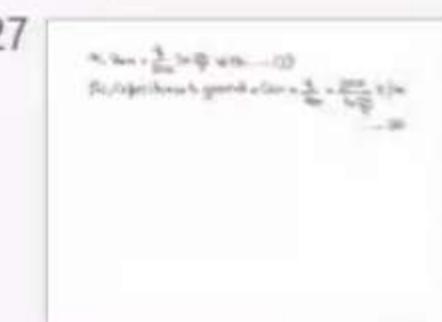
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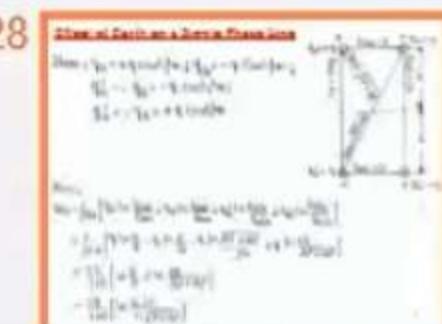
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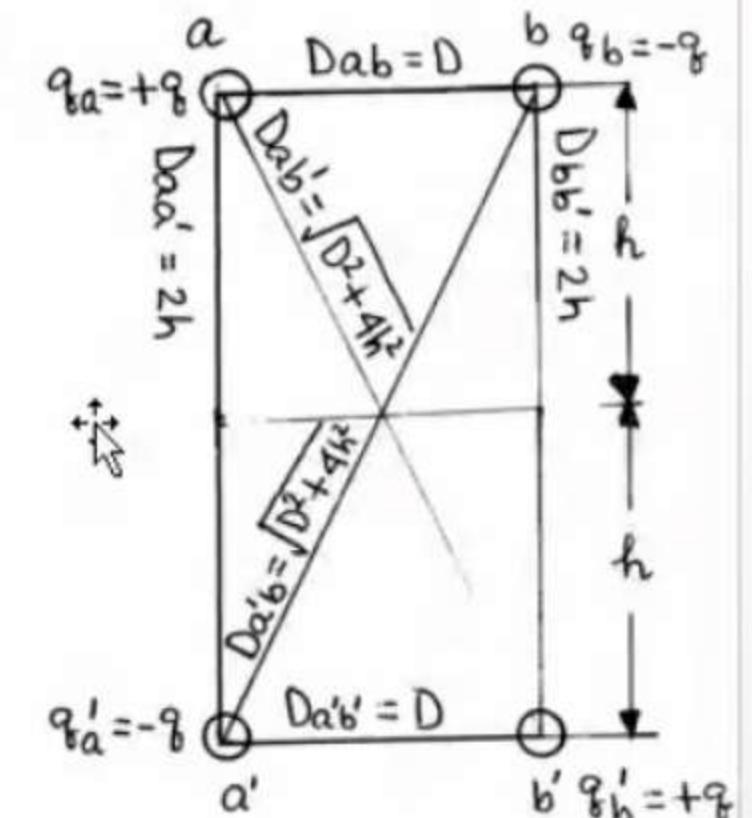


Effect of Earth on a Single Phase Line

Here, $q_{fa} = +q \text{ coul./m}$; $q_{fb} = -q \text{ coul./m}$;
 $q'_{fa} = -q_{fa} = -q \text{ coul./m}$;
 $q'_{fb} = -q_{fb} = +q \text{ coul./m}$.

Now,

$$\begin{aligned} V_{ab} &= \frac{1}{2\pi K} \left[q_a \ln \frac{D_{ab}}{D_{aa}} + q_b \ln \frac{D_{bb}}{D_{ba}} + q'_a \ln \frac{D_{ab}'}{D_{aa'}} + q'_b \ln \frac{D_{bb}'}{D_{ba'}} \right] \\ &= \frac{1}{2\pi K} \left[q \ln \frac{D}{r} - q \ln \frac{r}{D} - q \ln \frac{\sqrt{D^2 + 4h^2}}{2h} + q \ln \frac{2h}{\sqrt{D^2 + 4h^2}} \right] \\ &= \frac{2q}{2\pi K} \left[\ln \frac{D}{r} + \ln \frac{2h}{\sqrt{D^2 + 4h^2}} \right] \\ &= \frac{2q}{2\pi K} \left[\ln \frac{D \cdot 2h}{r \cdot \sqrt{D^2 + 4h^2}} \right] \end{aligned}$$



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 • The space existing between two parallel vertical conductors for some portion of the equivalent circuit of the earth system (for instance, the total of two equivalent capacitors connected in series to ground) is given by eqn. (1).

• This is the basic formula for calculating line-to-line capacitance.

• This is also the formula for calculating line-to-ground capacitance.

Given, potential difference between conductors $V_A - V_B$ (neglecting V_B) is
 $V_A - V_B = \frac{q_b}{2\pi K} \left[\ln \frac{D}{r} + \ln \frac{4h^2}{D^2 + 4h^2} \right]$
 $\Rightarrow \frac{q_b}{2\pi K} \left[\ln \frac{D}{r} + \ln \frac{4h^2}{D^2 + 4h^2} \right] = \frac{V_A - V_B}{2}$

27
 $A_1, V_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r}$ with $D = 0.2$
 $\text{For } D = 0.2, \text{ then } V_{ab} = \frac{q_b}{2\pi K} \times \frac{0.2}{0.2} = q_b$

28
 • Effect of earth as a finite plane sheet
 $Q_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r} + \frac{q_b}{2\pi K} \ln \frac{4h^2}{D^2 + 4h^2}$
 $\Rightarrow Q_{ab} = q_b \left[\frac{1}{2\pi K} \ln \frac{D}{r} + \frac{1}{2\pi K} \ln \frac{4h^2}{D^2 + 4h^2} \right]$
 $\Rightarrow Q_{ab} = q_b \left[\frac{1}{2\pi K} \ln \frac{D}{r} + \frac{1}{2\pi K} \ln \frac{4h^2}{D^2/4h^2 + 1} \right]$
 $\Rightarrow Q_{ab} = q_b \left[\frac{1}{2\pi K} \ln \frac{D}{r} + \frac{1}{2\pi K} \ln \frac{4h^2}{D^2/4h^2 + 1} \right]$

29
 • Negligible effect of earth as a finite plane sheet
 $Q_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r}$
 $\Rightarrow Q_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r} + \frac{q_b}{2\pi K} \ln \frac{4h^2}{D^2/4h^2 + 1}$
 $\Rightarrow Q_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r} + \frac{q_b}{2\pi K} \ln \frac{4h^2}{D^2/4h^2 + 1} \rightarrow 0$
 $\Rightarrow Q_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r}$
 $\Rightarrow Q_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r} + \frac{q_b}{2\pi K} \ln \frac{4h^2}{D^2/4h^2 + 1}$
 $\Rightarrow Q_{ab} = \frac{q_b}{2\pi K} \ln \frac{D}{r} + \frac{q_b}{2\pi K} \ln \frac{4h^2}{D^2/4h^2 + 1} \rightarrow 0$

30
 • Due to presence of $\frac{1}{2\pi K} \ln \frac{4h^2}{D^2/4h^2 + 1}$ the total value of the dielectric medium
 • Hence, the capacitance value increases with the presence of earth.

Therefore, line to line capacitance $C_{ab} = \frac{q_b}{V_{ab}}$

$$= \frac{q_b}{2\pi K} \left[\ln \frac{D \cdot 2h}{r \cdot \sqrt{D^2 + 4h^2}} \right]$$

$$= \frac{\pi K}{\ln \left(\frac{D}{r} \cdot \frac{1}{\sqrt{D^2/4h^2 + 1}} \right)} F/m \dots\dots (1)$$

- To neglect effect of earth put $h \rightarrow \infty$. Then, $\sqrt{D^2/4h^2 + 1} \rightarrow 1$.

$$\text{So, } C_{ab} = \frac{\pi K}{\ln D} F/m \dots\dots (2)$$

$$\therefore \text{Line to neutral capacitance} = C_n = \frac{q_b}{\frac{1}{2} V_{ab}}$$

$$= \frac{2\pi K}{\ln \left(\frac{D}{r} \cdot \frac{1}{\sqrt{D^2/4h^2 + 1}} \right)} F/m \dots\dots (3)$$

27

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Effect of Earth as a Dielectric Material

Calculation:

$$C_{air} = \frac{\epsilon_0 A}{D}$$

$$C_{earth} = \frac{\epsilon_0 A}{D}$$

$$C_{total} = C_{air} + C_{earth} = \frac{\epsilon_0 A}{D} + \frac{\epsilon_0 A}{D} = \frac{2\epsilon_0 A}{D}$$

$$\frac{2\epsilon_0 A}{D} = \frac{2\epsilon_0 A}{D^2/4h^2 + D} = \frac{8\epsilon_0 A h^2}{D^2 + 4h^2 D} = \frac{8\epsilon_0 A h^2}{D(D + 4h^2)}$$

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Calculation for Dielectric Constant $\epsilon_{rel} = \frac{\epsilon_{air}}{\epsilon_{earth}}$

$$\epsilon_{air} = \frac{1}{D^2/4h^2 + D} = \frac{4h^2}{D^2 + 4h^2 D}$$

To neglect effect of earth, $\epsilon_{air} \approx \epsilon_{earth}$. Then, $\frac{4h^2}{D^2 + 4h^2 D} \approx 1$

$$\epsilon_{air} \approx \frac{4h^2}{D^2} \Rightarrow \epsilon_{air} \approx \frac{4h^2}{D^2}$$

$$\therefore \text{Effect of earth, } \epsilon_{rel} = \frac{\epsilon_{air}}{\epsilon_{earth}} = \frac{4h^2}{D^2}$$

$$= \frac{4 \times (10^{-2})^2}{(0.1)^2} = 400$$

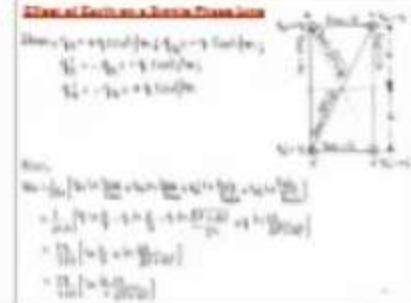
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- Due to presence of $\frac{1}{D^2/4h^2 + D}$ the total value of the denominator reduces.
- Hence, the capacitance value increases with the presence of earth.

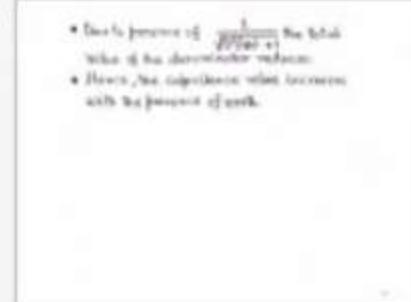
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- Due to presence of $\frac{1}{D^2/4h^2 + D}$ the total value of the denominator reduces.
- Hence, the capacitance value increases with the presence of earth.

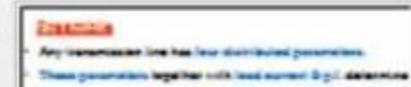
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Performance of Transmission Lines

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- Basic purpose of transmission lines
- Minimize power loss
- Minimize voltage drop
- Minimize cost of construction

31

Performance of Transmission Lines

32

Exams

Any transmission line has four distributed parameters.
These parameters together with load current & p.f. determine the electrical performance of the line.
The term 'performance' basically includes the evaluation of sending end voltage, sending end current, sending end p.f., power loss in line, efficiency of transmission, regulation etc.
Usually the values of receiving end voltage, current & p.f. are known.
Prior performance calculations are useful in system planning.
The predominance of one or more of the parameters of a line is governed by its length & conductor configuration.

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The transmission losses up to 300 km is negligible.
All other losses are due to heating due to current flow in the line.

Preamble

- Any transmission line has **four distributed parameters**.
- These parameters together with **load current & p.f.** determine the electrical '**performance**' of the line.
- The term '**performance**' basically includes the calculation of **sending end voltage**, **sending end current**, **sending end p.f.**, **power loss in line**, **efficiency** of transmission, **regulation** etc.
- Usually the values of **receiving end voltage**, **current & p.f.** are known.
- Prior performance calculations are useful in **system planning**.
- The predominance of one or more of the parameters of a line is governed by its **length & conductor configuration**.

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• For overhead lines up to 80 km, 'C' is negligibly small.

• All low voltage overhead lines having length up to 80 km are generally categorized as short lines.

• The lines ranging in length from 80 km to 240 km are termed as medium or moderately long lines.

• For such lines, 'C' is considered to be lumped at one or more points of the line. The leakage conductance 'G' is neglected.

• Long line refers to a line having its length more than 240 km.

• The long line treatment takes all four parameters into account in completely distributed way.

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Performance of Transmission Lines

32

Example

Any transmission line has four distributed parameters. These parameters together with load current & voltage determine the overall performance of the line. The four performance factors include the evaluation of receiving end voltage, receiving end current, sending end voltage and power loss in line. Inference of transmission regulation will depend on the values of receiving end voltage, receiving end current and power loss.

Four performance evaluations are useful in system planning. The predominance of one or more of the parameters of a line is governed by its length & conductor configuration.

33

Example - contd.

- The overhead lines up to 20 km, 10 kV is negligible small.
- All other voltage overhead lines having length up to 20 km are generally categorized as short lines.
- The lines ranging in length from 20 km to 200 km are referred as medium or moderately long lines.
- For such lines, 10 kV is considered to be long at one or more points of the line. The voltage regulation 10 kV is required.
- Long line refers to a line having its length more than 200 km.
- The long line treatment takes all four parameters into account in a completely distributed way.

34

Example - contd.

Classification on the basis of length is not entirely a perfect criterion to distinguish between short, medium & long lines.

This classification has been done for desired accuracy.

Methods used for short & medium lines are approximate.

Method adopted for long line is rigorous.

However, the approximate methods are simple without much appreciable error.

35

Show Transmission Line

Shows all 10 kV are neglected.

Shows all 10 kV are considered.

Current 10 kV entering the line is equal to current 10 kV leaving the line.

Preamble – cont.

- Classifications on the basis of length is not certainly a perfect criterion to distinguish between short, medium & long lines.
- This classification has been done for desired accuracy.
- Methods used for short & medium lines are approximate.
- Method adopted for long line is rigorous.
- However, the approximate methods are simple without much appreciable error.

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32 **Example - 001**

- Any transmission line has four distributed parameters.
- These parameters together with load current & voltage determine the overall performance of the line.
- The line performance basically includes the evaluation of sending end voltage, sending end current, receiving end voltage and the value of receiving end voltage across the line.
- Usually the values of receiving end voltage across the line are known.
- Four performance evaluations are useful in system planning.
- The predominance of values over all the parameters of a line is governed by its length & transmission qualities.

33 **Example - 002**

- For overhead lines up to 30 km, 12 is negligible.
- All transmission overhead lines having lengths up to 30 km are generally categorized as short lines.
- The lines ranging in length from 30 km to 300 km are referred to as medium or moderately long lines.
- For such lines, C is considered to be lumped at one or more points of the line. The voltage distribution is negligible.
- Long lines refer to a line having a length more than 300 km.
- The long line treatment basis of four parameters can be conveniently summarized as:

34 **Example - 003**

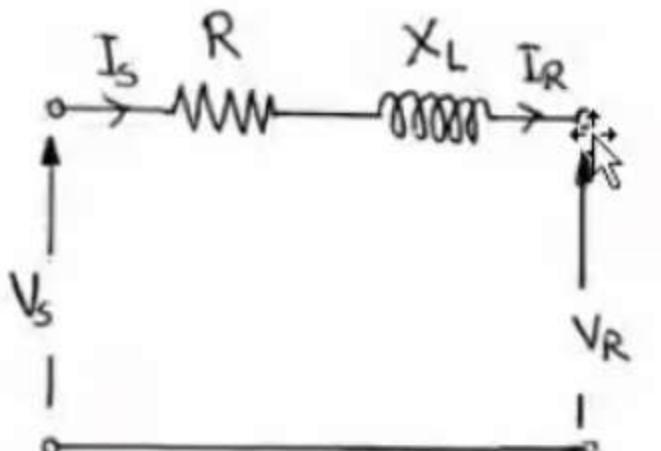
- Classification on the basis of length is not necessarily a proper criterion to distinguish between short, medium & long lines.
- This classification has been done for didactic convenience.
- Methods used for short & medium lines are approximate.
- Method adopted for long lines is rigorous.
- However, the approximate methods are simple without much computational errors.

35 **Short Transmission Line**

- Effects of C & G are neglected.
- Effects of R & L are considered.
- Current (I_S) entering the line is equal to current (I_R) leaving the line.
- Since same current flows through all the sections, R & L are treated as lumped.
- Here,

Short Transmission Line

- Effects of C & G are neglected.
- Effects of R & L are considered.
- Current (I_S) entering the line is equal to current (I_R) leaving the line.
- Since same current flows through all the sections, R & L are treated as lumped.
- Here,
 - V_S = phase voltage at sending end,
 - V_R = phase voltage at receiving end,
 - I_S = phase current at sending end &
 - I_R = phase current at receiving end.



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Example - 201

- The overhead lines up to 30 km, 12 m height above ground.
- All other voltage overhead lines having length up to 30 km are generally regarded as short lines.
- The lines having a length less than 30 km to 300 km are termed as medium or moderately long lines.
- For such lines, 12 m is assumed to be the height at one or more points of the line. The voltage regulation 12 is neglected.
- Long lines refers to a line having its length more than 300 km.
- The long line treatment takes of four parameters into account in a simplified manner.

Example - 202

- Classification on the basis of length is not entirely a precise criterion to distinguish between short, medium & long lines.
- This classification has been done for desired economy.
- Methods used for short & medium lines are approximate.
- Method adopted for long lines is rigorous.
- However, the approximate methods are simple without much approximation.

Short Transmission Lines

- Effects of 12 & 13 are neglected.
- Effects of 12 & 13 are considered.
- Current I_S entering the line is equal to current I_R leaving the line.
- Since same current flows through all the sections, 12 & 13 are treated as lumped.
- Now,

 - V_S = phase voltage at sending end.
 - V_R = phase voltage at receiving end.
 - I_S = phase current at sending end.
 - I_R = phase current at receiving end.

Case (i) = sending end p.f.
Case (ii) = receiving end p.f.

Z = total resistance per phase &
 X_L = total inductive reactance per phase

Now, I_S & I_R are equal in magnitude but not in phase.
 Then the equivalent circuit,

$$(I_S) = (I_R) \quad \text{---(1)}$$

$$(V_S - V_R) = (R + jX_L) I_R \quad \text{---(2)}$$

$$\text{Hence, } Z = (R + jX_L) \quad \text{---(3)}$$

Hence, if the receiving end conditions are known, sending end voltage may be calculated.

A more approximate method involving scalar quantities is as follows:

$$V_S = V_R + (Z + jX_L) I_R \quad \text{---(4)}$$

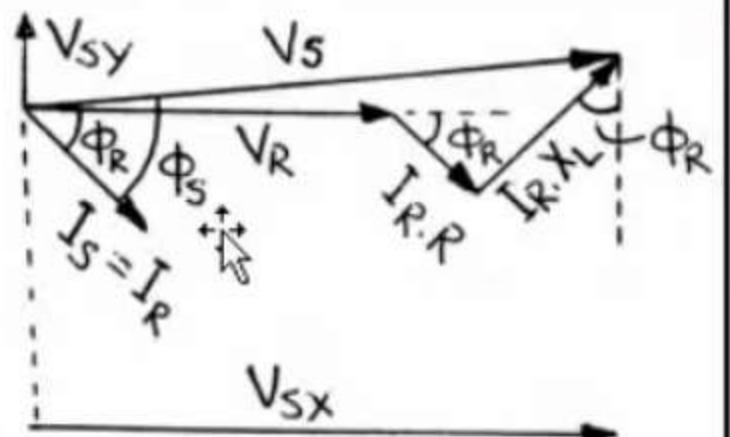
$$V_S = V_R + Z I_R + jX_L I_R \quad \text{---(5)}$$

$\cos \varphi_S$ = sending end p.f.

$\cos \varphi_R$ = receiving end p.f.

R = total resistance per phase &

X_L = total inductive reactance per phase.



- Here, I_S & I_R are equal in magnitude but not in phase.

From the equivalent circuit,

$$|I_S| = |I_R| \quad \text{.....(1)}$$

$$\begin{aligned} V_S &= V_R + (R + jX_L) \cdot I_R \\ &= V_R + Z \cdot I_R \end{aligned} \quad \text{.....(2)}$$

where, $Z = (R + jX_L)$

- Hence, if the receiving end conditions are known, sending end voltage may be calculated.

34

Example - cont

- Classification on the basis of length is not necessarily a perfect criterion to distinguish between short, medium & long lines.
- This classification has been done for theoretical accuracy.
- Methods used for short & medium lines are approximate.
- Method adopted for long lines is rigorous.
- However, the approximate methods are simpler without much approximation.

35

Short Transmission Lines

- Ohms of R & L are neglected.
- Ohms of D & C are assumed.
- Current I is entering the line at point A current I leaving the line at point B.
- Since same current flows through all the sections, R, L & C are treated as lumped.
- Note:
 - V_1 = phase voltage at sending end,
 - V_2 = phase voltage at receiving end,
 - I_1 = phase current at sending end &
 - I_2 = phase current at receiving end.

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Derivation:

- Case (i) - sending end gen.
- Case (ii) - receiving end gen.
- $Z = \text{total resistance per phase} + j\text{total reactance per phase}$
- Note: V_1, V_2 are equal in magnitude but not in phase. Then the equivalent circuit is
$$(V_1 - V_2) = (I_1 - I_2)Z \quad (1)$$

$$V_1 = V_2 + (I_1 - I_2)Z \quad (2)$$
- Hence, $Z = (V_1 - V_2)/(I_1 - I_2)$
- Hence, if the receiving end voltages are known, sending end voltage may be calculated.

37

A more approximate method involving scalar quantities is as follows:

$V_{SX} = V_R + (I_R \cdot R) \cdot \cos \varphi_R + (I_R \cdot X_L) \cdot \sin \varphi_R \quad (3)$

$V_{SY} = (I_R \cdot X_L) \cdot \cos \varphi_R - (I_R \cdot R) \cdot \sin \varphi_R \quad (4)$

& $V_S^2 = V_{SX}^2 + V_{SY}^2 \quad (5)$

However, $(I_R \cdot R)$ & $(I_R \cdot X_L)$ are very much larger than V_{SY} .

Also, the small V_{SY} is in quadrature with V_{SX} .

Hence,

$V_S \approx V_{SX} = V_R + (I_R \cdot R) \cdot \cos \varphi_R + (I_R \cdot X_L) \cdot \sin \varphi_R \quad (6)$

38

Voltage regulation of the line is the rise in voltage when load is increased.

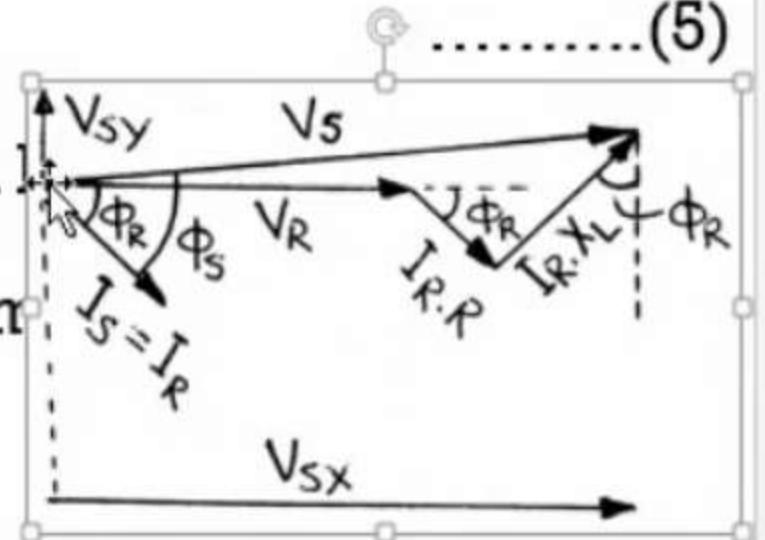
Note: $\Delta V = V_2 - V_1 = (I_2 - I_1)Z = (I_2 - I_1)(R + jX_L)$

A more approximate method involving scalar quantities is as follows:

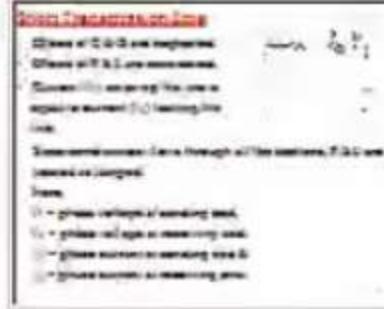
$$V_{SX} = V_R + (I_R \cdot R) \cdot \cos \varphi_R + (I_R \cdot X_L) \cdot \sin \varphi_R \quad (3)$$

$$V_{SY} = (I_R \cdot X_L) \cdot \cos \varphi_R - (I_R \cdot R) \cdot \sin \varphi_R \quad (4)$$

$$\& \quad V_S^2 = V_{SX}^2 + V_{SY}^2 \quad (5)$$



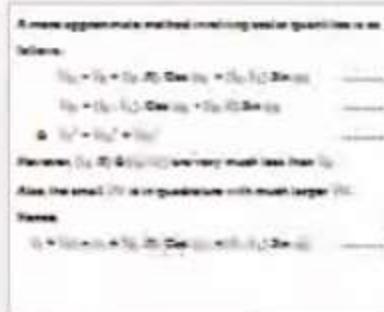
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Voltage regulation of the line is the rise in voltage when full load is removed.

Hence,

$$\% \text{ Voltage regulation} = \frac{(V_s - V_R)}{V_R} \cdot 100$$

$$= \frac{(I_R \cdot R) \cdot \cos \varphi_R + (I_R \cdot X_L) \cdot \sin \varphi_R}{V_R} \cdot 100 \quad \dots \dots \dots (7)$$

Moderately Long Transmission Line

- As the length & voltage of transmission line increase – effect of capacitance – hence, charging current becomes significant.
- For medium length lines, voltages up to about 100kV, it is sufficiently accurate to consider total capacitance to be lumped at some particular points.
- Some arrangements are shown.

Nominal T – Representation

- Shunt conductance is neglected.

Here,

$$V_C = V_R + I_R \cdot \frac{Z}{2}, \text{ where } Z = R + jX_L$$

$$I_C = V_C \cdot Y, \text{ where } Y = j\omega C$$

$$\begin{aligned} I_S &= I_R + I_C \\ &= I_R + V_C \cdot Y \\ &= I_R + (V_R + I_R \cdot \frac{Z}{2}) \cdot Y \\ &= V_R \cdot Y + I_R \cdot \left(1 + \frac{YZ}{2}\right) \dots\dots (1) \end{aligned}$$

$$\begin{aligned} V_S &= V_C + I_S \cdot \frac{Z}{2} \\ &= V_R + I_R \cdot \frac{Z}{2} + \{V_R \cdot Y + I_R \cdot \left(1 + \frac{YZ}{2}\right)\} \cdot \frac{Z}{2} \\ &= V_R \cdot \left(1 + \frac{YZ}{2}\right) + I_R \cdot \left(1 + \frac{YZ}{4}\right) \cdot Z \dots\dots (2) \end{aligned}$$

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38 Voltage regulation of the line is the rise in voltage when full load is removed.

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

($I_s = I_c_1 + I_R$)

39 Generalized Line Representation

- The length & voltage of transmission line increase w.r.t. all impedances. Hence, shunting current increases exponentially.
- For medium length lines, voltage drop is about 1000V in sufficiently accurate to consider total regulation to be constant at some particular point.
- Some arrangements are shown.

40 Nominal π -Representation

Shunt conductance is neglected.

Y = $\frac{1}{Z}$, where $Z = R + jX$

$I_s = V_R \cdot \frac{Y}{2}$

$I = I_{c_1} + I_R = V_R \cdot \frac{Y}{2} + I_R$

$V_s = V_R + I \cdot Z = V_R + (V_R \cdot \frac{Y}{2} + I_R) \cdot Z$

$= V_R \cdot \left(1 + \frac{YZ}{2}\right) + I_R \cdot Z \dots\dots (1)$

41 Nominal π -Representation

Shunt conductance is neglected.

$I_s = V_R \cdot \frac{Y}{2}$

$I = I_{c_1} + I_R = V_R \cdot \frac{Y}{2} + I_R$

$I_s = V_R \cdot \frac{Y}{2} + I_R \cdot Z$

$I_s = V_R \cdot \frac{Y}{2} + I_R \cdot \left(R + jX\right)$

$I_s = V_R \cdot \frac{Y}{2} + I_R \cdot R + I_R \cdot jX$

$I_s = I_R \cdot R + V_R \cdot \frac{Y}{2} + I_R \cdot jX$

$I_s = I_R \cdot R + I_R \cdot jX + V_R \cdot \frac{Y}{2}$

$I_s = I_R \cdot (R + jX) + V_R \cdot \frac{Y}{2}$

42 Line Transmission Loss

R, L, C & G are considered to be uniformly distributed R, L, C & G are given per unit length of the line.

Consider an elemental distance 'l' of a line of any distance 'L' from the receiving end.

Line current & voltage leaving the section l is respectively

Nominal π - Representation

- Shunt conductance is neglected.

Here,

$$I_{c_1} = V_R \cdot \frac{Y}{2}$$

$$I = I_{c_1} + I_R = V_R \cdot \frac{Y}{2} + I_R$$

$$V_s = V_R + I \cdot Z = V_R + (V_R \cdot \frac{Y}{2} + I_R) \cdot Z$$

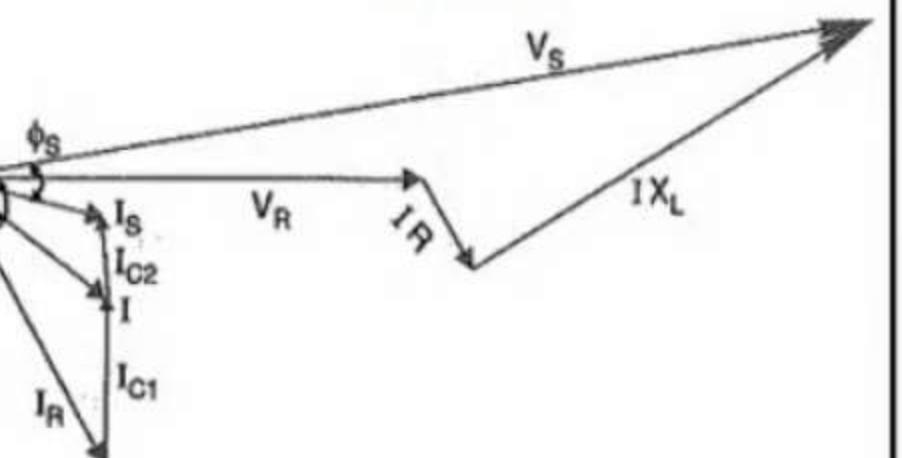
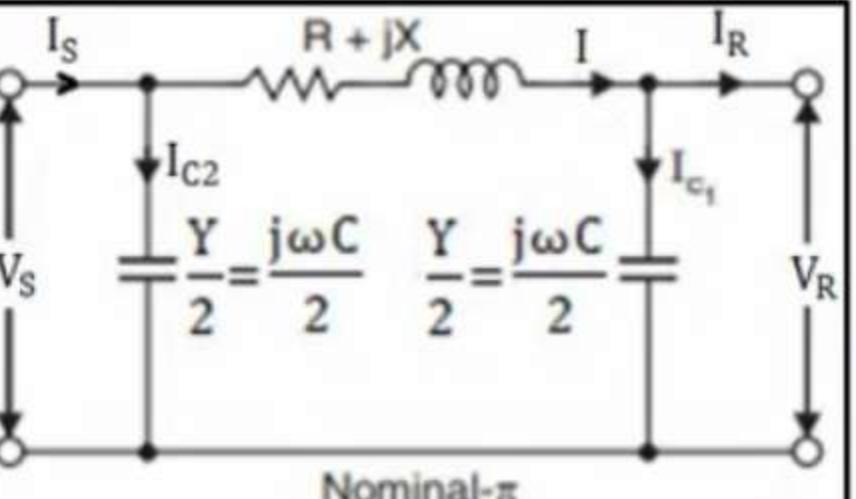
$$= V_R \cdot \left(1 + \frac{YZ}{2}\right) + I_R \cdot Z \dots\dots (1)$$

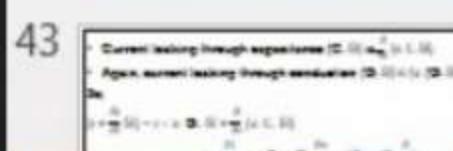
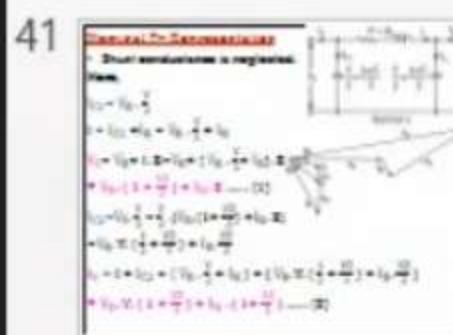
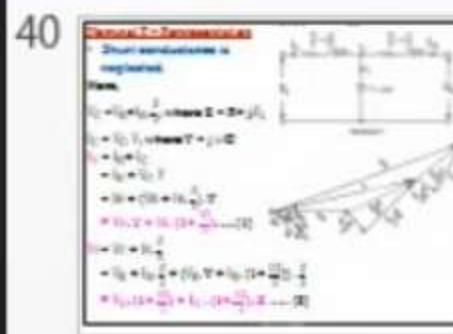
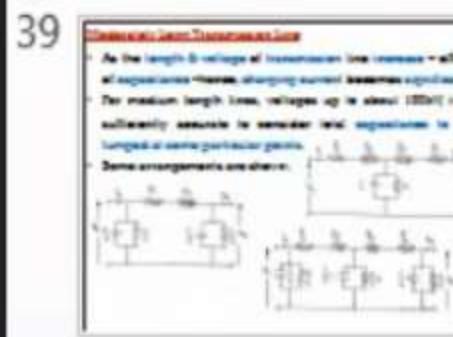
$$I_{c_2} = V_s \cdot \frac{Y}{2} = \frac{Y}{2} \cdot \{V_R \cdot \left(1 + \frac{YZ}{2}\right) + I_R \cdot Z\}$$

$$= V_R \cdot Y \cdot \left(\frac{1}{2} + \frac{YZ}{4}\right) + I_R \cdot \frac{YZ}{2}$$

$$I_s = I + I_{c_2} = \left(V_R \cdot \frac{Y}{2} + I_R\right) + \{V_R \cdot Y \cdot \left(\frac{1}{2} + \frac{YZ}{4}\right) + I_R \cdot \frac{YZ}{2}\}$$

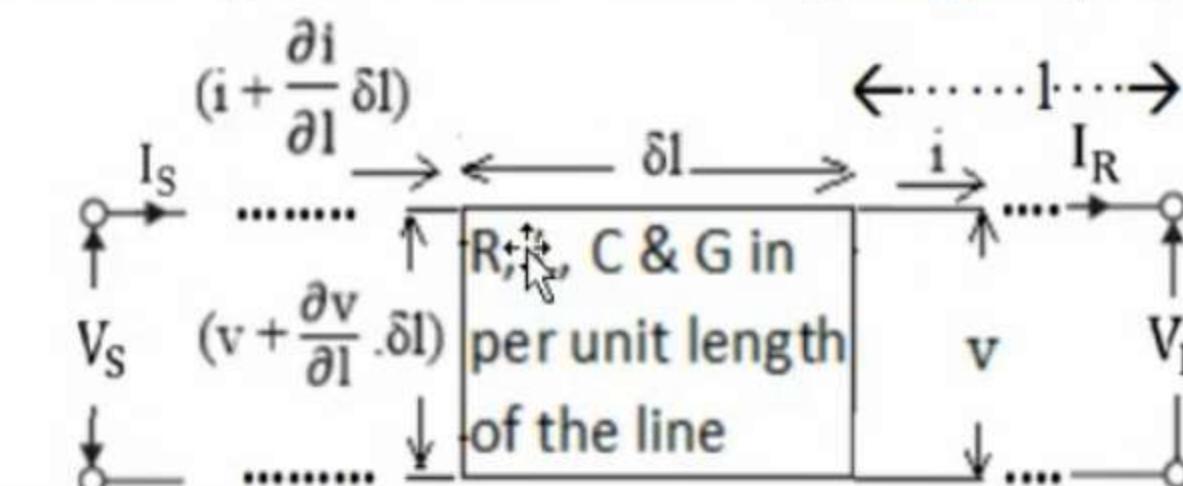
$$= V_R \cdot Y \cdot \left(1 + \frac{YZ}{4}\right) + I_R \cdot \left(1 + \frac{YZ}{2}\right) \dots\dots (2)$$

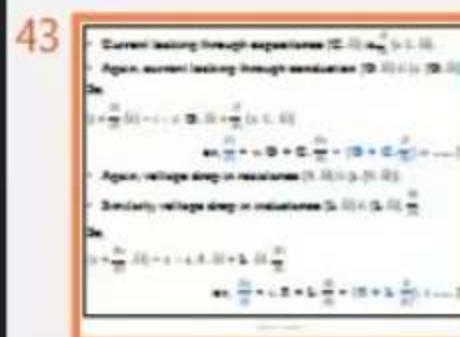
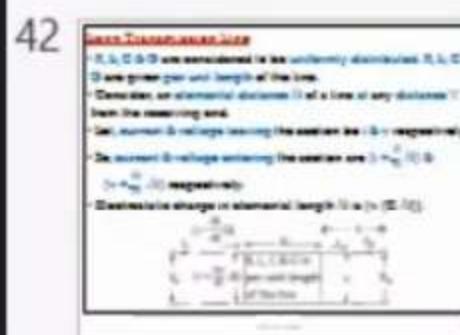
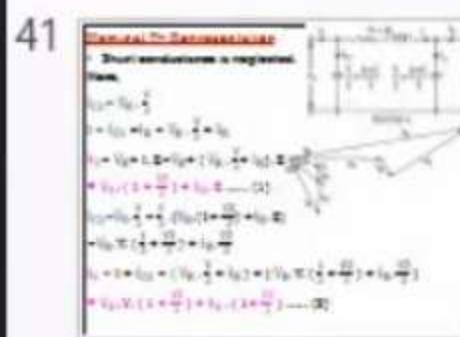
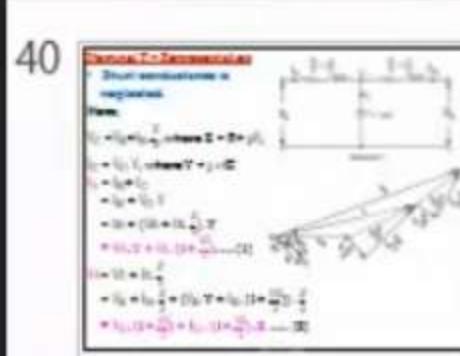




Long Transmission Line

- R, L, C & G are considered to be uniformly distributed. R, L, C & G are given per unit length of the line.
- Consider, an elemental distance δl of a line at any distance 'l' from the receiving end.
- Let, current & voltage leaving the section be i & v respectively.
- So, current & voltage entering the section are $(i + \frac{\partial i}{\partial l} \delta l)$ & $(v + \frac{\partial v}{\partial l} \delta l)$ respectively.
- Electrostatic charge in elemental length δl is $\{v \cdot (C \cdot \delta l)\}$.





- Current leaking through capacitance ($C \cdot \delta I$) is $\frac{\partial}{\partial t} (v \cdot C \cdot \delta I)$.
- Again, current leaking through conduction ($G \cdot \delta I$) is $\{v \cdot (G \cdot \delta I)\}$.

So,

$$(i + \frac{\partial i}{\partial t} \delta I) - i = v \cdot G \cdot \delta I + \frac{\partial}{\partial t} (v \cdot C \cdot \delta I)$$

$$\text{or, } \frac{\partial i}{\partial t} = v \cdot G + C \cdot \frac{\partial v}{\partial t} = (G + C \cdot \frac{\partial}{\partial t}) \cdot v \quad \dots \dots (1)$$

- Again, voltage drop in resistance ($R \cdot \delta I$) is $\{i \cdot (R \cdot \delta I)\}$.
- Similarly, voltage drop in inductance ($L \cdot \delta I$) is $(L \cdot \delta I) \cdot \frac{\partial i}{\partial t}$.

So,

$$(v + \frac{\partial v}{\partial t} \cdot \delta I) - v = i \cdot R \cdot \delta I + L \cdot \delta I \cdot \frac{\partial i}{\partial t}$$

$$\text{or, } \frac{\partial v}{\partial t} = i \cdot R + L \cdot \frac{\partial i}{\partial t} = (R + L \cdot \frac{\partial}{\partial t}) \cdot i \quad \dots \dots (2)$$

41

Series R-L-C circuit analysis

- Draw equivalent circuit diagram.
- If R, L, C are considered to be uniformly distributed, R, L, C & l are given per unit length of the line.
- Consider an elemental distance dl at a distance l from the starting end.
- Let current & voltage flowing the section be i & v respectively.
- Due to current i , voltage across the section will be $(R + j\omega L) \cdot i$.
- Due to voltage v , current flowing the section will be $\frac{v}{j\omega C}$.
- Change in current in elemental length dl is $(i - \frac{v}{j\omega C}) \cdot dl$.

42

Series R-L-C circuit analysis

- R, L, C & l are considered to be uniformly distributed R, L, C & l are given per unit length of the line.
- Consider an elemental distance dl at a distance l from the starting end.
- Let current & voltage flowing the section be i & v respectively.
- Due to current i , voltage across the section will be $(R + j\omega L) \cdot i$.
- Due to voltage v , current flowing the section will be $\frac{v}{j\omega C}$.
- Change in current in elemental length dl is $(i - \frac{v}{j\omega C}) \cdot dl$.

43

Current flowing through inductor

- Current flowing through inductor (I_1) is i .
- Again, current flowing through inductor (I_1) is $i + \frac{dv}{dt}$.
- So, $i = i + \frac{dv}{dt} - i = \frac{dv}{dt} \Rightarrow \frac{di}{dt} = \frac{dv}{dt}$.
- Again, voltage drop in inductor (V_1) is $j\omega L \cdot i$.
- Similarly, voltage drop in inductor (V_1) is $j\omega L \cdot (i + \frac{dv}{dt})$.
- So, $\frac{dv}{dt} = (i + \frac{dv}{dt}) \cdot j\omega L - i \cdot j\omega L \Rightarrow \frac{dv}{dt} = j\omega L \cdot i$.

44

When dealing with sinusoidal functions, the operator $\frac{\partial}{\partial t}$ may be replaced by $j\omega$, where $\omega = 2\pi f$.

Solution of eqn. (4) is of the form: $v = C_1 \cdot e^{ml} + C_2 \cdot e^{-ml}$ (6)

where, C_1 & C_2 are constants.

From eqn. (6), $\frac{\partial v}{\partial l} = C_1 \cdot m \cdot e^{ml} - C_2 \cdot m \cdot e^{-ml}$

or, $(R + j\omega L) \cdot i = C_1 \cdot m \cdot e^{ml} - C_2 \cdot m \cdot e^{-ml}$ {from eqn. (2)}

45

$$D_{11} = \frac{1}{(R + j\omega L)} \cdot (R + j\omega L) = 1$$

$$\therefore D_{11} = 1 + j\omega L \cdot \frac{1}{(R + j\omega L)} = 1 + j\omega L \cdot \frac{1}{R + j\omega L} = 1 + j\omega L \cdot \frac{R - j\omega L}{R^2 + \omega^2 L^2} = 1 + j\omega L \cdot \frac{R}{R^2 + \omega^2 L^2} - j\omega L \cdot \frac{j\omega L}{R^2 + \omega^2 L^2} = 1 + \frac{R}{R^2 + \omega^2 L^2} + j\frac{-\omega^2 L^2}{R^2 + \omega^2 L^2}$$

$$\text{or, } \frac{\partial^2 V}{\partial l^2} = (R + L \cdot \frac{\partial}{\partial t}) \cdot \frac{\partial i}{\partial l} = (R + L \cdot \frac{\partial}{\partial t}) \cdot (G + C \cdot \frac{\partial}{\partial t}) \cdot v \quad \dots \dots (3)$$

- When dealing with **sinusoidal functions**, the operator $\frac{\partial}{\partial t}$ may be replaced by $j\omega$, where $\omega = 2\pi f$. So,

$$\frac{\partial^2 V}{\partial l^2} = (R + j\omega L) \cdot (G + j\omega C) \cdot v = m^2 \cdot v \quad \dots \dots (4)$$

$$\text{where, } m^2 = (R + j\omega L) \cdot (G + j\omega C) \quad \dots \dots (5)$$

Solution of eqn. (4) is of the form: $v = C_1 \cdot e^{ml} + C_2 \cdot e^{-ml}$ (6)

where, C_1 & C_2 are constants.

$$\text{From eqn. (6), } \frac{\partial v}{\partial l} = C_1 \cdot m \cdot e^{ml} - C_2 \cdot m \cdot e^{-ml}$$

$$\text{or, } (R + j\omega L) \cdot i = C_1 \cdot m \cdot e^{ml} - C_2 \cdot m \cdot e^{-ml} \quad \{ \text{from eqn. (2)} \}$$

42

Ques. Two parallel wires of length 'l' are connected to two voltage sources V_1 & V_2 . The current flowing through each wire is i_1 & i_2 respectively. If the resistance of each wire is R , then the total current flowing through the system is:

$$i = \frac{V_1}{R} + \frac{V_2}{R}$$

43

Ques. A transmission line has a length of l and a load of Z_L at its receiving end. The line has a series resistance of R and shunt admittance of G . The voltage drop across the line is V . The voltage drop across the load is V_L . The voltage drop across the line is V . The voltage drop across the load is V_L .

44

Ques. A transmission line has a length of l and a load of Z_L at its receiving end. The line has a series resistance of R and shunt admittance of G . The voltage drop across the line is V . The voltage drop across the load is V_L .

45

Ques. A transmission line has a length of l and a load of Z_L at its receiving end. The line has a series resistance of R and shunt admittance of G . The voltage drop across the line is V . The voltage drop across the load is V_L .

46

Ques. A transmission line has a length of l and a load of Z_L at its receiving end. The line has a series resistance of R and shunt admittance of G . The voltage drop across the line is V . The voltage drop across the load is V_L .

$$\text{Or, } i = \frac{\sqrt{(R + j\omega L) \cdot (G + j\omega C)}}{(R + j\omega L)} \cdot [C_1 \cdot e^{ml} - C_2 \cdot e^{-ml}]$$

$$= \frac{1}{n} \cdot [C_1 \cdot e^{ml} - C_2 \cdot e^{-ml}] \quad \dots \dots (7)$$

$$\text{Where, } \sqrt{\frac{(G + j\omega C)}{(R + j\omega L)}} = \frac{1}{n} \quad \dots \dots (8)$$

$$\text{So, } n \cdot i = [C_1 \cdot e^{ml} - C_2 \cdot e^{-ml}] \quad \dots \dots (9)$$

- Eqns. (6) & (9) give **values of voltage & current at any distance 'l'** from receiving end of the line, if values of C_1 & C_2 are known.
 - At receiving end $l=0$, $v = V_R$ & $i = I_R$. Hence, from (6) & (9),
- $$V_R = C_1 + C_2 \quad \dots \dots (10)$$
- $$\text{& } n \cdot I_R = C_1 - C_2 \quad \dots \dots (11)$$

44

- When dealing with unbalanced loadings, the equation (1) may be replaced by $v = (V_R + n \cdot I_R) e^{-ml} + (V_R - n \cdot I_R) e^{ml}$ where, $l^2 = (l_1 + l_2)$, $(l_1 + l_2) = l$
Because of eqn. (1) & (2) we have $V_R = C_1 e^{ml} + C_2 e^{-ml}$ where, $C_1 & C_2$ are constants.
Then eqn. (2) $\frac{dV}{dl} = C_1 m e^{ml} + C_2 m e^{-ml}$
 $\Rightarrow (l_1 + l_2) \frac{dV}{dl} = C_1 m e^{ml} + C_2 m e^{-ml}$ (Deriv. eqn. (2))

45

$$D_{l_1} = \frac{(V_R + n \cdot I_R) e^{-ml} + (V_R - n \cdot I_R) e^{ml}}{(l_1 + l_2)} \Rightarrow D_{l_1} = e^{-ml} + e^{ml} \quad \dots \dots (7)$$

where, $\sqrt{\frac{D_{l_1}}{D_{l_2}}} = e^{-ml}$
Eqn. (2) & (3) give values of voltage & current at any distance 'l' from receiving end of the line, if values at $(l_1 + l_2)$ are known.
At receiving end $l = 0 \Rightarrow V_R = V_0$. Hence from (2) & (3)
 $I_0 = I_1 + I_2 \quad \dots \dots (8)$
 $\Rightarrow n \cdot I_0 = n \cdot I_1 + n \cdot I_2 \quad \dots \dots (12)$

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$$\text{Der. eqn. } (1) \quad \dots \dots (13)$$

$$\text{At } l_1 = \frac{l_1 + l_2}{2} \quad \dots \dots (13)$$

At any distance 'l' from receiving end, from eqn. (2),
$$V = \frac{V_R + n \cdot I_R}{2} e^{-ml} + \frac{V_R - n \cdot I_R}{2} e^{ml}$$

$$= V_R \cdot \left[\frac{e^{-ml} + e^{ml}}{2} \right] + n \cdot I_R \cdot \left[\frac{e^{-ml} - e^{ml}}{2} \right]$$

$$= V_R \cdot \text{Cosh } ml + n \cdot I_R \cdot \text{Sinh } ml \quad \dots \dots (14)$$

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$$n \cdot i = \frac{V_R + n \cdot I_R}{2} e^{-ml} - \frac{V_R - n \cdot I_R}{2} e^{ml}$$

$$= V_R \cdot \left[\frac{e^{-ml} - e^{ml}}{2} \right] + n \cdot I_R \cdot \left[\frac{e^{-ml} + e^{ml}}{2} \right]$$

$$= V_R \cdot \text{Sinh } ml + n \cdot I_R \cdot \text{Cosh } ml \quad \dots \dots (15)$$

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Answers Given Below
Ques. of the sending end voltage & current for all responses will be (a short, medium & long) one of same type, namely

So, $C_1 = \frac{V_R + n \cdot I_R}{2} \quad \dots \dots (12)$

& $C_2 = \frac{V_R - n \cdot I_R}{2} \quad \dots \dots (13)$

So, at any distance 'l' from receiving end, from eqn. (6),

$$\begin{aligned} v &= \frac{V_R + n \cdot I_R}{2} \cdot e^{ml} + \frac{V_R - n \cdot I_R}{2} \cdot e^{-ml} \\ &= V_R \cdot \left[\frac{e^{ml} + e^{-ml}}{2} \right] + n \cdot I_R \cdot \left[\frac{e^{ml} - e^{-ml}}{2} \right] \\ &= V_R \cdot \text{Cosh } ml + n \cdot I_R \cdot \text{Sinh } ml \quad \dots \dots (14) \end{aligned}$$

Also, from eqn. (9),

$$\begin{aligned} n \cdot i &= \frac{V_R + n \cdot I_R}{2} \cdot e^{-ml} - \frac{V_R - n \cdot I_R}{2} \cdot e^{ml} \\ &= V_R \cdot \left[\frac{e^{-ml} - e^{ml}}{2} \right] + n \cdot I_R \cdot \left[\frac{e^{-ml} + e^{ml}}{2} \right] \\ &= V_R \cdot \text{Sinh } ml + n \cdot I_R \cdot \text{Cosh } ml \quad \dots \dots (15) \end{aligned}$$

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or, $i = \frac{V_R}{n} \cdot \text{Sinh } ml + I_R \cdot \text{Cosh } ml \dots\dots (16)$

If 'l' be the distance from the receiving end to the sending end, then $v = V_s$ & $i = I_s$, the sending end values. Then,

$$V_s = V_R \cdot \text{Cosh } ml + n \cdot I_R \cdot \text{Sinh } ml \dots\dots (17)$$

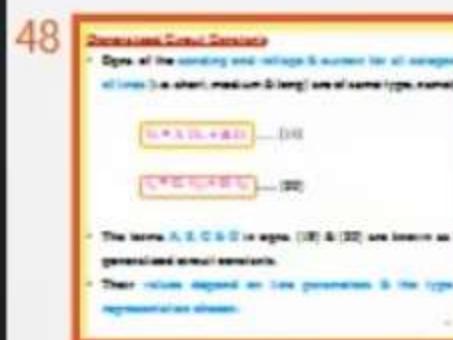
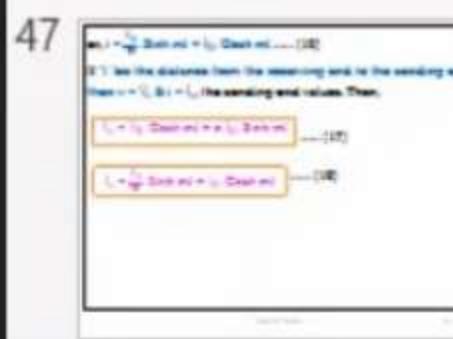
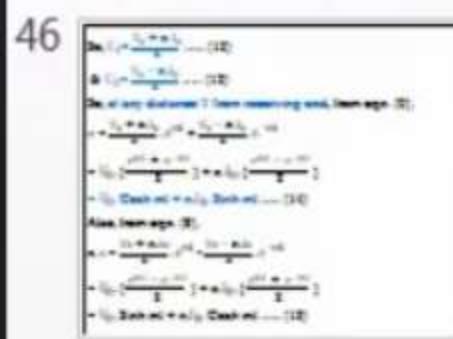
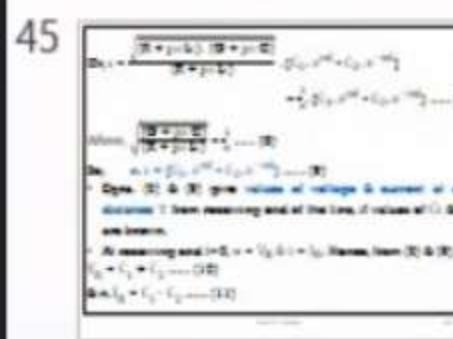
$$I_s = \frac{V_R}{n} \cdot \text{Sinh } ml + I_R \cdot \text{Cosh } ml \dots\dots (18)$$

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Generalized Circuit Constants

- Eqns. of the sending end voltage & current for all categories of lines (i.e. short, medium & long) are of same type, namely,

$$V_s = A \cdot V_R + B \cdot I_R \quad \dots \dots (19)$$

$$I_s = C \cdot V_R + D \cdot I_R \quad \dots \dots (20)$$

- The terms A, B, C & D in eqns. (19) & (20) are known as the generalized circuit constants.
- Their values depend on line parameters & the type of representation chosen.

	<u>Generalized Circuit Constant</u>	<u>Medium – T representation</u>	<u>Medium – π representation</u>	<u>Long</u>
47	A	1	(1+YZ/2)	(1+YZ/2) Cosh ml
	B	Z	(1+YZ/4). Z	n. Sinh ml
	C	0	Y	$\frac{1}{n}$. Sinh ml
48	D	1	(1+YZ/2)	(1+YZ/2) Cosh ml

- In all the cases **A = D & I**
- A. D – B. C = 1**
- The constants are **complex numbers.**
- A & D** are **dimension less.**
- B** has the dimension of **impedance (ohm)** & **C** has the dimension of **admittance (mho).**

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Determination of A, B, C & D Constants

- It may be done in **two ways.**
- (i) From the **knowledge of** line parameters **R, L, C & G** and the table given in last slide.
- (ii) By **direct measurement** from the actual network.

It is known that,

$$V_s = A \cdot V_R + B \cdot I_R$$

$$I_s = C \cdot V_R + D \cdot I_R$$

❖ If the receiving end is **open circuited** & a voltage of V_s' be applied at sending end to give a voltage V_R' at receiving end, then receiving end current $I_R' = 0$. If I_s' be the corresponding sending end current, then

$$A = \frac{V_s'}{V_R'} \quad \& \quad C = \frac{I_s'}{V_R'}$$

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❖ If the receiving end of the line is now short circuited & a voltage of V_s'' be applied at sending end to give sending end & receiving end currents of I_s'' & I_R'' respectively, then $V_R'' = 0$.

Hence,

$$B = \frac{V_s''}{I_R''} \quad \& \quad D = \frac{I_s''}{I_R''}$$

51

Example: A single-phase 30 kVA, power factor unit load of 0.800 p.f. is applied at receiving end. The receiving end voltage is 11 kV. The line resistance and inductance per km are 0.167 ohm/km and 0.07 mH/km. The voltage at 20 km from the receiving end is

NOTES COMMENTS

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Example: A single-phase 50 Hz generator supplies an inductive load of 5,000 kW at a power factor of 0.707 lagging by means of an overhead transmission line 20 km long. The line resistance and inductance are 0.0195Ω and 0.63 mH per km. The voltage at the receiving end is required to be kept constant at 10 kV. Find the sending end voltage and voltage regulation of the line.

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Soln:

The line constants are

$$R = 0.0195 \times 20 = 0.39 \Omega$$

and $L = 0.63 \times 10^{-3} \times 20 = 0.0126 \text{ H}$

$$X = 314.2857 \times 0.0126 = 3.96 \Omega$$

This is the case of a short line with $I = I_R = I_S$.

So, $|I| = \frac{5,000}{10 \times 0.707} = 707.2136 \text{ A}$

Now, $|V_S| \approx |V_R| + |I| (R \cos \phi_R + X \sin \phi_R)$

$$= 10,000 + 707.2136 (0.39 \times 0.707 + 3.96 \times 0.707) \text{ V}$$

$$= 12.175 \text{ kV}$$

Voltage regulation = $\frac{12.175 - 10}{10} \times 100 = 21.75\%$

Example : Using the nominal- π -method, find the sending-end voltage and voltage regulation of a 250 km, three-phase, 50 Hz, transmission line delivering 25 MVA at 0.8 lagging power factor to a balanced load at 132 kV. The line conductors are spaced equilaterally 3 m apart. The conductor resistance is 0.11 ohm/km and its effective diameter is 1.6 cm. Neglect leakage.

Soln:

$$L = 2 \cdot 10^{-7} \cdot \ln \frac{D}{r'} \text{ H/m} = 2 \cdot 10^{-7} \cdot \ln \frac{300}{0.7788 \times 0.8}$$

$$= 1.24 \text{ mH/km}$$

$$C = \frac{2\pi K}{\ln \frac{D}{r'}} \text{ F/m} = \frac{0.0556}{\ln \frac{300}{0.8}} = 0.0094 \mu\text{F/km}$$

$$R = 0.11 \times 250 = 27.5 \Omega$$

$$X = 2\pi f L = 2\pi \times 50 \times 1.24 \times 10^{-3} \times 250 = 97.4 \Omega$$

$$Z = R + jX = 27.5 + j97.4 = 101.2 \angle 74.2^\circ \Omega$$

$$Y = j\omega Cl = 2\pi \times 50 \times 0.0094 \times 10^{-6} \times 250 \angle 90^\circ$$

$$= 7.38 \times 10^{-4} \angle 90^\circ \Omega$$

52 Example: A single-phase 10 kV generator supplies an resistive load of 1,000 kW at a power factor of 0.787 lagging by means of an open lead transmission line 20 km long. The line resistance and inductance are 0.0085 ohm and 0.02 mili per km. The voltage at the receiving end is required to be kept constant at 10 kV. Find the sending end voltage and voltage regulation of the line.

53 Data:
 The line constants are:
 $R = 0.0085 \times 20 = 0.170$ ohm
 and $L = 0.02 \times 20 = 0.4$ mili per km.
 $Z = j(0.0085 + 0.02) \times 20 = 0.170 + j0.4$
 This is the case of a short line i.e. $I_2 = 0$.
 $\frac{V_R}{V_S} = \frac{1}{1 + \frac{ZI_R}{2}}$
 Now, $V_R = V_S + (jZI_R)$
 $= 10.000 + j(0.170 \times 10^3 \times 0.787) + j0.4 \times 0.300 \times 10^3$
 $= 12.776$ kV
 Voltage regulation: $\frac{12.776 - 10}{10} \times 100 = 27.7\%$

54 Example: Two parallel-connected, neutrally connected voltage and current sources are connected to the transmission line. The transmission line has a length of 10 km and a total resistance of 0.1 ohm. The transmission line has a total inductance of 0.2 mili per km. The voltage regulation is to be kept constant at 2.5%. The voltage regulation is to be determined for the two different cases of the load impedances. Both I_1 and I_2 have a phase angle of 74.2° .

55 $I_1 = \frac{25 \times 1,000}{\sqrt{3} \times 132} \angle -36.9^\circ = 109.3 \angle -36.9^\circ$ A

V_R (per phase) = $(132/(\sqrt{3})) \angle 0^\circ = 76.2 \angle 0^\circ$ kV

$$V_S = \left(1 + \frac{1}{2} YZ \right) V_R + ZI_R$$

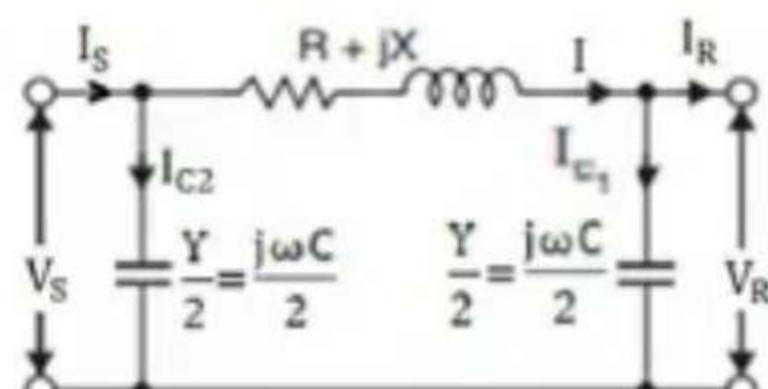
$$= \left(1 + \frac{1}{2} \times 7.38 \times 10^{-4} \angle 90^\circ \times 101.2 \angle 74.2^\circ \right) \times 76.2$$

$$+ 101.2 \angle 74.2^\circ \times 109.3 \times 10^{-3} \angle -36.9^\circ$$

$$= 76.2 + 2.85 \angle 164.2^\circ + 11.06 \angle 37.3^\circ$$

$$= 82.26 + j7.48 = 82.6 \angle 5.2^\circ$$

$$\therefore |V_S| (\text{line}) = 82.6 \times \sqrt{3} = 143$$
 kV



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The line constants are
 $Z = 0.0005 \times 20 + j0.01 \Omega$
 $\text{and } G = 0.005 \times 20^{-1} = 0.00025 \text{ S}$
 $X = 0.01374 \times 0.00025 = 0.000343 \Omega$
This is the case of a short line with $Z = Z_0 = Z_L$
 $Z_0 = \frac{Z}{Z + jX} = \frac{0.000343}{0.000343 + j0.000343}$
 $= 0.000343 \times 0.000343 + j0.000343$
 $= 0.000343 + j0.000343$
Voltage regulation = $\frac{132 - 100}{100} \times 100 = 21.7\%$

54
Example: Using the method mentioned, find the reading on voltmeter connected across the primary of a 1000 kVA, 1000V, 50 Hz, 10% lossless transformer at no load. If the primary resistance is 0.1 ohm and the leakage reactance is 0.2 ohm. The secondary resistance is 0.2 ohm and the leakage reactance is 0.1 ohm. The primary voltage is 100 V and the primary current is 10 A. The secondary voltage is 100 V.
 $\Delta = 2.13 \times 10^{-3} \text{ ohms} \times 10^3 = 2.13 \text{ ohms}$
 $C = \frac{1000}{2.13} = 469.1 \mu\text{F}$
 $R = 0.1 \times 100 = 10 \Omega$
 $X = 100 \times 30 \times 1.58 \times 10^{-7} = 4.776 \times 10^3 \Omega$
 $Z = R + jX = 10 + j4.776 \times 10^3 \Omega$
 $V_{no\ load} = 100 \times 30 + 9.8884 \times 10^{-7} \times 100 \times 10^3$
 $= 132 \times 10^3 \angle 45^\circ$

55
 $I_s = \frac{100 \times 1000}{100 \times 100} = 100 \text{ A} \angle -90^\circ$
 $V_s \text{ per phase} = (100 \sqrt{3}) \angle 90^\circ = 173.2 \angle 90^\circ \text{ V}$
 $I_p = \left(1 + \frac{1}{2} \frac{R}{X} \right) I_s = 10 \text{ A}$
 $= \left(1 + \frac{1}{2} \times \frac{0.1}{4.776 \times 10^3} \times 10^3 \right) \times 10 \text{ A}$
 $= 10.12 \angle 90^\circ = 100 \text{ A} \angle -90^\circ$
 $= 10.12 \times 100 \times 10^3 \times 10^{-7} = 10.12 \text{ ohms}$
 $= 10.26 + j4.68 + j0.27$
 $= 10.26 + j4.68 + j0.27$

56
Now, $A = 1 + \frac{1}{2} \frac{R}{X} = 1 + 0.00025 \times 3000 \times 10^{-7} = 0.9999 + j0.0003$
 $\text{Find } V_{no\ load} = \frac{100}{1 + \frac{1}{2} \frac{R}{X}} = 148.3 \text{ V}$
 $\therefore \text{Voltage regulation} = \frac{148.3 - 100}{100} \times 100 = 12.3\%$

Now, $A = 1 + \frac{1}{2} YZ = 1 + 0.0374 \angle 164.2^\circ = 0.964 + j0.01$

$$|V_{R0}| \text{ (line no load)} = \frac{143}{\left| 1 + \frac{1}{2} YZ \right|} = \frac{143}{0.964} = 148.3 \text{ kV}$$

$$\therefore \text{Voltage regulation} = \frac{148.3 - 132}{132} \times 100 = 12.3\%$$

Problem: Using nominal T-method find the voltage, current & power factor at the sending end, voltage regulation & efficiency of a 100km, 3φ, 50Hz transmission line when delivering 50MVA at 0.8 lagging power factor to a balanced load at 132kV. The line conductors are spaced equilaterally 4.0m apart. The conductor resistance is $0.11\Omega/\text{km}$ & effective diameter is 2.5cm. Neglect leakage.

Soln: Total resistance for 100km = $0.11 \times 100 = 11 \Omega = R$ (say).

$$\text{Inductance of the line} = 2 \cdot 10^{-7} \cdot \ln \frac{400}{1.25 \times 0.7788} \text{ H/m}$$
$$= 12.03664 \cdot 10^{-7} \text{ H/m}$$

$$\text{Total inductance for 100km} = L = 12.03664 \cdot 10^{-7} \times (100 \times 1000)$$
$$= 0.1203664 \text{ H}$$

$$\text{Capacitance} = \frac{2\pi K_0}{\ln \frac{400}{1.25}} = \frac{2\pi}{36\pi \cdot 10^9 \cdot \ln \frac{400}{1.25}} = 9.63115 \cdot 10^{-12} \text{ F/m}$$

$$\text{Capacitance for } 100\text{ km} = C = 9.63115 \cdot 10^{-12} \cdot (100 \times 1000) \text{ F} \\ = 9.63115 \cdot 10^{-7} \text{ F}$$

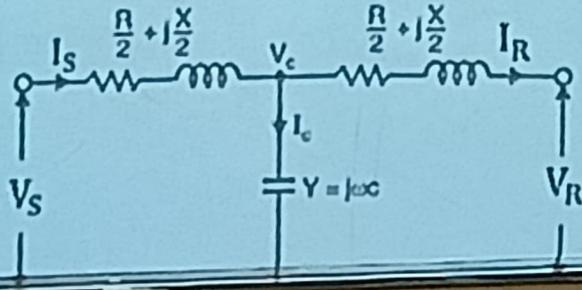
$$\text{Receiving end current} = I_R = \frac{50 \cdot 10^6}{\sqrt{3} \cdot 132 \cdot 10^3} \angle -\cos^{-1} 0.8$$

$$= 218.69328 \angle -36.86989^\circ \text{ A} = 174.95463 - j 131.21597 \text{ A}$$

$$\text{Here, } Z = R + j\omega L = 11 + j(2\pi \cdot 50) \times 0.1203664 = 11 + j 37.81423 \Omega \\ = 39.38167 \angle 73.78051^\circ \Omega$$

$$Y = j\omega C = j(2\pi \cdot 50) \times 9.63115 \cdot 10^{-7} = 3025.71438 \cdot 10^{-7} \angle 90^\circ \Omega$$

$$V_R = \frac{132 \cdot 10^3}{\sqrt{3}} \angle 0^\circ = 76210.23553 \angle 0^\circ \text{ V (Taken as reference)}$$



$$V_C = V_R + I_R \cdot \frac{Z}{2} = 76210.23553 \angle 0^\circ + 218.69328 \angle -36.86989^\circ.$$

$$\frac{39.38167 \angle 73.78051^\circ}{2}$$

$$= 79653.16603 + j 2586.19964 \text{ V} = 79695.13967 \angle 1.85964^\circ \text{ V}$$

$$I_C = V_C \cdot Y = 79695.13967 \angle 1.85964^\circ \cdot 3025.71438 \cdot 10^{-7} \angle 90^\circ$$

$$= 24.11347 \angle 91.85964^\circ = -0.78251 + j 24.10077 \text{ A}$$

$$I_S = I_R + I_C = 174.95463 - j 131.21597 + -0.78251 + j 24.10077$$

$$= 174.17212 - j 107.11520 \text{ A} = 204.47394 \angle -31.59136^\circ \text{ A}$$

$$V_S = V_C + I_S \cdot \frac{Z}{2}$$

$$= 79653.16603 + j 2586.19964 + 204.47394 \angle -31.59136^\circ.$$

$$\frac{39.38167 \angle 73.78051^\circ}{2} \text{ V}$$

$$= 82636.35215 + j 5290.15852 = 82805.50991 \angle 3.66292^\circ \text{ V (L-N)}$$

$$\text{Sending end Power factor} = \cos(3.66292^\circ + 31.59136^\circ) \\ = 0.81660 \text{ (lagging)}$$

$$\text{Efficiency of transmission} = \frac{|V_R| \cdot |I_R| \cdot \cos \varphi_R}{|V_S| \cdot |I_S| \cdot \cos \varphi_S} \times 100 = 82.37688\%$$

$$\text{Now, } A = \left(1 + \frac{YZ}{2}\right)$$

$$= \left(1 + \frac{3025.71438 \cdot 10^{-7} \angle 90^\circ \cdot 39.38167 \angle 73.78051^\circ}{2}\right)$$

$$= 1 + 5.95788 \cdot 10^{-3} \angle 163.78051^\circ$$

$$= 1 + 5.95788 \cdot 10^{-3} (-0.96020 + j 0.27932)$$

$$= (0.99428 + j 1.66414 \cdot 10^{-3})$$

$$= 0.99428 \angle 0.09590^\circ$$

$$\% \text{ Voltage regulation} = \frac{\left|\frac{V_S}{A}\right| - |V_R|}{|V_R|} \times 100 = 9.27912\%$$

Electromagnetic Effect

- Let, currents I_a, I_b & I_c be flowing through power line conductors **a, b & c** respectively.
- They form a circuit, i.e.

$$I_a + I_b + I_c = 0 \dots\dots (1)$$

- Flux linkage of cond. 'd' up to infinity,

due to $I_a = \Psi_{ad} = 2.10^{-7} \cdot I_a \cdot \ln \frac{\infty}{D_{ad}}$ wbT/m

- Similarly, flux linkage of conductor 'e' up

to infinity, due to $I_a = \Psi_{ae} = 2.10^{-7} \cdot I_a \cdot \ln \frac{\infty}{D_{ae}}$ wbT/m

- So, mutual flux linkage of the loop formed by conductors 'd' &

'e' due to $I_a = \Psi_{de} = \Psi_{ad} - \Psi_{ae} = 2.10^{-7} \cdot I_a \cdot \ln \frac{D_{ae}}{D_{ad}}$ wbT/m

O_a

c O

O_b

o o
d e

Fig. a, b & c: power line conductors;
d & e: communication line conductors.

- So, mutual inductance between cond. 'a' & the communication circuit consisting of cond. 'd' & 'e' is

$$M_a = \frac{\Psi}{I_a} = 2 \cdot 10^{-7} \cdot \ln \frac{D_{ae}}{D_{ad}} \text{ H/m} \dots \dots (2)$$

- Likewise, M_b & M_c are mutual inductances between cond. 'b' & the loop 'de' and between cond. 'c' & the loop 'de' respectively.
- These are given by

$$M_b = 2 \cdot 10^{-7} \cdot \ln \frac{D_{be}}{D_{bd}} \text{ H/m} \dots \dots (3)$$

$$M_c = 2 \cdot 10^{-7} \cdot \ln \frac{D_{ce}}{D_{cd}} \text{ H/m} \dots \dots (4)$$

- Here, M_a , M_b & M_c are due to fluxes which have mutual phase displacement of 120° .
- So, net effect of the magnetic field is

$$\vec{M} = \vec{M}_a + \vec{M}_b + \vec{M}_c \dots\dots (5)$$

- Here \vec{M} is net mutual inductance \rightarrow phasor sum of three inductances.
- If 'I' be the current in power conductors & 'f' is the frequency, then the induced voltage in the communication line consisting of conductors 'd' & 'e' is

$$V = 2\pi f \cdot M \cdot I \text{ Volts/m} \dots\dots (6)$$

- There is a partial cancellation of the induced voltages due to power line currents.
- This cancellation is almost complete for balanced 3φ line.
- However, greater the distance between two circuits lesser is the mutual effect (see expressions of M_a , M_b & $M_c \rightarrow$ all distances D_{ae} , D_{ad} , D_{be} , D_{bd} , D_{ce} & D_{cd} tend to become equal).

Electrostatic Effect

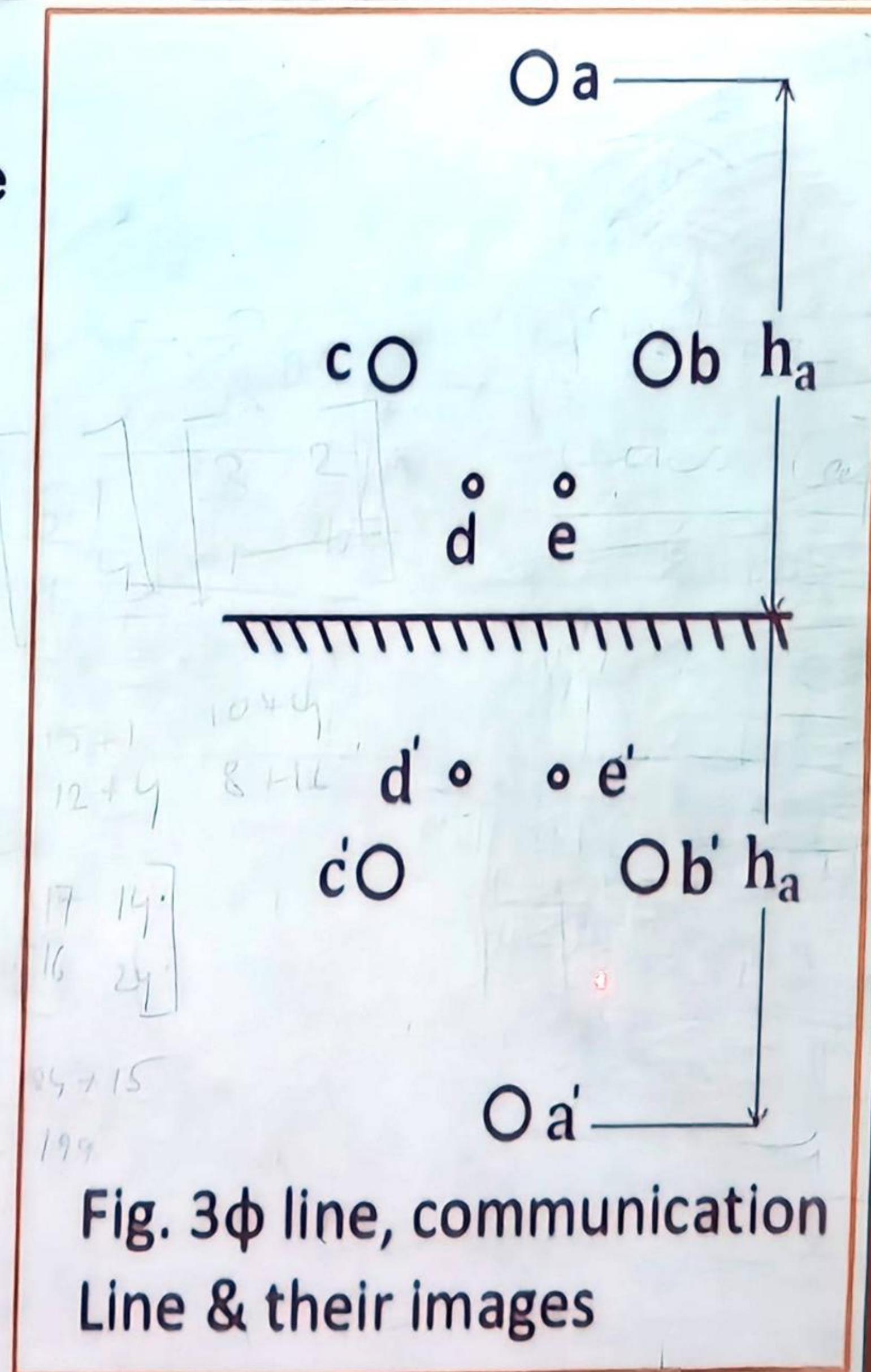
- Let, cond. 'a' be carrying a charge of $q_a = +q$ coulomb/m.
- So, potential difference 'a' and its image 'a'' is $V_{aa'} = 2V_{an}$

$$= \frac{1}{2\pi\kappa_0} [q_a \cdot \ln \frac{D_{aa'}}{D_{aa}} + q_{a'} \cdot \ln \frac{D_{a'a'}}{D_{a'a}}]$$

$$= \frac{q}{2\pi\kappa_0} \left[\ln \frac{2.h_a}{r} - \ln \frac{r}{2.h_a} \right] \dots\dots (1)$$

$$\text{or, } V_{an} = \frac{q}{2\pi\kappa_0} \cdot \ln \frac{2.h_a}{r} \dots\dots (2)$$

$$\text{or, } \boxed{\frac{q}{2\pi\kappa_0} = \frac{V_{an}}{\ln \frac{2.h_a}{r}}} \dots\dots \dots\dots (3)$$



- Similarly, potential difference $V_{dd'a}$ between communication line conductors 'd' & its image 'd'' due to a charge ' $q_a = +q$ ' on cond. 'a' & a charge of ' $q_{a'} = -q$ ' on image 'a'' is

$$\begin{aligned}
 V_{dd'a} &= \frac{1}{2\pi\kappa_0} [q_a \cdot \ln \frac{D_{ad'}}{D_{ad}} + q_{a'} \cdot \ln \frac{D_{a'd'}}{D_{a'd}}] \\
 &= \frac{q}{2\pi\kappa_0} [\ln \frac{D_{ad'}}{D_{ad}} - \ln \frac{D_{a'd'}}{D_{a'd}}] = \frac{q}{2\pi\kappa_0} [\ln \frac{(2.h_a - D_{ad})}{D_{ad}} - \ln \frac{D_{ad}}{(2.h_a - D_{ad})}] \\
 &= \frac{q}{2\pi\kappa_0} \cdot 2 \cdot \ln \frac{(2.h_a - D_{ad})}{D_{ad}} \dots\dots (4)
 \end{aligned}$$

- So, potential of cond. 'd' w.r.t. neutral due to charges q_a & $q_{a'}$ is

$$V_{dn_a} = \frac{q}{2\pi\kappa_0} \cdot \ln \frac{(2.h_a - D_{ad})}{D_{ad}} \dots\dots (5)$$

Substituting the value of $\frac{q}{2\pi k_0}$ from eqn. (3),

$$V_{dn_a} = \frac{V_{an}}{\ln \frac{2.h_a}{r}} \cdot \ln \frac{(2.h_a - D_{ad})}{D_{ad}} = V_{an} \cdot \frac{\ln \frac{(2.h_a - D_{ad})}{D_{ad}}}{\ln \frac{2.h_a}{r}} \quad \dots \dots (6)$$

- Similarly, one can obtain potential of cond. 'd' w.r.t. neutral due to charges q_b & $q_{b'}$ as

$$V_{dn_b} = V_{bn} \cdot \frac{\ln \frac{(2.h_b - D_{bd})}{D_{bd}}}{\ln \frac{2.h_b}{r}} \quad \dots \dots (7)$$

- And potential of cond. 'd' w.r.t. neutral due to charges q_c & $q_{c'}$ as

$$V_{dn_c} = V_{cn} \cdot \frac{\ln \frac{(2.h_c - D_{cd})}{D_{cd}}}{\ln \frac{2.h_c}{r}} \quad \dots \dots (8)$$

- So, the potential of cond. 'd' due to all the cond. a, b & c is

$$\vec{V}_{dn} = \vec{V}_{dn_a} + \vec{V}_{dn_b} + \vec{V}_{dn_c} \dots \dots (9)$$

- Similarly, potential of cond. 'e' may be calculated.

Example: The sending end voltage per phase of a long transmission line is given by the expression

$$V_s = (0.986 \angle 0.32^\circ) \cdot V_R + (70.3 \angle 69.2^\circ) \cdot I_R.$$

Determine the capacity of a phase modifier to be installed at the receiving end so that when a load of 50MVA is delivered at 132kV and power factor 0.707 lagging, the sending end voltage can also be 132kV.

Soln: It is known that

$$V_s = A \cdot V_R + B \cdot I_R$$

By the problem

$$\begin{aligned} A &= 0.986 \angle 0.32^\circ \\ &= (0.986 + j 0.0055) \text{ &} \\ B &= 70.3 \angle 69.2^\circ \\ &= (24.96 + j 65.72) \end{aligned}$$

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Load current magnitude $|I_L| = \frac{50,000}{\sqrt{3} \cdot 132} = 218.6933 \text{ A}$

Taking receiving end voltage as reference phasor,

$$V_R = \frac{132}{\sqrt{3}} = 76.2102 \angle 0^\circ \text{ kV/phase} = (76.2102 + j 0.0) \text{ kV/phase}$$

Load current $I_L = 218.6933 \angle -45^\circ \text{ A}$ (as p.f. is 0.707 lagging)

$$= (154.6395 - j 154.6395) \text{ A}$$

- Problem is to determine the capacity of a phase modifier (**What is it?**) to be installed at the receiving end.
- Let, modifier current be $j I_m$ (assuming losses negligible).

So, receiving end current $= I_R = I_L + j I_m$ (as two are in parallel).

$$= (154.6395 - j 154.6395) + j I_m = (154.6395 - j (154.6395 - I_m)) \text{ A}$$

Then, sending end voltage is

$$V_s = A \cdot V_R + B \cdot I_R$$

$$= (0.986 + j 0.0055) \cdot (76210.2 + j 0.0) + (24.96 + j 65.72) \cdot \\ \{154.6395 - j (154.6395 - I_m)\}$$

$$= (89152.33 - 65.72 \cdot I_m) + j (6728.21 + 24.96 I_m)$$

Given that, $|V_s| = |V_R| = 76210.2 \text{ V/phase}$

Hence,

$$(76210.2)^2 = (89152.33 - 65.72 \cdot I_m)^2 + (6728.21 + 24.96 I_m)^2$$

Solving, $I_m = 2093 \text{ A}$ or 212 A

- Although both values of I_m seem to be valid, but they are mathematical results only.
- In practice, higher value is invalid as it lies outside the region of stable operation.

- So, the accepted value of I_m is 212 A.
- Hence, phase modifier capacity to meet the specification would be

$$\frac{\sqrt{3} \cdot 132 \cdot 212}{1000} \text{ MVAR} = 48.47 \text{ MVAR}$$

Preamble

- In practice power lines may be erected in close proximity to telephone lines or communication circuits.
- The communication circuits may be the property of the power company → used for protection or communication link.
- Power lines give rise to electromagnetic & electrostatic fields of sufficient magnitudes.
- These induce currents & voltages respectively in the neighbouring communication lines.
- Induced currents are superimposed on true speech currents and thereby setup distortion.
- Induced voltages raise potential of communication circuits with consequent risk to both equipment & users.

Preamble - Cont.

- In extreme cases, raising of potential may become too high to handle the communication equipment highly dangerous.
- Magnitudes of induced currents & voltages depend on the distance between the two circuits & length of the route over which they run approximately in parallel.
- In case of public telephone lines, the two circuits may run in parallel only for a short distance.
- But, if the communication circuit is the property of the power company, same towers may be used for both circuits.
- Hence, adequate measures must always be taken to reduce the electromagnetic & electrostatic effects on the communication lines.

Reduction of Interference

- Thorough transposition of both the (i) power line & (ii) communication line conductors.
 - It has the effect of splitting the induced emf into a series of mutually opposed emfs.
 - Use of screened cables for communication lines overcomes the trouble due to electrostatic interference.
 - Same effect is obtained by the use of an earth wire between the power line & the communication line.
 - Further, electromagnetic interference may be reduced by splitting the telephone line into short lengths each being separated from the adjacent section by 1:1 isolating transformer.
- Such a method can't be used if d.c. signal needs to be sent.

Prob: A load of 30MW is delivered at a distance of 160km at a voltage of 132kV & at a frequency of 50Hz, the p.f. being 0.9. The line conductors which have a radius of 5.5mm are situated at the corners of an equilateral triangle with a side of 3.5m and arranged as shown in the fig. The height of the lowest cond. is 15m from the ground. A telephone line runs on the same supporting towers, the distances between the telephone line & the power line cond. being as shown. Find magnitudes of (i) the electromagnetic & (ii) the electrostatic emf induced in the telephone line.

Soln: Electromagnetic Effect

From the Δabo,

$$(3.5)^2 = D_{ao}^2 + \left(\frac{3.5}{2}\right)^2$$

$$\text{or, } D_{ao} = 3.0311\text{m}$$

$$\text{Now, } D_{ad} = D_{ao} + 3 = 6.0311\text{m}$$

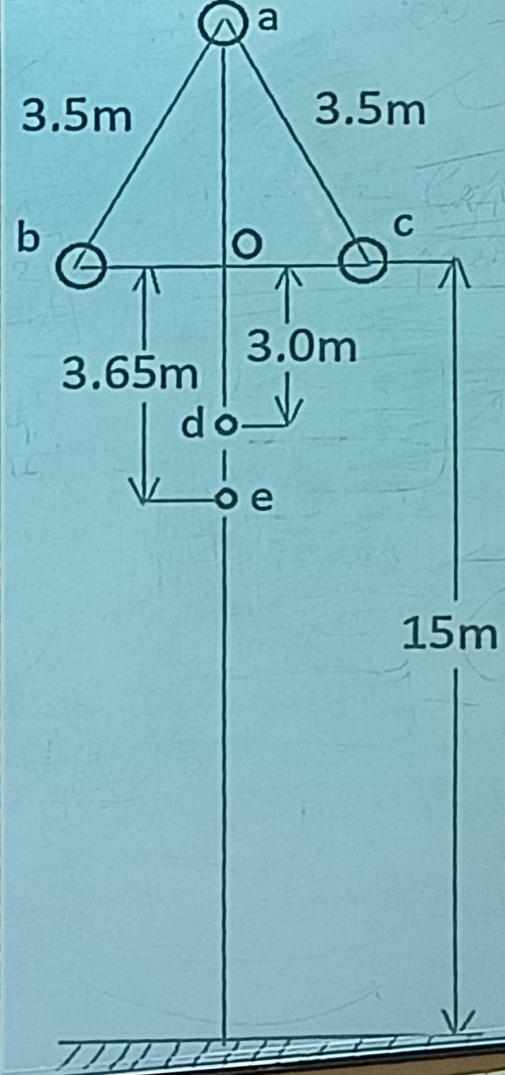
$$D_{ae} = D_{ao} + 3.65 = 6.6811\text{m}$$

$$\text{Again, } (D_{bd})^2 = (3)^2 + \left(\frac{3.5}{2}\right)^2$$

$$\text{or, } D_{bd} = 3.4731\text{m} = D_{cd}$$

$$(D_{be})^2 = (3.65)^2 + \left(\frac{3.5}{2}\right)^2$$

$$\text{or, } D_{be} = 4.0478\text{m} = D_{ce}$$



$$M_a = 2 \cdot 10^{-7} \cdot \ln \frac{D_{ae}}{D_{ad}} = 2 \cdot 10^{-7} \cdot \ln \frac{6.6811}{6.0311} = 0.2047 \cdot 10^{-7} \text{ H/m}$$

$$= 0.2047 \cdot 10^{-4} \text{ H/km}$$

$$M_b = M_c = 2 \cdot 10^{-7} \cdot \ln \frac{D_{be}}{D_{bd}} = 2 \cdot 10^{-7} \cdot \ln \frac{4.0478}{3.4731} = 0.3063 \cdot 10^{-7} \text{ H/m}$$

$$= 0.3063 \cdot 10^{-4} \text{ H/km}$$

- Net mutual inductance is equal to phasor sum of M_a , M_b & M_c .
 - So, $\vec{M} = \vec{M}_a + \vec{M}_b + \vec{M}_c = M_a + M_b \angle 120^\circ + M_c \angle 240^\circ$ (ph seq. a-b-c)
- or, $|M|^2 = (M_a + M_b \cdot \cos 120^\circ + M_c \cdot \cos 240^\circ)^2 +$

$$(M_b \cdot \sin 120^\circ + M_c \cdot \sin 240^\circ)^2$$

or, $|M| = 0.1016 \cdot 10^{-4} \text{ H/km}$

$$\text{Now, current } I = \frac{30 \cdot 10^6}{\sqrt{3} \cdot 132 \cdot 10^3 \cdot 0.9} = 145.7955 \text{ A}$$

Electromagnetically induced emf = $2\pi f \cdot |M| \cdot I = 0.4654 \text{ V/km}$

Total electromagnetically induced emf = $0.4654 \cdot 160 = 74.464 \text{ V}$

Electrostatic Effect

- Height of cond. 'a' above ground = $15 + D_{ao} = 18.0311 \text{ m}$
- Height of cond. 'b' & 'c' above ground = 15 m
- So, magnitude of potential of cond. 'd' w.r.t. neutral = $|V_{dn_a}|$

$$= |V_{an}| \cdot \frac{\ln \frac{(2.h_a - D_{ad})}{D_{ad}}}{\ln \frac{2.h_a}{r}} = \frac{132 \cdot 10^3}{\sqrt{3}} \cdot \frac{\ln \frac{(2.18.0311 - 6.0311)}{6.0311}}{\ln \frac{2.18.0311}{5.5 \cdot 10^{-3}}} = 13920.8142 \text{ V}$$

Likewise, magnitude of potential of cond. 'd' w.r.t. neutral due to cond. 'b' = magnitude of potential of cond. 'd' w.r.t. neutral due to cond. 'c' (due to symmetry) = $|V_{dn_b}| = |V_{dn_c}|$

$$= |V_{bn}| \cdot \frac{\ln \frac{(2 \cdot h_b - D_{bd})}{D_{bd}}}{\ln \frac{2 \cdot h_b}{r}} = \frac{132 \cdot 10^3}{\sqrt{3}} \cdot \frac{\ln \frac{(2.15 - 3.4731)}{3.4731}}{\ln \frac{2.15}{5.5 \cdot 10^{-3}}} \\ = 18007.8369 \text{ V}$$

- So, total potential of cond. 'd' w.r.t. neutral = \vec{V}_{dn}

$$= \vec{V}_{dn_a} + \vec{V}_{dn_b} + \vec{V}_{dn_c} = |V_{dn_a}| + |V_{dn_b}| \angle 120^\circ + |V_{dn_c}| \angle 240^\circ \\ \text{or, } |V_{dn}| = 4087.0227 \text{ V}$$

Similarly, the potential of cond. 'e' can be determined.