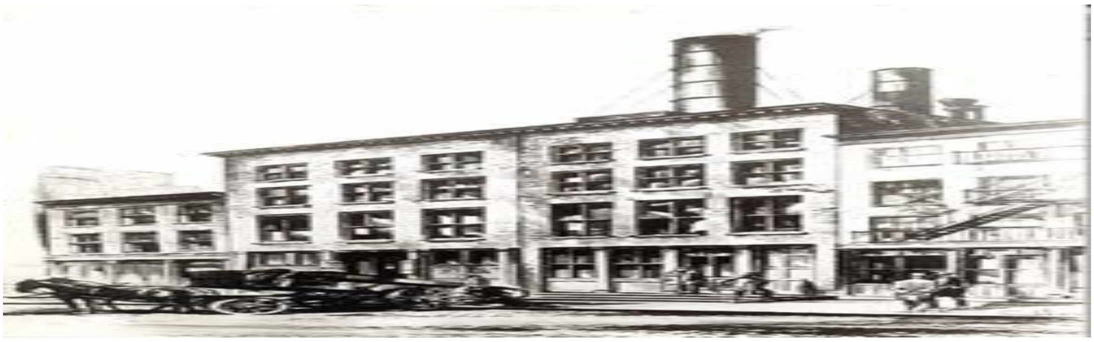
Prepared By:- Er. Chandan Mandal, Assistant Professor, EE department, ABIT, Cuttack

INTRODUCTION:- Present Day Civilization & Historical Days mankind, both are very much linked with energy & for our future needs also we are dependent upon different forms of energy.

In the Energy Hierarchy, electrical energy occupies the top position which is widely used in home, industry, agriculture & Transport.

Electrical Energy is the most convenient form of energy as it is generated in bulk at a place & transmitted over long distances in economical way.

EVOLUTION OF POWER SYSTEMS:- A continuous development is going on in the field of Electricity for past 130 Years. Evolution of what we see in present can be dated back to 1882, when Edison started the first power station in the world i.e. Pearl Street Generating Station in USA.



The Pearl street station powered 59 customers & generated DC which operated at a single voltage value. Due to the disadvantage of inability to step up the voltage, so that loss can be minimized, the distance to which customers were served was 800m approx.

It was in 1872, when first known electric motor was patented by Samuel Gardiner in which an electromagnet started & stopped a clock in order to measure the flow duration & not the amount of current.

In another development, Hermann Aron Patented a recording meter in 1883 which showed the energy used on clock dials. Edison devised a meter which consisted of two electrodes in an electrolyte to measure the amount of energy consumed.

In 1885, G. Westinghouse patented Gaulard-Gibbs Transformer. In 1886, one of the engineers of Westinghouse came to know about the disadvantage of series connection & advantage of parallel connection of transformers.

In 1888, Westinghouse licensed Nikola Tesla's Patents for polyphase AC induction motor & design of the transformer. 1891, Westinghouse installed first major power system to drive a 100HP synchronous motor.

In 1895, AC was choosen as transmission standard & Westinghouse built Adams No.1 Generating Station at Niagara Falls.

In 1936, first HVDC line using Mercury Arc Valves was built between Schenectady & Mechanicville Newyork.

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1n 1957, General Electric Research Group developed first thyristor suitable for use in power application area & Siemens developed a Solid State Rectifier. In Recent Years, Computers are used significantly for load flow studies.

PRESENT DAY SCENARIO:- As of March 31, 2024, India's total installed power capacity is 442 gigawatts (GW). This includes 43% renewable energy plants, such as large hydroelectric power plants.

The total installed capacity is broken down by sector as follows:

Central Sector: 102,274.94 MW
State Sector: 106,332.93 MW
Private Sector: 219,691.40 MW

As of 31 March 2024, India's electricity generation in 2023-24 was 1731.28 billion units (BU).

Ministry had set a target of 1750 BU for 2023-24, which includes: 1324.110 BU thermal, 156.700 BU hydro, 46.190 BU nuclear, 8 BU import from Bhutan, and 215 BU RES (excluding large hydro).

Details of installed capacity and power generation in the country, categorized by source, can be referred to from the picture above.

Peak Demand

Peak demand, or peak load, is the highest electrical power demand measured over a certain period of time, which can be annual, daily, or seasonal.

Factors that can affect peak demand include: Demography, Economy, Weather, Climate, Season, and Day of the week.

India's peak demand in 2023-24 – 243271 MW.

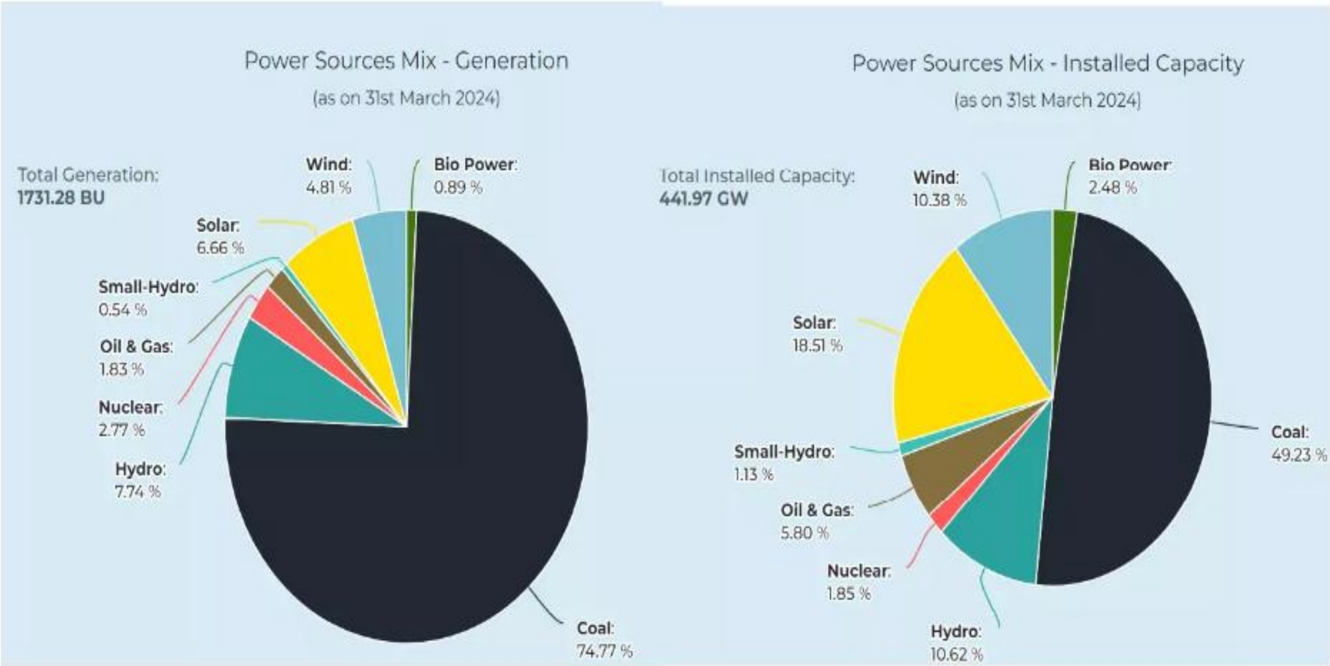
Peak Demand deficit

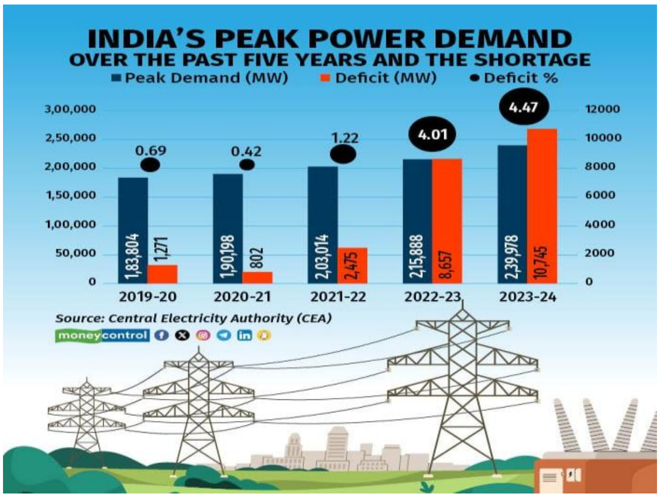
An electricity shortage, or demand deficit, occurs when electricity production and imports are not enough to meet consumption.

To manage a shortage, system operators may ration small amounts of energy to some consumers for a short time, while still allowing essential services to continue.

For 2023-24, the all-India peak demand was 2,43,271 MW, but only 2,39,931 MW was fulfilled, resulting in a 1.4% deficit.

The average gap between Peak demand and Peak supply was 4.5 % in 2013-14 – when the demand was just 136 GW


Power Sources Mix - Generation
(as on 31st March 2024)
Total Generation:
1731.28 BU
Wind: 4.81 %
Bio Power: 0.89 %
Solar: 6.66 %
Small-Hydro: 0.54 %
Oil & Gas: 1.83 %
Nuclear: 2.77 %
Hydro: 7.74 %
Coal: 74.77 %
Power Sources Mix - Installed Capacity
(as on 31st March 2024)
Total Installed Capacity:
441.97 GW
Wind: 10.38 %
Bio Power: 2.48 %
Solar: 18.51 %
Small-Hydro: 1.13 %
Oil & Gas: 5.80 %
Nuclear: 1.85 %
Hydro: 10.62 %
Coal: 49.23 %


INDIA'S PEAK POWER DEMAND
OVER THE PAST FIVE YEARS AND THE SHORTAGE
Peak Demand (MW)
Deficit (MW)
Deficit %
3,00,000
2,50,000
2,00,000
1,50,000
1,00,000
50,000
0
12000
10000
8000
6000
4000
2000
0
0.69
0.42
1.22
4.01
4.47
1,83,804
1,271
1,90,198
802
2,03,014
2,475
2,15,888
8,657
2,39,978
10,745
2019-20
2020-21
2021-22
2022-23
2023-24
Source: Central Electricity Authority (CEA)
moneycontrol

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STRUCTURE OF POWER SYSTEM:- Usually electrical energy is generated by hydro, thermal or nuclear power plants. Usually generating stations are located very far away from load centres & hence a power supply network is of utmost importance.

The power supply network is divided into

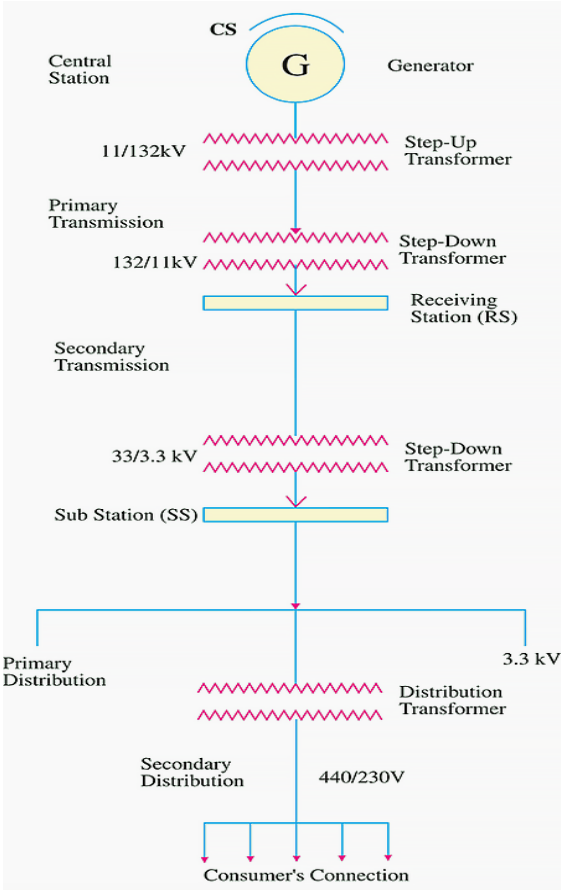
1. Transmission System
    - Primary Transmission
    - Secondary Transmission
2. Distribution System
    - Primary Distribution
    - Secondary Distribution

Power must be fed to consumer at a voltage within variation of ±6% by distributor whereas there can be voltage variation of 10% to 15% in transmission system.

Each transmission system of an area or state is known as Grid & grids are interconnected through tie-lines with different regional grids & regional grids are interconnected forming National Grid.

In India, voltage generation level is at 11KV & this needs to be stepped up to very higher value in order to avoid power losses during transmission. Hence generated voltage is stepped up by transformer near generating stations to 66KV, 110KV, 132KV, 220/230KV, 400KV, 765KV etc. This high value of transmitted voltage is stepped down at receiving sub-stations at 66KV, 33KV or 11KV at the outskirts of area. The secondary transmission starts at this sub-station & at next receiving station voltage is further stepped down to 33KV, 11KV or 3.3KV. The heavy load consumers can be fed from this point. From this Sub-station primary distribution starts & power is fed through feeders which terminate in distribution sub-station

These distribution sub-stations are located near the localities of which power to be supplied. In these distribution sub-stations, step down transformers of Delta-Star type are used which reduces the voltage to 400V. The secondary distribution starts from here and distributors lines are laid along roads and service lines are tapped to the consumers. Usually 3-phase lines are used in order to have economic operation & reduce losses. Thus transmission lines & feeders are 3-phase 3 wire circuits & distributors are 3-phase 4-wire circuits because neutral wire is necessary for supplying single phase load of domestic & commercial consumers.



Generation Mix:

a) Conventional Sources:

- Coal-fired power plants: Base-load supply but high emissions.
- Natural gas plants: Flexible operation; used for peaking and mid-merit loads.
- Hydropower: Renewable, used for both base-load and peaking.
- Nuclear power: Base-load generation, low operational emissions.

b) Renewable Energy Sources (RES):

- Solar PV and Solar Thermal: Rapidly growing due to falling costs.
- Wind Energy: Large-scale deployment in coastal and high-wind regions.
- Biomass and Small Hydro: Localized generation.
- Geothermal (in specific regions): Used in countries with geothermal resources.

c) Present Mix (example data):

- Coal: ~30-40% (reducing gradually)
- Natural Gas: ~20-25%
- Hydro: ~15-20%
- Nuclear: ~10%
- Renewables (solar, wind, biomass): ~20-30% (rapidly increasing)

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SOURCES OF ENERGY:-

Sources of energy are broadly classified into two categories i.e.

i. Conventional
ii. Non-conventional

i) Conventional Sources of Electrical Energy

a) Thermal Power Plants (Coal/Oil/Gas):

Uses **coal, natural gas, or oil to produce steam**.

Steam rotates the turbine, driving the generator to produce electricity.

Forms **base-load supply in many countries**.

b) Hydro Power Plants:

Uses **water stored in dams at a height**.

Water flows through turbines to produce electricity.

Renewable and flexible, can supply **peak demand** efficiently.

c) Nuclear Power Plants:

Uses **nuclear fission (Uranium/Thorium) to produce heat**, generating steam to drive turbines.

Provides **large-scale, base-load power with low greenhouse gas emissions**.

ii) Non-Conventional Energy Sources and Their Significance

a) Solar Energy:

- Uses **solar photovoltaic (PV) panels** to convert sunlight directly into electricity.
- Can be installed **on rooftops, solar parks**.
- **Significance:** Clean, abundant, and essential for **decentralized generation and grid decarbonization**.

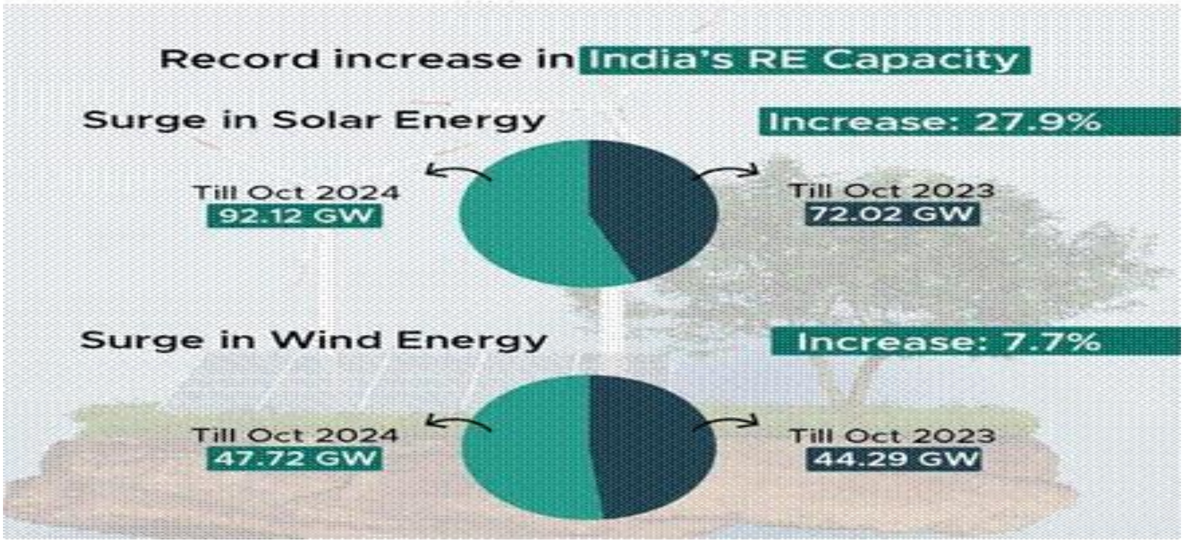
b) Wind Energy:

- Uses **wind turbines** to convert wind kinetic energy into electrical energy.
- Suitable in **coastal and high-wind regions**.
- **Significance:** Variable but rapidly growing, reduces dependency on fossil fuels.

c) Biomass Energy:

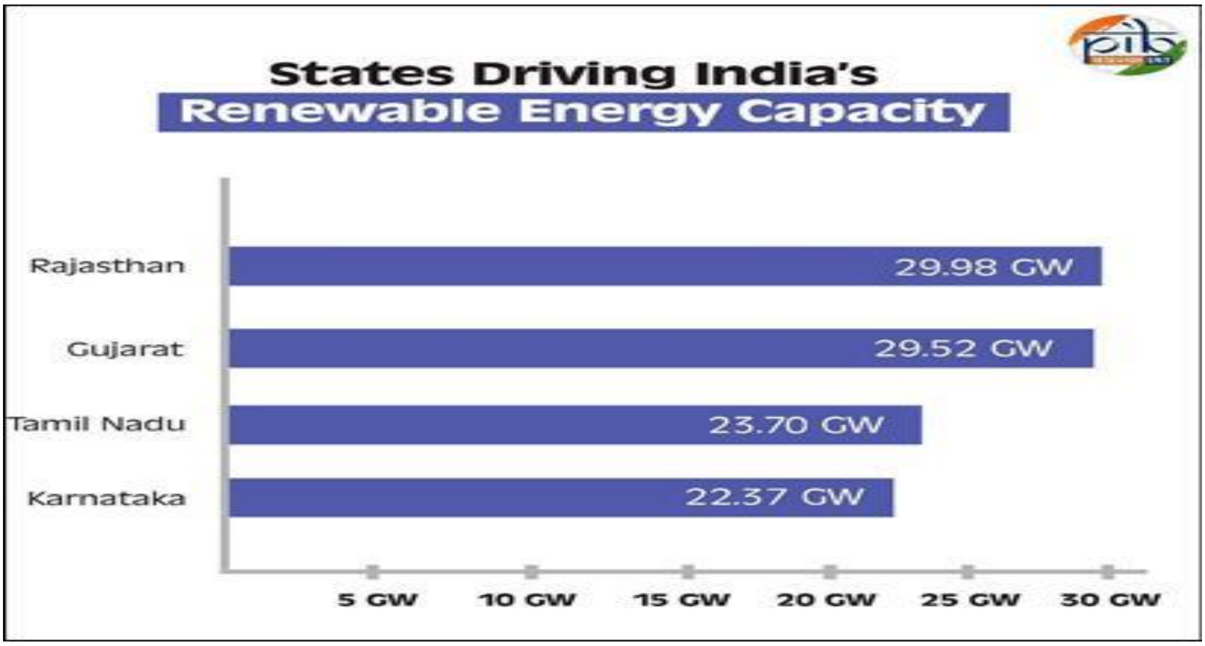
- Uses **organic materials (agricultural waste, wood, animal waste)** to produce electricity via combustion or biogas.
- **Significance:** Supports waste management while providing renewable energy.

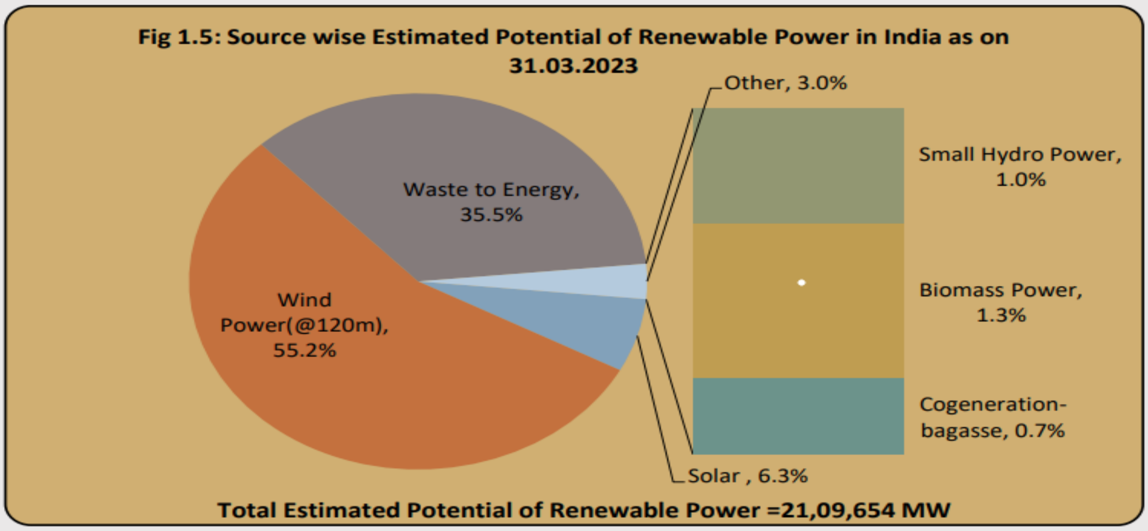
The estimated potential of Renewable sources in India as on 31-10-2024 is shown below:-

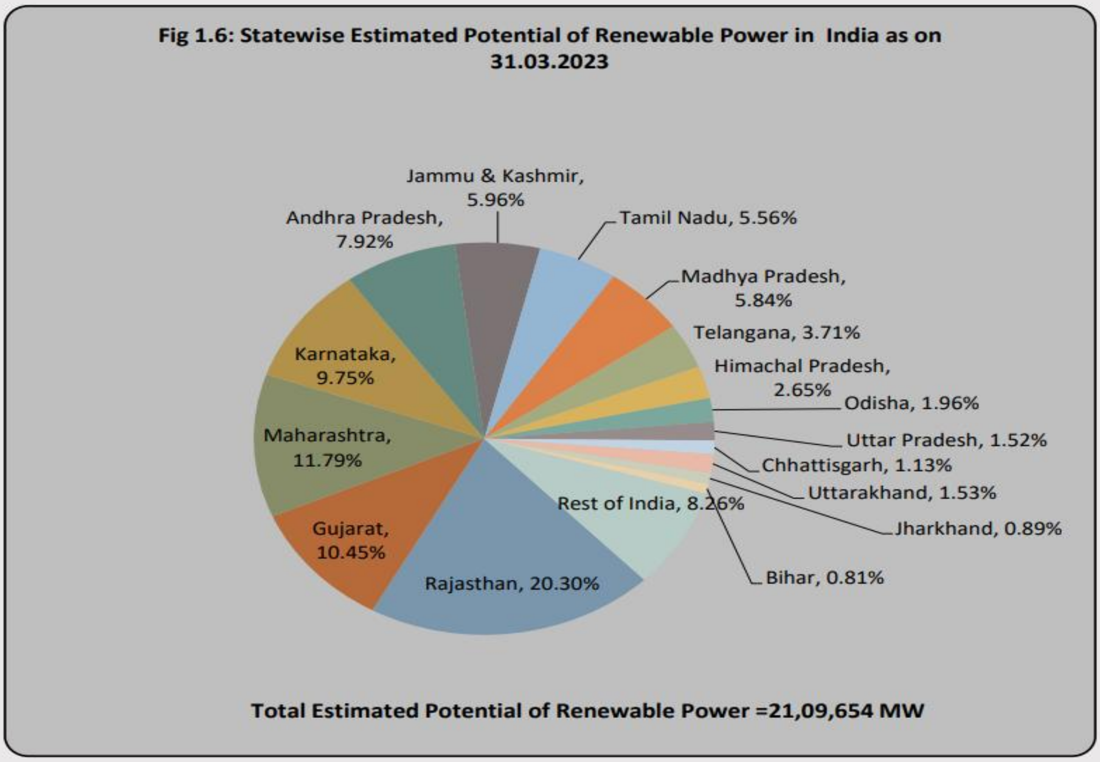


Solar power leads the way with 92.12 GW, playing a crucial role in India's efforts to harness its abundant sunlight. Wind power follows closely with 47.72 GW, driven by the vast potential of the coastal and inland wind corridors across the country. Hydroelectric power is another key contributor, with large hydro projects generating 46.93 GW and small hydro power adding 5.07 GW, offering a reliable and sustainable source of energy from India's rivers and water systems.

Biopower, including biomass and biogas energy, adds another 11.32 GW to the renewable energy mix. These bioenergy projects are vital for utilizing agricultural waste and other organic materials to generate power, further diversifying India's clean energy sources. Together, these renewable resources are helping the country reduce its dependence on traditional fossil fuels, while driving progress toward a more sustainable and resilient energy future.







<u>PRIVATE SECTOR IN ENERGY MANAGEMENT:-</u> We know that very large investments are required for setting up of central power plants and transmission & Distribution network. In order to meet the growing demand of country, private sector participation is very much necessary & thus is gaining popularity

Captive Power refers to generation from a unit set up by industry for its exclusive consumption. A number of industries rely on their own generation in place of grids due to

- Non-availability of adequate grid supply
- Poor quality & reliability of grid supply

- High tariff as a result of heavy cross-subsidisation

Need for Captive Power Plants:-

- Large gap between demand & supply from central power stations
- Frequent power cuts
- Frequent increase in power tariffs by utilities

Advantage:-

- Low overall cost
- No energy theft
- No transmission losses

Captive power generation has following options

a) By Industry
    - ✓ For own use
    - ✓ Supply excess power to neighbouring industry
    - ✓ Use & supply excess power to the utilities
    - ✓ Supply to both i.e. neighbouring industry as well as utility
b) CPP set up by a co-operative society
c) CPP set up by private company

ADVANTAGE OF ELECTRICAL ENERGY:- Electrical Energy is always considered more advantageous to other forms of energy for e.g. Heat, Light, Chemical, Sound & Mechanical) due to

i) Easy Control:- Electrical Machines are simple & convenient to start, control & operate
ii) Cheapness:- Much Cheaper & thus economical than other forms of energy
iii) Convenient & Efficient Transmission:- Can be easily transmitted over long distances by choosing conductors of suitable size
iv) Cleanliness:- Electrical energy is much cleaner to use & does not produce smoke, fumes, dust or poisonous gases
v) Greater Flexibility:- It can be taken to any corner of house, factory, street, hospital, farm, mine, etc. through various conductors
vi) Versatile Form:- Electrical energy can be easily converted to other forms i.e. heat, light, mechanical, sound or chemical

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TRANSMISSION LINE PARAMETERS:-

Transmission system involves use of conductors to supply power. The transmission system uses 3-phase lines to transmit power i.e. R, Y, B. Double circuit transmission is mostly preferred which uses 6 conductors, with one ground wire on top. Transmission lines have distributed constants i.e. R, L, C & G and are called line parameters. Performance of transmission lines depend largely on these parameters.

Resistance:- Resistance is the opposition offered to the flow of current and it is the most important factor behind the I^2R losses. We know from basic knowledge of Science that

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

Where ρ is the resistivity or specific resistance of any conductor which depends on material of conductor and its temperature.

For ρ_1 and ρ_2 be resistivity for different values of temperature t_1 and t_2, then

$$\rho_2 = \rho_1\big(1 + \alpha(t_2 - t_1)\big)$$

Where α is the temperature coefficient of resistance of material

The temperature coefficient at any temperature t_1 is given by

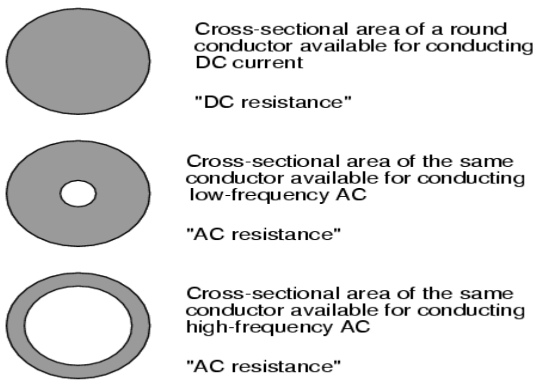
$$\alpha_1 = \frac{\alpha_0}{1 + \alpha_0 t_1} \qquad \alpha_0 = \text{temperature coefficient at } 0^0\text{C}$$

For single phase line, loop resistance is double of resistance of single conductor, but in three phase line, per phase resistance is the resistance of any conductor.

Skin Effect:- For DC supply, current is distributed uniformly throughout the cross section of conductor, but in AC supply, current in not distributed uniformly, but remains confined to surface of the conductor. Thus the effective area of conductor decreases and results in increase in AC resistance. This effective increase in resistance is due to one effect called, *Skin Effect*.

A solid conductor consists of large number of annular filaments and each filaments carry some fraction of total current. Flux linkages due to filaments lying on the surface of the conductor links whole conductor, but flux linkages due to inner one, does not links with outer surface. So it can be said that inner filaments have large inductance as compared to outer one. Hence due to high reactance of inner filaments, current is confined at the outer surface and causes Skin Effect.

Skin effect depends upon material type, frequency of supply, diameter of conductor and its shape.



Skin effect increases with supply frequency, cross section & permeability

Stranded Conductor:- This conductor consists of a central wire and one or more than one layer over it in twisted form. The twist in the conductor is done in opposite manner to the layer below it. This is done in order to increase the mechanical strength of the conductor.

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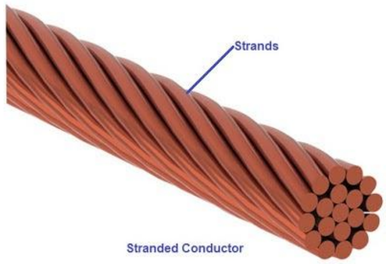
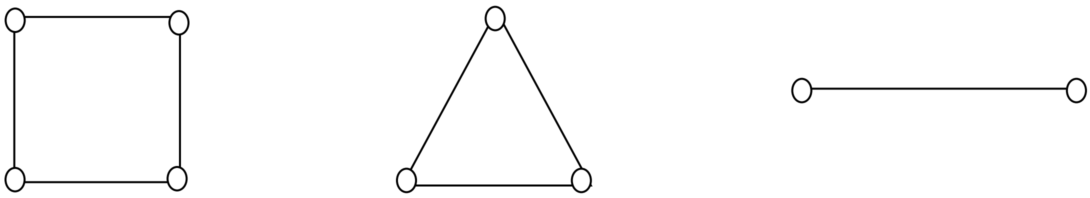


Bundled Conductor:- We know that electricity demand is going on increasing and also it is well known that power plants are generally located very far away from load centres. In order to have economic operation in transmission of power, bundled conductors are used in which more than one conductor is used per phase and lines of 400KV are usually bundled. Bundled Conductor is made up of two or more than that number of conductors and known as sub-conductors per phase. In the bundled conductors, the sub-conductors are spaced by a distance of constant value throughout by the help of spacers, but in composite conductors the wires are touching each other.

By the help of bundled conductors, the voltage gradient near the line reduces and hence corona phenomenon also decreases.

The bundling of the conductor also increases the transmission efficiency by transmitting bulk power.



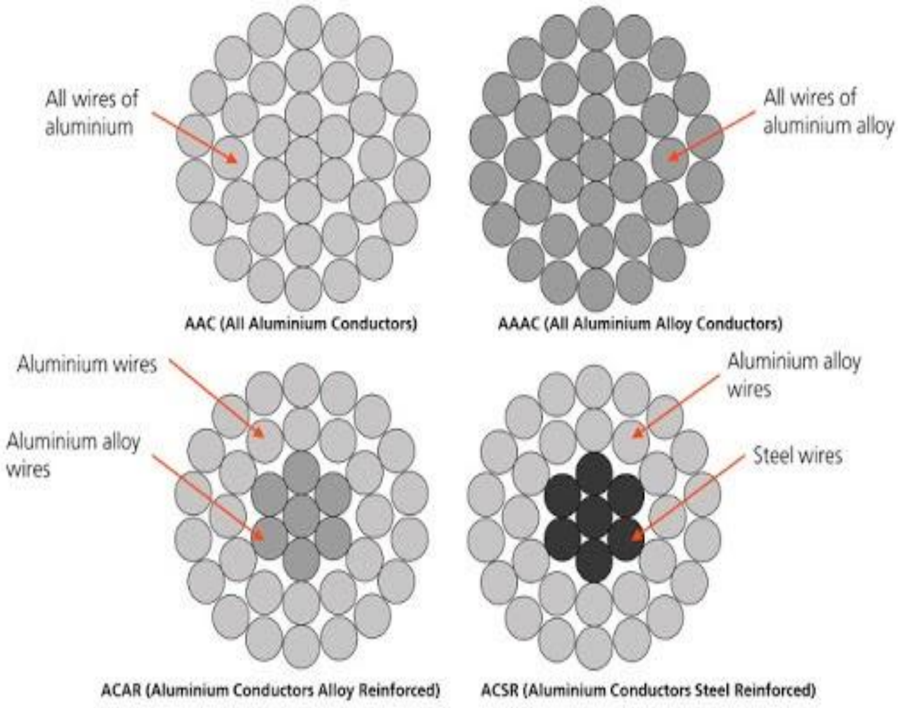
Arrangements of Bundled Conductors

Types of Conductors:-

Different types of conductors are used in overhead lines nowadays

Aluminium conductors are preferred over copper due to their low cost and lesser weight. For same value of resistance, aluminium conductor has larger diameter as compared to copper conductor. The tensile strength of Aluminium is low hence all aluminium conductor is not used for transmission purposes.

1. AAC:- All Aluminium Conductor- Used in L.V distribution of short spans
2. ACSR:- Aluminium Conductor Steel Reinforced- Consists of core of galvanized steel wire and surrounded by strands of hard drawn aluminium wire. Its weight is 25% lesser than copper conductor of equivalent value. Overhead line with ACSR conductor has less sag
3. AAAC:- All Aluminium Alloy Conductor:- It is lighter and has higher conductivity than ACSR.
4. ACAR:- Aluminium Conductor Alloy Reinforced:- It consists of alloy as the core material and surrounded by Aluminium Wires. It gives more strength to the wire. These are used for overhead distribution lines and transmission lines



Inductance:- An Introduction

It is well known from electromagnetic field theory, that a current carrying conductor has a magnetic field around it. Lines of forces are concentric circles and have centre at centre of conductor arranged in planes perpendicular to the conductor.

Also according to Faraday's law, whenever there is change in flux, an emf is induced in the conductor which is given by

$$e = \frac{d\lambda}{dt} = \frac{d\lambda}{di} x \frac{di}{dt} = L\frac{di}{dt}$$

Where λ is number of flux linkages in Wb-turns.

If flux linkages vary linearly with current, then

$$L = \frac{\lambda}{i} \qquad in\ H$$

Also,

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

Where ψ is the RMS value of sinusoidal flux linkages & I is the RMS value of sinusoidal current

Also, according to ampere's law, the MMF around any closed path is equal to net current enclosed by the path

i.e.

$$MMF = \oint H.dl = I_{enclosed}$$

Also

$$B = \mu H \ where\ \mu = \mu_0\mu_r\ ;\ \mu_0 = 4\pi x 10^{-7} H/m$$

Inductance of a Conductor due to Internal flux:-

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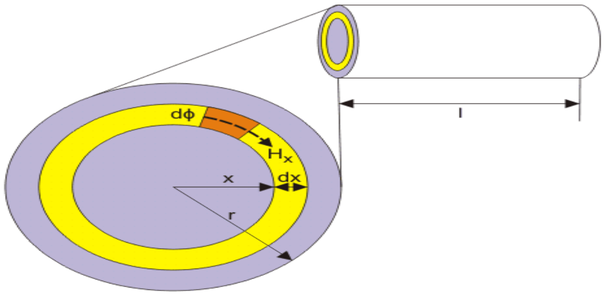
Let us consider a cross section of a long cylindrical conductor of radius 'r' carrying a sinusoidal current of RMS value I. Magnetic Lines are concentric as return path is assumed to be far away & hence no effect.



From Ampere's law

$$\oint H_x.dl = I_x$$

Where H_x is magnetic field intensity at 'x' distance from centre of the conductor

I_x is current enclosed upto distance x

Assuming uniform distribution of current over cross section

$$=> 2\pi x H_x = I_x$$

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

From above two equations, we have

$$H_x = \frac{I_x}{2\pi x} = \frac{Ix}{2\pi r^2}\frac{AT}{m}$$

Flux density B_x at distance 'x' from centre

$$B_x = \mu H_x = \frac{\mu I x}{2\pi r^2}\ ,\frac{Wb}{m^2}$$

Let us consider a tubular element of thickness dx and axial length 1m

$$\therefore d\phi = \frac{\mu I x}{2\pi r^2}\ x1x\ dx = \frac{\mu I x}{2\pi r^2}\ dx \qquad \frac{Wb}{m}$$

A flux line positioned at $x(0 \le x \le r) links\ with\ \left(\frac{\pi x^2}{\pi r^2}\right) I$

$$\therefore d\psi = flux\ linkage\ for\ flux\ d\phi = \frac{\pi x^2}{\pi r^2}.d\phi = \frac{\mu I x^3}{2\pi r^4}dx, Wb - \frac{T}{m}$$

Now

$$\psi_{int} = Total\ Internal\ Flux\ linkages = \int_0^r \frac{\mu I x^3}{2\pi r^4}dx = \frac{\mu I}{8\pi}\ Wb - \frac{T}{m}$$

Also,

$$\mu = \mu_0 = 4\pi x 10^{-7}\frac{H}{m}(Non - magnetic)$$

$$\therefore \psi_{int} = Total\ Internal\ Flux\ linkages = 0.5 I x 10^{-7} Wb - \frac{T}{m}$$

$$L_{int} = \frac{\psi_{int}}{I} = 0.5x10^{-7}\ H/m$$

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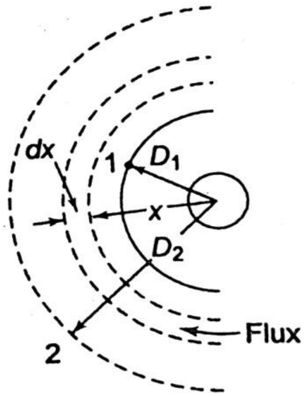
Flux Linkages between two points external to an isolated conductor:-

Let us consider two points 1 and 2 at distance D_1 and D_2 from the centre of a conductor. Whole of the flux between 1 and 2 lies within cylindrical surfaces as the magnetic lines of flux are concentric.



$$\therefore H_x = \frac{I}{2\pi x} \; and \; B_x = \frac{\mu I}{2\pi x}$$

Flux dΦ in a tubular element of thickness dx and length 1 m is

$$d\phi = \frac{\mu I}{2\pi x} dx, \qquad \frac{Wb}{m}$$

Flux external to the conductor links current once

$$\therefore d\psi = \frac{\mu I}{2\pi x} dx, \;\; Wb - \frac{T}{m}$$

Flux linkages between 1 and 2 is found by integrating between x= D_1 and x=D_2

$$\psi_{12} = \frac{\mu I}{2\pi} \ln \frac{D_2}{D_1} \quad Wb - \frac{T}{m}$$

For relative permeability as 1

$$\psi_{12} = 2x10^{-7} I \ln \frac{D_2}{D_1} \quad Wb - \frac{T}{m}$$

$$L_{int} = \frac{\psi_{int}}{I} = 2x10^{-7} \ln \frac{D_2}{D_1} \quad H/m$$

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Problem:- An AAC is composed of 37 strands, each having a diameter of 0.333cm. Compute the DC resistance in ohms per km at 75^0C. Assume that the increase in resistance due to spiralling is 2%

Solution:-

$$\text{Area} = \pi x \frac{(0.333x10^{-2})^2}{4} x37 = 3.222x10^{-4} \quad m^2$$

$$R_{dc1} = \rho \frac{l}{a} = \frac{2.83x10^{-8}x1000}{3.222x10^{-4}} = 0.0878 \quad \frac{\Omega}{km}$$

(Since for Aluminium Conductor, ρ= 2.83x 10^{-8} Ω-m at 20^0C)

$$\therefore \text{At } 75^0\text{C and corrected for stranding, we have}$$

$$\frac{R_{dc2}}{R_{dc1}} = \frac{T + t_2}{T + t_1}$$

Where T= $1/\alpha_0$ = 228 for aluminium (Hard Drawn)

$$\therefore \; R_{dc2} = 0.0878x\left(\frac{228 + 75}{228 + 20}\right)x1.02 = 0.1094 \; \frac{\Omega}{km} \qquad \text{at } 75^0\text{C}$$

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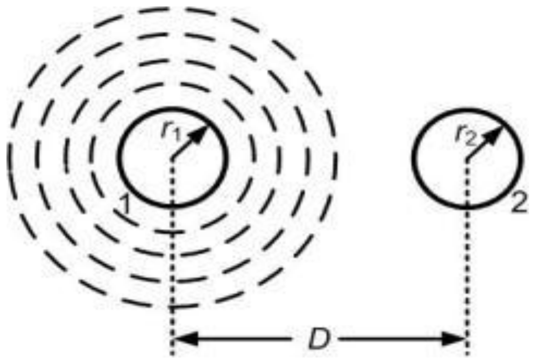
Inductance of Single Phase Two Wire Line:-

Let us consider a simple two wire line consisting of Solid round conductor of radii r_1 and r_2. One conductor is return circuit of another. Inductance in each conductor is because of internal flux linkages and external flux linkages.



Points to note:-

- A line of flux which is produced by current in conductor 1 at a distance equal to or greater than ($D+r_2$) from then centre of conductor 1 links a net zero current
- Fraction of the current which is linked by above line of flux at a distance equal to or less than ($D-r_2$) is 1
- Fraction of current linked by above line of flux between distance ($D-r_2$) and ($D+r_2$) varies from 1 to 0

Assuming D as much greater than r_1 and r_2, such that D is used instead of ($D-r_2$) and ($D+r_2$)

$$L_{1,ext} = 2x10^{-7}\ln\frac{D_1}{r_1} \quad \frac{H}{m}$$

$$L_{1,int} = 0.5x10^{-7} \quad \frac{H}{m}$$

Hence, total inductance of conductor 1 is

$$L_1 = 10^{-7}x(0.5 + 2\ln\frac{D}{r_1}) \quad H/m$$

$$= 2x10^{-7}x(0.25 + \ln\frac{D}{r_1}) \quad H/m$$

$$= 2x10^{-7}x(\ln(e^{\frac{1}{4}}) + \ln\frac{D}{r_1}) \quad H/m$$

$$= 2x10^{-7}x(\ln D/r_1 e^{-\frac{1}{4}})$$

$$= 2x10^{-7}x(\ln D/r_1') \quad H/m$$

$$= 0.4605x(\log D/r_1') \quad mH/Km$$

Where $r_1' = r_1 e^{-\frac{1}{4}} = 0.7788 r_1$

Similarly,

$$L_2 = 2\ x\ 10^{-7} x(\ln \frac{D}{r_2'}) \quad H/m$$

$$\therefore\ L = L_1 + L_2 = 4x10^{-7} \ln(\frac{D}{\sqrt{r_1' r_2'}}) \qquad H/m$$

For $r_1' = r_2' = r', then$

$$L = 4x10^{-7} \ln(\frac{D}{r'}) = 0.921 \log\ (\frac{D}{r'}) \qquad mH/Km$$

This inductance is known as Loop Inductance and Inductance per conductor is one half of loop inductance.

Problem:- Calculate the loop inductance per km of a single phase line comprising of 2 parallel conductors 1m apart and 1cm in diameter, when the material of conductor is (i) Copper (ii) Steel of relative permeability 50

Solution:- Conductor radius, r′= 0.5cm, Spacing of Conductors ,d= 1 metre=100cm

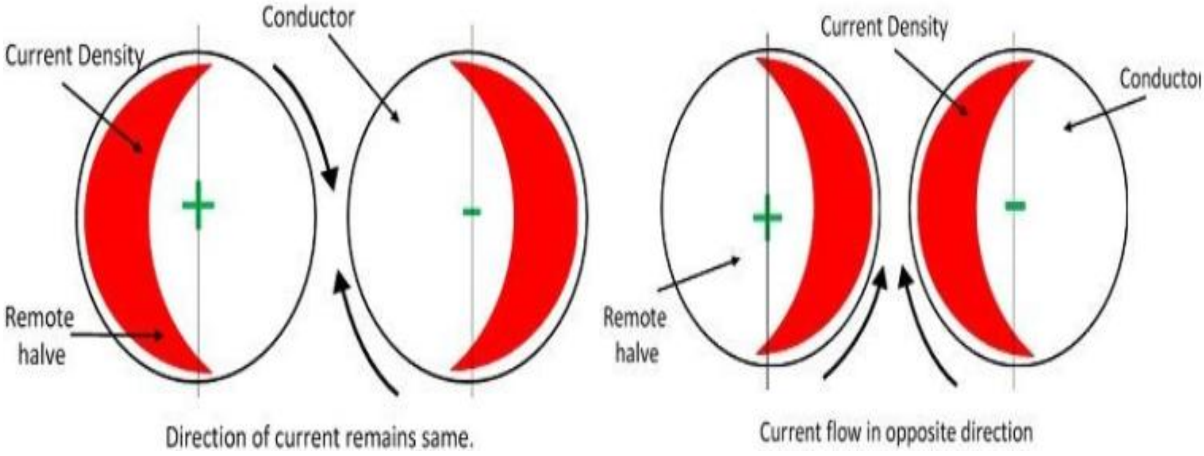
(i) Loop inductance per km of line with copper conductor
$= (1 + 4 \log \frac{d}{r}) x10^{-7} x1000H = (0.1 + 0.4 \log \frac{100}{0.5}) x10^{-3} H = 2.22mH$ Ans.

(ii) Loop inductance per km of line with steel conductor
$= (\mu + 4 \log \frac{d}{r}) x10^{-7} x1000H = (50 + 4 \log \frac{100}{0.5}) x10^{-4} H = 7.12mH$ Ans.

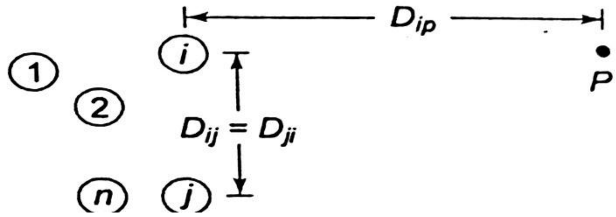
Proximity Effect: - Sometimes the inductance along with the current distribution in a conductor is affected by the presence of the other conductors in close proximity. This type of effect is known as Proximity Effect. When conductors carry currents in opposite direction, the magnetic field will cause an increase in the current density in the adjacent portions of conductors whereas when the currents are in same direction, the density of current increases in farther part of conductor.

This proximity effect also increases the resistance of the conductor and decrease of self reactance. The proximity effect depends on size of the conductor, supply frequency, resistivity and relative permeability of the material.

In case of underground cables, the proximity effect is more pronounced as the conductor lies in close vicinity. In case of overhead line it is not so much pronounced.


Current Density
Conductor
Remote halve
+
-
Direction of current remains same.
Current Density
Conductor
Remote halve
+
-
Current flow in opposite direction

Flux linkages in one conductor in a group:-



The above figure shows a group of 'n' number of long round conductors placed parallel to each other in space and carrying currents I_1, I_2, I_3, s.t. $I_1 + I_2 + I_3 + \ldots\ldots I_n = 0$

The radii of conductor are r_1, r_2, $r_3 \ldots\ldots r_n$ and distances of these conductors from remote point P are D_{1P}, D_{2P}, D_{3P}, ...D_{nP}. Distance between conductors are large as compared to their radii(assume). Current of each conductor produces its own flux and sum of this is total flux. Similarly total flux linkages of any conductor is the sum of linkages of that conductor with others.

Flux linkage of ith conductor /unit length due to I_1 in conductor 1 upto P

$$\psi_{i1} = 2x10^{-7} I_1 \ln \frac{D_{1P}}{D_{i1}} \quad Wb - \frac{T}{m}$$

Similarly

$$\psi_{i2} = 2x10^{-7} I_2 \ln \frac{D_{2P}}{D_{i2}} \quad Wb - \frac{T}{m}$$

....

$$\psi_{ii} = 2x10^{-7} I_i \ln \frac{D_{iP}}{D_{ii}} \quad Wb - \frac{T}{m}$$

$$\psi_{in} = 2x10^{-7} I_n \ln \frac{D_{nP}}{D_{in}} \quad Wb - \frac{T}{m}$$

$$Where\ Dii = r_i' = 0.7788 r_i = Distance\ of\ conductor\ i\ from\ itself$$

Total Flux linkages,

$$\psi_i = 2x10^{-7}(I_1 \ln \frac{D_{1P}}{D_{i1}} + I_2 \ln \frac{D_{2P}}{D_{i2}} + \cdots I_i \ln \frac{D_{iP}}{D_{ii}} + \cdots + I_n \ln \frac{D_{nP}}{D_{in}})$$

$$= 2x10^{-7}[I_1 \ln \frac{1}{D_{i1}} + I_2 \ln \frac{1}{D_{i2}} + \cdots I_i \ln \frac{1}{D_{ii}} + \cdots + I_n \ln \frac{1}{D_{in}} + I_1 \ln D_{1P} + I_2 \ln D_{1P} + \cdots I_n \ln D_{nP}]$$

The point P must approach infinity for total flux linkages of conductor i

$$\therefore\ D_{1P} \approx D_{2P} \approx D_{3P} \approx D_{nP} \approx D$$

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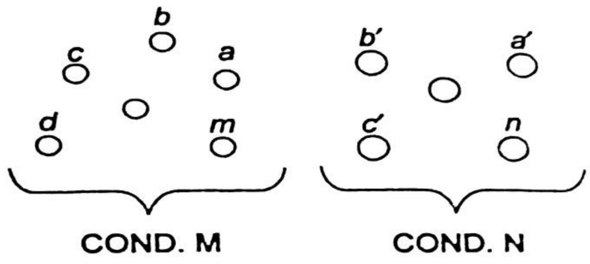
$$=> \lim_{D\to\infty}(I_1 + I_2 + I_3 + \cdots + I_n)\ln D = 0$$

$$\psi_i = 2x10^{-7}[I_1 \ln\frac{1}{D_{i1}} + I_2 \ln\frac{1}{D_{i2}} + \cdots I_i \ln\frac{1}{D_{ii}} + \cdots + I_n \ln\frac{1}{D_{in}}]$$

<u>Inductance of Composite Conductor Lines:-</u>

Composite conductors means conductor composed of two or more elements or strands electrically in parallel i.e. Stranded Conductors

Let us consider conductor M consisting of 'm' similar parallel sub-conductors and conductor N consisting of 'n' parallel sub-conductors. All strands are assumed identical for equal current sharing. Each strand of M carries I/m current and N carries I/n current



Flux Linkage of Sub-conductor are

$$\psi_a = 2x10^{-7}x\ \frac{I}{m}[\ln\frac{1}{D_{aa}} + \ln\frac{1}{D_{ab}} + \cdots \ln\frac{1}{D_{am}}] - 2x10^{-7}x\ \frac{I}{n}[\ln\frac{1}{D_{aa'}} + \ln\frac{1}{D_{ab'}} + \cdots \ln\frac{1}{D_{an}}]$$

$$=> \psi_a = 2x10^{-7}x\ Ix\ln\frac{(D_{aa'}D_{ab'} \dots . D_{an})^{\frac{1}{n}}}{(D_{aa}D_{ab} \dots . D_{am})^{\frac{1}{m}}} \quad Wb - \frac{T}{m}$$

Inductance of Sub-conductor 'a' is

$$L_a = \frac{\psi_a}{I/m} = 2mx10^{-7}x\ln\frac{(D_{aa'}D_{ab'} \dots . D_{an})^{\frac{1}{n}}}{(D_{aa}D_{ab} \dots . D_{am})^{\frac{1}{m}}}$$

Similarly

$$L_b = \frac{\psi_b}{I/m} = 2mx10^{-7}x\ln\frac{(D_{ba'}D_{bb'} \dots . D_{bn})^{\frac{1}{n}}}{(D_{ba}D_{bb} \dots . D_{bm})^{\frac{1}{m}}}$$

The average inductance of a sub-conductor of conductor M is

$$L_{av} = \frac{L_a + L_b + \cdots + L_m}{m}$$

Since there are m sub-conductors in M, hence its inductance is 1/m times of average inductance

$$L_M = \frac{L_{av}}{m} = \frac{L_a + L_b + \cdots + L_m}{m^2}$$

Substituting the values in above equation we get

$$L_M = 2x10^{-7} x \ln \frac{[(D_{aa'}D_{ab'} \dots . D_{an})(D_{ba'}D_{bb'} \dots . D_{bn}) \dots (D_{ma'}D_{mb'} \dots . D_{mn})]^{\frac{1}{mn}}}{[(D_{aa}D_{ab} \dots . D_{am})(D_{ba}D_{bb} \dots . D_{bm}) \dots (D_{ma}D_{mb} \dots . D_{mm})]^{\frac{1}{m^2}}} \quad \frac{H}{m}$$

Numerator is the 'mn'th root of product of mn terms. For each sub-conductor of M there are n distances to different sub-conductor of N. Since M has m sub-conductors, the total number of distances is 'mn.

- Note:- The 'mn'th root of product of mn distances is known as Geometric Mean Distances(GMD) between M & N. It is denoted as D_m
- The denominator is m^2 root of the product of m^2 terms. The sub-conductor 'a' has m distances to the other sub-conductors of M(including distance D_{aa}= 0.7788r_a) since there are m sub-conductors of M, total number of distances is m^2
- The denominator is called self GMD and is denoted as D_S or is also known as GMR(Geometric Mean Radius)

$$\therefore\ L_M = 2x10^{-7} \ln \frac{D_m}{D_S} \quad \frac{H}{m} = 0.4605 \log \frac{D_m}{D_S} \quad \frac{mH}{Km}$$

For solid conductor, GMD=D, GMR=0.7788r

For return path, L_N is similar and thus the loop inductance is L_M+L_N

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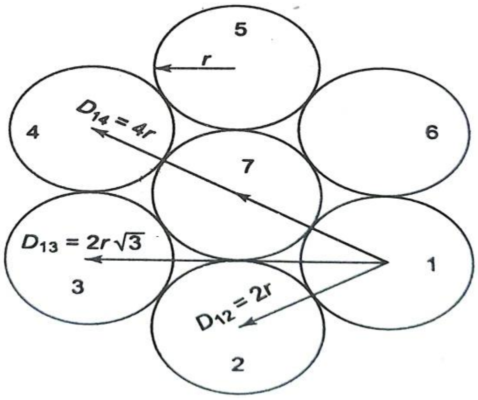
Problem:- A conductor is composed of seven identical copper strands, each having a radius r as shown below. Find the self GMD of the conductor.



Solution:- From the above figure we have

$D_{11}= r$; $D_{12}=D_{16}=D_{17}=2r$; $D_{14}=4r$ & $D_{13}=D_{15}=[D_{14}^2- D_{34}^2]^{1/2}=2\sqrt{3}r$

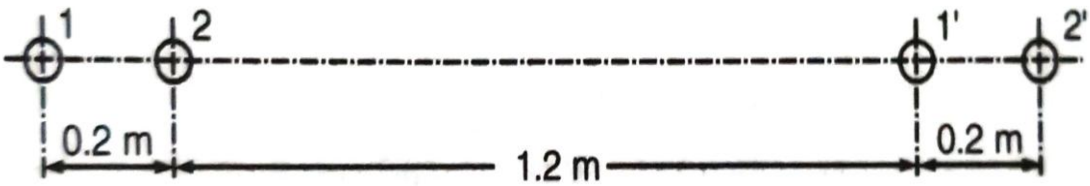
Also, $D_{s1}= D_{s2}=D_{s3}=D_{s4}=D_{s5}=D_{s6}$

$D_{s1}= [0.7788r x 2r x 2\sqrt{3}r x 4r x 2\sqrt{3}r x 2r x 2r]^{1/7}=[299]^{1/7}r$

And $D_{s7}= [0.7788r x 2r x 2r x 2r x 2r x 2r x 2r]^{1/7}=[49.8432]^{1/7}r$

Thus Geometric Mean Radius(GMR), $D_S= [D_{s1} x D_{s2} x D_{s3} x D_{s4} x D_{s5} x D_{s6} x D_{s7}]^{1/7}= r[299^6 x 49.8432]^{1/49}=2.176r$

Problem:- A split phase, single phase transmission line is shown in figure below. Conductors 1 and 2 in parallel form one path while conductors 1' and 2' in parallel form the return path. The current is equally shared by two parallel conductors. Determine the total inductance per km of the line. The radius of each conductor is 1.2cm



Solution:- Let the current flowing in each conductor be 1A. Radius of each conductor r=1.2cm.

GMR, $r'=0.7788r=0.93456$cm

Spacings of conductor, $D_{12}=0.2m=20cm$

$D_{11'}=(0.2+1.2)m=140cm$; $D_{22'}=(0.2+1.2)m=140cm$; $D_{12'}=(0.2+1.2+0.2)m=160cm$; $D_{21'}=1.2m=120cm$

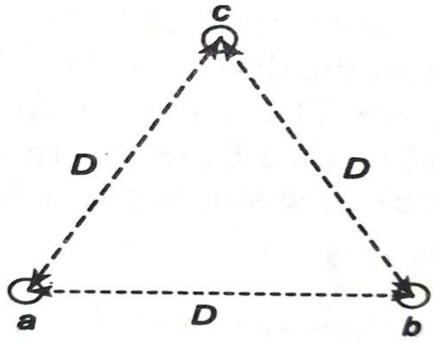
Mutual GMD, $D_m= [D_{11'} x D_{12'} x D_{21'} x D_{22'}]^{1/4}= 139.28cm$

Self GMD, $D_S= [D_{11} x D_{12} x D_{21} x D_{22}]^{1/4}= 4.32cm$

Loop Inductance, L= 0.4ln (D_m/ D_S) mH/Km= 0.4 ln (139.28/4.32)=1.389 mH/Km

Inductance of 3-phase line with Equilateral Spacing:-

Let us consider conductor of a 3-phase line spaced at the corners of an equilateral triangle. If there is no neutral wire, then $I_a+I_b+I_c=0$



Also from earlier discussion

$$\psi_a = 2x10^{-7}[I_a \ln\frac{1}{D_{aa}} + I_b \ln\frac{1}{D_{ab}} + I_c \ln\frac{1}{D_{ac}}]$$

$$= 2x10^{-7}[I_a \ln\frac{1}{D_S} + I_b \ln\frac{1}{D} + I_c \ln\frac{1}{D}]$$

$$=> \psi_a = 2x10^{-7}[I_a \ln\frac{1}{D_S} - I_a \ln\frac{1}{D}] \ldots \qquad \{\because I_a = -(I_b + I_c)\}$$

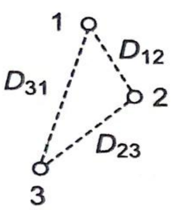
$$=> L_a = \frac{\psi_a}{I_a} = 2x10^{-7}[\ln\frac{D}{D_S}] \qquad H/m = 0.4605 \log\left(\frac{D}{D_S}\right) \quad \frac{mH}{Km}$$

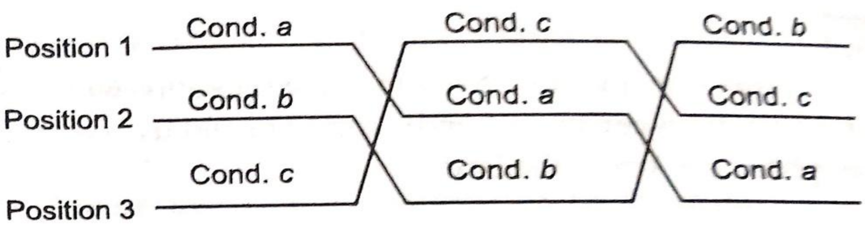
Due to symmetry, $L_b=L_C=L_a$

Inductance of 3-phase line with Unsymmetrical Spacing:-

In general conditions, each phase is not placed at the corners of equilateral triangle. For unbalanced conditions, lines are transposed

Transposition:- Exchange of position of the conductors at regular intervals along the line so that each conductor occupies original position of every other conductor over an equal distance in order to restore balance.





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Average inductance of a conductor of a transposed line is found by finding flux linkages for each position occupied by conductor.

Hence, flux linkage of conductor ‘a’ for position 1, conductor ‘b’ in position 2 and conductor ‘c’ in position 3 is

$$\psi_{a1} = 2x10^{-7}[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}} + I_c \ln\frac{1}{D_{31}}] \qquad Wb - \frac{T}{m}$$

Similarly, flux linkage of conductor ‘a’ for position 2, conductor ‘b’ in position 3 and conductor ‘c’ in position 1 is

$$\psi_{a2} = 2x10^{-7}[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{23}} + I_c \ln\frac{1}{D_{12}}] \qquad Wb - \frac{T}{m}$$

& flux linkage of conductor ‘a’ for position 3, conductor ‘b’ in position 1 and conductor ‘c’ in position 2 is

$$\psi_{a3} = 2x10^{-7}[I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{31}} + I_c \ln\frac{1}{D_{23}}] \qquad Wb - \frac{T}{m}$$

$$\therefore \text{Average Flux linkages of 'a' are,} \quad \psi_a = \frac{\psi_{a1} + \psi_{a2} + \psi_{a3}}{3}$$

$$= \frac{2x10^{-7}}{3}[3I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D_{12}D_{23}D_{31}} + I_c \ln\frac{1}{D_{31}D_{12}D_{23}}]$$

Since $I_a = -(I_b + I_c)$

$$\therefore \psi_a = \frac{2x10^{-7}}{3}[3I_a \ln\frac{1}{r'} - I_a \ln\frac{1}{D_{12}D_{23}D_{31}}]$$

$$= \frac{2x10^{-7}}{3}[I_a \ln\frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r'}]$$

$$=> L_a = \frac{\psi_a}{I_a} = 2x10^{-7}\left[\ln\frac{\sqrt[3]{D_{12}D_{23}D_{31}}}{r'}\right] = 2x10^{-7}\left[\ln\frac{D_{eq}}{r'}\right] \quad \frac{H}{m} = 0.4605 \log\frac{D_{eq}}{r'}$$

Where $D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}}$ = Geometric Mean of distances of line

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Inductance of Bundled Conductor Lines

The GMR of bundled conductor can be calculated similar to the stranded conductor.

For a two conductor (duplex) arrangement of the line

$$D_S^b = \sqrt[4]{(D_S.d)^2} = \sqrt{D_S.d}$$

For a three conductor (triplex) arrangement of the line

$$D_S^b = \sqrt[9]{(D_S.d.d)^3} = \sqrt[3]{D_S.d^2}$$

For a four conductor (quadruplex) arrangement of the line

$$D_S^b = \sqrt[16]{\left(D_S.d.d\sqrt{2}.d\right)^4} = 1.09x\sqrt[4]{D_S.d^3}$$

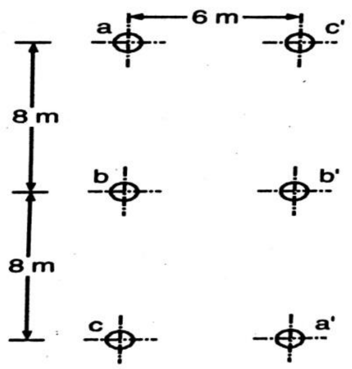
GMD is found by taking root of product of distances from each conductor of a bundle to every other conductor of other bundles.

Problem:- A 3-phase transmission line has its conductors at the corners of an equilateral triangle with side 3m. The diameter of each conductor is 1.63cm. Find the inductance per phase per kilometre of the line.

Solution:- r'=0.7788x0.5x1.63=0.635cm

L= 0.4605 log (D/r')= 0.4605 log (300/0.635)= 1.2315 mH/Km

Problem:- A 100Km double circuit transmission line with 7 strand copper conductors each strand having 5mm diameter has 6 conductors arranged in the form shown in figure below. The line is transposed at regular intervals. Evaluate the GMD and GMR and calculate the overall inductance per phase of the line.



Solution:- Radius of each strand of conductor= 5/2 mm = 2.5mm

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GMR of conductor, r' = 2.176 x 2.5 mm= 5.44 x 10^{-3} m (r'= 2.176r, Since stranded conductor)

Distance between Conductors

$$D_{aa'} = \sqrt{6^2 + 16^2} = 17.089 \text{ m} ; D_{bb'} = 6 \text{ m} ; D_{cc'} = D_{aa'} = 17.089\text{m};$$
$$D_{ab'} = 10\text{m}; D_{ab} = 8\text{m}$$

GMR of Phase 'a'

$$D_{sa} = \sqrt[4]{D_{aa'}D_{aa}D_{a'a'}D_{a'a}} = \sqrt{r'xD_{aa'}} = \sqrt{5.44x10^{-3}x17.089} = 0.305\text{m}$$

Similarly

$$D_{sb} = \sqrt{r'xD_{bb'}} = \sqrt{5.44x10^{-3}x6} = 0.1807\text{m}$$

And

$$D_{sc} = \sqrt{r'xD_{cc'}} = \sqrt{5.44x10^{-3}x17.089} = 0.305\text{m}$$

Self GMD or GMR

$$D_S = \sqrt[3]{D_{sa}D_{sb}D_{sc}} = \sqrt[3]{0.305x0.1807x0.305} = 0.2562\text{m} \quad \text{Ans.}$$

$$D_{ab} = \sqrt[4]{D_{ab'}D_{ab}D_{a'b'}D_{a'b}} = \sqrt{D_{ab}xD_{ab'}} = \sqrt{8x10} = 8.944\text{m}$$

Similarly

$$D_{bc} = \sqrt{D_{bc}xD_{bc'}} = \sqrt{8x10} = 8.944\text{m}$$

$$D_{ca} = \sqrt{D_{ca}xD_{ca'}} = \sqrt{16x6} = 9.8\text{m}$$

$$D_{eq} \text{ or } D_m = \sqrt[3]{D_{ab}D_{bc}D_{ca}} = 9.22\text{m} \qquad \text{Ans.}$$

Inductance per phase, L= 0.2 log D_m/D_S = 0.2 log(9.22/0.2562) = 0.717 mH/Km

Inductance of 100Km line= (0.717 x 100) / 1000= 0.0717 H Ans.

Capacitance:- An Introduction:- Capacitance in a transmission line is due to potential difference between conductors, causes them to be charged as the plates of a capacitor. Capacitance between parallel conductors is constant depending on size & spacing of conductors.

The flow of charge is current and current caused by alternate charging and discharging of a line due to an alternating voltage is called charging current.

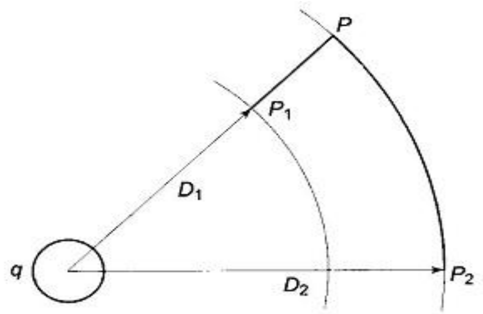
This charging current affects the voltage drop along the lines as well as efficiency and power factor of the line and stability of the system.

Electric Field of a long Straight Conductor:- Let us consider an infinitely long straight conductors for removed from other conductors(including earth) carrying a uniform charge of q coulomb/m length. Charge for this will be uniformly distributed around periphery and flux is radial. Points equidistant from such a conductor are points of equidistant potential and have same electric flux density.

The electric field intensity at a distance x from the axis of conductor is

$$E = \frac{q}{2\pi\epsilon x} \; \frac{V}{m}$$

The electric field intensity is equal to the electric flux density divided by permittivity of the medium. The potential difference V_{12} (between P_1 and P_2) is given by integrating electric field intensity w.r.t distance. Point P_1 and P_2 are situated at distance D_1 and D_2 from centre of conductor. The potential difference between two points is equal to the work in joules necessary to move a unit positive charge between two points.

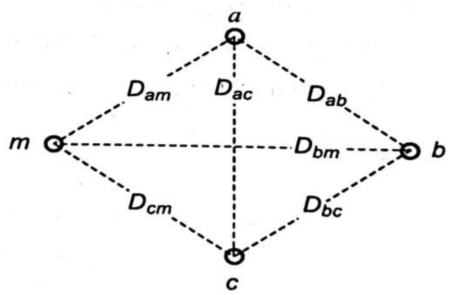


The potential difference is found by integrating over the radial path between two points. The points P and P_2 lie on an equi-potential surface and are at the same potential.

$$\therefore\ V_{12} = \int_{D_1}^{D_2} \frac{q}{2\pi\epsilon x} dx = \frac{q}{2\pi\epsilon} \ln\frac{D_2}{D_1} \quad Volts$$

The above concept is used to find p.d between two conductors of an array of parallel conductors. For an array of M conductors, we assume the distance between the conductors to be large as compared to the radii so that charge on each conductor is uniformly distributed over its surface.

Assuming that each conductor 'm' has an AC charge q_m C/m uniformly distributed along the conductor.



The voltage V_{ab} between conductors a and b due to the charge q_a acting alone is

$$\therefore\ V_{ab} = \int_{D_{aa}}^{D_{ab}} \frac{q_a}{2\pi\epsilon x} dx = \frac{q_a}{2\pi\epsilon}[\ln D_{ab} - \ln D_{aa}] = \frac{q_a}{2\pi\epsilon} \ln\frac{D_{ab}}{r_a}$$

Similarly considering other charges, V_{ab} can be found

Using Superposition, V_{ab} between a and b due to all charges is

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon} \sum_{m=a}^{m} q_m \ln\frac{D_{mb}}{D_{ma}} \quad Volts$$

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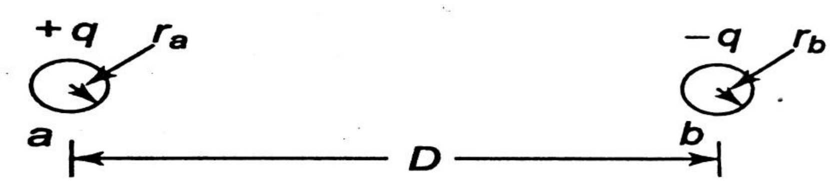
Capacitance of two wire line:-

Let us consider two conductors of a single phase line. For conductor ‘a’, charge per unit length is q and on ‘b’ charge per unit length is –q.



For k=a, i=b, m=a,b, q_a= q_b=q, we have

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}\left(q\ln\frac{D}{r_a} - q\ln\frac{r_b}{D}\right) = \frac{q}{2\pi\epsilon}\ln\frac{D^2}{r_a r_b}$$

Now capacitance/unit length, C_{ab} is

$$C_{ab} = \frac{q}{V_{ab}} = \frac{2\pi\epsilon}{\ln\frac{D^2}{r_a r_b}} = \frac{\pi\epsilon}{\ln\frac{D}{\sqrt{r_a r_b}}} \qquad \frac{F}{m}$$

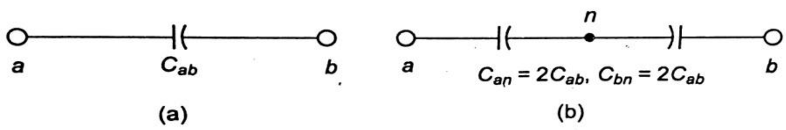
$$\therefore C_{ab} = \frac{0.01206}{\log\frac{D}{\sqrt{r_a r_b}}} \quad \mu F/Km$$

For r_a=r_b=r

$$\therefore C_{ab} = \frac{0.01206}{\log\frac{D}{r}} \quad \mu F/Km$$

For a single phase line, charging current I_C is

$$I_C = j\omega C_{ab} V_{ab}$$



From the above figure, it can be seen that line-line capacitance is considered as composed of two capacitance in series. The voltage between lines divides equally and point ‘n’ is at ground potential. By the equation of series capacitors, we find that

$$C_{ab} = \frac{C_{an}C_{bn}}{C_{an}+C_{bn}} = \frac{C_{an}C_{an}}{C_{an}+C_{an}} = \frac{C_{an}}{2}$$

⇨ $\mathrm{C_{an}} = 2\mathrm{C_{ab}}$ & *Similarly* $\mathrm{C_{an}} = 2\mathrm{C_{ab}}$

Capacitance of each line to neutral is twice the line to line capacitance

$$\therefore C_n = C_{an} = C_{bn} = 2C_{ab} = \frac{0.02412}{\log\frac{D}{r}} \quad \mu F/Km$$

Problem:- Find the capacitance between the conductors of a single phase 10Km long line. The diameter of each conductor is 1.213cm. The spacing between conductors is 1.25m. Also find the capacitance of each conductor to neutral.

Solution:- Solution:- We know that

$$C_{ab} = \frac{0.01206}{\log\frac{D}{r}}$$

$$= \frac{0.01206}{\log\frac{125}{1.213x0.5}} = 5.21x10^{-3}\ \mu F/Km$$

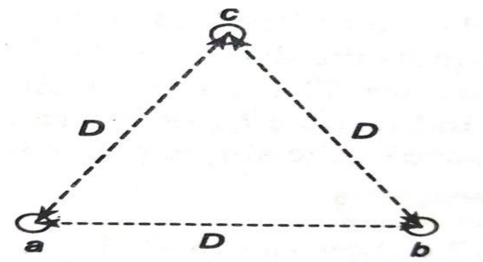
For 10Km length,

$$C_{ab} = 5.21x10^{-3}x10 = 0.0521\ \mu F$$

$$C_n = 2C_{ab} = \ 0.1042\ \mu F$$

<u>Capacitance of 3-phase line with Equilateral Spacing:-</u>

Let us consider the figure below in which the conductors are spaced at the corners of an equilateral triangle with radius of conductor 'r' and spacing between conductors D



Using D=D_{ab}=D_{ba}=D_{cb}; D_{aa}=D_{bb}=r; k=a; i=b; m=a,b,c

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D}{r} + q_b \ln\frac{r}{D} + q_c \ln\frac{D}{D}]$$

Similarly for k=a, i=c

$$\therefore\ V_{ac} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D}{r} + q_b \ln\frac{D}{D} + q_c \ln\frac{r}{D}]$$

Adding both the above equations, we have

$$V_{ab} + V_{ac} = \frac{1}{2\pi\epsilon}[2q_a \ln\frac{D}{r} + (q_b + q_c)\ln\frac{r}{D}]$$

If there are no other charges in vicinity then, $q_a + q_b + q_c = 0\ or\ q_b + q_c = -q_a$

$$\therefore\ V_{ab} + V_{ac} = \frac{3q_a}{2\pi\epsilon}\ln\frac{D}{r}$$

Let V_{an}, V_{bn} and V_{cn} are 3-phase voltages such that

$$V_{an} = V\angle 0^0, V_{bn} = V\angle{-120^0}, V_{cn} = V\angle 120^0$$

$$\therefore\ V_{ab} = V_{an} - V_{bn} = V\angle 0^0 - V\angle{-120^0} = \sqrt{3}\,V\angle 30^0$$

$$\&\ V_{ac} = V_{an} - V_{cn} = V\angle 0^0 - V\angle 120^0 = \sqrt{3}\,V\angle -30^0$$

$$\therefore\ V_{ab} + V_{ac} = 3V_{an}$$

$$\therefore\ V_{ab} + V_{ac} = \frac{3q_a}{2\pi\epsilon}\ln\frac{D}{r}$$

$$or\ \ V_{an} = \frac{q_a}{2\pi\epsilon}\ln\frac{D}{r}$$

$$\therefore\ C_n = \frac{q_a}{V_{an}} = \frac{2\pi\epsilon}{\ln\frac{D}{r}} = \frac{0.02412}{\log\frac{D}{r}}\ \ \frac{\mu F}{Km}$$

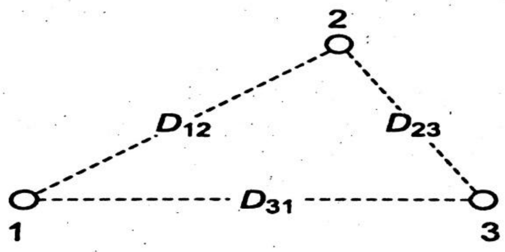
The charging current / phase = $I_C = j\omega C_n V_{an}$

$$I_C = j\omega q_a\ ,\quad A$$

Prepared By:- Er. Chandan Mandal, Assistant Professor, EE department, ABIT, Cuttack

Capacitance of 3-phase line with Asymmetrical Spacing

It is again found out as for inductance i.e. with transposed line



For the configuration shown above, the three equations for V_{ki} for different parts of transposition cycle are:

For k=a; i=b; m=a, b, c or 1, 2, 3 position wise

Now for phase 'a' in position 1, 'b' in position 2 & 'c' in position 3

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D_{12}}{r} + q_b \ln\frac{r}{D_{12}} + q_c \ln\frac{D_{23}}{D_{31}}]$$

For phase 'a' in position 2, 'b' in position 3 & 'c' in position 1

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D_{23}}{r} + q_b \ln\frac{r}{D_{23}} + q_c \ln\frac{D_{31}}{D_{12}}]$$

For phase 'a' in position 3, 'b' in position 1 & 'c' in position 2

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D_{31}}{r} + q_b \ln\frac{r}{D_{31}} + q_c \ln\frac{D_{12}}{D_{23}}]$$

Average V_{ab} is calculated as

$$V_{ab} = \frac{1}{6\pi\epsilon}[q_a \ln\frac{D_{12}D_{23}D_{31}}{r^3} + q_b \ln\frac{r^3}{D_{12}D_{23}D_{31}} + q_c \ln\frac{D_{12}D_{23}D_{31}}{D_{12}D_{23}D_{31}}]$$

$$\text{or}\quad V_{ab} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D_{eq}}{r} + q_b \ln\frac{r}{D_{eq}}]$$

Where $D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}}$

$$\text{Similarly,}\quad V_{ac} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D_{eq}}{r} + q_c \ln\frac{r}{D_{eq}}]$$

Adding both the above equations, we have

$$V_{ab} + V_{ac} = \frac{1}{2\pi\epsilon}[2q_a \ln\frac{D_{eq}}{r} + (q_b + q_c)\ln\frac{r}{D_{eq}}]$$

If there are no other charges in vicinity then, $q_a + q_b + q_c = 0 \ or \ q_b + q_c = -q_a$

Prepared By:- Er. Chandan Mandal, Assistant Professor, EE department, ABIT, Cuttack

Let V_{an}, V_{bn} and V_{cn} are 3-phase voltages such that

$$V_{an} = V\angle 0^0, V_{bn} = V\angle -120^0, V_{cn} = V\angle 120^0$$

$$\therefore\ V_{ab} = V_{an} - V_{bn} = (V\cos 0^0 + jV\sin 0^0) - (V\cos 120^0 - jV\sin 120^0)$$

$$\therefore\ V_{ab} = V_{an} - V_{bn} = (V) - (Vx - 0.5 - jVx0.866) = V + 0.5V + j0.866V = 1.5V + j0.866V$$

$$\therefore\ V_{ab} = V_{an} - V_{bn} = \sqrt{3}\left[\frac{\sqrt{3}}{2}V + \frac{jV}{2}\right] = \sqrt{3}[V\cos 30^0 + jV\sin 30^0] = \sqrt{3}xV\angle 30^0$$

Similarly;

$$\therefore\ V_{ac} = V_{an} - V_{cn} = (V\cos 0^0 + jV\sin 0^0) - (V\cos 120^0 + jV\sin 120^0)$$

$$\therefore\ V_{ac} = V_{an} - V_{cn} = (V) - (Vx - 0.5 + jVx0.866) = V + 0.5V - j0.866V = 1.5V - j0.866V$$

$$\therefore\ V_{ac} = V_{an} - V_{cn} = \sqrt{3}\left[\frac{\sqrt{3}}{2}V - \frac{jV}{2}\right] = \sqrt{3}[V\cos 30^0 - jV\sin 30^0] = \sqrt{3}xV\angle -30^0$$

$$\therefore\ V_{ab} + V_{ac} = \sqrt{3}[V\cos 30^0 + jV\sin 30^0] + \sqrt{3}[V\cos 30^0 - jV\sin 30^0] = \sqrt{3}x2V\cos 30^0 = 3V = 3V_{an}$$

$$\therefore\ V_{ab} + V_{ac} = \frac{3q_a}{2\pi\epsilon}\ln\frac{D_{eq}}{r} = 3V_{an}$$

$$\therefore\ C_n = \frac{q_a}{V_{an}} = \frac{2\pi\epsilon}{\ln\frac{D_{eq}}{r}} = \frac{0.02412}{\log\frac{D_{eq}}{r}}\ \frac{\mu F}{Km}$$

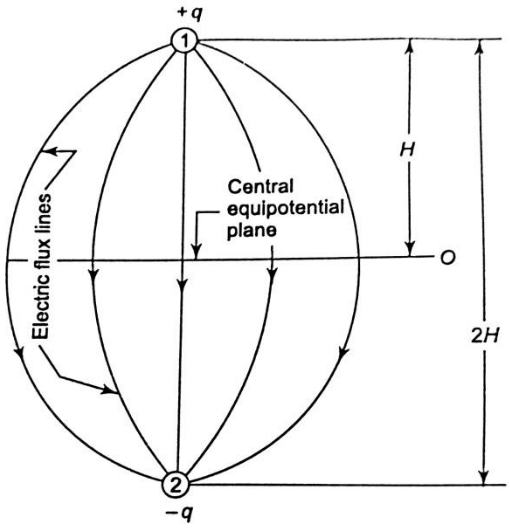
<u>Effect of Earth on the capacitance of 3-phase Lines:-</u>

Presence of ground alters the electric field of a line and hence affects the line capacitance.

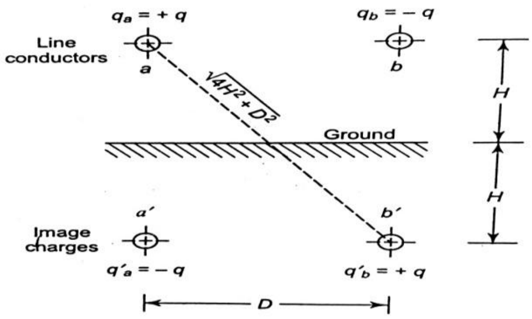
Let us consider a circuit consisting of a single overhead conductor with a return path through earth. In charging the conductor, charges come from the earth to reside on the conductor and a potential difference exists between conductor and the earth. The earth has a charge equal in magnitude to conductor but of opposite sign. The electric flux from the charges on the conductor to the charges on earth is perpendicular to earth's equi-potential surface since surface is assumed to be a perfect conductor.

Now let us imagine a fictious conductor of same size and shape as the overhead conductor lying just below the original conductor at a distance equal to twice the distance of the conductor above the plane of the ground. It means that fictious conductor is below the surface of earth by a distance equal to distance of overhead conductor above the earth. If earth is removed, an equal and opposite charge is assumed on fictious conductor then the plane midway between them is an equi-potential surface and occupies the same position as the equi-potential surface of the earth. The flux between overhead conductor and this equi-potential surface is same as that which existed between conductor and earth. This fictious conductor is called image conductor.

The figure below shows above theory



For a single phase line:- The figure below shows conductors of a single phase line with image conductors and radius of conductor is r.



The equation of V_{ab} is given by

$$V_{ab} = \frac{1}{2\pi\epsilon}[q_a \ln\frac{D}{r} + q_b \ln\frac{r}{D} + q'_a \ln\frac{\sqrt{4H^2+D^2}}{2H} + q'_b \ln\frac{2H}{\sqrt{4H^2+D^2}}$$

Substituting the values of charges as shown in figure and then simplifying

$$V_{ab} = \frac{q}{\pi\epsilon}\ln\frac{2HD}{r\sqrt{4H^2+D^2}}$$

And

$$C_{ab} = \frac{q}{V_{ab}} = \frac{\pi\epsilon}{\ln\frac{D}{r\sqrt{1+\frac{D^2}{4H^2}}}} \qquad \frac{F}{m}$$

$$C_{ab} = \frac{q}{V_{ab}} = \frac{0.01206}{\log\frac{D}{r\sqrt{1+\frac{D^2}{4H^2}}}} \qquad \frac{\mu F}{Km}$$

And $C_n = 2C_{ab}$. Due to the presence of ground, the line capacitance increases by small amount.

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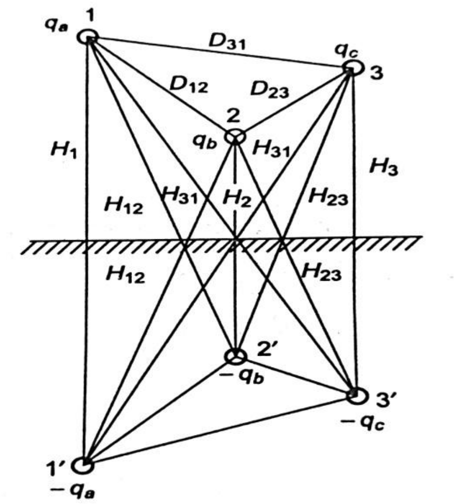
For a three phase line, method of calculating capacitance is discussed below. The figure below shows 3-phase lines along with image conductor



The line is assumed to be transposed. For the 1st part of transposition cycle, conductor 'a' is assumed in position 1, 'b' in position 2 and 'c' in position 3. Charges on line conductors are q_a, q_b & q_c and those on image conductors are $-q_a$, $-q_b$ & $-q_c$.

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a(\ln\frac{D_{12}}{r} - \ln\frac{H_{12}}{H_1}) + q_b(\ln\frac{r}{D_{12}} - \ln\frac{H_2}{H_{12}}) + q_c(\ln\frac{D_{23}}{D_{31}} - \ln\frac{H_{23}}{H_{31}})]$$

For the 2nd part of transposition cycle, conductor 'a' is assumed in position 2, 'b' in position 3 and 'c' in position 1

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a(\ln\frac{D_{23}}{r} - \ln\frac{H_{23}}{H_2}) + q_b(\ln\frac{r}{D_{23}} - \ln\frac{H_3}{H_{23}}) + q_c(\ln\frac{D_{31}}{D_{12}} - \ln\frac{H_{31}}{H_{12}})]$$

For the 3rd part of transposition cycle, conductor 'a' is assumed in position 3, 'b' in position 1 and 'c' in position 2

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a(\ln\frac{D_{31}}{r} - \ln\frac{H_{31}}{H_3}) + q_b(\ln\frac{r}{D_{31}} - \ln\frac{H_1}{H_{31}}) + q_c(\ln\frac{D_{12}}{D_{23}} - \ln\frac{H_{12}}{H_{23}})]$$

Average V_{ab} is calculated as

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a(\ln\frac{D_{eq}}{r} - \ln\frac{\sqrt[3]{H_{12}H_{23}H_{31}}}{\sqrt[3]{H_1H_2H_3}}) + q_b(\ln\frac{r}{D_{eq}} - \ln\frac{\sqrt[3]{H_1H_2H_3}}{\sqrt[3]{H_{12}H_{23}H_{31}}})]$$

Where $D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}}$

Similarly obtaining average value of V_{ac} and using relation $V_{ab}+V_{ac}= 3V_{an}$ and $q_a+q_b+q_c=0$, we have

$$C_n = \frac{2\pi\epsilon}{\ln\frac{D_{eq}}{r} - \ln\frac{\sqrt[3]{H_{12}H_{23}H_{31}}}{\sqrt[3]{H_1H_2H_3}})} \quad F/m$$

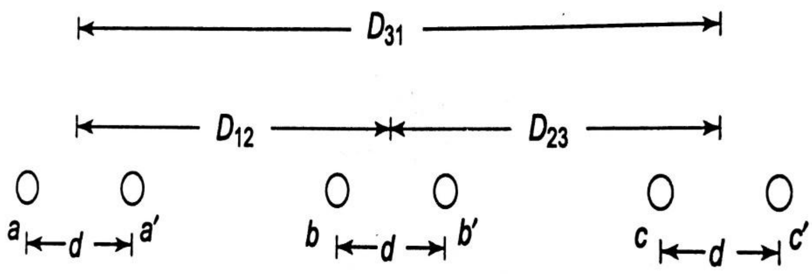
Or,

$$C_n = \frac{0.02412}{\log\frac{D_{eq}}{r} - \log\frac{\sqrt[3]{H_{12}H_{23}H_{31}}}{\sqrt[3]{H_1H_2H_3}})} \quad \mu F/Km$$

It is seen that, presence of ground increases line capacitance by small amount.

Capacitance Calculations for Bundled Conductors:-

Let us consider a 3-phase bundled conductor line with two sub-conductors per phase



The charges on all the 6 sub-conductors are considered. Charge per bundle is assumed to be equally divided between sub-conductors of a bundle as the two sub-conductors of each phase are in parallel

Since D_{12}>>d, hence in place of (D_{12}-d) & (D_{12}+d) ; D_{12} is used

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

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a\ln\frac{D_{12}}{\sqrt{rd}} + q_b\ln\frac{\sqrt{rd}}{D_{12}} + q_c\ln\frac{D_{23}}{D_{31}}]$$

The above equation is same as

$$\therefore\ V_{ab} = \frac{1}{2\pi\epsilon}[q_a\ln\frac{D_{12}}{r} + q_b\ln\frac{r}{D_{12}} + q_c\ln\frac{D_{23}}{D_{31}}]$$

Thus $\sqrt{rd} = r$

Lines are assumed to be transposed & hence

$$C_n = \frac{2\pi\epsilon}{\ln\frac{D_{eq}}{\sqrt{rd}}}\ \frac{F}{m} = \frac{0.02412}{\log\frac{D_{eq}}{\sqrt{rd}}}\ \frac{\mu F}{Km}$$

The term $\sqrt{rd}$ is same as

$$D_s^b = \sqrt[4]{(D_S.d)^2} = \sqrt{D_S.d}$$

r has replaced D_S.

For a two conductor (duplex) arrangement of the line

$$D_{sc}^{b} = \sqrt{r.d}$$

For a three conductor (triplex) arrangement of the line

$$D_{sc}^{b} = \sqrt[9]{(r.d.d)^3} = \sqrt[3]{r.d^2}$$

For a four conductor (quadruplex) arrangement of the line

$$D_{s}^{b} = \sqrt[16]{\left(r.d.d\sqrt{2}.d\right)^4} = 1.09x\sqrt[4]{r.d^3}$$

Prepared By:- Er. Chandan Mandal, Assistant Professor, EE department, ABIT, Cuttack

Problem:- A 3-phase, 50Hz transmission line has flat horizontal configuration with 3.5m between adjacent conductors. The conductors are number 2/0 hard drawn 7 strand copper (outside diameter=1.05cm). The voltage of the line is 110KV. Find the capacitance to neutral and the charging current per km

Solution:-

Conductor radius, r= 1.05/2= 0.5025cm

Spacings, D_{12}= 3.5m; D_{23}= 3.5cm; D_{13}= 7m

Capacitance to neutral,

$$C_n = \frac{2\pi\epsilon}{\ln\frac{D_{eq}}{r}} = \frac{2\pi\epsilon_0}{\ln\frac{\sqrt[3]{D_{12}D_{23}D_{13}}}{r}}$$

$$\therefore\ C_n = \frac{2\pi x 8.854 x 10^{-12}}{\ln\frac{\sqrt[3]{3.5x3.5x7}x100}{0.5025}} = 8.21x10^{-12}\frac{F}{m} = 8.21x10^{-12}x1000 = \frac{0.00821\ \mu F}{km}$$

Charging Current per phase

$$I_C = 2\pi f C_n V_{ph}$$

$$= 2\pi x 50 x 0.00821 x 10^{-6} x \frac{110x1000}{\sqrt{3}} = 0.164 A/Km$$

Problem:- The conductors in a single phase line are 6m above the ground. Each conductor is of 1.5cm diameter and they are spaced 3m apart. Taking the effect of earth into account, Calculate the capacitance per km .

Solution:- We know that

$$C_n = 2C_{ab} = \frac{\pi\varepsilon}{\ln\frac{D}{r(1+\frac{D^2}{4H^2})^{0.5}}}$$

$$C_n = 2C_{ab} = \frac{2x\pi x 8.854 x 10^{-12}}{\ln\frac{300}{0.5 * 1.5(1+\frac{300^2}{4x600x600})^{0.5}}}$$

$$C_n = \frac{5.563x10^{-11}}{\ln\frac{300}{2.0194}} = 0.011126\ \mu F/Km$$

Problem:- A 3-phase 50Hz 132Kv overhead line has conductors placed in a horizontal plane 4m apart. Conductor diameter is 2cm. If the line length is 100Km, calculate the charging current per phase assuming complete transposition.

Solution:-

Conductor radius, r= 2/2= 1cm= 0.01m

Spacings, D_{12}= 4m; D_{23}= 4m; D_{13}= 8m

Capacitance to neutral,

$$C_n = \frac{2\pi\epsilon}{\ln\frac{D_{eq}}{r}} = \frac{2\pi\epsilon_0}{\ln\frac{\sqrt[3]{D_{12}D_{23}D_{13}}}{r}}$$

$$\therefore\ C_n = \frac{2\pi x 8.854 x 10^{-12}}{\ln\frac{\sqrt[3]{4x4x8}}{0.01}} = 0.00885x10^{-6}\frac{F}{Km} = \frac{0.00885\ \mu F}{km}$$

Capacitance/phase for 100Km line is C_n= 0.00885x10^{-6}x100= 0.885x10^{-6}F

Charging Current per phase

$$I_C = 2\pi f C_n V_{ph}$$

$$= 2\pi x 50 x 0.885 x 10^{-6} x \frac{132x1000}{\sqrt{3}} = 21.18A$$

Problem:- Determine the capacitance of the arrangement shown in the figure when (i) the effect of earth is neglected and (ii) the effect of earth is considered. The height of the conductors from ground is 10m and radius of each of the conductor is 2cm

Solution:-

Conductor radius, r= 2 cm=0.02m

Spacings, D_{ab}= 4m; D_{bc}= 4m; D_{ca}= 8m

Capacitance to neutral,

$$C_n = \frac{2\pi\epsilon}{\ln\frac{D_{eq}}{r}} = \frac{2\pi\epsilon_0}{\ln\frac{\sqrt[3]{D_{12}D_{23}D_{13}}}{r}}$$

$$\therefore\ C_n = \frac{2\pi x 8.854 x 10^{-12}}{\ln\frac{\sqrt[3]{4x4x8}}{0.02}} = 10.06x10^{-12}\frac{F}{m}$$

Taking the effect of ground

H_1=H_2=H_3= 20m

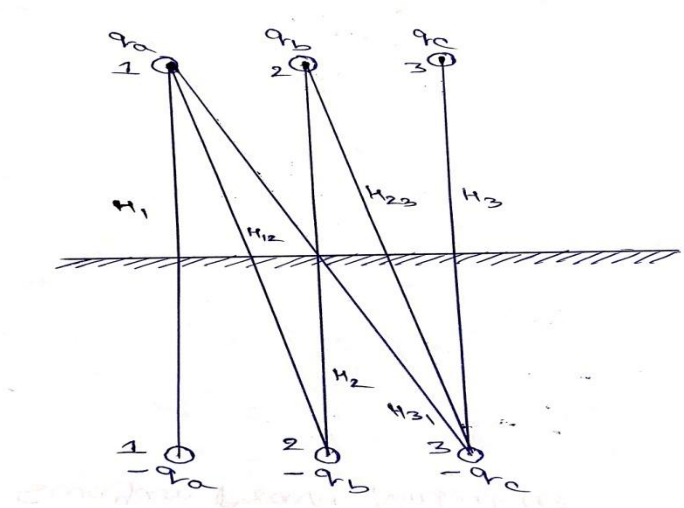
H_{12}=H_{23}= $[20^2+4^2]^{1/2}$= 20.396m

H_{31}=$[20^2+8^2]^{1/2}$= 21.54m

We know that

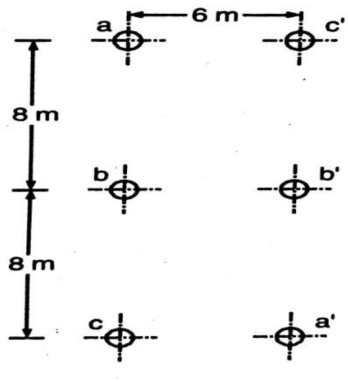
$$C_n = \frac{2\pi\epsilon}{\ln\frac{D_{eq}}{r} - \ln\frac{\sqrt[3]{H_{12}H_{23}H_{31}}}{\sqrt[3]{H_1H_2H_3}})} \quad F/m$$

Using above equation, we have $C_n = 10.13x10^{-12}\frac{F}{m}$



Prepared By:- Er. Chandan Mandal, Assistant Professor, EE department, ABIT, Cuttack

Problem:- Six conductors of a double circuit transmission line are arranged as shown below. The diameter of each conductor is 2.5cm. Find the capacitive reactance to neutral and the charging current per km per phase at 132KV and 50Hz, assuming that the line is regularly transposed. Neglect the effect of earth



Solution:- Radius of each conductor= 2.5/2 cm = 1.25cm

GMR of conductor, r' = 2.176 x 2.5 mm= 5.44 x 10^{-3} m (r'= 2.176r, Since stranded conductor)

Distance between Conductors

$$D_{RR'} = D_{BB'} = \sqrt{7^2 + 8^2} = 10.63 \text{ m}$$
$$D_{RY} = \sqrt{4^2 + (4.5 - 3.5)^2} = 4.12 \text{ m}$$
$$D_{RY'} = \sqrt{(9-1)^2 + (4)^2} = 8.95 \text{ m}$$

GMR of Phase 'R'

$$D_{sR} = \sqrt[4]{D_{RR'}D_{RR}D_{R'R'}D_{R'R}} = \sqrt{rxD_{RR'}} = \sqrt{5.44x10^{-3}x17.089} = 0.305m$$

Similarly

$$D_{sb} = \sqrt{r'xD_{bb'}} = \sqrt{5.44x10^{-3}x6} = 0.1807m$$

And

$$D_{sc} = \sqrt{r'xD_{cc'}} = \sqrt{5.44x10^{-3}x17.089} = 0.305m$$

Self GMD or GMR

$$D_S = \sqrt[3]{D_{sa}D_{sb}D_{sc}} = \sqrt[3]{0.305x0.1807x0.305} = 0.2562m \quad \text{Ans.}$$

$$D_{ab} = \sqrt[4]{D_{ab'}D_{ab}D_{a'b'}D_{a'b}} = \sqrt{D_{ab}xD_{ab'}} = \sqrt{8x10} = 8.944m$$

Similarly

$$D_{bc} = \sqrt{D_{bc}xD_{bc'}} = \sqrt{8x10} = 8.944m$$

$$D_{ca} = \sqrt{D_{ca}xD_{ca'}} = \sqrt{16x6} = 9.8m$$

$$D_{eq} \text{ or } D_m = \sqrt[3]{D_{ab}D_{bc}D_{ca}} = 9.22m \quad \text{Ans.}$$

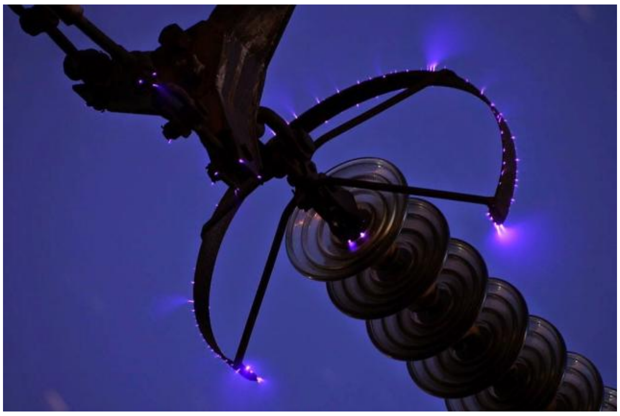
Prepared By:- Er. Chandan Mandal, Assistant Professor, EE department, ABIT, Cuttack

Inductance per phase, L= 0.2 log D_m/D_S = 0.2 log(9.22/0.2562) = 0.717 mH/Km

Inductance of 100Km line= (0.717 x 100) / 1000= 0.0717 H Ans.

Prepared By:- Er. Chandan Mandal, Assistant Professor, EE department, ABIT, Cuttack

Corona:- When the voltage between conductors of an overhead line exceeds the disruptive critical voltage value, a hissing noise accompanied by a violet glow appears. This phenomenon is called Corona Effect.



- It is known that air is not a perfect insulator and always contains small number of electrons and ions. Whenever electric gradient is set up in air, electrons and ions are set up in movement by the electric field and thus a small current is maintained by convection.
- When electric field intensity reaches critical value of 30KV/cm, ions gain high velocity and collision with other neutral molecule; some electrons are liberated along with positive ions. This process is repeated again and thus more electrons are produced.
- When ion avalanche is reached then breakdown occurs and an arc is produced in the gap between the two electrode. This ionization is also accompanied by a luminous glow around the conductor and when the surface is rough, the brightest part of luminous glow is near the peak of rough surface.
- During the corona phenomenon, hissing noise is heard along with smell of ozone. The glow, hissing and light intensity increases with increase in voltage.
- Corona occurs in lines of 100KV and above.
- The energy which is required for the movement of ions is taken from the conductor and the corresponding energy loss is known as Corona loss.
- This energy is dissipated in the form of heat, light & sound & some chemical action.

- The transmission lines transmit bulk power at relatively higher voltages and, therefore these lines give rise to electromagnetic and electrostatic fields of sufficient magnitude which induce currents and voltages in the neighbouring communication lines.
- In extreme cases, the effects of electrostatics and electromagnetic fields produced by power lines may take it impossible to transmit any message faithfully and may raise the potential of telephone receiver above the ground to such an extent to render the handling of the telephone receiver extremely dangerous.

Disruptive Critical Voltage:-

The potential difference between conductors at which the electric field intensity at the surface of the conductor exceeds the critical value and generates corona is known as Disruptive Critical Voltage.

Corona begins when peak value of critical field intensity equals 30KV/cm or $3x10^6$V/m in case of smooth conductors of large diameter in air at normal temperature and pressure.

Taking the relative density at $\theta_0{}^0$C and 76cm of mercury as 1.0, the relative density at a barometric pressure of p cm and temperature θ^0C

$$\delta = \frac{p}{76}\left(\frac{273+\theta_0}{273+\theta}\right)$$

When θ_0= 20^0C,

$$\delta = \frac{3.92p}{273+\theta}$$

Roughness of surface causes distortion in electric field and gives rise to local regions of high potential gradient which results in lower critical intensity

The stranding and surface condition is taken into account by surface factor or roughness factor m_0

The RMS value of Critical intensity is

$$E_0 = \left(3x\frac{10^6}{\sqrt{2}}\right)\delta.m_0 \qquad \frac{V}{m}$$

m_0= 1 for smooth conductors and 0.93-0.98 for rough conductors

The voltage V between two conductors of 1-phase line of radius r, metre and spacing D metre is

$$V = \frac{q}{\pi\varepsilon_0}\ln\frac{D}{r}$$

Comparing the above equation with Electric intensity E_r

$$V = 2rE_r\ln\frac{D}{r}$$

When E_r reaches E_0, the voltage between conductors is critical disruptive voltage V_d. Substituting the value of E_0 in above equation

$$V = 6x\frac{10^6}{\sqrt{2}}r\delta.m_0\ln\frac{D}{r},\ \ Volts$$

For 3-phase line

$$V = 3x\frac{10^6}{\sqrt{2}}r\delta.m_0\ln\frac{D_{eq}}{r},\ \ Volts$$

$$V = g_0r\delta.m_0\ln\frac{D_{eq}}{r},\ \ Volts$$

Visual corona occurs somewhat higher than the condition of E_r=E_0, i.e. at E_v as the breakdown of air requires a finite volume of over stressed air

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$$E_v = \left(3x\frac{10^6}{\sqrt{2}}\right)\delta.m_v\left(1+\frac{0.03}{\sqrt{\delta r}}\right) \quad \frac{V}{m}$$

Thus

$$V = 2rE_v \ln\frac{D}{r}$$

$$V_v = 6x\frac{10^6}{\sqrt{2}}r\delta.m_v\left(1+\frac{0.03}{\sqrt{\delta r}}\right)\ln\frac{D}{r}, \ Volts$$

For 3-phase line

$$V_v = g_0 r\delta.m_v\left(1+\frac{0.03}{\sqrt{\delta r}}\right)\ln\frac{D_{eq}}{r}, \ Volts$$

Corona loss can be determined by Peek's Empirical Formula i.e.

$$P_c = 244\frac{(f+25)}{\delta}\sqrt{\frac{r}{d}}(V-V_d)^2 x10^{-5}\frac{\frac{KW}{Km}}{Phase}$$

Adverse effects of corona are

- Power loss but not very important except under abnormal weather conditions
- Corrosion due to production of ozone gas,
- Interference with neighbouring communication circuits

Factors Affecting Corona:-

- System frequency:- Corona loss is directly proportional to system frequency
- System voltage:- Greater the potential difference, greater is the electric field & greater is corona loss
- Air conductivity:- Conductivity of air depends upon no. of ions per unit volume of air , size & charge per ion. These factors differ with altitude & atmosphere. Higher conductivity leads to higher corona loss
- Air density:- Corona loss increases with decrease in density of air.
- Conductor Radius:- A higher conductor radius means less surface field intensity & hence reduced corona loss. An ACSR conductor has larger radius than copper conductor. Hence ACSR conductor has lower corona loss
- Conductor surface condition:- The breakdown voltage is low & high corona loss for stranded conductors. Any kind of roughness also increases the corona loss.
- Load current:- The load current raises the conductor temperature and thus leads to indirect reduction in corona loss.

Steps to reduce Corona loss:-

- Using large diameter
- Conductors which may be accomplished by using hollow conductors with a hemp core.
- ACSR conductors or bundled conductors.
- By increasing the spacing between the conductors.

Problems:- Define Disruptive Critical voltage. A 3-phase, 220KV, 50Hz transmission line consists of 1.2cm radius conductors spaced 2m at the corners of an equilateral triangle. Calculate the disruptive critical voltage between the lines. Irregularity factor = 0.96; temperature = 20^0C, Barometric Pressure = 72.2 cm of mercury. Dielectric Strength of air = 21.1 KV(RMS)/cm

Solution:- Disruptive Critical Voltage:- The disruptive critical voltage is defined as the minimum phase to neutral voltage at which corona occurs.

$$\text{Air Density Factor}, \delta = \frac{3.92\text{p}}{273+\theta} = \frac{3.92\text{x}72.2}{273+20} = 0.966$$

Disruptive Critical Voltage to neutral,

$$V_{d_0} = g_0 \delta m_0 r \log\frac{d}{r} = 21.1\text{x}0.966\text{x}0.96\text{x}1.2\log\frac{200}{1.2} = 120.1 \text{ KV (RMS)}$$

Disruptive Critical Voltage from Line to line

$$= \sqrt{3}V_{d_0} = \sqrt{3}\text{ x }120.1 = 208\text{KV (RMS)} \qquad \text{Ans.}$$

b) **A 3-phase, 220KV, 50Hz transmission line consists of 2cm radius conductor spaced 2.5m apart in equilateral triangular formulation. If the temperature is 20^0C and atmospheric pressure 75cm, m_0= 0.80, determine the corona loss per km of line**

Solution:- Conductor radius = 2.0 cm

Spacing of conductors, d = 2.5m = 250cm

Dielectric Strength of air= 21.1 KV/cm (RMS) as assumed

Irregularity factor, m_0 = 0.8

$$\text{Air Density Factor}, \delta = \frac{3.92\text{p}}{273+\theta} = \frac{3.92\text{x}75}{273+20} = 1.00$$

Disruptive Critical Voltage to neutral,

$$V_{d_0} = g_0 \delta m_0 r \log\frac{d}{r} = 21.1\text{x}1.0\text{x}0.8\text{x}2\log\frac{250}{2} = 163 \text{ KV (RMS)}$$

Supply Voltage/Phase= 220/√3= 127KV

Corona Loss

$$P_C = \frac{244}{\delta}(f+25)\sqrt{\frac{r}{d}}\left(V_{ph} - V_{d_0}\right)^2 x10^{-5} \frac{\frac{KW}{Km}}{Phase}$$

$$P_C = \frac{244}{1.00}(50+25)\sqrt{\frac{2}{250}}(127-163)^2 x10^{-5} \frac{\frac{KW}{Km}}{Phase}$$

= 21.2 KW/Km/Phase

Total Corona Loss per Km for 3-phase line

= 3x21.2= 63.6 KW **Ans.**

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Performance of Transmission Line:- The performance of a power system is mainly dependent on the performance of the transmission lines in the system. The transmission line performance is governed by its 4 parameters-series resistance and inductance, shunt capacitance and conductance which are distributed throughout the length of the line. Since the leakage currents are small, thus the shunt conductance i.e. G can be neglected.

Transmission lines may be classified as short, medium and long. Short transmission line is referred as to those whose length is less than 80Km and the effect of shunt capacitance is ignored.

Medium Transmission line length lies between 80 to 250Km and shunt capacitance is considered as lumped.

Long Transmission line has the length more than 250Km and requires calculations in terms of distributed parameters.

Short Transmission Line:- The figure below shows the equivalent circuit and phasor diagram of a short transmission line

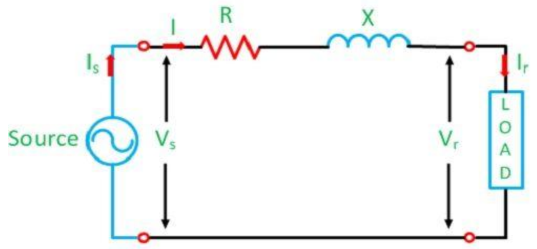

Figure 1a Equivalent Circuit

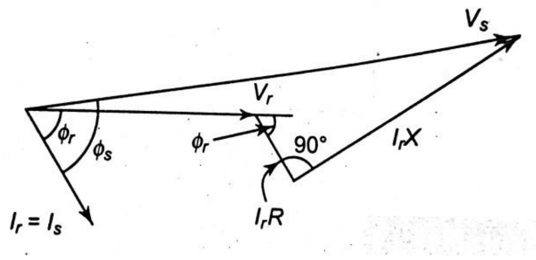

Figure 1b. Phasor Diagram

It can be seen that, $I_S = I_r$ & $V_S = V_r + I_r Z$

In matrix form

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

From the phasor diagram, taking V_r as the reference phasor, we have

$$V_S = V_r + IZ$$

$$V_r = V_r\angle 0^0 = V_r + j0; I = I\angle - \emptyset_r = I(\cos\emptyset_r - j\sin\emptyset_r)$$

$$\therefore\ V_S = V_r + IZ = (V_r + j0) + I\,(\cos\emptyset_r - j\sin\emptyset_r)(R + jX_L)$$

$$= (V_r + IR\cos\emptyset_r + IX_L\sin\emptyset_r) + j(IX_L\cos\emptyset_r - IR\sin\emptyset_r)$$

$$\therefore V_S = \sqrt{(V_r + IRcos\emptyset_r + IX_L sin\emptyset_r)^2 + (IX_L\cos\emptyset_r - IR\sin\emptyset_r)^2}$$

The second term under root is quite small as the IX_L & IR drop is quite small as compared to V_r & can be neglected

$$\therefore V_S = (V_r + IRcos\emptyset_r + IX_L sin\emptyset_r)$$

We know that

Voltage regulation is defined as the rise in receiving end voltage when full load at a certain p.f is removed with sending end voltage held constant.

$$\therefore Regulation, \frac{V_S - V_r}{V_r} = \frac{IRcos\emptyset_r \pm IX_L sin\emptyset_r}{V_r}$$

Negative sign is used for leading p.f. Regulation is zero when p.f is leading i.e.

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$$IRcos\emptyset_r = IX_L sin\emptyset_r$$

$$\tan\emptyset_r = \frac{R}{X_L}$$

Conclusions from Voltage Regulation Expressions

1. For lagging p.f, unity p.f voltage regulation is positive or it can be said that receiving end voltage is less than sending end voltage
2. For given receiving end voltage and current, V.R increases with decrease in p.f. for lagging loads
3. For leading p.f, V.R is negative i.e. receiving end voltage is greater than sending end voltage
4. For given receiving end voltage and current, V.R decreases with decrease in p.f. for leading loads

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Problem:- A short 3-phase transmission line connected to 33KV generating station at the sending end is to supply a load of 10MW at 0.8p.f lagging at 30KV at the receiving end. If the minimum transmission efficiency is to be 0.96, determine the per phase values of line resistance and reactance.

Solution:- $|V_S|$ = 33000/√3 = 19052.6V

$|V_r|$ = 30000/√3 = 17320.5V

$|I_r|$ = $(10x10^6)$/ (√3x30000x0.8) = 240.56A

Sending end power = $(10x10^6)$/ 0.96 = $10.4167x10^6$ W

Line losses= $10.4167x10^6$- $10x10^6$= $0.4167x10^6$W

$3I_r^2R = 0.4167x10^6$W

Or, R= $0.4167x10^6$/ (3x240.56x240.56)= 2.4Ω/phase

$$|V_S - V_r| = I_r R cos\emptyset_r + I_r X_L sin\emptyset_r$$

$$X_L = \frac{|V_S - V_r| - I_r R cos\emptyset_r}{I_r sin\emptyset_r} = 8.8\Omega/\text{phase}$$

Problem:- Estimate the distance over which a load of 15000KW at p.f 0.8 lagging can be delivered by a 3-phase transmission line having conductors each of resistance 1Ω per Km. The voltage at the receiving end is to be 132KV and the loss in the transmission line is to be 5%

Solution:- Line Current

$$\text{I} = \frac{\text{Power Delivered}}{\sqrt{3}\text{xLine voltagexpower factor}}$$

$$\therefore \text{I} = \frac{15000\text{x}10^3}{\sqrt{3}\text{x}132\text{x}10^3\text{x}0.8} = 82\text{A}$$

Line losses= 5% of power delivered = 0.05x15000 = 750KW

Let R Ω be the resistance of one conductor

Line losses = 3 I^2R

Or , $750x10^3$= 3x $(82)^2$R

Or, R= 37.18Ω

Resistance of each conductor per km is 1Ω

Thus, length of the line = 37.18 Km **Ans.**

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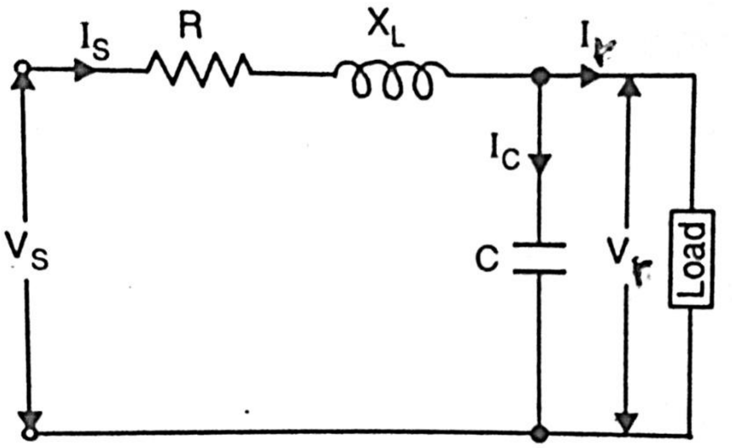
Medium Length Transmission Line:-

Shunt capacitance effect cannot be neglected with the increase in length and hence in medium length line, it can be considered as lumped. The most commonly used methods for the solution of medium length transmission lines are

i) End condenser Method:

In this method, capacitance is considered to be lumped or concentrated at the receiving end or load end.



In the figure shown above, one phase of the 3-phase transmission line is shown

Let I_r = load current/phase

R= Resistance/phase

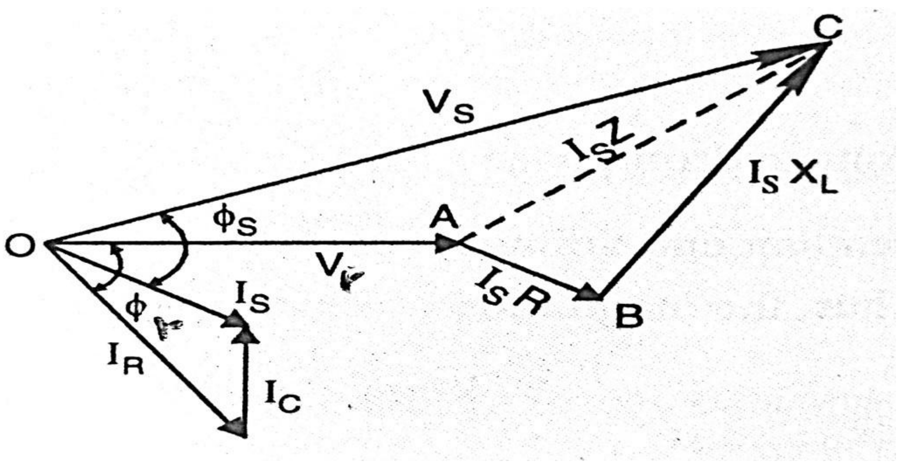
X_L= Inductive Reactance/Phase

C= Capacitance/ phase

Cos Φ_r= Receiving end power factor (lagging)

V_S= Sending end voltage/phase

The phasor diagram for the above circuit is shown below



From the phasor diagram, taking V_r as the reference phasor, we have

$$I_r = I_r(\cos \emptyset_r - j\sin \emptyset_r)$$

$$I_C = jV_r\omega C = j2\pi f C V_r = YV_r$$

$$I_S = I_r + I_C = I_r + YV_r$$

$$or \quad I_S = I_r(\cos \emptyset_r - j\sin \emptyset_r) + j2\pi f C V_r$$

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$$or \quad I_S = I_r \cos\emptyset_r + j(-I_r \sin\emptyset_r + 2\pi f C V_r)$$

$$Voltage\ drop\ per\ phase = I_S Z = I_S(R + jX_L)$$

$$\therefore\ V_S = V_r + IZ = V_r + I_S(R + jX_L) = V_r + I_S Z = (1 + YZ)V_r + ZI_r$$

Comparing the equations of V_S and I_S with the governing equation of ABCD parameter, we have

$$V_S = (1 + YZ)V_r + ZI_r$$

$$I_S = YV_r + I_r$$

In matrix form, the governing equation can be written as

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 + YZ & Z \\ Y & 1 \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Where A= 1+YZ; B=Z; C=Y; D=1

$$\therefore Regulation, \frac{V_S - V_r}{V_r} x100$$

$$\%\ Transmission\ efficiency, \eta_T = \frac{Power\ delivered\ per\ phase}{Power\ delivered\ per\ phase + losses\ per\ phase} x100$$

$$\%\ Transmission\ efficiency, \eta_T = \frac{V_r I_r \cos\emptyset_r}{V_r I_r \cos\emptyset_r + I_S^2 R} x100$$

Problem:- A medium length single phase transmission line 100Km long has the following constants:

Resistance/Km= 0.25Ω

Reactance/Km= 0.8Ω

Susceptance/Km= 14x10^{-6} siemens

Receiving end line voltage= 66000V

Assuming that the total capacitance of the line is localized at the receiving end alone, determine (i) the sending end current (ii) the sending end voltages (iii) regulation (iv) supply power factor. The line is delivering 15000KW at 0.8 power factor lagging.

Solution:-

Total Resistance, R= 0.25x100= 25Ω

Total Reactance, X_L= 0.8x100= 80Ω

Total Susceptance, Y= 14x10^{-6} x100= 14x10^{-4} S

Receiving end voltage, V_r= 66000V

Thus, Load Current I_r = (15000x10^3)/(66000x0.8)=284A

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

Taking receiving end voltage as the reference phasor

$$I_r = I_r(\cos\emptyset_r - j\sin\emptyset_r) = 284(0.8 - j0.6) = 227 - j170$$

$$I_C = jYV_r = j14\text{x}10^{-4}\text{x}66000 = \text{j}92$$

$$I_S = I_r + I_C = 227 - j170 + j92 = 227 - j78$$

$$|I_S| = \sqrt{227^2 + 78^2} = 240A$$

Voltage Drop= $I_S Z = I_S(R + jX_L) = (227 - j78)(25 + j80) = 11915 + j16210$

Sending end Voltage, $V_S = V_r + IZ = 66000 + 11915 + j16210 = 77915 + j16210$

$$|V_S| = \sqrt{77915^2 + 16210^2} = 79583A$$

$$Regulation, = \frac{V_S - V_r}{V_r} x100 = \frac{79583 - 66000}{66000} x100 = 20.58\%$$

Phase Angle between V_r and I_S is θ_1= $\tan^{-1}(-78/227)$= -18.96^0

Phase Angle between V_r and V_S is θ_2= $\tan^{-1}(16210/77915)$= 11.50^0

Thus, Supply power factor angle, $\emptyset_S$= 18.96+11.5= 30.46^0

Supply Power factor= cos $\emptyset_S$= $\cos 30.46^0$= 0.86 lag

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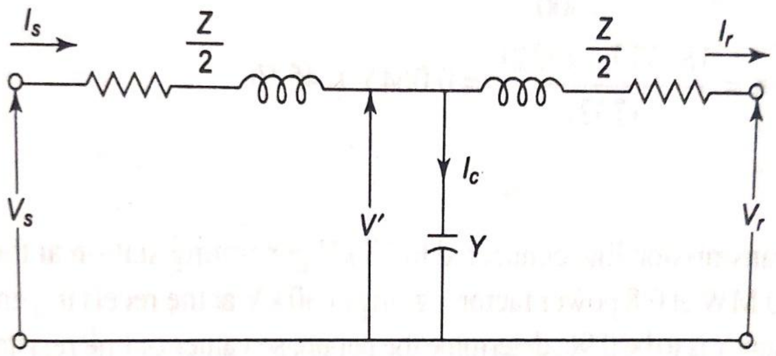
i) Nominal-T Method:

In this method, whole of the line is assumed to be concentrated at the middle point of the line and half of the line resistance and reactance are lumped on either side



Let I_r = load current/phase

R= Resistance/phase

X_L= Inductive Reactance/Phase

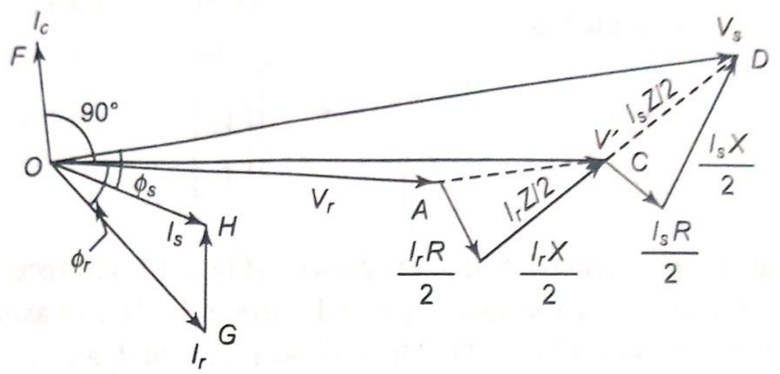
C= Capacitance/ phase

Cos Φ_r= Receiving end power factor (lagging)

V_S= Sending end voltage/phase

V'= Voltage across capacitor C

The phasor diagram for the above circuit is shown below



From the phasor diagram, taking V_r as the reference phasor, we have

$$I_r = I_r(\cos \emptyset_r - j\sin \emptyset_r)$$

$$Voltage\ across\ Capacitor\ C = V' = V_r + \frac{I_r Z}{2}$$

$$or, \quad V' = V_r + I_r(\cos \emptyset_r - j\sin \emptyset_r)\left(\frac{R}{2} + \frac{jX_L}{2}\right)$$

$$Capacitive\ Current, \quad I_C = jV'\omega C = j2\pi f C V'$$

$$Sending\ end\ current, \quad I_S = I_r + I_C$$

$$\therefore\ Sending\ end\ Voltage\ \ V_S = V' + I_S\left(\frac{R}{2} + \frac{jX_L}{2}\right)$$

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Also $$I_C = Y\left(V_r + \frac{I_r Z}{2}\right)$$

$$\therefore \; I_S = I_r + Y\left(V_r + \frac{I_r Z}{2}\right) = YV_r + I_r\left(1 + \frac{YZ}{2}\right)$$

$$Also, \quad V_S = V' + I_S\left(\frac{R}{2} + \frac{jX_L}{2}\right) = V_r + \frac{I_r Z}{2} + \frac{I_S Z}{2} = V_r + \frac{I_r Z}{2} + \frac{YV_r + I_r\left(1 + \frac{YZ}{2}\right)Z}{2}$$

$$Thus \quad V_S = V_r(1 + \frac{YZ}{2}) + \frac{Z + YZ^2}{4} I_r$$

Comparing the equations of V_S and I_S with the governing equation of ABCD parameter, we have

$$V_S = V_r\left(1 + \frac{YZ}{2}\right) + \frac{Z + YZ^2}{4} I_r$$

$$I_S = YV_r + I_r\left(1 + \frac{YZ}{2}\right)$$

In matrix form, the governing equation can be written as

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} (1 + \frac{YZ}{2}) & Z(1 + \frac{YZ}{4}) \\ Y & (1 + \frac{YZ}{2}) \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Where $A = D = 1 + \frac{YZ}{2}$; $B = Z(1 + \frac{YZ}{4})$; C=Y

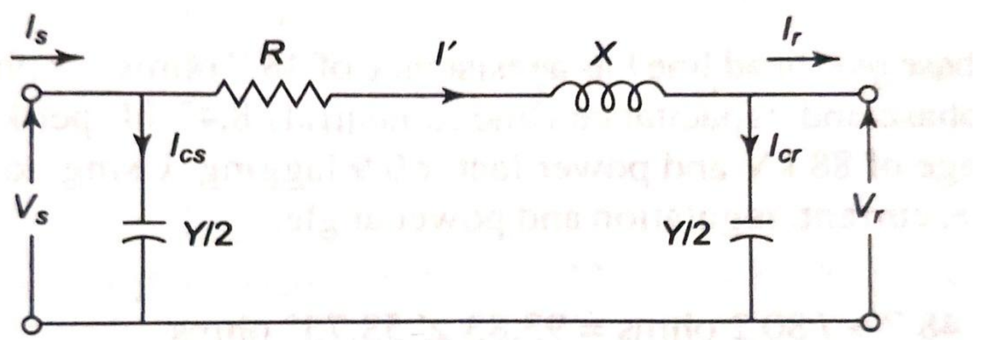
$$\therefore Regulation, \frac{V_S - V_r}{V_r} x100$$

$$\% \; Transmission\, efficiency, \eta_T = \frac{Power\ delivered\ per\ phase}{Power\ delivered\ per\ phase + losses\ per\ phase} x100$$

$$\% \; Transmission\, efficiency, \eta_T = \frac{V_r I_r \cos\phi_r}{V_r I_r \cos\phi_r + I_S^2 R} x100$$

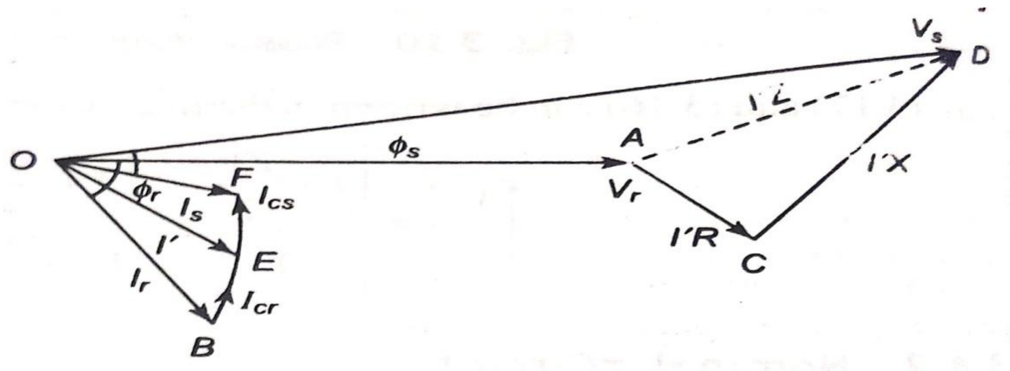
i) Nominal-π Method:

In this method, capacitance of each conductor (L-N) is divided into two halves, one half being lumped at the sending end and other half at the receiving end



Let I_r = load current/phase

R= Resistance/phase
X_L= Inductive Reactance/Phase
C= Capacitance/ phase
Cos Φ_r= Receiving end power factor (lagging)
V_S= Sending end voltage/phase
The phasor diagram for the above circuit is shown below



From the phasor diagram, taking V_r as the reference phasor, we have

$$I_r = I_r(\cos\emptyset_r - j\sin\emptyset_r)$$

$$Charging\ current\ at\ receiving\ end\quad I_{C_r} = jV_r\omega C/2 = j\pi f C V_r$$

$$Line\ Current, I' = I_r + I_{C_r}$$

$$\therefore\ Sending\ end\ Voltage\quad V_S = V_r + I'Z$$

$$Charging\ current\ at\ sending\ end\quad I_{C_S} = \frac{jV_S\omega C}{2} = j\pi f C V_S = \frac{V_S Y}{2}$$

$$Sending\ end\ current,\qquad I_S = I' + I_{C_S} = I' + \frac{V_S Y}{2}$$

$$Also, I' = I_r + I_{C_r} = I_r + \frac{V_r Y}{2}$$

$$Now,\quad V_S = V_r + I'Z = V_r + (I_r + \frac{V_r Y}{2})Z$$

$$Thus,\quad V_S = V_r(1 + \frac{ZY}{2}) + I_r Z$$

$$Since,\quad I_S = I' + \frac{V_S Y}{2} = I_r + \frac{V_r Y}{2} + \frac{V_S Y}{2}$$

Substituting the value of V_S

$$I_S = I_r + \frac{V_r Y}{2} + \frac{[V_r(1 + \frac{ZY}{2}) + I_r Z]Y}{2} = I_r\left(1 + \frac{ZY}{2}\right) + V_r Y(1 + \frac{ZY}{4})$$

Comparing the equations of V_S and I_S with the governing equation of ABCD parameter, we have

$$V_S = V_r\left(1 + \frac{ZY}{2}\right) + I_r Z$$

$$I_S = I_r\left(1 + \frac{ZY}{2}\right) + V_r Y(1 + \frac{ZY}{4})$$

In matrix form, the governing equation can be written as

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$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} (1+\frac{YZ}{2}) & Z \\ Y(1+\frac{YZ}{4}) & (1+\frac{YZ}{2}) \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Where $A = D = 1+\frac{YZ}{2}$;B=Z ; $C = Y(1+\frac{YZ}{4})$

$$\therefore Regulation, \frac{V_S - V_r}{V_r} x100$$

$$\%\ Transmission\ efficiency, \eta_T = \frac{Power\ delivered\ per\ phase}{Power\ delivered\ per\ phase + losses\ per\ phase} x100$$

$$\%\ Transmission\ efficiency, \eta_T = \frac{V_r I_r \cos\emptyset_r}{V_r I_r \cos\emptyset_r + I_S^2 R} x100$$

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Problem:- A 200Km long 3-phase overhead line has a resistance of 48.7 ohm per phase, inductive reactance of 80.2 ohms per phase and capacitance(L-N) 8.42nF per km. It supplies a load of 13.5MW at a voltage of 88KV and power factor 0.9 lagging. Using Nominal- T circuit, find the sending end voltage, current, regulation & power angle.

Solution

$$Z = 48.7 + j\,80.2 \text{ ohms} = 93.83 \angle 58.73° \text{ ohms}$$

$$Y = j\,\omega C l = 2\pi \times 50 \times 8.42 \times 10^{-9} \times 200 \angle 90°$$

$$= 529 \times 10^{-6} \angle 90° \text{ siemens}$$

$$V_r = \frac{88 \times 1000}{\sqrt{3}} = 50808.3 \angle 0 \text{ V}$$

$$I_r = \frac{13.5 \times 10^6}{\sqrt{3} \times 88 \times 1000 \times 0.9} \angle (-\cos^{-1} 0.9)$$

$$= 50808.3\,(0.9788 + j\,0.0129) + (9233.81 \angle 32.89°) \times (0.9894 + j\,0.00645)$$

$$= 57369.73 + j\,5648.77 = 57647.2 \angle 5.62°$$

Sending end line voltage $= \sqrt{3} \times 57647.2 \text{ V} = 99.85 \text{ kV}$

Power angle $= 5.62°$

$$\times (93.83 \angle 58.73°)\left[1 + \frac{(93.83 \angle 58.73°)(529 \times 10^{-6} \angle 90°)}{4}\right]$$

$$I_s = V_r Y + I_r \left(1 + \frac{ZY}{2}\right)$$

$$= (50808.3 \angle 0°)(529 \times 10^{-6} \angle 90°) + (98.41) \angle -25.84°)$$

$$\times \left[1 + \frac{(93.73 \angle 58.73°)(529 \times 10^{-6} \angle 90°)}{2}\right]$$

$$= (26.88 \angle 90°) + (98.41 \angle -25.84°)(0.9788 + j\,0.0129)$$

$$= j\,26.88 + 87.25 - j\,40.83 = 87.25 - j\,13.95 = 88.36 \angle -9.08° \text{ A}$$

Sending end line current $= 88.36$ A

Also we Know that

Hence, the receiving end voltage at no load is

$$|V_r| \text{ at no load} = \frac{|V_s|}{\left|1 + \frac{ZY}{2}\right|} = \frac{57647.2}{|0.9788 + j\,0.0129|} = 58890.98$$

$$\text{Regulation} = \frac{58890.98 - 50808.3}{50808.3} = 0.159 \text{ or } 15.9\%$$

Problem:- A 200Km long 3-phase overhead line has a resistance of 48.7 ohm per phase, inductive reactance of 80.2 ohms per phase and capacitance(L-N) 8.42nF per km. It supplies a load of 13.5MW at a voltage of 88KV and power factor 0.9 lagging. Using Nominal- pi circuit, find the sending end voltage, current, regulation & power angle.

Solution:- We know from Nominal-Pi Method that

$$V_s = V_r\left(1+\frac{ZY}{2}\right)+I_rZ$$

$$= (50808.3\angle 0^\circ\left[1+\frac{(93.83\angle 58.73^\circ)\,(529\times 10^{-6}\angle 90^\circ)}{2}\right]$$

$$+ (98.41\angle -25.84^\circ)\,(93.83\angle 58.73^\circ)$$

$$= 50808.3\,(0.9788 + j\,.0.0129) + 9233.81\angle 32.89^\circ$$

$$= 49731.16 + j\,655.43 + 7753.76 + j\,5014.21$$

$$= 57484.92 + j\,5669.64 = 57763\angle 5.63^\circ \text{ V}$$

Sending end line voltage

$$= \sqrt{3}\times 57763 \text{ V} = 100.05 \text{ kV}$$

Power Angle $= 5.63^\circ$

$$I_s = V_r\,Y\left(1+\frac{ZY}{4}\right)+I_r\left(1+\frac{ZY}{2}\right)$$

$$= (50808.3\angle 0^\circ)\,(529\times 10^{-6}\angle 90^\circ)\left[1+\frac{(93.83\angle 58.73^\circ)\,(529\times 10^{-6}\angle 90^\circ)}{4}\right]$$

$$+ (98.41\angle -25.84^\circ)\left[1+\frac{(93.83\angle 58.73^\circ)\,(529\times 10^{-6}\angle 90^\circ)}{2}\right]$$

$$= (26.88\angle 90^\circ)\,(0.9894 + j\,0.00645) + (98.41\angle -25.84^\circ)\times(0.9788 + j.0129)$$

$$= j\,26.6 - 0.17 + 87.2 - j\,40.84 = 87.03 - j\,14.24 = 88.19\angle -9.29^\circ \text{ A}$$

$$V_r \text{ at no load} = \frac{|V_s|}{\left|1+\frac{ZY}{2}\right|} = \frac{57763}{[0.9788 + j\,0.0129]}$$

$$= 59009.4 \text{ V}$$

$$\text{Regulation} = \frac{59009.4 - 50808.3}{50808.3} = \frac{8201.1}{50808.3} = 0.1614 \text{ or } 16.14\%$$

Problem:- A 3-phase, 50Hz 100Km long overhead line has the following line constants: resistance per phase per km= 0.153 ohm, inductance per phase per km=1.21 mH, capacitance per phase per km = 0.00958 micro-F. The line supplies a load of 20MW at 0.9 power factor lagging at a line voltage of 110KV at the receiving end. Using Nominal Pi representation, calculate sending end voltage, current, power factor, regulation & efficiency.

Solution

$$V_r = \frac{110000}{\sqrt{3}} = 63508.5\angle 0$$

$$I_r = \frac{20\times 10^6}{\sqrt{3}\times 110000\times .9}\angle -\cos^{-1}0.9) = 116.64\angle -25.84^\circ \text{ A}$$

$$Z = (0.153 + j\,2\,\pi\times 50\times 1.21\times 10^{-3})\,100 = 15.3 + j\,38.0 = 40.96\angle 68.07^\circ\,\Omega$$

$$Y = (j\,2\,\pi\times 50\times 0.00958\times 10^{-6})\,100 = 300.96\times 10^{-6}\angle 90^\circ \text{ Siemens}$$

$$V_s = V_r\left(1 + \frac{ZY}{2}\right) + I_r Z$$

$$= (63508.5 \angle 0^\circ\left[1 + \frac{(40.96 \angle 68.07^\circ)(300.96 \times 10^{-6} \angle 90^\circ)}{2}\right]$$

$$+ (116.64 \angle -25.84^\circ)(40.96 \angle 68.07^\circ)$$

$$= (63508.5 \angle 0^\circ)(1 + 6163.66 \times 10^{-6} \angle 158.07)$$

$$+ (116.64 \angle -25.84^\circ)(40.96 \angle 68.07^\circ),$$

$$= (63508.5 \angle 0^\circ)(0.994282 + j\,0.0023) + 4777.57 \angle 42.23^\circ$$

$$= 63145.4 + j\,146.07 + 3537.57 + j\,3211.04$$

$$= 66682.97 + j\,3357.11 = 66767.42 \angle 2.88^\circ \text{ V}$$

$$I_s = V_r Y\left(1 + \frac{ZY}{4}\right) + I_r\left(1 + \frac{ZY}{2}\right)$$

$$= (63508.5 \angle 0^\circ)(300.96 \times 10^{-6} \angle 90^\circ)$$

$$\times\left[1 + \frac{(40.96 \angle 68.07^\circ)(300.96 \times 10^{-6} \angle 90^\circ)}{4}\right]$$

$$+ (116.84 \angle -25.84^\circ) \times \left[1 + \frac{(40.96 \angle 68.07^\circ)(300.96 \times 10^{-6} \angle 90^\circ)}{2}\right]$$

$$= (19.11 \angle 90^\circ)(1 + 3081.83 \times 10^{-6} \angle 158.07^\circ)$$

$$+ (116.84 \angle -25.84^\circ)(1 + 6163.66 \times 10^{-6} \angle 158.07^\circ)$$

$$= (j19.11)(0.997141 + j\,0.00115) + (116.84 \angle -25.84^\circ) \times (0.994284 \angle 0.13^\circ)$$

$$= (-0.022 + j\,19.055) + (116.17 \angle -25.71^\circ)$$

$$= -0.022 + j\,19.055 + 104.67 - j\,50.4$$

$$= 104.648 - j\,31.345$$

$$= 109.24 \angle -16.67^\circ \text{ A}$$

Sending end line voltage $= \sqrt{3} \times 66767.42 \text{ V} = 115.64 \text{ kV}$

Sending end line current $= 109.24$ A

Sending end power factor $= \cos(2.88^\circ + 16.67^\circ)$

$= \cos(19.55^\circ) = 0.942$ lagging

$$V_r \text{ at no load} = \frac{|V_s|}{\left|1 + \frac{ZY}{2}\right|} = \frac{66767.42}{0.994282} = 67151.39 \text{ V}$$

$$\text{Regulation} = \frac{67151.39 - 63508.5}{63508.5} \times 100 = 5.74\%$$

$$\text{Efficiency} = \frac{20 \times 10^6}{3\,V_s\,I_s\,\cos\phi_s} \times 100$$

$$= \frac{20 \times 10^6}{3 \times 66767.42 \times 109.24 \times 0.942}$$

$$= 97\%$$

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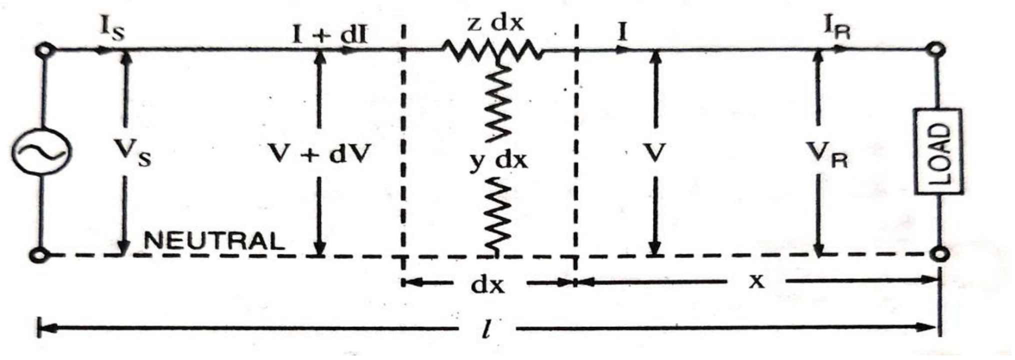
Analysis of long Transmission line:- The figure below shows the exact equivalent circuit of a transmission line. Consider an infinitely small length dx at a distance 'x' from receiving end



Let 'z' be the impedance per unit length of line
'y' be admittance per unit length of line
'V' = voltage/phase at the end of element towards receiving end
V+dV= Voltage/phase at the end of element towards sending end
I+dI= Current entering element dx
I= Current leaving element dx
Thus, Voltage drop in element dx ; dV= I(zdx)

⇨ dV/dx= zI

and current drawn by element dx; dI= V(ydx)

⇨ dI/dx= Vy

Differentiating the above equation of dV/dx w.r.t 'x', we get

$$\frac{d^2V}{dx^2} = z\frac{dI}{dx} = zVy$$

Solution of the above 2nd order differential equation is

$$V = A_1 e^{\sqrt{yz}x} + A_2 e^{-\sqrt{yz}x}$$

$$\therefore \frac{dV}{dx} = \sqrt{yz}\{A_1 e^{\sqrt{yz}x} - A_2 e^{-\sqrt{yz}x}\}$$

$$\& \ I = \frac{1}{z}\frac{dV}{dx}$$

$$\therefore I = \frac{1}{z}\sqrt{yz}\{A_1 e^{\sqrt{yz}x} - A_2 e^{-\sqrt{yz}x}\} = \sqrt{\frac{y}{z}}\{A_1 e^{\sqrt{yz}x} - A_2 e^{-\sqrt{yz}x}\}$$

The above two equations give the expression of V & I in the form of unknown constants A_1 and A_2
Let at receiving end, x=0
Thus, $V=V_R$; $I=I_R$
Hence from the above equations of V and I, we have

$$V_R = A_1 + A_2; \quad I_R = \sqrt{\frac{y}{z}}(A_1 - A_2)$$

For a transmission line $\sqrt{\frac{z}{y}}$ is a constant called the characteristic constant i.e. z_C and $\sqrt{yz}$ is propagation constant γ

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$$\therefore A_1 = \frac{1}{2}V_R + \frac{1}{2}\sqrt{\frac{z}{y}}\,I_R = \frac{1}{2}[V_R + I_R z_c]$$

$$\therefore A_2 = \frac{1}{2}V_R - \frac{1}{2}\sqrt{\frac{z}{y}}\,I_R = \frac{1}{2}[V_R - I_R z_c]$$

We know that; $V = A_1 e^{\sqrt{yz}x} + A_2 e^{-\sqrt{yz}x}$

$$\therefore V = \frac{1}{2}[V_R + I_R z_c]e^{\gamma x} + \frac{1}{2}[V_R - I_R z_c]e^{-\gamma x}$$

And

$$I = \left(\frac{1}{z_c}\right)\left[\frac{1}{2}[V_R + I_R z_c]e^{\gamma x} - \frac{1}{2}[V_R - I_R z_c]e^{-\gamma x}\right]$$

Expanding V and I, we have

$$V = V_R\left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right) + I_R z_c\left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right) = V_R \cosh\gamma x + I_R z_c \sinh\gamma x$$

Similarly,

$$I = \frac{V_R}{z_c}\left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right) + I_R\left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right) = \frac{V_R}{z_c}\sinh\gamma x + I_R \cosh\gamma x$$

For V_S and I_S, x=l

$$V_S = V_R \cosh\gamma l + I_R z_c \sinh\gamma l$$

$$I_S = \frac{V_R}{z_c}\sinh\gamma l + I_R \cosh\gamma l$$

Where $\gamma l = \sqrt{yz}l = \sqrt{ylxzl} = \sqrt{YZ}$

$$\therefore V_S = V_R \cosh\sqrt{YZ} + I_R z_c \sinh\sqrt{YZ}$$

$$\& \quad I_S = \frac{V_R}{z_c}\sinh\sqrt{YZ} + I_R \cosh\sqrt{YZ}$$

Comparing both the above equation with governing equation of ABCD parameter we get

$$\mathrm{A} = \cosh\sqrt{YZ}, \quad B = z_c \sinh\sqrt{YZ}, \qquad C = \frac{1}{z_c}\sinh\sqrt{YZ}, \quad D = \cosh\sqrt{YZ}$$

Let $\sqrt{YZ} = \alpha + j\beta$

Thus,

$$\cosh\sqrt{YZ} = \cosh(\alpha + j\beta) = \cosh\alpha\cosh j\beta + \sinh\alpha\sinh j\beta = \cosh\alpha\cos\beta + j\sinh\alpha\sin\beta$$

$$\sinh\sqrt{YZ} = \sinh(\alpha + j\beta) = \sinh\alpha\cosh j\beta + \cosh\alpha\sinh j\beta = \sinh\alpha\cos\beta + j\cosh\alpha\sin\beta$$

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The square root of the ratio of line impedance (Z) & shunt admittance (Y) is called surge impedance (Z_0) of the line

i.e. $Z_0 = \sqrt{(Z/Y)}$

Surge impedance is the characteristics impedance of a loss free line, $Z_0 = \sqrt{(L/C)}$

Load (UPF) that can be delivered by the line of negligible resistance is known as Surge Impedance Loading(SIL).

Thus, Power Transmitted,

$$P_R = \frac{V_{RL}^2}{Z_0}$$

It is useful in design of Transmission line & gives a limit of maximum power that can be delivered by a line.

Equivalent Circuit (π & T):-

A long line can be replaced by an equivalent π and T circuit and it is valid for only one frequency and only for terminal conditions

From Nominal π circuit

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} (1+\frac{Y'Z'}{2}) & Z' \\ Y'(1+\frac{Y'Z'}{4}) & (1+\frac{Y'Z'}{2}) \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Also from exact solution of long transmission line we have

$$\mathrm{A} = \cosh\sqrt{YZ}, \;\; B = z_c \sinh\sqrt{YZ}, \qquad C = \frac{1}{z_c}\sinh\sqrt{YZ}, \;\; D = \cosh\sqrt{YZ}$$

Comparing the above two equations

$$Z' = z_c \sinh\gamma l = \sqrt{\frac{z}{y}}\sinh\gamma l = \left(\frac{Z}{\gamma l}\right)\sinh\gamma l$$

$$1+\frac{Y'Z'}{2} = \cosh\gamma l \;\; or \;\; 1+\frac{Y' z_c \sinh\gamma l}{2} - \cosh\gamma l = 0$$

$$\frac{Y'}{2} = \frac{1}{z_c}(\cosh\gamma l - 1)/\sinh\gamma l = \frac{1}{z_c}\tanh\frac{\gamma l}{2} = \frac{Y}{2}\frac{\tanh\frac{\gamma l}{2}}{\frac{\gamma l}{2}}$$

Similarly for Nominal-T circuit we have

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} (1+\frac{Y"Z"}{2}) & Z"(1+\frac{Y"Z"}{4}) \\ Y" & (1+\frac{Y"Z"}{2}) \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Also from exact solution of long transmission line we have

$$\mathrm{A} = \cosh\sqrt{YZ}, \;\; B = z_c \sinh\sqrt{YZ}, \qquad C = \frac{1}{z_c}\sinh\sqrt{YZ}, \;\; D = \cosh\sqrt{YZ}$$

Comparing the above two equations

$$Y^{"} = \frac{1}{z_c}\sinh\gamma l = Y\frac{\sinh\gamma l}{\gamma l}$$

And

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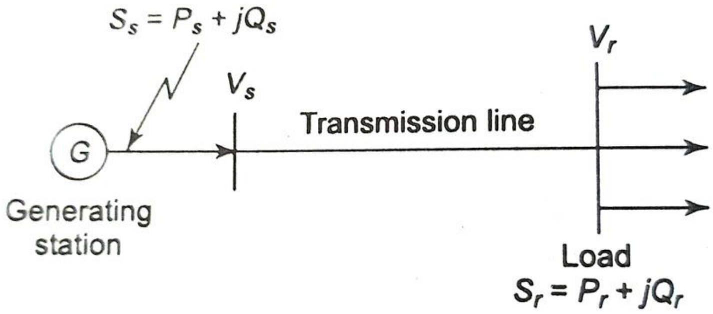
$$\frac{Z''}{2} = z_c(\cosh\gamma l - 1)/\sinh\gamma l = \frac{Z}{2}\frac{\tanh\frac{\gamma l}{2}}{\frac{\gamma l}{2}}$$

Power Formulae for Transmission Lines:-

The below figure shows a single line diagram of a 3-phase transmission line and ends of transmission line is designated as buses.



Using the previous equations of sending end and receiving end currents, we have

$$I_r = \frac{1}{B}V_S - \frac{A}{B}V_r$$

And

$$I_S = \frac{D}{B}V_S - \frac{1}{B}V_r = \frac{A}{B}V_S - \frac{1}{B}V_r$$

$$Let\ V_r = |V_r|\angle 0,\ V_S = |V_S|\angle\delta, \quad D = A = |A|\angle\alpha, \quad B = |B|\angle\beta$$

$$\therefore I_r = \frac{|V_S|}{B}\angle(\delta-\beta) - \frac{A|V_r|}{B}\angle(\alpha-\beta)$$

$$\therefore I_S = \frac{A|V_S|}{B}\angle(\alpha+\delta-\beta) - \frac{|V_r|}{B}\angle(-\beta)$$

The conjugates of I_r and I_S are

$$I_r^* = \frac{|V_S|}{B}\angle(\beta-\delta) - \frac{A|V_r|}{B}\angle(\beta-\alpha)$$

$$\therefore I_S^* = \frac{A|V_S|}{B}\angle(\beta-\alpha-\delta) - \frac{|V_r|}{B}\angle(\beta)$$

The complex power per phase at the receiving end and sending end are

$$S_r = P_r + jQ_r = V_r I_r^*$$

$$= |V_r|\angle 0\left[\frac{|V_S|}{B}\angle(\beta-\delta) - \frac{A|V_r|}{B}\angle(\beta-\alpha)\right]$$

$$= \frac{|V_r||V_S|}{B}\angle(\beta-\delta) - \frac{A|V_r|^2}{B}\angle(\beta-\alpha)$$

Similarly

$$S_S = P_S + jQ_S = V_S I_S^*$$
$$= |V_S|\angle\delta\left[\frac{A|V_S|}{B}\angle(\beta-\alpha-\delta) - \frac{|V_r|}{B}\angle(\beta)\right]$$
$$= \frac{A|V_S|^2}{B}\angle(\beta-\alpha) - \frac{|V_r||V_S|}{B}\angle(\beta+\delta)$$

The real and reactive power at receiving end is

$$P_r = \frac{|V_r||V_S|}{B}cos(\beta-\delta) - \frac{A|V_r|^2}{B}cos(\beta-\alpha)$$
$$Q_r = \frac{|V_r||V_S|}{B}sin(\beta-\delta) - \frac{A|V_r|^2}{B}sin(\beta-\alpha)$$

The real and reactive power at sending end is

$$P_S = \frac{A|V_S|^2}{B}cos(\beta-\alpha) - \frac{|V_r||V_S|}{B}cos(\beta+\delta)$$
$$Q_S = \frac{A|V_S|^2}{B}sin(\beta-\alpha) - \frac{|V_r||V_S|}{B}sin(\beta+\delta)$$

For maximum power at receiving end, with fixed values of voltages; δ=β

$$P_{r,max} = \frac{|V_r||V_S|}{B} - \frac{A|V_r|^2}{B}cos(\beta-\alpha)$$

$$Q_r = -\frac{A|V_r|^2}{B}sin(\beta-\alpha)$$

Thus it can be said that load must draw leading VAR for maximum real power achievement at receiving end.

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Mechanical Design of Overhead Lines: - Electric power is usually transmitted or distributed by the help of overhead lines or underground cables out of which underground cable means is seldom used for transmission purpose due to heavy cost involved & insulation problems.

An overhead line is subjected to different weather conditions and interferences and thus proper safety is required for proper operation. The main components of overhead lines are:-

a) Conductors:- These carry power from sending end to receiving end
b) Supports:- These are poles or towers which keep conductors at a suitable level
c) Insulators:- These are attached to supports & insulate conductors from ground
d) Cross Arms:- These provide support to the insulators

Conductor Materials:- Following properties should be satisfied by the conductor materials

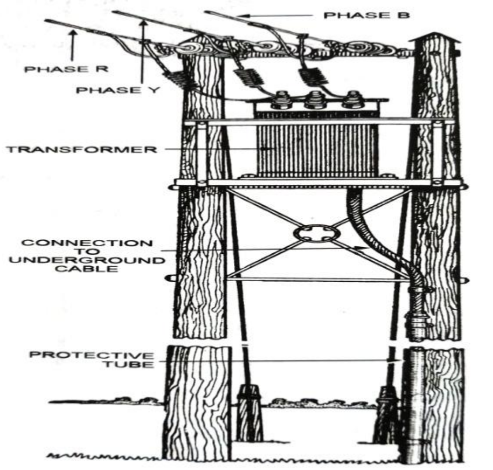
a) High electrical conductivity
b) High tensile strength
c) Low cost
d) Low specific gravity

The most commonly used material for conductor material are copper, aluminium, steel cored aluminium, galvanized steel and cadmium copper. Conductors are stranded to increase the flexibility.

Line Supports:- The supporting structures for overhead line conductors are various types of poles & towers which are called line supports. They should have following properties i.e.

i. High mechanical strength
ii. Light in weight without loss of mechanical strength
iii. Cheap in cost and economical to maintain
iv. Longer life
v. Easy accessibility of conductors for maintenance

1. Wooden Poles: - These are made of seasoned wood (sal or chir) and suitable for lines of moderate cross sectional area and shorter spans(upto 50m). These are widely used in distribution lines due to cheapness, availability and good insulation properties. The common disadvantages of wooden poles are its tendency to rot below the ground level and thus causing failure in foundation & shorter life span (20-25 years). This rotting is prevented by impregnating the below portion with creosote oil & periodic inspection.



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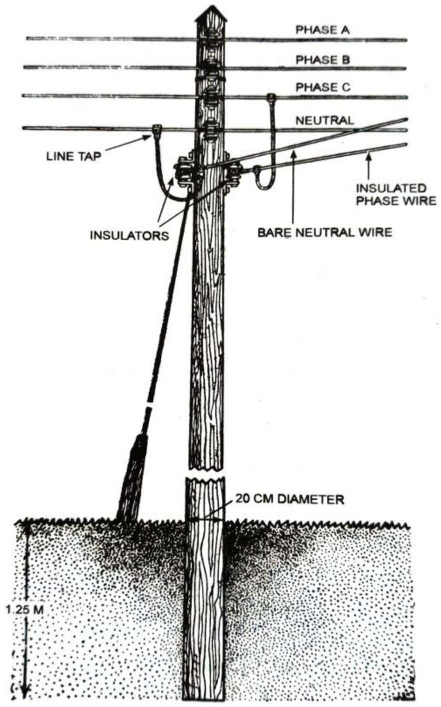
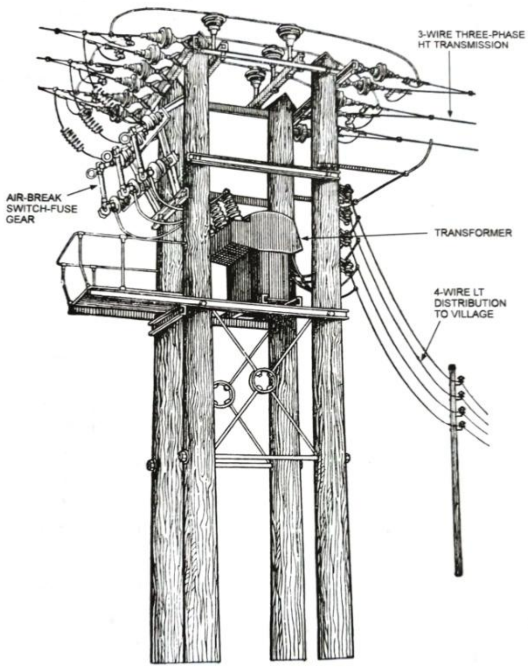
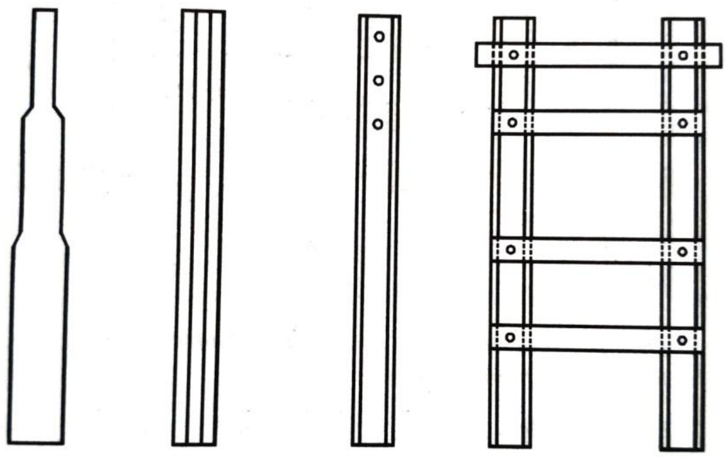




2. Steel Poles:- These are good substitute of wooden poles as it provides greater mechanical strength, longer life and permits longer spans. These can be used for distribution of power within cities and they are required to be galvanized or painted for longevity. The steel poles are of 3 types i.e. rail poles, tubular poles and rolled steel joints.



3. RCC poles:- These are Reinforced Concrete Poles and have greater mechanical strength, longer life and permits longer spans. They require negligible maintenance & can be used for single or double circuit line. Holes are provided in the poles for climbing and to reduce its weight.
These poles are manufactured at the installation site itself due to problem of transportation.

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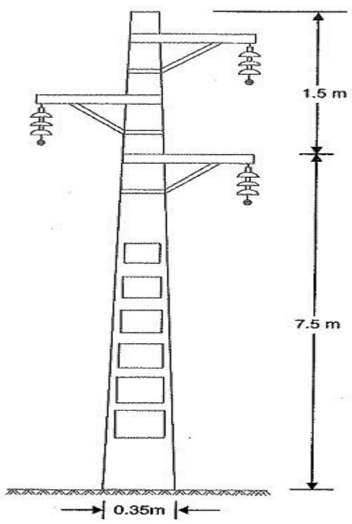
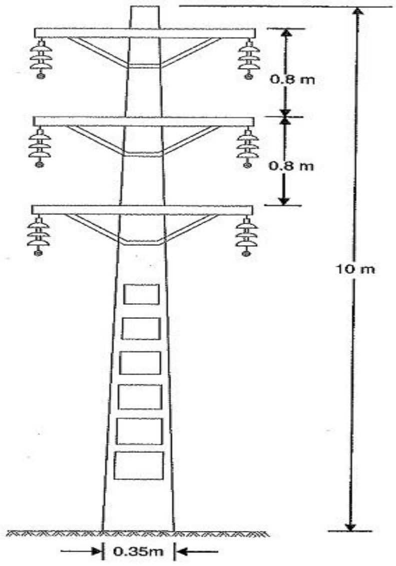
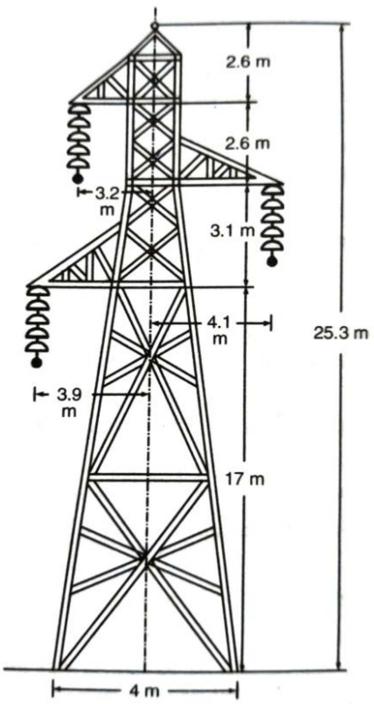
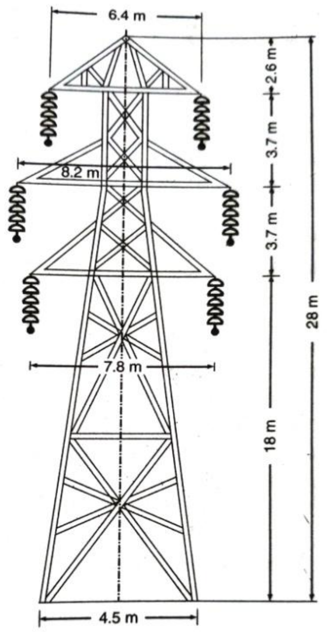




4. Steel Towers:- For long distance transmission at high voltages, steel towers are employed. It has greater mechanical strength, longer life, can withstand severe climatic conditions. Tower footings are grounded by the help of driving rods into the earth to minimize lightning trouble and each tower acts as lightning conductor itself.





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Insulators:- It is to be kept in mind that line conductors must be properly insulated from supports. This can be achieved by securing line conductors to supports with the help of insulators. Insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth.

Insulators should have following properties:-

a) High mechanical strength
b) High electrical resistance of insulator material
c) High relative permittivity of insulator material
d) Material should be non-porous, free from impurities and cracks
e) High ratio of puncture strength to flash over

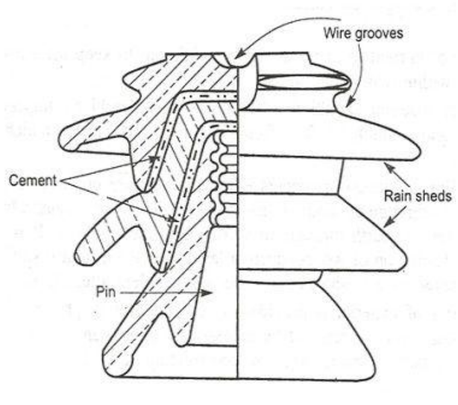
The most common material for insulator of overhead lines is porcelain, glass, steatite(magnesium silicate). Porcelain is formed by firing a mixture of kaolin, feldspar & quartz at high temperature. It is mechanically stronger than glass.

1) Pin Type Insulators:- In this type of insulator, the insulator is screwed on the pin & there is a groove on the upper side and used for housing the conductors. The conductor is bounded by annealed wire of same material all around the groove. It is used for transmission & distribution purpose of voltages upto 33KV.

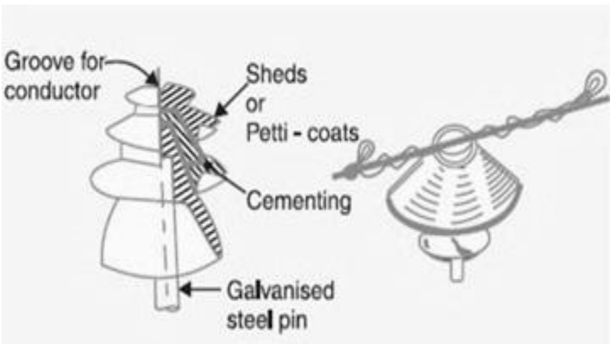
   In the insulator, electrical breakdown may occur either by flash over or puncture. The high voltage pin type insulator differ in construction from l.v type as they consist of 2 to 3 pieces of porcelain cemented together and form petticoats or rain sheds.

   These are provided in order to have an adequate length of leakage path such that flash over voltage between line conductor & insulator pin is increased.

   The inner surface of petticoats remains dry and sufficient leakage resistance is provided in rains.



Pin-type insulator



2) Suspension Type Insulator:- Extremely high voltages are utilized in transmission system such as 765KV and the pin type insulator cannot be utilized for these lines. It consists of a number of porcelain disc flexibly connected in series by metal links in the form of a string.

   The suspension type insulator hangs from cross arms and conductor is connected in lower end. The major advantage of suspension type insulator is that in the event of failure of any one disc, the disc can be removed without need of replacement of entire insulator string.

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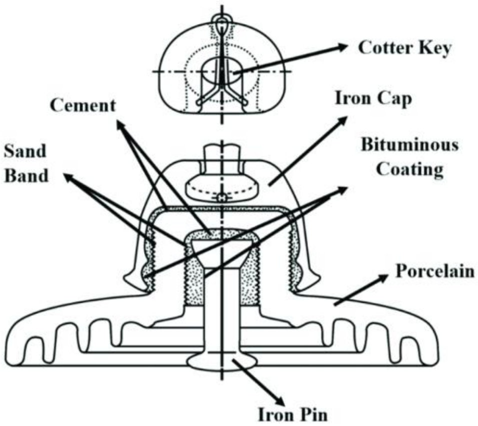
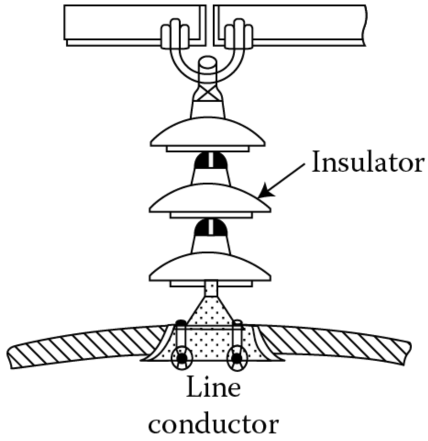
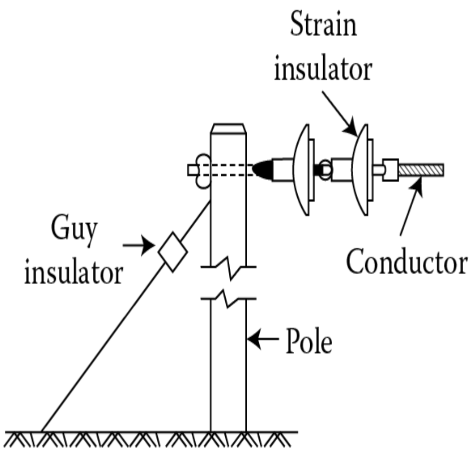
Each insulator disc is designed for voltage about 11KV and the number of discs depend upon the working voltage.

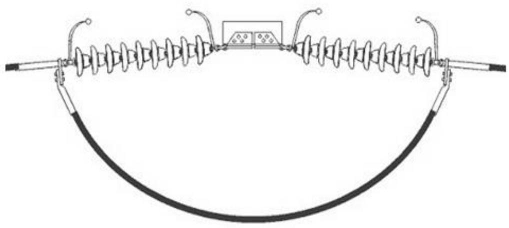
For increase in load, it can be met by increasing the number of discs to the string.



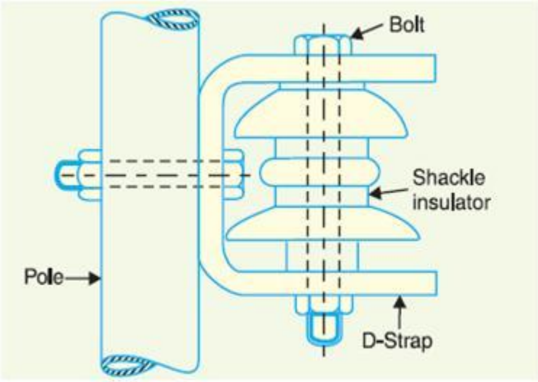


3) Strain Insulators:- Strain insulators are also string of insulators but are used in dead ends or corners or sharp curves where the conductors are subjected to higher tension. Strain insulators are used for voltages above 11KV and the discs of strain insulators are employed in vertical plane. For extremely high tension such as in case of long river spans, two or more strings are used in parallel.



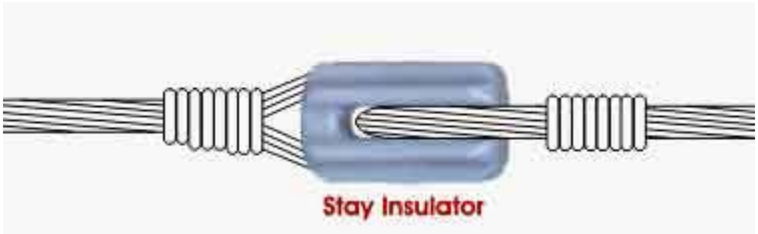


4) Shackle Insulators:- These are used for low voltage distribution lines and these insulators can be used either in horizontal or vertical position. These are directly fixed to the pole with a bolt or to the cross arm.



5) Post Insulators:- These insulators are employed for supporting bus-bars and isolating switches etc. It is similar to pin type but has a metal base with a metal cap to facilitate mounting more than one unit in series.

6) Stay Insulators:- These are also known as egg insulators or guy insulators. These are used in guy cables to insulate the lower part of the guy cable from the pole for safety of people & animals. These insulators has a porcelain piece which is pierced with two holes at right angles to each other through which two ends of guy wires are looped.



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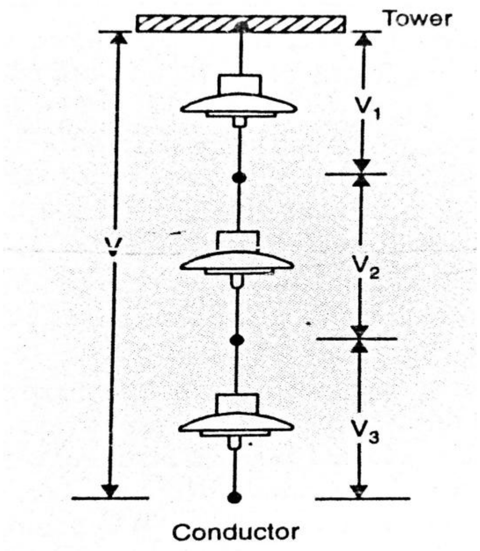
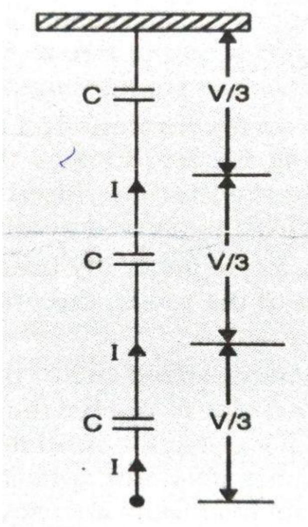
Potential Distribution over Suspension Insulator String:-

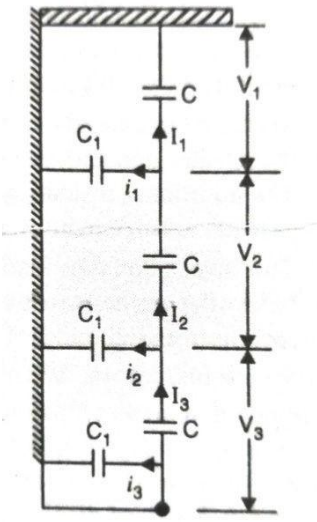
The figure below shows a 3-disc string of suspension insulators and the porcelain portion of each disc is between two metal links.





Each disc forms a capacitor C and is known as mutual capacitance or self capacitance.

For mutual capacitance alone, charging current would be same through all the discs and voltage across each unit will be same i.e. V/3



In actual practice, capacitance also exists between metal fitting of each disc and tower or earth. It is also known as Shunt Capacitance C_1 and due to this, charging current is not same through all discs. Hence the voltage across each discs will be different and disc nearest to line conductor will have maximum voltage (due to maximum charging current in disc nearest to conductor)

Unit nearest to the conductor is under maximum electrical stress and thus it is likely to be punctured.

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String Efficiency:-

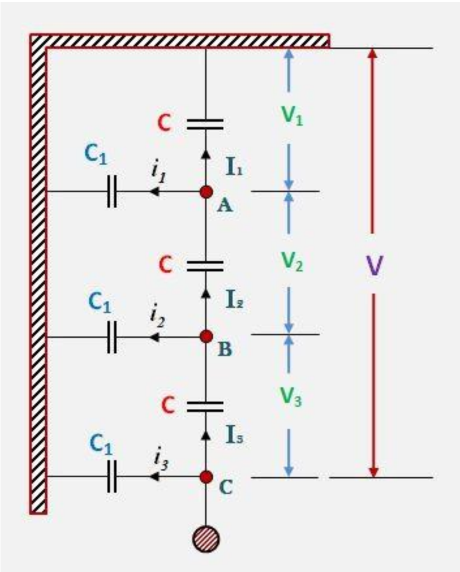
The unequal potential distribution is undesirable & is usually expressed in terms of string efficiency. **The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as String Efficiency**

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

Where 'n' = number of discs in the string

String Efficiency gives the potential distribution along the string. In case of 100% string efficiency is an ideal case where voltage across each disc will be exactly the same.

Let us consider the equivalent circuit of a 3-disc string and self capacitance of each disc is C. Let us assume that shunt capacitance C_1 is some fraction K of self capacitance C_1= KC



Starting from cross arm of tower and applying KCL to node A, we have

$$I_2 = I_1 + i_1$$

- ⇨ $V_2\omega C = V_1\omega C + V_1\omega C_1$
- ⇨ $V_2\omega C = V_1\omega C + V_1\omega KC$
- ⇨ $V_2 = V_1(1+K)$

Similarly applying KCL at node B, we have

$$I_3 = I_2 + i_2$$

- ⇨ $V_3\omega C = V_2\omega C + (V_1+V_2)\,\omega C_1$
- ⇨ $V_3\omega C = V_2\omega C + (V_1+V_2)\,\omega KC$
- ⇨ $V_3 = V_2 + (V_1+V_2)K$
- ⇨ $V_3 = KV_1 + V_2(1+K)$
- ⇨ $V_3 = KV_1 + V_1(1+K)^2$
- ⇨ $V_3 = V_1[K + (1+K)^2]$
- ⇨ $V_3 = V_1[1+3K + K^2]$

Voltage between conductor and earth (i.e. tower)

$V = V_1+V_2+V_3 = V_1 + V_1(1+K) + V_1[1+3K + K^2] = V_1(3+4K+K^2)$

- ⇨ $V = V_1(1+K)(3+K)$

From expressions of V_2, V_3 & V, we have

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

Voltage across top unit,

$$V_1 = \frac{V}{(1+K)(3+K)}$$

Voltage across second unit from top, $V_2 = V_1(1+K)$

Voltage across third unit from top, $V_3 = V_1(1+3K+K^2)$

$$\%\text{age String Efficiency} = \frac{\text{Voltage across the string}}{\text{n x Voltage across disc nearest to conductor}} \text{x}100 = \frac{\text{V}}{3\text{x}\text{V}_3}\text{x}100$$

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Methods of Improving String Efficiency:

Voltage distribution across an insulator string is not uniform due to presence of shunt capacitance effect. Insulator unit present nearest to the line conductor is highly stressed and that nearest to tower is lightly stressed.

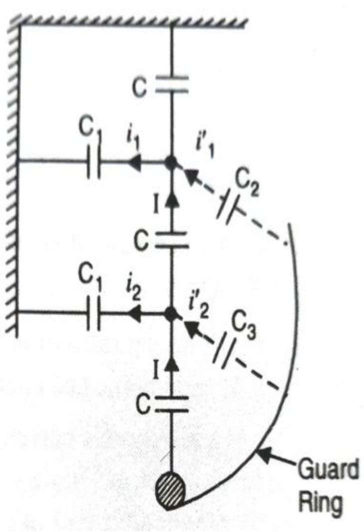
Due to this non-uniform voltage distribution, if the voltage near the conductor reaches beyond prescribed limit it may lead to breakdown and successive breakdown of next discs.

The string efficiency indicates the extent of wastage. Efforts can be made to improve the efficiency and hence reduce the wastage. Some of the methods of improving string efficiency are:-

a) **By using longer Cross Arms:-** The ratio K(shunt capacitance to self capacitance) can be reduced by using longer cross arms such that the horizontal distance between string and line support is increased and reduces the effect of shunt capacitance. This method has the limitation of mechanical strength and increase in cost.

b) **By using Capacitance Grading:-** Non-uniform distribution of voltage across an insulator string is due to leakage current from insulator pin to supporting structure. It is possible that discs of different capacities are used such that the product of their capacitive reactance and current flowing through respective unit is same. This can be achieved by grading the mutual capacitance of the insulator units by having lower units of more capacitance- maximum at the line unit and minimum at the top unit(nearest to cross arm). This method suffers from the drawback that different discs are required of different sizes and hence increase in spare parts cost and maintenance cost.

c) **By Static Shielding(Using guard ring):-** In static shielding, pin to supporting structure charging current is exactly cancelled so that same current flows through the identical insulator units and produce equal voltage drops across each discs. In this method guard ring is used which takes the form of a large metal ring surrounding the bottom unit and electrically connected to metal work at the bottom of the unit and thus to line conductor. Guard ring screens the lower units, reduce their earth capacitance C_1 and introduces a number of capacitances between line conductor and various insulator unit caps. These capacitances are greater for lower units and thus voltage across them is reduced.



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Tests on Insulators: Two tests are conducted normally i.e. type tests(to check the design features & the quality) and routine tests (to check the quality of individual test piece)

i. **Power Frequency Tests**:-

- **Wet & dry power frequency tests:-** In these tests, AC voltage of power frequency is applied across the insulators & increased at a uniform rate of about 2% per second of 75% of estimated test voltage, to such a value that breakdown occurs along the surface.

  If test is conducted under normal conditions without any rain or precipitation, it is called **dry flashover test**.

  If test is done under conditions of rain, it is called **wet flashover test**. In this, test object is subjected to a spray of water of given conductivity by means of nozzle such that water drops at 45^0 to vertical. The test object is sprayed for at least one minute before voltage application & spray is continued during the test voltage application
- **Wet & dry Withstand Tests (One minute)**:- In these tests, voltage specified is applied under dry or wet conditions for one minute with an insulator mounted as in service condition.

ii. Impulse Tests:-

- **Impulse Withstand Voltage Test:-** This test is done by applying standard impulse voltage under dry conditions with positive and negative polarities of the wave.

  If 5 consecutive waves do not cause a flashover or puncture then the insulator passes the test.

  If 2 applications cause flashover, object is deemed to have failed.

  If there is 1 failure, more 10 applications are done & if test object withstands, object passes test.
- **Impulse flashover Test:-** Using specified voltage, the probability of failure is determined for 40 % and 60% failure values. The average values of upper & lower limits are taken.
- **Pollution Testing:-** The normal types of pollution are dust, micro-organisms, bird secretions, flies etc, industrial pollution, coastal pollution, desert pollution, ice & fog deposits. These pollutions cause corrosion, non-uniform gradients along insulation strings. Pollution causes partial discharges & radio interference. In salt fog test, maximum withstand voltage is applied & then artificial salt fog is created by jets of salt water & compressed air. If flashover occurs in one hour, test is repeated with lower salinity else higher.

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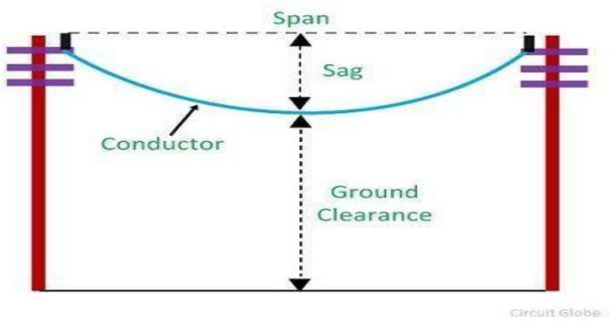
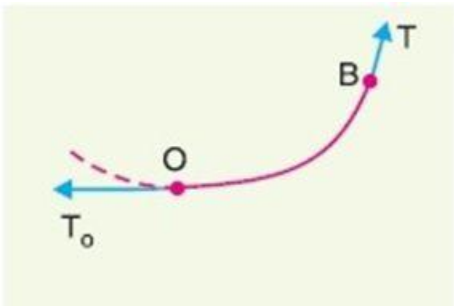
SAG:- The difference in level between points of supports and the lowest point on the conductor is called Sag. Overhead lines are supported by mechanical structures like cross arms, supports, insulators etc. These components must have adequate mechanical strength. Generally conductor is acted upon by some forces such as weight of itself, pressure of wind and tension.
While stringing overhead lines, a reasonable factor of safety in respect to tension should be allowed. Tension in the conductor depends on the diameter of conductor, length of conductor between supports, material of conductor, sag in conductor, wind pressure and temperature.



Sag plays an important role in mechanical design of overhead lines. If more sag is provided then more conductor material is required, higher supports and greater swing. If less sag is provided then there is more tension in the conductor and thus possibility to break.

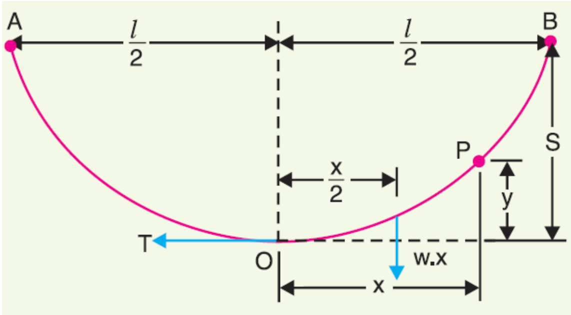
Points to remember:-

- Conductor takes the shape of catenary, between two supports at same level.
- Tension at any point on conductor acts tangentially
- Horizontal component of tension is constant throughout the length of wire.



Calculation of Sag:- Generally tension is always kept within safe limits and sag is adjusted to keep so. Tension is governed by weight of conductor, effect of wind, ice loading and temperature variation. Sag can be calculated for following cases:

i) When supports are at equal levels: - Let us consider a conductor tied between equi-level supports A and B and O as the lowest point.
Let l= length of span, w= weight per unit length of conductor, T= Tension in the conductor



Consider a point P on the conductor. Let us take the lowest point O as the origin and co-ordinates of point P be x and y. The two forces acting on the portion OP on the conductor are:

a) Weight wx of conductor acting at a distance x/2 from O
b) Tension T acting at O

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

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

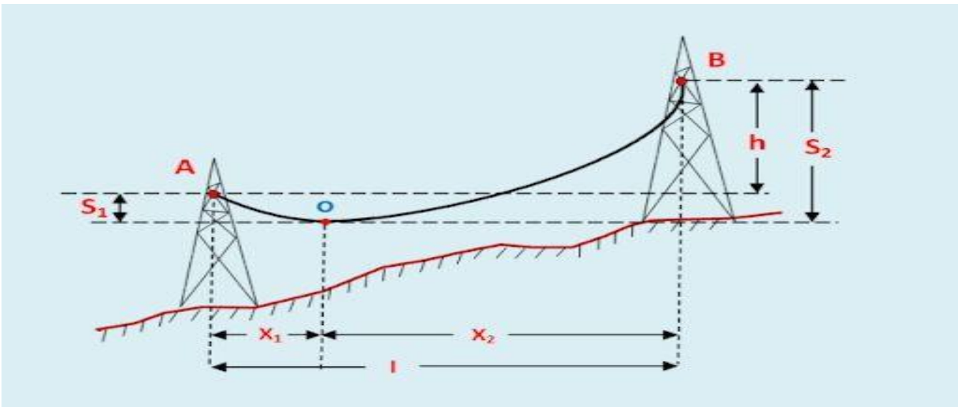
$$y = \frac{wx^2}{2T}$$

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

At supports A, $x = \frac{l}{2}$ $and\ y = S$

$$\therefore Sag,\ \ S = \frac{w\left(\frac{l}{2}\right)^2}{2T} = \frac{wl^2}{8T}$$

ii) <u>When supports are at unequal level:-</u> In case of hilly regions, conductors are supported at unequal levels. The below figure shows two supports A and B at different levels with lowest point O



Let l= Span length

h=Difference in levels between two supports

x_1= Distance of support at lower level (i.e. A) from O

x_2= Distance of support at higher level (i.e. B) from O

T= Tension in the conductor

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If the weight per unit length of the conductor, then

$$Sag, S_1 = \frac{wx_1^2}{2T} \quad and \quad Sag, S_2 = \frac{wx_2^2}{2T}$$

Also $x_1 + x_2 = l$

Now

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

But from the figure, S_2-S_1= h

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

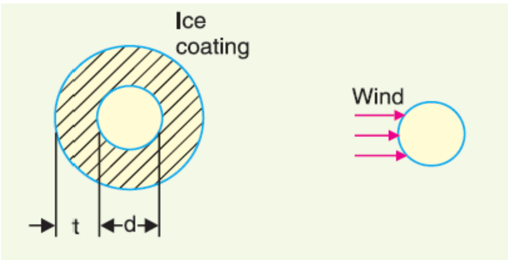
$$or, \; x_2 - x_1 = \frac{2Th}{wl} \qquad and\ also, \; x_2 + x_1 = l$$

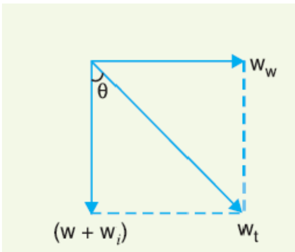
Solving both the equations, we get

$$x_1 = \frac{l}{2} - \frac{Th}{wl} \qquad and \qquad x_2 = \frac{l}{2} + \frac{Th}{wl}$$

Finding these values, sag can be calculated

Effect of Wind and ice:- The above formula for sag calculation is valid only in still air under normal temperature. In actual practice, conductor may be also subjected to wind pressure and ice coating. Weight of ice acts vertically downwards i.e. in the direction of weight of conductor. The force due to wind is assumed horizontally and thus the total force is the vector sum of both.





Total weight of conductor per unit length is

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

Where w= weight of conductor per unit length= conductor material density x volume per unit length

w_i = Weight of ice per unit length= density of ice x volume of ice per unit length

= density of ice x {π/4[(d+2t)^2-d^2]x1= density of ice x πt(d+t)

w_w= wind force per unit length=wind pressure per unit area x projected area per unit length

= wind pressure x [(d+2t)x1]

When the conductor has wind and ice loading,

i. Conductor sets itself in a plane at an angle θ to the vertical

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

ii. Sag in the conductor is given by

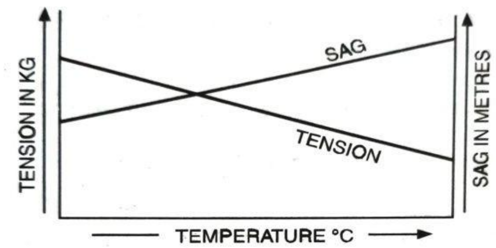
$$Sag, S = \frac{w_t l^2}{2T}$$

'S' represents Slant Sag

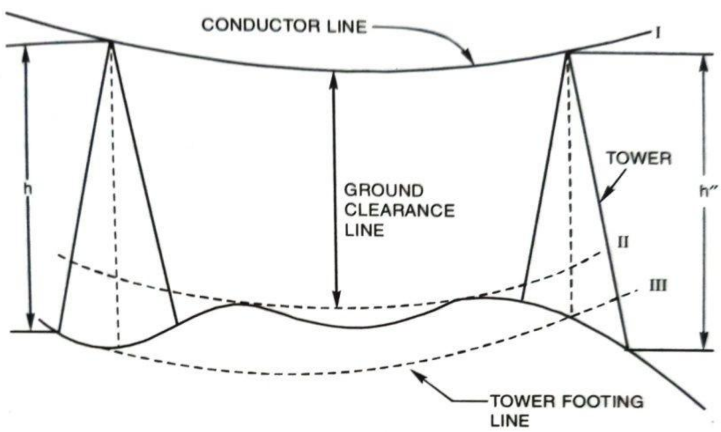
Factors Affecting Sag:-

a. **Weight of the Conductor**: - Weight of conductors affects sag directly. Heavier the conductor more will be sag.
b. **Length of Span**: - Sag is directly proportional to square of span length. If all other conditions such as tension, temperature, type of conductor etc. remains same, then longer span results in greater sag.
c. **Working Tensile Strength**: - Sag is inversely proportional to working tensile strength if all other conditions remain same. Working tensile strength is determined by multiplying ultimate stress and area of cross section and dividing by safety factor.
d. **Temperature:** - Length of conductor increases with rise in temperature and hence the sag.
e. **Ground Clearance**: - Sag should be so maintained that minimum ground clearance as recommended by IE rules should be satisfied.

Stringing Chart:- Stringing Chart is a plot between tension vs. Temperature and sag vs. Temperature for a fixed span. Stringing chart is useful for the designer in erection by knowing the sag and tension at any temperature. This chart gives the data for sag to be allowed and tension to be allowed at a certain temperature. At first sag and tension on the conductor is calculated under worst conditions, i.e. maximum wind pressure and minimum temperature. Then the sag and tension for a series of temperature in steps is evaluated within working range of temperature.



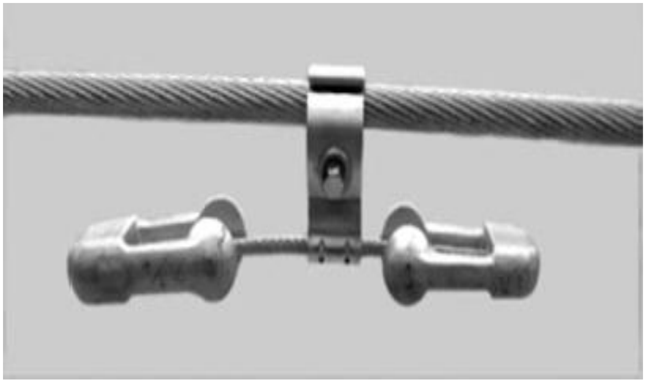
Sag Template:- Sag template is usually drawn on celluloid or tracing cloth and in the initial stages a profile is drawn by conducting survey of the proposed route meeting the minimum clearance requirements. In the Sag template shown below, curve I represents conductor line, the middle curve is below the curve I by a uniform vertical distance and equal to desired minimum vertical clearance to ground. Lower curve III is below the upper curve by a uniform vertical distance equal to the height of a standard tower measured to the point of support of the conductor. If the location of left tower is known, then location of right hand tower can be determined by adjusting the sag template so that conductor line passes through the point of support on the left tower and clearance line is tangent to ground at one or more points.



VIBRATIONS & DAMPERS:- Overhead conductors experiences vibrations in vertical plane and mainly there are two types of vibrations, namely

i. Aeoline Vibrations or Resonant Vibrations:-
ii. Galloping or dancing Vibrations

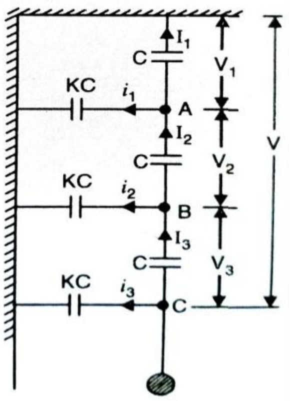
i. Aeoline Vibrations or Resonant Vibrations are high frequency vibrations (5-100Hz) and low amplitude (20mm to 50mm) vibrations. They are caused by vortex phenomenon in light winds and line conductor vibrates in a number of loops. The harmful effects of such vibrations take place at clamps or supports where the conductor suffers fatigue and breaks eventually.
Stock bridge dampers are used to prevent the resonant vibrations from reaching clamps r supports. This consists of two weights attached to a piece of stranded cable which is clamped to the line conductor. The energy of vibration is absorbed by stranded cable and hence vibrations eventually damps out.



ii. Galloping or Dancing Conductors:- These are low frequency vibrations of about 1Hz and occur during sleet storms with a strong wind. The amplitude is very large and conductors seem to dance. Dancing of the conductors takes place horizontally and vertically and in an irregular manner. There is no specific method of prevention of this type of vibrations.

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

Solution: - The figure below shows a string of insulator and let V_1, V_2 and V_3 be the voltage across top, middle and bottom unit respectively. If C is self capacitance of each unit, then KC will be shunt capacitance



⇨ $C_1 = KC$
⇨ $K = C_1/C = 0.11$

Voltage across string, $V = 33/\sqrt{3} = 19.05KV$
Starting from cross arm of tower and applying KCL to node A, we have

$$I_2 = I_1 + i_1$$

⇨ $V_2\omega C = V_1\omega C + V_1\omega C_1$
⇨ $V_2\omega C = V_1\omega C + V_1\omega KC$
⇨ $V_2 = V_1(1+K) = V_1(1+0.11) = 1.11\ V_1$

Similarly applying KCL at node B, we have

$I_3 = I_2 + i_2$

- ⇨ $V_3\omega C = V_2\omega C + (V_1+V_2)\,\omega C_1$
- ⇨ $V_3\omega C = V_2\omega C + (V_1+V_2)\,\omega KC$
- ⇨ $V_3 = V_2 + (V_1+V_2)K$
- ⇨ $V_3 = 1.11\,V_1 + (V_1 + 1.11\,V_1)0.11$
- ⇨ $V_3 = 1.342V_1$

Voltage across whole string is given by

$V = V_1+V_2+V_3 = V_1 + 1.11\,V_1 + 1.342V_1 = V_1 x3.452$

- ⇨ $19.05 = 3.452\,V_1$

Voltage across top unit, $V_1 = 19.05/3.452 = 5.52KV$

Voltage across middle unit, $V_2 = 1.11\,V_1 = 6.13KV$

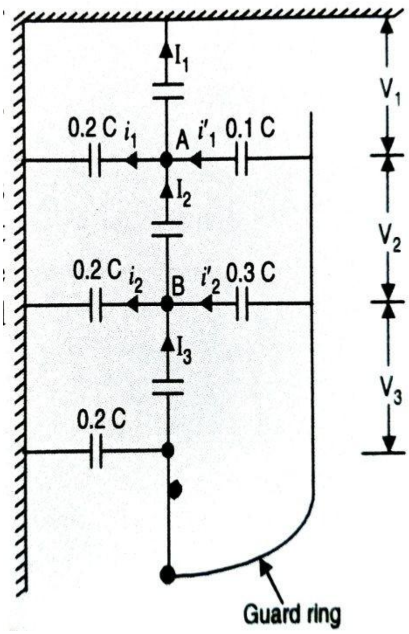
Voltage across bottom unit, $V_3 = 1.342x5.52 = 7.4KV$

$$\%\text{age String Efficiency} = \frac{\text{Voltage across the string}}{\text{n x Voltage across disc nearest to conductor}}\text{x}100$$

$$= \frac{19.05}{3\text{x}7.4}\text{x}100 = 85.8\%$$

<u>Problem:-</u> Each line of a 3-phase system is suspended by a string of 3 identical insulators of self capacitance C farad. The shunt capacitance of connecting metal work of each insulator is 0.2C to earth and 0.1C to line. Calculate the string efficiency of the system if a guard ring increases the capacitance to the line of metal work of the lowest insulator to 0.3C

Solution:- Let us consider the figure shown below consisting of guard ring.



Starting from cross arm of tower and applying KCL to node A, we have

$I_2 + i_1' = I_1 + i_1$

- ⇨ $V_2\omega C + (V_2+V_3)\omega x0.1C = V_1\omega C + V_1\omega 0.2C$
- ⇨ $V_3 = 12V_1 - 11\,V_2$

Similarly applying KCL at node B, we have

$I_3 + i_2' = I_2 + i_2$

- ⇨ $V_3\omega C + V_3 x\omega x0.3C = V_2\omega C + (V_1+V_2)\,\omega 0.2C$
- ⇨ $1.3V_3 = 1.2V_2 + 0.2\,V_1$

Substituting the value of V_3 in the above equation, we have

- ⇨ $1.3(12V_1 - 11\,V_2) = 1.2V_2 + 0.2\,V_1$
- ⇨ $15.5V_2 = 15.4V_1$
- ⇨ $V_2 = 15.4V_1/\,15.5 = 0.993V_1$

Substituting the value of V_2 in the equation of V_3, we get

- ⇨ $V_3 = 12V_1 - 11\,V_2 = 12V_1 - 11\,(0.993V_1) = 1.077V_1$

Voltage across whole string is given by

$V = V_1+V_2+V_3 = V_1 + 0.993\,V_1 + 1.077V_1 = V_1 x3.07$

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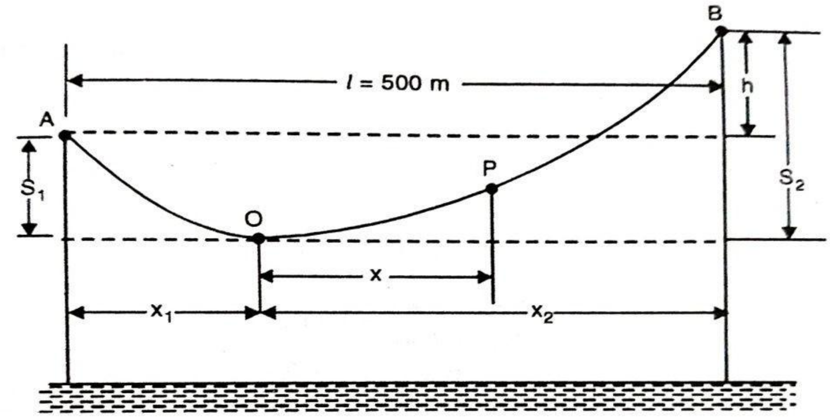
$$\%\text{age String Efficiency} = \frac{\text{Voltage across the string}}{\text{n x Voltage across disc nearest to conductor}} \text{x100}$$

$$= \frac{3.07V_1}{3\text{x}1.077V_1} \text{x}100 = 95\%$$

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

Solution:- The figure below shows the conductor suspended between two supports A and B at different levels with O as the lowest point on the conductor.
Here l= 500m, w= 1.5Kg, T=1600Kg



Difference in levels between supports, h= 90-30=60m. Let the lowest point O of the conductor be at distance x_1 from the support level at lower level i.e. A and at distance x_2 from the support at higher level i.e. B
i.e. x_1+x_2= 500m

$$Sag, S_1 = \frac{wx_1^2}{2T} \quad and \quad Sag, S_2 = \frac{wx_2^2}{2T}$$

$$h = S_2 - S_1 = \frac{w(x_2 + x_1)((x_2 - x_1)}{2T}$$

$$60 = S_2 - S_1 = \frac{w * 500 * (x_2 - x_1)}{2T}$$

$$or, \ x_2 - x_1 = \frac{2 * 1600 * 60}{1.5 * 500} = 256m \qquad and\ also, \ x_2 + x_1 = 500$$

Solving both the equations, we get

$$x_1 = 122m \qquad and \qquad x_2 = 378m$$

Finding these values, sag can be calculated

$$Sag, S_1 = \frac{wx_1^2}{2T} = \frac{1.5 * 122^2}{2 * 1600} = 7m$$

Clearance of lowest point O from water level= 30-7= 23m ***Ans.***

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

Thus, $x = 250 - x_1 = 250 - 122 = 128m$

$$Sag\ at\ mid-point\ P, \qquad S_{mid} = \frac{wx^2}{2T} = \frac{1.5 * 128^2}{2 * 1600} = 7.68\ m$$

Clearance of mid-point P from water level, = 23+7.68= 30.68m ***Ans.***

Problem:- A transmission line has a span of 275m between level supports. The conductor has an effective diameter of 1.96cm and weighs 0.865Kg/m. Its ultimate strength is 8060Kg. If the conductor has ice coating of radial thickness 1.27cm and is subjected to a wind pressure of 3.9gm/cm^2 of projected area, calculate sag for a safety factor of 2. Weight of 1c.c of ice is 0.91gm

Solution:-

Given datas:- l= 275m, Weight of conductor/m length, w= 0.865Kg, Conductor diameter, d= 1.96cm

Ice coating thickness, t= 1.27cm, Working Tension, T= 8060/2= 4030 Kg

Volume of ice per metre (i.e. 100cm) length of conductor= πt(d+t)x100 cm^3

= πx1.27x(1.96+1.27)x100= 1288cm^3

Weight of ice per metre length of conductor is w_i= 0.91x1288= 1172 gm = 1.172Kg

Wind force/m length of conductor is

w_w= [Pressure]x [(d+2t)x100]= [3.9]x(1.96+2x1.27)x100=1755gm= 1.755Kg

Total weight of conductor per metre length of conductor is

$w_t = [(w+w_i)^2 + w_w^2]^{1/2} = [(0.865+1.172)^2 + 1.755^2]^{1/2} = 2.688Kg$

$$Sag = \frac{w_t l^2}{8T} = \frac{2.688 * 275^2}{8 * 4030} = 6.3m$$

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DISTRIBUTION SYSTEMS

Introduction:- Electrical energy at the generating station is transmitted through the transmission line to the receiving sub-stations. A Transmission & Distribution system plays an important role in conveying power from generating station to the consumer end.

Distribution System:- The conductor system by means of which electrical energy is conveyed from bulk power source to the consumers is known as Distribution systems. The distribution system may be divided into two parts i.e.

a) Primary distribution system:- Power is transmitted from generating stations through the transmission lines to receiving substations. From these sub-stations power is conveyed to different sub-stations after stepping down the high voltage to 33KV, 11KV or 6.6KV. This distribution system is known as Primary Distribution systems.

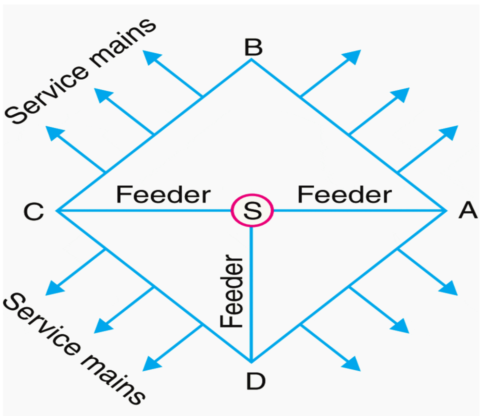
b) Secondary Distribution Systems:- At distribution substations the voltage is stepped down to 415V. These distribution sub-stations are located near the localities & power is fed to the consumers through distribution transformers after stepping down 11KV (usually) voltage to 415V .

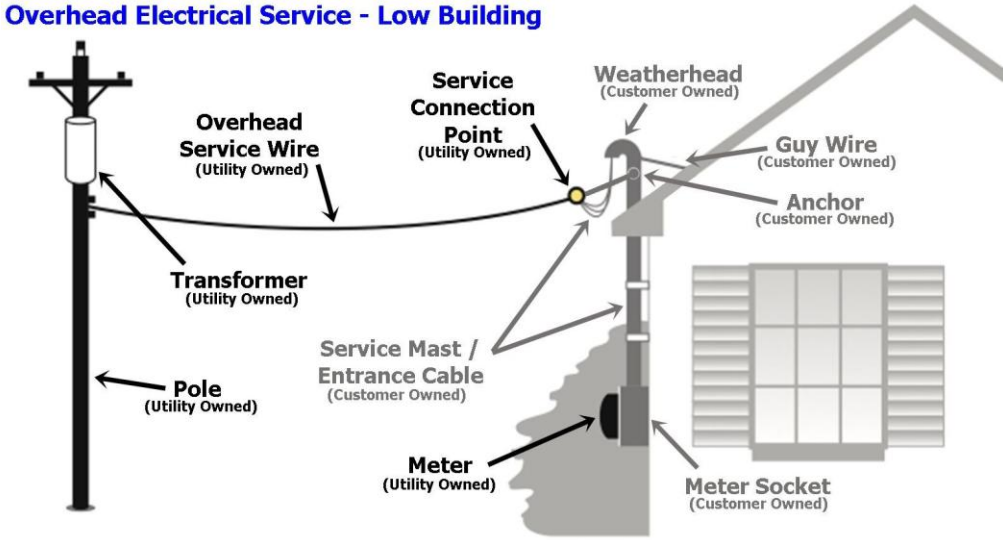
Distribution system generally consists of

a) **Feeders**:- A feeder is a conductor which connects the sub-stations to the area where power needs to be distributed.
Generally no tappings are brought out from the feeders and thus the current throughout its length remains same.

b) **Distributor:**- A distributor is a conductor from which tappings are taken for supply to the consumers. In the figure shown below, AB, BC, CD and DA are the distributors.
Current through a distributor is different at different points as tappings are taken at various places along its length.

c) **Service Mains**:- A service mains is generally a small cable which connects the distributor to the consumer's terminal.





Classification of Distribution Systems:-

a) Nature of Current:- According to nature of current, distribution system is classified as DC and AC
b) Type of Construction:- According to construction, distribution system can be overhead system or underground system
c) Scheme of Connection:- According to scheme of connection, distribution system may be classified as

❖ Radial system
❖ Ring main system
❖ Inter-connected system

Overhead Vs. Underground Cable- A Comparison:-

1. Public Safety:- The underground system is more safe than overhead system as there is little chance of any hazards due to high wind or breakage.
2. Initial Cost:- Underground system is more expensive due to high cost involved while laying them i.e. trenching, insulation of cables, manholes etc.
3. Flexibility:- The overhead system is more flexible as the underground cable is permanently laid and expansion is done by laying new trenches, manholes, but this demerit is not faced in overhead system.
4. Faults:- Chances of faults in underground system are very rare
5. Appearance:- General appearance of underground cable system is better and provides a clean look to the city.
6. Fault location & repairs:- In case of underground system, fault location & repair is difficult but in case of overhead system faults are easily visible by naked eye.
7. Current carrying capacity & voltage drop: An overhead distribution conductor has a considerably higher current carrying capacity but in case of underground system, conductors have much lower inductive reactance due to closer spacing.

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8. Useful Life:- The useful life of underground system is much longer than overhead system. An overhead system has a useful life of 25 years whereas underground system has useful life of more than 50 years
9. Maintenance cost:- Underground system has very less maintenance cost as compared to overhead system because of less chances of faults and service interruptions due to wind, ice or storms, traffic hazards.
10. Interference with Communication Circuits:- An overhead system causes electromagnetic interference with telephone lines but this case does not occur in underground system.

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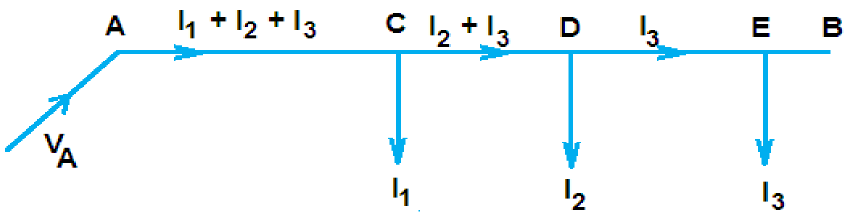
DC Distribution:- In the early days of electric power system, power was generated as Direct current and the voltage was very low. With the invention of transformer, electric power generation, transmission & distribution was started in AC. But still, DC supply is necessary for certain applications, such as for the operation of variable speed machinery, electro-chemical work and electric traction.

Types of Distributors:- The general way of classifying the DC distributors are the manner in which they are fed by the feeders.

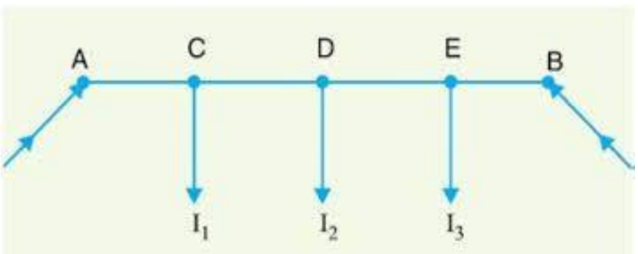
a) Distributor fed at one end
b) Distributor fed at the centre
c) Distributor fed at both ends
d) Ring Distributors

- Distributor fed at one end:- In this type, distributor is connected to the supply at one end and loads can be taken at different points all along the length of distributor. The figure below shows the distributor AB fed at one end i.e. end A and loads or tappings are taken at point C, D and E.



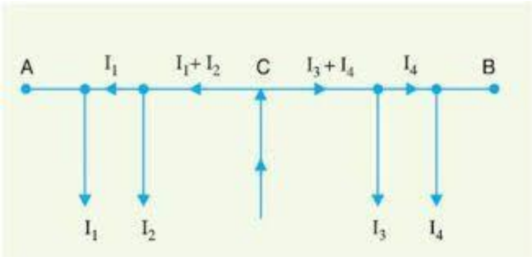
- Current in various sections of the distributor goes on decreasing as it moves away from supply end.
- Voltage across the loads away from feeding end goes on decreasing
- In case of fault on any section, whole distributor will have to be disconnected from the supply mains.

- Distributor fed at both ends:- In this type, distributor is connected to the supply at both ends and loads can be taken at different points all along the length of distributor. The figure below shows the distributor AB fed at both end i.e. end A & B and loads or tappings are taken at point C, D and E.

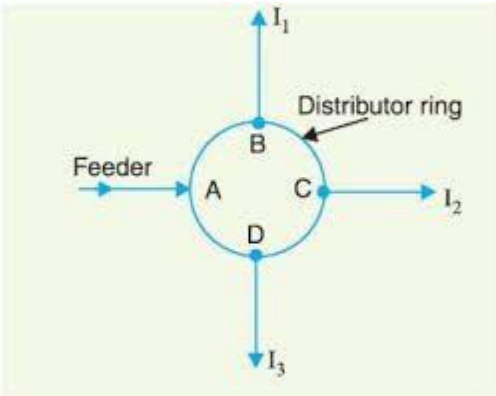


- Voltage at feeding points may or may not be equal
- Voltage across the loads away from feeding end A, goes on decreasing and reaches minimum value and then again increases when reaches the feeding point B
- In case of fault on any end, whole distributor will not have to be disconnected from the supply mains & continuity of supply is maintained from other end.
- In case of fault on any section, continuity of supply is maintained from other end.

- Distributor fed at centre:- In this type, distributor is connected to the supply as shown below. It is equivalent to two singly fed distributors, each having a common feeding point and length equal to half of the total length.



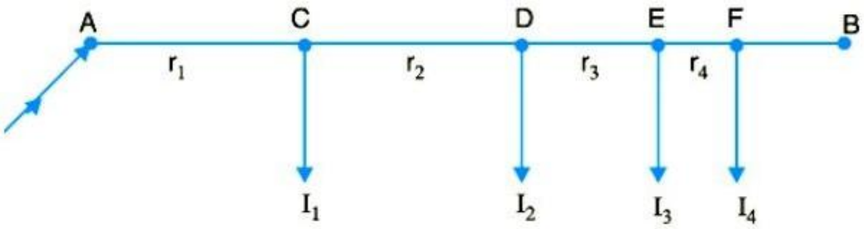
- Ring Mains:- In this type, distributor is in form of closed ring and is equivalent to a straight distributor fed at both ends with equal voltages and two ends brought together to form a closed ring. The distributor ring may be fed at one or more than one points.



DC DISTRIBUTION CALCULATION:-

a) DC distributor fed at one end (Concentrated Loading)

The figure below shows a single line diagram of 2 wire distributor AB fed at one end A with concentrated loads at points C, D , E, and F respectively i.e. I_1, I_2, I_3 and I_4



Let r_1, r_2, r_3 and r_4 be the resistances of both wires (go and return) of the section AC, CD, DE and EF of the distributor respectively.

Current fed from point A= $I_1 + I_2+I_3+I_4$

Current in section AC= $I_1 + I_2+I_3+I_4$

Current in section CD= $I_2 + I_3+I_4$

Current in section DE= I_3+I_4

Current in section EF= I_4

Voltage drop in section AC= $r_1(I_1 + I_2+I_3+I_4)$

Voltage drop in section CD= $r_2(I_2+I_3+I_4)$

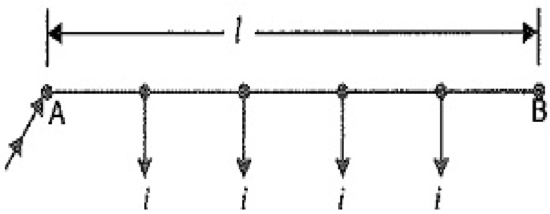
Voltage drop in section DE= $r_3(I_3+I_4)$

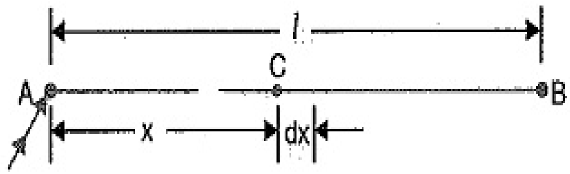
Voltage drop in section EF= r_4I_4

Total voltage drop in the distributor= $r_1(I_1 + I_2+I_3+I_4)+ r_2(I_2+I_3+I_4)+ r_3(I_3+I_4)+ r_4I_4$

- ☞ It can be seen that minimum potential will occur at point F (farthest from A)

b) Uniformly Loaded Distributor fed at one end:- Figure below shows diagram of a DC distributor AB fed at one end A and loaded uniformly with i amperes/ m length.





Consider a point C on the distributor at a distance x metres from feeding point A.

Hence the current at point C = il-ix amperes= i(l-x) amperes

Let us consider a small length dx near point C. Its resistance is rdx and

Voltage drop = dv= i(l-x) rdx= ir(l-x)dx

Total voltage drop in the distributor upto point C is

$$v = \int_0^x ir(l-x)dx = ir(lx - \frac{x^2}{2})$$

Thus, voltage drop upto point B can be obtained by putting x=l in the above equation

$$Voltage\ drop\ over\ distributor\ AB = ir\,(l*l - \frac{l^2}{2}) = \frac{1}{2}(il)*(rl) = \frac{1}{2}IR$$

Where I= total current entering at A and R= total resistance of the distributor

☞Thus it can be said that total voltage drop is equal to that produced by the whole of the load assumed to be concentrated at middle point.

c) Distributor fed at both ends- Concentrated Loading:- The two ends of the distributor may be supplied with (i) Equal Voltages (ii) Unequal Voltages

i) Two ends fed with equal Voltages:- Consider a distributor AB which is fed at both the sides with equal voltages V and have concentrated loads I_1, I_2, I_3, I_4 and I_5 at points C, D, E, F and G.

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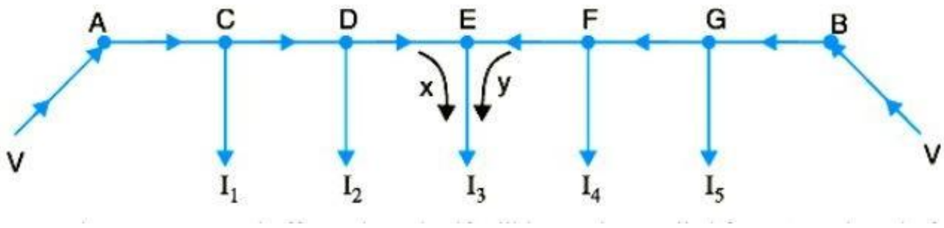


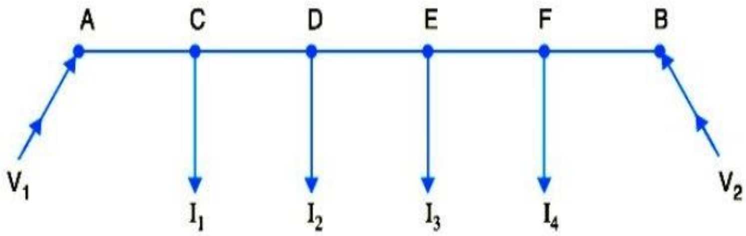
The potential drop goes on decreasing as we move away from one of feeding point (say A) and becomes minimum at some point E(say) and again starts rising and becomes V as it reaches B

Current tapped between A and E is supplied from A and those tapped in between B and E is supplied from B. Thus we can say that

$$I_3 = x+y$$

It can be concluded that point E is the point of minimum potential.

ii) Two ends fed with unequal Voltages:- Consider a distributor AB which is fed at both the sides with unequal voltages V_1 at end A and V_2 at end B.



Point of minimum potential can be found by finding

Voltage drop in between A and B= Voltage drop over AB

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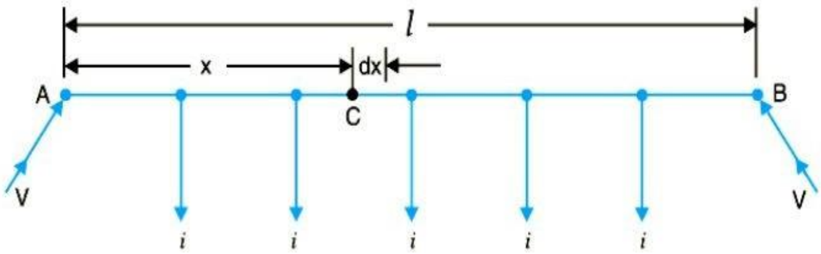
d) Uniformly Loaded Distributor Fed at both Ends:- Distributor fed at both ends can be fed with equal voltages or unequal voltages

i. Distributor Fed at both ends with equal voltages: Consider a distributor AB of length l metres, having resistance r ohm/m run with uniform loading of i amperes/m run.



Let the distributor be fed at feeding points A and B at equal voltages and total current supplied to the distributor is il. Since the two end voltages are equal, thus the current supplied from each of the feeding point is il/2

Consider a point C on the distributor at a distance x metres from feeding point A.
Hence the current at point C =(il/2)-ix amperes= i(l/2-x) amperes
Let us consider a small length dx near point C. Its resistance is rdx and
Voltage drop = dv= i(l/2-x) rdx= ir(l/2-x)dx
Total voltage drop in the distributor upto point C is

$$v = \int_0^x ir(l/2 - x)dx = ir(lx/2 - \frac{x^2}{2})$$

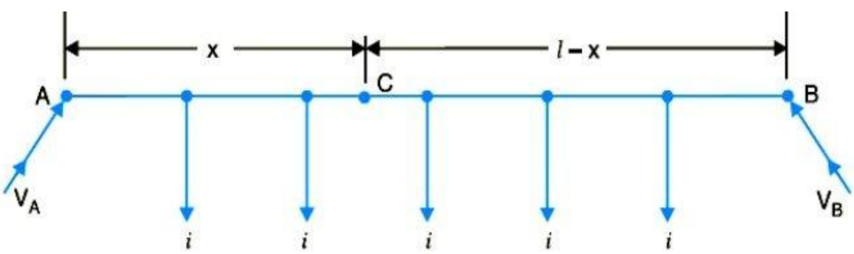
The point of minimum potential will occur at mid-point and maximum voltage drop will occur at x=l/2.

$$Maximum\ Voltage\ drop = ir/2\,(l * l/2 - \frac{l^2}{4}) = \frac{1}{8}(il) * (rl) = \frac{1}{8}IR$$

Where I= total current entering at A and R= total resistance of the distributor

Minimum Voltage= V- IR/8 Volts

ii. Distributor Fed at both ends with unequal voltages: Consider a distributor AB of length l metres, having resistance r ohm/m run with uniform loading of i amperes/m run.



Let the distributor be fed at feeding points A and B with unequal voltages of V_A and V_B

Consider a point C on the distributor at a distance x metres from feeding point A.

Current supplied from feeding point A = ix

Voltage drop in section AC= $irx^2/2$

As distance from B to C is l-x, thus current fed from B is i(l-x)

$$Voltage\ drop\ in\ section\ BC = \frac{ir(l-x)^2}{2}\ volts$$

Voltage at point C, $V_C = V_A$- Drop over AC

$$= V_A - \frac{irx^2}{2}$$

Also, Voltage at point C, $V_C = V_B$- Drop over BC

$$= V_B - \frac{ir(l-x)^2}{2}$$

Equating both the equations, we get

$$V_A - \frac{irx^2}{2} = V_B - \frac{ir(l-x)^2}{2}$$

Solving we get,

$$x = \frac{V_A - V_B}{irl} + \frac{l}{2}$$

Problem:- Two tram cars A and B 2km and 6km away from a sub-station returns 40A and 20A respectively to the rails. The sub-station voltage is 600V dc. The resistance of trolley wire is 0.25Ω/km and that of track is 0.03Ω/km. Calculate the voltage across each tram car.

Solution:- The tram car operates on dc. The positive wire is placed overhead while the rail track acts as the negative wire. The figure below shows the signal line diagram of the arrangement

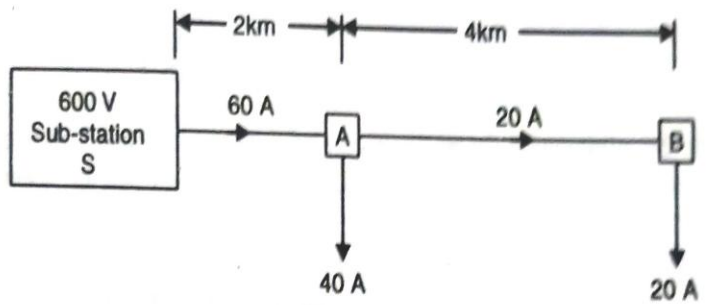


Fig. 13.8

Resistance of trolley wire and track/km

$= 0{\cdot}25 + 0{\cdot}03 = 0{\cdot}28\ \Omega$

Current in section SA $= 40 + 20 = 60$ A

Current in section AB $= 20$ A

Voltage drop in section SA $= 60 \times 0{\cdot}28 \times 2 = 33{\cdot}6$ V

Voltage drop in section AB $= 20 \times 0{\cdot}28 \times 4 = 22{\cdot}4$ V

∴ Voltage across tram A $= 600 - 33{\cdot}6 = 566{\cdot}4$ V

Voltage across tram B $= 566{\cdot}4 - 22{\cdot}4 = 544$ V

Problem:- A two wire dc distributor cable 1000m long is loaded with 0.5A/m. Resistance of each conductor is 0.05Ω/km. Calculate the maximum voltage drop if the distributor is fed from both ends with equal voltages of 220V. What is the minimum voltage and where it occurs?

Solution:-

Current loading, $i = 0{\cdot}5$ A/m

Resistance of distributor/m, $r = 2 \times 0{\cdot}05/1000 = 0{\cdot}1 \times 10^{-3}\ \Omega$

Length of distributor, $l = 1000$ m

Total current supplied by distributor, $I = i\,l = 0{\cdot}5 \times 1000 = 500$ A

Total resistance of the distributor, $R = r\,l = 0{\cdot}1 \times 10^{-3} \times 1000 = 0{\cdot}1\ \Omega$

$$\therefore \quad \text{Max. voltage drop} = \frac{I\,R}{8} = \frac{500 \times 0{\cdot}1}{8} = \mathbf{6{\cdot}25\ V}$$

Minimum voltage will occur at the mid-point of the distributor and its value is

$$= 220 - 6{\cdot}25 = \mathbf{213{\cdot}75\ V}$$

Problem:- A 2-wire dc distributor ABCDEA in the form of a ring main is fed at point A at 220V and is loaded as under:

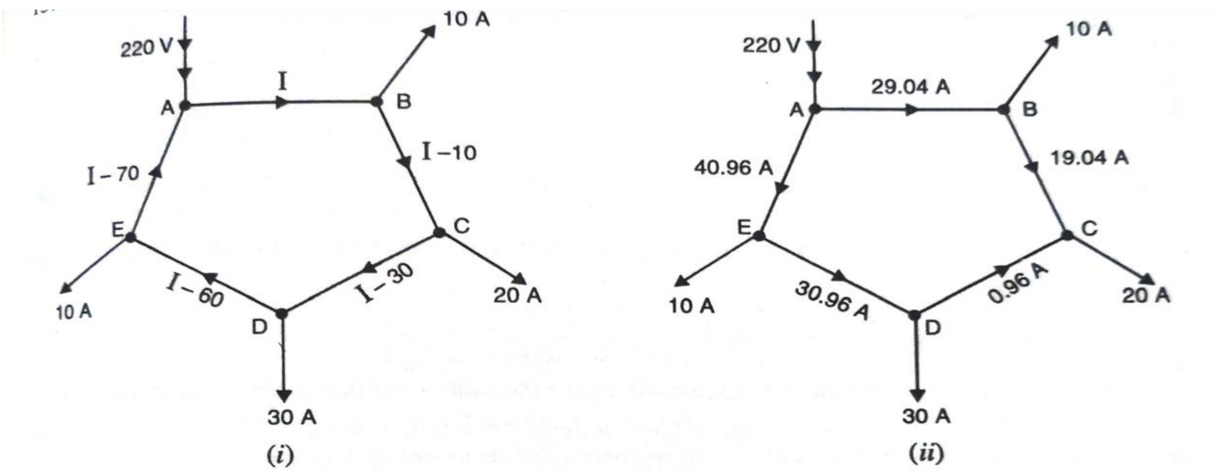
10A at B; 20A at C; 30A at D; and 10A at E

The resistances of various sections (go and return) are :- AB= 0.1Ω; BC= 0.05Ω; ,CD= 0.01Ω; DE= 0.025Ω and EA =0.075Ω. Calculate:

i) Point of Minimum Potential

ii) Current in each section of distributor

Solution:- Let I current flows in section AB as shown below



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(*i*) According to Kirchhoff's voltage law, the voltage drop in the closed loop *ABCDEA* is zero *i.e.*

$$I_{AB} R_{AB} + I_{BC} R_{BC} + I_{CD} R_{CD} + I_{DE} R_{DE} + I_{EA} R_{EA} = 0$$

or $$0{\cdot}1I + 0{\cdot}05\,(I - 10) + 0{\cdot}01\,(I - 30) + 0{\cdot}025\,(I - 60) + 0{\cdot}075\,(I - 70) = 0$$

or $$0{\cdot}26\,I = 7{\cdot}55$$

∴ $$I = 7{\cdot}55/0{\cdot}26 = 29{\cdot}04 \text{ A}$$

The actual distribution of currents is as shown in Fig. 13.37 (*ii*) from where it is clear that *C* is the point of minimum potential.

∴ *C* is the point of minimum potential.

(*ii*) Current in section *AB* = I = **29·04 A** *from A to B*

Current in section *BC* = $I - 10 = 29{\cdot}04 - 10$ = **19·04 A** *from B to C*

Current in section *CD* = $I - 30 = 29{\cdot}04 - 30 = -0{\cdot}96$ A = **0·96 A** *from D to C*

Current in section *DE* = $I - 60 = 29{\cdot}04 - 60 = -30{\cdot}96$ A = **30·96 A** *from E to D*

Current in section *EA* = $I - 70 = 29{\cdot}04 - 70 = -40{\cdot}96$ A = **40·96 A** *from A to E*

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ECONOMICS OF POWER TRANSMISSION

The following two economic principles influence the electrical design of transmission line

a) Economic Choice of Conductor Size
b) Economic Choice of Transmission Voltage

The cost of conductor material is a very important part of total cost of transmission line.

Kelvin's Law

"The Most Economical area of conductor is that for which the total annual cost of transmission line is minimum"

The total annual cost of transmission line is broadly divided into

a) Annual Charge on Capital Outlay
b) Annual charge of energy wasted in the conductor

a) Annual Charge on Capital Outlay

This is on account of interest & depreciation on the capital cost of complete installation

Annual Charge on an overhead line can be expressed as

$$\text{Annual Charge} = P_1 + P_2 a$$

b) Annual cost of energy wasted: - Assuming a constant current in the conductor throughout the year, the energy lost in the conductor is proportional to resistance.

Annual cost of Energy Wasted = P_3/a where P_3 is a constant

$$\text{Total annual cost, } C = P_1 + P_2 a + P_3/a$$

In the above expression, only area of X-section a is variable. Therefore total annual cost of transmission line will be minimum if differentiation of C w.r.t a is zero

$$\frac{d}{da}(C) = 0$$

$$\text{or} \quad \frac{d}{da}(P_1 + P_2 a + P_3/a) = 0$$

$$\text{or} \quad P_2 - \frac{P_3}{a^2} = 0$$

$$\text{or} \quad P_2 = P_3/a^2$$

$$\text{or} \quad P_2 a = \frac{P_3}{a}$$

i.e. Variable part of annual charge= Annual cost of energy wasted

Limitations of Kelvin's Law:-

i. It is not easy to estimate the energy loss in the line
ii. Assumption that annual cost on account of interest & depreciation on capital outlay is not true. For example, in cables, neither the cost of cable dielectric and sheath nor the cost of laying vary in said manner.
iii. This law does not take into account physical factors like safe current density, mechanical strength, corona loss
iv. Conductor size may not be practicable
v. Interest & depreciation on capital outlay cannot be determined accurately.

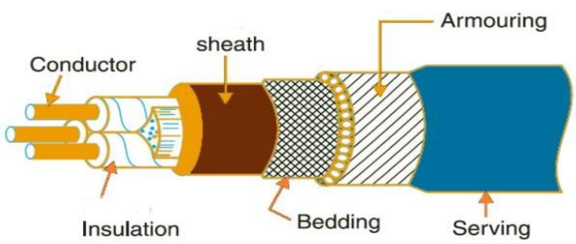
UNDERGROUND CABLE: - It is known that transmission & distribution system can be achieved by both overhead means as well as underground means. Mostly Underground system is not used in the Transmission system due to its high cost of insulation & laying down of trenches. But Underground system is preferred in the distribution system as it is a convenient method of distribution & provides better look to the cities. The Underground cable consists of a central conductor with insulation to isolate the conductors from each other and their surroundings.

The materials employed for conductors generally are annealed copper & aluminium. The use of copper is limited to cables used for control circuits, signalling & communications.

Construction of Cables:-

The figure below shows the constructional details of underground cable. The different parts are:-

a) Core or Conductor:- An underground cable have one or more than one core which depends on its type of service. Cores are made up of tinned copper or Aluminium and are stranded to gain flexibility.
b) Insulation:- The core or conductor is provided with a suitable thickness which depends upon the voltage to be withstood. Most commonly used material for insulation is impregnated paper, varnished cambric, rubber mineral compound
c) Metallic Sheath:- To protect the cable from moisture, gases or other damaging liquids in the soil or atmosphere, metallic sheath of lead or aluminium is provided over the insulation.
d) Bedding:-A layer of bedding is applied over the metallic sheath consisting of fibrous material like jute and is provided to protect the sheath from corrosion and mechanical injury
e) Armouring:- Over bedding, armouring is provided consisting of one or two layers of galvanized steel wire or steel tape and it protects the cable from mechanical injury while laying down or handling
f) Serving:- To protect the armouring from atmospheric conditions, a layer of fibrous material like jute is provided over the armouring. It is known as Serving.



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INSULATION:- The conductors of a cable needs to be covered by an insulation to isolate the conductors from each other & from their surroundings.

Properties of insulation material:-

a) It should have high dielectric strength
b) It should have high insulation resistance
c) It should have good mechanical strength
d) It should be able to withstand temperatures from -30^{0}C to over 100^{0}C

Insulation Materials:-

i. VIR Cables:- Vulcanized India Rubber insulation was developed in 1870 and has dielectric strength of about 10-20KV/mm and a dielectric constant of about 2.5. Sulphur is mainly used as Vulcanizing agent.
The insulation is limited to wiring cables for lighting & minor power installations.
ii. Elastomer Insulated Cables:- Elastomeric insulation includes-rubber, butyl rubber, silicone rubber and ethylene propylene rubber. Elastomers have rubber like characteristics which is achieved by compounding the basic polymer with selective additives. Polychloroprene or Neoprene is obtained by polymerization of chloroprene. The raw polymer contains about 35% chlorine hence it is self extinguishing.
iii. PVC Cables:- Polyvinyl Chloride is a synthetic material obtained from acetylene and can be produced in number of grades depending on polymerization process. It is in form of white powder that is odourless, tasteless, chemically inert, non-inflammable and insoluble at ordinary temperatures in all liquids.
iv. XLPE Cables:- Low density polythene, when vulcanized under controlled conditions results in cross linking of carbon atoms and produces cross linked polythene. This material does not melt although it carbonizes at 250^{0}C-300^{0}C. XLPE has the advantages of light weight, small overall cable dimensions, low dielectric constant and good mechanical strength. These conductors can be buried directly in soil as this has low water absorption.
v. Paper insulated Cables:- Paper is the most important insulating material which is used in the manufacture of power cables upto 500KVA rating. It has the advantages of superior heat conductivity, ability to withstand, high temperature, durability, high dielectric strength, low cost and low electrostatic capacitance.
For providing insulation over the conductor the paper tape is lapped on to the conductor until the required thickness is obtained, it is then dried and impregnated with insulating compound. The thickness of insulation depends on the mechanical and electrical requirements which it has to withstand in service.

Classification of Cables:- Depending upon the type of voltage for which it is to be used, cables are classified as

Low Tension(L.T) Cables:- upto 1000V

High Tension(H.T) Cables:- upto 11000V

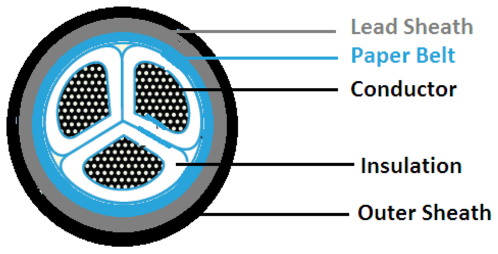
Super Tension (S.T) Cables:- from 22KV to 33KV

Extra High Tension(EHT) Cables:- from 33KV to 66KV

Extra Super Voltage Cables:- beyond 132KV

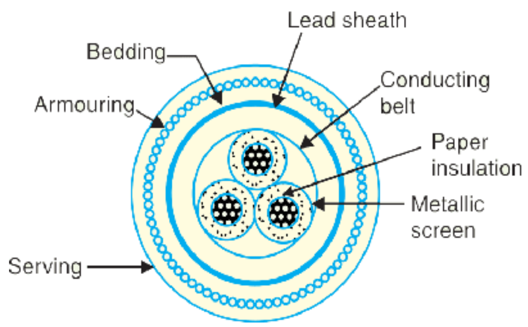
The following type of cables are generally used for 3-phase services

1. Belted Cables:- These are used for voltages upto 11KV and may be extended to 22KV. The cores are insulated from each other by layers of impregnated paper.
   - ☞ Another type of insulation, called paper belt is wound round the grouped insulated cores.
   - ☞ The gap is filled by fibrous material like jute and belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury.
   - ☞ The lead sheath is covered with one or more layers of armouring with an outer serving.



Belted Cable

2. Screened Cables:- These cables are used for using lines upto 33KV and in some cases upto 66KV.
   a) H-Type Cables:- It was designed by H.Hochstadter and each core is insulated by layers of impregnated papers.
   - ☞ Insulation on each core is covered with a metallic screen consisting of perforated Aluminium foil.
   - ☞ The cores are placed such that metallic screens make contact with each other.
   - ☞ An additional conducting belt is wrapped round three cores



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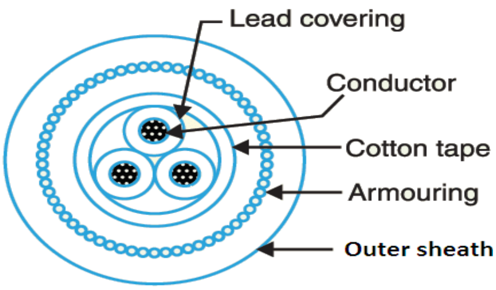
b) S.L Type Cables:- It is Separate Lead Cables and the screen round each core insulation is covered by its own lead sheath.

- There is no overall lead sheath but only armouring & serving are provided.
- Separate sheaths minimize the possibility of core to core breakdown.
- Bending of cables becomes easy due to elimination of overall lead sheath

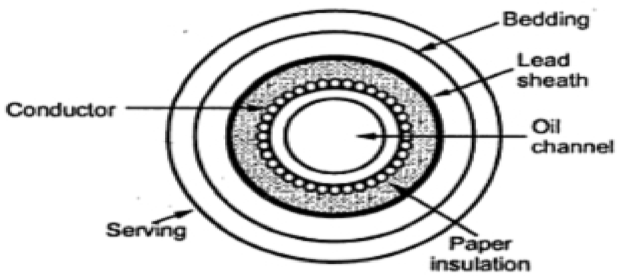


S. L. Cable

3. Pressure Cables:- For voltages beyond 66KV, solid type cables are unreliable due to voids and hence breakdown. Voids are eliminating by increasing the pressure of compound and thus called pressure cables.

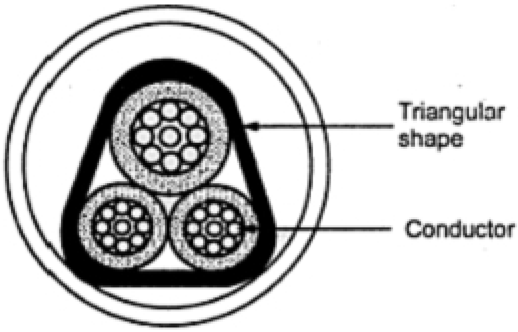
a) Oil Filled Cables:- In these type of cables, channels of ducts are provided in the cable for oil circulation. Oil under pressure is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances along the route of the cable.

- Due to elimination of voids, oil filled cables can be used for higher voltages



b) Gas pressure Cables:- The voltage required to set up ionization inside a void increases as the pressure is increased. The below figure shows the gas pressure cable and it has triangular shape and thickness of lead sheath is 75% that of solid cable. The triangular section reduces the weight and gives low thermal resistance and triangular shape acts as pressure membrane. Sheath is made up of thin metal tape and cable is laid in a gas tight steel pipe. The pipe is filled with nitrogen gas at 12 to 15 atm.

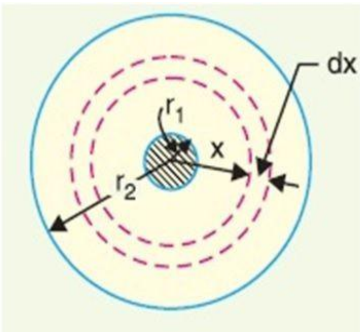
The gas pressure produces radial compression and closes the voids.



Parameters of Cables

1. Insulation Resistance: - The opposition offered by insulation to leakage current is known as insulation resistance of the cable.

Consider a single core cable of conductor radius r_1 and internal sheath radius r_2. Let l be the length of the cable and ρ be the resistivity



Consider a very small layer of insulation of thickness dx at a radius x. The length through which leakage current tends to flow is dx and the area of X-section offered to this flow is 2πxl

∴ Insulation resistance of considered layer

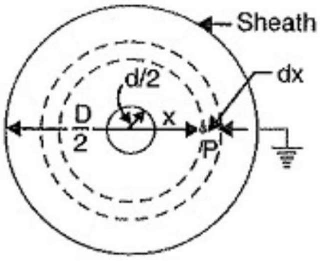
$$= \rho \frac{dx}{2\pi x l}$$

Insulation resistance of the whole cable is

$$R = \int_{r_1}^{r_2} \rho \frac{dx}{2\pi x l} = \frac{\rho}{2\pi l} \int_{r_1}^{r_2} \frac{1}{x} dx$$

$$\therefore \quad R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}$$

2. Capacitance of Single core Cable:- Consider a single core cable with conductor diameter d and inner sheath diameter D. Charge per meter axial length be Q and ε be the permittivity of insulation material between core and lead sheath



Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is $= 2\pi x \times 1 = 2\pi x \ m^2$

$\therefore$ Electric flux density at any point P on the considered cylinder is

$$D_x = \frac{Q}{2\pi x} \ C/m^2$$

Electric intensity at point P, $E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r}$ volts/m

Work done in moving a unit positive charge from conductor to sheath

$$V = \int_{d/2}^{D/2} E_x dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} dx = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} log_e \frac{D}{d}$$

Capacitance of the Cable is

$$C = \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log_e \frac{D}{d}} \ F/m$$

$$= \frac{2\pi \varepsilon_o \varepsilon_r}{\log_e(D/d)} \ F/m$$

$$= \frac{2\pi \times 8\cdot854 \times 10^{-12} \times \varepsilon_r}{2\cdot303 \log_{10}(D/d)} \ F/m$$

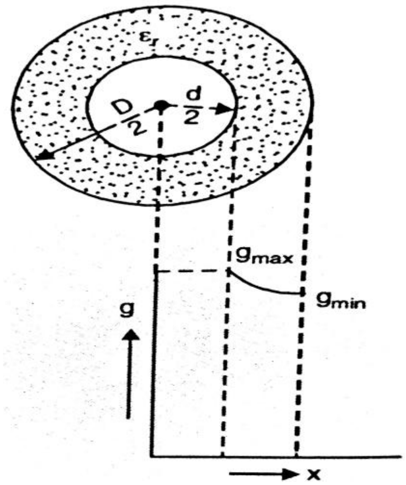
$$= \frac{\varepsilon_r}{41\cdot4 \log_{10}(D/d)} \times 10^{-9} \ F/m$$

If the cable has a length of l metres, then capacitance of the cable is

$$= \frac{\varepsilon_r \ l}{41\cdot4 \log_{10} \frac{D}{d}} \times 10^{-9} \ F$$

3. Dielectric Stress in a Single Core Cable

Consider a single core cable with core diameter d and internal sheath diameter D.



Electric intensity at a point x meters from centre of cable

$$E_x = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x} \text{ volts/m}$$

Electric intensity is equal to potential gradient. Therefore potential gradient g at a point x metres from the centre of cable is

$$g = E_x$$

$$g = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r x} \text{ volts/m}$$

Potential difference V between conductor and sheath is

$$V = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log_e \frac{D}{d} \text{ volts}$$

$$Q = \frac{2\pi \varepsilon_0 \varepsilon_r V}{\log_e \frac{D}{d}}$$

Substituting the Value of Q in 'g', we get

$$g = \frac{V}{x \log_e \frac{D}{d}}$$

Potential gradient varies inversely as distance x. Potential gradient will be maximum when x is minimum when x= d/2 or at surface of conductor. Similarly potential gradient will be minimum at x= D/2 or at sheath surface.

$$g_{max} = \frac{2V}{d \log_e \frac{D}{d}} \quad \text{and } g_{min} = \frac{2V}{D \log_e \frac{D}{d}}$$

$$\frac{g_{max}}{g_{min}} = \frac{D}{d}$$

Dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from conductor.

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Grading of Cables:- The process of achieving uniform electrostatic stress in the dielectric of cables.

Unequal stress distribution is undesirable due to

a. Greater thickness is required thus increasing the size of cable
b. May lead to breakdown of insulation

Two main methods of Grading

a. Capacitance Grading:- The process of achieving uniformity in the dielectric stress by using layers of different dielectrics
b. Intersheath Grading:- In this method, a homogenous dielectric is used but it is divided into various layers by placing metallic intersheaths between core and lead sheath

POWER SYSTEM EARTHING

Objectives of Earthing:-

a) To ensure that no part of equipments should assume a potential which is dangerously different from that of surroundings.
b) To allow sufficient current to flow safely for proper operation of protective devices
c) To limit over voltages between neutral and ground and between line and ground
d) To suppress dangerous potential gradients.

Definitions:-

i) Earth Electrode:- A rod, pipe, plate or array of conductors, embedded in earth horizontally or vertically.
ii) Earth current:- Current dissipated by earth electrode into the ground
iii) Resistance of earth electrode:- The resistance offered by the earth electrode to the flow of current into the ground
iv) Step Potential:- Potential difference shunted by a human body between two accessible points on the ground separated by the distance of one pace assumed to be equal to 1m
v) Touch Potential:- The potential difference between a point on the ground and a point on an object likely to carry fault current and which can be touched by a person.

Soil Resistivity:-

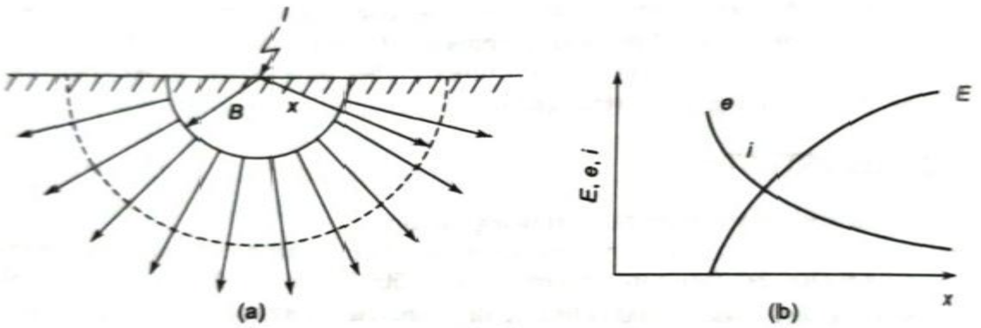
The resistivity of soil depends on

a) Soil Type:- Some typical values are :- Sea Water(2.5 ohm-m), Tap water(20 ohm-m), Clay (50 ohm-m), Sand Clay mixture(100 ohm-m), Sand(2000 ohm-m), Wet concrete (100 ohm-m), dry concrete(10000 ohm-m), rock(10000 ohm-m)
b) Moisture Content:- Electrical Conduction in soils is electrolytic. Soil resistivity decreases with increase in moisture content
c) Temperature:- When temperature is more than 0 deg C, its effect on soil resistivity is negligible
d) Salt Content
e) Magnitude of Current:- If the value of current being dissipated by the soil is high, it may cause significant drying of soil and increase in its resistivity.

Earth Resistance:-

a) Hemispherical Electrode:- The figure below shows a buried hemisphere.

The total resistance is divided into 3 parts i.e. Resistance of conductor, contact resistance between the surface of electrode and main body of earth and resistance of body of earth surrounding the electrode.



(a) (b)

Resistance of conductor & contact resistance is negligible and thus main part of resistance is that part of body of earth surrounding the electrode

The current density ‘i’ at a distance x from centre of electrode is

$$i = \frac{I}{2\pi x^2}$$

As per ohm's law electric field strength e due to current density i is:

$$e = \rho i = \frac{\rho I}{2\pi x^2}$$

The voltage is the line integral of field strength e from surface of sphere of radius B to distance x.

$$E = \int_B^x e\,dx = \frac{\rho I}{2\pi}\int_B^x \frac{dx}{x^2} = \frac{\rho I}{2\pi}\left[\frac{1}{B} - \frac{1}{x}\right]$$

The voltage between the hemispherical electrode and a point of infinity is

$$E = \frac{\rho I}{2\pi B}$$

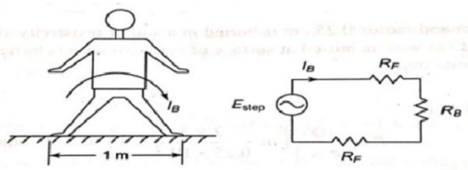
The earth resistance is

$$R = \frac{E}{I} = \frac{\rho}{2\pi B}$$

TOLERABLE STEP & TOUCH POTENTIAL:-

- Tolerable Potential:- The potential difference between a point on the ground and a point on an object likely to carry fault current(e.g frame of equipment) and which can be touched by a person
- Step Potential:- The potential difference shunted by a human body between two accessible point on the ground separated by the distance of one pace assumed to be equal to 1m

The figure below shows the circuit for step contact



Human body can be taken as equivalent to a circular plate electrode with a radius of 0.08m and its earth resistance is assumed to be 3ρ(s)

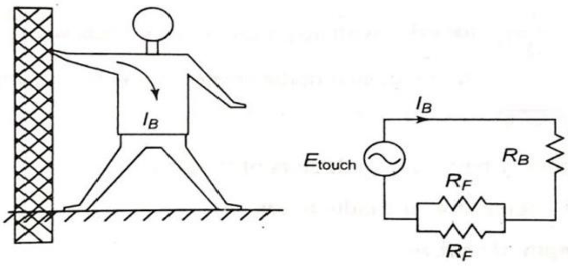
$$E_{step} = (R_B + 2\,R_F)\,I_B \text{ volts}$$

Substituting the values of R_B, R_F and I_B (from Eq. 18.1), we get

$$E_{step} = (1000 + 6\rho_s)\,0.116/\sqrt{t} \text{ volts}$$

Touch Voltage:- The figure below shows circuit for touch contact. The maximum earth p.d intercepted would be that which would occur a distance along the ground equal to maximum possible horizontal reach. Tolerable value of touch potential is

$$E_{touch} = (R_B + 0.5\,R_F)\,I_B = (1000 + 1.5\,\rho_s)\,0.116/\sqrt{t} \text{ volts}$$



Actual Touch & Step Voltages:- For calculation of actual touch & step voltages for a grid is very difficult & is possible by computer.
The maximum voltage within the mesh of the grid is known as mesh voltage

$$E_m = \rho\,K_m\,K_i\,I/L$$

E_m = mesh voltage, volts

ρ = soil resistivity, ohm-m

I = Total current dissipated by grid

$L = L_c + 1.1.5\,L_r$ for grids with rods along perimeter, m

$= L_c + L_r$ for grids with no rods or rods evenly spread all over, m

L_c = total length of horizontal grid conductors, m

L_r = total length of ground rods, m

$K_i = 0.656 + 0.172\,n$

$$K_m = \frac{1}{2\pi}\left[\ln\left(\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{K_{ii}}{K_h}\ln\frac{8}{\pi(2n-1)}\right]$$

Single Wire Earth Return Concept in Distribution System:-

- A Single Wire Earth Return (SWER) system is a single wire distribution line for supplying single phase electric power.
- It has a distinguishing feature in that it uses the earth as the return path for the current thus avoiding the need for a second wire or neutral wire to act as a return path