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The Supply System

- It is the interlink between the generating stations and the consumers over which power is transferred.

Or, in a more simple way -

- Power is generated in the generating stations and this power is made available to the consumers by the supply system.
- It consists of network of conductors and associated items/equipment over which the energy is transferred from generating stations to the consumers.

A lot of people are here. The people list shows them all. View all
NOTES COMMENTS 74%

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The supply system is subdivided into two distinct parts:

1. Transmission system and
2. Distribution system.

- Transmission system may further be subdivided into:

(i) Primary transmission (765kV, 400kV, 275kV & 220kV)

and

(ii) Secondary transmission (132kV & 66kV).

- Distribution system may further be subdivided into:

(i) Primary distribution (33kV),

(ii) Secondary distribution (11kV & 6.6kV) and

(iii) Tertiary distribution (400V – Line to line, 230V – Line to neutral).

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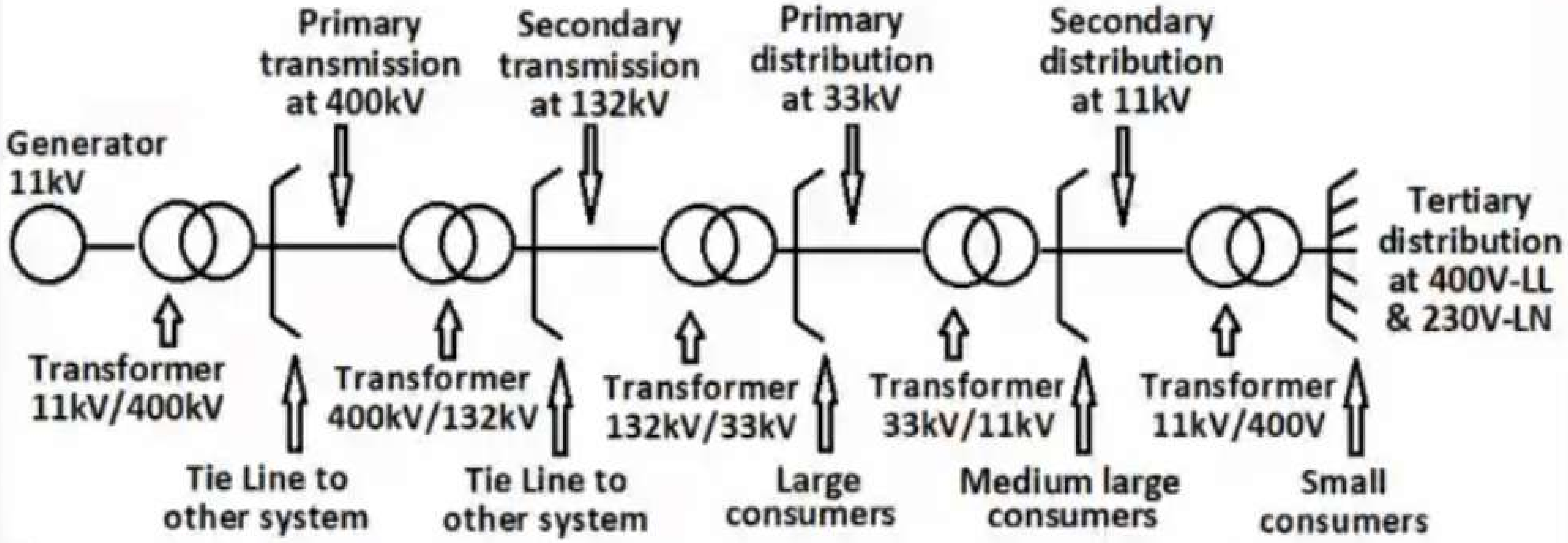


Fig. A typical supply system

SLIDE 5 OF 160 ENGLISH (INDIA)

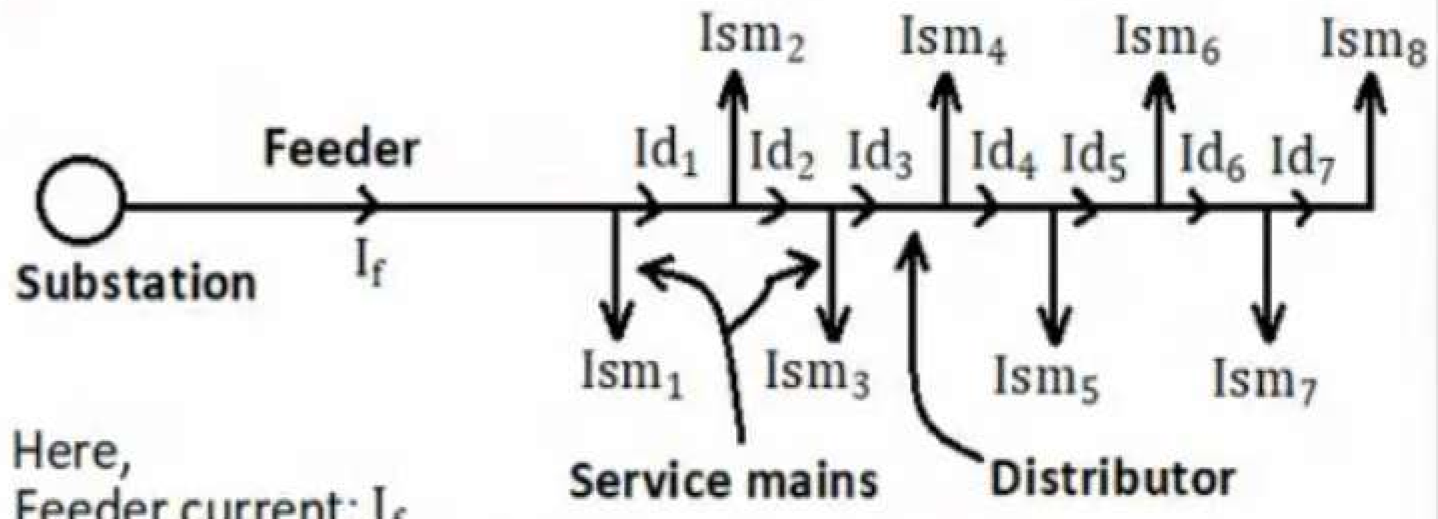
➤ Points to note:

- There are several working voltages in the same system.
- Change of voltage takes place where is a subdivision → at a place known as substation.
- Change of voltage is effected by means of a transformer.
- For equipment manufacturing reasons & for interconnections, voltages are standardized.
- Standard frequency in our country is 50Hz.

Distribution Systems (where from consumers are connected)

In general conductors in distribution system may be grouped under three distinct categories:

1. Feeder,
2. Distributor &
3. Service mains.



Here,
Feeder current: I_f
Distributor currents: $Id_1, \ldots, Id_7$
$(Id_1 > Id_2 > Id_3 \ldots\ldots > Id_7)$
Service main currents: $Ism_1, \ldots, Ism_8$

Fig. A typical distribution system.

Feeder: Connecting link between the substation and the area served by the station.

- Current loading of a feeder is same along the whole length.
- No tapping/connection is taken from the feeder along the length.

Distributor: Connecting link between the feeder & the service mains.

- It is characterised by numerous tappings in the form of service mains for connecting the consumers.
- Current loading of distributor decreases from the feeding point to the far end of it.

Service mains: Connecting link between the distributor & the terminals of the consumer.

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Copper Efficiency Comparison for Various Systems

- It is necessary to design the supply systems most economically → i.e. use of resources as much as possible.
- Accordingly, it is necessary to compare the amounts of copper necessary for various possible systems of supply.

➤ Assumptions:

(1) To supply the same power P.

(2) Distance 'l' is same for all the systems.

(3) Efficiency is same, i.e. losses are same for all the systems.

(4) Cost of insulation is same for all the systems.

- For overhead lines maximum voltage 'V' between conductor to earth is same for all the systems.

- For under ground cables maximum voltage 'V' between the conductors is same for all the systems.

Comparison for Overhead Systems

Systems under consideration:

(i) D.C. three wire,

(ii) A.C. single phase,

(iii) A.C. three phase three wire,

(iv) A.C. three phase four wire,

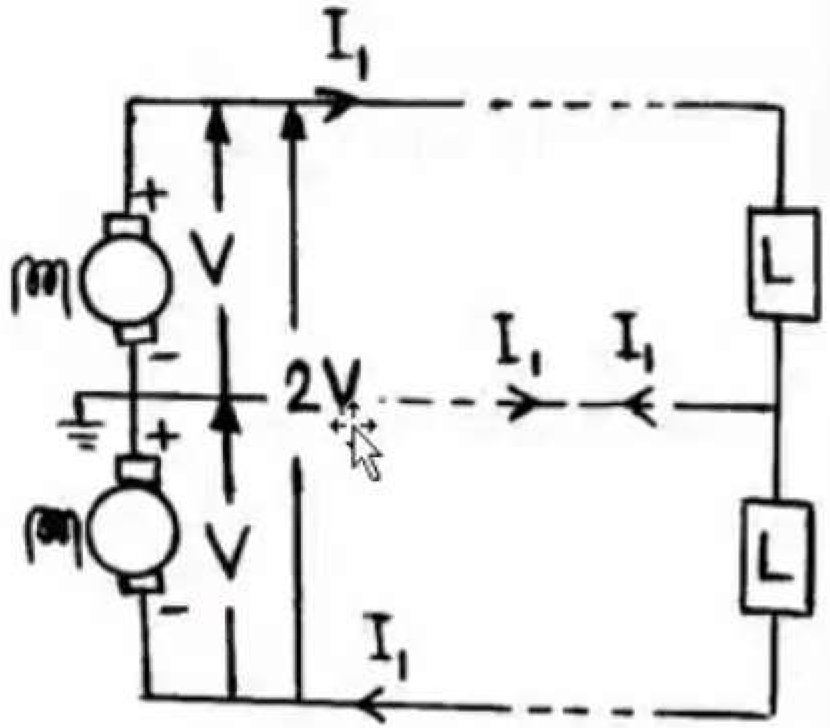
(v) D.C. two wire system.

D.C. Three Wire System

- The two outer wires are at

Potentials $\pm$V.

- The centre wire is earthed.
- Voltage between lines is 2V.



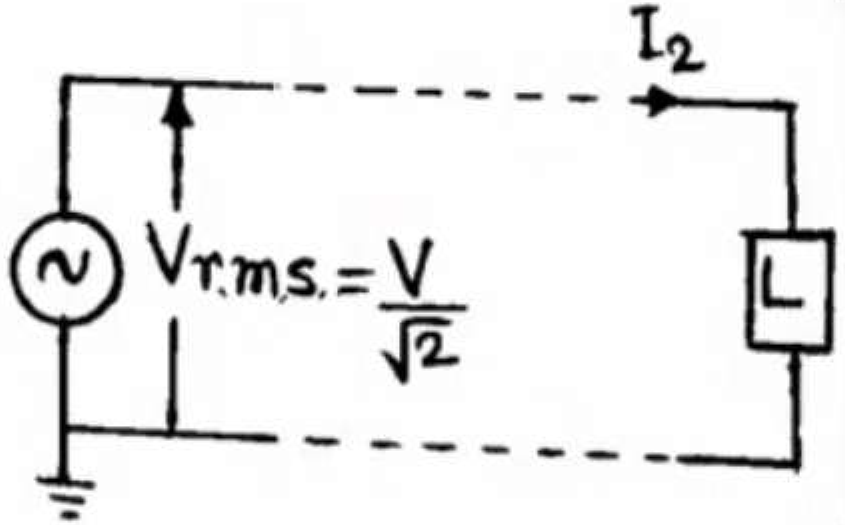
Line current $I_1 = \dfrac{P}{2V}$

Line loss $= 2I_1^2 R_1 = 2\left(\dfrac{P^2}{4V^2}\right) \cdot R_1$

$$= \frac{P^2}{2V^2} \cdot R_1 \quad ----(1)$$

where,
R_1 is the resistance per conductor.

A.C. Single Phase System



Line current $I_2 = \dfrac{P}{\frac{V}{\sqrt{2}} \cdot \cos\phi} = \dfrac{\sqrt{2}P}{V \cdot \cos\phi}$

where, $\cos\phi$ is the power factor.

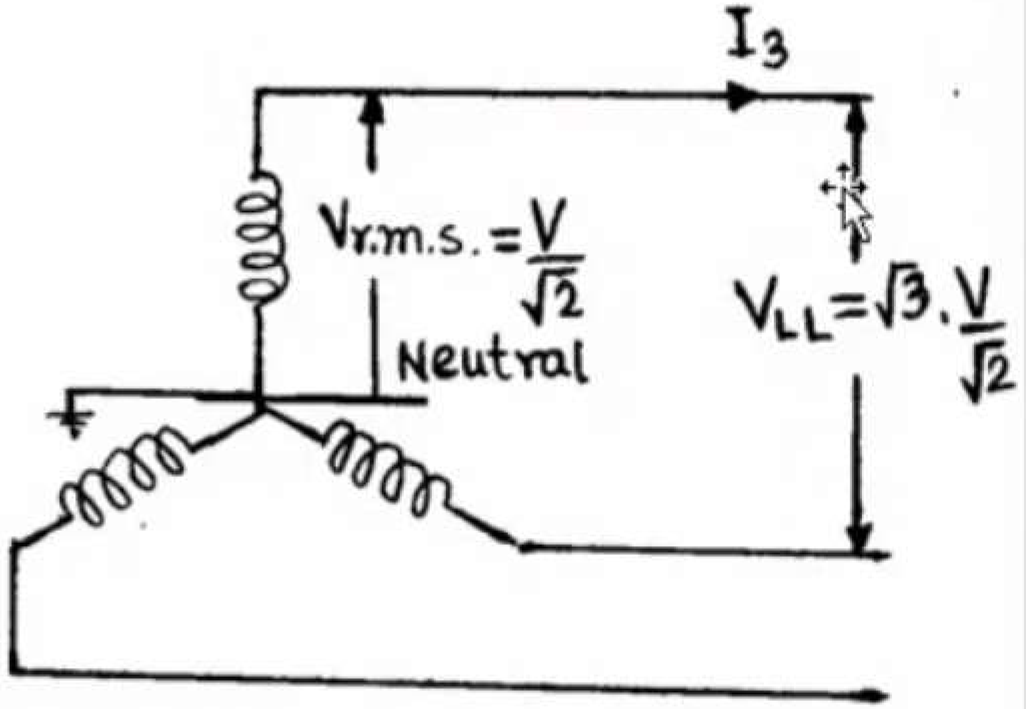
Line loss $= 2I_2^2 \cdot R_2 = 2\left(\dfrac{2P^2}{V^2 \cdot \cos^2\phi}\right) \cdot R_2$

$$= \frac{4P^2}{V^2 \cdot \cos^2\phi} \cdot R_2 \quad ----(2)$$

where,
R_2 is the resistance per conductor.

A.C. Three Phase Three Wire System

- In this case neutral is earthed but it is not provided to the consumers.
- Load is assumed to be balanced.



Line current $I_3 = \frac{P}{\sqrt{3}.V_{LL}.\cos\phi}$

$$= \frac{P}{\sqrt{3}.\sqrt{3}\frac{V}{\sqrt{2}}\cos\phi} = \frac{\sqrt{2}P}{3V\cos\phi}$$

Line loss $= 3I_3^2 R_3 = 3\left(\frac{\sqrt{2}P}{3V\cos\phi}\right)^2.R_3$

$$= \frac{2P^2}{3V^2\cos^2\phi}R_3 \text{ ----(3)}$$

where,

R_3 is the resistance per conductor.

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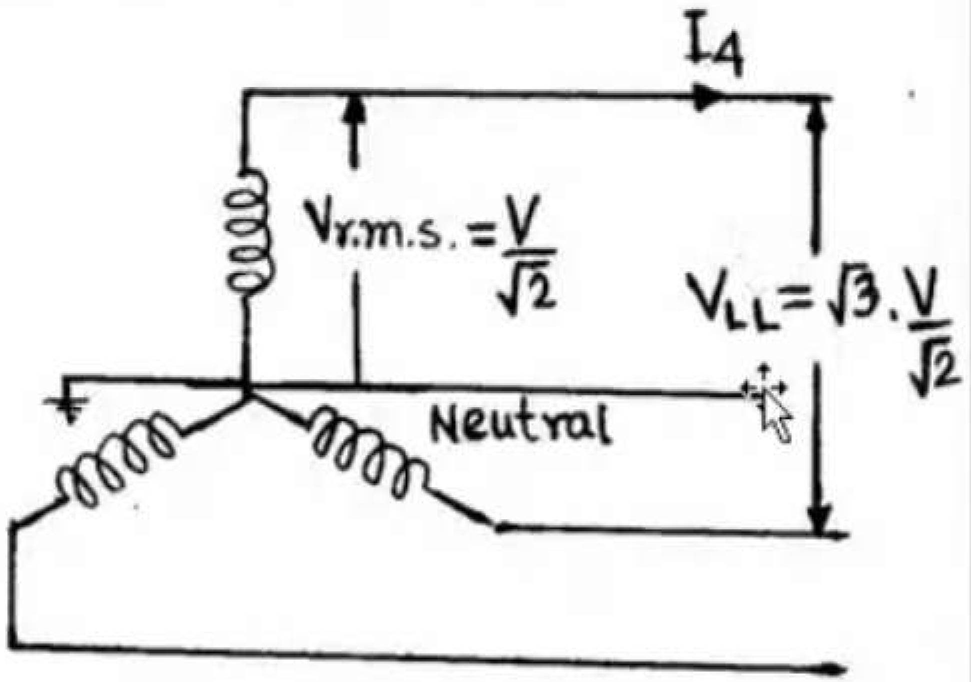
A.C. Three Phase Four Wire System

- In this case neutral is earthed and is also provided to the consumers.
- Load is assumed to be balanced→ i.e. no current flows through the neutral.
- So, loss remains same as in three phase three wire case.



$$\text{Line current } I_4 = \frac{P}{\sqrt{3}.V_{LL}.\cos\phi}$$

$$= \frac{P}{\sqrt{3}.\sqrt{3}\frac{V}{\sqrt{2}}\cos\phi} = \frac{\sqrt{2}P}{3V\cos\phi}$$

$$\text{Line loss} = 3I_4^2 R_4 = 3\left(\frac{\sqrt{2}P}{3V\cos\phi}\right)^2.R_4$$

$$= \frac{2P^2}{3V^2\cos^2\phi}R_4 \text{ ----(4)}$$

where,

R_4 is the resistance per conductor.

Prof. S. S. Thakur

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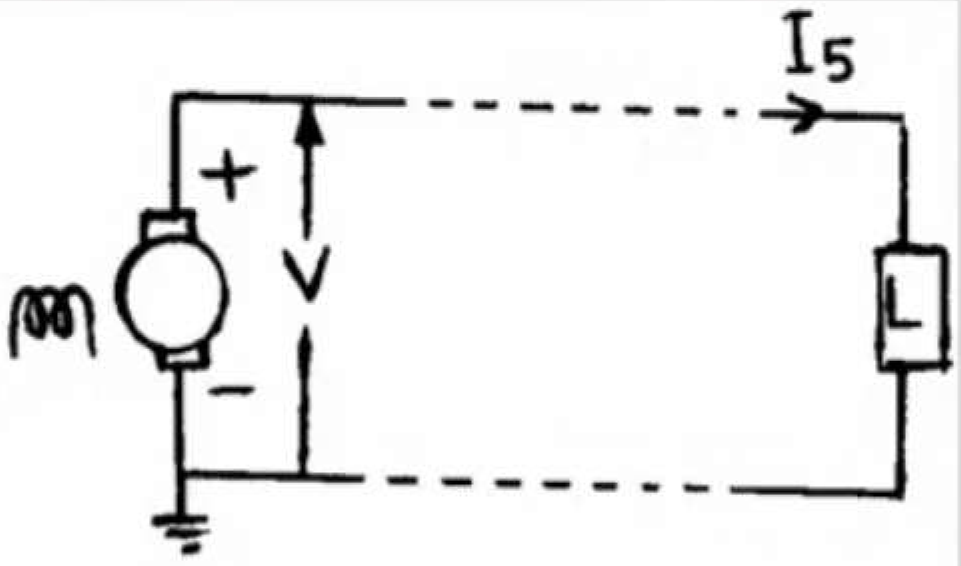
D.C. Two Wire System



Line current $I_5 = \frac{P}{V}$

Line loss $= 2I_5^2 R_5 = 2\frac{P^2}{V^2} \cdot R_5$ ----(5)

where,

R_5 is the resistance per conductor.

- Let, a_1, a_2, a_3, a_4 and a_5 be the areas of cross sections for the five cases respectively.

Again,

$R_1 = \rho \cdot \frac{l}{a_1}$; $R_2 = \rho \cdot \frac{l}{a_2}$; $R_3 = \rho \cdot \frac{l}{a_3}$; $R_4 = \rho \frac{l}{a_4}$ and $R_5 = \rho \frac{l}{a_5}$

Then,

$\frac{R_1}{R_2} = \frac{a_2}{a_1}$; $\frac{R_1}{R_3} = \frac{a_3}{a_1}$; $\frac{R_1}{R_4} = \frac{a_4}{a_1}$ and $\frac{R_1}{R_5} = \frac{a_5}{a_1}$ ----(6)

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Equating losses of the first two cases,

$$\frac{P^2}{2V^2} \cdot R_1 = \frac{4P^2}{V^2 \cos^2\phi} \cdot R_2$$

$$\text{Or, } \frac{R_1}{R_2} = \frac{8}{\cos^2\phi} = \frac{a_2}{a_1} \quad \text{----(7)}$$

Equating losses of the 1st and 3rd Cases,

$$\frac{P^2}{2V^2} \cdot R_1 = \frac{2P^2}{3V^2 \cos^2\phi} \cdot R_3$$

$$\text{Or, } \frac{R_1}{R_3} = \frac{4}{3\cos^2\phi} = \frac{a_3}{a_1} \quad \text{----(8)}$$

Equating losses of the 1st and the 4th Cases,

$$\frac{P^2}{2V^2} \cdot R_1 = \frac{2P^2}{3V^2 \cos^2\phi} \cdot R_4$$

$$\text{Or,}\quad \frac{R_1}{R_4} = \frac{4}{3\cos^2\phi} = \frac{a_4}{a_1} \text{ - - - -(9)}$$

Equating losses of the 1st and the 5th Cases,

$$\frac{P^2}{2V^2} \cdot R_1 = 2\frac{P^2}{V^2} \cdot R_5$$

$$\text{Or,}\quad \frac{R_1}{R_5} = 4 = \frac{a_5}{a_1} \text{ - - - -(10)}$$

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Therefore,

$$v_1 : v_2 : v_3 : v_4 : v_5 = 2a_1 l : 2a_2 l : 3a_3 l : 4a_4 l : 2a_5 l$$

$$= 1 : \frac{2a_2 l}{2a_1 l} : \frac{3a_3 l}{2a_1 l} : \frac{4a_4 l}{2a_1 l} : \frac{2a_5 l}{2a_1 l}$$

$$= 1 : \frac{a_2}{a_1} : \frac{3}{2}\frac{a_3}{a_1} : 2\frac{a_4}{a_1} : \frac{a_5}{a_1}$$

$$= 1 : \frac{8}{\cos^2\phi} : \frac{3}{2}\cdot\frac{4}{3\cos^2\phi} : 2\cdot\frac{4}{3\cos^2\phi} : 4$$

$$= 1 : \frac{8}{\cos^2\phi} : \frac{2}{\cos^2\phi} : \frac{8}{3\cos^2\phi} : 4 \qquad ----(11)$$

1st 5th 2nd 3rd 4th

In the above v_1, v_2, v_3, v_4 and v_5 are volumes of conductors in the five cases.

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So, according to copper efficiency,

1. D.C. three wire system,
2. A.C. three phase three wire system,
3. A.C. three phase four wire system,
4. D.C. two wire system and
5. A.C. single phase two wire system.

Problem: A 1Φ load of 10MW is transmitted by a pair of overhead conductors. If a third conductor of same cross section be added and a 3Φ supply be thus substituted for the original single phase supply, calculate the 3Φ load which can now be transmitted if voltage between conductors and the percentage loss in the systems remain unchanged.

Soln.: Let, 1Φ power be P_1 = 10MW and the same for 3Φ system be P_2 MW. Further, assume,

V= voltage between conductors for both the 1Φ & 3Φ system.

I_1= Current in 1Φ system,

I_2= Current in 3Φ system,

$\cos\varphi$ = p.f. for both 1φ & 3φ systems &

R= resistance per conductor.

$$\therefore I_1 = \frac{P_1}{V\cos\phi}$$

$$\text{Loss in } 1\phi \text{ system} = 2I_1^2R = 2.\left(\frac{P_1}{V\cos\phi}\right)^2.R$$

$$= \frac{2P_1^2}{V^2\cos^2\phi}R$$

$$\text{Similarly, } I_2 = \frac{P_2}{\sqrt{3}\,V\cos\phi}$$

$$\text{Loss in } 3\phi \text{ System} = 3I_2^2R = 3.\left(\frac{P_2}{\sqrt{3}\,V\cos\phi}\right)^2R$$

$$= \frac{P_2^2}{V^2\cos^2\phi}R$$

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Equating % losses of the two systems,

$$\frac{\frac{2P_1^2}{V^2\cos^2\phi}\cdot R}{V.I_1\cos\phi} = \frac{\frac{P_2^2}{V^2\cos^2\phi}\cdot R}{\sqrt{3}V\, I_2\cos\phi}$$

$$\text{or, } P_2^2 = 2\sqrt{3}P_1^2\cdot\frac{I_2}{I_1} = 2\sqrt{3}P_1^2\cdot\frac{\frac{P_2}{\sqrt{3}V\cos\phi}}{\frac{P_1}{V\cos\phi}}$$

$$= 2\sqrt{3}\,P_1^2\cdot\frac{P_2}{\sqrt{3}P_1}$$

$$= 2P_1P_2$$

$$\text{or, } P_2 = 2P_1 = 2\times 10\text{MW}$$

$$= 20\text{MW}$$

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Choice of Voltage of Transmission

- In both a.c. & d.c. systems, power is proportional to product of voltage & current.
- So, to transmit a certain amount of power as system voltage increases, current reduces.

→ This, in turn allows to reduce conductor cross sectional area,

→ i.e. amount of conductor material requirement reduces for a specified voltage drop & line loss.

Further, for any existing system as the operating voltage increases → regulation & efficiency improves.

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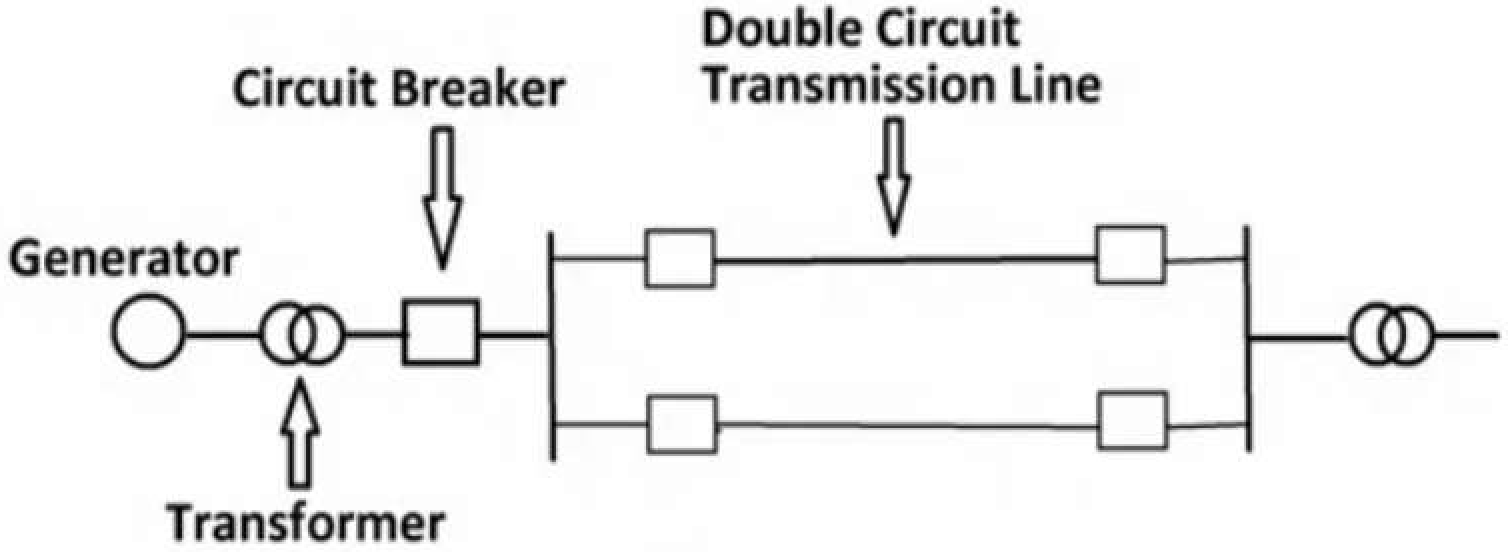
- But, a part of saving thus achieved is offset by the additional cost involved in the increased insulation level of the system.
- Also, there are some technical difficulties in designing insulation.
- With increased voltage level, spacing of conductors, ground clearance & charging current increase.

For the purpose of analysis consider a typical system:



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- Cost of transmission line includes the following costs:

(i) Transformer,

(ii) Switchgear,

(iii) Costs of insulators & line supports,

(iv) Cost of conductor,

(v) Costs of relays & protection systems and

(vi) Sundry costs.

Costs of transformer & switchgear: May be represented as Rs.(A+BV)P, where A & B are constants and V & P being the system voltage & power respectively.

Costs of insulators & line supports: May be represented as Rs.(C+DV)L, where C & D are constants & L is length of the line.

Cost of conductor: A fixed current density (∂) is assumed.

$$\text{Now, } \partial \propto \frac{P}{V.a}$$

where, a is cross section of the conductor.

$$\text{So, } a \propto \frac{P}{\partial . V}$$

For a fixed current density, $a \propto \frac{P}{V}$

So, cost of conductor $\propto$ Volume of conductor (a.L).

Thus, cost of conductor = Rs. E. $\frac{PL}{V}$, E being a constant.

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Costs of relays & protection systems and sundry costs: These are represented by a constant component of Rs. F.

So, total cost of the transmission line is

$$S = Rs.\left[(A+BV)P + (C+DV)L + E.\frac{PL}{V} + F\right]$$

To find out the voltage for minimum cost set $\dfrac{dS}{dV} = 0.$

i.e. $\dfrac{d}{dV}\left[(A+BV)P + (C+DV)L + E.\dfrac{PL}{V} + F\right] = 0.$

Or, $BP + DL - E\dfrac{PL}{V^2} = 0$

Or, $E\dfrac{PL}{V^2} = BP + DL$

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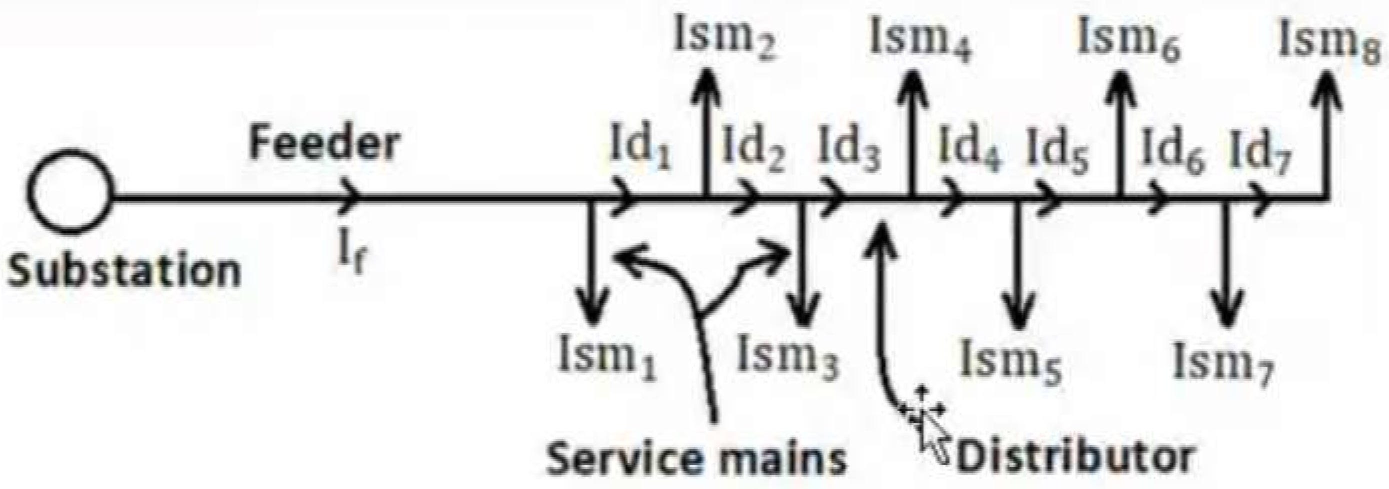
Or, $V = \sqrt{\frac{EPL}{(BP+DL)}}$

While selecting the voltage, the following factors are to be considered:

1. The standard voltages,
2. Mechanical strength of the conductor,
3. Corona loss,
4. Voltage regulation &
5. Future growth.

Kelvin's Law



- Voltage drop is an important factor for distributor → since supply voltage to consumer must remain within ±5% for LV distribution & $\pm 12\frac{1}{2}\%$ for HV.
- Connections in the form of service mains are taken from the distributor,
- So, a distributor has variable loading.
- Consumers situated near the feeding point enjoy better voltage compared to those situated at the far end.
- So, the distributor is designed on the basis of voltage drop.

On the contrary,

- Current loading of feeder is constant throughout whole length.
- So, feeder is designed on the basis of current carrying capacity & wherever practicable following maximum financial economy as stated in Kelvin's Law.

Statement of Kelvin's law

The most economical cross section of conductor is that which makes annual value of interest & depreciation on the conductor equal to annual cost of energy wasted in conductor resistance.

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➢ Proof

- Cost of conductor ∞ Volume Conductor (a.l)

  ∞ Cross 'a' → for a given length 'l'

- Annual cost of interest & depreciation ∞ Cost of conductor

  ∞ Cross section 'a'

So, annual cost of interest & depreciation = Rs. P.a .....(1)

where, P is a constant.

Now, resistance of conductor $R = \rho \dfrac{l}{a}$, ρ = specific resistance.

So, a given length, $R ∞ \dfrac{1}{a}$

Annual energy loss ∞ $R ∞ \dfrac{1}{a}$

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Annual cost of energy loss = Rs. $\frac{Q}{a}$ ….. (2)

where Q is a constant.

Therefore, total annual cost 'S' = Rs.(Pa + $\frac{Q}{a}$) …..(3)

To find out cross sectional area for minimum cost set $\frac{ds}{da} = 0$

$$\text{Or, } \frac{ds}{da} = P - \frac{Q}{a^2} = 0$$

$$\text{Or, } Pa = \frac{Q}{a} \quad \text{….(4)}$$

Thus, for minimum total annual cost → cost of interest & depreciation = cost of energy loss → This is Kelvin's law.

Or, the most economic cross section $a = \sqrt{\frac{Q}{P}}$ …..(5)

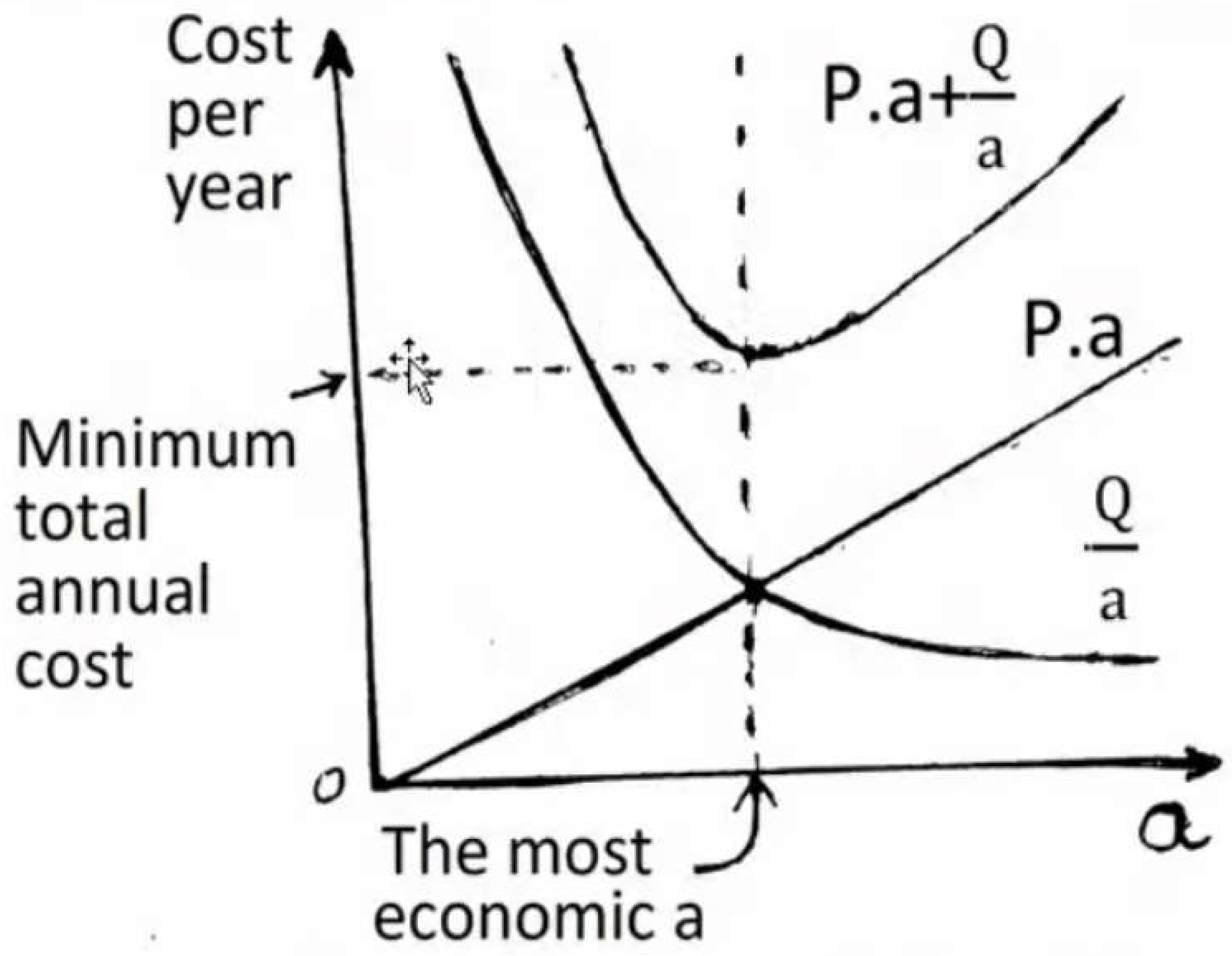

Fig. Illustration of Kelvin's law

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Kelvin's law considering cost of insulation

- If cost of insulation is considered → as for u.g. cables, then
- It is independent of cross section 'a' &
- Insulation (i.e. cost of it) depends mainly on voltage.

Then, annual cost of interest & depreciation = Rs. (P.a + T).....(6)
where T is a constant.

Therefore, total annual cost 'S' = $Rs.(Pa + T + \frac{Q}{a})$ .....(7)

$$\frac{ds}{da} = \frac{d}{da}(Pa + T + \frac{Q}{a}) = 0 \rightarrow P - \frac{Q}{a^2} = 0$$

Or, $Pa = \frac{Q}{a}$ .....(8)

Or, the most economic cross section $a = \sqrt{\frac{Q}{P}}$ .....(9)

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So, cost of insulation has no influence on the most economic cross section.

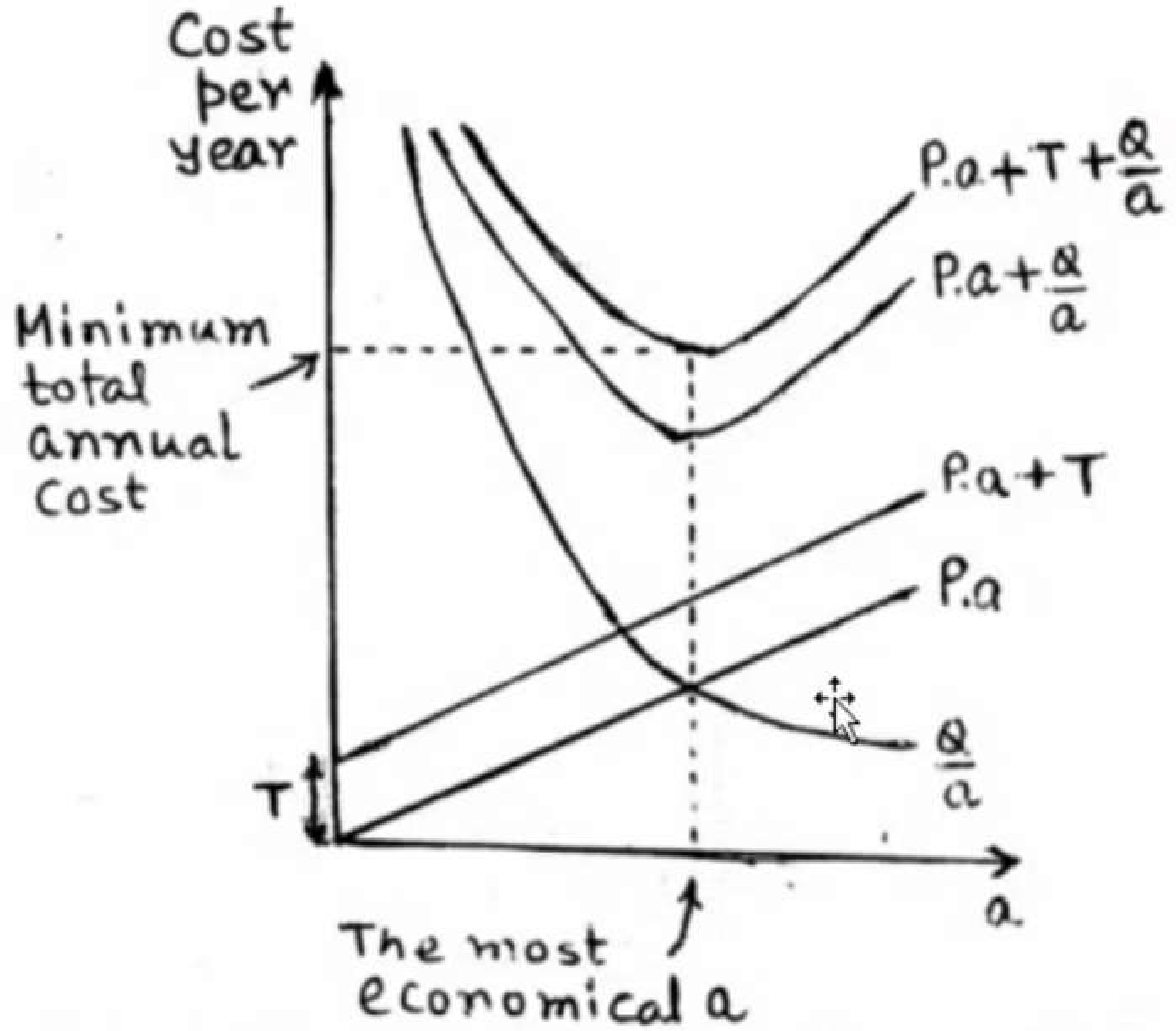

Fig. Illustration of Kelvin's law considering insulation cost

Prob. 20 (PS, pp 233): Determine the most economical cross section for a 3Φ line, 6km long to supply at a constant voltage of 30kV, following the daily load cycle: 10hr. at 3MW, 0.8p.f. ; 6hr. at 1.5MW, 0.9p.f. ; 8hr. at 0.5MW, 0.9p.f. The line is in use 365 days yearly. The cost per km of line, completely erected = £(1500 + 1200a), where a = cross section in cm^2 of each conductor. Interest = 8% of capital cost. Energy costs = 1.4d per kWh. The resistance per km of conductor of cross section a is $\frac{0.185}{a}\ \Omega$.

Daily energy loss

$$= 3\left[\left(\frac{3.10^6}{\sqrt{3}.30.10^3.0{\cdot}8}\right)^2.10+\left(\frac{1{\cdot}5.10^6}{\sqrt{3}.30.10^3.0{\cdot}9}\right)^2.6+\left(\frac{0{\cdot}5.10^6}{\sqrt{3}.30.10^3.0{\cdot}9}\right)^2.8\right].R$$

$$= 177512{\cdot}033R$$

R = Resistance per conductor for 6km $= \frac{0{\cdot}185}{a}.6$

Energy loss per year $= 365.177512{\cdot}033.\frac{0{\cdot}185}{a}.6$

$$= \frac{71918987{\cdot}90}{a} \text{ Watt-hour}$$

$$= \frac{71918{\cdot}98790}{a} \text{ kWh}$$

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Cost of annual energy loss

$$= \frac{1.4}{240} \cdot \frac{71918.98790}{a}$$

[Note: 12 Pence = 1 shilling
20 shilling = 1 Pound]

Cost of interest $= \frac{8}{100} \cdot (1200a \cdot 6)$

According to Kelvin's law:

$$\frac{8}{100} \cdot (1200a \cdot 6) = \frac{1.4}{240} \cdot \frac{71918.98790}{a}$$

$$\text{or, } a = 0.8534 \text{ cm}^2$$

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Limitations of Kelvin's law

1. It is difficult to calculate the energy loss correctly as the load varies continuously.
2. This law is artificial and has no relation to the physical aspects like temperature rise, voltage drop etc.
3. The size of conductor obtained from Kelvin's law might be too small so as to have adequate mechanical strength.

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Distribution Systems Calculations

- Voltage drop is an important factor for distributor.
- Supply voltage to consumer must remain within ±5% for LV distribution & $\pm 12\frac{1}{2}\%$ for HV.
- Consumers situated near the feeding point enjoy better voltage compared to those situated near the far end.
- So, it is necessary to calculate the voltage at the consumer's terminals.
- Accordingly, distribution systems calculations are important.

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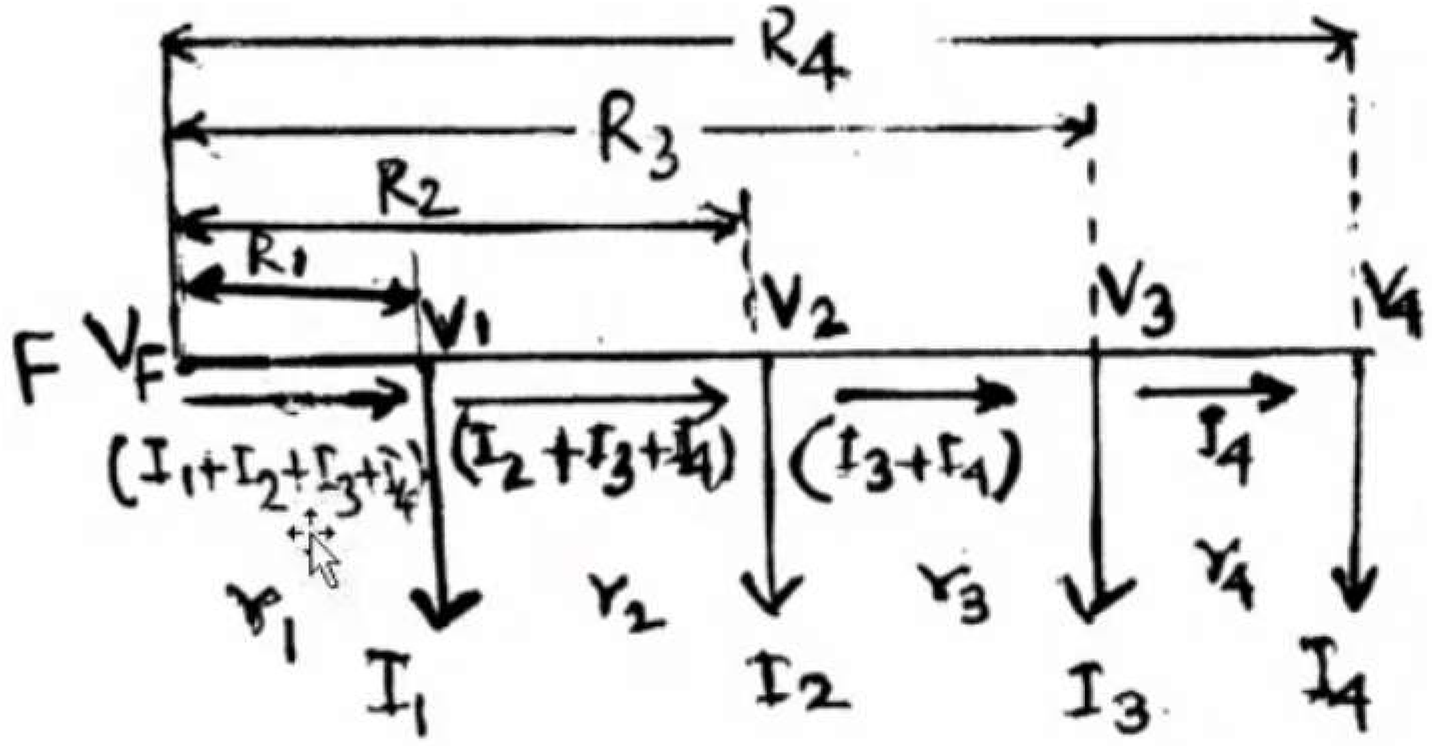
D.C. Radial Distributor Fed at One End (for concentrated loads)

- Consider the distributor with four load currents I_1, I_2, I_3 & I_4.
- Voltages of the four load points be V_1, V_2, V_3 & V_4.
- Resistance of each conductor of sections be r_1, r_2, r_3 & r_4.
- Feeding point be F & voltage at feeding point voltage be V_F.



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Total voltage drop $= 2.(I_1+I_2+I_3+I_4).\, r_1 + 2.(I_2+I_3+I_4).\, r_2 + 2.(I_3+I_4).\, r_3 + 2.(I_4).\, r_4$

$= 2.\, I_1.\, r_1 + 2.\, I_2.\, (r_1+r_2) + 2.\, I_3.\, (r_1+r_2+r_3) + 2.\, I_4.\, (r_1+r_2+r_3+r_4)$

$= 2.\, I_1.\, R_1 + 2.\, I_2.\, R_2 + 2.\, I_3.\, R_3 + 2.\, I_4.\, R_4$

$= 2.\sum I.\, R$

In the above, '2' comes for go & return.

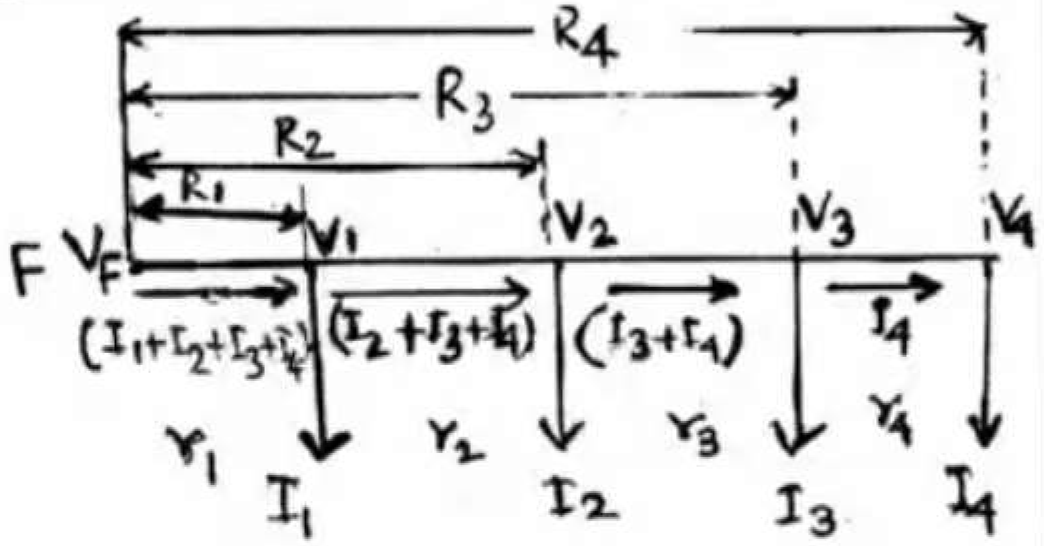
So,

$V_1 = V_F - 2.(I_1+I_2+I_3+I_4).\, r_1$

$V_2 = V_1 - 2.(I_2+I_3+I_4).\, r_2$

$V_3 = V_2 - 2.(I_3+I_4).\, r_3$

$V_4 = V_3 - 2.(I_4).\, r_4$



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D.C. Radial Distributor Fed at Both Ends

(For concentrated loads)

- For long distributors carrying heavy loads voltage drop may be considerably high → may result voltages of the consumers at far end beyond tolerable limits.
- Under such situation distributors are fed at both ends.
- Then, point of minimum potential occurs at some point where currents meet from both ends.
- Voltage drop up to point of minimum potential is much less compared to the distributor fed at one end only.

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Forward 5 sec - [00:10:00 / 25%]
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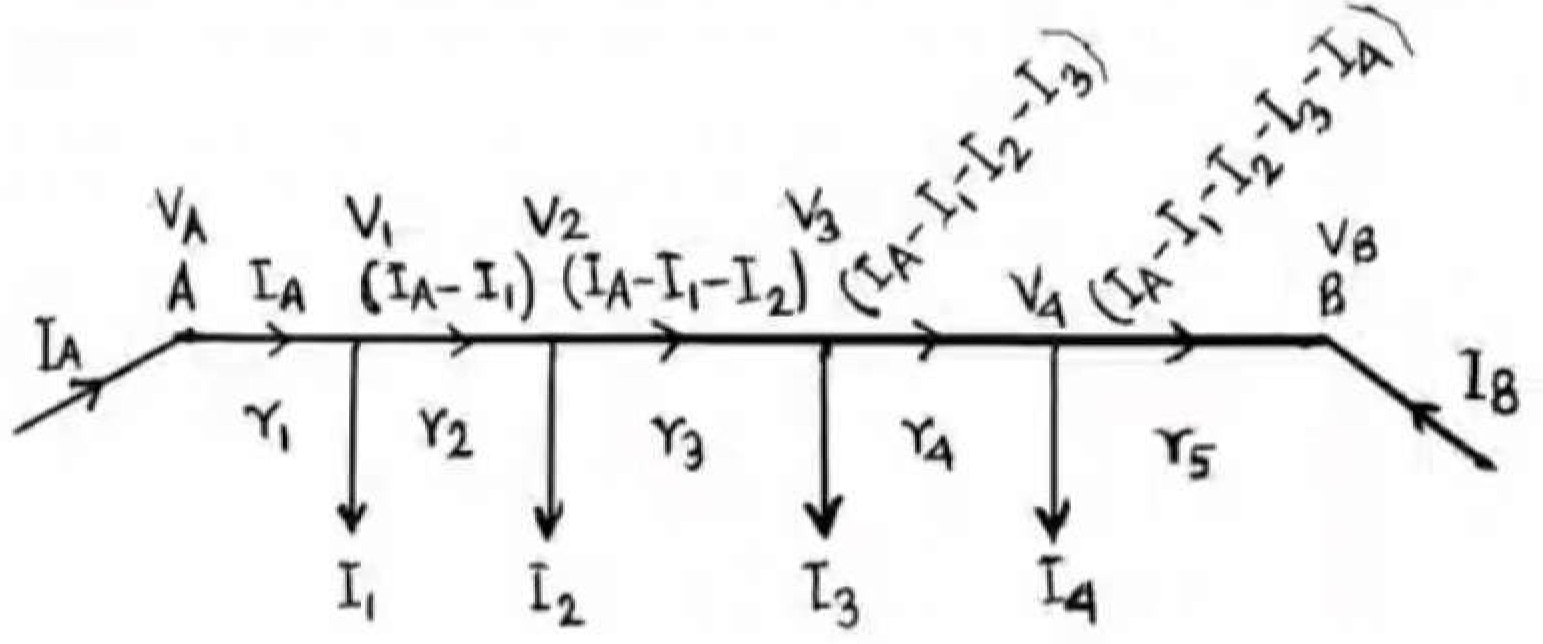
- Consider the distributor with four load currents I_1, I_2, I_3 & I_4.
- Voltages of the four load points be V_1, V_2, V_3 & V_4.
- Resistance of each conductor of sections be r_1, r_2, r_3, r_4 & r_5.
- Two feeding points (A & B) voltages be V_A & V_B.
- I_A & I_B be the currents fed from the two ends.



SLIDE 43 OF 160 ENGLISH (INDIA)

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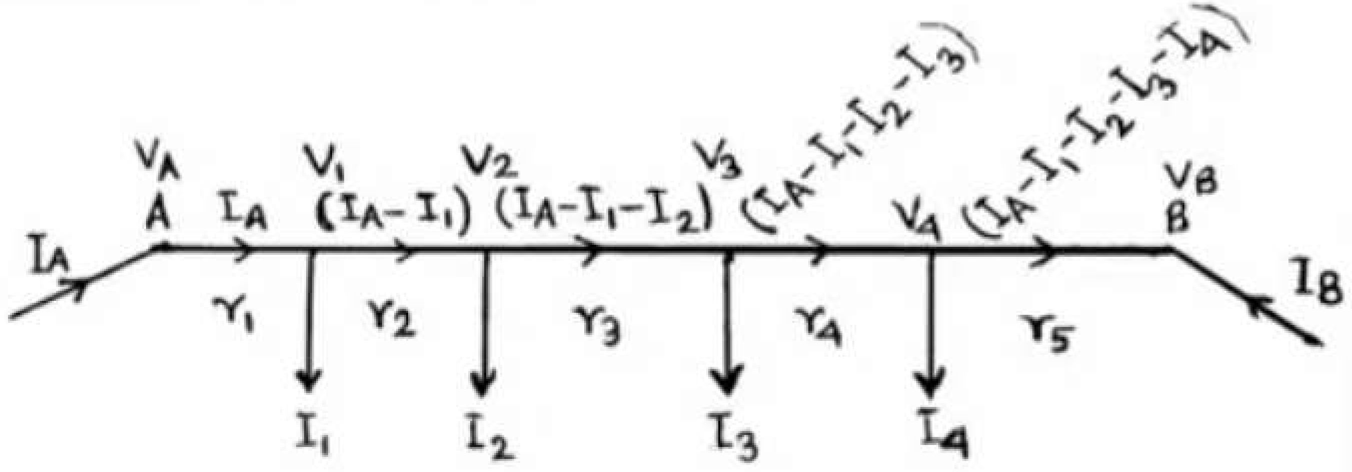
Using Kirchhoff's current law, $I_A + I_B = I_1 + I_2 + I_3 + I_4$ ....(1)

Voltage drop from A to B,

$$V_A - V_B = 2.\, I_A.\, r_1 + 2.(I_A - I_1)\, r_2 + 2.(I_A - I_1 - I_2).\, r_3$$
$$+ 2.(I_A - I_1 - I_2 - I_3).\, r_4 + 2.(I_A - I_1 - I_2 - I_3 - I_4).\, r_5 \text{ ....(2)}$$

In eqn. (2) known values are –

- Two feeding point voltages V_A & V_B.
- Load currents I_1, I_2, I_3 & I_4.
- Sectional resistances r_1, r_2, r_3, r_4 & r_5.



SLIDE 44 OF 160 ENGLISH (INDIA)

So, I_A can be calculated.

- Then I_B can be calculated from eqn. (1).

Once I_A is known, one may find –

- Currents in all the sections.
- Voltage at any loading point.

$V_1 = V_A - 2.I_A.r_1$

$V_2 = V_1 - 2.(I_A - I_1).r_2$

$V_3 = V_2 - 2.(I_A - I_1 - I_2).r_3$

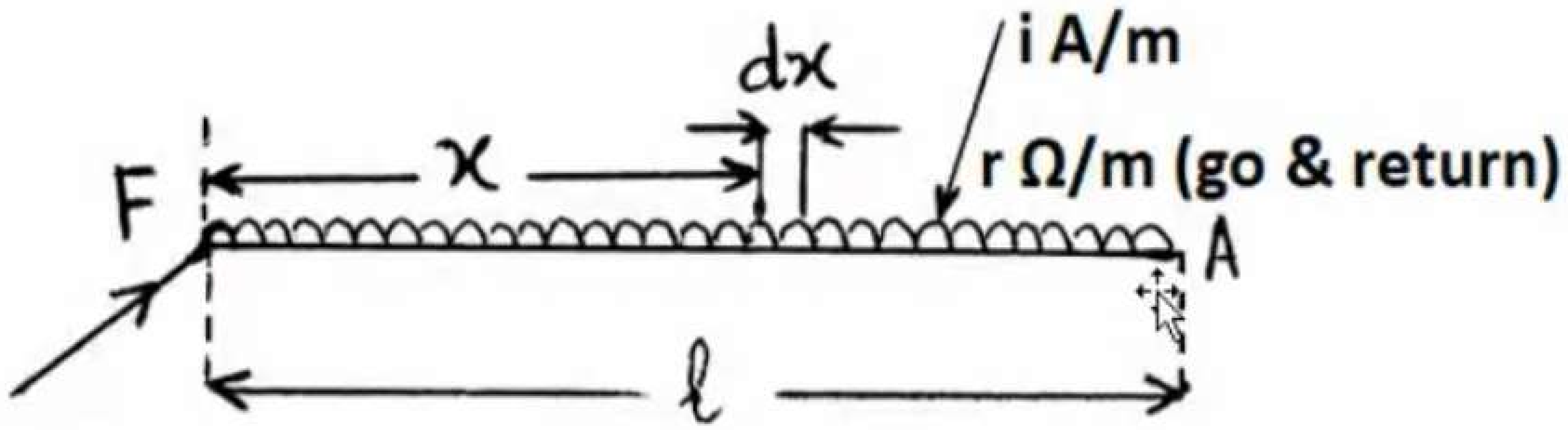
$V_4 = V_3 - 2.(I_A - I_1 - I_2 - I_3).r_4$

❖ The point of minimum potential is that load point where currents meet from the two sides.

Forward 5 sec - [00:19:30 / 49%]

Uniformly Loaded Distributor Fed At One End

- When the distributor supplies similar houses or establishments on a long street &
- When approximately equal loads are tapped off at regular & brief intervals.
- Then, loads can be considered to be uniformly distributed.
- Let, the uniformly loaded distributor be fed at one end only.



- Here, current loading is i A/m & r= Ω/m (go & return).

Forward 5 sec -[00:24:10 / 61%]

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Current through the small section dx = $(l.\,i - x.\,i) = (l - x).\,i$ Amp

In small section dx voltage drop $dv = (l - x).i.(r.dx) = (l - x).i.r.dx$

So, total voltage drop from the feeding point F to far end A

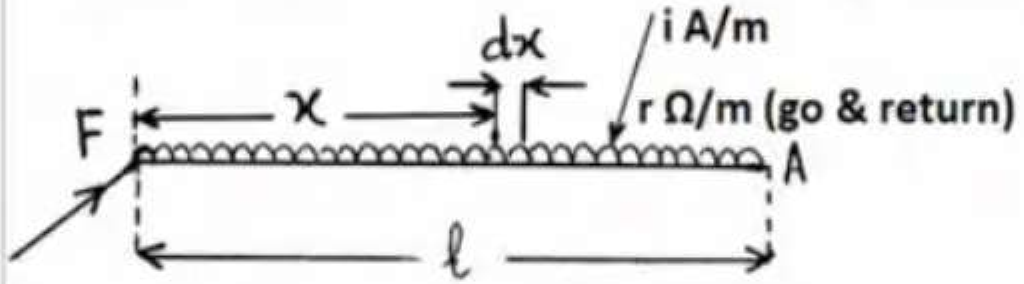
$$\int_0^l dv = \int_0^l (l - x).i.r.dx = \int_0^l l.i.r.dx - \int_0^l i.r.x.dx$$

$$= l^2.i.r - i.r.\left[\frac{x^2}{2}\right]_0^l = \frac{1}{2}\, l^2.i.r = \frac{1}{2}\,(l.\,i).\,(l.\,r) = \frac{1}{2}\, I.\,R \text{ Volt}$$

where, $I = (l.\,i)$ = total consumption in the distributor &

$R = (l.\,r)$ = total go & return resistance of the distributor.

Up to any distance 'x' voltage drop is given by



$$v_x = \left(l.\,i.\,r.\,x - i.\,r.\,\frac{x^2}{2}\right) \text{ Volt}$$

Backward 5 sec - [00:26:50 / 68%]

Uniformly Loaded Distributor Fed At Both Ends

- For long uniformly distributors (fed at one end) voltage drop may be considerably high → resulting voltage of consumers at far end beyond the tolerable limits.
- Under such situation Uniformly loaded distributors are fed at both ends.
- Then, point of minimum potential occurs at some point where currents meet from both the ends.
- Voltage drop up to point of minimum potential is much less compared to the case when distributor fed at one end only.

Forward 5 sec - [00:28:20 / 71%]

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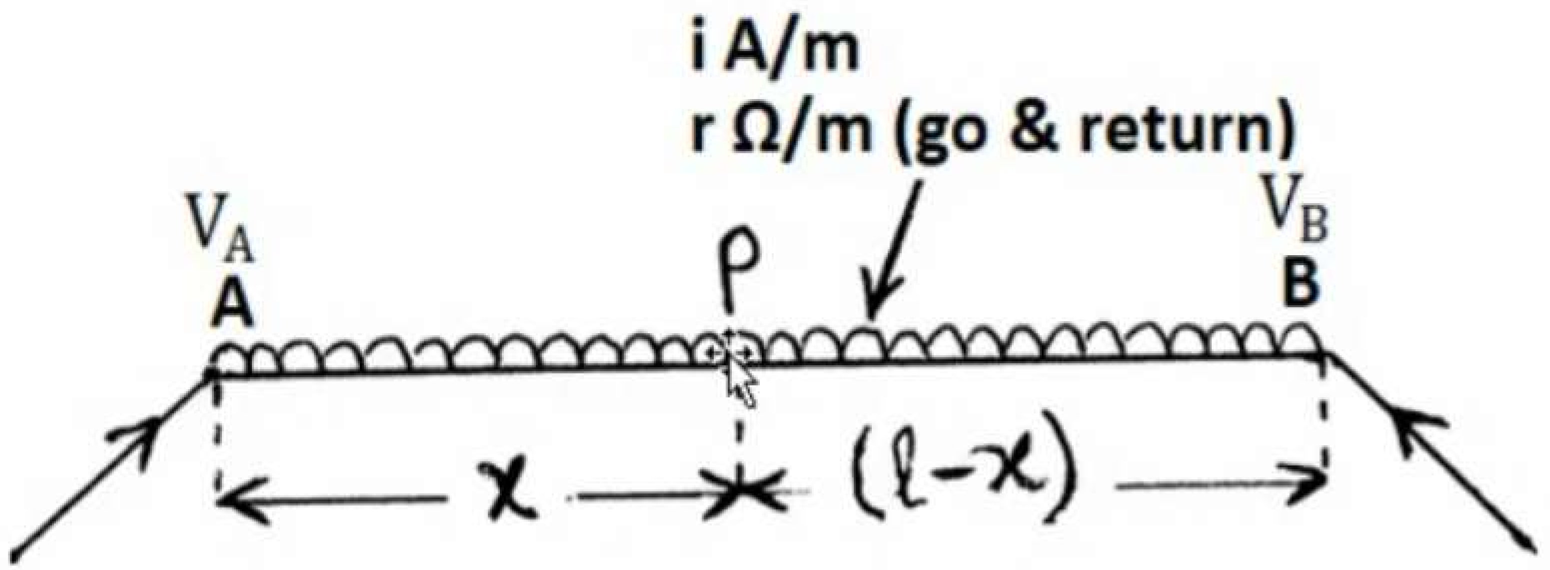

- Consider, P be the point of min. potential in the system situated at a distance x from end A.
- So, current fed from end A is just enough to meet the load from A to P.
- Likewise, current fed from end B is just enough to meet the load from B to P.

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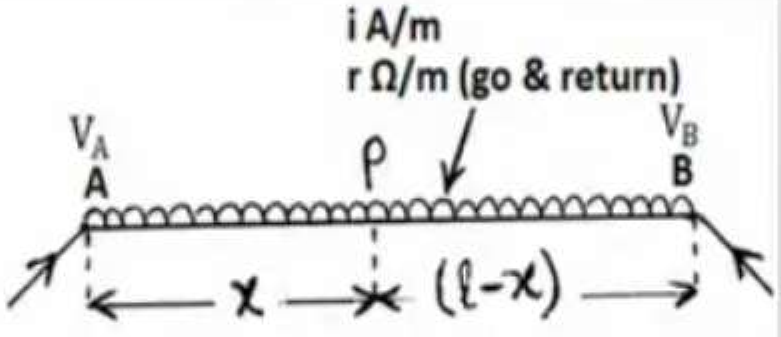
Voltage drop from A to P = $v_1 = \dot{i}\, r \frac{x^2}{2}$

Voltage drop from B to P = $v_2 = \dot{i}\, r \frac{(l-x)^2}{2}$



Voltage drop from A to B $= V_A - V_B = v_1 - v_2 = v$ (say)

So, $v = \dot{i}\, r \frac{x^2}{2} - \dot{i}\, r \frac{(l-x)^2}{2} = \frac{\dot{i}\, r}{2}\left[x^2 - (l-x)^2\right]$

$$= -\frac{\dot{i}\, r}{2} \cdot l^2 + \dot{i}\, r l x$$

Therefore, point of minimum potential

$$x = \left[\frac{l}{2} + \frac{v}{\dot{i}\, r l}\right]$$

Knowing x, voltage drop upto P may be calculated.

If $V_A = V_B$, $v = 0$ and $x = \frac{l}{2}$, i.e. at the mid point.

Forward 5 sec -[00:34:19 / 87%]
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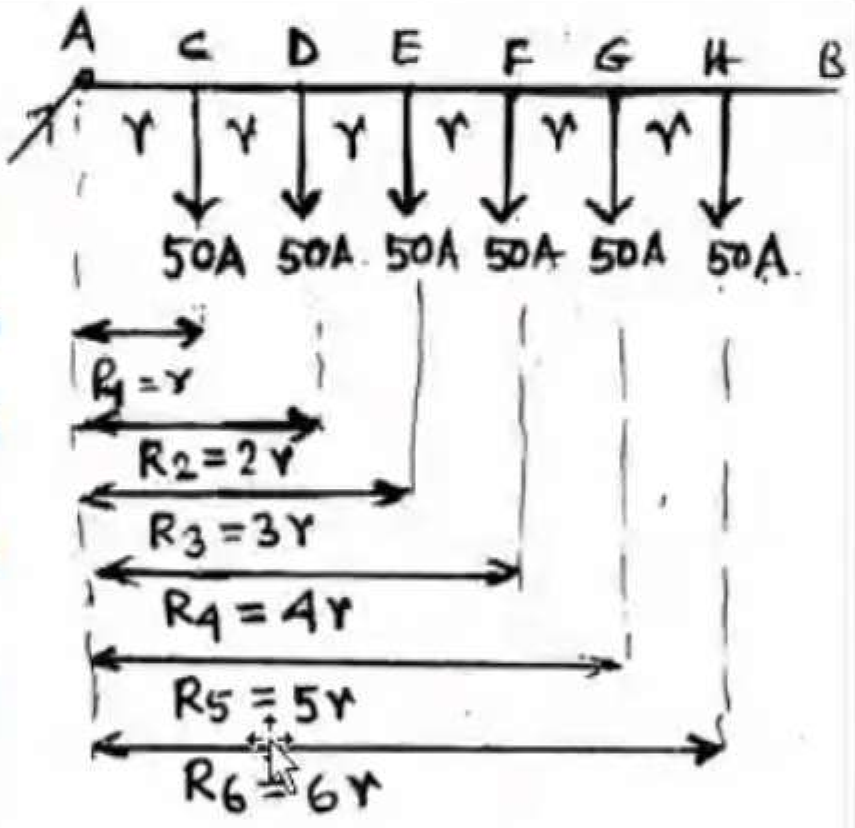
Problem: A 2-wire distributor AB is fed at A & supplies six concentrated loads, each of 50A at C, D, E, F, G & H, as shown in the fig. What must be the resistance of each section so that the max. voltage drop for any consumer does not exceed 7V? Also calculate the power loss with this resistance. Assume, AC=CD=DE=EF=FG=GH=HB.



Soln: Since all the segments are of equal length, consider resistance of each segment is r (go & return). So, the resistance from the feeding point to different loads are as shown.

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$\therefore$ Total voltage drop from A to B

$= $ voltage drop from A to H

$$= \sum I.R = 50[r + 2r + 3r + 4r + 5r + 6r] = 50.21r$$

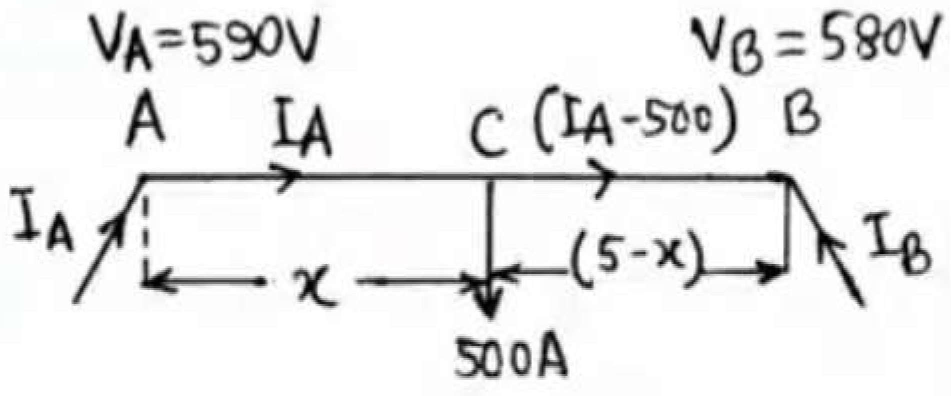
By the problem, $50.21r = 7$

$$\text{or, } r = \frac{7}{50.21} = \frac{1}{150}\,\Omega$$

$$\text{Total power loss} = r.(300)^2 + r(250)^2 + r(200)^2 + r(150)^2 + r(100)^2 + r(50)^2$$

$$= r.\,227500 = \frac{1}{150}.\,227500 = 1516.6\dot{6}\,W$$

Problem: An electric train moving in a section of line between two substations, takes a current of 500A. The substations are 5km apart & are maintained at 590V and 580V respectively. The track resistance is 0.06Ω/km go and return. Show graphically the variation of current received from either substation & find the point of min. potential along the track. Also, calculate current taken from each substation at the point of min. potential.



Soln: Let, the train is at some point 'C', at a distance of 'x' km from the feeding point 'A.' Then,

potential at 'C' = $590 - I_A.(x.0.06) = 580 + (I_A - 500).(5 - x).0.06$

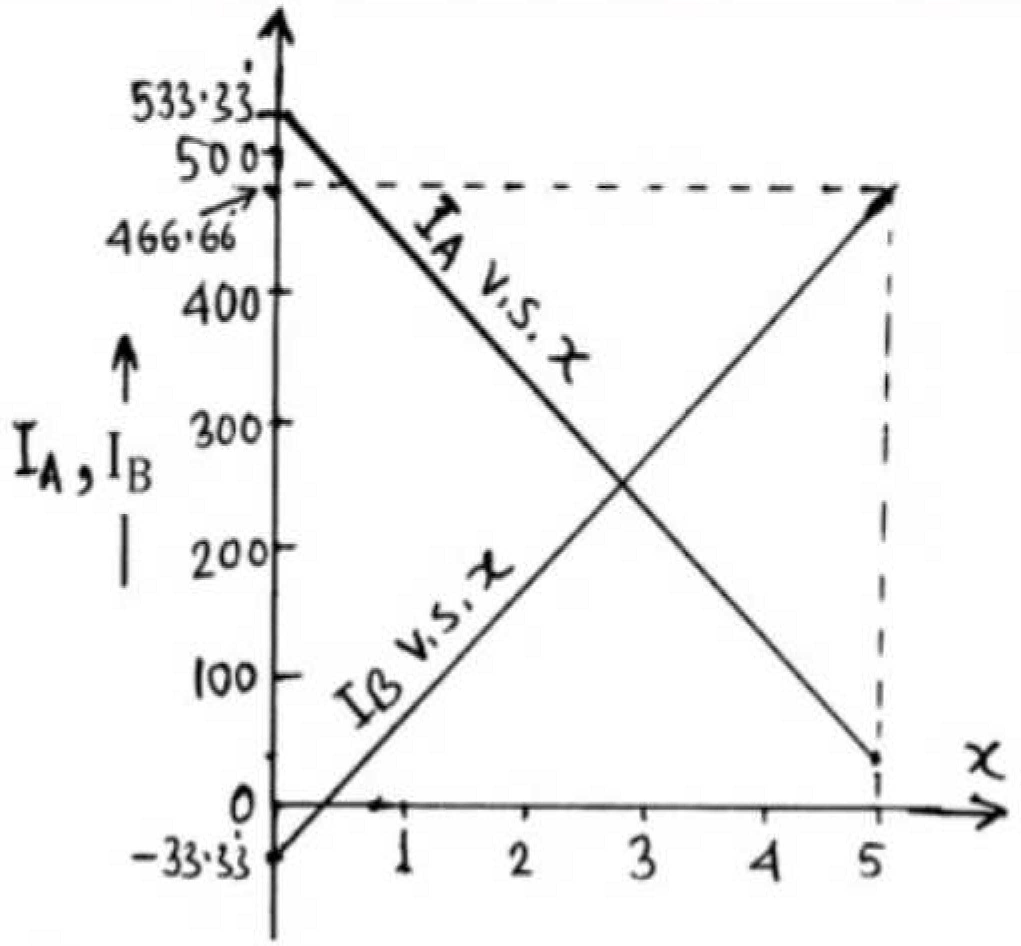
Simplifying,

$$I_A = 533.3\dot{3} - 100x \text{ ---- } (1)$$

Current supplied by substation B,

$$I_B = -(I_A - 500)$$

$$= -33.3\dot{3} + 100x \text{ --- } (2)$$



So, potential at C $= 590 - I_A.(x.0.06)$

$$= 590 - (533.3\dot{3} - 100x)(x.0.06)$$

$$= 590 - 31.9\dot{9}x + 6x^2 \text{ ---- } (3)$$

$$= V_C \text{ (Say)}$$

For point of minimum potential,

$$\frac{dV_c}{dx} = -31.9\dot{9} + 12x = 0$$

$$\text{or, } x = 2.66\text{ km (from A)}$$

At point of min. potential $V_C = 590 - 31.9\dot{9} \cdot 2.6\dot{6} + 6 \cdot (2.6\dot{6})^2$

$= 511.77\text{ V}$

For point of min. potential

$$I_A = 533.3\dot{3} - 100 \cdot 2.66 = 266.6\dot{6}\text{ A}$$

$$I_B = -33.3\dot{3} + 100x = 233.3\dot{3}\text{ A}$$

Forward 5 sec - [00:20:50 / 53%]
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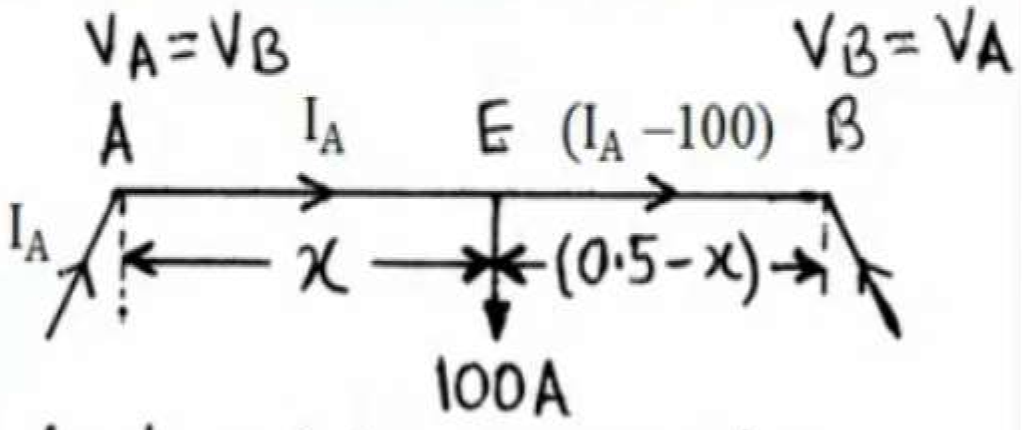
Problem: A bus running at 30miles/hour takes 100A from a system which has a loop resistance of 0.25Ω/mile & is fed at equipotential points 0.5 mile apart. Find the rate of change of voltage w.r.t. time at the bus when it is (i) 220 yards & (ii) 440 yards from a feeding point.



Loop resistance = go & return resistance = $r = 0.25\ \Omega/\text{mile}$

Soln:

Consider, the bus is at a distance x mile from the feeding point A.

Voltage drop from A to B $= V_A - V_B$

$$= I_A.(r.x) + (I_A - 100)\{r.(0.5-x)\} = 0$$

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Simplifying, $I_A = 100 - 200x$ ......(1)

Then, voltage at point E $= V_E = V_A - I_A.(r.x)$

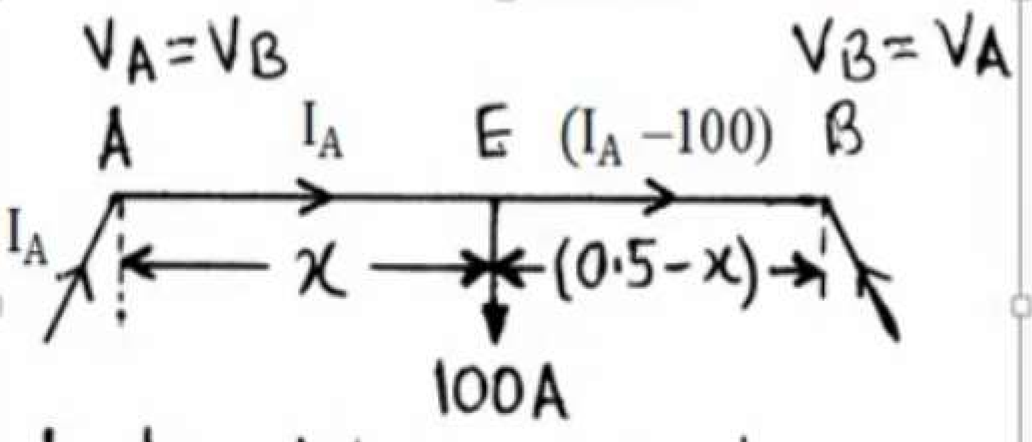
$$= V_A - (100 - 200x).(r.x)$$

$$= V_A - 100r.x + 200.r.x^2$$

Differentiating w.r.t. time,

$$\frac{dV_E}{dt} = 0 - 100.r.\frac{dx}{dt} + 400.r.x.\frac{dx}{dt}$$

$$= [400.r.x - 100r].\frac{dx}{dt} \quad .....(2)$$



Loop resistance = go & return resistance = r = 0.25 Ω/mile

Now, speed of the bus $= \frac{dx}{dt} = 30$ miles/hour

$$= \frac{30}{60.60} \text{ miles/sec} = \frac{1}{120} \text{ miles/sec}$$

$$\therefore \frac{dV_E}{dt} = [400.0.25.x - 100.0.25].\frac{1}{120}$$

$$= [100x - 25].\frac{1}{120} \quad ......(3)$$

Forward 5 sec - [00:27:50 / 72%]
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(a) $220 \text{ yards} = \dfrac{220}{1760} = \dfrac{1}{8} \text{ mile}$

$$\therefore \left.\frac{dV_E}{dt}\right|_{220\,\text{yards}} = \left[100 \cdot \frac{1}{8} - 25\right] \cdot \frac{1}{120} = -0.10416\ \text{V/sec}$$

(b) $440 \text{ yards} = \dfrac{440}{1760} = \dfrac{1}{4} \text{ mile}$

$$\therefore \left.\frac{dV_E}{dt}\right|_{440\,\text{yards}} = \left[100 \cdot \frac{1}{4} - 25\right] \cdot \frac{1}{120} = 0\ \text{V/sec}$$

Forward 5 sec - [00:29:19 / 75%]
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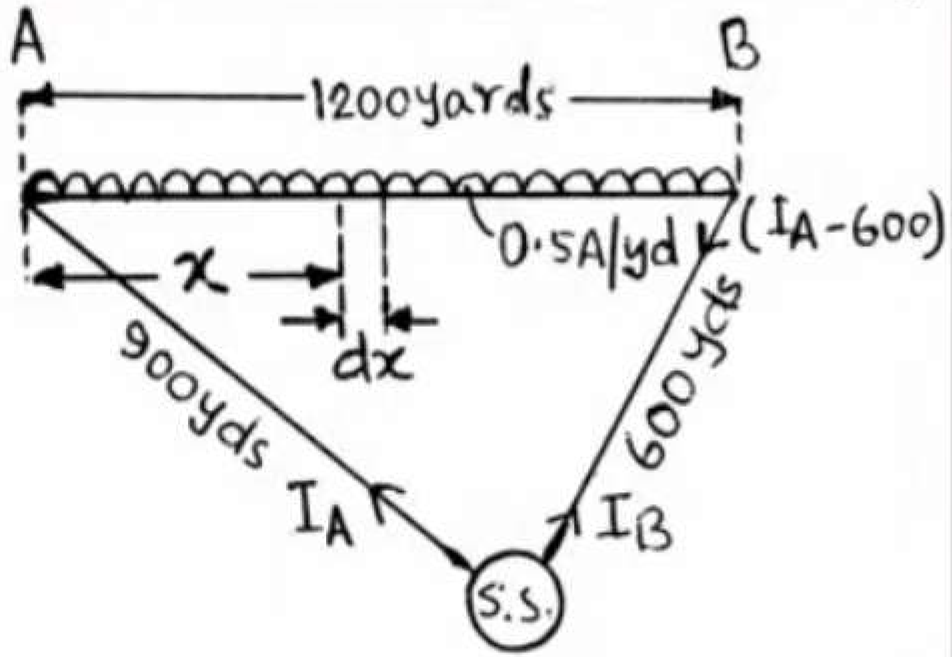
Prob: A distributor 1200yds long, carries a uniformly distributed load of 0.5A/yd. It is supplied at both ends from a substation by feeders, one 900yds & the other 600yds long. The feeders have a cross sectional area 50% greater than that of distributor. Find the point where the consumer's voltage is the lowest & the current supplied by each feeder.



Soln: Let, the resistance of the feeder for one conductor be $r\,\Omega/yd$. Then distributor resistance is $1.5r\,\Omega/yd$.

Forward 5 sec - [00:31:39 / 81%]

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[$r_{dist.} = \rho \frac{l}{a}$; $r_{feeder} = \rho \frac{l}{1.5a} = \frac{1}{1.5} . r_{dist.}$

or, $r_{dist.} = 1.5\, r_{feeder}$.

If, $r_{feeder} = r\,\Omega/yd$, then $r_{dist.} = 1.5\, r\,\Omega/yd$]

Equating voltagedrop from s.s. through A & B and back to s.s.

$$I_A.(2r.900) + \int_0^{1200}(I_A - 0.5x)(2.1.5r\,dx) + (I_A - 600).(2r.600) = 0$$

Solving, $I_A = 272.7272\,A$

Current supplied by the other feeder $= I_B = -(I_A - 600)$

$$= 327.2727\,A$$

For point of minimum potential, $\frac{dv}{dx} = 0$

Backward 5 sec - [00:38:19 / 99%]
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Now, the voltage drop in the elemental distance dx

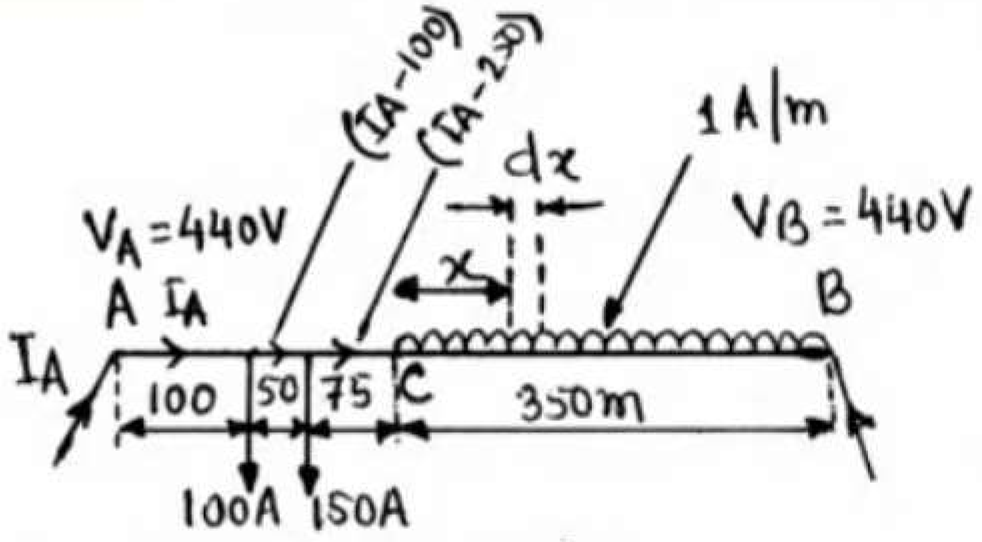
$= dv = (I_A - 0.5x)(2.1.5r\,dx)$

or, $\frac{dv}{dx} = (I_A - 0.5x)(2.1.5r) = 0$

or, x = distance of point of minimum potential from A

$= 545.4545$ yds.

Problem: A direct current 2-wire distributor 575m long is fed at both points A & B at 440V. The load consists of 100A at 100m from A, 150A at 150m from A & a uniform loading of 1A/m for the last 350m. Resistance of each cond. is 0.05Ω/km. At what point is the load voltage a minimum & what is its value?



r = go & return resistance

$= 2 \cdot 0.05\ \Omega/km = 0.1\ \Omega/km$

$= 0.1 \cdot 10^{-3}\ \Omega/m = 10^{-4}\ \Omega/m$

Soln:

Let, I_A be the current supplied from end A.

Then, voltage drop from A to B

$$= V_A - V_B = I_A \cdot 100r + (I_A-100) \cdot 50r + (I_A-250) \cdot 75r + \int_0^{350} (I_A - 250 - x \cdot 1) \cdot r\,dx = 0$$

Simplifying, $I_A = 300A$

Since $I_A = 300A$, the point of minimum potential occurs in between C & B.

Now, the voltage drop in the elemental distance dx at a distance 'x' from C = $dv = (I_A - 250 - x.\ 1).\ r.\ dx$

- For point of minimum potential $\frac{dv}{dx} = 0$

or, $\frac{dv}{dx} = (I_A - 250 - x).\ r = 0$

or, $x = I_A - 250 = 50m$ (from C towards B)

Therefore, distance of point of minimum potential from end A = $(100 + 50 + 75) + 50 = 275m$

Similarly, distance of point of minimum potential from end B

= 350 – 50 = 300m

Load voltage at point of minimum potential

= Voltage at end B – Voltage drop in distributed load for 300m from end B

$$= 440 - \frac{1}{2} . 300^2 . 1 . 10^{-4} = 435.5\,V$$

Forward 5 sec - [00:17:40 / 47%]

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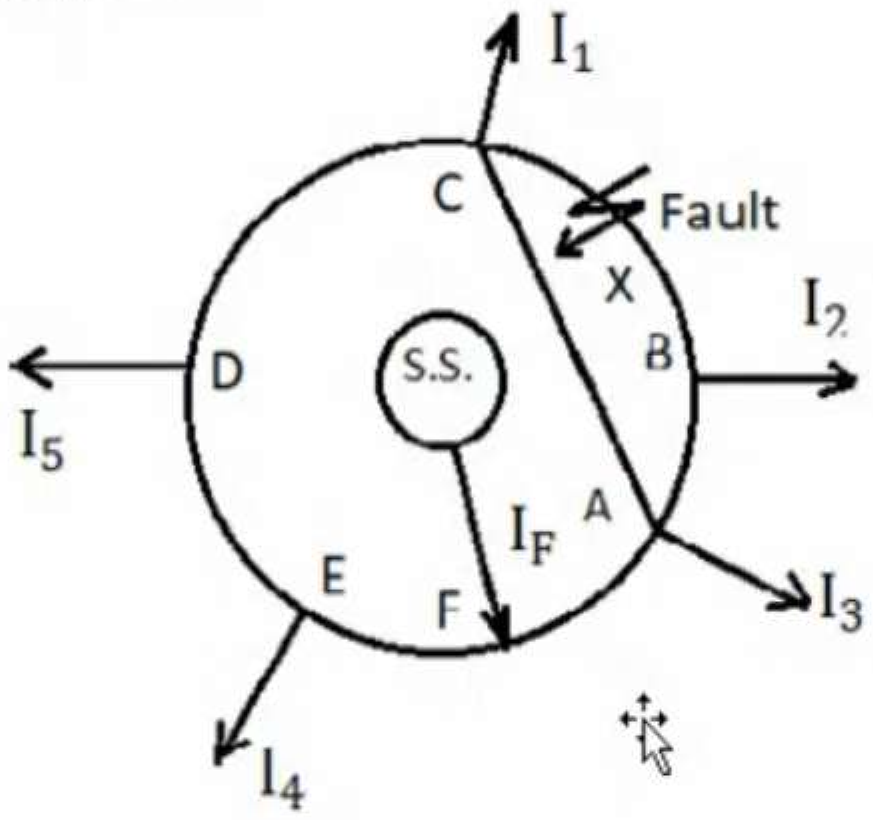
Ring Distributor

- It employs a distributor which after covering the whole area of supply returns back to starting point.
- It is closed on itself.
- ABCDEFA forms a complete ring.
- Loads are connected at A, B, C, D & E; F is feeding point.
- For any load, there are two parallel paths→ greater reliability of supply.



- For fault at 'X', 'BC' is isolated for continuity of supply.
- More saving in conductor compared to a radial distributor.
- Often, two points are joined to reduce voltage drop further.

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- Two examples of ring distributors are shown in the figures.
- In second fig. current directions are are chosen arbitrarily.
- Let, r Ω/m be go & return of distributor.
- Applying Kirchhoff's law in closed path FABCF,

$$I.(l_1.r) + (I - I_1).(l_2.r) + (I - I_1 - I_2).(l_3.r) - I_A.(l_7.r) = 0 \ldots\ldots\ldots(1)$$

- Applying Kirchhoff's law in closed path FEDCF,

$$(I_F - I - I_A).(l_6.r) + (I_F - I - I_A - I_5).(l_5.r) + (I_F - I - I_A - I_5 - I_4).(l_4.r) - I_A.(l_7.r) = 0 \ldots(2)$$

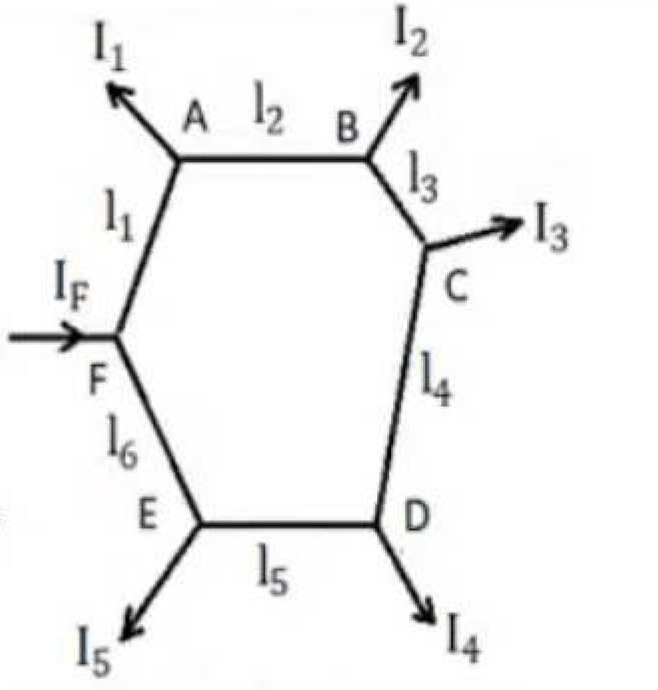


Fig. Simple ring distributor.

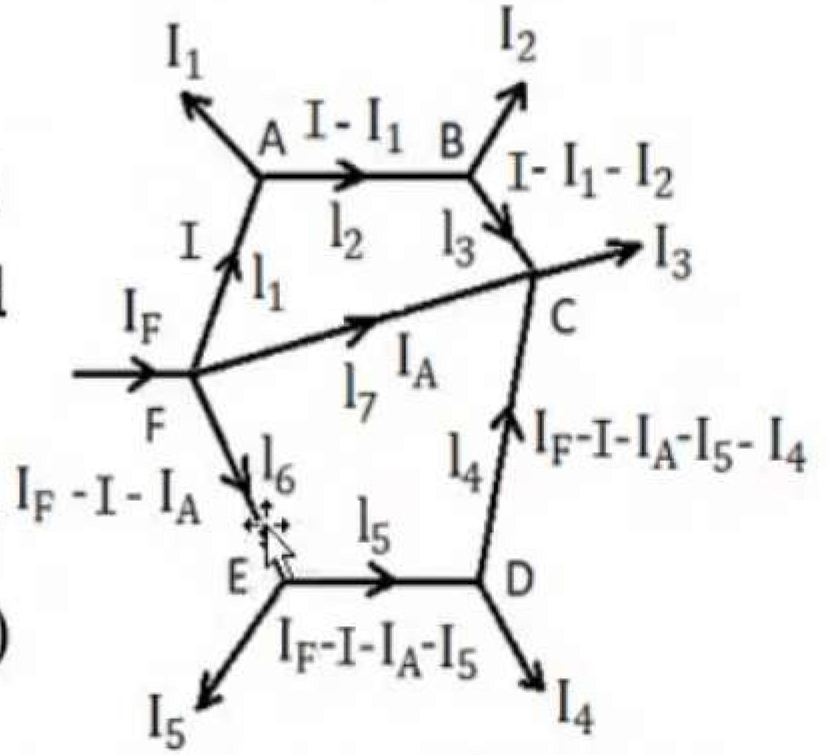


Fig. Ring distributor with inter-connection.

Further,

$I_F = I_1 + I_2 + I_3 + I_4 + I_5$ ....(3)

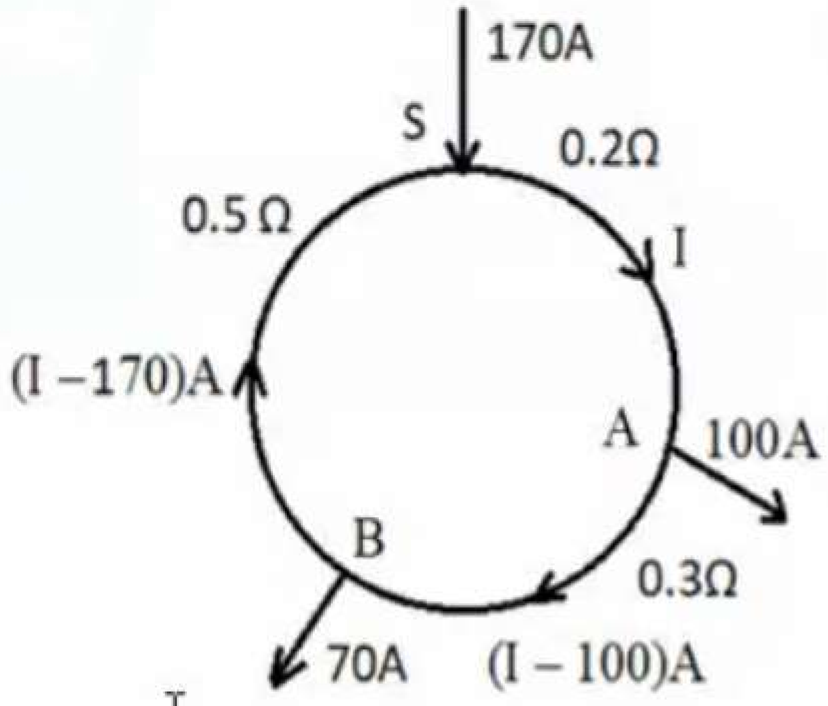
- So, in eqns. (1) & (2),

(i)loads I_1, I_2, I_3, I_4 & I_5 & feeding current I_F &

(ii)distances $l_1, l_2, l_3, l_4, l_5, l_6$ & $l_7$are known.

- Hence, eqns. (1) & (2) may be solved for I & I_A.
- So, voltage drop up to any load point may be calculated.

Problem: A ring main is supplied at point S and is loaded at point A with 100A & at point B with 70A. The sectional resistances are: SA, 0.2Ω; AB, 0.3 Ω; BS, 0.5 Ω. (a) Find the current in AB. (b) Find the voltage drop between S & each Load point. (c) Find the voltage drop between S & A when load at B is removed.



Soln: Considering the current directions, voltage drop in the closed path,

$$I.\,0.2 + (I - 100).\,0.3 + (I - 170).\,0.5 = 0$$

Solving, I = Current from S to A = 115A.

(a) Current in AB = (115 – 100)A = 15A (from A to B).

Current from S to B = - (I – 170) = 55A

(b) Voltage drop between S & A= I. 0.2 = 23V (from S to A).

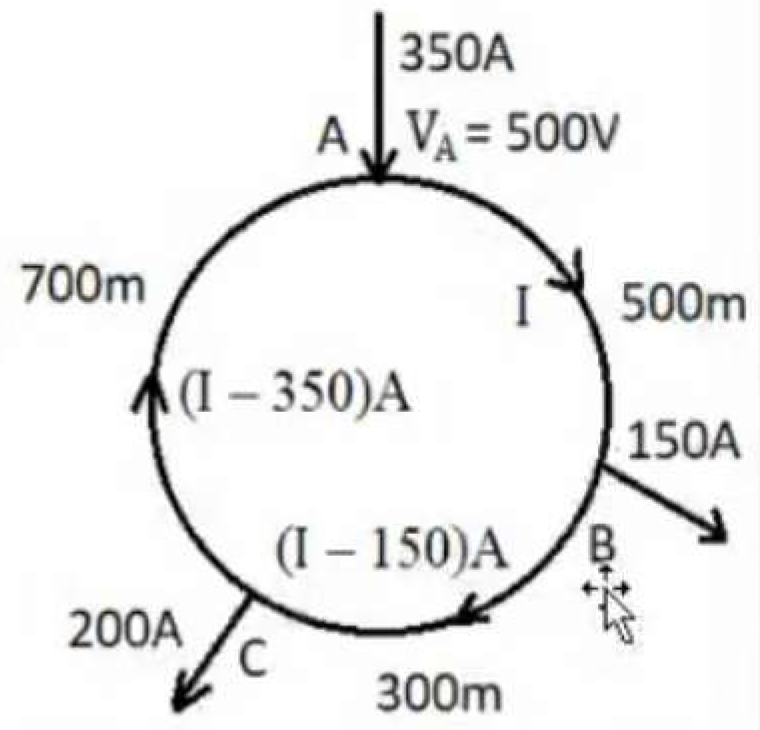
Voltage drop between S & B= 55 . 0.5 =27.5V (from S to B).

(c) When load at B is removed, then current at A is received through two parallel paths: S – A & S – B - A.

So, equivalent resistance = $\dfrac{0.2.\,(0.5 + 0.3)}{0.2 + (0.5 + 0.3)} = 0.16\Omega$

Therefore, voltage drop between S & A = 0.16. 100 = 16V.

Prob: In the direct-current ring distributor shown, a voltage of 500V is maintained at A. At B, a load of 150A is taken & at C, a load of 200A is taken. Find voltages at B & C. Resistance of each conductor of the main is 0.03Ω/km.



Resistance of each conductor =0.03Ω/km = 0.03 .10⁻³ Ω/m

Soln: Applying Kirchhoff's Voltage law,

$I.\ (0.03.\ 10^{-3}.\ 2.\ 500) +$

$(I - 150).\ (0.03.\ 10^{-3}.\ 2.\ 300) +$

$(I - 350).\ (0.03.\ 10^{-3}.\ 2.\ 700) = 0$

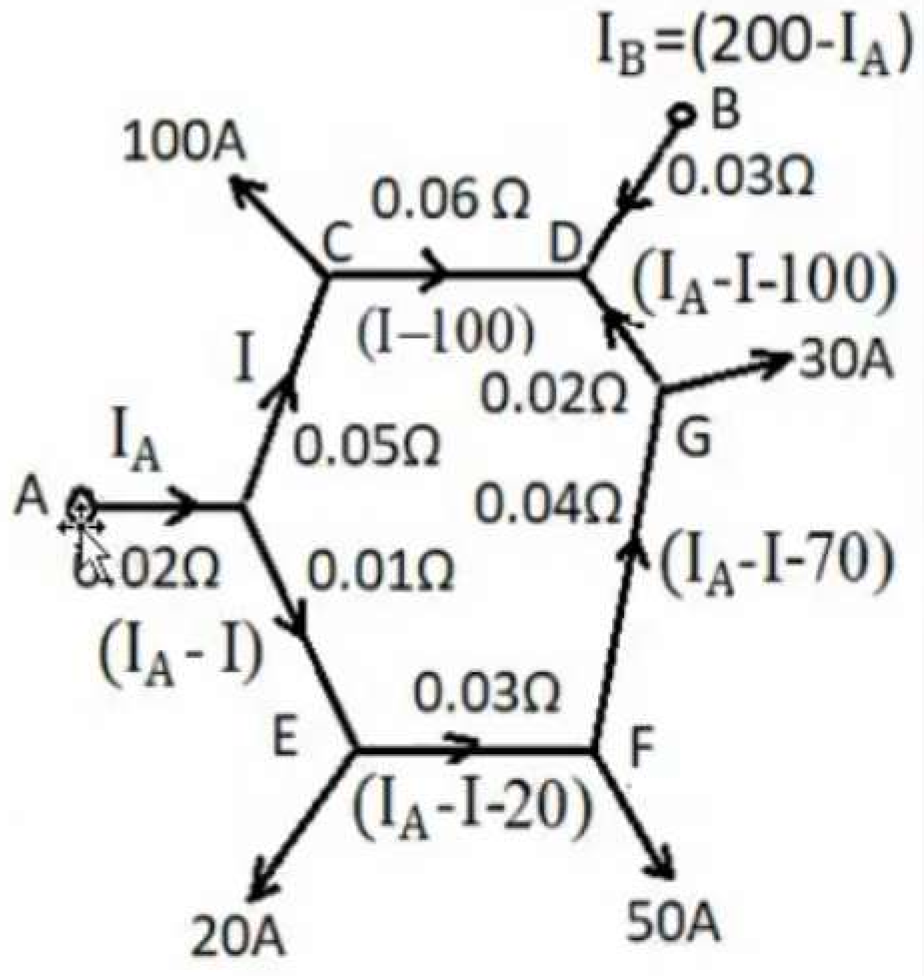
Solving, I = 193.3333A

Voltage at B $= V_A - \{I.\ (0.03.\ 10^{-3}.\ 2.\ 500)\} = 494.2V$ (A - B).

Voltage at C $= V_A - \{-(I - 350).\ (0.03.\ 10^{-3}.\ 2.\ 700)\} = 493.42V$ (A - C)

Forward 5 sec - [00:15:30 / 47%]

Prob: Find the current supplied to the ring main from A & B (a) for equal voltages at A & B, (b) for the voltage at B higher than that at A by 5V.



Soln: $I_A + I_B = 100+20+50+30$

$= 200A$

Or, $I_B = 200 - I_A$ .....(1)

(a) Voltage drop from A to B, via C & D,

$I_A.\ 0.02 + I.\ 0.05 + (I - 100).\ 0.06 - (200 - I_A).\ 0.03 = 0$

Simplifying,

$5.\ I_A + 11.\ I = 1200$ .....(2)

Forward 5 sec - [00:20:03 / 61%]
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Similarly, Voltage drop from A to B, via E, F & G,

$$I_A . 0.02 + (I_A - I) . 0.01 + (I_A - I - 20) . 0.03 + (I_A - I - 70) . 0.04 + (I_A - I - 100) . 0.02 - (200 - I_A) . 0.03 = 0$$

Simplifying,

$15 . I_A - 10 . I = 1140$ .....(3)

Solving eqns. (2) & (3),

$I = 57.2093A$ & $I_A = 114.1395A$

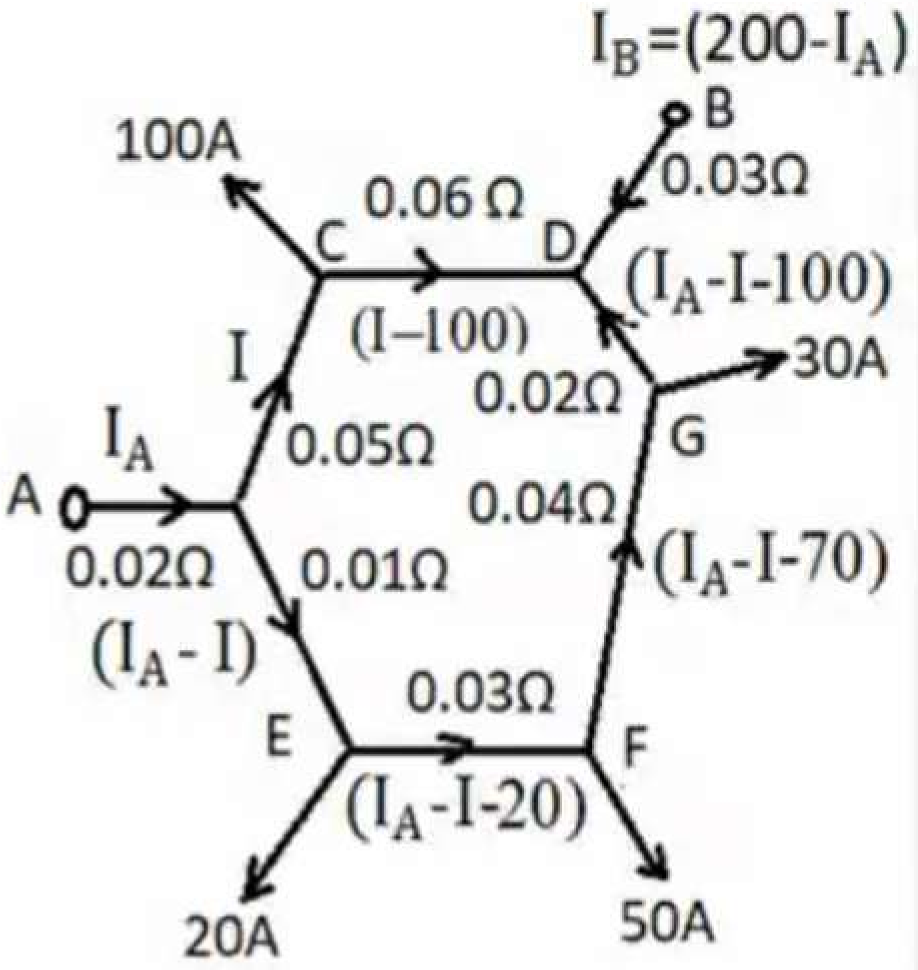
Therefore, $I_B = 200 - I_A = 85.8605A$

(b) $V_B = V_A + 5$ .....(4)

So, from eqn. (2),

$5 . I_A + 11 . I - 1200 = -500$

Or, $5 . I_A + 11 . I = 700$ .....(5)



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From eqn. (3),

$15.I_A - 10.I = 1140 - 500 = 640$ .....(6)

Solving eqns. (5) & (6),

$I = 33.9535A$ & $I_A = 65.3023A$

$I_B = 200 - I_A = 134.6977A$

Forward 5 sec - [00:23:15 / 71%]

Alternating Current Distribution

Differences of a.c. & d.c. distributions are

1. Unlike d.c. distribution where only conductor resistance is considered, in a.c. distribution the conductor reactance, along with conductor resistance are considered.
2. The different loads that are tapped off the distributor will, in general, be at different power factors.
3. There are two components of voltage drops, the in phase voltage drop due to conductor resistance & a quadrature voltage drop due to conductor reactance.

- Keeping in mind these differences, all the techniques used for d.c. distribution may be used in a.c. distribution.

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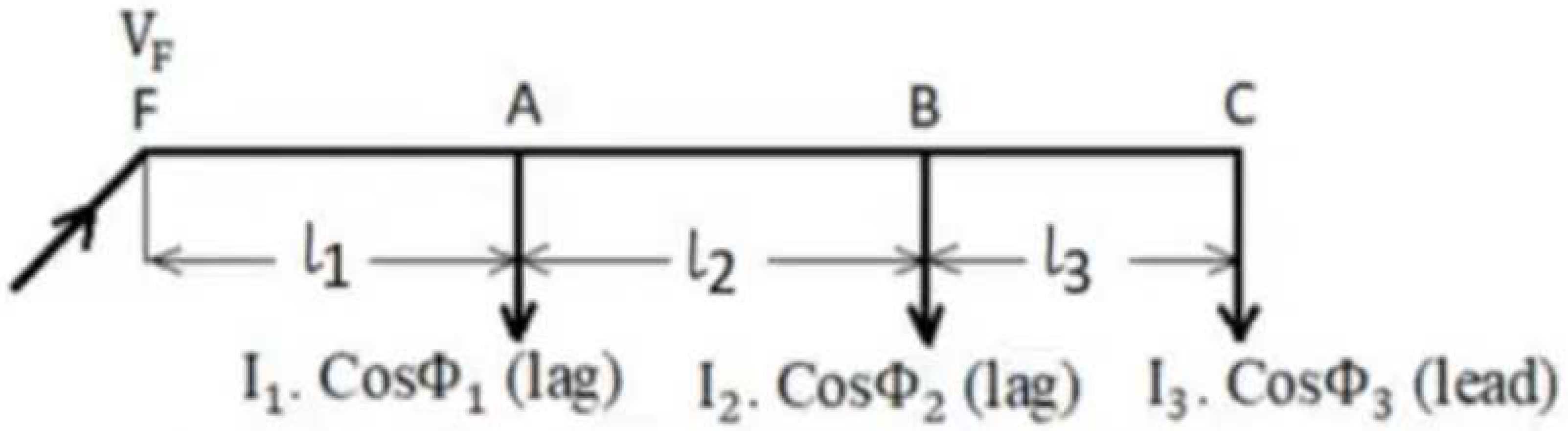

Distributor impedance = Z = (R + j X) Ω/unit length

Example: Consider the a.c. two wire distributor fed at one end.

Then, the total voltage drop from F to C = V_{FC} =

$l_1.(R + jX).(I_1.Cos\Phi_1 - j.I_1.Sin\Phi_1) + (l_1 + l_2).(R + jX).(I_2.Cos\Phi_2 - j.I_2.Sin\Phi_2) + (l_1 + l_2 + l_3).(R + jX).(I_3.Cos\Phi_3 + j.I_3.Sin\Phi_3)$

So, consumer voltage at C = $V_C = V_F - V_{FC}$

Similarly, consumer voltages at A & B may also be calculated.

SLIDE 75 OF 159 ENGLISH (INDIA) NOTES COMMENTS 74%

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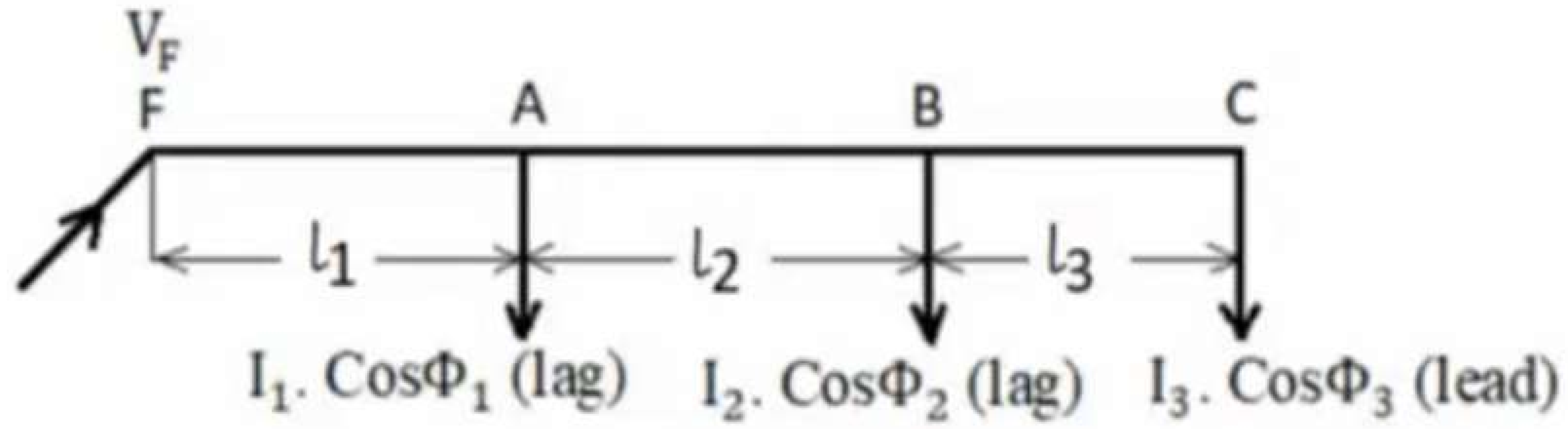

Distributor impedance = Z = (R + j X) Ω/unit length

Example: Consider the a.c. two wire distributor fed at one end.

Then, the total voltage drop from F to C = V_{FC} =

$l_1 . (R + jX) . (I_1 . Cos\Phi_1 - j . I_1 . Sin\Phi_1) + (l_1 + l_2) . (R + jX) . (I_2 . Cos\Phi_2 - j . I_2 . Sin\Phi_2) + (l_1 + l_2 + l_3) . (R + jX) . (I_3 . Cos\Phi_3 + j . I_3 . Sin\Phi_3)$

So, consumer voltage at C = $V_C = V_F - V_{FC}$

Similarly, consumer voltages at A & B may also be calculated.

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Sag & Tension

Forward 5 sec - [00:00:10 / 0%]
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• Span: Horizontal distance between two adjacent supports.

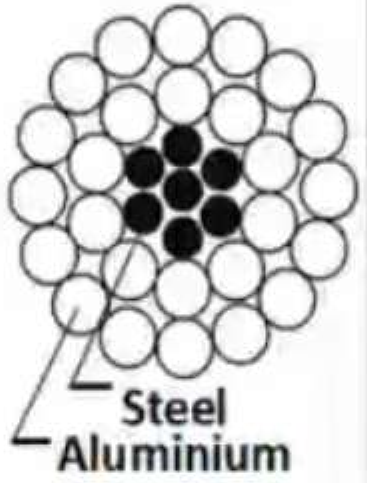
• Under normal condition of erection height of the conductor at centre of span is less than that at the support.

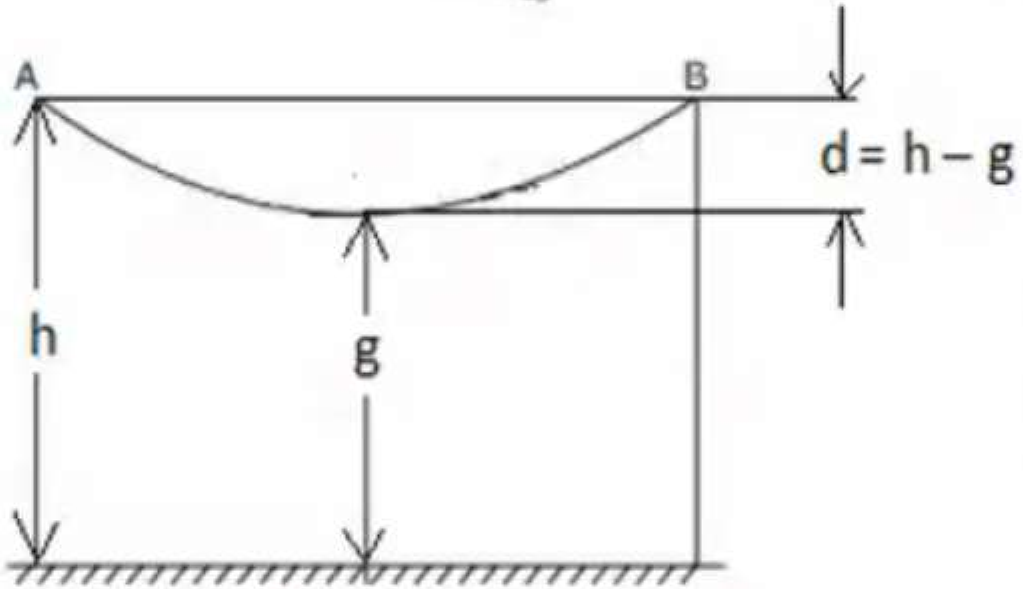
• Difference between the two is known sag (d).

• Sag calculation is easy for conductors of homogeneous material → all Cu or all Al.

• More involved for conductors of composite materials → ACSR (Aluminium Conductor Steel Reinforced) conductors.

• Sag determines min. ground clearance.





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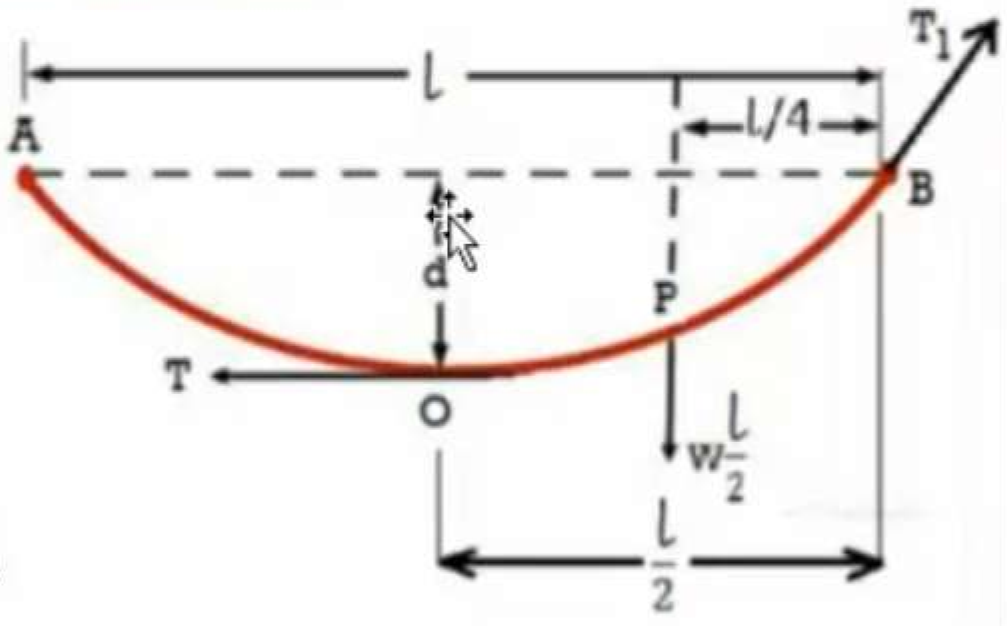
Parabolic Method of Sag Calculation

- If weight of cond. is uniformly distributed horizontally, a freely suspended cond. hangs in shape of a parabola. Let,



w = weight of cond./unit length.

T = tension in cond. at point O,

T_1 = tension in cond. at B & d= sag.

Consider equilibrium of OPB. At P, at a distance $\frac{l}{4}$, a force $w.\frac{l}{2}$ due to weight of cond. for portion OPB is acting downwards. Taking moment of all forces about point B,

$$T.d + \{-(w.\frac{l}{2}).\frac{l}{4}\} + T_1.0 = 0 \Rightarrow \text{Sag} = d = \frac{wl^2}{8T} = \frac{w.(\frac{l}{2})^2}{2T}$$

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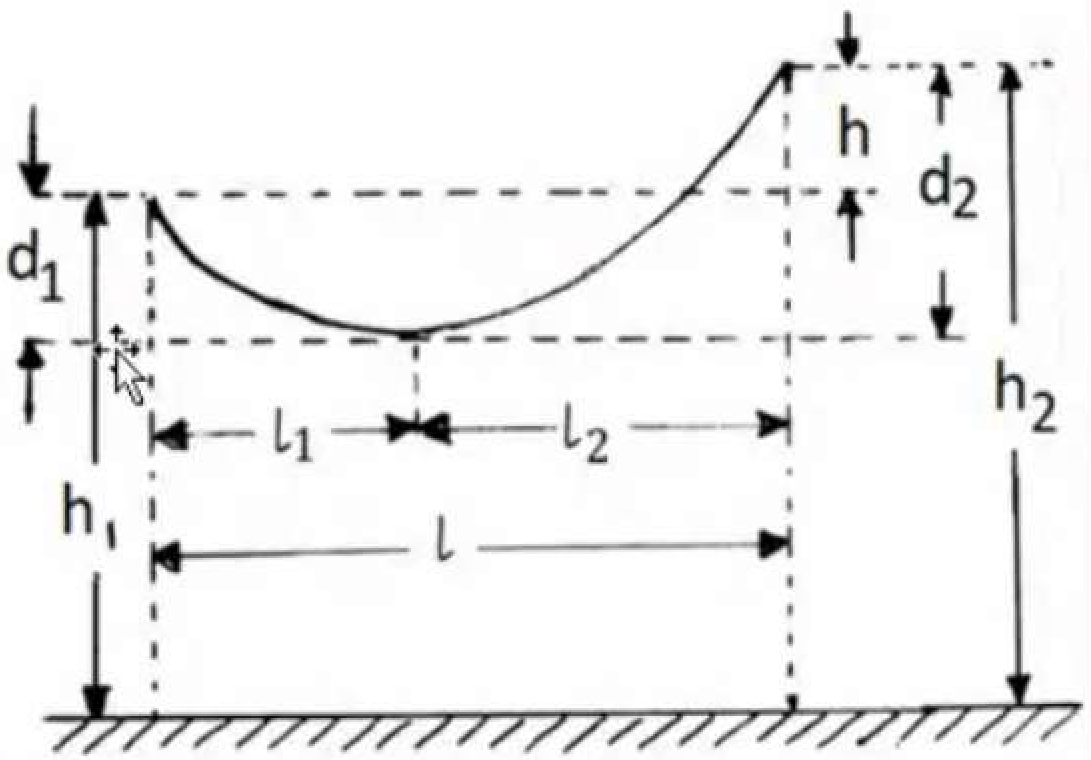
Expression of Sag for Supports at Different Levels

- This case inevitably arises in hilly areas, uneven lands or in sloping grounds.
- Maximum benefit is taken by erecting supports at most elevated spots.



Here, $d_1 = \dfrac{w . l_1^2}{2T}$ ---(1)

$d_2 = \dfrac{w l_2^2}{2T}$ ---(2)

So, $d_2 - d_1 = h_2 - h_1 = h$ ---(3)

Backward 5 sec - [00:22:01 / 54%]

$$\text{Or, } h = \frac{w l_2^2}{2T} - \frac{w l_1^2}{2T}$$

$$= \frac{w}{2T}\left(l_2^2 - l_1^2\right)$$

$$= \frac{w}{2T}\left(l_2 + l_1\right)\left(l_2 - l_1\right)$$

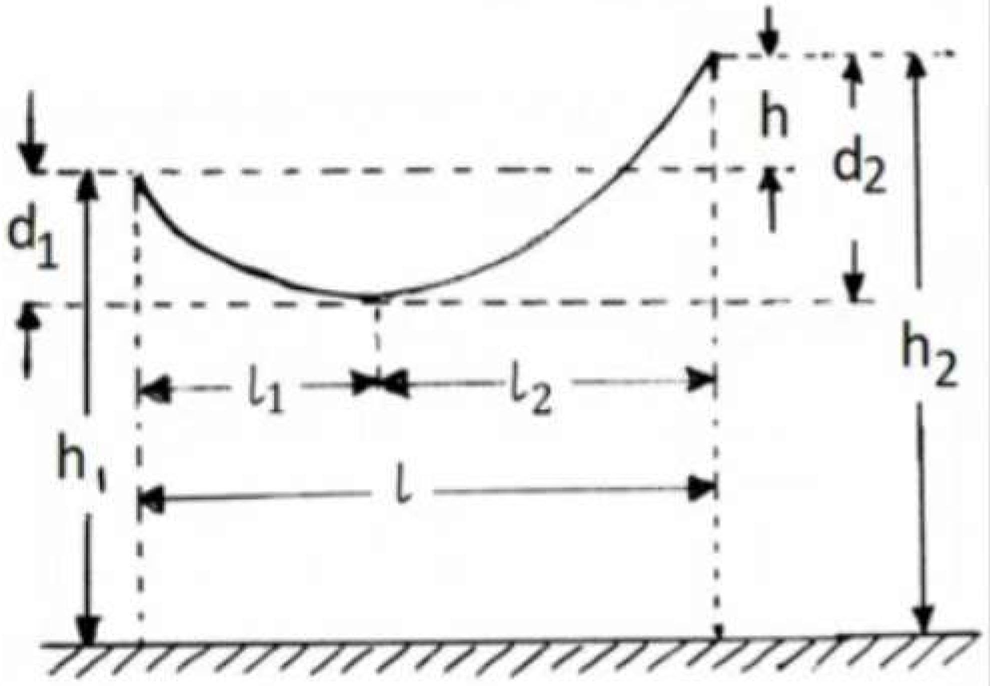
$$= \frac{w}{2T} \cdot l \cdot \{l_2 - (l - l_2)\}$$

$$= \frac{w}{2T} \cdot l \cdot (2l_2 - l)$$

$$\text{Or, } (2l_2 - l) = \frac{2Th}{wl}$$

$$\text{Or, } l_2 = \frac{1}{2}\left(l + \frac{2Th}{wl}\right) \text{ --- (4)}$$

$$\text{Similarly, } l_1 = \frac{1}{2}\left(l - \frac{2Th}{wl}\right) \text{ --- (5)}$$



First l_1 & l_2 are calculated from eqns. (5) & (4), then d_1 & d_2 are calculated from eqns. (1) & (2).

Effects of Wind & Ice Covering

During service conductor is subjected to forces due to:

(i) It's own weight (w), acting vertically downwards,

(ii) Wind load (w_w) of various strength, acting horizontally &

(iii) Weight of ice covering (w_i), acting vertically downwards.

Let,

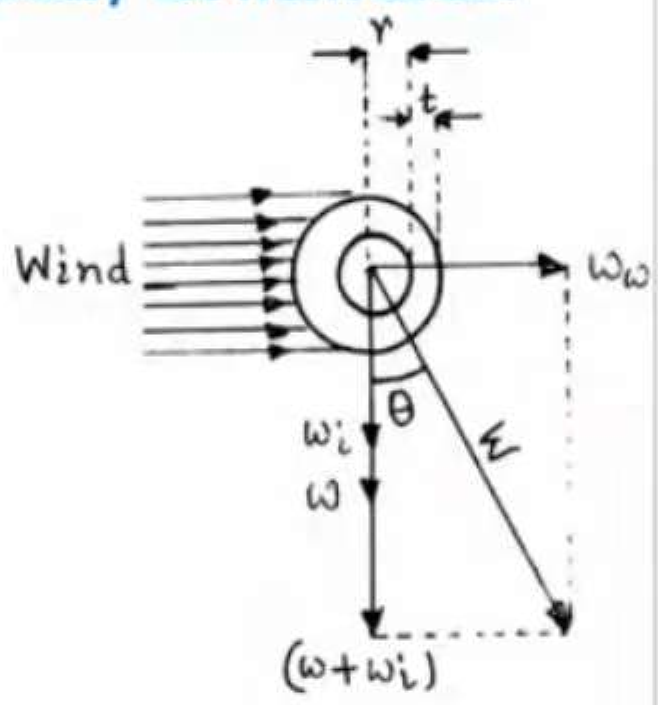
r = radius of conductor in mm.

t = thickness of ice covering in mm.

w = weight of conductor/m in kg,

P = wind pressure in kg/m^2,

w_{ice} = weight/unit volume of ice in kg/m^3



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Then, volume of ice per metre length of conductor

$$= \frac{\{\pi(r+t)^2 - \pi r^2\}}{10^6} . 1.0\, m^3 = \frac{\pi(r+t+r)(r+t-r)}{10^6} . 1.0\, m^3$$

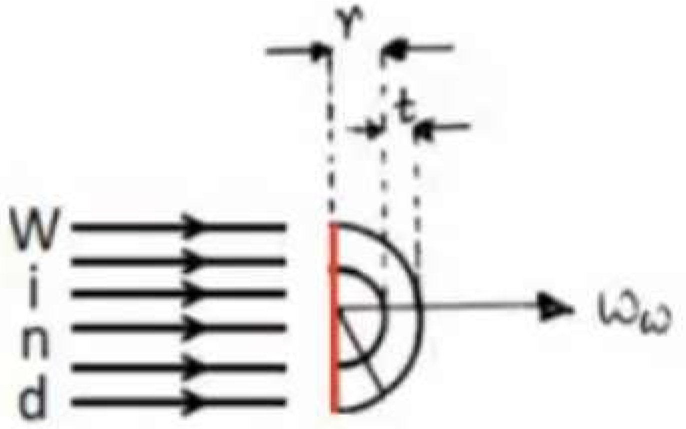
$$= \frac{\pi.(2r+t).t}{10^6}\, m^3$$

So, weight of ice covering $= w_i$

$$= w_{ice} \cdot \frac{\pi.(2r+t).t}{10^6}\, kg.$$

Without ice covering wind load w_w

$$= P. \frac{2r}{10^3} . 1.0\, kg.$$



With ice covering wind load w_w

$$= P. \frac{2.(r+t)}{10^3} . 1.0\, kg.$$

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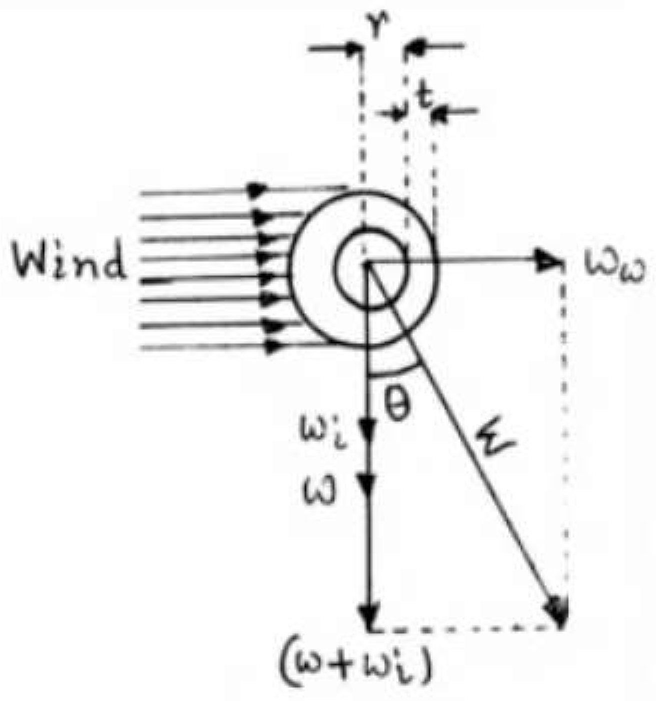
So, resultant load W

$$= \sqrt{(\omega + \omega_i)^2 + \omega_\omega^2} \text{ kg}$$

and $\tan\theta = \dfrac{\omega_\omega}{(\omega + \omega_i)}$

Hence, sag $d = \dfrac{Wl^2}{8T}$



Vertical sag $= d.\cos\theta$

If wind velocity is given, then wind pressure is found from the formula,

$$P = 0.006\, V^2 \text{ kg/m}^2$$

Loading factor is defined as $q = \dfrac{W}{\omega}$

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Problem: A single span of a transmission line is 150m long, the supporting structures being level. The conductors have a cross section of 2.5 cm^2 hard drawn copper. Find the sag which must be allowed if tension is not to exceed one-fifth of the ultimate strength (40,000N per cm^2), (a) in still air & (b) with a wind pressure of 13N per metre & a 1.25cm ice-coating. In the later case also find the vertical sag. Take specific gravity of copper as 8.9gm/cc & density of ice as 920kg/m^3.

Solution: Given data: Span l = 150m

Cross section $\pi r^2 = 2.5\ cm^2$ (r = radius)

Or, r = 0.892 cm = 8.92 mm

Ice coating = t = 1.25 cm =12.5 mm

Forward 5 sec - [00:36:41 / 90%]

Working tension $T = \frac{1}{5} \times 40{,}000 \ N/cm^2$

$= \frac{1}{5} \times 40{,}000 \times \frac{1}{9.81} \ Kg/cm^2$

$= 815.494 \times 2.5 \ kg$

$= 2038.735 \ kg.$

Weight of conductor/cm $= 2.5 \times 1 \times 8.9 \ gm$

So, weight of conductor/m $= \frac{2.5 \times 8.9}{1000} \times 100$

$= 2.225 \ kg \ (= \omega \text{ say})$

(a) Sag in still air $d = \frac{\omega l^2}{8T} = \frac{2.225 \times (150)^2}{8 \times 2038.735}$

$= 3.0695 \ m$

(b) Weight of ice/m $= \dfrac{w_{ice} \times \pi.(2r+t).t}{10^6}$ kg $(= w_i \text{ say})$

$$= \frac{920 \times \pi \times (2 \times 8.92 + 12.5)12.5}{10^6} \text{ kg} = 1.0961 \text{ kg}$$

Wind load $w_w = 13\,N = \dfrac{13}{9.81}$ kg $= 1.3252$ kg

So, resultant load $W = \sqrt{(w+w_i)^2 + w_w^2}$

$$= \sqrt{(2.225+1.0961)^2 + (1.3252)^2}$$

$$= 3.5756 \text{ Kg}$$

Hence, sag $d = \dfrac{Wl^2}{8T} = \dfrac{3.5756 \times (150)^2}{8 \times 2038.735}$

$$= 4.9727 \text{ m}$$

Vertical sag = $d \cos\theta$

$$= d.\cos\left[\tan^{-1}\left(\frac{w_w}{w + w_i}\right)\right]$$

$$= 4.9327 \times \cos\left[\tan^{-1}\left(\frac{1.3252}{2.225 + 1.0961}\right)\right]$$

$$= 4.58145 \text{ m}$$

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- **Problem:** An overhead line conductor consists of seven strands silicon-bronze, having an ultimate strength of 78500N per cm^2 & an area of 2.2 cm^2. When erected between supports 600m apart & having a 15m difference in level, find the vertical sag which must be allowed so that factor of safety shall be 5 with conductor loaded with 1kg of ice per metre & a wind pressure of 17.15N per metre. The conductor weighs 2.03kg per metre.

Soln:

Given data :

Span $l = 600m$; difference of height of supports $= h = 15m$;

weight of conductor/m $= \omega = 2.03\,kg$; ice loading/m $= \omega_i = 1\,kg$;

wind load $= \omega_\omega = 17.15N = \frac{17.15}{9.81}\,kg = 1.7482\,kg$.

$$\text{Working tension } T = \frac{78500}{5}\,N/cm^2$$

$$= \frac{78500}{5 \times 9.81} \times 2.2\,kg = 3520.8970\,kg$$

Cross sectional area $= 2.2\,cm^2$

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$\therefore$ Resultant load $W = \sqrt{(\omega + \omega_i)^2 + \omega_\omega^2} = \sqrt{(2{\cdot}03 + 1)^2 + (1{\cdot}7482)^2}$

$= 3{\cdot}4981$ kg.

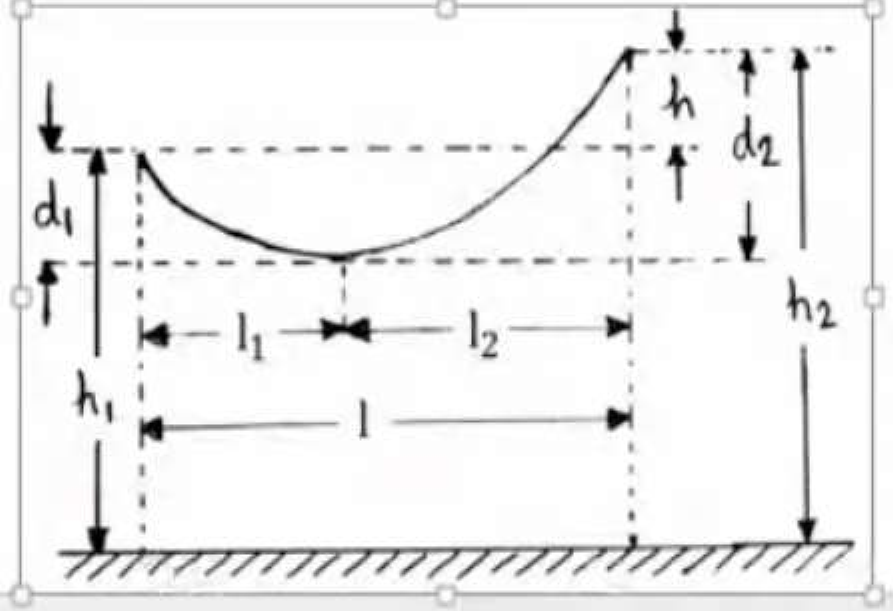
Here, $l_1 = \frac{1}{2}\left[l - \frac{2Th}{Wl}\right] = \frac{1}{2}\left[600 - \frac{2 \times 3520{\cdot}8970 \times 15}{3{\cdot}4981 \times 600}\right] = 274{\cdot}8375$ m

So, sag w.r.t. the lower support $d_1 = \frac{Wl_1^2}{2T} = \frac{3{\cdot}4981 \times (274.8375)^2}{2 \times 3520{\cdot}8970}$

$= 37{\cdot}5259$ m

Now, $\cos\theta = \cos\left[\tan^{-1}\left(\frac{\omega_\omega}{\omega + \omega_i}\right)\right] = 0{\cdot}8662$

Hence, vertical sag $= d_1 \cos\theta = 37{\cdot}5259 \times 0{\cdot}8662 = 32{\cdot}5021$ m



Problem: A transmission line conductors have an effective diameter of 19.5m.m. & weight of 0.85kg/m. If the maximum permissible sag is 6.3m, with a horizontal wind pressure of $39 kg/m^2$ of projected area & 12.7m.m. radial ice coating, calculate the permissible span between two supports when they are at same level, allowing a factor of safety of 2. Ultimate strength of the conductor is 8000kg & weight of ice is $910 kg/m^3$.

Solution:

Given data :

Conductor diameter = 19.5 m.m.

$\therefore$ Radius $= r = \frac{19.5}{2} = 9.75$ m.m ; weight of conductor/m $= w = 0.85$ kg ;

maxm. permissible sag $= d = 6.3$ m ; wind pressure $P = 39\ kg/m^2$;

ice coating $= t = 12.7$ m.m ; ultimate strength = 8000 kg ;

factor of safety = 2 ; weight of ice/unit volume $= w_{ice} = 910\ kg/m^3$

Here, weight of ice covering $= w_i = \dfrac{w_{ice}\cdot\pi(2r+t).t}{10^6}$ kg

$$= \frac{910\times\pi\times(2\times 9.75+12.7)\times 12.7}{10^6}\ \text{kg} = 1.169\ \text{kg}$$

Wind load $= \dfrac{P.\,2.(r+t)}{10^3}$ kg $= \dfrac{39\times 2\times(9.75+12.7)}{10^3} = 1.7511$ kg $= w_w$

So, resultant load $= W = \sqrt{(w+w_i)^2+w_w^2} = \sqrt{(0.85+1.169)^2+(1.7511)^2}$

$$= 2.6727\ \text{kg}$$

Now, working tension $= T = \dfrac{8000}{2} = 4000$ kg

As, sag $d = \dfrac{Wl^2}{8T}$, span $= l = \sqrt{\dfrac{8Td}{W}} = \sqrt{\dfrac{8\times 4000\times 6.3}{2.6727}}$ m

$$= 274.646\ \text{m}$$

Forward 5 sec -[00:23:09 / 58%]
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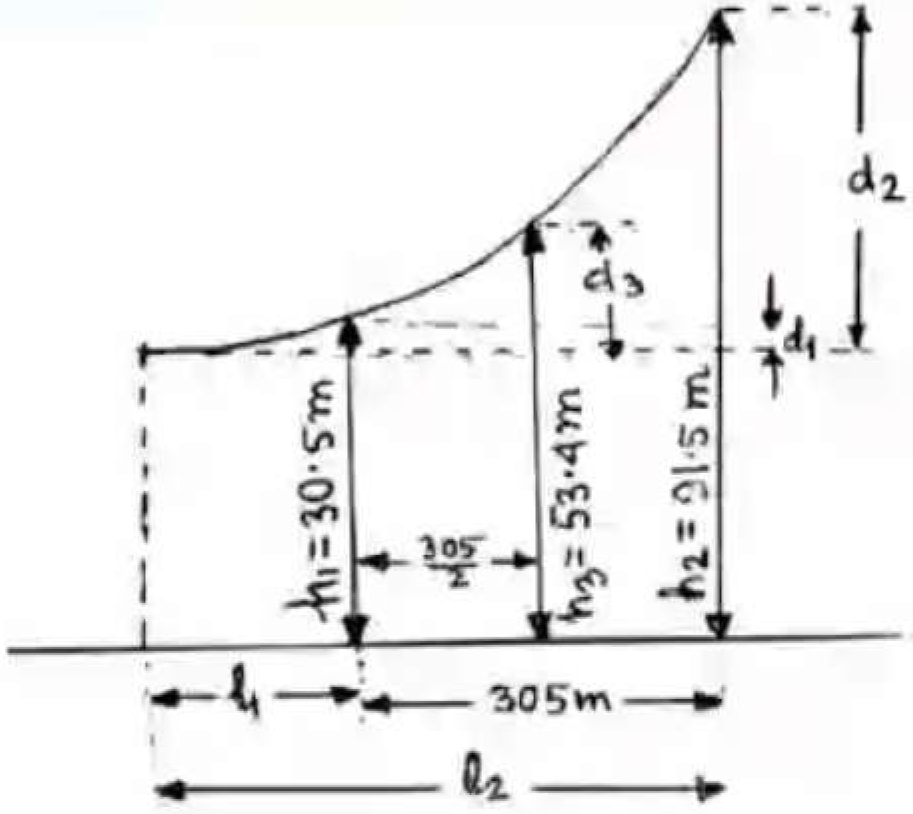
Problem: An overhead line at a river crossing is supported from two towers of heights 30.5m & 91.5m above the water level with a span of 305m. If the required clearance between the conductor & water level midway between the towers is 53.4m and if both the towers are on the same side of maximum point of the parabolic configuration, calculate the string tension on the conductor. Weight of conductor is 0.88kg/m. Also calculate the distances of the two towers from the point of maximum sag.

Solution:



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Given data:

Height of towers $h_1 = 30.5\,m$ and $h_2 = 91.5\,m$; Span $= l = 305\,m$;

clearance of conductor at middle of span $= h_3 = 53.4\,m$;

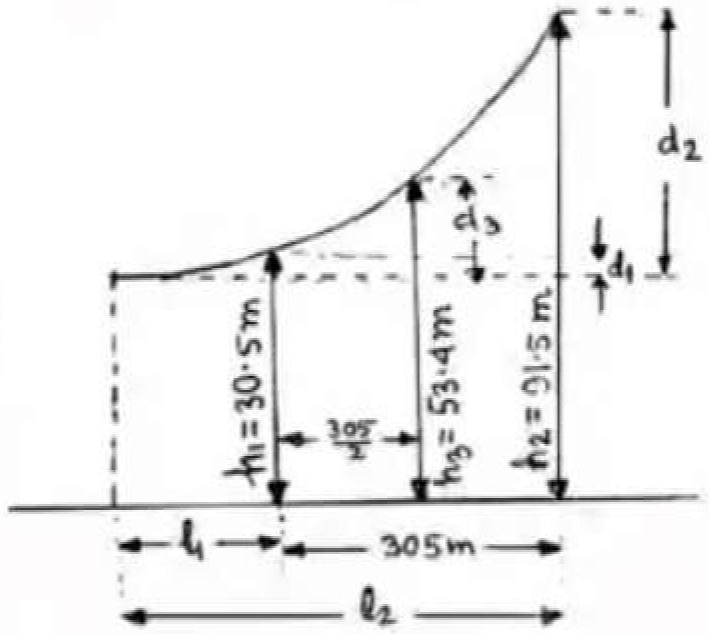
weight of conductor/m $= \omega = 0.88$ kg.

Here, $d_2 - d_1 = h_2 - h_1 = \frac{\omega}{2T}(l_2^2 - l_1^2)$

Or, $91.5 - 30.5 = \frac{0.88}{2T}(l_2 + l_1)(l_2 - l_1)$

$= \frac{0.88}{2T}(305 + 2l_1) \times 305$

Or, $T = 2.2(305 + 2l_1)$ - - - (1)



Again, $d_3 - d_1 = h_3 - h_1 = \frac{\omega}{2T}\left\{\left(l_1 + \frac{305}{2}\right)^2 - l_1^2\right\}$

or, $53.4 - 30.5 = \frac{0.88}{2T}\left(l_1 + \frac{305}{2} + l_1\right)\left(l_1 + \frac{305}{2} - l_1\right)$

or, $T = 2.930\left(2l_1 + \frac{305}{2}\right)$ - - - (2)

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Equating (1) and (2),

$$2\cdot 930\left(2l_1+\frac{305}{2}\right)=2\cdot 2(305+2l_1)$$

Solving, $l_1 = 153\cdot 5032\,m$

$l_2 = l_1 + 305 = 458\cdot 5032\,m$

$\therefore$ Tension $T = 2\cdot 2(305+2l_1) = 1346\cdot 4145$ kg

Forward 5 sec - [00:28:39 / 72%]
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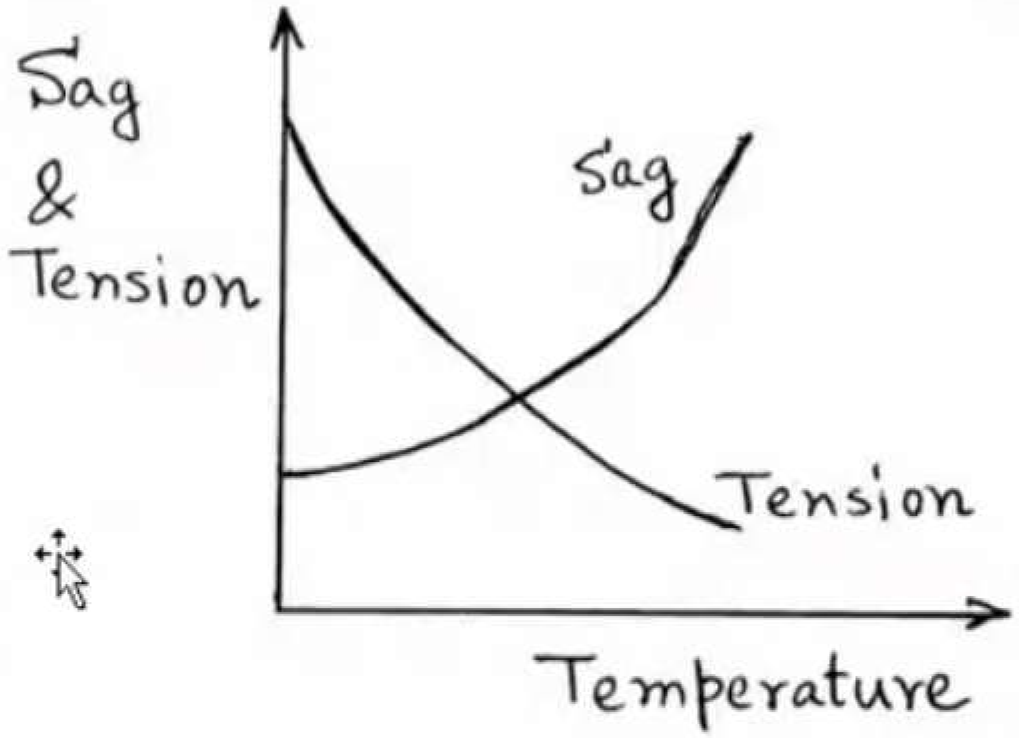
Stringing Chart

- Both sag & tension depends on temperature.
- Maxm. & min. temp. of the proposed route are known From previous years records
- Both sag & tension are calculated in this range of temp.
- Curves of sag vs. temp. & tension vs. temp. are known as stringing charts/erection sag curves.
- These are useful to adjust sag & tension properly at the time of erection.



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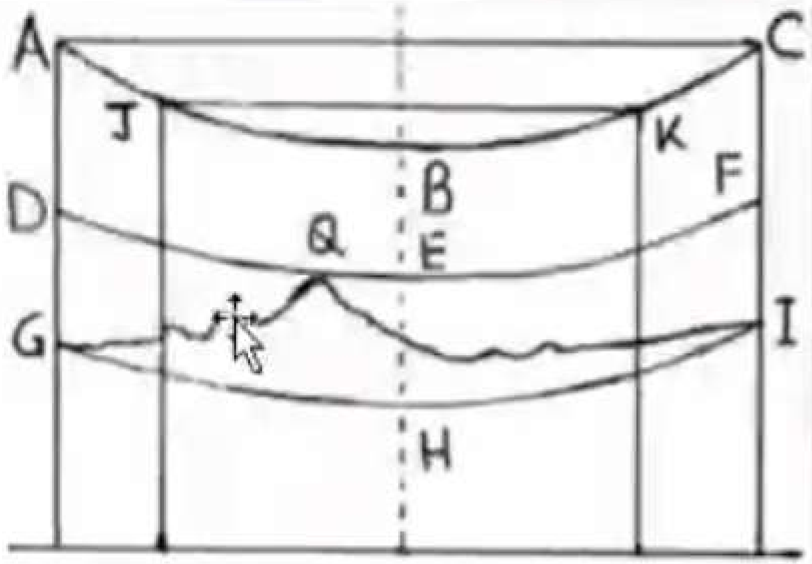
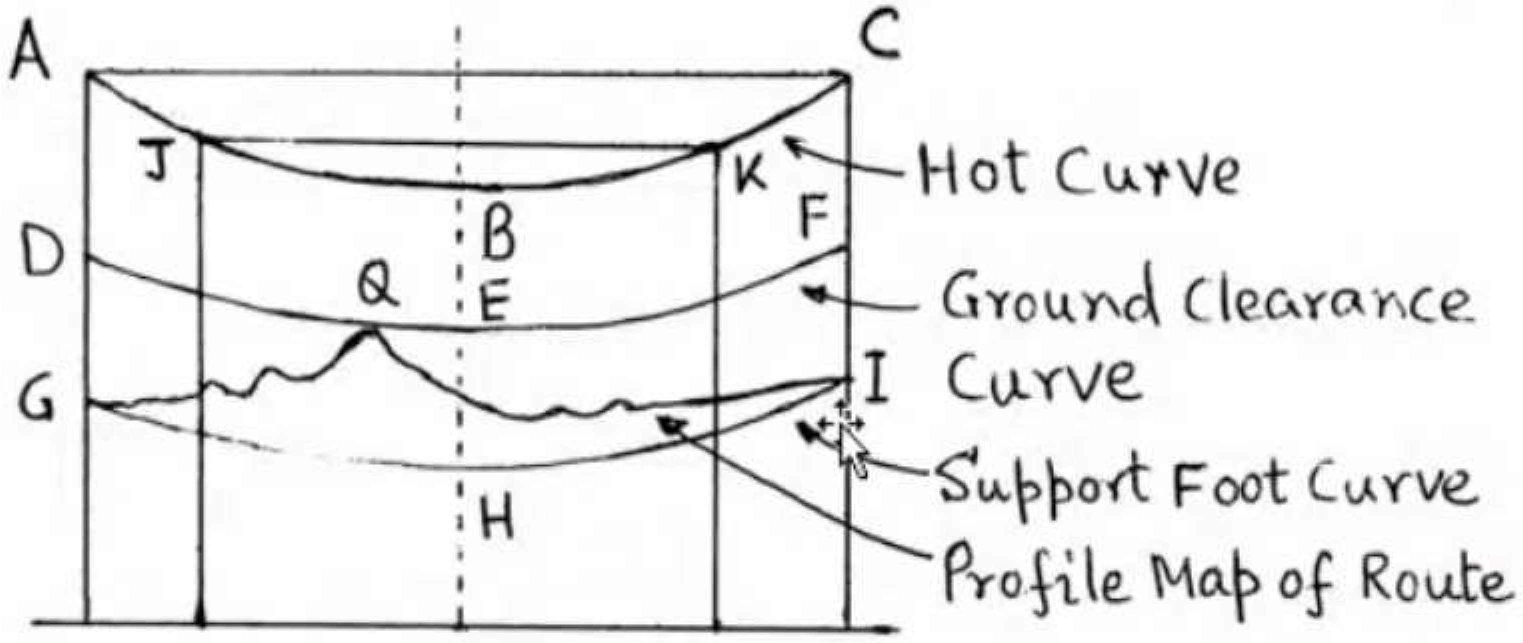
Sag Template



- Essential to allocate position & height of supports correctly on profile.
- Made of transparent celluloid, perspex or sometimes cardboard.
- Following curves are marked on it.

1. Hot temperature curve: Obtained by plotting sag at maxm. temp. vs. span length (AJBKC).
2. Ground clearance curve: Situated below the hot curve & is at a distance from it, equal to the ground clearance as prescribed by the regulations for the given line (DQEF).
3. Support foot curve: It gives location of the footing of towers. It is situated below the hot curve at a distance – height of a standard tower from the lowest point of attachment to the ground level (GHI).

- If such a template is placed on the profile map of the route & the two are adjusted such that –
- The ground clearance curve touches the profile map at one point (i.e. at 'Q') then –
- If 'G' & 'I' be the points where the profile map intercepts the support foot curve then GA & IC indicate the two supports.



4. Cold Curve or Uplift Curve:

- It is obtained by plotting sag at a minimum temperature without wind load against span length.
- This curve is drawn to check whether upliftment of conductor occurs on any support.
- The uplift conductor may occur at low temperature when one support is much lower than either of the adjoining ones.

Spacing of Conductors

- Trouble free service requires proper spacing of conductors.
- Spacing should be such that

(i) Corona loss is minimum &

(ii) Conductors do not clash during swing/vibration.

- There is no exact rule to calculate proper spacing of conductors.
- If spacing is not governed by (i) & (ii), a simple rule of 1 metre for every 100m span seems to be fairly accurate.
- Different countries use various empirical formulae → that give different spacing for same span & conductor size.

→ deduced from experience of conductor loading, conditions of temperature, wind, ice etc.

Some of the empirical formulae are

$$S = \sqrt{d} + \frac{V}{150}$$

$$S = \sqrt{d} + 0.012V$$

$$S = 0.75\sqrt{d} + \frac{V}{150}$$

$$S = 0.75\sqrt{d} + \frac{V^2}{20000}$$

$$S = 0.7\sqrt{d} + \frac{V}{100} + 0.25$$

$$S = 0.65\sqrt{d} + 0.007$$

$$S = 2d\sin\theta$$

$$S = 0.8\sqrt{d+l} + \frac{V}{150}$$

$$S = 0.75\sqrt{(d+l)\sin\theta} + \frac{V}{125}$$

where,

d = sag in metre,

V = voltage(kV) betn. conductors,

l = insulator string length (m) &

θ = deflection of insulator string.

❖ These formulae serve as guide, final choice depends on local conditions of temperature, ice & wind.

Forward 5 sec - [00:01:30 / 4%]

Ground Clearance

- For safety reasons, adequate clearance of conductor above ground must be maintained under all loading conditions.
- It depends on system voltage.
- Indian Electricity Act says a clearance of 17feet/ 5.18m is to be provided for 33kV line & for every additional 33kV or part thereof, additional 1 foot/ 0.3048m clearance should be provided.

Example : 132 kV line

$$132\,kV = 33 + \frac{(132-33)}{33} \times 33 = 33 + 3 \times 33\,kV$$

$\therefore$ Ground clearance $= 5.18 + 3 \times 0.3048 = 6.0944\,m$

Example : 400 kV line

$$400\,kV = 33 + \frac{(400-33)}{33} \times 33 = 33 + 11.1212 \times 33\,kV$$

$\therefore$ Ground clearance $= 5.18 + 11.1212 \times 0.3048 = 8.5697\,m$

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Line Inductance

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Line Parameters

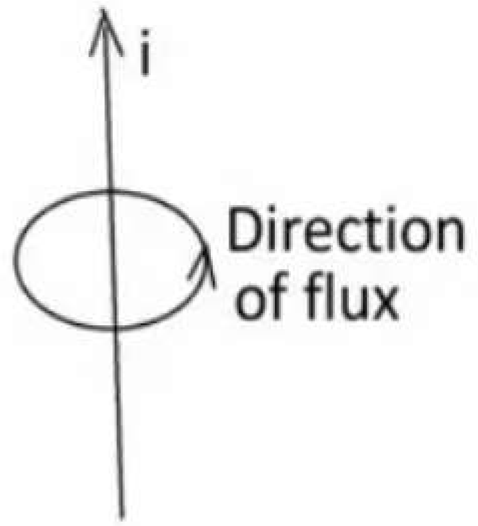
- Any electric transmission line has four parameters- resistance (R), inductance (L), capacitance (C)& shunt conductance (G).
- Design & performance of lines depend on these parameters.
- These are uniformly distributed along the whole line.
- So, theses are known as distributed parameters.
- Their values are given for unit length of the line.
- These are denoted as R, L, C & G.
- Their values depend on conductor geometry, line geometry & conductor material.
- R & L form the series impedance; C & G form the shunt admittance of the line.

SLIDE 103 OF 161 ENGLISH (INDIA) NOTES COMMENTS 74%

Forward 5 sec -[00:08:51 / 26%] EEC 401 - PPT 05.03.2021 USE IT - PowerPoint (Product Activation Failed)

Line Inductance

- A current carrying conductor produces flux surrounding it.
- With variation of current flux linkage of the conductor changes & an emf is induced in it (Faraday's law), i.e.,



$$|e| = \frac{d}{dt}(N\Phi) = N.\frac{d\Phi}{dt} \text{ Volt ..... (1)}$$

- Here, $N\Phi$ is the flux linkage of the conductor. in weber-turns.
- Again, self induced emf is proportional to rate of change of current, $\frac{di}{dt}$, i.e.

$$|e| \propto \frac{di}{dt} \quad \text{or, } |e| = L.\frac{di}{dt} \text{ Volt ..... (2)}$$

where, L is the constant of proportionality & is known as self inductance of the circuit.

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Equating eqns. (1) & (2),

$$L.\frac{di}{dt} = N.\frac{d\Phi}{dt}$$

$$\text{or, } L = N.\frac{d\Phi}{di} \; ..... (3)$$

- If permeability of the magnetic circuit is assumed to be constant, then, $\frac{d\Phi}{di} = \frac{\Phi}{i}$.
- Therefore, from eqn. (3),

$$L = N.\frac{\Phi}{i} \text{ Henry } ..... (4)$$

- For a single conductor,

$$L = \frac{\Phi}{i} \text{ Henry } ..... (5)$$

Forward 5 sec -[00:13:51 / 41%]

Inductance of a Conductor

- Consider, a solid, round, infinitely long conductor, situated in air - of radius 'r' & carrying a current of 'i.'
- Flux linking with conductor has two parts –

(i) the internal flux & (ii) the external flux.

- Internal flux is present inside conductor, due to its own current – does not link with whole conductor but only a fraction of it.
- External flux is present around the cond. -due to its own current & currents in other conductors in the vicinity.
- External flux links with the whole cond.

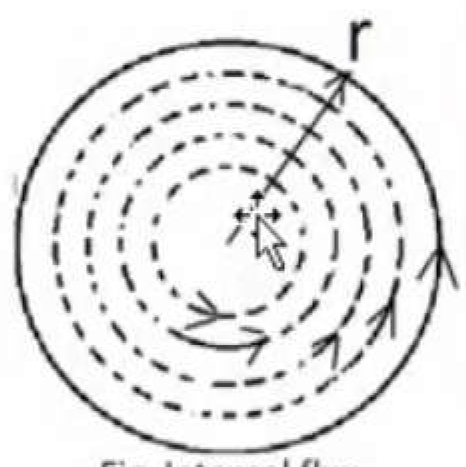

Fig. Internal flux

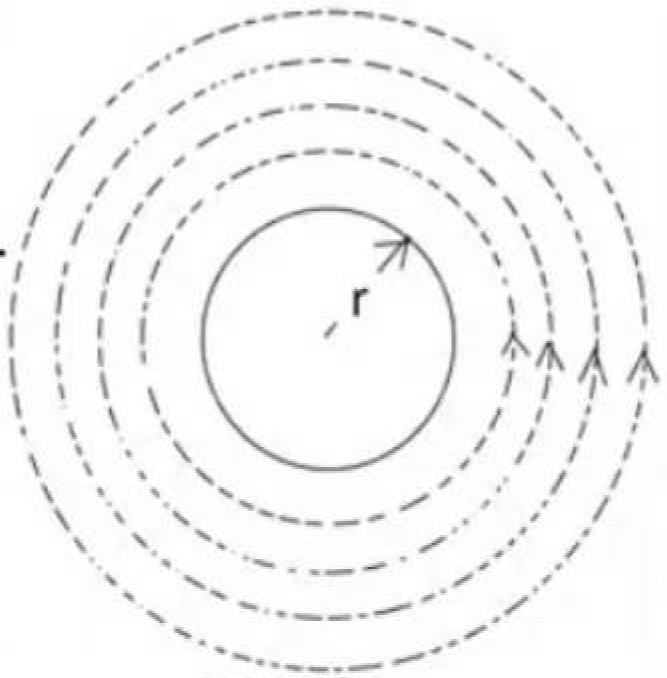

Fig. External flux

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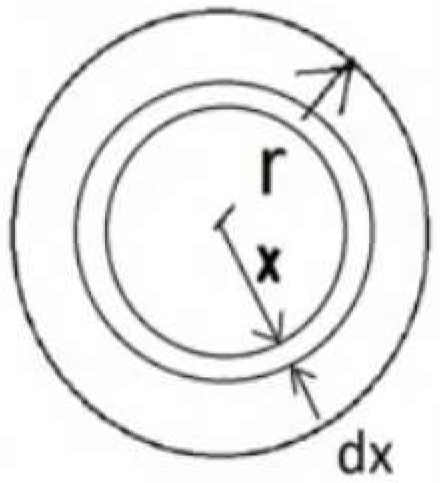
•Inductance due to internal flux – internal inductance (L_{in} H/m).

•Inductance due to external flux –external inductance(L_{ex} H/m).

- So, total inductance (per metre length) = [$L_{in} + L_{ex}$] H/m.

Internal Inductance



•Let, return path of the current in the cond. be so far away that its magnetic field is not affected.

• Current distribution is uniform over the cross section of the conductor.

- Consider, a distance ‘x’ & an elemental distance ‘dx’ there.
- Magnetic field intensity at distance ‘x’ be ‘H_x.’

Applying Ampere’s law,

$$2.\pi.x.\,H_x = i_x \;\ldots..\;(1)$$

where i_x is current enclosed by the path.

Or, $H_x = \frac{i_x}{2.\pi.x}$ AT/m .... (2)

Now, current density $= \frac{i}{\pi.r^2}$ .... (3)

Therefore, $i_x = \pi.x^2$. current density $= \pi.x^2.\frac{i}{\pi.r^2} = \frac{x^2}{r^2}.i$ A .. (4)

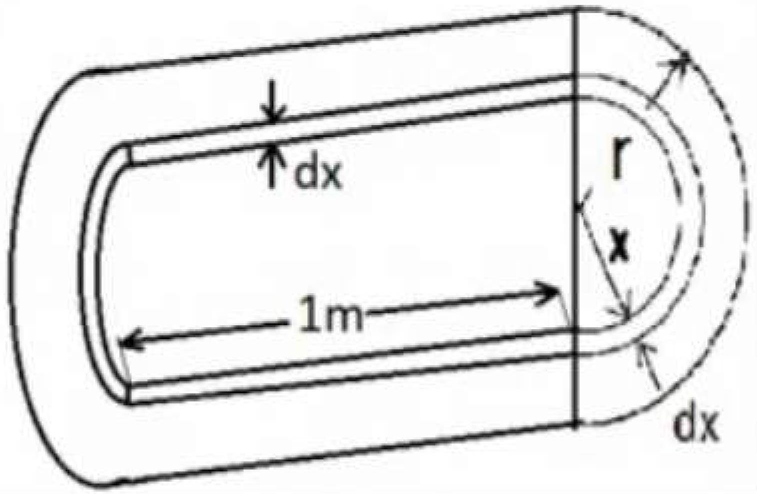
So, $H_x = \frac{x^2}{r^2}.i.\frac{1}{2.\pi.x} = i.\frac{x}{2.\pi.r^2}$ AT/m............................ (5)

Now, flux density $= B_x = \mu.H_x = \mu.i.\frac{x}{2.\pi.r^2}$ wb/m^2 .... (6)

where μ is permeability of cond. material. Now, flux through a cylindrical shell at a distance 'x' from the centre with thickness 'dx' & 1m length $= d\Phi_x = B_x.(dx.1) = \mu.i.\frac{x}{2.\pi.r^2}.dx$ wb......... (7)

Again, flux linkage = flux . (no. of turns)

Here, $d\Phi_x$ links with $\frac{x^2}{r^2}$ fraction of cond.



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So, flux linkage up to 'x' $= d\lambda_x = d\Phi_x . \frac{x^2}{r^2} = \mu.\, i.\, \frac{x}{2.\pi.r^2} .\, dx .\, \frac{x^2}{r^2}$

$$= \mu.\, i.\, \frac{x^3}{2.\pi.r^4} .\, dx \text{ wbT/m} \quad \ldots\ldots\ldots\ldots\ (8)$$

Total internal flux linkage $= \int_0^r d\lambda_x = \int_0^r \mu.\, i.\, \frac{x^3}{2.\pi.r^4} .\, dx$

$$= \frac{\mu.\, i}{2.\pi.r^4} . \frac{r^4}{4} = \frac{\mu.i}{8\pi} \text{ wbT/m} \quad \ldots\ldots\ldots\ldots\ (9)$$

Internal inductance $L_{in} = \dfrac{\text{Total internal flux linkage}}{\text{Current}}$

$$= \frac{\frac{\mu.i}{8\pi}}{i} = \frac{\mu}{8\pi} = \frac{\mu_0 .\, \mu_r}{8\pi} \text{ H/m} \quad \ldots\ldots\ldots\ldots\ (10)$$

If the conductor is suspended in air & conductor material is non-magnetic, then $\mu_r = 1$.

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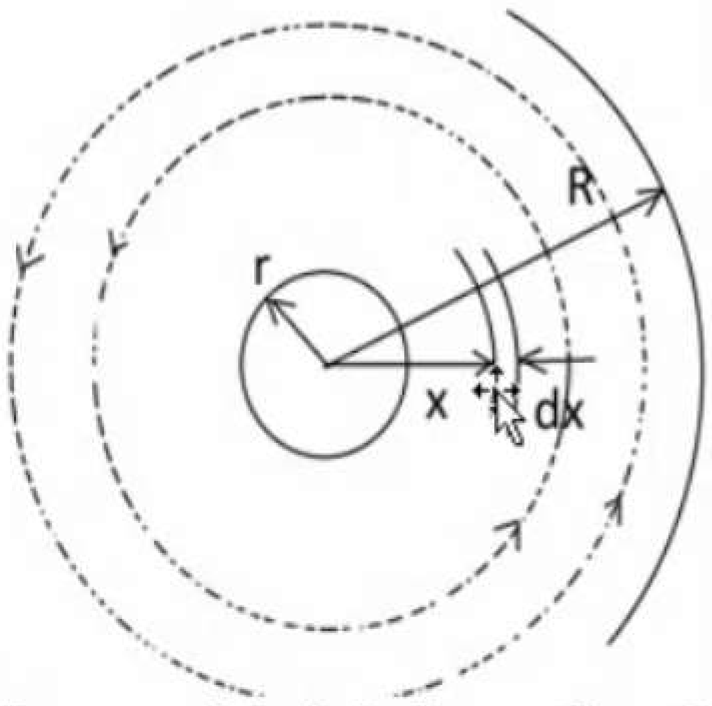
Then, $L_{in} = \frac{\mu_0}{8\pi}$ H/m $= \frac{4.\pi.10^{-7}}{8\pi} = \frac{1}{2}.10^{-7}$H/m .... (11)

Hence, internal inductance of any conductor is independent of cond. geometry (radius).

External Inductance

- Flux lines surrounding the cond. are in the form of concentric circles.



Magnetic field intensity at any distance

'x' = $H_x = \frac{i}{2.\pi.x}$ AT/m .... (12)

Flux density $= B_x = \mu_0 . H_x = \frac{\mu_0 . i}{2.\pi.x}$ wb/m^2

Flux through the cylindrical shell of thickness 'dx' & length of

1m $= d\Phi_x = B_x.(dx.1) = \frac{\mu_0 . i}{2.\pi.x} . dx$ .... (13)

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This flux links with the whole conductor. So, flux linkage

$$d\lambda_x = d\Phi_x.1 = d\Phi_x = \frac{\mu_0.i}{2.\pi.x}\,.\,dx \ \ wbT/m \ ..\ (14)$$

Therefore, total external flux linkage up to any very large but finite distance 'R' $= \int_r^R d\lambda_x = \int_r^R \frac{\mu_0.i}{2.\pi.x}\,.\,dx = \frac{\mu_0.i}{2.\pi}\,.\ln\frac{R}{r}$ wbT/m ..... (15)

Then, external inductance $L_{ex} = \dfrac{\text{Total external flux linkage}}{\text{Current}}$

$$= \frac{\mu_0}{2\pi}\,.\ln\frac{R}{r}\ H/m = \frac{4.\pi.10^{-7}}{2\pi} = 2.10^{-7}.\ln\frac{R}{r}\ H/m\ .....\ (16)$$

So, total inductance of the cond. per metre $= L = L_{in} + L_{ex}$

$$= \frac{1}{2}.10^{-7} + 2.10^{-7}.\ln\frac{R}{r}\ H/m\ .....\ (17)$$

Simplifying, $L = 2.10^{-7}.\ln\frac{R}{r'}$ H/m .... (18)

where $r' = r.\,e^{-\frac{1}{4}} = 0.7788.\,r$ = equivalent radius of cond.

Flux Linkage in a Group of Conductors

- Consider a group of 'n' long, parallel & round conductors a, b, c, ….n.
- Carrying currents $I_a, I_b, I_c, \ldots. I_n$.
- Forming a circuit, i.e.

  $I_a + I_b + I_c + \ldots. + I_n = 0$
- Distances $D_{ab}, D_{bc}, D_{ca}, \ldots., D_{an}$ etc. are large compared to the radii of the conductors $r_a, r_b, r_c, \ldots. r_n$ etc.
- Current distribution is uniform over the cross sectional area.
- The system is unaffected by external fields.

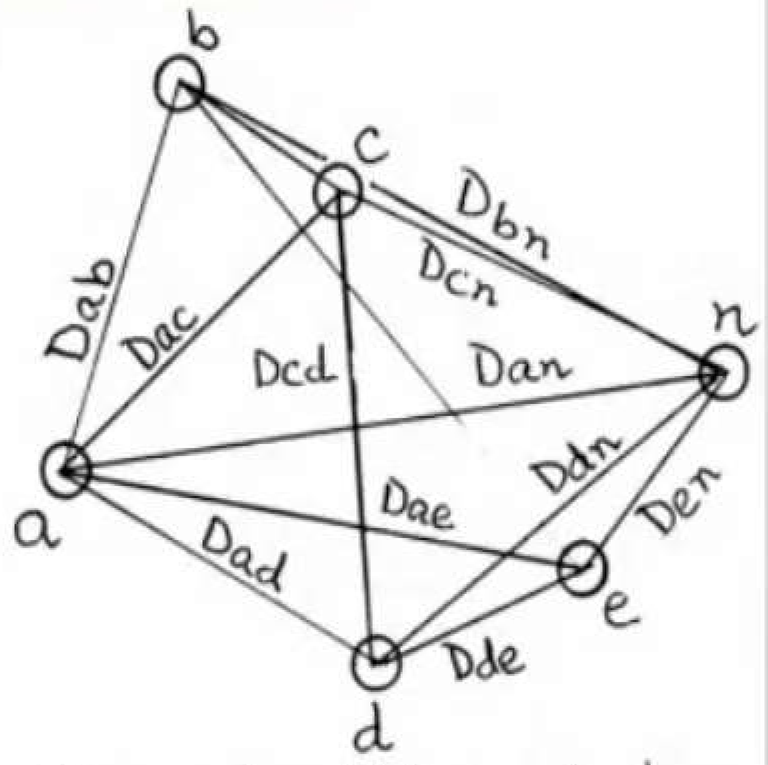


Fig. n-parallel conductors

Flux linkage λ_a of any conductor 'a' may be given as

$$\lambda_a = 2.10^{-7}\left[I_a.\ln\frac{1}{D_{aa}} + I_b.\ln\frac{1}{D_{ab}} + I_c.\ln\frac{1}{D_{ac}} + \cdots + I_n\ln\frac{1}{D_{an}}\right] \text{WbT/m}$$

$$= 2.10^{-7}\sum_{x=a}^{n} I_x \ln\frac{1}{D_{ax}} \text{ WbT/m}$$

Inductance of conductor 'a' = $L_a = \dfrac{\lambda_a}{I_a}$ H/m

Similarly, flux linkage λ_b of any conductor 'b' may be given as

$$\lambda_b = 2.10^{-7}\left[I_b.\ln\frac{1}{D_{bb}} + I_a.\ln\frac{1}{D_{ba}} + I_c.\ln\frac{1}{D_{bc}} + \cdots + I_n\ln\frac{1}{D_{bn}}\right] \text{WbT/m}$$

$$= 2.10^{-7}\sum_{x=b}^{n} I_x \ln\frac{1}{D_{bx}} \text{ WbT/m}$$

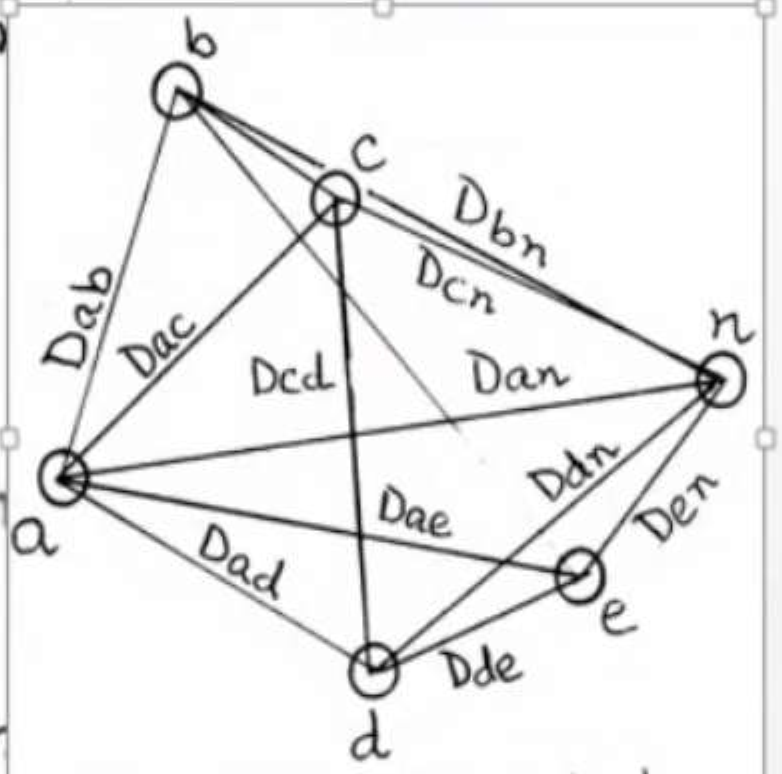
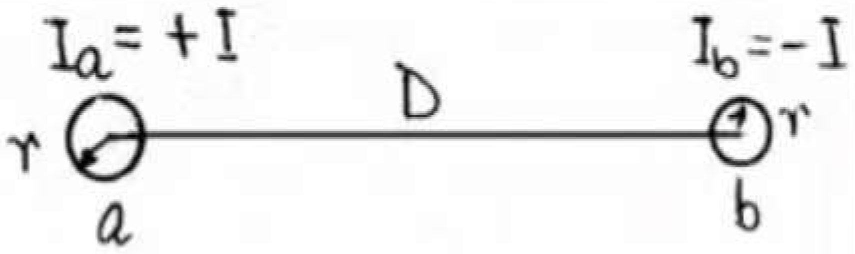


Fig. n-parallel conductors

Inductance of conductor 'b' = $L_b = \dfrac{\lambda_b}{I_b}$ H/m

Here, D_{aa} & D_{bb} are $r_a' = 0.7788\, r_a$ & $r_b' = 0.7788\, r_b$ respectively.

Inductance of 1Φ Line



Flux linkage of conductor 'a' $= \lambda_a$

$$= 2.10^{-7} \sum_{x=a}^{b} I_x . \ln \frac{1}{D_{ax}} = 2.10^{-7} \left[I_a \ln \frac{1}{D_{aa}} + I_b . \ln \frac{1}{D_{ab}} \right]$$

$$= 2.10^{-7} \left[I . \ln \frac{1}{r'} - I . \ln \frac{1}{D} \right] = 2.10^{-7} I \ln \frac{D}{r'} \ \text{wbT/m}$$

Inductance of conductor 'a' $= L_a = \frac{\lambda_a}{I_a} = 2.10^{-7} \ln \frac{D}{r'}$ H/m

Similarly, inductance of conductor 'b'

$$= L_b = 2.10^{-7} \ln \frac{D}{r'} \ \text{H/m}$$

So, total inductance $= L_{ab}$

$$= L_a + L_b = 4 . 10^{-7} . \ln \frac{D}{r'} \ \text{H/m}$$

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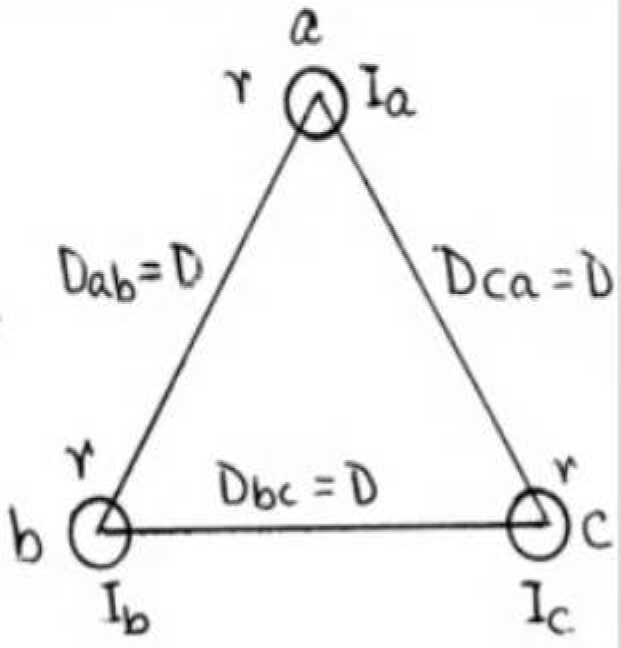
Inductance of Symmetrical 3Φ Line

- Symmetrical 3φ line: Conductors placed at corners of an equilateral triangle.
- Arrangement is also known as equilateral spacing.



Here, $I_a + I_b + I_c = 0$

$r' = 0.7788\,r$

Flux linkage of conductor 'a' $= \lambda_a$

$$= 2.10^{-7} \sum_{x=a} I_x \ln \frac{1}{D_{ax}} \ \text{wbT/m}$$

$$= 2.10^{-7} \left[I_a \ln \frac{1}{D_{aa}} + I_b \ln \frac{1}{D_{ab}} + I_c \ln \frac{1}{D_{ac}} \right] \text{wbT/m}$$

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$$= 2.10^{-7}\left[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D} + I_c . \ln\frac{1}{D}\right] \text{wbT/m}$$

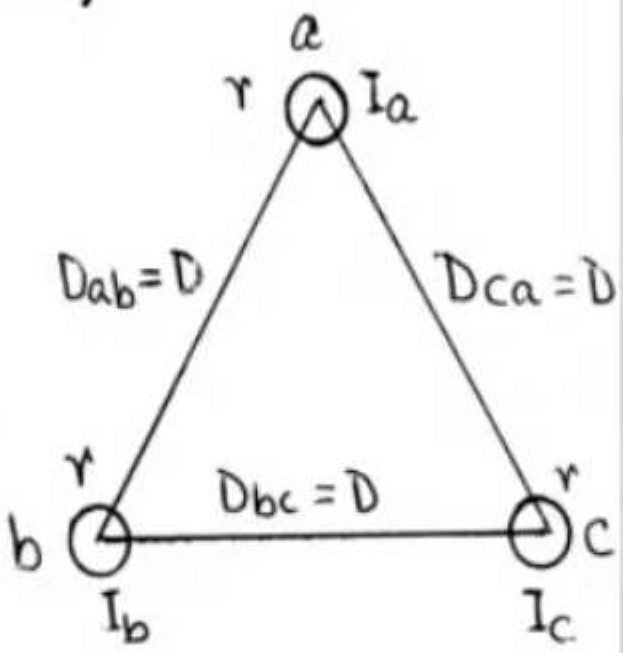
$$= 2.10^{-7}\left[I_a \ln\frac{1}{r'} + (I_b + I_c) \ln\frac{1}{D}\right]$$

$$= 2.10^{-7}\left[I_a \ln\frac{1}{r'} - I_a \ln\frac{1}{D}\right] (\text{as, } I_b + I_c = -I_a)$$

$$= 2.10^{-7} . I_a . \ln\frac{D}{r'} \ \text{wbT/m}$$

So, inductance of conductor 'a' $= L_a = \frac{\lambda_a}{I_a}$

$$= 2.10^{-7} \ln\frac{D}{r'} \ \text{H/m}$$



Here, $I_a + I_b + I_c = 0$

$r' = 0.7788r$

Again, flux linkage of conductor 'b' $= \lambda_b$

$$= 2.10^{-7} \sum_{x=b}^{c} I_x . \ln\frac{1}{D_{bx}} \ \text{wbT/m}$$

$$= 2.10^{-7}\left[I_b . \ln\frac{1}{D_{bb}} + I_a \ln\frac{1}{D_{ba}} + I_c \ln\frac{1}{D_{bc}}\right]$$

$$= 2.10^{-7}\left[I_b \ln\frac{1}{r'} + (I_a + I_c)\ln\frac{1}{D}\right]$$

$$= 2.10^{-7}\left[I_b \ln\frac{1}{r'} - I_b \ln\frac{1}{D}\right]$$

$$= 2.10^{-7} I_b . \ln\frac{D}{r'} \text{ WbT/m}$$

So, inductance of conductor 'b' $= L_b = \frac{\lambda_b}{I_b}$

$$= 2.10^{-7} \ln\frac{D}{r'} \text{ H/m}$$

Similarly, inductance of conductor 'c' $= L_c$

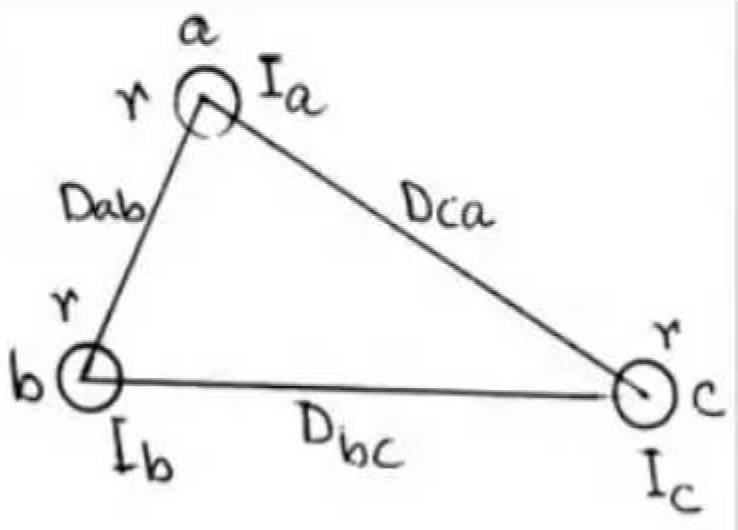
$$= 2.10^{-7} \ln\frac{D}{r'} \text{ H/m}$$

Hence, for same conductor and line geometry inductance per conductor of 3ϕ symmetrical line and 1ϕ line are equal.

Inductance of unsymmetrical 3Φ Line

- Take phase sequence as a-b-c.
- Take I_a as reference phasor.

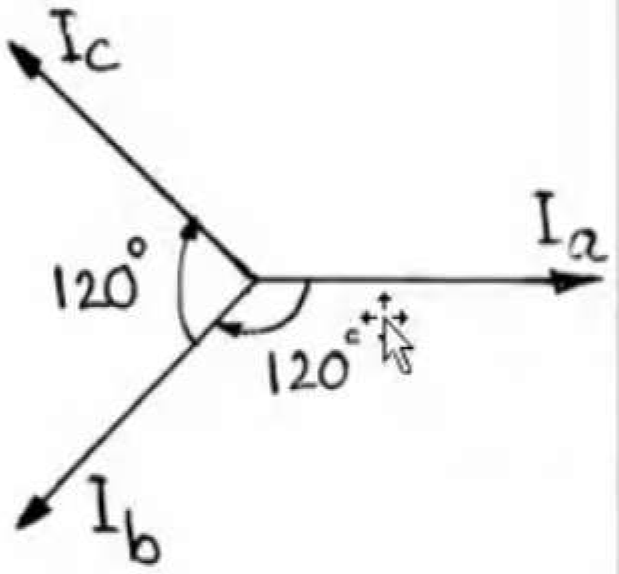
$$I_a = I\,(1 + j0)$$
$$I_b = I\,(-1/2 - j\sqrt{3}/2)$$
$$I_c = I\,(-1/2 + j\sqrt{3}/2)$$



Flux linkage of conductor 'a' $= \lambda_a$

$$= 2.10^{-7} \sum_{x=a}^{c} I_x \ln \frac{1}{D_{ax}} \quad Wb\,T/m$$

$$= 2.10^{-7}\left[I_a \ln \frac{1}{D_{aa}} + I_b \ln \frac{1}{D_{ab}} + I_c \ln \frac{1}{D_{ac}}\right]$$



$$= 2.10^{-7}\left[I(1+j0).\ln \frac{1}{r'} + I\left(-\frac{1}{2} - j\sqrt{3}/2\right).\ln \frac{1}{D_{ab}} + I\left(-\frac{1}{2} + j\sqrt{3}/2\right) \ln \frac{1}{D_{ac}}\right]$$

$$= 2.10^{-7}.I\left[\ln \frac{1}{r'} - \frac{1}{2} \ln \frac{1}{D_{ab}} - \frac{1}{2} \ln \frac{1}{D_{ac}} + j\sqrt{3}/2 . \ln \frac{1}{D_{ac}} - j\sqrt{3}/2 \ln \frac{1}{D_{ab}}\right]$$

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$$= 2.10^{-7} I \left[\ln \frac{1}{r'} - \frac{1}{2} \ln \frac{1}{D_{ab}.D_{ac}} + j\sqrt{3}/2 \ln \frac{D_{ab}}{D_{ac}} \right]$$

$$= 2.10^{-7}. I \left[\ln \frac{\sqrt{D_{ab}.D_{ac}}}{r'} + j\sqrt{3}/2 . \ln \frac{D_{ab}}{D_{ac}} \right] WbT/m$$

So, inductance of conductor 'a' $= L_a = \frac{\lambda_a}{I_a}$

$$= 2.10^{-7} \left[\ln \frac{\sqrt{D_{ab} D_{ac}}}{r'} + j\sqrt{3}/2 \ln \frac{D_{ab}}{D_{ac}} \right] H/m$$

Similarly,

Inductance of conductor 'b' $= L_b$

$$= 2.10^{-7} \left[\ln \frac{\sqrt{D_{bc} D_{ba}}}{r'} + j\sqrt{3}/2 \ln \frac{D_{bc}}{D_{ba}} \right] H/m$$

Inductance of conductor 'c' $= L_c$

$$= 2.10^{-7} \left[\ln \frac{\sqrt{D_{ca} D_{cb}}}{r'} + j.\sqrt{3}/2 \ln \frac{D_{cb}}{D_{ca}} \right] H/m$$

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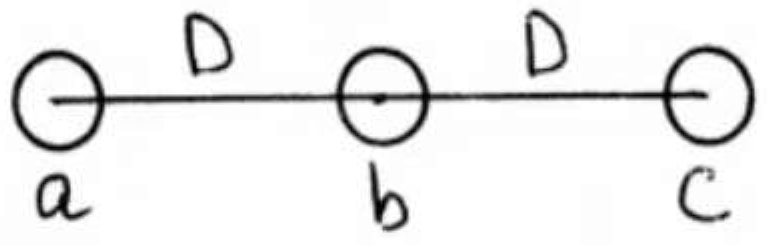
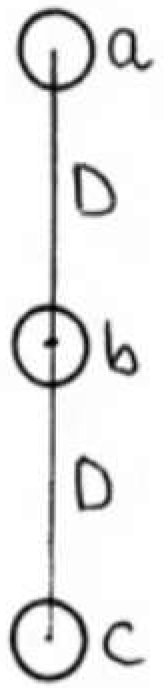
❖ Points to note -

- Inductances of the three phases are unequal.
- Although currents are balanced, inductances are unbalanced.
- Inductive voltage drops are unequal.
- Inductances are complex as λ_a, λ_b & λ_c are not in phase with I_a, I_b & I_c respectively.
- Due to the imaginary part power transfer takes amongst the phases by mutual induction.
- However, total power transfer in any case is zero.

Determine Inductances of the following 3ϕ systems.



Horizontal spacing



Vertical spacing

Power transfer between different phases by mutual induction

Let, inductance be represented by: $L = (a + jb - jc)$

So, inductive reactance $= j\omega L = j\omega\ (a + jb - jc)$

Taking current 'I' as reference, inductive voltage drop $= V_L$

$= I.\ j\omega L = j\omega.\ I\ (a + jb - jc)$

Therefore, apparent power $= V_L.\ I = j\omega.\ I^2 (a + jb - jc)$

$= j\omega\ I^2 a - \omega.\ I^2 b + \omega.\ I^2 c$ ..... (1)

In eqn. (1):

$j\omega\ I^2 a$ = reactive power.

$-\ \omega.\ I^2 b$ = negative active power = power received from other phases by mutual induction.

$+\ \omega.\ I^2 c$ = positive active power = power supplied to other phases by mutual induction.

Transposition of Transmission Lines

- Unsymmetrical spacing of line conductors is more common.
- It is due to cheapness & convenience of design & construction.
- However, unsymmetrical spacing of conductors makes -

(i) Unequal inductances, hence unequal inductive reactances of the three phases.

(ii) So, inductive voltage drops are unequal in the three phases for balance currents.

(iii) So, although the sending end voltages are balance, receiving end voltages are unbalanced.

(iv) Further, disturbance/interference takes place with the near by communication lines.

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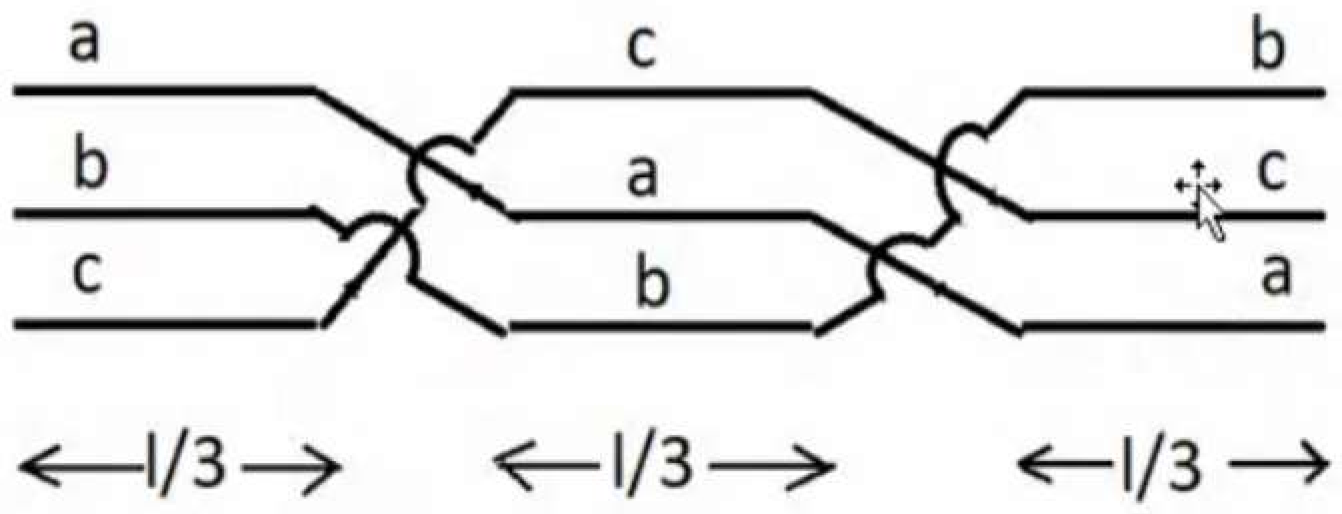
- These problems can be avoided/ reduced by transposition of transmission line conductors.
- In transposed 3Φ transmission lines all phase conductors occupy positions of other phase conductors for almost same length.



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Inductance of conductor ‘a’ = L_a

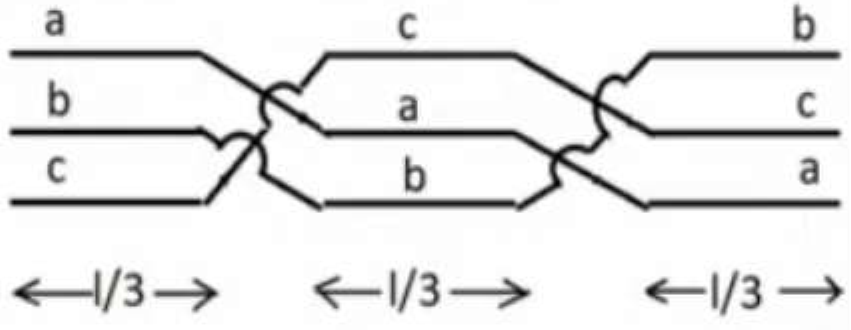
$= \frac{1}{3}$ [Inductance for first $\frac{1}{3}$rd length + Inductance for second $\frac{1}{3}$rd length + Inductance for third $\frac{1}{3}$rd length]

$$= \frac{2.10^{-7}}{3}\left[\ln\frac{\sqrt{D_{ab}.D_{ac}}}{r'} + j\frac{\sqrt{3}}{2}\ln\frac{D_{ab}}{D_{ac}} + \ln\frac{\sqrt{D_{bc}D_{ba}}}{r'} + j\frac{\sqrt{3}}{2}\ln\frac{D_{bc}}{D_{ba}} + \ln\frac{\sqrt{D_{ca}D_{cb}}}{r'} + j\frac{\sqrt{3}}{2}\ln\frac{D_{ca}}{D_{cb}}\right] H/m$$

$$= \frac{2.10^{-7}}{3}\left[\ln\frac{\sqrt{D_{ab}^2\,D_{bc}^2\,D_{ca}^2}}{(r')^3} + j\frac{\sqrt{3}}{2}\ln\frac{D_{ab}.D_{bc}.D_{ca}}{D_{ab}.D_{bc}.D_{ca}}\right]$$

$$= \frac{2.10^{-7}}{3}.3.\ln\frac{\sqrt[3]{D_{ab}.D_{bc}.D_{ca}}}{r'} + j.0$$

$$\text{So, } L_a = 2.10^{-7}\ln\frac{\sqrt[3]{D_{ab}.D_{bc}.D_{ca}}}{r'}\ H/m$$



Similarly, $L_b = L_c = 2.10^{-7} . \ln \dfrac{\sqrt[3]{D_{ab}.D_{bc}.D_{ca}}}{r'}$ H/m

$$= 2.10^{-7} \ln \frac{D_{eq.}}{r'} \text{ H/m}$$

Where, $D_{eq} = \sqrt[3]{D_{ab}.D_{bc}D_{ca}}$

= Geometric mean of D_{ab}, D_{bc} & D_{ca}

= Equivalent delta spacing/

Equivalent equilateral spacing

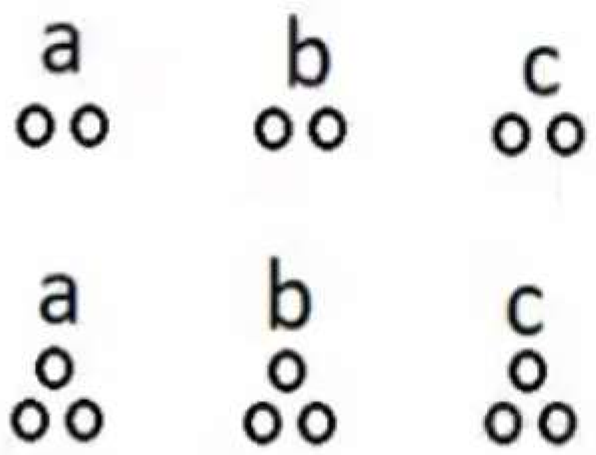
Method of Geometric Mean Distance (GMD)

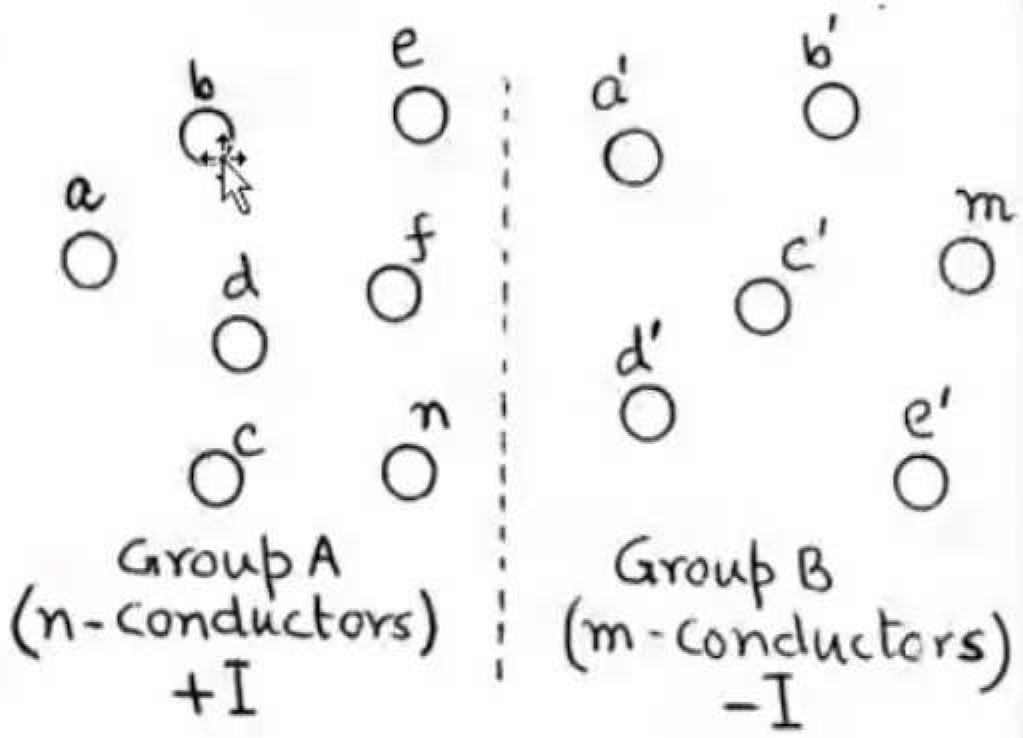
- This method is very convenient & useful to calculate inductance of lines, having several conductors connected in parallel for each phase.
- It is applicable to all cases of multi-strand or bundled conductor lines.

ao oc

bo ob

co oa





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- Consider, a 1ϕ line with two groups of conductors 'A' & 'B.'
- Group 'A' consists of 'n' straight, round & very long conductors, connected in parallel.
- Total current carried by group 'A' is + I.
- Each conductor in group 'A' carries a current of + I/n.
- Group 'B' consists of 'm' straight, round & very long conductors, connected in parallel.
- Each conductor in group 'B' carries a current of -I/m. Then,

Inductance of group A, consisting of 'n' conductors $= L_A$

$$= 2.10^{-7} \ln \frac{\left[(D_{aa'}.D_{ab'}\cdots D_{am}).(D_{ba'}.D_{bb'}\cdots D_{bm})\cdots\cdots(D_{na'}D_{nb'}\cdots D_{nm})\right]^{\frac{1}{n.m}}}{\left[(D_{aa}.D_{ab}\cdots D_{an}).(D_{ba}.D_{bb}\cdots D_{bn})\cdots\cdots(D_{na}.D_{nb}\cdots D_{nn})\right]^{\frac{1}{n^2}}} \ H/m$$

$$= 2.10^{-7} \ln \frac{D_m}{D_s} \ H/m$$

- Here, $D_{aa}, D_{bb}, \ldots, D_{nn} \rightarrow$ equivalent radius of conductors.

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Where,

- $D_m = [(D_{aa'}.D_{ab'}...D_{am}).(D_{ba'}.D_{bb'}...D_{bm}).....(D_{na'}D_{nb'}....D_{nm})]^{\frac{1}{m.n}}$

  = All possible distances $(m \times n)$ between conductors of groups A & B for which $(m \times n)$ th root is taken.

- This geometric mean is called mutual geometric mean distance (Mutual GMD) between conductors of groups A & B.

- $D_s = [(D_{aa}.D_{ab}...D_{an}).(D_{ba}.D_{bb}...D_{bn}).....(D_{na}.D_{nb}...D_{nn})]^{\frac{1}{n^2}}$

  = All possible distances $(n \times n)$ between conductors of group A for which $(n \times n = n^2)$ th root is taken.

- This geometric mean is called self geometric mean distance (Self GMD).

A.C. Single Phase Circuit

Here, $n = m = 1$

$$D_m = D$$

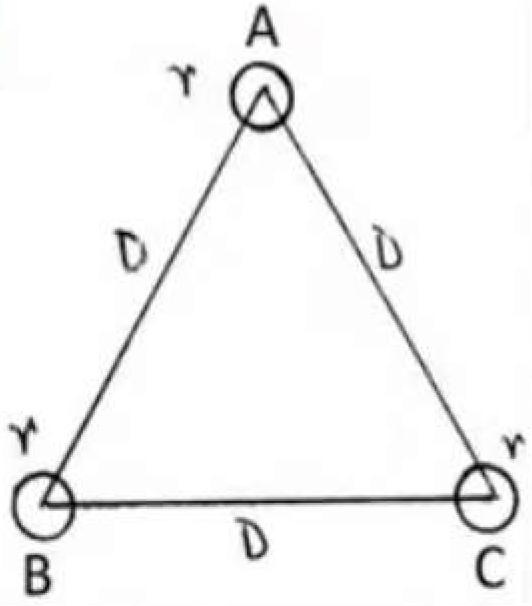
$$D_s = D_{aa} = 0.7788\,r = r'$$

$$\therefore L_A = 2.10^{-7} \ln \frac{D_m}{D_s} = 2.10^{-7} \ln \frac{D}{r'} \text{ H/m}$$

Similarly, $L_B = 2.10^{-7} \ln \frac{D}{r'}$ H/m

Total inductance $= L = L_A + L_B = 4.10^{-7} \ln \frac{D}{r'}$ H/m

A.C. Symmetrical Three Phase Line



Here, $n = 1$, $m = 2$

Inductance of conductor A is found first.

$$D_m = (D.D)^{\frac{1}{2.1}} = D, \quad D_s = D_{aa} = r'$$

$$\therefore L_A = 2.10^{-7} \ln \frac{D_m}{D_s} = 2.10^{-7} \ln \frac{D}{r'} \text{ H/m} = L_B = L_C$$

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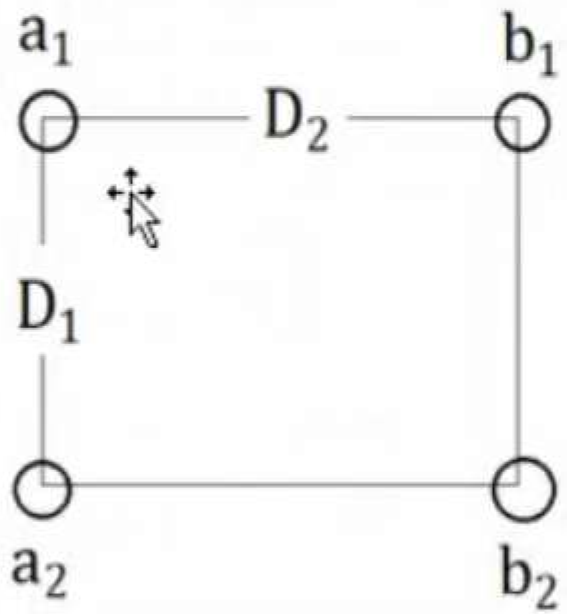
Inductance of 1Φ Double Circuit Line

- It consists of four parallel conductors.
- Conductors a_1 and a_2 are connected in parallel & carry current in one direction. In effect they form conductor A.
- Conductors b_1 & b_2 form the return path & they constitute the conductor B.
- All the conductors have same radius r.



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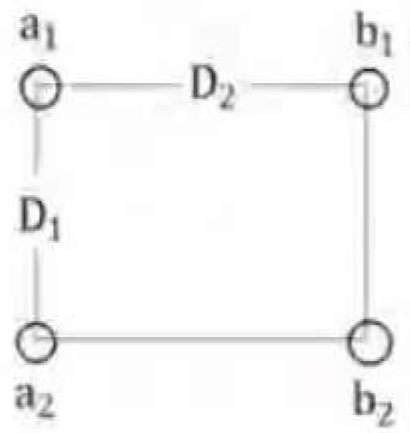
Here, $m = n = 2$

$$\therefore D_{s}' = \left[(D_{a_1a_1} \cdot D_{a_1a_2})(D_{a_2a_1} \cdot D_{a_2a_2})\right]^{1/4} = \left[(r' \cdot D_1)(D_1 \cdot r')\right]^{1/4} = (r' \cdot D_1)^{1/2}$$



$$D_m = \left[(D_{a_1b_1} \cdot D_{a_1b_2}) \cdot (D_{a_2b_1} \cdot D_{a_2b_2})\right]^{1/4}$$

$$= \left[\left(D_2 \cdot \sqrt{D_1^2 + D_2^2}\right) \cdot \left(\sqrt{D_1^2 + D_2^2} \cdot D_2\right)\right]^{1/4}$$

$$= \left(D_2 \cdot \sqrt{D_1^2 + D_2^2}\right)^{1/2}$$

Inductance of conductor A $= L_A = 2 \cdot 10^{-7} \ln \frac{D_m}{D_s}$ H/m

$$= 2 \cdot 10^{-7} \ln \frac{\left(D_2 \cdot \sqrt{D_1^2 + D_2^2}\right)^{1/2}}{(r', D_1)^{1/2}} \text{ H/m}$$

$$= 10^{-7} \ln \left(\frac{D_2 \cdot \sqrt{D_1^2 + D_2^2}}{(r' \cdot D_1)}\right) \text{ H/m} = L_B$$

Total inductance of the system $= L = L_A + L_B = 2 \cdot 10^{-7} \ln \left(\frac{D_2 \cdot \sqrt{D_1^2 + D_2^2}}{(r' \cdot D_1)}\right)$ H/m

Line Capacitance

Fundamentals -

- A capacitor essentially consists of two conducting surfaces separated by a layer of insulating (dielectric) material.
- The conducting surfaces may be in the form of either circular (or rectangular) plates or spherical or cylindrical shape.
- Overhead line conductors act as conducting surfaces & are separated by air dielectric→ condition for capacitor satisfied → capacitance exists amongst conductors.
- If one of the two surfaces has a charge of q coulomb & V be the potential difference between the two surfaces.
- Then, capacitance between the two surfaces $= C = \frac{q}{V}\ \frac{\text{Coulomb}}{\text{Volt}}$

$$= \frac{q}{V}\ \text{Farad}$$

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- One Farad is actually too large for all practical purposes.
- Much smaller units like micro-Farad (μF) & pico-Farad (pF) are more commonly used.
- $1\ \mu F = 10^{-6}\ F\ \&\ 1\ pF = 10^{-12}\ F$

Electric Field Intensity or Field Strength (E)

It may be defined in two ways:

(i) At any point in an electric field, E is proportional to the flux passing normally through a unit area at that point.

If, q = charge (flux) in Coulomb,

❖ In MKSA →One Coulomb charge emanates→ one line of flux.

A = area through which q flux pass normally &

$K = K_0 \, . \, K_r$ = permittivity of the medium where,

K_0 = permittivity of air = $\dfrac{1}{36.\pi.\,10^{-9}}$ F/m = $8.84194.\,10^{-12}$ F/m

K_r = relative permittivity.

$$E \propto \frac{q}{A} \text{ or, } E = \frac{1}{K}\cdot\frac{q}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Again, flux density $D = \dfrac{q}{A}$ ……………………………(2)

So, $D = K.E$ ……………………………………(3)

Hence, D & E both are vectors.

(ii) Electric field intensity at any point in an electric field is also defined as the force experienced by a unit +ve charge placed at that point.

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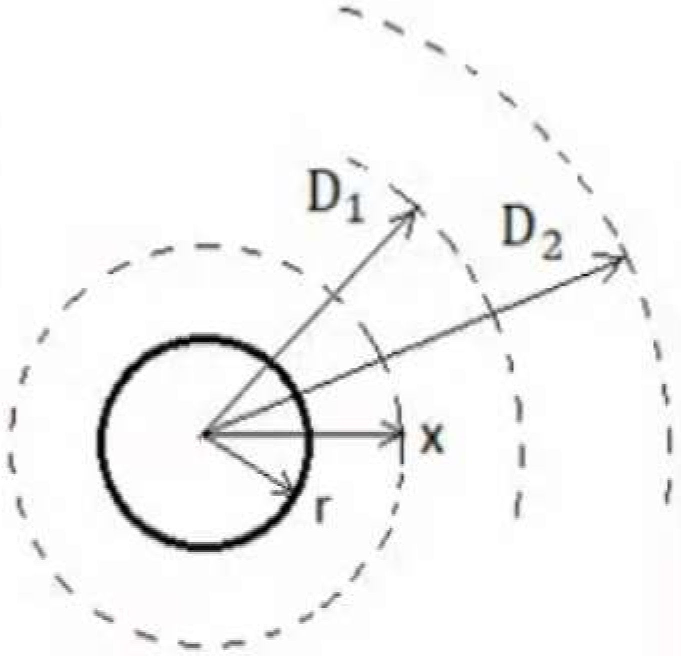
Potential at a Point

It is equal to the work done in bringing a unit +ve charge from infinity to that point.



- Consider a cond. carrying a charge of +q coulomb/m length.
- Electric flux density at a distance x =

$$D_x = \frac{q}{(2\pi x.1)} \text{ coulomb/m}^2$$

- Electric field intensity $E_x = \frac{D_x}{K} = \frac{1}{K} \cdot \frac{q}{2\pi x}$ Volts/m
- Potential at that point $= \int_{x=\infty}^{x=x} E_x.dx = \frac{q}{2\pi K} \cdot \int_{x=\infty}^{x=x} \frac{dx}{x}$
- For any equipotential surfaces at distances D_1 & D_2,

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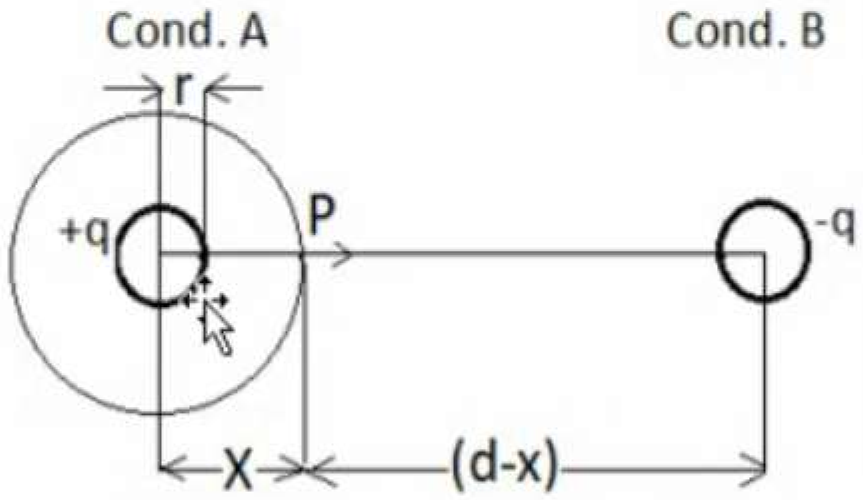
Potential difference $V_{D_1D_2} = \frac{q}{2\pi K} . \int_{D_1}^{D_2} \frac{dx}{x} = \frac{q}{2\pi K} . \ln \frac{D_2}{D_1}$

Capacitance between these equipotential surfaces $= \frac{q}{V_{D_1D_2}}$

$$= \frac{2\pi K}{\mathrm{Ln}\frac{D_2}{D_1}} \text{ F/m}$$

Capacitance of a single phase line

- Spacing of the conductors be d.
- Charge on conductor ‘A’ is +q Coulomb/m & charge on conductor ‘B’ is –q Coulomb/m.
- Radius of both conductors be r.
- P be any point at a distance x from conductor ‘A’.



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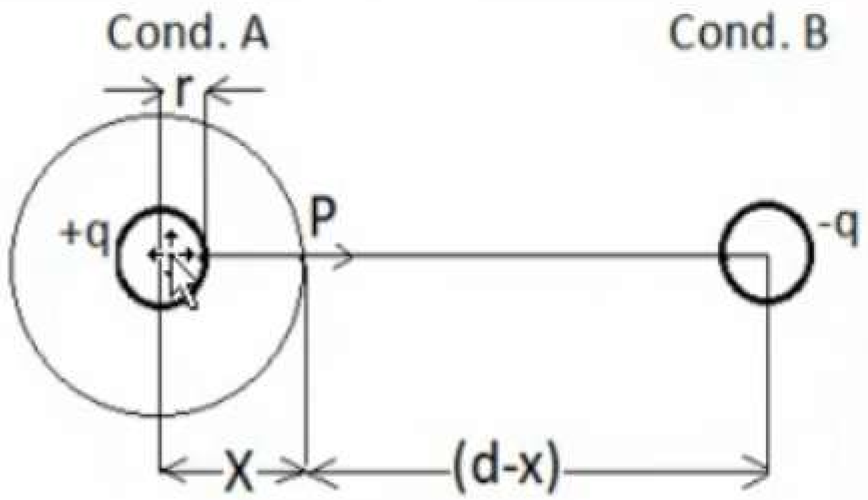
- Electric field intensity at P, due to charge of +q on cond. A =

$E_{xA} = \frac{q}{(2\pi x.1).K}$ V/m, acting in the direction of arrow ..... (1)



- Similarly, electric field intensity at P, due to charge of -q on cond. B = $E_{xB} = \frac{q}{\{2\pi(d-x).1\}.K}$ V/m, acting in the same direction ..... (2)
- Total electric field intensity at P due to both conds. A & B

$=E_x = E_{xA} + E_{xB}$

$= \frac{q}{(2\pi x.1).K} + \frac{q}{\{2\pi(d-x).1\}.K} = \frac{q}{2\pi K}\left[\frac{1}{x} + \frac{1}{d-x}\right]$ V/m ..... (3)

- Now, potential difference between conds. A & B= V_{AB} =Work done in moving 1 coulomb of charge from cond. A to cond. B.

- If 1 coulomb is moved through a distance of dx, then work done is $E_x.dx$.
- So, $V_{AB} = \int_{X=r}^{X=d-r} E_x.dx = \frac{q}{2\pi K}.\int_{r}^{d-r} [\frac{1}{x} + \frac{1}{d-x}].dx$

$$= \frac{q}{\pi K}.\ln\frac{d-r}{r} \text{ Volts} \; ..... (4)$$

So, capacitance between A & B $C_{AB} = \frac{q}{V_{AB}} = \frac{\pi K}{\ln\frac{d-r}{r}}$ F/m ..... (5)

As $r << d$, $d-r \approx d$.

Then, $C_{AB} = \frac{\pi K}{\ln\frac{d}{r}}$ F/m ..... (6)

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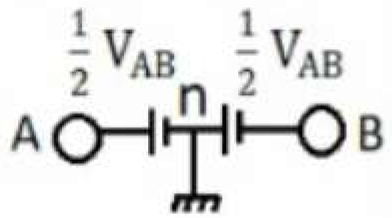
- Since the two conds. are oppositely charged, potential of the points mid way between the conds. is zero.
- So, this is a zero potential (neutral) plane between A & B.
- So, potential of each cond. w.r.t. this neutral plane $= \frac{1}{2}.V_{AB}$.
- Therefore, capacitance between each cond. & zero potential plane $= C_n = \dfrac{q}{\frac{1}{2}.V_{AB}} = \dfrac{2\pi K}{\ln\frac{d}{r}}$ F/m $= 2.C_{AB}$ ..... (7)



- C_n is called the capacitance to neutral/ground.
- The term capacitance to neutral is more common in transmission line calculations.

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System of n-conductors

- Consider, a system with 'n' long, straight and parallel conds.
- Conds. have a radius of 'r'.
- Charges on conds. be $q_a, q_b, q_c, \ldots, q_n$.
- Conds. are forming a circuit, i.e.

  $q_a + q_b + q_c + \ldots + q_n = 0$ ..... (1)
- Spacing between conds. D_{ab}, D_{bc}, D_{cd} etc. are very large compared to radius 'r'.
- Conds. are far removed from ground.

➤ Principle of superposition is applied to find out the potential difference between any two conds.

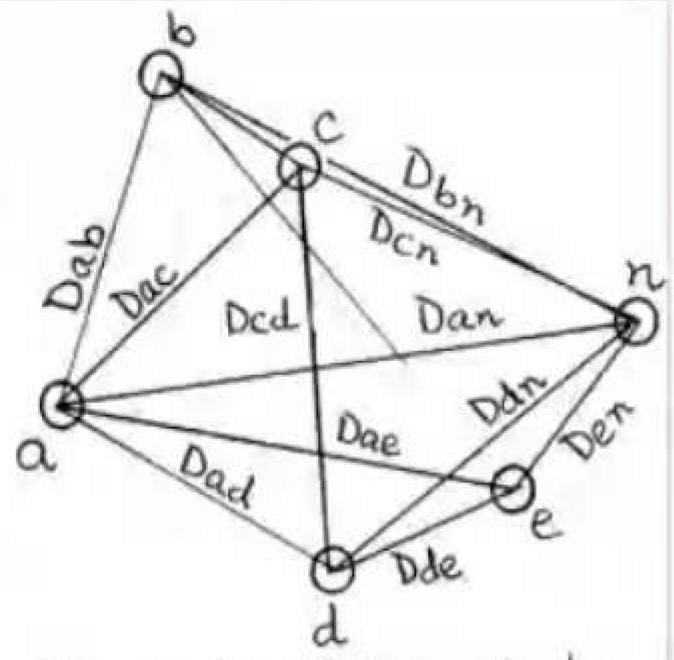

Fig. n-parallel conductors

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Principle: Potential difference between any two conds.=

Potential difference due to charge on the 1st cond. alone +

Potential difference due to charge on the 2nd cond. alone +

Potential difference due to other charged conds. present individually. This means

Potential difference between conds. 'a' & 'b' = V_{ab} =

Potential diff. between conds. 'a' & 'b' due to charge q_a on 'a' +

Potential diff. between conds. 'a' & 'b' due to charge q_b on 'b' +

Potential diff. between conds. 'a' & 'b' due to charge q_c on 'c' +

..............+

Potential diff. between conds. 'a' & 'b' due to charge q_n on 'n'

$$= \frac{q_a}{2\pi K}.\ln\frac{D_{ab}}{r} + \frac{q_b}{2\pi K}.\ln\frac{r}{D_{ba}} + \frac{q_c}{2\pi K}.\ln\frac{D_{cb}}{D_{ca}} + \ldots + \frac{q_n}{2\pi K}.\ln\frac{D_{nb}}{D_{na}}\ \text{V}$$

[Taking help of the relation $\rightarrow V_{D_1D_2} = \frac{q}{2\pi K}.\ln\frac{D_2}{D_1}$, take 'a' → first surface (D_1) & 'b' as the second surface (D_2).]

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$$= \frac{1}{2\pi K}\left[q_a . \ln\frac{D_{ab}}{r} + q_b . \ln\frac{r}{D_{ba}} + q_c . \ln\frac{D_{cb}}{D_{ca}} + \ldots + q_n . \ln\frac{D_{nb}}{D_{na}}\right] V \quad \ldots (2)$$

For symmetrical results 'r' may be written as D_{aa}, D_{bb}, D_{cc} etc.

So, eqn. (2) can be written as

$$V_{ab} = \frac{1}{2\pi K}\left[q_a . \ln\frac{D_{ab}}{D_{aa}} + q_b . \ln\frac{D_{bb}}{D_{ba}} + q_c . \ln\frac{D_{cb}}{D_{ca}} + \ldots + q_n . \ln\frac{D_{nb}}{D_{na}}\right] V \quad \ldots (3)$$

Similarly, potential diff. between conds. 'a' & 'n' = V_{an}

$$= \frac{1}{2\pi K}\left[q_a . \ln\frac{D_{an}}{D_{aa}} + q_b . \ln\frac{D_{bn}}{D_{ba}} + q_c . \ln\frac{D_{cn}}{D_{ca}} + \ldots + q_n . \ln\frac{D_{nn}}{D_{na}}\right] V$$

$$= \frac{1}{2\pi K} . \sum_{x=a}^{x=n} q_x . \ln\frac{D_{xn}}{D_{xa}} \text{ Volts} \quad \ldots (4)$$

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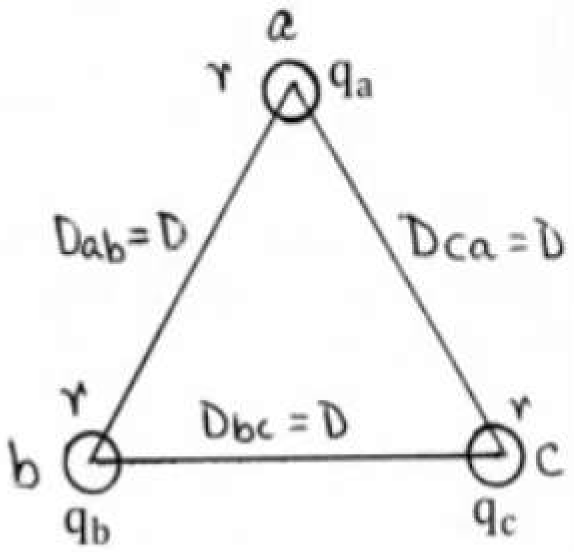
Capacitance of Symmetrical Three Phase Line

- Let, a balanced voltage be applied.
- Charges on the conductors be q_a, q_b and q_c Coulomb/m.



$$V_{ab} = \frac{1}{2\pi K}[q_a . \ln \frac{D_{ab}}{D_{aa}} + q_b . \ln \frac{D_{bb}}{D_{ba}} + q_c . \ln \frac{D_{cb}}{D_{ca}}]$$

$$= \frac{1}{2\pi K}[q_a . \ln \frac{D}{r} + q_b . \ln \frac{r}{D} + q_c . \ln \frac{D}{D}]$$

$$= \frac{1}{2\pi K}[q_a . \ln \frac{D}{r} + q_b . \ln \frac{r}{D}] \quad ..... (1)$$

Similarly, $V_{ac} = \frac{1}{2\pi K}[q_a . \ln \frac{D_{ac}}{D_{aa}} + q_b . \ln \frac{D_{bc}}{D_{ba}} + q_c . \ln \frac{D_{cc}}{D_{ca}}]$

$$= \frac{1}{2\pi K}[q_a . \ln \frac{D}{r} + q_b . \ln \frac{D}{D} + q_c . \ln \frac{r}{D}] = \frac{1}{2\pi K}[q_a . \ln \frac{D}{r} + q_c . \ln \frac{r}{D}]$$

..... (2)

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$$V_{ab}+V_{ac}=\frac{1}{2\pi K}\left[\,2q_a.\ln\frac{D}{r}+(q_b+q_c).\ln\frac{r}{D}\right] \;.....\;(3)$$

For a balanced system $q_a+q_b+q_c=0$ Or, $q_b+q_c=-q_a$

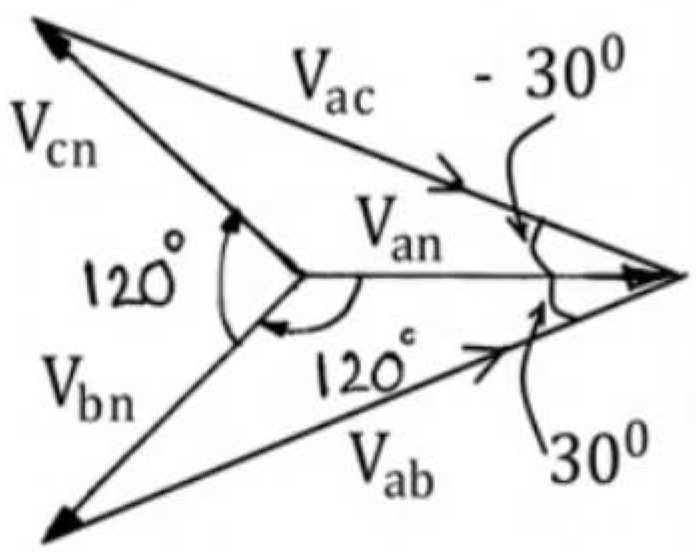
So, $$V_{ab}+V_{ac}=\frac{1}{2\pi K}\left[\,2q_a.\ln\frac{D}{r}-q_a.\ln\frac{r}{D}\right]=\frac{3q_a}{2\pi K}.\ln\frac{D}{r} \;.....\;(4)$$

Here, $V_{ab}=|V_{ab}|\angle 30^0$

$= \sqrt{3}.V_{an}\angle 30^0 = \sqrt{3}.V_{an}\left(\frac{\sqrt{3}}{2}+j.\frac{1}{2}\right)$

Also, $V_{ac}=|V_{ac}|\angle -30^0$

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



Therefore, $V_{ab}+V_{ac}=3.V_{an}$ ..... (5)

From eqns. (4) & (5)

$$3.V_{an}=\frac{3q_a}{2\pi K}.\ln\frac{D}{r}$$

Or, $V_{an} = \frac{q_a}{2\pi K}.\ln\frac{D}{r}$ V

Hence, line to neutral capacitance= $C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi K}{\ln\frac{D}{r}}$ F/m.....(6)

$= C_{bn} = C_{cn}$ (due to symmetrical spacing)

- So, for same cond. spacing and cond. radius capacitance to neutral is same for single phase line & three phase symmetrical line.

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Capacitance of Unsymmetrical Three Phase Line

$$V_{ab}=\frac{1}{2\pi K}[q_a.\ln\frac{D_{ab}}{D_{aa}}+q_b.\ln\frac{D_{bb}}{D_{ba}}+q_c.\ln\frac{D_{cb}}{D_{ca}}]$$

$$=\frac{1}{2\pi K}[q_a.\ln\frac{D_{ab}}{r}+q_b.\ln\frac{r}{D_{ba}}+q_c.\ln\frac{D_{cb}}{D_{ca}}]\text{ Volts ..... (1)}$$

$$V_{ac}=\frac{1}{2\pi K}[q_a.\ln\frac{D_{ac}}{D_{aa}}+q_b.\ln\frac{D_{bc}}{D_{ba}}+q_c.\ln\frac{D_{cc}}{D_{ca}}]$$

$$=\frac{1}{2\pi K}[q_a.\ln\frac{D_{ac}}{r}+q_b.\ln\frac{D_{bc}}{D_{ba}}+q_c.\ln\frac{r}{D_{ca}}]\text{ Volts ..... (2)}$$

$$V_{ab}+V_{ac}=\frac{1}{2\pi K}[q_a.\ln\frac{D_{ab}.D_{ac}}{r^2}+q_b.\ln\frac{r.D_{bc}}{D_{ba}^2}+q_c.\ln\frac{D_{cb}.r}{D_{ca}^2}]\quad V$$

..... (3)

For a complete circuit $q_a+q_b+q_c=0$.

Taking phase sequence as a-b-c

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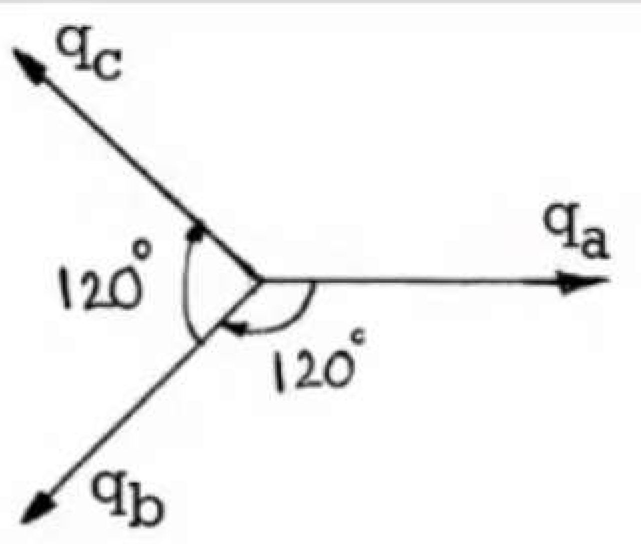
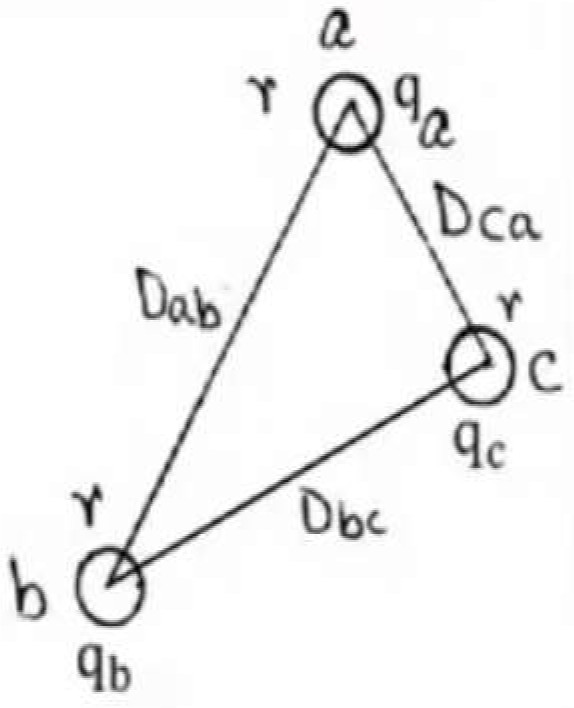
$$q_a = q(1 + j.0)$$

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

$$q_c = q\left(-\frac{1}{2} + j.\frac{\sqrt{3}}{2}\right)$$





Substituting in eqn. (3)

$$V_{ab}+V_{ac} = \frac{q}{2\pi K}\left[\ln\frac{D_{ab}D_{ac}}{r^2} + \left(-\frac{1}{2} - j.\frac{\sqrt{3}}{2}\right).\ln\frac{r.D_{bc}}{D_{ba}^{\ 2}} + \left(-\frac{1}{2} + j.\frac{\sqrt{3}}{2}\right).\ln\frac{D_{cb}.r}{D_{ca}^{\ 2}}\right] \text{ V} \quad \ldots\ldots (4)$$

Simplifying and rearranging the real and imaginary parts,

$$V_{ab}+V_{ac} = \frac{q}{2\pi K}\left[\ln\frac{(D_{ab}D_{ac})^2}{r^3.D_{bc}} + j.\sqrt{3}.\ln\frac{D_{ab}}{D_{ac}}\right] = 3.V_{an}$$

$$V_{an} = \frac{q}{6\pi K}\left[\ln \frac{(D_{ab}.D_{ac})^2}{r^3.D_{bc}} + j.\sqrt{3}.\ln \frac{D_{ab}}{D_{ac}}\right] \text{ Volts ..... (5)}$$

$$C_{an} = \frac{q_a}{V_{an}} = \frac{6\pi K}{\left[\ln \frac{(D_{ab}.D_{ac})^2}{r^3.D_{bc}} + j.\sqrt{3}.\ln \frac{D_{ab}}{D_{ac}}\right]} \text{ F/m ..... (6)}$$

Similarly,

$$C_{bn} = \frac{6\pi K}{\left[\ln \frac{(D_{bc}.D_{ba})^2}{r^3.D_{ac}} + j.\sqrt{3}.\ln \frac{D_{bc}}{D_{ba}}\right]} \text{ F/m ..... (7)}$$

$$C_{bn} = \frac{6\pi K}{\left[\ln \frac{(D_{ca}.D_{cb})^2}{r^3.D_{ab}} + j.\sqrt{3}.\ln \frac{D_{ca}}{D_{cb}}\right]} \text{ F/m ..... (8)}$$

- Capacitance of different phases are different.
- It is due to unsymmetrical spacing of conductors.
- So, different charging currents for different phases.
- This causes unbalanced receiving end voltages although sending end voltages are balanced.
- Capacitances are complex numbers as q_a, q_b & q_c are not in phase with V_{an}, V_{bn} & V_{cn} respectively.
- Due to presence of the imaginary part power transfer takes place between various phases, although at any instant of time total power transfer is zero.

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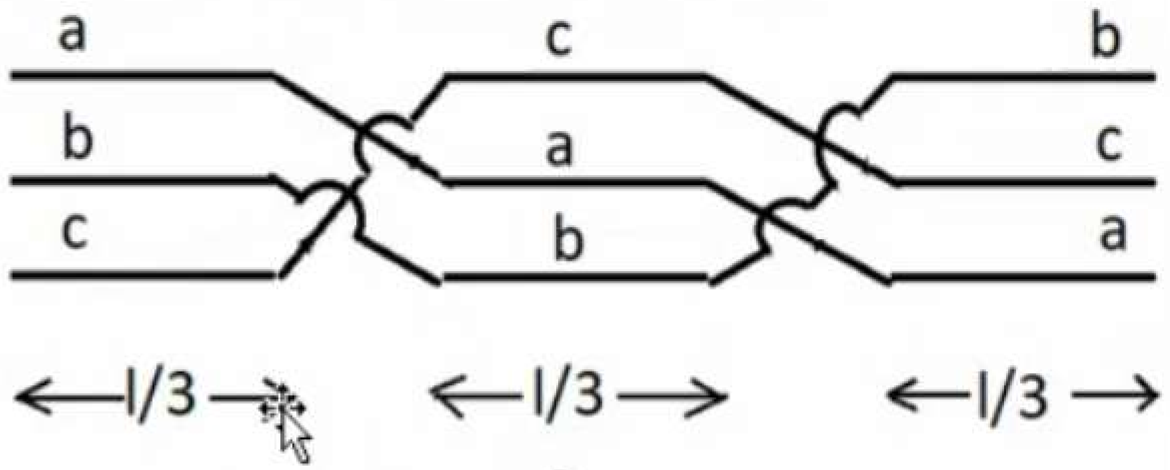
Capacitance of a Transposed 3Φ Unsymmetrical Line

- Here, average capacitance of 3Φ are equal.



For the 1st 1/3 distance,

$$(V_{ab}+V_{ac})_1=\frac{q}{2\pi K}\left[\ln\frac{(D_{ab}.D_{ac})^2}{r^3.D_{bc}}+j.\sqrt{3}.\ln\frac{D_{ab}}{D_{ac}}\right]\ \text{V}$$

For the 2nd 1/3 distance,

$$(V_{ab}+V_{ac})_2=\frac{q}{2\pi K}\left[\ln\frac{(D_{bc}.D_{ba})^2}{r^3.D_{ac}}+j.\sqrt{3}.\ln\frac{D_{bc}}{D_{ba}}\right]\ \text{V}$$

For the 3rd 1/3 distance,

$$(V_{ab}+V_{ac})_3=\frac{q}{2\pi K}\left[\ln\frac{(D_{ca}.D_{cb})^2}{r^3.D_{ab}}+j.\sqrt{3}.\ln\frac{D_{ca}}{D_{cb}}\right]\ \text{V}$$

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$$(V_{ab}+V_{ac}) = \frac{1}{3}\cdot[(V_{ab}+V_{ac})_1 + (V_{ab}+V_{ac})_2 + (V_{ab}+V_{ac})_3]$$

$$= \frac{q}{6\pi K}\left[\ln\left\{\frac{(D_{ab}.D_{bc}.D_{ca})^4}{(r^9 D_{ab}.D_{bc}.D_{ca})}\right\} + j.\sqrt{3}.\ln\left\{\frac{(D_{ab}.D_{bc}.D_{ca})}{(D_{ab}.D_{bc}.D_{ca})}\right\}\right]$$

$$= \frac{q}{6\pi K}.\ln\left\{\frac{(D_{ab}.D_{bc}.D_{ca})^3}{r^9}\right\}$$

$$= \frac{9q}{6\pi K}.\ln\left\{\frac{\sqrt[3]{D_{ab}.D_{bc}.D_{ca}}}{r}\right\} \quad V \;\ldots..\;(1)$$

Again, $V_{ab}+V_{ac} = 3.V_{an}$ V ..... (2)

So, from eqns. (1) & (2),

$$3.V_{an} = \frac{9q}{6\pi K}.\ln\left\{\frac{\sqrt[3]{D_{ab}.D_{bc}.D_{ca}}}{r}\right\} \;\ldots..\;(3)$$

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Or, $V_{an} = \frac{q}{2\pi K} . \ln \{\frac{\sqrt[3]{D_{ab}.D_{bc}.D_{ca}}}{r}\}$ Volts ..... (4)

Hence, line to neutral capacitance= $C_{an} = \frac{q}{V_{an}}$

$$= \frac{2\pi K}{\ln \{\frac{\sqrt[3]{D_{ab}.D_{bc}.D_{ca}}}{r}\}} = \frac{2\pi K}{\ln \frac{D_{eq}}{r}} = C_{bn} = C_{cn} \text{ F/m.....(5)}$$

Where, $D_{eq} = \sqrt[3]{D_{ab}.D_{bc}.D_{ca}}$

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Thank you.